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OPTIMUM DESIGN OF STIFFENED PANELS WITH SUBSTIFFENERS

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(This is an abridged version. See the full-length paper for more: panda2.papers/2005.substiff.pdf)

ABSTRACT

The capability of the computer program PANDA2 to generate minimum-weight designs of stiffened panels and cylindrical shells is enhanced to permit the adding of substiffeners with rectangular cross sections between adjacent major stringers and major rings. As a result many new buckling margins exist that govern buckling over various domains and sub-domains of the doubly stiffened panel or shell. These generally influence the evolution of the design during optimization cycles. The substiffeners may be stringers and/or rings or may form an isogrid pattern. The effects of local, inter-ring, and general buckling modal imperfections can be accounted for during optimization. Perfect and imperfect cylindrical shells with external T-shaped stringers and T-shaped rings and with and without substringers and subrings and under combined axial compression, external pressure, and in-plane shear are optimized by multiple executions of a "global" optimizer called SUPEROPT. It is found that from the point of view of minimum weight there is little advantage of adding substiffeners. However, with substiffeners present the major stringers and rings are spaced farther apart at the optimum design than is so when there are no substiffeners. The weight of a cylindrical shell with substiffeners is much less sensitive to the spacing of the major T-shaped stringers than is the case for a cylindrical shell without substiffeners. The optimum designs obtained by PANDA2 are evaluated by comparisons with buckling loads obtained from a general-purpose finite element program called STAGS. Predictions from STAGS agree well with those from PANDA2.

INTRODUCTION

Local and overall buckling and optimization of panels can be determined with the PANDA2 [1], POSTOP [2], VICONOPT [3], and PASCO [4] computer programs. These four programs are capable of obtaining optimum designs, and PANDA2, POSTOP, and VICONOPT can do so including the effect of local postbuckling of the panel skin and/or parts of the stringers.

Other contributions to the field of buckling and postbuckling of panels include works by Weaver and his colleagues [5-7], Hilburger, et al [8], Baruch and Singer [9], the creators of the STAGS general purpose program, Almroth, Rankin, Brogan, and Riks [10-12], Arbocz and his colleagues [13-15], Stein [16], Leissa [17], Arnold and Parekh [18], Starnes, Knight, and Rouse [19], Spier [20,21], Khot and Bauld [22,23], Zhang and Matthews [24], Gürdal and his colleagues [25-30], Haftka and his colleagues [30-32], Librescu and his colleagues [33-35], Sridharan and his colleagues [36,37], Myers and Hyer [38], Nemeth [39], and Noor, Starnes, and Peters [40], to identify but a few in a vast literature.

PURPOSE OF THIS PAPER

The purpose of this paper is to report on an enhancement to PANDA2 that permits the optimization of flat and/or cylindrical panels and shells with the "usual" stringers and rings and also with "substiffeners". That is, the skin between the "usual" stringers and rings can be further stiffened by additional members, called "substiffeners" in this work. The substiffeners must be of rectangular cross section. The "usual" stiffeners (stringers and rings) can, as always, have a variety of cross sections, such as rectangular, Tee, Jay, Zee, Hat, Truss-Core, as described in [1]. The new version of PANDA2 is used to find minimum weight designs of cylindrical shells with T-shaped stringers and T-shaped rings and with rectangular substringers and subrings. Figure 1 shows a STAGS model of a piece of a cylindrical shell with major T-shaped stringers, major T-shaped rings and rectangular (blade) substringers and subrings.

Thermal loading is not included in cases that involve substiffeners. Also, local postbuckling is not permitted in such cases. The objective of this research is to determine if the minimum-weight designs of cylindrical shells with the more complex "double" stiffening scheme are significantly lighter than those optimized with just T-shaped stringers and T-shaped rings.

The substiffeners can also form an isogrid pattern between major axial stiffeners (stringers) and circumferential major stiffeners (rings). If the major stiffeners form an isogrid there cannot be any substiffeners. If there are substiffeners present, there can be no post-local buckling analysis (no "Koiter" analysis, [1,45]). There are no discretized single-module models of a segment of panel skin with one substiffener, as with the major stiffeners [1]. In the skin-stringer and skin-ring discretized modules, the substiffeners are smeared out in the manner of Baruch and Singer [9]. Hence, in these discretized module models the new panel "skin" between major stiffeners is the actual panel skin plus smeared substringers and smeared subrings.

Only the panel skin can have substiffeners. As of this writing there can be no substiffeners attached to the webs or outstanding flanges of major stiffeners. The substiffeners cannot be laminated composite. They are modelled as if they were of a single orthotropic material with user-specified E1, E2, G, nu, density, and maximum allowable stress components.

No attempt has yet been made to account properly for THERMAL loading in cases that have substiffeners. This paper is a summary of a section of the file called .../panda2/doc/panda2.news called "Item no. 600" [1b]. Please see that file for details about input data, output data, and "how to.." directions and suggestions with regard to obtaining optimum designs with the new version of PANDA2. (NOTE: This paper has been updated to account for changes to PANDA2 since panda2.news Item No. 600 was written. However, Item No. 600 has not been updated.)

DESCRIPTION OF PANDA2

PANDA2 is a computer program for the minimum weight design of stiffened, composite, flat or cylindrical, perfect or imperfect panels and shells subjected to multiple sets of combined in-plane loads, normal pressure, edge moments, and temperature. For most configurations the panels can be locally postbuckled. Previous work on PANDA2 is documented in [1]. PANDA2 incorporates the theories of earlier codes PANDA [41] and BOSOR4 [42]. The optimizer used in PANDA2 is called ADS [43,44]. Panels are optimized subject primarily to buckling and stress constraints.

PANDA2 Processors and Types of Analysis

As described in [1], the PANDA2 system consists of several processors, BEGIN, SETUP, DECIDE, MAINSETUP, PANDAOPT, CHOOSEPLOT, CHANGE, STAGSMODEL, STAGSUNIT, etc. The functions of these processors are as follows:

BEGIN	User establishes starting design, material properties, prebuckling and buckling boundary conditions.
SETUP	System sets up BOSOR4-type templates for stiffness and load geometric matrices.
DECIDE	User chooses decision variables and bounds and sets up equality and inequality constraints.
MAINSETUP	User chooses analysis type, loading, and solution strategies.
PANDAOPT	Analysis type is performed (e.g. optimization).
CHOOSEPLOT	User chooses what to plot.
DIPLOT	The system obtains plots (postscript files).
CHANGE	User changes selected variables and constants.
AUTOCHANGE	A new starting design is automatically generated in a random manner.
SUPEROPT	An attempt is made to find a global optimum design.
PANEL	A BOSOR4 (now BIGBOSOR4) input file is generated for inter-ring buckling of panel skin and stringers, with stringers modeled as flexible shell branches.
PANEL2	A BOSOR4 (now BIGBOSOR4) input file is generated for inter-ring buckling of panel skin+smeared stringers with rings modelled as flexible shellbranches.
STAGSMODEL	Input files for STAGS [10-12] are generated (one finite element unit, only stringers are permitted).
STAGSUNIT	Input files for STAGS are generated (multiple shell units, both stringers and rings are permitted. For most cases STAGSUNIT supersedes STAGSMODEL.)
CLEANPAN	Delete all files except files containing user-provided input data for BEGIN, DECIDE, MAINSETUP, CHANGE, PANEL, PANEL2, STAGSMODEL and STAGSUNIT.

DESCRIPTION OF STAGS

STAGS (STructural Analysis of General Shells) is a finite element code for general-purpose nonlinear analysis of stiffened shell structures of arbitrary shape and complexity. Its capabilities include stress, stability, vibration, and transient analyses with both material and geometric nonlinearities permitted in all analysis types. STAGS includes enhancements, such as a higher order thick shell element, more advanced nonlinear solution strategies, and more comprehensive post-processing features such as a link with STAPL [1b].

Research and development of STAGS by Brogan, Almroth, Rankin, Stanley, Cabiness, Stehlin and others of the Computational Mechanics Department of the Lockheed Palo Alto Research Laboratory has been under continuous sponsorship from U.S. government agencies for the past 30 years. During this time particular emphasis has been placed on improvement of the capability to solve difficult nonlinear problems such as the prediction of the behavior of axially compressed stiffened panels loaded far into their locally postbuckled states. STAGS has been extensively used worldwide for the evaluation of stiffened panels and shells loaded well into their locally postbuckled states. See [12], for example.

A large rotation algorithm that is independent of the finite element library has been incorporated into STAGS [46]. With this algorithm there is no artificial stiffening due to large rotations. The finite elements in the STAGS library do not store energy under arbitrary rigid-body motion and the first and second variations of the strain energy are consistent. These properties lead to quadratic convergence during Newton iterations.

Solution control in nonlinear problems includes specification of load levels or use of the advanced Riks-Crisfield path parameter [12] that enables traversal of limit points into the post-buckling regime. Two load systems with different histories (Load Sets A and B) can be defined and controlled separately during the solution process. Flexible restart procedures permit switching from one strategy to another during an analysis. This includes shifts from bifurcation buckling to nonlinear collapse analyses and back and shifts from static to transient and transient to static analyses with modified boundary conditions and loading. STAGS provides solutions to the generalized eigenvalue problem for buckling and vibration from a linear or nonlinear stress state.

Quadric surfaces can be modeled with minimal user input as individual substructures called "shell units" in which the analytic geometry is represented exactly. "Shell units" can be connected along edges or internal grid lines with partial or complete compatibility. In this way complex structures can be assembled from relatively simple units. Alternatively, a structure of arbitrary shape can be modeled with use of an "element unit".

Geometric imperfections can be generated automatically in a variety of ways, thereby permitting imperfection-sensitivity studies to be performed. For example, imperfections can be generated by superposition of several buckling modes determined from previous STAGS analyses of a given case.

A variety of material models is available, including both plasticity and creep. STAGS handles isotropic and anisotropic materials, including composites consisting of up to 60 layers of arbitrary orientation. Four plasticity models are available, including isotropic strain hardening, the White Besseling (mechanical sublayer model), kinematic strain hardening, and deformation theory.

Two independent load sets, each composed from simple parts that may be specified with minimal input, define a spatial variation of loading. Any number of point loads, prescribed displacements, line loads, surface tractions, thermal loads, and "live" pressure (hydrostatic pressure which remains normal to the shell surface throughout large deformations) can be combined to make a load set. For transient analysis the user may select from a menu of loading histories, or a general temporal variation may be specified in a user-written subroutine.

Boundary conditions (B.C.) may be imposed either by reference to certain standard conditions or by the use of single- and multi-point constraints. Simple support, symmetry, antisymmetry, clamped, or user-defined B.C. can be defined on a "shell unit" edge. Single-point constraints which allow individual freedoms to be free, fixed, or a prescribed non-zero value may be applied to grid lines and surfaces in "shell units" or "element units". A useful feature for buckling analysis allows these constraints to differ for the prestress and eigenvalue analyses. Langrangian constraint equations containing up to 100 terms may be defined to impose multi-point constraints.

STAGS has a variety of finite elements suitable for the analysis of stiffened plates and shells. Simple four node quadrilateral plate elements with a cubic lateral displacement field (called "410" and "411" elements) are effective and efficient for the prediction of postbuckling thin shell response. A linear (410) or quadratic (411) membrane interpolation can be selected. For thicker shells in which transverse shear deformation is important, STAGS provides the Assumed Natural Strain (ANS) nine node element (called "480" element). A two node beam element compatible with the four node quadrilateral plate element is provided to simulate stiffeners and beam assemblies. Other finite elements included in STAGS are described in the STAGS literature [10-12].

Table 3 Starting design and optimum designs from PANDA2 with and without substiffeners (dimensions in inches)

.	.	Perfect Shell With Substiffeners	Imperfect Shell With Substiffeners	Perfect Shell Without Substiffeners	Imperfect Shell Without Substiffeners
Variable Name	Starting Design	Optimum Design	Optimum Design	Optimum Design	Optimum Design
B(STR)	20.0	14.775	11.461	5.2141	5.7718
B2(STR)	2.0	1.4775	1.1461	0.52141	0.57718
H(STR)	10.0	4.5048	4.9955	2.7194	3.8575
W(STR)	10.0	2.9341	3.5908	2.1716	2.9305
T(1)(SKN)	1.0	0.30150	0.36755	0.49158	0.55232
TSUB,substr	1.0	0.23625	0.15374	-------	-------
HSUB,substr	5.0	1.1934	0.82430	-------	-------
BSUB,substr	5.0	2.8821	2.4256	-------	-------
TSUB,subrng	1.0	0.24665	0.20833	-------	-------
HSUB,subrng	5.0	2.4665	2.0833	-------	-------
BSUB,subrng	5.0	7.0617	4.9854	-------	-------
T(2)(STR)	1.0	0.52520	0.49773	0.25874	0.33045
T(3)(STR)	1.0	0.27664	0.31908	0.17386	0.23108
B(RNG)	20.0	39.157	42.874	22.208	28.291
B2(RNG)	0.0	0.0	0.0	0.0	0.0
H(RNG)	10.0	11.046	9.5948	8.2778	8.7430
W(RNG)	10.0	4.661	8.0986	3.4935	6.2876
T(4)(RNG)	1.0	0.55228	0.95512	0.41389	0.72687
T(5)(RNG)	1.0	0.25829	0.54145	0.26031	0.43056
WEIGHT	-----	**16712 lb**	**21480 lb**	**16846 lb**	**22820 lb**

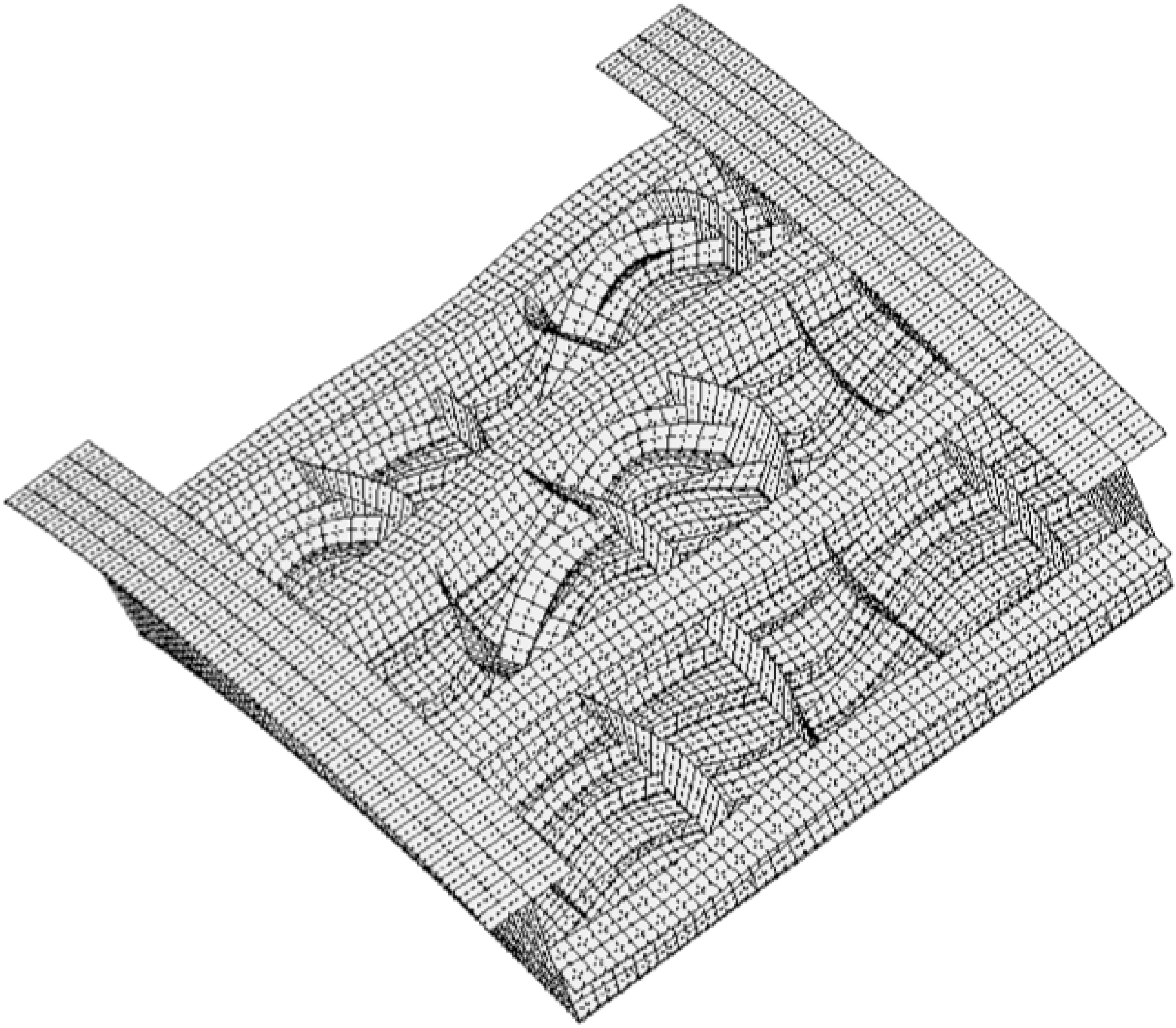

Fig. 1 STAGS model for local and for inter-ring buckling: 1 major ring bay x 3 major stringer bays; case name = testax4p; bifurcation buckling mode 1, buckling load factor, Pcr = 0.98903. Pcr = 1.0 is the design load. (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

Loading used for all cases:
Axial Resultant (lb/in), Nx(1) Load Set A = -100000 lb/in
Hoop Resultant (lb/in), Ny(1) Load Set A = -20000 lb/in
In-plane shear (lb/in), Nxy(1) Load Set A = 20000 lb/in
Uniform pressure, (psi),p(1) Load Set A = -200 psi
Zero loading in Load Set B

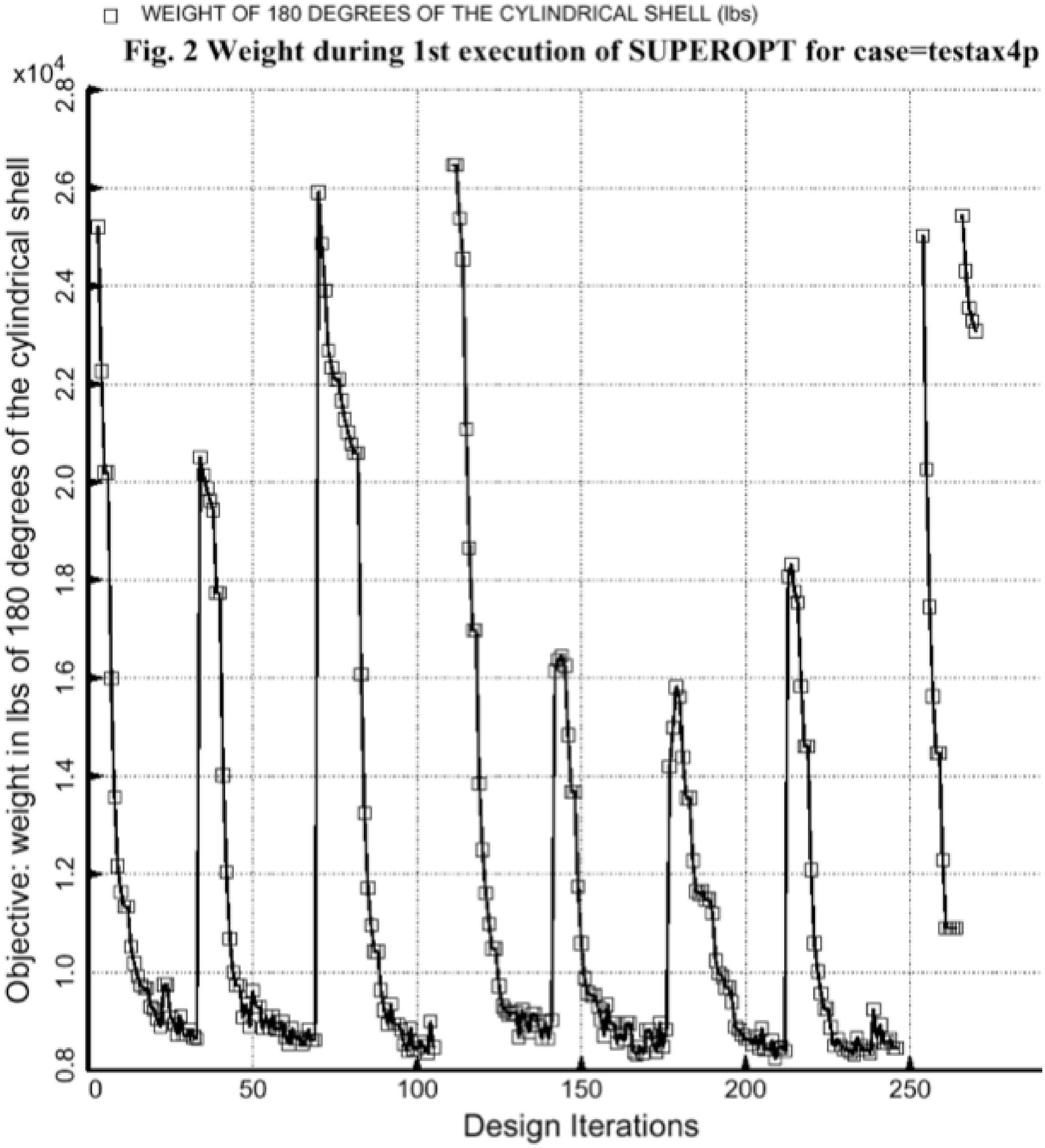

Fig. 2 Weight during the first execution of SUPEROPT for the perfect shell; Case name = testax4p. Each "spike" in the curve corresponds to a new "starting" design obtained randomly by the PANDA2 processor called AUTOCHANGE. Five PANDAOPTs per AUTOCHANGE were specified for the execution of SUPEROPT. (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

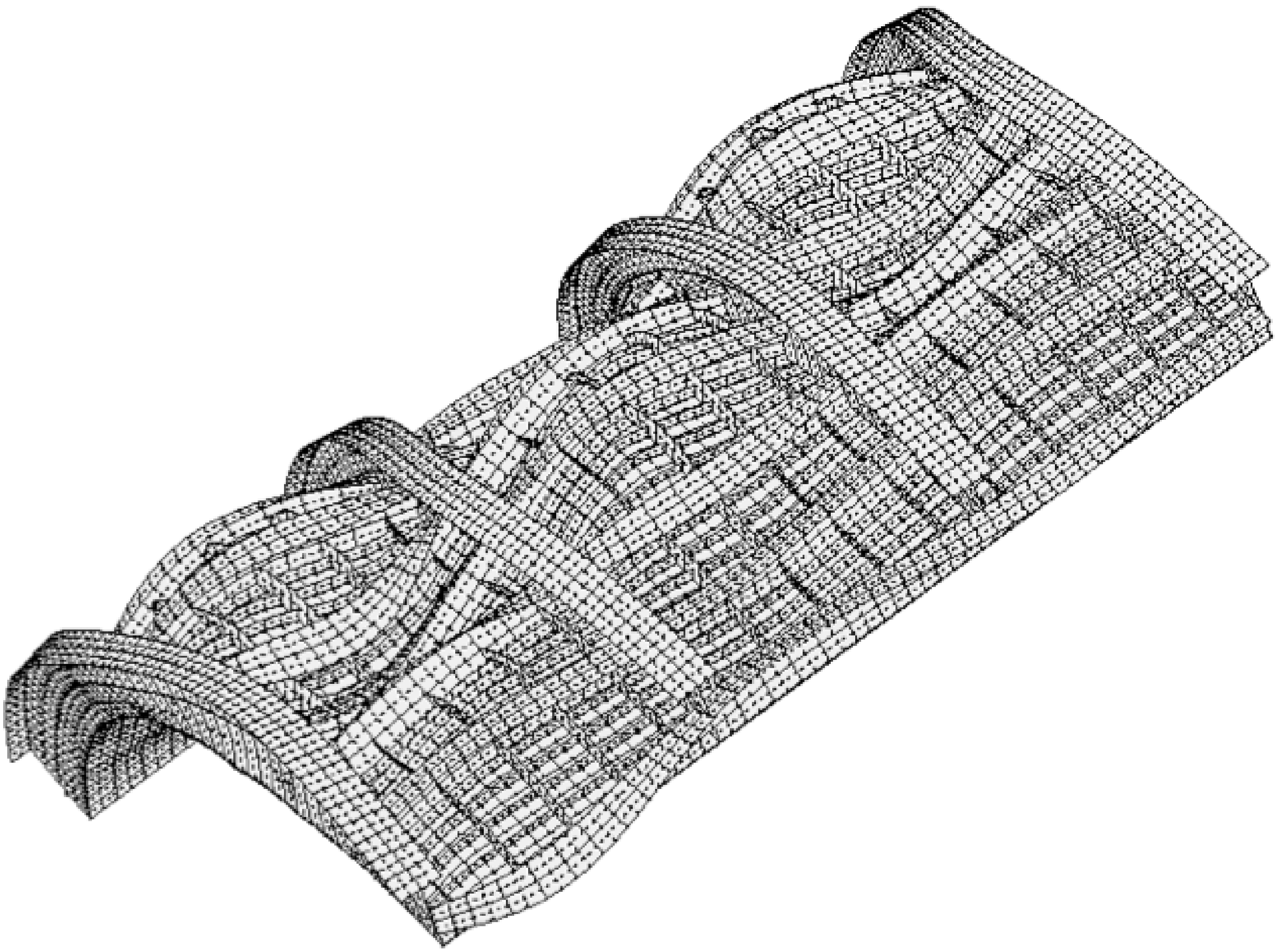

Fig. 3 STAGS model for inter-ring and local buckling: 3 major ring bays x 9 major stringer bays; all major stiffeners and sub-stiffeners are modeled with shell units; the STAGS 480 finite element is used. This is bifurcation buckling mode 1 for the optimized perfect shell; buckling load factor, Pcr = 0.97738. (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

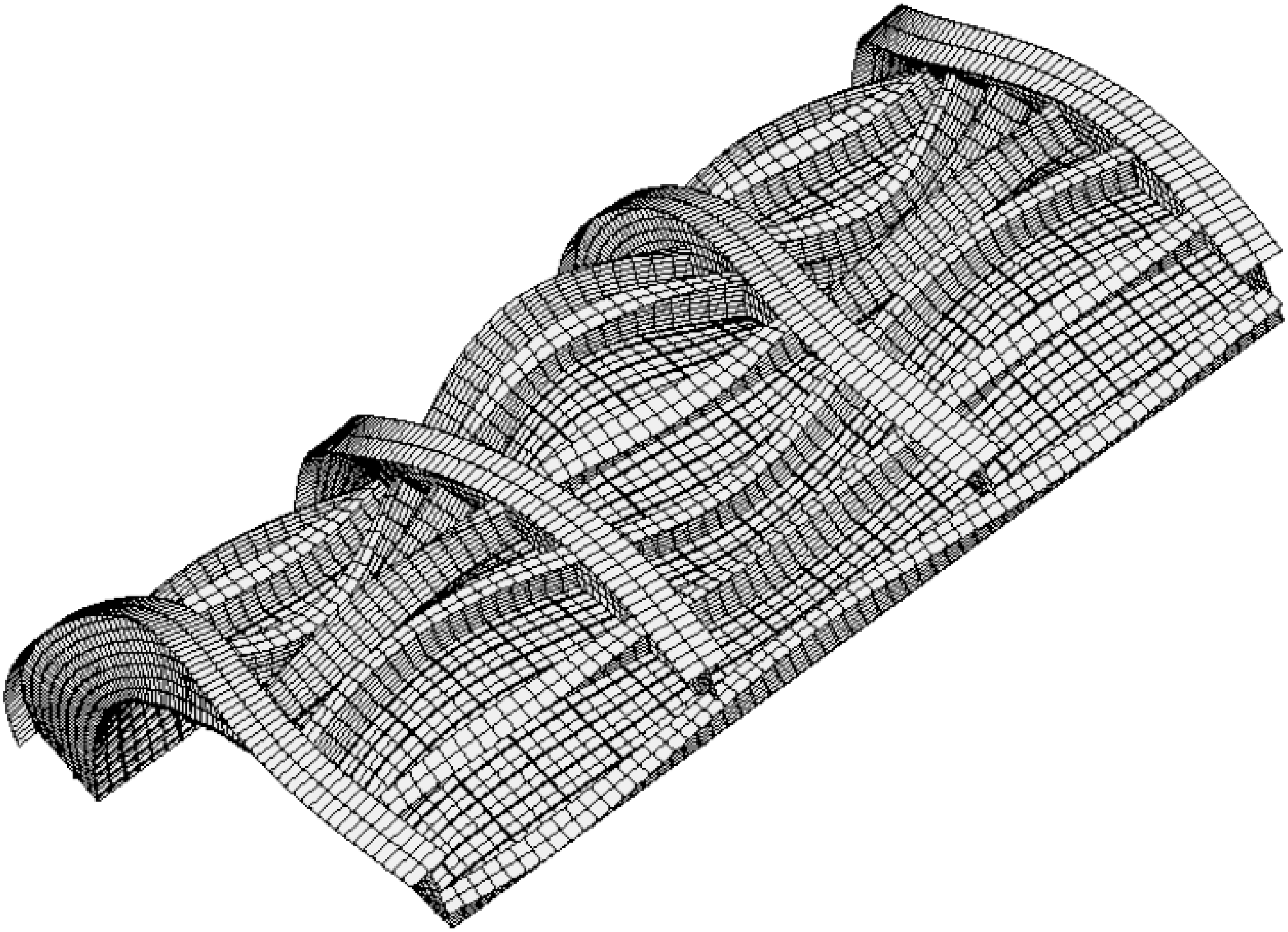

Fig. 4 STAGS model for inter-ring buckling: 3 major ring bays x 9 major stringer bays; the sub-stringers and sub-rings are modeled as beams, and the major stringers and major rings are modeled with shell units; the STAGS 410 finite element is used. This is bifurcation buckling mode 1 for the optimized perfect shell; buckling load factor, Pcr = 1.0259. (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

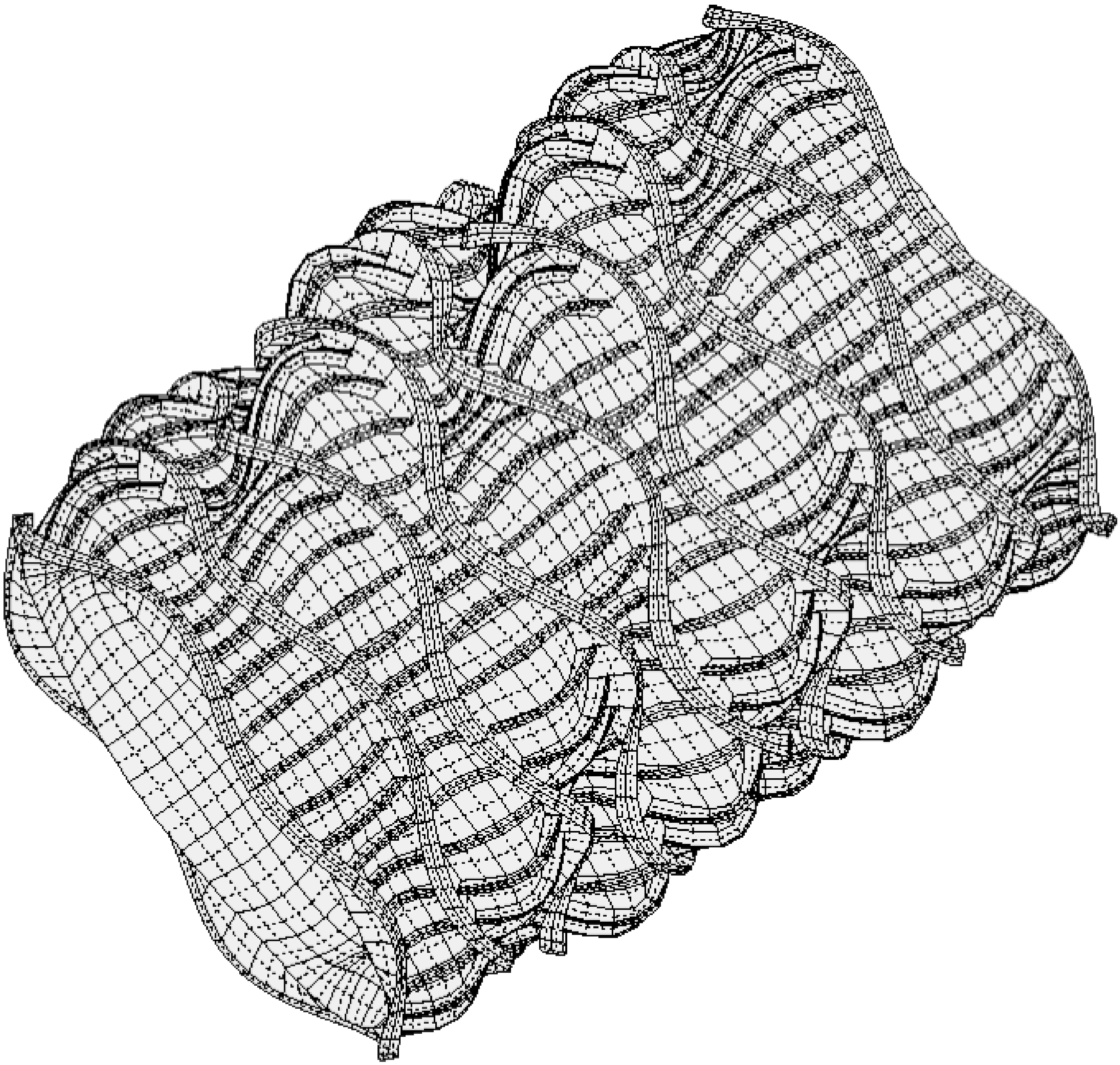

Fig. 6 STAGS model of the entire cylindrical shell: the sub-stringers and sub-rings are smeared, and the major stringers and major rings are modeled with shell units; the STAGS 480 finite element is used. This is bifurcation buckling mode 1 for the optimized perfect shell; buckling load factor, Pcr = 1.0222. (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

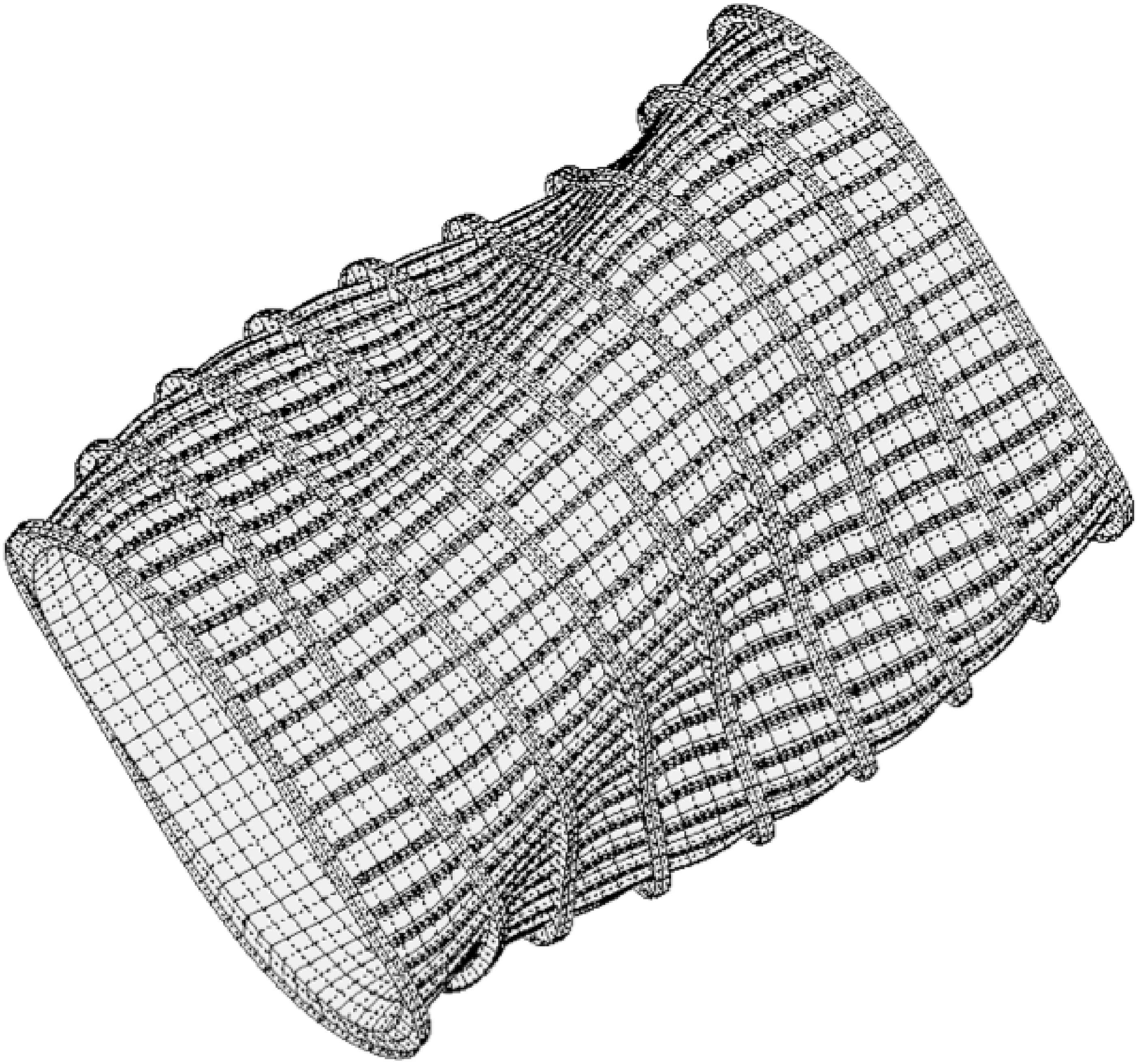

Fig. 7 STAGS model of the entire cylindrical shell: the sub-stringers and sub-rings are smeared, and the major stringers and major rings are modeled with shell units; the STAGS 480 finite element is used. This is the bifurcation buckling mode 19 for the optimized perfect shell; buckling load factor, Pcr = 1.0511 (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

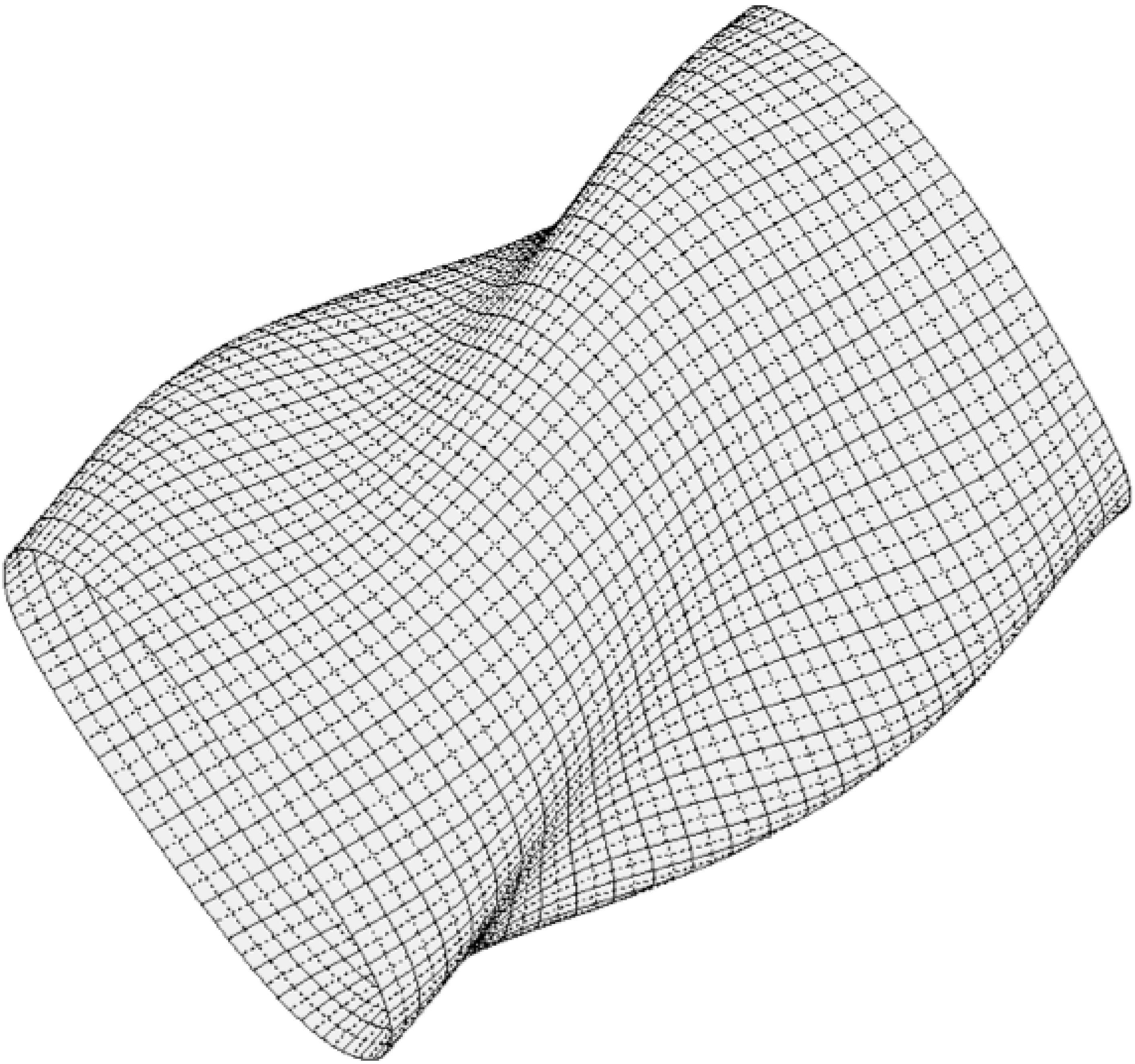

Fig. 9 STAGS model of the entire cylindrical shell: all major stiffeners and all sub-stiffeners are smeared; the STAGS 480 finite element is used. This is bifurcation buckling mode 1 for the optimized perfect shell; buckling load factor, Pcr = 1.2883 (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)

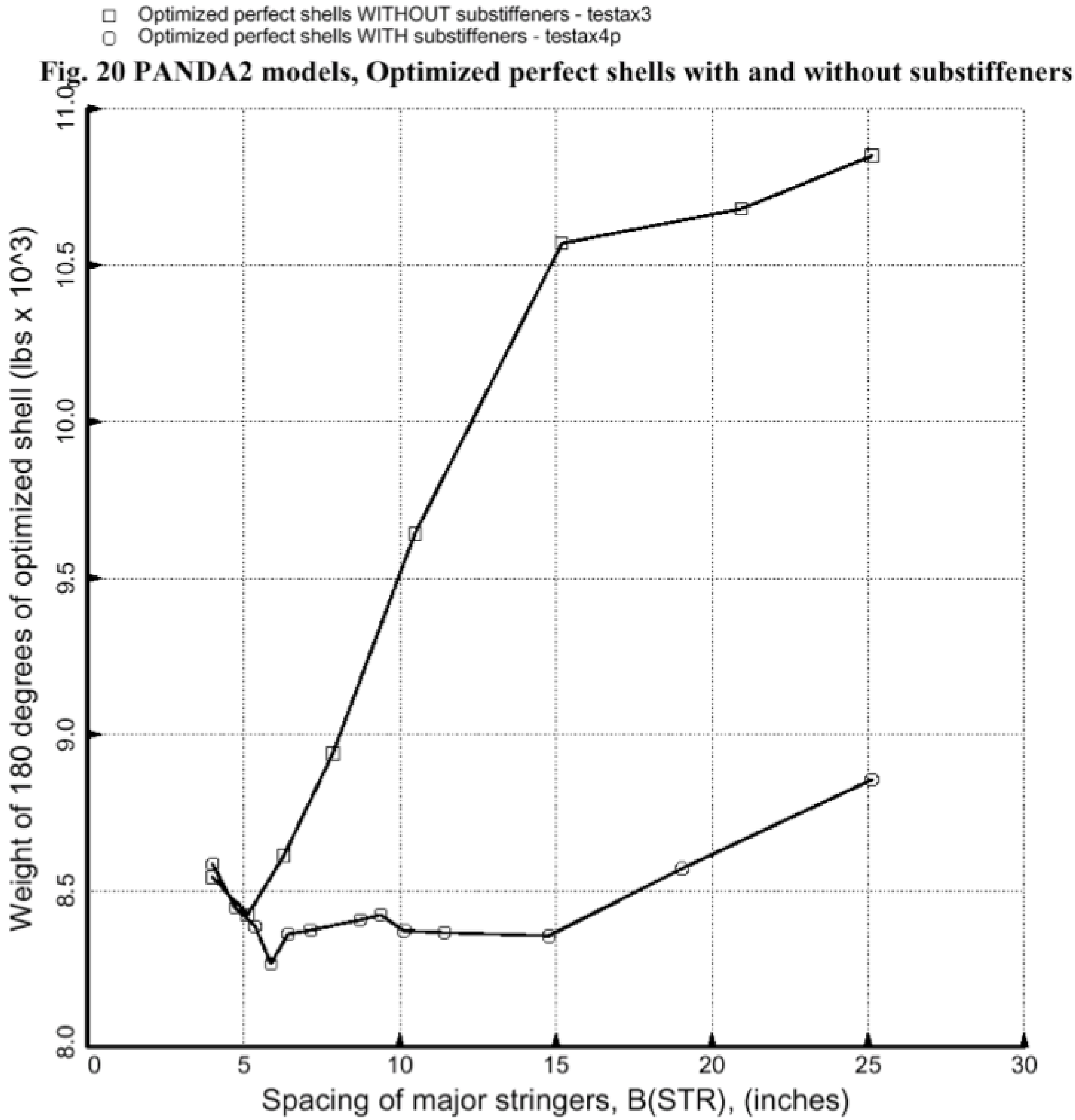

Fig. 20 PANDA2 models: optimized perfect shells with and without sub-stiffeners. Notice that the minimum weight is not significantly reduced in models with sub-stiffeners. However, when sub-stiffeners are present the spacing of the major stringers can be significantly increased with little sacrifice in weight. (from the AIAA 46th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2005-1932, 2005)