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From the file, ...panda2/doc/panda2.news :

790. April, 2009

THE INTRODUCTION OF COLD-BENDING RING BUCKLING MARGINS INTO PANDA2

This is an important news item. Often cylindrical shells are fabricated by cold bending a flat plate or sheet into a cylindrical form. NASA fabricates some light-weight stiffened cylindrical shells with use of the following steps:

1. A regular array of "pockets" is "hogged out" of a rather thick flat plate. The "hogged out" flat plate is then a "stiffened" flat plate, with the stiffeners (stringers and rings) being the thicker material between the "pockets".

2. The "hogged out" plate is then cold bent into a cylindrical shell, or rather into a part of a cylindrical shell, say a panel subtending 120 degrees or something like that. The cold-bending is applied usually with the stiffeners on the inside. In this process the plate is bent into a radius, call it "RCOLD", which is smaller than the design radius, call that "RCYL". Upon elastic spring-back the final radius should be close to RCYL.

3. An annealing process is applied to the cold-bent cylindrical panel.

4. A number of cylindrical panels fabricated in this way are welded together to form a complete (360-degree) cylindrical shell.

This news item is concerned with Step 2. The question arises, "How can the designer determine the best "slenderness" (height-to-thickness ratio) of the rings, which experience potentially destabilizing hoop compression during the cold-bending process?" The designer wants the rings to be thick enough so that they do not buckle during the cold-bending process, but not so thick as to represent an unnecessary weight penalty. This question does not arise in the case of the stringers because they do not bend during the cold bending process.

In order to provide an answer to this question, three new design margins have been introduced into PANDA2 in Load Set 1, Subcase 1, In the list of margins presented for Load Set 1, Subcase 1 the **three new margins** (for an optimized shell without internal sub-rings) appear as follows:

17 6.59E-01 Cold-bending ring buckling, closed form soln; N=154;FS=1.1
18 6.41E-01 Cold-bending ring buckling, "skin"-ring module; N=92 ;FS=1.1
19 1.43E-03 Cold-bending ring buckling, skin-ring module; N=61 ;FS=1.1

in which N is the number of circumferential halfwaves in the critical buckling mode. If there are internal sub-rings, then there is an additional cold-bending buckling margin of the form:

31 -2.46E-04 Cold-bending subring buckling, closed form soln; N=102;FS=1.1

The first of the three margins listed above (Margin 17) is derived from a "closed form" analysis in which it is assumed that the skin plays no role in the buckling. A polynomial expression in assumed for the distribution of normal deflection of the internal ring web. This polynomial has three undetermined coefficients. An eigenvalue problem of rank 3 is set up and solved for the three real eigenvalues, the lowest positive one of which is the critical ring web buckling load factor. These computations are carried out in **SUBROUTINE COLDBD**, which is called from SUBROUTINE STRUCT.

The new SUBROUTINE COLDBD first computes iteratively what the cold-bending radius, RCOLD, is, that is, the radius, RCOLD, such that after elastic spring-back the final radius is close to the nominal (design) radius, RCYL, of the fabricated cylindrical shell.

Next, SUBROUTINE COLDBD computes the effective wall stiffnesses (the 6 x 6 integrated constitutive matrices, Cij) of the skin, ring web, and ring outstanding flange (if any) to be used in the various buckling analyses leading to the three new margins listed above.

The second of the three margins listed above is derived from a discretized single-module "skin"-ring module of the type described in the paper, "Additional buckling solutions in PANDA2", AIAA Paper AIAA-99-1233, 40th AIAA Structures Meeting, 1999, pp. 302-345; (See pp. 318 - 321 and Fig. 30). The word, "skin", is in quotes because "skin" represents the skin plus smeared stringers (and smeared substiffeners, if any). The prebuckling distribution of stress resultants over the "skin" ring module is derived in the new SUBROUTINE COLDBD. Also, the elastic-plastic integrated 6 x 6 constitutive matrices Cij (called CXCOLD and CYCOLD) for the "skin"-ring module segments ("skin", ring web, ring outstanding flange) are computed in SUBROUTINE COLDBD. The critical elastic-plastic cold-bending buckling load factor is obtained over a range of circumferential wave numbers in search of the critical (lowest) eigenvalue (buckling load factor).

The third of the three margins listed above is derived from the same type of model as the second. In this case the stringers are eliminated. Therefore, the buckling model is a discretized skin-ring single module model with smeared sub-stiffeners, if any. The word, skin, is not in quotes because in this model the shell skin without any smeared stiffeners forms the first part of the discretized module. **This margin is usually the most critical of the three.** Buckling load factors from this third model are more accurate than the first model, the "closed-form" model, because the deformation of the panel skin in the cold-bending buckling mode is accounted for, whereas in the "closed-form" model the skin is assumed to remain undeformed during buckling. The third model is more conservative than the second model because the stringers are neglected (sub-stiffeners are smeared). **The third model is appropriate, however, because the critical circumferential wavelength of the cold-bending buckling mode is restricted to be less than or equal to the spacing between the stringers.**

The cold-bending buckling analysis is entered only if the PANDA2 user chooses that he or she wants to provide input data for a stress-strain "curve" for Material Type 1 . The nonlinear stress-strain curve is used ONLY in the cold-bending ring buckling analysis. All the other buckling and stress margins computed by PANDA2 are still based on elastic material behavior.

The prompting file, .../execute/**PROMPT.DAT**, was modified as follows:

```
-----------------------------------------------------------------
238.1 Want to supply a stress-strain "curve" for this mat'l (H)?
238.2
      Please use elastic properties only unless you want to
      simulate the cold-bending fabrication process. (See Item
      No. 790 in the file, ...panda2/doc/panda2.news).

      The stress-strain curve is used ONLY in the analysis of
      cold-bending. (See Item No. 790 in ...panda2/doc/panda2.news).
      PANDA2 does not account for plasticity or nonlinear stress-
      strain curves in its ordinary buckling and stress analyses,
      even if you choose to provide a stress-strain curve here..

      The stress-strain curve is used ONLY for generating a buckling
      constraint condition for buckling of an INTERNAL Tee-shaped or
      rectangular ring during the cold-bending of a flat plate with
      "hogged out" pockets that form stiffeners into a cylindrical
```

panel.

If you want to simulate the cold-bending process:

1. The entire structure must be fabricated from the same isotropic material. (You can supply more than one material type in the PANDA2 model, but all material types must have the same isotropic elastic properties.)

2. If in the PANDA2 model you plan to introduce more than one material type (in order to identify what the maximum stresses are in the various parts of the shell structure) the stress-strain curve must be supplied ONLY FOR THE FIRST MATERIAL TYPE in the PANDA2 model, that is, for material index no. 1 . All other material types must correspond to elastic, isotropic materials with the same elastic properties as those of material type 1 .

NOTE: The stress-strain curve is assumed to be the same for both tension and compression.

239.0

The stress-strain curve is used ONLY in the analysis of cold-bending. (See Item No. 790 in ...panda2/doc/panda2.news). PANDA2 does not account for plasticity or nonlinear stress-strain curves in its ordinary buckling and stress analyses. The stress-strain curve is used ONLY for generating a buckling constraint condition for buckling of an INTERNAL Tee-shaped or rectangular ring during the cold-bending of a flat plate with "hogged out" pockets that form stiffeners into a cylindrical panel.

If you want to simulate the cold-bending process:

1. The entire structure must be fabricated from the same isotropic material. (You can supply more than one material type in the PANDA2 model, but all material types must have the same isotropic elastic properties.)

2. If in the PANDA2 model you plan to introduce more than one material type (in order to identify what the maximum stresses are in the various parts of the shell structure) the stress-strain curve must be supplied ONLY FOR THE FIRST MATERIAL TYPE in the PANDA2 model, that is, for material index no. 1 . All other material types must correspond to elastic, isotropic materials with the same elastic properties as those of material type 1 .

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      NOTE: The stress-strain curve is assumed to be the same
            for both tension and compression.

      Next, supply a table of (strain, stress) values, starting with
      (0., 0.).   Maximum of 20 (strain, stress) pairs permitted.

240.1 strain coordinate for stress-strain "curve", strain
240.2
      NOTE: the first strain entry must be zero.
      NOTE: the second strain entry (the first non-zero entry)
      must have the value: strain(2) = stress(proportional limit)/E.

241.1 stress coordinate for stress-strain "curve", stress
241.2
      NOTE: the first stress entry must be zero.
      NOTE: the second stress entry (the first non-zero entry)
      must have the value: stress(2) = stress(proportional limit).

242.1 any more (strain, stress) pairs (Y or N)?

 (lines skipped to save space)

270.1 Does cold bending include the outstanding ring flange?
270.2
      If there are no outstanding ring flanges, answer "N".
      If the final fabricated panel or shell has rings with
      outstanding flanges, then read on.

      The cylindrical shell may be cold bent before outstanding
      flanges are welded on to the tips of the ring webs, or the
      outstanding ring flanges may be present during the cold
      bending process. If only the ring webs exist when the cold
      bending process takes place, then the analysis of buckling
      during the cold-bending process will be undertaken with the
      assumption that the flanges are made of very, very soft
      material and experience no prebuckling compression at all.

271.1 ring web radial compression, FN1WEB
271.2
      When the flat plate with "hogged out" pockets is formed into
      a cylindrical panel by cold bending, there may, during the
      cold-bending process, occur a compressive radial resultant,
      FN1WEB, generated. FN1WEB (units=force/length) is the maximum
      radial compression in a ring web during the cold-bending
      process.

      It is best for now to use zero: FN1WEB = 0.
-----------------------------------------------------------------
```

An example of the input file for BEGIN appropriate for a case
in which cold-bending will be simulated follows (*.BEG file, etc.,etc.
(for more please see the file, panda2.papers/2009.coldbend.pdf