

# Use of GENOPT and BIGBOSOR4 to optimize weld lands in axially compressed stiffened cylindrical shells and evaluation of the optimized designs by STAGS

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BIGBOSOR4 is used in an optimization loop in which the dimensions of a typical axially oriented weld land and the cross-section dimensions of reinforcing Tee-shaped stringers along the two straight edges (generators) of the weld land are decision variables. The optimization is carried out in a GENOPT context. Any number of equally spaced identical T-stiffened weld lands in a 360-degree cylindrical shell can be accommodated. The weld lands are embedded in an internally stiffened "acreage" cylindrical shell that has been previously optimized by PANDA2. The previously optimized "acreage" cylindrical shell has internal "acreage" stringers and internal "acreage" rings with rectangular cross sections. The spacings, heights, and thicknesses of the internal "acreage" stiffeners are not decision variables for the optimization problem in which the weld land and its reinforcing edge T-stringers are optimized. The design constraints for the cylindrical shell with the T-stiffened weld lands are: 1. general buckling, 2. inter-ring buckling, and 3. stress. The prebuckled state is assumed to be uniform end shortening, with the membrane axial compression in each segment of the structure proportional to the axial membrane stiffness of that segment. The prebuckled state is assumed to be a membrane state: no prebuckling bending. The entire shell structure is fabricated of the same material. In the model for general buckling the previously optimized "acreage" rings and stringers are smeared out and the cylindrical shell is simply supported at its ends. In the model for inter-ring buckling adjacent "acreage" rings are replaced by simple supports, that is, a length of shell equal to the ring spacing is analyzed, and the previously optimized "acreage" stringers are smeared out. The maximum stress in the weld-land-edge-stringer region is computed as if there were no prebuckling bending (membrane compression only). The cylindrical shell is modeled as a 180-degree segment of a huge torus, with symmetry conditions applied along the generators at zero and at 180 degrees. In the GENOPT examples studied here there are three identical T-stiffened weld lands spaced at 120-degree intervals. The adequacy of the optimized "acreage" cylindrical shell with and without the optimized T-stiffened weld lands is evaluated with various STAGS finite element models. There is good agreement between predictions from the GENOPT/BIGBOSOR4 model and the various STAGS models.

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## SECTION 1 INTRODUCTION AND SUMMARY

### Motivation and Previous work done

The effort that resulted in this paper was motivated by Robert Thornburgh's paper on the buckling behavior of axially oriented weld lands in axially compressed, internally ring and stringer stiffened cylindrical shells [1]. A capability to optimize an axially oriented weld land with "extra" stringers added to its two longitudinal edges was needed. This paper reports results from a continuation of the work documented in [1 - 3]. Reference [2], derived from a case called "nasacoldbend", reports results from the use of PANDA2 [4, 13] and BIGBOSOR4 [5]. Reference [3], derived from a case called "wcold", reports results from the use of GENOPT [6] and BIGBOSOR4 [5]. A brief overview of the GENOPT program is given here. Extensive details about how to use GENOPT in connection with BIGBOSOR4 are presented in [7] and will not be repeated here. The GENOPT/BIGBOSOR4 capability has been used to optimize axially compressed cylindrical shells with a composite truss-core sandwich wall construction [8] and a ring-stiffened cylindrical shell with a "wavy" wall [5]. The work reported in [3] and [8] is based on "huge torus" models [9] of cylindrical shells. The results from GENOPT/BIGBOSOR4 reported in this paper are based on a new version of BIGBOSOR4 in which cylindrical shells with and without weld lands are modeled as true prismatic assemblages of shell segments. The "true prismatic shell" formulation is reported in [10]. Brief descriptions of the "huge torus" model and of the "true prismatic shell" model are given in this paper.

Both the PANDA2 [4, 13] and the GENOPT [6] computer programs perform optimization with the use of a gradient-based optimizer called "ADS", created many years ago by Vanderplaats and his colleagues [11,12]. In [2 - 8] ADS is "hard wired" in a "modified-method-of-steepest-descent" (1-5-7) mode. In PANDA2 and GENOPT a matrix of constraint gradients is computed from finite differences of the behavior of the perturbed design minus the behavior of the current design in which the decision variables are perturbed one at a time by a certain percentage, usually five per cent.

### Purposes of this paper

The main purpose of the work reported here is to produce a "quick and dirty" way of optimizing axially oriented T-stiffened weld lands embedded in previously optimized stiffened cylindrical shells. Figure 1 presents an end view of a typical configuration. An auxiliary purpose is to provide enough information in this paper so that the reader can use GENOPT/BIGBOSOR4 [6,5] to optimize other shell structures and can subsequently use STAGS [15-18] or some other general-purpose finite element computer program to evaluate those optimized designs.

### Summary of this paper

The objective of the optimization is to minimize the weight per axial length of one T-stiffened weld land such as one of the six identical T-stiffened weld lands shown in Fig. 1. Next and in SECTIONS 2 - 4 descriptions are given of the "quick and dirty" models of stiffened cylindrical shells with embedded T-stiffened weld lands. A brief description of GENOPT [6] appears in SECTION 5. SECTION 6 describes how GENOPT is used to produce a user-friendly capability to optimize any number of identical T-stiffened weld lands embedded in a previously optimized "acreage" cylindrical shell. SECTION 7 emphasizes that there is a two-phase optimization process: first the acreage stiffened cylindrical shell must be optimized, then a typical T-stiffened weld land to be embedded in that previously optimized acreage must be optimized. SECTIONS 8 - 12 present results for optimized acreage and T-stiffened weld lands that evolve when there is no constraint with regard to the slenderness (height/thickness) of the T-stringers that reinforce the weld land curved plate. SECTION 13 presents results for a T-stiffened weld land optimized under the condition that the height/thickness of the T-stringer web and outstanding flange are constrained to be less than or equal to 10. Some conclusions are given in SECTION 14.

### Models used

The models used in this paper are much simpler than those used by Thornburgh [1]. Thornburgh used STAGS [15 - 18], a general-purpose finite element code. Naturally, the models here are approximate. For example, the prebuckled state is assumed to be a membrane state: there is no prebuckling bending of the axially compressed cylindrical shell with multiple identical axially oriented, edge-stiffened weld lands. The axial compression,  $N_x$ , in the various segments of the model such as that displayed in Fig. 1 is distributed in proportion to the membrane axial stiffness of

those segments, and this distribution of  $N_x$  is prismatic, that is, it does not vary along the axis of the cylindrical shell. There is no "boundary layer" prebuckling nonuniformity of radial displacement  $w$  in the neighborhoods of the two ends of the axially compressed cylindrical shell caused by the restriction of Poisson ratio radial expansion there. The prebuckled state is a membrane state.

The models used here for the optimization of T-stiffened weld lands are BIGBOSOR4 models [5]. Therefore, the discretization is one-dimensional (strip method), which causes solution times on the computer to be much less than for the usual two-dimensionally discretized models such as those used in connection with the STAGS general-purpose finite element computer program [15-18]. This property leads to efficient optimization.

## SECTION 2 MODELING A CYLINDRICAL SHELL AS A HUGE TORUS

In this study of the optimization and behavior of a T-stiffened weld land embedded in a cylindrical shell the structure is modeled as a huge torus [9]. More precisely, part of the cylindrical shell (90 or 180 degrees of its circumference) is modeled as part of a huge torus. Figure 3a shows the "huge torus" concept.

Viewing a cylindrical shell or a sector of a cylindrical shell as a part of a huge toroidal shell is a "trick" that permits, for example, the detailed modeling of an axially oriented weld land with added edge stringers [3] while working within the restriction that BIGBOSOR4 only handles shells of revolution. See Figs. 1, 2, 6, and 7, for examples.

With the "huge torus" model [3,8,9] the shell coordinates are exchanged: what was the axial coordinate of the cylindrical shell modeled in the usual way becomes the circumferential coordinate of the "huge torus" model, and what was the circumferential coordinate of the cylindrical shell modeled in the usual way becomes the meridional coordinate of the "huge torus" model. In the "huge torus" model of a stiffened cylindrical shell what were stringers become rings, and what were rings become stringers. What were axial half waves in the buckling mode of the cylindrical shell become circumferential half waves in the "huge torus" model of that cylindrical shell, and what were circumferential waves in the buckling mode of the cylindrical shell become meridional waves in the "huge torus" model of that cylindrical shell.

If the radius from the axis of revolution to the center of meridional curvature of the huge torus is large enough, then under certain circumstances the behavior of the huge torus or a segment of the huge torus should be close to that of the cylindrical shell that the "huge torus" model simulates. The "certain circumstances" are:

**Item 1:** The cylindrical shell must be simply supported at its ends. In the "huge torus" model of a cylindrical shell meridionally oriented buckling nodal lines occur at buckling modal half-wavelength intervals around the circumference of the huge torus. The conditions at a buckling nodal line are identical to simple support (antisymmetry of the buckling modal displacement components,  $u$ ,  $v$ ,  $w$ , and shell wall rotation). In the "huge torus" model of a cylindrical shell the BIGBOSOR4 user must choose the circumferential wave numbers, N0B, NMNB, NMAXB, INCRB, such that buckling nodal lines will always fall at intervals around the circumference of the huge torus that correspond to an integral number of half waves over the circumferential length of the huge torus that is equal to the axial length of the cylindrical shell that is being simulated by the "huge torus" model.

**Item 2:** The prebuckled state must be a membrane state [3,8], that is, there is no prebuckling bending. In terms of input data, the BIGBOSOR4 user must choose INDIC = 4 (linear buckling) and IPRE = 0 (membrane prebuckling state to be specified by the BIGBOSOR4 user rather than being calculated by BIGBOSOR4).

In Items 1 and 2 reference is made to "the BIGBOSOR4 user". In the GENOPT/BIGBOSOR4 optimization context there is no "BIGBOSOR4 user". The requirements just stipulated are satisfied automatically, except that the GENOPT user must specify ranges of wave numbers that must be covered in the searches for the critical (lowest) buckling load factors that correspond to general buckling and to inter-ring buckling.

In the usual BIGBOSOR4 model of an axially stiffened (stringer stiffened) cylindrical shell the stringers have to be smeared out because BIGBOSOR4 handles only shells of revolution. In the usual BIGBOSOR4 model of a ring-stiffened cylindrical shell the rings can be treated as little elastic, deformable shell segments; they do not have to be

smeared out. In the "huge torus" model the situation is reversed: what were rings and now become stringers (meridionally oriented stiffeners in the huge torus) have to be smeared out. What were stringers and now become rings (circumferentially oriented stiffeners in the huge torus) can be modeled as little flexible shell segments. For example, an axially oriented weld land with T-shaped edge stringers in the cylindrical shell can be modeled in the "huge torus" model as a meridionally thickened cylindrical skin segment (the weld land curved plate) with T-shaped edge rings, as displayed in Figs. 1, 2, 6 and 7. The two segments of each T-shaped edge ring (the web and the outstanding flange) can be modeled as little flexible shell segments, as indicated in Fig. 1.

In the "huge torus" model, as in any shell-of-revolution model, the meridional coordinate is discretized and variation of the buckling mode in the circumferential coordinate direction is trigonometric with  $n$  (or  $N$ ) circumferential waves around the huge circumference of the torus. There is a relationship between the axial length of the cylindrical shell and the smallest huge torus circumferential wave number that corresponds to one half wavelength spanning that axial length. As mentioned above, simple support end conditions on the cylindrical shell are implied because simple support (antisymmetry) is what naturally occurs along the meridionally oriented buckling nodal lines in the "huge torus" model of the cylindrical shell.

A question naturally arises, "What huge radius should the BIGBOSOR4 user choose?" This huge radius equals the distance from the axis of revolution of the huge torus to the center of meridional curvature. If this huge radius is too small, then the behavior of the "not-so-huge" torus will not be close enough to that of the cylindrical shell that the huge torus is to simulate because the portion of the huge torus that represents the cylindrical shell will have significant curvature (like a curved tube instead of a straight tube). If this radius is too large, then numerical difficulties (small differences of large numbers) will be encountered. The first author has found that the following choice:

$$\text{RAVE} = 100 \times \text{LENGTH} \times \text{FACLEN}/\pi$$

is appropriate. RAVE is approximately given by

$$\text{RAVE} = R + 0.5x(r_{\max} - r_{\min})$$

in which  $R$  is the huge radius from the axis of revolution of the huge torus to the center of meridional curvature;  $r_{\max}$  is the radius of the largest parallel circle in the "huge torus" model; and  $r_{\min}$  is the radius of the smallest parallel circle in the "huge torus" model. LENGTH is the axial length of the cylindrical shell. FACLEN is a length modifier that is 1.0 for general buckling and usually much smaller than 1.0 for local buckling. (In the example, "nasatru2" [8], FACLEN = 0.05.)  $\pi = 3.1415927$ . This choice for RAVE means that  $N = 100$  full waves around the circumference of the huge torus corresponds to a circumferential half-wavelength that is close to the axial length, LENGTH, or close to the modified axial length, LENGTH  $\times$  FACLEN, of the cylindrical shell. We have:

$$2\pi R \times \text{RAVE}/(100 \text{ full circ. waves}) = 2 \times \text{LENGTH} \times \text{FACLEN}$$

The number of half waves around the circumference of the huge torus is 200, so that

$$2\pi R \times \text{RAVE}/(200 \text{ half circ. waves}) = \text{LENGTH} \times \text{FACLEN}$$

Therefore, in the "huge torus" model of the cylindrical shell the BIGBOSOR4 input for the circumferential wave numbers, N0B, NMNB, NMXB, INCRB, would typically be:

```
100 $ N0B    = starting number of circ. waves (buckling analysis)
100 $ NMNB   = minimum number of circ. waves (buckling analysis)
900 $ NMXB   = maximum number of circ. waves (buckling analysis)
100 $ INCRB  = increment in number of circ. waves (buckling)
```

The BIGBOSOR4 input for N0B, NMNB, NMXB, INCRB just listed means that, in our search for the critical (lowest) buckling mode and load factor, we want to explore the range of buckling half waves along the axis of the cylindrical shell from 1 to 9. The "huge torus" model implies that the cylindrical shell is simply supported along its

two curved ends because that is where meridionally oriented buckling nodal lines occur in the "huge torus" model. Buckling nodal lines correspond to anti-symmetry of buckling modal displacement, which is the same as "classical" simple support. (That is where the notion of "simple support" originated. "Simple support" means that simple trigonometric variation of the buckling modal displacements in a given coordinate direction represents the exact solution of the buckling equations: the solution is "simple".)

The first trace in Fig. 3b, obtained with the "huge torus" model, shows the general buckling load factor versus normalized huge radius, R/RAVE, for the case called "nasatruss2" [8]. For  $R/RAVE < 1$  the "huge torus" model becomes somewhat unconservative because of the circumferential curvature of the "equivalent" cylindrical shell; the cylindrical shell is a slightly curved tube. For  $R/RAVE > 10$  numerical difficulties that arise from small differences of large numbers become a problem.

In the discussion above it is implied that the "huge torus" model only applies to circular cylindrical shells. However, this is not so. The "huge torus" model can be used for shells or panels of any cross section, such as the "oval-shaped" cylindrical shells and corrugated panels discussed in [9]. The same holds for true prismatic shells and for true prismatic assemblages of shells to be discussed in the next section.

### **SECTION 3 TRUE PRISMATIC SHELLS AND TRUE PRISMATIC ASSEMBLAGES OF SHELLS: THE NEW INDEX CALLED "IPRISM" IN BIGBOSOR4**

In principle, predictions for a "huge torus" model of a cylindrical shell should approach those for a true prismatic shell as the normalized radius, R/RAVE, approaches infinity. From the first trace in Fig. 3 we see that values of R/RAVE less than about 0.2 lead to predictions that are unacceptably unconservative because the cylindrical shell represented by the "huge torus" model is actually a slightly curved tube. We want to avoid this unconservativeness by introducing into BIGBOSOR4 new kinematic relations and other new coding so that BIGBOSOR4 can handle true prismatic assemblages of shell segments as well as shells of revolution. This new coding in BIGBOSOR4 is listed in the files, addbosor4.changes, questions.changes, and input.changes contained in [10]. Please note that only BIGBOSOR4 was modified as listed in those files. The older BOSOR4 program [19] remains as it has always been for many, many years. [The first author regards BIGBOSOR4 as superseding BOSOR4. However, BOSOR4 is retained because some of its subroutines are used by PANDA2. BIGBOSOR4 is given that name because it will handle shells with many more segments (up to 295 segments) than will BOSOR4.]

The input data for a true prismatic shell is the same as that for a "huge torus" model except as described next. In the plots of buckling modes of a true prismatic shell the "x,y" coordinates are the same as for the "huge torus" model. All the figures analogous to Figs. 5 - 16 in this paper and all the GENOPT/BIGBOSOR4 results were generated with use of the new "true prismatic shell" formulation in BIGBOSOR4.

The choice of the usual BIGBOSOR4 shell-of-revolution model versus the true prismatic shell model is governed by a new index, IPRISM:

**IPRISM = 0** means the usual shell-of-revolution BIGBOSOR4 model is used by BIGBOSOR4, that is, the kinematic relationships are those appropriate for a shell of revolution.

**IPRISM = 1** means the true prismatic shell model is used by BIGBOSOR4, that is, the kinematic relationship are those appropriate for a true prismatic structure.

The true prismatic shell model is invoked by the user's including the string, "ixprism" in the title of the BIGBOSOR4 case. If the string, "ixprism", occurs in this title, then BIGBOSOR4 sets the index, IPRISM, to 1 and BIGBOSOR4 requires that the user supply one additional input datum immediately following the title record. This additional input datum is the axial length of the cylindrical shell that is to be modeled as a prismatic shell structure rather than as a shell of revolution. (NOTE: In the GENOPT/BIGBOSOR4 context for the "weldland" generic case all of this is done automatically in SUBROUTINE BOSDEC, to be described below.)

An example of BIGBOSOR4 input pertaining to an ordinary shell of revolution (the "huge torus" model) is as

follows:

Input data for shell-of-revolution ("huge torus") model:

```
-----  
torus test  
4 $ INDIC = analysis type indicator  
1 $ NPRT = output options (1=minimum, 2=medium, 3=maximum)  
0 $ ISTRES= output control (0=resultants, 1=sigma, 2=epsilon)  
0 $ IPRE = indicator for prebuckling stress calculation (0 or 1)  
1 $ NSEG = number of shell segments (less than 295)  
H $  
H $ SEGMENT NUMBER 1 1 1 1 1 1 1  
(lines skipped to save space)  
100 $ N0B = starting number of circ. waves (buckling analysis)  
100 $ NMINB = minimum number of circ. waves (buckling analysis)  
900 $ NMAXB = maximum number of circ. waves (buckling analysis)  
100 $ INCRB = increment in number of circ. waves (buckling)  
-----.
```

The string, "ixprism" does not occur in the title record. Therefore, IPRISM = 0, and the rest of the input data are appropriate for a shell of revolution as has always held for BIGBOSOR4. In particular, the input data for the range of buckling wave numbers, N0B, NMINB, NMAXB, INCRB, are as listed above, for example.

An example of BIGBOSOR4 input data for a true prismatic shell structure is as follows:

```
-----  
torus test ixprism <--note the string, "ixprism"  
68.75 $ AXIALL= length of the prismatic shell <--new input datum required  
4 $ INDIC = analysis type indicator  
1 $ NPRT = output options (1=minimum, 2=medium, 3=maximum)  
0 $ ISTRES= output control (0=resultants, 1=sigma, 2=epsilon)  
0 $ IPRE = indicator for prebuckling stress calculation (0 or 1)  
1 $ NSEG = number of shell segments (less than 295)  
H $  
H $ SEGMENT NUMBER 1 1 1 1 1 1 1  
(lines skipped to save space)  
1 $ N0B = starting number of axial half waves(buckling analysis)  
1 $ NMINB = minimum number of axial half waves (buckling analysis)  
9 $ NMAXB = maximum number of axial half waves (buckling analysis)  
1 $ INCRB = increment in number of axial half waves (buckling)  
-----
```

The appearance of the string, "ixprism" in the title record is the signal to BIGBOSOR4 to set the index, IPRISM, equal to 1. The input data for the range of buckling wave numbers, N0B, NMINB, NMAXB, INCRB, are as listed above, for example.

The quantities, N0B, NMINB, NMAXB, INCRB, have different meanings in the two models:

**"huge torus" model:** number of full circumferential waves around the huge torus.

**"true prismatic" model:** number of axial half waves over the length, AXIALL, of the cylindrical shell;  
AXIALL = LENGTH x FACLEN

In order to accommodate true prismatic shells in BIGBOSOR4, the file, ...bigbosor4/execute/PROMPT.DAT, was

modified as follows:

---

31.0      IPRISM = 1 in this BIGBOSOR4 case.  
Therefore, the BIGBOSOR4 analysis applies to a true prismatic shell or true prismatic assemblage of shells. The next four input data, N0B, NMINB, NMAXB, INCRB, that you must supply are numbers of axial half waves, N0B, NMINB, NMAXB, along the length, AXIALL, of the prismatic shell and the increment, INCRB, of axial half waves to be used in the search for the buckling load factor and mode shape of the true prismatic shell structure. Please see the file,  
.../bigbosor4/case/prismatic/prismatic.tar.gz  
for complete information on true prismatic shells and how the true-prismatic-shell option has been included into BIGBOSOR4.

32.1    N0B    = starting number of axial half waves (buckling analysis)  
34.1    NMINB = minimum number of axial half waves (buckling analysis)  
36.1    NMAXB = maximum number of axial half waves (buckling analysis)  
38.1    INCRB = increment in number of axial half waves (buckling)  
40.1    IPRISM=0 for shell of revolution, 1 for true prismatic shell  
40.2    Please see the file, .../bigbosor4/case/prismatic/prismatic.tar.gz,  
for complete information about true prismatic shells. In order  
to unpack the compressed tar file, prismatic.tar.gz, type the  
following two commands:  
gunzip prismatic.tar.gz  
tar xvf prismatic.tar  
Then read the file, prismaticshell.readme .

---

The above "help" paragraph, 31.0, and prompts for input, 32.1 - 40.2, were added to the previous version of the /home/progs/bigbosor4/execute/PROMPT.DAT file, which prompts the BIGBOSOR4 user for input data.

\*\*\*\*\* IMPORTANT NOTE \*\*\*\*\*

As of this writing please do NOT use the IPRISM = 1 model except for cases in which INDIC = 4 and IPRE = 0 . IPRE = 0 means that the pre-buckling loaded state is specified by the BIGBOSOR4 user, not computed by BIGBOSOR4. INDIC = 4 denotes a linear bifurcation buckling analysis.

\*\*\*\*\*

The numerous modifications to the source file, addbosor4.src, required to incorporate the true prismatic shell model are listed in the file, "addbosor4.changes" [10]. Changes required in the files, questions.src, and input.src are listed in the files, "questions.changes" and "input.changes", respectively [10].

The analysis of "true prismatic shells" by BIGBOSOR4 involves a change in the kinematic relationships. The quantity,  $n(s.o.r)/r$ , is changed to  $n(prismatic) \times \pi/L$  if the new BIGBOSOR4 index, IPRISM, equals unity. The quantity,  $n(s.o.r.)$ , is the number of full waves around the circumference of the shell of revolution (s.o.r.) in the linear buckling or vibration mode;  $n(prismatic)$  is the number of half waves along the axis of the prismatic shell;  $r$  is the radius of the parallel circle at a point on the reference surface meridian of the shell of revolution; and  $L$  is the axial length of the prismatic shell. In the new coding in BIGBOSOR4, dated APR 2009 and JAN 2010, The quantity FN/R is everywhere replaced by FNBAR, where FNBAR = FN/R for shells of revolution and FNBAR = FN\*PI/AXIALL for "true prismatic shells". The quantity FN is the buckling or vibration wave number in floating point format, interpreted by BIGBOSOR4 as either the number of full waves around the circumference of the shell of revolution if the new index IPRISM = 0 or interpreted by BIGBOSOR4 as the number of half waves along the axis of the prismatic shell if IPRISM = 1. The quantity R is the radius of the parallel circle at a point on the reference surface meridian, and AXIALL is the axial length of the prismatic shell.

In the BIGBOSOR4 coding the circumferential curvature at a point on the reference surface meridian of the shell of revolution is called "FK2", in which  $FK2 = 1/R2$ , where  $R2$  is the corresponding circumferential radius of curvature. Everywhere the string,  $R*FK2$ , formerly occurred in the BIGBOSOR4 coding has now been replaced by the string, RFK2. The quantity,  $r/R2 = R*FK2 = RFK2$ , is the sine of the slope of the reference surface at a point on the meridian of the shell of revolution. In the BIGBOSOR4 coding, after the quantities FNBAR and RFK2 have been established with use of the values of  $R$  and  $FK2$  derived from the user's input data, the quantity  $R$  is replaced by  $R*1000000.0$ , and the quantity  $FK2$  is replaced by  $FK2/1000000.0$  in order to simulate a huge torus with an infinite radius. The segment-by-segment input data for the "true prismatic shell" are the same as for the "huge torus" model of the cylindrical shell. However, with the new "true prismatic shell" formulation the solution of the linear bifurcation buckling problem or the modal vibration problem becomes independent of the radius of the huge torus for  $R/RAVE < 1.0$ .

The second trace in Fig. 3b, obtained with the "true prismatic shell" model, shows the general buckling load factor versus the normalized huge radius,  $R/RAVE$ , for the case called "nasatruss2" [8]. For  $R/RAVE < 1$  the "true prismatic shell" model does not become unconservative in the way exhibited by the "huge torus" model (first trace in Fig. 3b). However, for  $R/RAVE > 10$  the same numerical difficulties occur as those for the "huge torus" model. Accordingly, with the "true prismatic shell" model the user should specify  $R/RAVE$  less than or equal to 1.0. (In the GENOPT/BIGBOSOR4 context this is done automatically.)

## SECTION 4 AN EXAMPLE

Figure 1 shows an example of a cylindrical shell with six identical T-stiffened weld lands over the 360 degrees of the circumference. Each weld land is reinforced by two Tee-shaped stringers. The circumferential coordinate in the "huge torus" or "true prismatic" model is the coordinate normal to the plane of the paper, and the meridional coordinate in the model is the coordinate in the plane of the paper along each of the 19 segments of the BIGBOSOR4 "huge torus" model displayed in Fig. 1.

The decision variables in the optimization problem presented here are the width and thickness, WLAND and TLAND, of a typical weld land curved plate, the height and thickness, HWLAND and TWLAND, of a typical edge stringer web, and the width and thickness, WFLAND and TFLAND, of a typical edge stringer outstanding flange. These decision variables are shown in Fig. 2. The specific name of the case is "wcold". The reference surface eccentricity variable, ECLAND, is not a decision variable but is established by a linking relationship in which the outer surface of the weld land curved plate remains flush with the outer surface of the "acreage" cylindrical shell skin throughout the optimization process.

The non-weld-land parts of the huge torus model (Segments 4, 10, and 16 in Fig. 1), called "acreage" in this paper, represent the stiffened cylindrical shell without any weld lands previously optimized by PANDA2 [2, 4, 13]. In the particular case analyzed here the previously optimized internally ring and stringer stiffened cylindrical shell without any weld lands is taken from the PANDA2 sample case called "nasacoldbend" (...panda2/case/nasacoldbend). This "acreage" cylindrical shell was previously optimized by PANDA2 accounting for the effect of cold bending during the fabrication process [14]. The internal "acreage" rings and "acreage" stringers have rectangular cross sections. The decision variables used during the previous "nasacoldbend" optimization by PANDA2 are the thickness of the shell skin,  $T(1)(SKN)$ , the spacing, height, and thickness of the internal "acreage" stringers,  $B(STR)$ ,  $H(STR)$ ,  $T(2)(STR)$ , and the spacing, height, and thickness of the internal "acreage" rings,  $B(RNG)$ ,  $H(RNG)$ ,  $T(3)(RNG)$ . These "nasacoldbend" "acreage" decision variables are listed in Tables 5 and 7. These "nasacoldbend" "acreage" quantities are not decision variables in the "wcold" optimization problem in which we wish to find the best dimensions of the weld land curved plate with its T-shaped edge stringers. (Except see Tables 6 and 8 for the comments about TSKIN). The names of the "acreage" stiffener variables in the "wcold" optimization are BSTR, HSTR, TSTR, BRNG, HRNG, TRNG, and the name of the "acreage" skin is TSKIN. These variables are listed in PARTS 5 of Tables 6 and 8.

Figure 6 displays a general buckling mode predicted by BIGBOSOR4 corresponding to a model analogous to that shown in Fig. 1: a cylindrical shell with T-stiffened weld lands spaced at 120-degree intervals rather than at 60-degree intervals as shown in Fig. 1. All of the results in this paper pertain to the configuration in which there are

three T-stiffened weld lands in the cylindrical shell.

## SECTION 5 ABOUT GENOPT

GENOPT [6] is a system by means of which one can convert any analysis into a user-friendly analysis and into an optimization capability. GENOPT is not limited to the field of structural mechanics [20]. In the GENOPT "universe" there are considered to be two types of user: 1. **the "GENOPT user"**, and 2. **the "end user"**. The GENOPT user creates the user-friendly analysis and optimization capability for a class of problems with a generic name ("weldland" in this paper), and the end user uses that capability to find optimum designs for a member of that class with a specific name ("wcold" in this paper). For the work reported here the GENOPT user and the end user are the same person: the first author.

References [3] and [5-8] provide examples in which GENOPT is used to optimize shell structures. References [3,5,7,8] and this paper provide examples in which GENOPT is used with BIGBOSOR4 to find optimum designs of complex cylindrical and ellipsoidal shells. Many details are given in Ref. [7] about what GENOPT does and how to use it. These details will not be repeated here.

It is the duty of **the GENOPT user** to create user-friendly names, one-line definitions, and "help" paragraphs for the variables to be used in the analysis or analyses. The GENOPT user must also supply software (subroutines and/or FORTRAN statements) that perform the analysis or analyses. The GENOPT user must decide what behaviors will constrain the design during optimization cycles, behaviors such as general buckling, local buckling, stress, vibration, etc. [5]. While identifying each variable to be used in the generic case, the GENOPT user must decide which of seven roles each of these variables plays. The seven possible roles are:

1. decision variable candidate (such as a structural dimension)
2. parameter that is not a decision variable candidate (such as a material property)
3. environmental variable (such as a load)
4. behavioral variable (such as a stress)
5. allowable variable (such as a maximum allowable effective stress)
6. factor of safety (such as a factor of safety for stress)
7. objective (such as weight)

It is the duty of **the end user** to provide, for a specific case, a starting design, loads, and material properties, to choose decision variables, lower and upper bounds, equality constraints, and inequality constraints, and to choose whether to optimize or simply to analyze an existing design or both.

Please read [6] first, followed by the first part of [7], which contains many details about how to use GENOPT.

## SECTION 6 PRODUCTION OF THE PROGRAM SYSTEM TO OPTIMIZE A WELD LAND

The generic case is called "weldland"

Table 9 in this paper, Table 8 in [8] and Table 4 in [3] list typical run streams for obtaining optimum designs for configurations in which GENOPT [6] is used in connection with BIGBOSOR4 [5]. Table 4 in [3] lists the run stream used to obtain results analogous to those presented here. The results are different in this paper from those listed in [3] because:

1. The objective function has been changed since [3] was written, and
2. The results of this paper are based on the "true prismatic shell" model [10] that did not exist when [3] was produced.

The long Table 9 first gives the run stream used to produce the generic "weldland" system of computer programs,

then lists the run stream to employ the generic "weldland" system to obtain optimum designs for the specific case called "wcold", and finally ends with the run stream for executing BIGBOSOR4 outside the GENOPT context in order to produce plots such as those in Figs. 5, 6, 8, 10, 12, and 14.

The GENOPT user first provides input during the long GENTEXT interactive session as listed in Table 5 of [3] (the weldland.INP file). During the interactive GENTEXT session, GENOPT automatically produces the files weldland.DEF and weldland.PRO. Table 1 of this paper contains a small part of the weldland.DEF file: a glossary of the GENOPT user's variable names, one-line definitions, the role of each variable, and other properties of each variable. Table 2 of this paper lists the complete weldland.PRO file for the generic case, "weldland". The weldland.PRO file contains the prompts and "help" paragraphs, created by the GENOPT user. These prompts and "help" paragraphs will be seen by the end user. The program system created by GENOPT for the "weldland" generic case will be end-user friendly if the one-line prompting phrases and "help" paragraphs created by the GENOPT user, such as the following:

| one-line<br>prompt  | "help"<br>paragraph |
|---|---------------------|
| 25.1 index for weld land edge stringer (0 or 1 or 2): KLAND |                     |
| 25.2  |                     |
| KLAND = 0 means no stringer at the edges of the weld land   |                     |
| KLAND = 1 means the weld land edge stringer has a           |                     |
| rectangular cross section                                   |                     |
| KLAND = 2 means the weld land edge stringer has a           |                     |
| Tee-shaped cross section                                    |                     |

are written clearly by the GENOPT user and are reasonably free of jargon with which the end user might not be familiar.

GENTEXT also produces FORTRAN fragments, weldland.\*, listed on page 1 of Table 4 of [3] and described on pages 2 and 3 of Table 6 of [3]. GENOPT automatically assembles these FORTRAN fragments into various programs (BEGIN.NEW, STOGET.NEW, STRUCT.NEW, BEHAVIOR.NEW, CHANGE.NEW) described on page 2 of Table 6 of [3]. BEGIN.NEW, STOGET.NEW, and CHANGE.NEW are complete programs and subroutines, created automatically entirely by GENOPT. The GENOPT user does not have to be concerned about them at all.

It is a different matter in the case of STRUCT.NEW and BEHAVIOR.NEW. These are "skeletal" subroutine libraries either or both of which must be "fleshed out" by the GENOPT user. In this particular application the GENOPT user adds merely three statements to the version of STRUCT.NEW automatically created by GENOPT. (See Tables 8 and 9 of [3] and Table 9 in this paper). In this particular application the GENOPT user does more to "flesh out" the BEHAVIOR.NEW library. (See Tables 10 and 11 of [3] and the file, /home/progs/genopt/case/weldland/behavior.weldland).

In preparing for the GENTEXT interactive session the GENOPT user here decided to introduce three behaviors:

1. general buckling (GENBUK in Table 1)
2. inter-ring ("panel") buckling (PANBUK in Table 1)
3. stress (STRESS in Table 1)

Corresponding to these three behaviors, GENTEXT automatically created three skeletal "behavioral" subroutines, SUBROUTINE BEHX1 (general buckling), SUBROUTINE BEHX2 (inter-ring buckling), and SUBROUTINE BEHX3 (stress). The GENOPT user had to "flesh out" each of these three "behavioral" subroutines, as listed in Tables 10 and 11 of [3]. (NOTE: SUBROUTINES BEHX1, BEHX2, BEHX3, and OBJECT have been changed somewhat since [3] was written. See the latest versions on which this paper is based in the file, /home/progs/genopt/case/weldland/behavior.weldland.)

In the "fleshed out" versions of SUBROUTINE BEHX1 and SUBROUTINE BEHX2 there are calls to SUBROUTINE BOSDEC. SUBROUTINE BOSDEC must be written by the GENOPT user. SUBROUTINE BOSDEC ("BOSorDECK") creates a valid input file for BIGBOSOR4. A general guideline on how to go about

creating SUBROUTINE BOSDEC is provided in the following file associated with the GENOPT sample case called "cylinder": /home/progs/genopt/case/cylinder/howto.bosdec. For the present application SUBROUTINE BOSDEC is listed in Table 12 of [3]. (SUBROUTINE BOSDEC has been changed some since [3] was written. See the latest version of SUBROUTINE BOSDEC (on which this paper is based) in the file, /home/progs/genopt/case/weldland/bosdec.weldland.)

## SECTION 7 A TWO-PHASE OPTIMIZATION

Producing an optimum design of an internally ring and stringer stiffened "acreage nasacoldbend" cylindrical shell with a number of embedded axially oriented T-stiffened "wcold" weld lands such as shown in Fig. 1 requires two major phases:

**PHASE 1:** The internally ring and stringer stiffened "acreage" cylindrical shell without any weld lands must first be optimized with the use of PANDA2 [4, 13]. This phase of the total effort is described in [2]. Table 10 lists the "nasacoldbend" run stream both to optimize the acreage shell and to compute buckling loads for that optimized shell with an optimized T-stiffened weld land embedded in it. The effect of the cold bending fabrication process is included in the optimization loop [14]. In [2] and in this paper this PANDA2 case is called "nasacoldbend" because the case is of interest to NASA and a simulation of the cold-bending fabrication process (when an orthogrid-stiffened flat plate is cold-bent into a cylindrical shell) is included inside the optimization loop. The "spring-back" phenomenon is included in the simulation of the cold-bending fabrication process. The cold-bending process puts the tips of the internal acreage rings into considerable compression, enough to cause significant plastic flow. If the acreage rings are too slender they will buckle during the cold-bending process. In order to prevent this type of failure the first author had to introduce additional "cold-bending" constraints (cold-bending design margins) into PANDA2 [14]. The effect of these additional cold-bending design margins is to generate optimum acreage designs with stockier rings than would otherwise evolve during optimization cycles. Notice in PART 3 of Table 5 that "nasacoldbend" Design Margin No. 18 is critical:

Margin 18 = 3.39E-03 Cold-bending ring buckling, skin-ring module; N=66 ;FS=1.1

In this paper the "nasacoldbend" shell geometry is called "acreage". The "acreage" geometry exists in the sectors of the cylindrical shell with weld lands represented by Segments 4, 10, and 16 in Fig. 1, for example. The decision variables during the "nasacoldbend" optimization process are the spacings, heights, and thicknesses of the internal acreage rings and the internal acreage stringers, which have rectangular cross sections, and the thickness of the skin of the "acreage" cylindrical shell. Optimized "acreage nasacoldbend" designs are listed in Table 5 (PANDA2 conservativeness index, ICONSV=1) and in Table 7 (PANDA2 conservativeness index, ICONSV=-1). See [13] and Items 676, etc. of [4L] and below for information on ICONSV.

**PHASE 2:** In the second phase of the total effort a T-stiffened weld land must next be optimized. The decision variables are shown in Fig. 2. This second optimization is accomplished with GENOPT [6,7] combined with BIGBOSOR4 [5]. The specific case name during this second phase of the two-phase design process is "wcold", which stands for "Weld land" and "COLD-bending". During this second phase of the total effort the "acreage" geometry is held constant. The spacings, heights, and thicknesses of the "acreage" internal rings and internal stringers play a role in the analysis, of course, but they are no longer decision variables in the optimization process. The thickness of the skin of the "acreage" cylindrical shell remains a decision variable with very tight lower and upper bounds so that its very, very small change during the optimization process does not materially affect the properties of the "acreage". The reason for the retention of TSKIN as a decision variable in the "wcold" optimization is given in Tables 6 and 8. Optimized "wcold" designs are listed in Table 6 ("nasacoldbend" acreage designed with ICONSV=1) and in Table 8 ("nasacoldbend" acreage designed with ICONSV=-1).

## SECTION 8 PROBLEM CHARACTERISTICS AND A SUMMARY OF NUMERICAL RESULTS

### Problem characteristics

Table 3 lists the properties of the "nasacoldbend" case and the "wcold" case. These properties remain constant during the two-phase optimization just described. The applied loading is uniform end shortening, which results, for the case in which the "nasacoldbend" acreage is designed with ICONSV = 1, in average axial compression,  $N_x = -3070$  lb/in, over the weld land curved plate plus T-shaped stringers, and average axial compression,  $N_x = -2219$  lb/in over the acreage skin plus acreage stringers. In the optimized "wcold" weld land listed in Table 6 the average applied axial compression,  $N_x = -3070$  lb/in, in the three parts, weld land curved plate, T-stringer web, and T-stringer outstanding flange, is distributed as follows:

$$\begin{aligned} N_x(\text{weld land curved plate}) &= -2447.8 \text{ lb/in} \\ N_x(\text{T-stringer web}) &= -997.5 \text{ lb/in} \\ N_x(\text{T-stringer outstanding flange}) &= -905.1 \text{ lb/in} \end{aligned}$$

In the "nasacoldbend" acreage optimized with ICONSV = 1 (Table 5) the average applied axial compression,  $N_x = -2219$  lb/in in the acreage skin and acreage stringers, is distributed as follows:

$$\begin{aligned} N_x(\text{acreage cylindrical shell skin}) &= -1354.9 \text{ lb/in} \\ N_x(\text{acreage internal stringers}) &= -1980.0 \text{ lb/in} \end{aligned}$$

In the "nasacoldbend" acreage case it is necessary to specify a stress-strain "curve" because the cold-bending fabrication process involves plastic flow in the internal rings. The acreage geometry, "nasacoldbend", is optimized with the use of plus and minus imperfections with amplitude,  $|W_{imp}| = 0.125$  inch. The imperfection has the shape of the critical general buckling mode, a mode analogous to that depicted in Fig. 17. (Of course, in the PANDA2 model the general buckling modal imperfection is expressed in the form,  $W_{imp} \cdot \sin(m \cdot \pi \cdot x/L) \cdot \sin(n \cdot \theta)$ , not in the form of a finite element grid as in Fig. 17, which was produced by STAGS.)

Because a general buckling modal imperfection is specified, the factors of safety for buckling are taken to be 0.999. (A number very slightly less than 1.00 is used so that PANDA2 will not automatically change the buckling factors of safety from 1.0 to 1.1, which it does in order to avoid numerical difficulties in the case of perfect shells and shells with very small initial imperfections.) The input data for the PANDA2 mainprocessor include a "conservativeness" index, ICONSV, that can be 1 (most conservative and the recommended value), or 0 (intermediate conservativeness) or -1 (least conservative). This paper reports results for optimized "nasacoldbend" acreage obtained first with ICONSV = 1 (Table 5) and second with ICONSV = -1 (Table 7). Explanations of ICONSV are given in [13] and in Items 676, etc. of [4L].

In the "wcold" case the material remains elastic. A factor of safety of 2.0 is given for general buckling (GENBUKF - Tables 1 and 9) and a factor of safety of 1.5 is given for inter-ring ("panel") buckling (PANBUKF - Tables 1 and 9) because in this application the shell geometry is perfect. It is not possible to introduce a general buckling modal imperfection in "huge torus" or in "true prismatic shell" BIGBOSOR4 models. Therefore, buckling factors of safety greater than unity are introduced in order to compensate.

Two "M-ranges" are given in the "wcold" part of Table 3:

```
1 $ low end of the M-range for general buckling: MLOWG
10 $ High end of the M-range for general buckling: MHIGHG
1 $ low end of the M-range for "panel" buckling: MLOWP
10 $ high end of the M-range for "panel" buckling: MHIGHP
```

These are the ranges in numbers of axial half waves M along the length, 68.75 inches, of the entire cylindrical shell for general buckling and along the length between acreage rings, 13.75 inches, for "panel" buckling. "Panel" buckling means "inter-ring" buckling: buckling between adjacent rings with the rings replaced by classical simple supports during the linear bifurcation buckling phase of the analysis. These two "M-ranges" are used to search for the critical (lowest) buckling load factors with respect to axial half waves M for general buckling (SUBROUTINE

BEHX1) and for inter-ring buckling (SUBROUTINE BEHX2) of the "wcold" cylindrical shell with its embedded T-stiffened weld lands.

#### **Summary of numerical results in Table 4**

Table 4 lists the most important results in this paper. Buckling load factors are given for the three models: "nasacoldbend", "wcold", and "stags". The buckling loads in pounds are obtained by multiplication of the buckling load factors by the applied load, 669235 lb (called "the design load"). Under the "nasacoldbend" columns there is a column with the heading, "PANEL3(weld)". The PANDA2 processor called "PANEL3" [Item 792 of 4L] is used to evaluate the cylindrical shell with the "nasacoldbend" acreage previously optimized by PANDA2 and with the T-stiffened weld land previously optimized with use of the GENOPT/BIGBOSOR4 "wcold" model. Tables 9 and 10 list the run streams that accomplish this. There is no capability in PANDA2/PANEL3 to optimize cylindrical shells with weld lands. "PANEL3" simply generates an input file for BIGBOSOR4 that includes the T-stiffened weld land dimensions obtained from a previous "wcold" GENOPT/BIGBOSOR4 optimization. Table 11 lists a run stream by means of which STAGS can be used to evaluate the predictions from the "nasacoldbend" and the "wcold" models.

Several comments should be made with respect to Table 4:

1. All the entries in Table 4 except one correspond to the "nasacoldbend" acreage design optimized with use of the PANDA2 conservativeness index, ICONSV = 1. The two "PANDA2(no weld)" entries for which ICONSV = -1 is indicated in the [a,b,c,d,e] array (d=2 means ICONSV = -1), that is, the Table 4 entries with general buckling load factor = 2.26 and with inter-ring bay buckling load factor = 2.350, correspond to the "nasacoldbend" acreage optimized with ICONSV = 1 and then the same optimized design evaluated by PANDA2 with ICONSV = -1. This was done in order to obtain additional comparisons between predictions from STAGS and predictions from the "nasacoldbend no weld" models. The one "stags no weld" entry, collapse load factor = 1.18, corresponds to the "nasacoldbend" acreage optimized with ICONSV = -1 (Table 7) and the "wcold" model optimized with ICONSV = -1 (Table 8).
2. There is good agreement between PANDA2 and STAGS predictions for general buckling and for inter-ring bay buckling for the "no weld" models if ICONSV = -1 is used in the PANDA2 model of the design optimized with ICONSV = 1. Compare the PANDA2 prediction, 2.26(2,7), with the two STAGS predictions, 2.266(2,7) and 2.2271(3,8), for "no weld" general buckling. Compare the PANDA2 prediction, 2.350(1,17), with the STAGS prediction, 2.3387(1,18), for "no weld" inter-ring bay buckling. Notice that the critical general buckling mode shape from the STAGS model changes from (axial, circumferential) half waves, (m,n) = (2,7), when the rings are smeared (Fig. 17) to (m,n) = (3,8) when the rings are modeled as little shell units (Fig. 18). The PANDA2 model of general instability, 2.26(2,7), has both rings and stringers smeared out. The PANDA2 prediction of general buckling with ICONSV = 1, 1.898(2,7), is somewhat conservative, which is to be expected. Reference [13] and Items 676, etc. in [4L] explain the various elements of conservativeness either included or not included in the PANDA2 model, depending on the value of ICONSV (either 1 or 0 or -1) specified by the PANDA2 user.
3. All the models for local "pocket" buckling in the acreage yield predictions of buckling load factors that are in reasonably good agreement with each other. Much of the difference between the prediction of local buckling from Thornburgh's STAGS model, 1.3924 (Fig. 33), compared with 1.3324 (Fig. 20) and 1.3488 (Figs. 25-27) from Bushnell's STAGS models is apparently caused primarily by Thornburgh's use of the STAGS 410 finite element versus Bushnell's use of the STAGS 480 finite element. Most of the additional difference is probably caused by the fact that in Thornburgh's STAGS model the acreage rings are connected to the acreage stringers where they intersect, whereas in Bushnell's STAGS models these acreage stiffeners are not connected to each other.
4. All the models with the T-stiffened weld land generate predictions of buckling load factors that are in good agreement with one another except the two predictions of T-stringer rolling from an inter-ring model: 1.668 from the "PANEL3(weld)" model and 1.8066 from the "wcold weld" model. The "PANEL3(weld)" model has acreage stringers modeled as little shell segments (Fig. 11), whereas the "wcold weld" model has acreage stringers smeared out (Fig. 10). The "PANEL3(weld)" model predicts the lower buckling load factor, 1.668, because there is an interaction between T-stringer rolling and local buckling of the acreage stringer bay adjacent to the T-stiffened weld land, as seen in Fig. 11. No such interaction is possible with the "wcold weld" model because the acreage stringers are always smeared out in "wcold" models, as seen in Fig. 10. The buckling load factor, 1.668, from the

"PANEL3(weld)" inter-ring case is in good agreement with the higher of the two "T-stringer-rolling" load factors, 1.6288, from the STAGS "60-degree" model in which all structural parts are modeled as shell units (Fig. 30). There is a lower "T-stringer-rolling" load factor, 1.5450, from the same "60-degree" STAGS model (Fig. 29). The mode shape for this lower of the two "T-stringer-rolling" load factors from STAGS is dominated by local buckling in which "T-stringer-rolling" is a relatively small component, as seen in Fig. 29. The prediction of T-stringer crippling from the "60-degree" STAGS model agrees well with the "nasacoldbend PANEL3(weld)" predictions. The "wcold" model generates somewhat higher T-stringer crippling predictions because the acreage stringers are smeared out in all "wcold" models. The "inter-ring bay buckling" phenomenon from the STAGS "60-degree" model is a mixture of local and inter-ring bay buckling, as seen from Fig. 31. Therefore, the corresponding buckling load factor, 2.1456, is somewhat lower than the STAGS prediction, 2.3387, from the inter-ring "no weld" model in which the acreage stringers are smeared and there is no T-stiffened weld land.

5. The last category of "buckling" listed in Table 4 is entitled, "collapse of shell with a general buckling modal imperfection with  $W_{imp} = + & - 0.125$  inch". The results listed under the heading, "PANDA2(no weld)" are obtained from nonlinear bifurcation buckling analyses for the "nasacoldbend" shell with prebuckling deformations that include the two effects of the initial general buckling modal imperfection [4K, 13]:

**Effect no. 1:** the fact that the imperfection shape, which is amplified by the applied loading, causes the minimum circumferential curvature of the axially loaded, imperfect shell to be less than the nominal value (48 inches in this case) for the perfect shell

**Effect no. 2:** the redistribution of prebuckling compression among the skin and the stiffeners caused by prebuckling bending of the imperfect shell as it is subjected to the applied load.

In PANDA2 there is no rigorous nonlinear collapse analysis in the sense that the applied loading reaches a peak and then declines as the imperfect shell collapses in a nonlinear manner. Instead, nonlinear collapse is simulated by nonlinear local, inter-ring, and general bifurcation buckling analyses that account in an approximate manner for the prebuckling deformation and stress redistribution that occurs as the imperfect shell deforms under the applied load.

6. In the "nasacoldbend" case for which the buckling factors of safety are close to unity and this generally unconservative practice is compensated for by the inclusion of plus and minus general buckling modal imperfections with amplitude,  $|W_{imp}| = 0.125$  inch, it is absolutely essential to verify via a nonlinear STAGS analysis, that the imperfect "acreage" shell without any weld lands will carry the applied load. The results of such nonlinear analyses are displayed in Fig. 42. Nonlinear STAGS analyses of imperfect "wcold" shells with T-stiffened weld lands must also be conducted in order to verify the ability of these optimized shells to carry the applied load. Results are shown in Fig. 23.

#### How to use STAGS to evaluate "nasacoldbend" and "wcold" predictions

Table 9 in [13] lists a sequence of STAGS linear and nonlinear executions that lead to the prediction of collapse of an optimized stiffened axially compressed cylindrical shell with an initial imperfection in the form of the critical linear general buckling mode. The STAGS user should obtain collapse loads of imperfect shells as follows [4K, 13]:

- Determine the critical general buckling mode from the STAGS linear buckling branch ( $INDIC = 1$ ) with the STAGS index,  $ILIN = 1$  in every shell unit. The general buckling mode is needed as an imperfection shape that will be used later in a nonlinear STAGS analysis ( $INDIC = 3$ ).  $ILIN = 1$  leads to overestimation of bifurcation buckling load factors. The overestimation is more pronounced the shorter the wavelengths in the buckling mode. Therefore,  $ILIN = 1$  tends to filter out eigenvalues (buckling load factors) that correspond to local (short-wavelength) buckling modes. The presence of numerous closely spaced eigenvalues that correspond to various types of local buckling often seriously interferes with the STAGS user's ability to discover the critical general buckling mode and eigenvalue. The general buckling eigenvalue is embedded in a "thicket" of local buckling eigenvalues. Looking for the general buckling mode is often like looking for a needle in a haystack. It is often a tedious process in which repeated linear buckling STAGS runs must be executed, each with a slightly different eigenvalue shift in the STAGS input file, \*.bin. The STAGS post-processor, STAPL, must be used after each execution of STAGS in order that the STAGS user can examine each linear buckling mode to see if it qualifies as a general buckling mode. The usual

practice is first to obtain a rough estimate of the general buckling load factor from a STAGS model in which local modes are prevented by a smearing of closely spaced stiffeners. Then, with a more elaborate STAGS model, begin the search for the general buckling mode, using as an initial eigenvalue shift the general buckling eigenvalue found from the "preliminary" crude STAGS model. With each eigenvalue shift it is best to specify NEIGS = 8 in the \*.bin file during the search for the critical general buckling mode and eigenvalue. (With NEIGS = 8 STAGS is instructed to find 8 eigenvalues for each execution of STAGS.)

2. Once the critical general buckling mode has been determined with ILIN = 1, then set ILIN = 0 in every shell unit and repeat the tedious process, using as an initial eigenvalue shift the general buckling eigenvalue that was determined with ILIN = 1 in every shell unit and executing STAGS repeatedly with successively small downward eigenvalue shifts, seeking 8 eigenvalues for each STAGS linear bifurcation buckling execution.

3. Once the critical general buckling mode has been determined with ILIN = 0, execute STAGS in its nonlinear static equilibrium mode (INDIC = 3). Use as an imperfection the critical general buckling mode from the linear buckling (INDIC=1) analysis with ILIN = 0. In this paper the imperfection amplitude, Wimp, equals plus or minus 0.125 inch. It is emphasized that the sign of Wimp is often important. For example, Wimp = -0.125 was used for the general buckling modal imperfection shape displayed in Fig. 22b. The sign of Wimp is not important for general buckling modal imperfections of the form shown in Fig. 22a, in which both inward and outward normal displacements are equally prevalent. Execute STAGS in the INDIC = 3 mode perhaps several times, each time starting at the load level corresponding to the highest load level reached in the previous nonlinear static run. After each nonlinear run search the STAGS \*.out2 file for the string, "roots", to make sure that no nonlinear buckling roots have been bypassed on the nonlinear static equilibrium path, or if they have been bypassed in one or more load steps they are no longer bypassed in later load steps at higher values of the load factor, PA.

4. At some point STAGS may have difficulty continuing to increase the load (actually, the load factor, PA). Or STAGS may find additional nonlinear solutions with the load factor PA declining with each load step. If the declining sequence of PA is associated with just one "skipped" root, STAGS has probably passed a load peak and the shell is collapsing, that is, the maximum deflection is increasing as the load factor PA decreases with each successive load step. If the declining sequence of PA is associated with zero skipped roots, "Riks path reversal" [4K] has probably occurred, and STAGS is simply unloading along the same nonlinear equilibrium path followed earlier when PA was increasing with each load step. If STAGS is unable to determine nonlinear static equilibrium states for increasing PA, even when the load step size has been cut repeatedly, then probably there are one or more nonlinear bifurcations on the nonlinear equilibrium path. In order to determine collapse it is then necessary to employ one of the following strategies:

**STRATEGY 1:** Introduce one or more new buckling modal imperfection shapes in the form of nonlinear eigenvectors computed during one or more nonlinear static (INDIC=3) STAGS runs. These new buckling modal imperfection shapes should have amplitudes, Wimp, that are very small compared to the amplitude of the general buckling modal imperfection: amplitudes such as 0.001 inch. These new buckling modal imperfection shapes act as "triggers" that convert nonlinear bifurcations on the primary nonlinear equilibrium path to local nonlinear "collapse" behavior, thereby allowing the Riks method [17] to continue. Start the nonlinear static equilibrium (INDIC=3) analysis over at PA = 0.0.

**STRATEGY 2:** Run STAGS in its nonlinear transient mode (INDIC = 6) at a load level from two to five per cent higher than the highest value of PA reached so far from the nonlinear static STAGS executions. After completion of the STAGS nonlinear transient run, if that run converges to a stable equilibrium state, execute STAGS in its "load relaxation" mode [4K, 13]. If the nonlinear transient response diverges, then the collapse load is between the highest load factor PA determined by STAGS in the previous nonlinear static run and the constant value of PA used for the nonlinear transient analysis.

**STRATEGY 3:** See the sub-section entitled "Thornburgh's STAGS models" in SECTION 11, "Some details concerning STAGS models", for a description of the strategy that Thornburgh uses to obtain collapse loads.

If the STAGS user chooses to introduce new imperfection shapes and start over with the nonlinear static equilibrium analysis, the best imperfection shapes are one or more of the nonlinear bifurcation buckling modes obtained in the nonlinear static run for which STAGS reached the highest value of load factor PA without skipping any roots.

Table 11 lists the run stream to accomplish part of one of the procedures just listed.

**Summary of results from the "two-phase" optimization process for the PANDA2 conservativeness index, ICONSV = 1 and ICONSV = -1**

Tables 5 - 8 list results for the "nasacoldbend" and for the "wcold" phases of the two-phase optimization described in SECTION 7. There are two sets of results, the first set (Tables 5 and 6) obtained with use of the recommended value of the PANDA2 conservativeness index, ICONSV = 1, and the second set (Tables 7 and 8) obtained with use of the PANDA2 conservativeness index, ICONSV = -1. With ICONSV = 1 [the most conservative choice, that is, the choice that leads to the most conservative (heaviest) acreage design] the weight of 180 degrees of the "acreage" cylindrical shell (no weld land) is 107.4 lb (Table 5). With ICONSV = -1 (least conservative choice) the weight of 180 degrees of the "acreage" cylindrical shell (no weld land) is 95.75 lb (Table 7). This difference corresponds to a weight saving of 23.3 lb for the entire (360-degree) "nasacoldbend" acreage cylindrical shell.

[**Small digression:** PANDA2 was written for the optimization of flat and curved panels. If the PANDA2 user wants to optimize a complete (360-degree) cylindrical shell, he or she models it as a panel that spans 180 degrees. In the PANDA2 model the boundary conditions along the two straight edges of a cylindrical panel are "classical" simple support, which are the boundary conditions that correspond to a buckling nodal line. The number of half waves over 180 degrees is equal to the number of full waves over 360 degrees. Therefore, in the absence of in-plane shear loading and/or anisotropy, the behavior of a 180-degree panel is the same as that of a complete cylindrical shell. That is why the weights given in the "nasacoldbend" PANDA2 models in Tables 5 and 7 are for 180 degrees of circumference rather than for 360 degrees.]

Notice from a comparison of Tables 6 and 8 that the T-stiffened weld land associated with the conservatively designed "nasacoldbend" acreage weighs much less than that associated with the not-so-conservatively designed "nasacoldbend" acreage: WEIGHT = 0.06128 lb/in listed in Table 6 versus WEIGHT = 0.1416 lb/in listed in Table 8. The total weight of the three T-stiffened weld lands is:

$$\text{Total weight of 3 weld lands} = \text{WEIGHT} \times \text{length of shell} \times \text{number of weld lands}$$

$$\begin{aligned} \text{Total weight of 3 weld lands} &= \text{WEIGHT} \times 68.75 \times 3 \\ &= 12.64 \text{ lb for the nasacoldbend ICONSV = 1 design} \\ &= 29.21 \text{ lb for the nasacoldbend ICONSV = -1 design} \end{aligned}$$

The weight of "acreage" shell replaced by the three T-stiffened weld lands is given by:

$$\begin{aligned} \text{weight of acreage replaced by weld lands} &= \text{number of weld lands} \\ &\quad \times \text{width of one weld land} \\ &\quad \times \text{weight/width of the acreage} \\ &= 3 \times 4.0 \times 2 \times 107.4 / 301.593 = 8.5466 \text{ lb} \end{aligned}$$

for the ICONSV = 1 design and

$$= 3 \times 4.0 \times 2 \times 95.75 / 301.593 = 7.6195 \text{ lb}$$

for the ICONSV = -1 design. Therefore the total weights of the optimized cylindrical shells with three optimized T-stiffened weld lands are:

$$\begin{aligned} \text{total weight} &= 2 \times 107.4 - 8.5466 + 12.64 = 218.9 \text{ lb for the ICONSV = 1 design} \\ \text{total weight} &= 2 \times 95.75 - 7.6195 + 29.21 = 213.1 \text{ lb for the ICONSV = -1 design} \end{aligned}$$

Hence, the less conservative acreage design leads to a net savings of only 5.8 lb. Notice from Table 8 that the T-stringer design obtained with the least conservative "nasacoldbend" acreage optimized with ICONSV = -1 has very tall webs: HWLAND = 3.401 inches compared with HWLAND = 1.656 inches listed in Table 6 for the ICONSV = 1 option. The taller T-stringer height might well violate some requirement concerning internal clearance.

The dramatic sensitivity of the optimized T-stiffened weld land designs to the properties of the acreage implies that the optimization problem should perhaps be reformulated. Perhaps all of the dimensions, weld land dimensions as well as acreage dimensions, should be optimized at the same time rather than in two successive optimizations: PHASE 1 for the acreage and PHASE 2 for the T-stiffened weld land, as described in SECTION 7. However, that alternative approach is left for a future research project.

Tables 5 - 8 list design margins corresponding to the optimized designs. The buckling load factor corresponding to a buckling margin is computed from

$$\text{buckling load factor} = (\text{buckling margin} + 1.0) \times (\text{factor of safety})$$

The total buckling load is given by

$$(\text{total buckling load}) = (2 \times \pi \times \text{radius}) \times N_x(\text{applied}) \times (\text{buckling load factor})$$

or in our cases

$$(\text{total buckling load}) = 669235 \times (\text{buckling load factor}) \text{ lb.}$$

Notice that PART 4 of Table 5 lists margins obtained with ICONSV = -1 applied to the optimum design obtained with ICONSV = 1. The purpose of including PART 4 in Table 5 is to provide comparisons with predictions from STAGS for models with the dimensions listed in Tables 5 and 6.

The various types of buckling modes listed in Table 4 are plotted in Figs. 5 - 35.

## SECTION 9 SOME DETAILS CONCERNING THE "WCOLD" CASE

Table 13 of [3] and Table 9 in this paper list the input for the "BEGIN" processor, a processor that is created automatically by GENOPT during the interactive GENTEXT session. Table 14 of [3] and Table 9 here list the input for the "DECIDE" processor of GENOPT. Notice that a linking expression is introduced for the weld land eccentricity, ECLAND. This linking expression maintains the flushness of the OUTER surfaces of the weld land curved plate and the acreage cylindrical shell skin during optimization cycles. Unfortunately, in the "DECIDE" processor, as currently written for GENOPT, all variables in the linking expression must be decision variables or decision variable candidates. Therefore, it was necessary to make the thickness, TSKIN, of the cylindrical shell skin a decision variable even though we do not want TSKIN to change significantly from its previously obtained optimum value in the "nasacoldbend" optimization phase of the overall effort. Accordingly, we establish very tight lower and upper bounds for TSKIN in the "wcold" optimization phase, as described in Tables 6 and 8, so that during "wcold" optimization cycles TSKIN will not change significantly.

Table 15 of [3] and Table 9 here list the input for the "MAINSETUP" processor. IDESIGN = 2 is the preferred value for IDESIGN, and IMOVE = 1 is the preferred value for IMOVE. These and other input variables listed in the wcold.OPT file in Table 9 are described in the file, /home/progs/genopt/execute/URPROMPT.DAT. Lists of the relevant sections of the file, URPROMPT.DAT, are provided in [3] and [8].

After completion of the SUPEROPT [4D] run (Table 9), which requires about two hours on the computer in this particular application, we want to see a plot of the objective versus the approximately 470 design iterations performed during the SUPEROPT execution. We use CHOOSEPLOT to select what to plot. In this case (and usually after a successfully completed execution of SUPEROPT) we choose to plot only the objective function, not the design margins nor any of the decision variables. Plots of the design margins and the decision variables for about 470 design iterations are very messy. These should be plotted only after several executions of OPTIMIZE, corresponding to which there may be something like a total of 50 design iterations or less, not after a successfully completed execution of SUPEROPT, corresponding to which there are about 470 design iterations.

Table 9 lists input for CHOOSEPLOT, and Fig. 4 displays the objective versus all the design iterations during the

successful execution of SUPEROPT for the "ICONSV=1" case summarized in Table 6. Notice that there are several "spikes" in the plot in Fig. 4. Each "spike" corresponds to a new "starting" design. Each new "starting" design is obtained randomly [4D] but consistently with the lower and upper bounds and linking expressions. The aim of the SUPEROPT run is to attempt to find a "global" optimum design by starting from many different points in design space and converging to various optimum designs. In this case the best design obtained after the SUPEROPT run is the design with the minimum weight that is either "FEASIBLE" or "ALMOST FEASIBLE" (IDESIGN = 2). In this particular execution of SUPEROPT the user chose to allow five executions of OPTIMIZE for each execution of AUTOCHANGE. The processor, AUTOCHANGE, randomly obtains a new "starting" design [4D].

Table 6 lists the optimum "wcold" design obtained after a single execution of SUPEROPT. Note that the thickness of the weld land is almost at its lower bound, set in this case equal to 0.1 inch. The width of the weld land stays at its lower bound of 4.0 inches throughout the SUPEROPT run. The height to thickness ratio of the web of the T-stringer is almost 39 and the width-to-thickness ratio of the outstanding flange of the T-stringer is almost 24. These optimized dimensions are probably inappropriate for various reasons, such as the infeasibility of welding thin parts together without the development of excessive local residual deformations. Therefore, a "wcold" case was optimized in which the slenderness of the T-stiffener web and outstanding flange were not allowed to exceed 10. The results from this perhaps more practical optimization are reported in SECTION 13. The first author knows very little about welding. Hence, his choices of upper and lower bounds of the decision variables in "DECIDE" (Table 9) are fairly arbitrary. Therefore, the reader should regard this paper and Reference [3] as guides for how to obtain optimum designs, not as guides about the good design of actual weld lands. Somebody who knows more about welding than the first author would doubtless specify different upper and lower bounds on the decision variables and establish different inequality relationships in "DECIDE" that constrain the slenderness of the weld land T-stiffener web and outstanding flange.

The design margins of the optimized "wcold" structure for which no constraints are imposed on the weld land T-stringer web and flange slenderness are listed in PART 3 of Table 6. Note that the stress margin is not critical, probably because the present application does not include any prebuckling bending.

The objective in this application is the weight per axial length of a single Tee-stringer-stiffened weld land, as computed in SUBROUTINE OBJECT of the behavior.weldland library (page 4 of Table 11 in [3]). The objective is called "WEIGHT" (units = lb/in), which is now computed from the formula:

$$\begin{aligned} \text{WEIGHT} = & (\text{WLAND} * \text{TLAND}) \\ & + 2 * (\text{TWLAND} * \text{HWLAND} + \text{TFLAND} * \text{WFLAND}) * \text{DENS} * 386.4 \end{aligned}$$

in which DENS is the mass density of the material:

0.250E-03 \$ mass density (aluminum = 0.00025 in English units): DENS

(NOTE: The formula for WEIGHT is incorrect on page 4 of Table 11 in [3]. The formula was changed to that listed above after [3] was completed. All results in this paper are based on the correct formula for the weight per axial length of one T-stiffened weld land, that is, the weight per axial length of the weld land curved plate plus the weight per axial length of the two T-stringers that reinforce the weld land curved plate.)

In this "weldland" application, whenever the GENOPT processor, OPTIMIZE, is executed in a "fixed design mode", that is, with ITYPE = 2 in the \*.OPT file (Table 9), SUBROUTINE BEHX1, which computes general buckling, produces two valid input files for BIGBOSOR4: wcold.BEHX0 and wcold.BEHX1. These two files can be used outside of the GENOPT context in order to see what the general buckling modes look like for the optimized shell without (wcold.BEHX0, Fig.5) and with (wcold.BEHX1, Fig.6) weld lands. SUBROUTINE BEHX2, which computes inter-ring ("panel") buckling, produces one valid input file for BIGBOSOR4: wcold.BEHX2. This file can be used outside of the GENOPT context in order to see various inter-ring buckling modes for the optimized shell with weld lands (Figs.10,12,14). Figure 5 shows, for the optimized structure, the critical general buckling mode obtained via wcold.BEHX0 (no weld land); Figs. 6 and 8 show two buckling modes obtained via wcold.BEHX1 (yes weld lands); Figures 10, 12, and 14 show various inter-ring ("panel") buckling modes obtained via wcold.BEHX2. The run stream required to obtain these results from BIGBOSOR4 as used outside the GENOPT context appears as the last part of Table 9.

Notice that both the acreage rings and the acreage stringers are always smeared out in all the "wcold" models that are associated with the full length, 68.75 inches, of the cylindrical shell. The acreage stringers are always smeared out in all the "wcold" models that are associated with the length of cylindrical shell equal to the acreage ring spacing, 13.75 inches. In these "inter-ring" ("panel") models the rings are replaced by classical simple support conditions in the bifurcation buckling phase of the analysis.

## SECTION 10 SOME DETAILS CONCERNING THE "NASACOLDBEND" CASE WITH "PANEL3"

Table 4 lists buckling load factors associated with the "nasacoldbend" model used in connection with the PANDA2 processor called "PANEL3". "PANEL3" [Item 792 of 4L] produces valid input files for BIGBOSOR4 in which one half of a T-stiffened weld land is included at a plane of symmetry. The acreage stringers can be smeared out or modeled as little flexible shell segments. Ninety degrees of the circumference of the cylindrical shell is covered in the "PANEL3 nasacoldbend" model, with symmetry conditions applied at both ends of the meridian. For general buckling models the "nasacoldbend" acreage rings are always smeared out. For inter-ring buckling the "nasacoldbend" acreage rings are replaced by classical simple support in the buckling phase of the calculations. The "nasacoldbend PANEL3(weld)" models imply that the complete (360-degree) cylindrical shell has two T-stiffened weld lands, one at 0 degrees and the other at 180 degrees. The presumption in using the "90-degree" "nasacoldbend" model and comparing the results from it with those from the "180-degree" "wcold" model (three T-stiffened weld lands in 360 degrees) is that the behavior is insensitive to the number of T-stiffened weld lands in the cylindrical shell provided that this number is small.

Figures 7 and 9 show buckling modes from the "nasacoldbend PANEL3" model in which the axial length of the cylindrical shell is 68.75 inches, which is the total length of the ring and stringer stiffened cylindrical shell. Figures 11, 13, 15 and 16 show buckling modes from the "nasacoldbend PANEL3" model in which the axial length of the cylindrical shell is 13.75 inches, which is the axial length equal to the spacing of the acreage rings. The "nasacoldbend" figures referred to in this paragraph should be compared with the analogous "wcold" figures: Figure 7 is analogous to Fig. 6; Figure 9 is analogous to Fig. 8; Figure 11 is analogous to Fig. 10; Figure 13 is analogous to Fig. 12; Figure 15 is analogous to Fig. 14. Figure 16 is not analogous to any "wcold" figures because the "wcold" model cannot predict local "pocket" buckling (buckling between adjacent acreage rings and adjacent acreage stringers), since the acreage stringers are always smeared out in all "wcold" models.

Notice that local "pocket" buckling in the acreage has the lowest load factor, 1.303, in the PANDA2 "nasacoldbend" model and a somewhat higher load factor, 1.3472, in the "nasacoldbend" model associated with the PANDA2 processor, "PANEL3". These "pocket" buckling load factors are the lowest when compared to those for all other types of buckling. Local "pocket" buckling is not present in the "wcold" application because the shell acreage stringers are smeared out in all "wcold" models. Therefore, the "wcold" models cannot determine local buckling outside the weld land. However, remember that the shell acreage away from any weld land was previously optimized by PANDA2 including a general buckling modal imperfection with amplitude,  $W_{imp}$  = plus and minus 0.125 inch. The local buckling mode depicted in Fig. 16 does not involve the weld land at all. Therefore, we do not need to be concerned that the "wcold" model is incapable of predicting local buckling away from any weld land, even though the local buckling load factor is lower than any of the buckling load factors determined in the case, "wcold". In previously optimizing the "nasacoldbend" stiffened cylindrical shell without any weld lands, we assumed that inclusion of the general buckling modal imperfection with amplitude,  $W_{imp}$  = plus and minus 0.125 inch would lead to a conservative optimum design of the shell acreage. The optimization of the weld land does not change that previously made assumption about the adequacy of the shell acreage away from any weld land with respect to local, inter-ring, and general instability. Of course, it is absolutely necessary to check that assumption by running STAGS models of the optimized imperfect shell both with and without T-stiffened weld lands. At least one of these STAGS models must be capable of predicting nonlinear local "pocket" buckling in a shell with one or more T-stiffened weld lands and having a general buckling modal imperfection with amplitude,  $W_{imp}$  = plus or minus 0.125 inch, such as is done in the case of Thornburgh's STAGS model, results from which are presented in Fig. 23 and Figs. 32-35, to be discussed in the next section.

## SECTION 11 SOME DETAILS CONCERNING STAGS MODELS

The general-purpose STAGS computer program [15-18] is used to evaluate the approximate results obtained by PANDA2 [2,4] and by GENOPT/BIGBOSOR4 [5-8].

STAGS models were produced by both authors. The first author generated STAGS models with the help of the PANDA2 processor called STAGSUNIT [4I]. Figures 17 - 20 are examples of STAGS models generated entirely with STAGSUNIT. (See Table 11.) The boundary conditions enforced in the STAGSUNIT-generated STAGS models are such that the prebuckled state of whatever sub-domain of the complete cylindrical shell is to be included in the STAGS model is very close to the prebuckled state of the sub-domain when that sub-domain is embedded in the entire cylindrical shell.

### Bushnell's STAGS models

Figures 21 - 31 represent "compound" STAGS models [4K and Item 643 in 4L]. In Item 643 of 4L step-by-step directions are given on how to produce a "compound" STAGS model of the type displayed in Fig. 21, which represents the "nasacoldbend" acreage cylindrical shell without any weld land. The "compound" STAGS model is produced by two executions of the PANDA2 processor, STAGSUNIT, leading to two STAGS input files, part1.inp and part2.inp. The file, part1.inp, contains the elaborate part of the compound STAGS model, that is, the part of the compound STAGS model in which the stiffeners are all modeled as shell units rather than as beams or rather than being smeared out. The file, part2.inp, contains the model of the remainder of the cylindrical shell. The file, part1.inp, has both acreage rings and acreage stringers modeled as shell units. In part2.inp the acreage rings are shell units (because there are not too many acreage rings) but the acreage stringers are smeared out (because there are so many acreage stringers). The directions in Item 643 of [4L] instruct the user how to combine the two files, part1.inp and part2.inp, into a single "compound.inp" file valid for input to STAGS.

Figures 22a and 22b show a compound STAGS model in which part1.inp represents the weld land and its two T-shaped stringers and part2.inp is the acreage shell with both acreage rings and acreage stringers smeared out. Figures 21 and 22a,b show general buckling modes that are used as initial imperfections with amplitude,  $|W_{imp}| = 0.125$  inch, in STAGS nonlinear analysis of the acreage cylindrical shell without any weld land (Fig. 21) and in STAGS nonlinear analysis of the acreage cylindrical shell in which one T-stiffened weld land is embedded (Figs. 22a and 22b).

Generation of the compound model shown in Figs. 22a,b is more difficult than generation of the compound model shown in Fig. 21 because the properties of the acreage stringers are different from those of the T-stringers that reinforce the weld land. The PANDA2 processor, STAGSUNIT, was created based on the assumption that the stiffeners in part1.inp have the same properties as those in part2.inp. STAGSUNIT can still be used to generate part1.inp and part2.inp, for the stiffened cylindrical shell with one T-stiffened weld land. However, the directions given in Item 643 in [4L] for combining part1.inp and part2.inp into a single "compound.inp" STAGS input file now apply only in a limited sense. A file, /home/progs//genopt/case/weldland/compound.weldland.news, has been created which describes how the generation of compound STAGS models such as that shown in Figs. 22a,b differs from the "standard" compound STAGS models such as that displayed in Fig. 21.

Figure 23 shows two load-deflection curves for an axially compressed, imperfect cylindrical shell with one T-stiffened weld land and one load-deflection curve from Thornburgh's STAGS model (three T-stiffened weld lands), which is described in the next sub-section.

The general buckling modal imperfection shape for the first trace in Fig. 23 is shown in Fig. 22a; it is the critical (lowest) general buckling mode shape, and it corresponds to the 95th eigenvalue of the STAGS linear buckling model. The buckling load factor, 2.0324, should be compared to the general buckling load factor, 1.9811, obtained from the "wcold weld" model (Table 4, Fig. 6). In a series of nonlinear static equilibrium runs (INDIC=3) STAGS failed, for this imperfection shape, to find any static equilibrium state for a load factor PA greater than 1.184. Therefore, a sequence of STAGS nonlinear transient runs (INDIC=6) was executed corresponding to a constant load factor, PA = 1.22. Figure 24 shows the kinetic energy versus time from this series of three transient runs, each with a different damping factor, BETA [17]. The horizontally arrayed data points in the first trace in Fig. 23 at load level, PA = 1.22, were generated during these three nonlinear transient STAGS runs. After the final transient run, when the

kinetic energy had decayed to a very, very small number, a STAGS load-relaxation run was attempted. Unfortunately, the STAGS load-relaxation run did not produce a converged static solution. The reason is unknown as of this writing. The collapse load factor is greater than 1.22, but how much so is unknown.

Figure 22b shows a "higher" general buckling mode corresponding to the 114th eigenvalue, 2.1559, which is about 6 per cent higher than the eigenvalue, 2.0324, corresponding to the critical general buckling mode displayed in Fig. 22a. The second trace in Fig. 23 shows the STAGS prediction of collapse of the imperfect shell with one T-stiffened weld land and with an imperfection shape that is the negative of the buckling mode depicted in Fig. 22b and with amplitude,  $|W_{imp}| = 0.125$  inch. It appears that in this case the general buckling modal imperfection shape with one axial half wave is more harmful than the imperfection shape that corresponds to the critical (lowest) general buckling mode. In this case STAGS had no difficulty finding the peak load from a static nonlinear analysis. No transient STAGS run was required.

The imperfection shape for the third trace in Fig. 23 is that displayed in Figs. 32a,b. This nonlinear collapse is predicted from Thornburgh's STAGS model, to be discussed in the next sub-section.

Figures 25 - 31 are all based on an approximately "60-degree" STAGS model that includes only a single ring bay. This STAGS model includes half of the weld land plus 21 acreage stringer spacings. There is no acreage stringer where the acreage shell is joined to the T-stiffened weld land. Symmetry conditions are applied at 0 degrees and at 59.229 degrees. (59.229 degrees equals the circumferential angle corresponding to half of the weld land width, 2.0 inches, plus 21 acreage stringer spacings at 2.2676 inches each.) All stiffeners are modeled as shell units. There are two acreage rings in the model, one at axial coordinate  $x = 0$  and the other at  $x = 13.75$  inches, the optimized spacing of the acreage rings. These rings have half their actual stiffnesses and densities because we want the one-ring-bay sub-domain to act in the prebuckling phase of the analysis as if that one ring bay were embedded in the entire cylindrical shell. The acreage stringer that runs along the generator at 59.229 degrees has half its actual stiffness and density for the same reason. The purpose of this "59.229-degree" STAGS model (called "60-degree" STAGS model elsewhere in this paper) is to generate predictions of the various types of buckling listed in Table 4 except general buckling. Results from this "60-degree" STAGS model are listed in the right-most column in Table 4. The various buckling modes are displayed in Figs. 25 - 31.

### **Thornburgh's STAGS model**

The second author set up an elaborate STAGS model independently of the first author. He used the STAGS 410 finite element everywhere and included the entire 68.75-inch length of the cylindrical shell and 120 degrees of its circumference in his STAGS model. Symmetry conditions are applied at zero degrees and at 120 degrees. The mid-widths of the two T-stiffened weld lands included in this 120-degree STAGS model are located at these two symmetry planes. There are 836514 degrees of freedom in Thornburgh's STAGS model. In Thornburgh's STAGS model the acreage rings are connected to the acreage stringers and to the webs of the weld land T-stringers. In contrast, in all of Bushnell's STAGS models there is no connection between the acreage rings and acreage stringers and no connection between the acreage rings and the webs of the T-stringers that reinforce the weld land curved plate. Bushnell's most elaborate STAGS model (Figs. 52-56) has about 238000 degrees of freedom. In all of Bushnell's STAGS models capable of predicting general buckling there is only one T-stiffened weld land in 360 degrees, not three T-stiffened weld lands as implied by Thornburgh's elaborate 120-degree STAGS model (Figs. 32-35) or as implied in the 180-degree "wcold" GENOPT/BIGBOSOR4 models (Figs. 6, 8, 10, 12, 14).

The linear buckling modes displayed in Figures 32 - 34 are derived from Thornburgh's STAGS model.

Figures 32a and 32b show the critical general buckling mode, the eigenvalue of which, 2.0599, is hidden in a "haystack" of more than one thousand eigenvalues corresponding to various kinds of local buckling. Notice that in Thornburgh's 120-degree STAGS model the critical (lowest) general buckling mode has one half axial wave over the 68.75-inch length of the cylindrical shell, whereas Bushnell's 360-degree cruder STAGS model with only one weld land has two axial half waves (Fig. 22a). The "wcold (weld)" prediction of the critical general buckling mode shape (Fig. 6 and Table 4) agrees with Bushnell's STAGS model in Fig. 22a. However, notice how close the "wcold (weld)" general buckling eigenvalues corresponding to one and to two axial half waves are. From Table 9 we have the following from the optimized "wcold (weld)" model, the dimensions of which are listed in Table 6:

\*\*\*\*\* EIGENVALUES AND MODE SHAPES \*\*\*\*\*

EIGENVALUE(AXIAL HALF WAVES)

=====

2.0826E+00(1) <--analogous to Thornburgh's general buckling mode shape (Figs.32a,b)  
1.9811E+00(2) <--Fig. 6 -general buckling from "wcold weld" model

The "nasacoldbend" 90-degree "PANEL3(weld)" model of the same (Table 6) design produces the following:

\*\*\*\*\* EIGENVALUES AND MODE SHAPES \*\*\*\*\*

EIGENVALUE(AXIAL HALF WAVES)

=====

2.1287E+00(1) <--analogous to Thornburgh's general buckling mode shape (Figs.32a,b)  
2.0079E+00(2) <--see Fig. 7 -general buckling from "nasacoldbend" model

In the "wcold weld" model of general buckling the acreage stringers and acreage rings are smeared out. In the "nasacoldbend PANEL3(weld)" model of general buckling the acreage stringers are modeled as little shell segments and the acreage rings are smeared out (Fig. 7). The buckling load factors (eigenvalues) for one axial half wave are only about 5 per cent higher than those for two axial half waves.

The difference in the critical (lowest) buckling mode in Thornburgh's STAGS model (Figs. 32a,b) from that in Bushnell's STAGS model (Fig. 22a) could be caused by the following characteristics of Thornburgh's STAG model:

1. The acreage rings and acreage stringers are connected to each other.
2. The acreage rings are connected to the webs of the weld land T-stringers.
3. There are T-stiffened weld lands spaced at 120-degree intervals, whereas Bushnell's STAGS model only has one T-stiffened weld land in 360 degrees. (However, note that the "wcold weld" model has T-stiffened weld lands spaced at 120-degree intervals.)
4. The STAGS 410 finite element is used, not the STAGS 480 finite element.

As mentioned in the previous sub-section, Bushnell's 360-degree STAGS model with only one T-stiffened weld land produces a general buckling mode with one axial half wave at a buckling load factor, 2.1559 (Fig. 22b), about 6 per cent higher than the critical (lowest) general buckling eigenvalue, 2.0324 (Fig. 22a).

Figure 33 shows the first (lowest) eigenvalue from Thornburgh's elaborate STAGS model. This lowest eigenvalue corresponds to local "pocket" buckling in the acreage. The local buckling load factor, 1.3924, should be compared with the value, 1.3472 (Fig. 16), obtained from the "nasacoldbend PANEL3" model, with the value, 1.3324 (Fig. 20), obtained from the small STAGS acreage "patch" model, and with the value, 1.3488, obtained from the STAGS "60-degree" model (Figs. 25-27). Much of the difference arises from the use of the STAGS 410 finite element in Thornburgh's STAGS model versus the use of the STAGS 480 finite element in Bushnell's STAGS models. For example, the local buckling load factor, 1.3324, obtained from the small STAGS "patch" model based on the STAGS 480 finite element (Fig. 20), becomes 1.3615 when the STAGS 410 finite element is used instead in the same model with the same finite element mesh density.

Figures 34a,b show the critical (lowest) eigenvalue from Thornburgh's STAGS model that corresponds to linear buckling of the weld land curved plate with some participation of the web of the reinforcing T-stringer. The buckling load factor for this mode from Thornburgh's elaborate STAGS model, 1.4345, should be compared with 1.4558 from the "nasacoldbend PANEL3" model (Fig. 13), with 1.5113 from the "wcold weld" model (Fig. 12), and with 1.3488 from the "60-degree" STAGS model (Figs. 25-27).

Thornburgh obtained a prediction of collapse from his 120-degree STAGS model. He introduced the general buckling mode displayed in Figs. 32a,b as an initial imperfection shape with amplitude,  $W_{imp} = +0.125$  inch (inward deformation from the imperfection predominates). The resulting nonlinear load-deflection curve, obtained by means of a STAGS nonlinear static equilibrium run (INDIC = 3) followed by a STAGS nonlinear transient run (INDIC = 6), is the third trace in Fig. 23. The collapse loads from Thornburgh's STAGS model and from Bushnell's STAGS model with use of the one-axial-half-wave mode shown in Fig. 22b are in excellent agreement. To obtain collapse loads from STAGS Thornburgh uses the procedure described in the next paragraph.

The nonlinear analysis of a STAGS model with an eigen-mode imperfection consists of a nonlinear static analysis followed by a nonlinear transient analysis. The nonlinear static analysis (INDIC=4) employs a user-written s2 ("s2" is the STAGS main processor where all the computations are performed) that automatically cuts the step size whenever STAGS converges to a solution with skipped roots. Static loading continues until STAGS reaches the limit of step cuts allowed (NCUT), at which point the load is considered to have converged to the static limit point, typically the highest value of load factor PA attained. The use of INDIC=4 causes STAGS to calculate a nonlinear bifurcation buckling eigenvalue and mode shape at this static limit load. The predicted nonlinear buckling eigenvalue is typically very small, and the nonlinear bifurcation buckling mode shape gives an indication of the actual buckling behavior of the loaded shell. In this case (third trace in Fig. 23) the mode is a local "pocket" buckling mode in the center of the panel acreage. The STAGS analysis is then restarted with INDIC = 6 (a nonlinear transient analysis) with the load factor PA set equal to its value at the static limit load. The applied load is increased at a constant rate during the nonlinear transient run, and the STAGS step size control is allowed to cut the step size as needed during a transient buckling event. In spite of the fact that the eigenmode typically implies that a local "pocket" buckling event is occurring at the static limit load, the dynamic deformation clearly indicates that the shell is in the midst of global collapse. The nonlinear transient analysis is stopped when the load factor PA reaches a value for which the transient response diverges.

Figures 35a,b show the distribution of effective stress at the highest load factor, PA, determined from Thornburgh's nonlinear static STAGS runs: PA = 1.16. The stress concentrations exist because the general buckling modal imperfection shape shown in Figs. 32a,b has a significant component of short-wavelength deformation.

For an imperfection shape with the opposite sign from that displayed in Fig. 32a Thornburgh found nonlinear collapse to occur at a load factor greater than 1.5.

## **SECTION 12 T-STIFFENED WELD LAND OPTIMIZED WITH "nasacoldbend" ACREAGE FIRST OPTIMIZED BY PANDA2 WITH ICONSV = -1**

The optimum acreage design is listed in Table 7 and the optimum T-stiffened weld land design is listed in Table 8. Figure 36, which is analogous to Fig. 5, shows the critical general buckling mode obtained from the "wcold" model without any weld lands (wcold.BEHX0). Figures 37 - 39, which are analogous to Fig. 6, show three general buckling modes from the "wcold" model with T-stiffened weld lands at zero degrees (symmetry plane) and at 120 degrees (wcold.BEHX1). The three general buckling eigenvalues are very close to one another. Figure 40, which is analogous to Fig. 12 (wcold.BEHX2), shows buckling of the weld land curved plate and its two edge stiffeners. Figure 41, which is analogous to Fig. 21, shows the critical general buckling mode obtained from the compound STAGS model of the optimized "nasacoldbend" acreage design without any weld lands listed in Table 7.

Figure 42 shows two load-deflection curves, both for optimized "nasacoldbend" shell acreages without any weld lands. The upper curve corresponds to the "nasacoldbend" acreage optimized by PANDA2 with ICONSV = 1 and the lower curve corresponds to the "nasacoldbend" acreage optimized by PANDA2 with ICONSV = -1. It is seen from Fig. 42 that the "nasacoldbend" acreage design will carry the applied load, 669235 lb, which corresponds to the STAGS load factor, PA = 1.0. The horizontally arrayed data points in the second trace in Fig. 42 were produced by a nonlinear transient STAGS run. The collapse load from STAGS was not determined (no completion of the nonlinear transient run nor any subsequent STAGS load-relaxation run) because we already know from the nonlinear static STAGS run that the ICONSV = -1 "nasacoldbend" acreage without a weld land will support the total applied load, 669235 lb, with a margin of more than 15 per cent.

## **SECTION 13 T-STIFFENED WELD LAND OPTIMIZATION WITH CONSTRAINTS ON THE WEB AND FLANGE SLENDERNESS (height/thickness) RATIOS**

The "nasacoldbend" acreage design is that listed in Table 5 (ICONSV = 1).

### "wcold" model

An optimum design was found via one execution of SUPEROPT for a T-stiffened weld land in which inequality constraints were introduced into "DECIDE" (a wcold.DEC file analogous to, but not the same as, the wcold.DEC file listed in Table 9). These two inequality constraints force the T-stringer web height, HWLAND, to be less than ten times the web thickness, TWLAND, and the outstanding flange width, WFLAND, to be less than ten times the outstanding flange thickness, TFLAND.

The "wcold" optimized design after one execution of SUPEROPT is as follows:

```
4.0878E+00  width of the weld land: WLAND
1.0216E-01  thickness of the weld land: TLAND
2.1989E-02  eccentricity of the weld land: ECLAND
1.1775E-01  web thickness of the weld land edge stringer: TWLAND
1.2172E+00  height of the web of the weld land edge stringer: HWLAND
1.1757E-01  thickness of the outstanding flange of the stringer: TFLAND
1.1770E+00  width of the outstanding flange of the stringer: WFLAND
5.8180E-02  thickness of the cylindrical shell skin: TSKIN
```

The corresponding "wcold" design margins are as follows:

| MARGIN CURRENT |            | DEFINITION   |
|----------------|------------|--|
| NO.            | VALUE      |  |
| 1              | -3.969E-02 | $1+10.0*V(4)-1.00*V(5) -1.$ (HWLAND/TWLAND < 10.)    |
| 2              | -1.330E-03 | $1+10.0*V(6)-1.00*V(7) -1.$ (WFLAND/TFLAND < 10.)    |
| 3              | -4.919E-02 | (GENBUK(1 )/GENBUKA(1 )) / GENBUKF(1 )-1; F.S.= 2.00 |
| 4              | 1.857E-01  | (PANBUK(1 )/PANBUKA(1 )) / PANBUKF(1 )-1; F.S.= 1.50 |
| 5              | 2.112E+00  | (STRESSA(1 )/STRESS(1 )) / STRESSF(1 )-1; F.S.= 1.00 |
| 6              |            |  |

The corresponding "wcold" objective (weight/axial length of one T-stiffened weld land) is:

WEIGHT = 0.09476 lb/in (compare to WEIGHT = 0.06128 lb/in from Table 6 obtained with no constraints on the T-stringer cross section slenderness)

Notice that there are three negative "wcold" design margins:

```
1    -3.969E-02  1+10.0*V(4)-1.00*V(5) -1.  (HWLAND/TWLAND < 10.)
2    -1.330E-03  1+10.0*V(6)-1.00*V(7) -1.  (WFLAND/TFLAND < 10.)
3    -4.919E-02  (GENBUK(1 )/GENBUKA(1 )) / GENBUKF(1 )-1; F.S.= 2.00
```

The GENOPT system accepts somewhat negative margins if the end user chooses the index, IDESIGN = 2 in the \*.OPT file (Table 9), as follows:

```
2      $ Choose 1 or 2 or 3 or 4 or 5 for IDESIGN
```

IDESIGN = 2 tells the GENOPT mainprocessor, OPTIMIZE, to accept as feasible any design that is either "FEASIBLE" or "ALMOST FEASIBLE". The string, "ALMOST FEASIBLE" means that no design margin can be less than -0.05. If the end user had chosen IDESIGN = 1, then GENOPT would have accepted as feasible any design for which all margins are greater than -0.01. Such a design would have been termed by GENOPT as "FEASIBLE". See Refs. [3,8] for more information on the index, IDESIGN. The index, IDESIGN, was introduced into the GENOPT system because there exist optimization problems for which it seems to be relatively easy to produce designs that are "ALMOST FEASIBLE" but very difficult to produce designs that are "FEASIBLE". If the end user objects to margins as low as -0.05, then he or she can easily introduce compensating factors of safety or use the "stricter" index, IDESIGN = 1, rather than IDESIGN = 2.

## The STAGS models

The "wcold" model and the STAGS compound model analogous to that displayed in Figs. 22a,b (except that the acreage rings are now modeled as shell units rather than being smeared out) predict the following linear buckling load factors [buckling load = 669235 x (buckling load factor) lb]:

|                       | wcold model              | STAGS model 1            | STAGS model 2             |
|-----------------------|--------------------------|--------------------------|---------------------------|
| general buckling      | 1.9016 (m=2,<br>Fig. 43) | 1.9022 (m=2,<br>Fig. 44) | 1.9339 (m=2,<br>Fig. 53)  |
| inter-ring<br>bucklng | 1.7787 (m=5,<br>Fig. 45) | 1.7112 (m=5,<br>Fig. 46) |                           |
| local buckling        |                          |                          | 1.3536 (m=4+,<br>Fig. 52) |

in which "m" is the number of axial half waves over 68.75 inches for general buckling and "m" is the number of axial half waves over 13.75 inches (the acreage ring spacing) for inter-ring buckling and for local buckling. The STAGS predictions were obtained with ILIN = 0 in every shell unit. The only STAGS models constructed for this section include the full length, 68.75 inches, of the cylindrical shell.

**The STAGS model 1** (Figs. 44, 46, and 48 - 51) covers 360 degrees of the cylindrical shell, has one T-stiffened weld land, and has smeared acreage stringers and acreage rings modeled as shell units. **The STAGS model 2** (Figs. 52 - 56) covers 180 degrees of the cylindrical shell with symmetry conditions imposed at zero and at 180 degrees, has one half of a T-stiffened weld land, has a second section adjacent to the weld land in which both acreage stringers and acreage rings are modeled as shell units, and has a third section from 59.229 degrees to 180 degrees in which the acreage stringers are smeared out and the acreage rings are modeled as shell units.

The inter-ring buckling load factor from the STAGS model 1, 1.7112, is the lowest (the first) buckling eigenvalue for that STAGS compound model. The corresponding eigenvector is shown in Fig. 46. There are close to 24 axial half waves over the 68.75-inch length of the cylindrical shell. Since there are five ring bays, 24 axial half waves over the 68.75-inch length of the cylindrical shell corresponds to close to five axial half waves in each of the five ring bays, each of axial length, 13.75 inches. The "wcold" inter-ring buckling load factor, 1.7787, and corresponding mode shape displayed in Fig. 45 represent the same buckling phenomenon as that displayed for the STAGS model in Fig. 46: local buckling in the curved weld land plate with very small participation by the two reinforcing T-stringers. No attempt was made to discover the analogous buckling mode from the STAGS model 2.

Figure 47 displays nonlinear load-deflection curves from STAGS model 1 and from STAGS model 2 with various general buckling modal imperfections taken one at a time, each with an amplitude,  $|W_{imp}| = 0.125$  inch. The first trace in Fig. 47 pertains to the STAGS model 1 with the general buckling modal imperfection shape shown in Fig. 44 (the critical general buckling mode according to STAGS). Figure 48 shows the state of the imperfect shell at the last load step processed, Load Step No. 22. During collapse the deformation pattern changes from one with two axial half waves (Fig. 44) to one with one axial half wave (Fig. 48). The one-axial-half-wave mode of collapse shown in Fig. 48 suggests that a general buckling mode with one axial half wave (Fig. 49) and with a negative amplitude,  $W_{imp} = -0.125$  inch, might be more harmful than the critical (lowest) general buckling mode, which has two axial half waves (Fig. 44). Indeed, the one-axial-half-wave imperfection shape (with negative amplitude,  $W_{imp}$ ) is more harmful, as is evident from the second trace in Fig. 47. This second trace corresponds to the shell with an imperfection in the form of the general buckling mode shape shown in Fig. 49 with an amplitude,  $W_{imp} = -0.125$  inch (maximum inward imperfection deflection). The third trace in Fig. 47 corresponds to the shell with the negative of the general buckling modal imperfection shape shown in Figs. 54a,b. The fourth and fifth traces in Fig. 47 correspond to shells with imperfection shapes shown in Figs. 50 and 51, respectively. A collapse load,  $PA = 1.20$ , was also computed with use of the imperfection shape from the STAGS model 2 displayed in Fig. 53.

As of this writing it is not known why STAGS model 2 yields a higher critical general buckling load factor, 1.9339, than does STAGS model 1, 1.9022. A lower critical general buckling load factor is expected because STAGS model 2 has a rather large section in which the acreage stringers are modeled as shell units instead of being smeared out. Perhaps the reason is that in all STAGS models in which the stiffeners are modeled as shell units the stiffener webs

are attached to the middle surfaces of adjacent structure. This means that a small amount of material overlaps.

Figures 55 and 56 show the distributions of inner fiber effective stress and outer fiber effective stress, respectively, corresponding to STAGS model 2 at the collapse load factor, PA = 1.1272. It is seen that in this case the maximum effective stress is well below the allowable stress, 70000 psi, that is listed in Table 3.

## SECTION 14 CONCLUSIONS

1. T-stiffened weld lands optimized by GENOPT/BIGBOSOR4 [5-8] appear to be suitable because evaluation of these designs by application of the general-purpose finite element STAGS computer program [15-18] indicates that the simpler, approximate GENOPT/BIGBOSOR4 model predicts linear bifurcation buckling loads that are reasonably close to those predicted by STAGS (Table 4). Nonlinear collapse analyses by STAGS of the optimized shells with general buckling modal imperfections with amplitude,  $|W_{imp}| = 0.125$  inch, demonstrate that these imperfect shells will carry the specified axial compression with a margin of at least 9.2 per cent (second trace in Fig. 47).
2. While it is about 50 per cent heavier, the optimized T-stiffened weld land design in which the T-stringer web and flange slenderness ratios are constrained (the web height must be less than 10 times the web thickness, and the flange width must be less than 10 times the flange thickness) is probably better than the optimized weld land design obtained without slenderness constraints because the T-stringer resulting from the latter formulation has (web height)/(web thickness) = 39 and (flange width)/(flange thickness) = 24 (Table 6). Such slender T-stringer web and flange would probably exhibit considerable residual deformation caused by welding.
3. It is probably not a good idea to design the acreage with the use of the least conservative PANDA2 index, ICONSV = -1, because the weight thus saved in the acreage is mostly cancelled by the need for heavier T-stiffened weld lands with very tall, slender T-stiffeners (Compare Tables 6 and 8.)
4. The behavior seems to be insensitive to the number of weld lands in the 360-degree cylindrical shell. Models were run in which there are from one to three T-stiffened weld lands over 360 degrees. The "wcold" model has three weld lands over 360 degrees (Figs. 6, 8, 10, 14); The 90-degree "nasacoldbend" model from PANEL3 has two weld lands over 360 degrees (Figs. 7, 9, 11, 15); and the various STAGS models have either one weld land (Figs. 22a,b, 44, 49-56) or three weld lands (Figs. 32-35) over 360 degrees. The predictions of buckling and collapse of these various models agree with one another.
5. It might be a good idea to create a capability to optimize the acreage and the T-stiffened weld land within the same optimization loop instead of optimizing the acreage first and then optimizing the T-stiffened weld land with the acreage fixed, which is the procedure used to obtain the results presented here. The suggested new capability is indicated because the cross section dimensions of the optimized weld land T-stringers are strongly influenced by the characteristics of the acreage in the two cases (Tables 5 - 8) explored here. The acreage optimized with the PANDA2 conservativeness index, ICONSV = 1 (Table 5) leads to the optimized T-stiffened weld land listed in Table 6, and the acreage optimized with ICONSV = -1 (Table 7) leads to the optimized T-stiffened weld land listed in Table 8. This task would be significant because the PANDA2 capability would have to be converted to work within the GENOPT context.
6. This long paper is detailed enough so that it can serve as a "user's manual" for someone who wants to use GENOPT/BIGBOSOR4 to obtain optimum designs of other shells of revolution or of other prismatic shells or panels.

## SECTION 15 ACKNOWLEDGMENTS

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TABLE 1

Glossary of variables used in the "weldland" generic case. This glossary is part of the weldland.DEF file and is created automatically by GENOPT. The **GENOPT user** creates the variable names and one-line definitions that will be seen by the **end user**.

| ARRAY<br>? | NUMBER OF<br>(ROWS,COLS) | PROMPT<br>ROLE | NUMBER | NAME    | DEFINITION OF VARIABLE                           |
|------------|--------------------------|----------------|--------|---------|--|
| n          | ( 0, 0)                  | 1              | 10     | WLAND   | = width of the weld land                         |
| n          | ( 0, 0)                  | 1              | 15     | TLAND   | = thickness of the weld land                     |
| n          | ( 0, 0)                  | 1              | 20     | ECLAND  | = eccentricity of the weld land                  |
| n          | ( 0, 0)                  | 2              | 25     | KLAND   | = index for weld land edge stringer(0 or 1 or 2) |
| n          | ( 0, 0)                  | 1              | 35     | TWLAND  | = web thickness of the weld land edge stringer   |
| n          | ( 0, 0)                  | 1              | 40     | HWLAND  | = height of web of the weld land edge stringer   |
| n          | ( 0, 0)                  | 1              | 45     | TFLAND  | = thickness of outstanding flange of stringer    |
| n          | ( 0, 0)                  | 1              | 50     | WFLAND  | = width of outstanding flange of the stringer    |
| n          | ( 0, 0)                  | 2              | 55     | NLAND   | = number of weld lands in 360 degrees            |
| n          | ( 0, 0)                  | 1              | 65     | TSKIN   | = thickness of the cylindrical shell skin        |
| n          | ( 0, 0)                  | 2              | 70     | RADCYL  | = radius of the cylindrical shell                |
| n          | ( 0, 0)                  | 2              | 75     | LENCYL  | = length of the cylindrical shell                |
| n          | ( 0, 0)                  | 2              | 85     | BSTR    | = stringer spacing                               |
| n          | ( 0, 0)                  | 2              | 90     | TSTR    | = stringer thickness                             |
| n          | ( 0, 0)                  | 2              | 95     | HSTR    | = stringer height                                |
| n          | ( 0, 0)                  | 2              | 100    | BRNG    | = ring spacing                                   |
| n          | ( 0, 0)                  | 2              | 105    | TRNG    | = ring thickness                                 |
| n          | ( 0, 0)                  | 2              | 110    | HRNG    | = ring height                                    |
| n          | ( 0, 0)                  | 2              | 120    | EMOD    | = Young's modulus                                |
| n          | ( 0, 0)                  | 2              | 125    | NU      | = Poisson ratio                                  |
| n          | ( 0, 0)                  | 2              | 130    | DENS    | = mass density (al=0.00025 in English units)     |
| n          | ( 0, 0)                  | 2              | 140    | MLOWG   | = low end of the M-range for general buckling    |
| n          | ( 0, 0)                  | 2              | 145    | MHIGHG  | = High end of the M-range for general buckling   |
| n          | ( 0, 0)                  | 2              | 150    | MLOWP   | = low end of the M-range for "panel" buckling    |
| n          | ( 0, 0)                  | 2              | 155    | MHIGHP  | = high end of the M-range for "panel" buckling   |
| n          | ( 0, 0)                  | 2              | 165    | NCASES  | = Number of load cases (number of environments)  |
| y          | (20, 0)                  | 3              | 170    | PX      | = total axial load ( $2\pi r^2 \sigma$ )         |
| y          | (20, 0)                  | 3              | 175    | PY      | = uniform normal pressure                        |
| y          | (20, 0)                  | 3              | 180    | PX0     | = axial load in Load Set B                       |
| y          | (20, 0)                  | 3              | 185    | PY0     | = pressure in Load Set B                         |
| y          | (20, 0)                  | 4              | 195    | GENBUK  | = general buckling load                          |
| y          | (20, 0)                  | 5              | 200    | GENBUKA | = allowable for general buckling                 |
| y          | (20, 0)                  | 6              | 205    | GENBUKF | = factor of safety for general buckling          |
| y          | (20, 0)                  | 4              | 210    | PANBUK  | = "panel" buckling                               |
| y          | (20, 0)                  | 5              | 215    | PANBUKA | = allowable for "panel" buckling                 |
| y          | (20, 0)                  | 6              | 220    | PANBUKF | = factor of safety for "panel" buckling          |
| y          | (20, 0)                  | 4              | 225    | STRESS  | = weld land effective stress                     |
| y          | (20, 0)                  | 5              | 230    | STRESSA | = maximum allowable effective stress             |
| y          | (20, 0)                  | 6              | 235    | STRESSF | = factor of safety for effective stress          |
| n          | ( 0, 0)                  | 7              | 245    | WEIGHT  | = weight of the weld land plus edge stringers    |

TABLE 2

The prompting file, weldland.PRO, created automatically during the GENTEXT interactive session conducted by the GENOPT user. The **end user** will see these prompts for input data and the "help" paragraphs. If the **GENOPT user** has done his or her job well the **end user** will find a user-friendly optimization and analysis system.

---

5.0

This GENOPT case is for optimization of a weld land in a stiffened cylindrical shell previously optimized by PANDA2 without any weld land. The decision variables are:  
WLAND = width of the weld land  
TLAND = thickness of the weld land  
and, if there are stringers at the edges of the weld land:  
TWLAND = thickness of the web of the edge stringer  
HWLAND = height of the web of the edge stringer  
TFLAND = thickness of the outstanding flange of the stringer  
WFLAND = thickness of the width of the outstanding flange  
The stiffened cylindrical shell with the weld land is subjected to uniform axial compression, PX, and possibly also to uniform external or internal pressure, PY.  
The design constraints are:  
GENBUK = general buckling  
PANBUK = "panel" buckling (buckling between rings)  
STRESS = stress in the weld land or edge stringer  
The objective is minimum weight of the weld land and any edge stringers.

10.1 width of the weld land: WLAND

10.2

WLAND is the circumferential dimension of the weld land

15.1 thickness of the weld land: TLAND

20.1 eccentricity of the weld land: ECLAND

20.2

ECLAND is the distance from the middle surface of the skin of the cylindrical shell to the middle surface of the weld land, positive if the outer surfaces of the weld land and the skin of the cylindrical shell are flush.

25.1 index for weld land edge stringer (0 or 1 or 2): KLAND

25.2

KLAND = 0 means no stringer at the edges of the weld land  
KLAND = 1 means the weld land edge stringer has a rectangular cross section  
KLAND = 2 means the weld land edge stringer has a Tee-shaped cross section

30.0

Next, you will be asked to supply the dimensions of the cross section of the stringers along the edges of the weld land: TWLAND, HWLAND, TFLAND, WFLAND

35.1 web thickness of the weld land edge stringer: TWLAND

40.1 height of the web of the weld land edge stringer: HWLAND

45.1 thickness of the outstanding flange of the stringer: TFLAND  
50.1 width of the outstanding flange of the stringer: WFLAND  
55.1 number of weld lands in 360 degrees: NLAND  
55.2  
Probably the maximum to use for NLAND is 6 (weld land every 60 degrees).

60.0

Next, you will be asked to supply several dimensions that are not decision variables.

65.1 thickness of the cylindrical shell skin: TSKIN

65.2

NOTE: TSKIN is NOT a decision variable because it is assumed here that TSKIN has a value obtained from a previous optimization of the stiffened cylindrical shell without a weld land.

70.1 radius of the cylindrical shell: RADCYL

75.1 length of the cylindrical shell: LENCYL

75.2

If the cylindrical shell is clamped, use as LENCYL the following: LENCYL = LENMOD \* AXIAL in which LENMOD is the value of the "length modifier" from PANDA2 and "AXIAL" is the actual axial length of the cylindrical shell. You can find the value of LENMOD by searching the PANDA2 \*.OPM file for the string, "LENMOD". If the cylindrical shell is simply supported along its curved ends, then use the actual length, "AXIAL", for LENCYL.

80.0

Next, you will be asked to provide the stiffener thicknesses and heights. These are the stiffeners that are in the acreage of the cylindrical shell, not the "extra" stringers located at the edges of each weld land.

NOTE: These stiffeners are assumed to have rectangular cross sections:

for the stringers: BSTR, TSTR, HSTR (spacing, thickness, height of the stringers)

for the rings: BRNG, TRNG, HRNG (spacing, thickness, height of the rings).

These quantities are NOT decision variables in this application because it is assumed that they have optimum values previously obtained from PANDA2 in the model of the cylindrical shell without the weld land(s).

85.1 stringer spacing: BSTR

90.1 stringer thickness: TSTR

95.1 stringer height: HSTR

100.1 ring spacing: BRNG

105.1 ring thickness: TRNG

110.1 ring height: HRNG

115.0

Next, you will be asked to provide material properties.

It is assumed that the material is elastic and that the same material is used for the entire structure.

120.1 Young's modulus: EMOD  
125.1 Poisson ratio: NU  
130.1 mass density (aluminum = 0.00025 in English units): DENS

135.0

Next, you will be asked to provide ranges of buckling axial half waves for the search for a critical number of axial half waves in the buckling mode first for general buckling, then for "panel" buckling "panel" buckling = buckling between adjacent rings with the stringers smeared out).

140.1 low end of the M-range for general buckling: MLOWG

140.2 You start by useing MLOWG = 1

145.1 High end of the M-range for general buckling: MHIGHG

145.2 You might have to experiment with this in order to find an appropriate value. The wider the M-range the more computer time is required.

150.1 low end of the M-range for "panel" buckling: MLOWP

150.2 "Panel" buckling is buckling between adjacent rings with the stringers smeared out.

155.1 high end of the M-range for "panel" buckling: MHIGHP

155.2 Don't use too high a number. Computer time increases the wider your M-range for "panel" buckling.

160.0

Next, supply the loading

165.1 Number NCASES of load cases (environments): NCASES

170.1 total axial load ( $2\pi r N_x$ ): PX

170.2 PX = the total axial load, such as  $2 \times \pi \times r \times N_x$ , in which  $N_x$  is an axial resultant.  
NEGATIVE FOR AXIAL COMPRESSION.

175.1 uniform normal pressure: PY

175.2 PY is the pressure, assumed to be applied only to the curved surface of the cylindrical shell.  
NEGATIVE FOR COMPRESSION (external pressure).

180.1 axial load in Load Set B: PX0

180.2 PX0 affects the stiffness matrix only. It is not an "eigenvalue" load.  
NEGATIVE FOR AXIAL COMPRESSION.

185.1 pressure in Load Set B: PY0  
185.2  
PY0 = pressure on the curved surface only. This load  
affects the stiffness matrix only. PY0 is not an  
"eigenvalue" load.  
NEGATIVE FOR COMPRESSION (external pressure).

190.0  
Next, you must provide an allowable and a factor of  
safety for each Role 4 variable, that is, for each  
"behavior" (such as general buckling, "panel" buckling,  
and stress).

195.0 general buckling load: GENBUK  
195.2  
In the model for the general buckling both stringers and  
rings are smeared out. NOTE: The "extra" stringers along  
each edge of the weld land are ALWAYS modeled as  
flexible shell segments.

200.1 allowable for general buckling: GENBUKA  
205.1 factor of safety for general buckling: GENBUKF  
210.0 "panel" buckling: PANBUK  
210.2  
PANBUK is buckling between adjacent rings with the  
stringers smeared out.

215.1 allowable for "panel" buckling: PANBUKA  
220.1 factor of safety for "panel" buckling: PANBUKF  
225.0 weld land effective stress: STRESS  
225.2  
This is the effective stress in the weld land or  
in the "extra" stringers at the edges of the  
weld land.

230.1 maximum allowable effective stress: STRESA  
235.1 factor of safety for effective stress: STRESSF

240.0  
Next, provide the objective.

245.0 weight of the weld land+"extra" edge stringers: WEIGHT  
245.2  
WEIGHT = weight of the weld land of width WLAND and  
thickness TLAND plus the weight of the extra  
stringers that run along the two axial edges of  
the weld land.

999.0 DUMMY ENTRY TO MARK END OF FILE

=====

TABLE 3

Properties of the "nasacoldbend" and "wcold" cylindrical shells that are not decision variables. Dimensions are in inches and lb.

---

**nasacoldbend properties:**

```

68.75000 $ Panel length normal to the plane of the screen, L1
150.7960 $ Panel length in the plane of the screen, L2 = pi x radius
r         $ Identify type of stiffener along L1 (N,T,J,Z,R,A,C,G)
1         $ choose external (0) or internal (1) stringers
1         $ choose external (0) or internal (1) rings
48.00000 $ Radius of curvature (cyl. rad.) in the plane of screen, R
n         $ Is panel curved normal to plane of screen? (answer N)
y         $ Is this material isotropic (Y or N)?
0.11000E+08 $ Young's modulus, E( 1)
0.3000000 $ Poisson's ratio, NU( 1)
4230769 $ transverse shear modulus, G13( 1)
0         $ Thermal expansion coeff., ALPHA( 1)
0         $ residual stress temperature (positive), TEMPTUR( 1)
y         $ Want to supply a stress-strain "curve" for this mat'l (H)?
0.000000 $ strain coordinate for stress-strain "curve", strain( 1)
0.000000 $ stress coordinate for stress-strain "curve", stress( 1)
y         $ any more (strain, stress) pairs (Y or N)?
0.636360E-02 $ strain coordinate for stress-strain "curve", strain( 2)
70000.00 $ stress coordinate for stress-strain "curve", stress( 2)
y         $ any more (strain, stress) pairs (Y or N)?
0.127273E-01 $ strain coordinate for stress-strain "curve", strain( 3)
100000.0 $ stress coordinate for stress-strain "curve", stress( 3)
y         $ any more (strain, stress) pairs (Y or N)?
0.190909E-01 $ strain coordinate for stress-strain "curve", strain( 4)
110000.0 $ stress coordinate for stress-strain "curve", stress( 4)
n         $ any more (strain, stress) pairs (Y or N)?
n         $ Does cold bending include the outstanding ring flange?( 1)
0.000000 $ ring web radial compression, FN1WEB( 1)
y         $ Want to specify maximum effective stress ?
70000.00 $ Maximum allowable effective stress in material type( 1)
0.95000E-01 $ weight density (greater than 0!) of material type( 1)
-2219.000 $ Resultant (e.g. lb/in) normal to the plane of screen, Nx( 1)
0         $ Prebuckling: choose 0=bending included; 2=use membrane theory
0         $ Buckling: choose 0=simple support or 1=clamping
0.9990000 $ Factor of safety for general instability, FSGEN( 1)
0.9990000 $ Factor of safety for panel (between rings) instability, FSPAN(1)
0.9990000 $ Minimum load factor for local buckling FSLOC( 1)
1.000000 $ Minimum load factor for stiffener buckling (Type H), FSBSTR( 1)
1.000000 $ Factor of safety for stress, FSSTR( 1)
0.125000 $ Initial buckling modal general imperfection amplitude,Wimpg2(1)
-0.125000 $ Initial buckling modal general imperfection amplitude,Wimpg2(2)
1 and -1 $ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV
(See Ref.[13] for information about the conservativeness index, ICONSV.)

```

---

**wcold properties:**

OVERALL DIMENSIONS, MATERIAL PROPERTIES, LOADING, BOUNDARY CONDITIONS,  
AND WAVE NUMBER RANGES OVER WHICH TO SEARCH FOR CRITICAL BUCKLING LOADS

```
        48      $ radius of the cylindrical shell: RADCYL
       68.75    $ length of the cylindrical shell: LENCYL
0.1100000E+08 $ Young's modulus: EMOD
0.3000000      $ Poisson ratio: NU
0.2500000E-03 $ mass density (aluminum = 0.00025 in English units): DENS
 70000.00     $ maximum allowable stress: STRESSA( 1)
-669234.63   $ total axial load (2*pi*r*Nx): PX( 1)
                  $ membrane prebuckled state
                  $ classical simple support for buckling
         1      $ low end of the M-range for general buckling: MLONG
        10     $ High end of the M-range for general buckling: MHIGHG
         1      $ low end of the M-range for "panel" buckling: MLOWP
        10     $ high end of the M-range for "panel" buckling: MHIGHP
 2.000E+00    $ factor of safety for general buckling: GENBUKF(1)
 1.500E+00    $ factor of safety for inter-ring buckling: PANBUKF(1)
 1.000E+00    $ factor of safety for effective stress: STRESSF(1)
=====
=====
```

TABLE 4

Buckling load factors obtained from various models. The smearing and non-smearing of stiffeners refers only to the "acreage" stiffeners, not to the T-shaped stringers that run along the two longitudinal edges of the weld land curved plate. The conservativeness index, ICONSV, has relevance only to the design and analysis of the "acreage" part of the cylindrical shell. In the "nasacoldbend" model the "acreage" is optimized with the use of PANDA2. In the "wcold" model the "acreage" properties are given. They are the optimized values from the PANDA2 "nasacoldbend" model without any weld lands. The optimum design of the T-stiffened weld land is obtained from GENOPT/BIGBOSOR4. The PANDA2 processor called "PANEL3" is used to evaluate the cylindrical shell with the T-stiffened weld land previously optimized with use of the "wcold" model and the "acreage" previously optimized by PANDA2. The STAGS computer program, a general-purpose finite element code, is used to verify the optimized cylindrical shells with and without T-stiffened weld lands.

|  | nasacoldbend   |  | wcold                                |                                      | stags                                |                                 |
|--|--|--|--------------------------------------|--------------------------------------|--------------------------------------|---------------------------------|
| PANDA2(no weld)  | PANEL3(weld)   | no weld                                  | weld                                 | no weld                              | weld                                 |                                 |
| buckling load & mode shape   | buckling load & mode shape                                 | buckling load & mode shape               | buckling load & mode shape           | buckling load & mode shape           | buckling load & mode shape           |                                 |
| (axial,circ. half waves) [a,b,c,d,e]*  | (axial,circ. half waves) [a,b,c,d,e]                       | (axial,circ. half waves) [a,b,c,d,e]     | (axial,circ. half waves) [a,b,c,d,e] | (axial,circ. half waves) [a,b,c,d,e] | (axial,circ. half waves) [a,b,c,d,e] |                                 |
| General Buckling   | 1.898(2,7)<br>[1,2,2,1,T5]                                 | 2.0079(2,-)<br>[1,1,2,1,7]               | 2.2393(2,-)<br>[1,2,2,1,5]           | 1.9811(2,-)<br>[1,2,2,1,6]           | 2.266(2,7)<br>[1,2,2,1,17]           | 2.0324(ILIN=0)<br>[1,2,2,1,22]  |
|  | 2.26(2,7)<br>[1,2,2,2,T5]                                  | 2.0678(2,-)<br>[1,2,2,1,-]               |                                      |                                      | 2.2271(3,8)<br>[1,2,1,1,18]          | 2.0892(ILIN=1)<br>[1,2,2,1,-]   |
|  |  |  |                                      |                                      | 2.3325(ILIN=1)<br>[1,compound,21]    | 2.0599(1,12)<br>[1,1,1,1,32]    |
| Inter-ring bay buckling  | 1.864(1,17)<br>[2,2,1,1,T5]                                |  |                                      |                                      | 2.3387(1,18)<br>[2,2,1,1,19]         | 2.1456(1,18)<br>[2,1,1,1,31]    |
| Local pocket Buckling  | 1.303(5,1)<br>[2,1,0,1,T5]                                 | 1.3472(5,-)<br>[2,1,0,1,16]              |                                      |                                      | 1.3324(4+,1)<br>[2,1,1,1,20]         | 1.3488(4+,1)<br>[2,1,1,1,25-27] |
|  |  |  |                                      |                                      |                                      | 1.3924(3+,1)<br>[1,1,1,1,33]    |
| weld plate/ T-stringer Buckling  |  | 1.4558(4,8th eigenvalue)<br>[2,1,0,1,13] |                                      | 1.5113(4,-)<br>[2,2,0,1,12]          |                                      | 1.3488(4+,1)<br>[2,1,1,1,25-27] |
|  |  |  |                                      |                                      |                                      | 1.4345(18+,-)<br>[1,1,1,1,34]   |
| T-stringer rolling   | 1.9484(5,-)<br>[1,1,2,1,9]                                 |  | 1.994(5,-)<br>[1,2,2,1,8]            |                                      |                                      |                                 |
|  | 1.9488(5,-)<br>[1,2,2,1,-]                                 |  | 1.8066(1,-)<br>[2,2,0,1,10]          |                                      |                                      | 1.5450(1,-)<br>[2,1,1,1,29]     |
|  |  | 1.668(1,-)<br>[2,1,0,1,11]               |                                      |                                      |                                      | 1.6288(1,-)<br>[2,1,1,1,30]     |
| T-stringer Crippling   | 1.4541(49,-)<br>[1,1,2,1,-]                                |  | 1.5102(49,-)<br>[1,2,2,1,-]          |                                      |                                      | 1.4278(10,-)<br>[2,1,1,1,28]    |
|  | 1.4542(49,-)<br>[1,2,2,1,-]                                |  | 1.5004(10,-)<br>[2,2,0,1,14]         |                                      |                                      |                                 |
|  | 1.4719(10,-)<br>[2,1,0,1,15]                               |  |                                      |                                      |                                      |                                 |
| Collapse of shell with a generalbucklng modal imperf. with Wimp=+-& 0.125 in | 1.094(4,1)(local buckling)<br>[2,1,0,1,Part 6 of T5]       |  |                                      | 1.35<br>[1,compound,1,42]            | 1.16<br>[1,1,1,1,23,22b]             |                                 |
|  | 1.185(1,43)(inter-ring buckling)<br>[2,2,0,1,Part 6 of T5] |  |                                      | 1.18<br>[1,compound,2,42]            | 1.16<br>[1,1,1,1,23,32a,b]           |                                 |
|  | 1.209(2,7)(general buckling)<br>[1,2,2,1,Part 6 of T5]     |  |                                      |                                      |                                      |                                 |

=====

\*The meanings of [a,b,c,d,e]:

a = axial length of the cylindrical shell included in the model:  
a = 1 means 68.75 inches (the entire length of the shell)  
a = 2 means 13.75 inches (the spacing of the "acreage" rings)

b = modeling of the "acreage" stringers:  
b = 1 means "acreage" stringers are discrete shell segments  
b = 2 means "acreage" stringers are smeared out

c = modeling of the "acreage" rings:  
c = 0 means "acreage" rings are replaced by classical simple support  
(buckling nodal lines)  
c = 1 means "acreage" rings are discrete shell segments  
c = 2 means "acreage" rings are smeared out

d = PANDA2 conservativeness index, ICONSV (see Ref.[13]):  
d = 1 means ICONSV = 1 (the most conservative option for ICOSNV)  
d = 2 means ICONSV = -1 (the least conservative option for ICONSV)

e = Table or figure number in the paper. (T5 means "Table 5"; 5 means "Fig.5")

"compound" means a compound STAGS model in which stiffeners are modeled differently in different parts of the STAGS model. (See Fig. 21, for example).

TABLE 5

Optimum design of the "acreage" cylindrical shell with use of the conservativeness index, ICONSV = 1. The PANDA2 computer program is used to obtain the optimum design. Dimensions are in inches and lb. See Ref.[13] for information about the conservativeness index, ICONSV. Critical and nearly critical margins are in **boldface**.

---

**PART 1**  
**Starting design of "acreage":**

DIMENSIONS OF THE STARTING DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 4.0000E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 1.3330E+00 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 3.0000E-01 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 1.0000E-01 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 1.0000E-01 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 4.0000E+00 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 3.0000E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.0000E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

---

**PART 2**

Optimum design of the "acreage" cylindrical shell determined with

```
1 $ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV:  
0.125 $ Initial buckling modal general imperfection amplitude, Wimpg2(1)  
-0.125 $ Initial buckling modal general imperfection amplitude, Wimpg2(2)
```

DIMENSIONS OF THE OPTIMIZED DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 2.2676E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 7.5902E-01 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 9.8977E-01 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 5.8191E-02 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 8.6462E-02 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 1.3750E+01 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 9.7173E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.8576E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION:

| VAR. | STR/ SEG. | LAYER | CURRENT |           |  |
|------|-----------|-------|---------|-----------|--|
| NO.  | RNG       | NO.   | NO.     | VALUE     | DEFINITION                                     |
|      |           | 0     | 0       | 1.074E+02 | WEIGHT OF THE ENTIRE PANEL (180 deg. of circ.) |

---

**PART 3**

Design margins for the optimized shell with imperfection amplitude, Wimp = 0.0:

```
1 $ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV  
0.0 $ Initial buckling modal general imperfection amplitude, Wimpg2(1)
```

MARGINS FOR THE OPTIMIZED DESIGN: LOAD CASE NO.1, SUBCASE NO.1 (PERFECT SHELL)

| MAR. | MARGIN |            |
|------|--------|------------|
| NO.  | VALUE  | DEFINITION |

```

1 3.05E-01 Local buckling from discrete model-1.,M=5 axial halfwaves;FS=0.99
2 3.03E-01 Bending-torsion buckling; M=5 ;FS=0.999
3 3.15E-01 Bending-torsion buckling: Koiter theory,M=5 axial halfwvav;FS=0.99
4 2.09E+00 eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=-0.0291; MID.;FS=1.
5 1.93E+00 eff.stress:matl=2,STR,Dseg=3,node=11,layer=1,z=0.0432; MID.;FS=1.
6 3.20E-01 (m=5 lateral-torsional buckling load factor)/(FS)-1;FS=0.999
7 8.64E-01 Inter-ring bucklng, discrete model, n=17 circ.halfwaves;FS=0.999
8 2.09E+00 eff.stress:matl=1,SKN,Iseg=2,at:n=6,layer=1,z=-0.0291;-MID.;FS=1.
9 1.93E+00 eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
10 1.16E+01 eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
11 9.43E-01 buckling margin stringer Iseg.3 . Local halfwaves=6 .MID.;FS=1.
12 9.43E-01 buckling margin stringer Iseg.3 . Local halfwaves=6 .NOPO;FS=1.
13 8.98E-01 buck.(SAND);simp-support general buck;M=2;N=7;slope=0.;FS=0.999
14 7.85E+00 buck.(SAND);rolling with smear rings; M=103;N=1;slope=0.;FS=0.999
15 2.01E+00 buck.(SAND);rolling only of stringers;M=40;N=0;slope=0.;FS=1.4
16 7.05E-01 Cold-bending ring buckling, closed form soln; N=155;FS=1.1
17 6.57E-01 Cold-bending ring buckling, "skin"-ring module; N=93 ;FS=1.1
18 3.39E-03 Cold-bending ring buckling, skin-ring module; N=66 ;FS=1.1
19 4.84E+02 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
-----
```

#### PART 4

Design margins for the same optimized shell, which was optimized with use of the conservativeness index, ICONSV = 1, but with ICONSV now set equal to -1 and with the imperfection amplitude, Wimp = 0.0:

```

-1      $ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV
0.0      $ Initial buckling modal general imperfection amplitude, Wimpg2(1)
```

MARGINS FOR THE OPTIMIZED DESIGN: LOAD CASE NO.1, SUBCASE NO.1 (PERFECT SHELL)

MAR. MARGIN

| NO. | VALUE | DEFINITION |
|-----|-------|------------|
|-----|-------|------------|

```

1 3.05E-01 Local buckling from discrete model-1.,M=5 axial halfwaves;FS=0.99
2 3.03E-01 Bending-torsion buckling; M=5 ;FS=0.999
3 3.15E-01 Bending-torsion buckling: Koiter theory,M=5 axial halfwvav;FS=0.99
4 2.09E+00 eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=-0.0291; MID.;FS=1.
5 1.93E+00 eff.stress:matl=2,STR,Dseg=3,node=11,layer=1,z=0.0432; MID.;FS=1.
6 3.20E-01 (m=5 lateral-torsional buckling load factor)/(FS)-1;FS=0.999
7 1.35E+00 Inter-ring bucklng, discrete model, n=17 circ.halfwaves;FS=0.999
8 2.09E+00 eff.stress:matl=1,SKN,Iseg=2,at:n=6,layer=1,z=-0.0291;-MID.;FS=1.
9 1.93E+00 eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
10 1.16E+01 eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
11 1.26E+00 buck.(SAND);simp-support general buck;M=2;N=7;slope=0.;FS=0.999
12 8.37E+00 buck.(SAND);rolling with smear rings; M=103;N=1;slope=0.;FS=0.999
13 7.05E-01 Cold-bending ring buckling, closed form soln; N=155;FS=1.1
14 6.57E-01 Cold-bending ring buckling, "skin"-ring module; N=93 ;FS=1.1
15 3.39E-03 Cold-bending ring buckling, skin-ring module; N=66 ;FS=1.1
16 4.84E+02 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
-----
```

#### PART 5

Design margins for the optimized shell with imperfection amplitude, Wimp=+0.125:

```

1      $ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV
0.125 $ Initial buckling modal general imperfection amplitude, Wimpg2(1)
```

MARGINS FOR THE OPTIMIZED DESIGN:LOAD CASE NO.1,SUBCASE NO.1 (IMPERFECT SHELL)

MAR. MARGIN

| NO. | VALUE | DEFINITION |
|-----|-------|------------|
|-----|-------|------------|

```

1 1.61E-01 Local buckling from discrete model-1.,M=5 axial halfwaves;FS=0.99
2 1.61E-01 Bending-torsion buckling; M=5 ;FS=0.999
3 1.30E-01 Bending-torsion buckling: Koiter theory,M=4 axial halfwvav;FS=0.99
4 2.42E+00 eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=-0.0291; MID.;FS=1.
5 6.16E-01 eff.stress:matl=2,STR,Dseg=3,node=11,layer=1,z=0.0432; MID.;FS=1.
6 3.05E-01 (m=5 lateral-torsional buckling load factor)/(FS)-1;FS=0.999
7 8.51E-01 Inter-ring bucklng, discrete model, n=15 circ.halfwaves;FS=0.999
8 1.57E+00 eff.stress:matl=1,SKN,Iseg=1,at:n=1,layer=1,z=-0.0291;-MID.;FS=1.
-----
```

```

9 6.43E-01 eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
10 3.16E-01 eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.
11 1.12E-01 buckling margin stringer Iseg.3 . Local halfwaves=5 .MID.;FS=1.
12 1.06E-01 buckling margin stringer Iseg.3 . Local halfwaves=5 .NOPO;FS=1.
13 2.09E+01 buck.(SAND);simp-support general buck;M=2;N=7;slope=0.;FS=0.999
14 8.07E+00 buck.(SAND);rolling with smear rings; M=101;N=1;slope=0.;FS=0.999
15 9.35E-01 buck.(SAND);rolling only of stringers;M=40;N=0;slope=0.;FS=1.4
16 3.63E+02 buck.(SAND);rolling only axisym.rings;M=0;N=0;slope=0.;FS=1.4
17 7.05E-01 Cold-bending ring buckling, closed form soln; N=155;FS=1.1
18 6.57E-01 Cold-bending ring buckling, "skin"-ring module; N=93 ;FS=1.1
19 3.39E-03 Cold-bending ring buckling, skin-ring module; N=66 ;FS=1.1
20 5.80E+02 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
=====

```

#### PART 6

Design margins for the optimized shell with imperfection amplitude, Wimp=-0.125:  
1     \$ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV  
-0.125 \$ Initial buckling modal general imperfection amplitude, Wimpg2(1)

MARGINS FOR THE OPTIMIZED DESIGN: LOADCASE NO.2, SUBCASE NO.1 (IMPERFECT SHELL)  
MAR. MARGIN

| NO. | VALUE           | DEFINITION  |
|-----|-----------------|---|
| 1   | <b>9.39E-02</b> | Local buckling from discrete model-1.,M=4 axial halfwaves;FS=0.99 |
| 2   | <b>9.66E-02</b> | Local buckling from Koiter theory,M=4 axial halfwaves;FS=0.999    |
| 3   | 1.65E+00        | eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=0.0291; MID.;FS=1.  |
| 4   | 5.99E+06        | stringer popoff margin:(allowable/actual)-1, web 1 MID.;FS=1.     |
| 5   | 1.72E+00        | eff.stress:matl=2,STR,Dseg=3,node=1,layer=1,z=0.0432; MID.;FS=1.  |
| 6   | <b>2.60E-02</b> | (m=1 lateral-torsional buckling load factor)/(FS)-1;FS=0.999      |
| 7   | <b>1.85E-01</b> | Inter-ring bucklng, discrete model, n=43 circ.halfwaves;FS=0.999  |
| 8   | 1.59E+00        | eff.stress:matl=1,SKN,Iseg=1,at:n=1,layer=1,z=0.0291;-MID.;FS=1.  |
| 9   | 6.43E-01        | eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.      |
| 10  | 3.16E-01        | eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.      |
| 11  | 3.11E+00        | buckling margin stringer Iseg.3 . Local halfwaves=5 .MID.;FS=1.   |
| 12  | <b>1.06E-01</b> | buckling margin stringer Iseg.3 . Local halfwaves=5 .NOPO;FS=1.   |
| 13  | <b>2.09E-01</b> | buck.(SAND);simp-support general buck;M=2;N=7;slope=0.;FS=0.999   |
| 14  | <b>2.80E-02</b> | buck.(SAND);rolling with smear string;M=1;N=46;slope=0.;FS=0.999  |
| 15  | 5.73E+00        | buck.(SAND);rolling with smear rings; M=103;N=1;slope=0.;FS=0.999 |
| 16  | 9.35E-01        | buck.(SAND);rolling only of stringers;M=40;N=0;slope=0.;FS=1.4    |
| 17  | 1.01E+01        | buck.(SAND);rolling only of rings; M=0;N=93;slope=0.;FS=1.4       |
| 18  | 3.63E+02        | buck.(SAND);rolling only axisym.rings;M=0;N=0;slope=0.;FS=1.4     |
| 19  | 4.16E+02        | (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.     |

=====

## TABLE 6

Optimized design of the T-stiffened weld land with use of the "acreage" design listed in Table 5. GENOPT/BIGBOSOR4 is used to obtain the optimum design. Dimensions are in inches and lb. See Ref.[13] for information about the conservativeness index, ICONSV. Critical and nearly critical margins are in **boldface**.

---

### PART 1 The starting design:

```
4.0000E+00 width of the weld land: WLAND
3.2500E-01 thickness of the weld land: TLAND
1.3340E-01 eccentricity of the weld land: ECLAND
2.0000E-01 web thickness of the weld land edge stringer: TWLAND
1.5000E+00 height of the web of the weld land edge stringer: HWLAND
2.0000E-01 thickness of the outstanding flange of the stringer: TFLAND
1.5000E+00 width of the outstanding flange of the stringer: WFLAND
5.8180E-02 thickness of the cylindrical shell skin: TSKIN
```

NOTE: TSKIN has to be a decision variable because it is involved in a linking expression. In the wcold.DEC file (input data for the GENOPT processor, "DECIDE") very tight lower and upper bounds are established for TSKIN because we do not want it to change materially from its previously optimized value of 0.05818 inch. The relevant lines from the file, wcold.DEC are:

```
y      $ Any more decision variables (Y or N) ?
     8      $ Choose a decision variable (1,2,3,...)
0.5818000E-01 $ Lower bound of variable no.( 8)
0.5820000E-01 $ Upper bound of variable no.( 8)
```

---

### PART 2 The optimized design:

```
4.0000E+00 width of the weld land: WLAND
1.0510E-01 thickness of the weld land: TLAND
2.3440E-02 eccentricity of the weld land: ECLAND
4.2830E-02 web thickness of the weld land edge stringer: TWLAND
1.6560E+00 height of the web of the weld land edge stringer: HWLAND
3.8860E-02 thickness of the outstanding flange of the stringer: TFLAND
9.2740E-01 width of the outstanding flange of the stringer: WFLAND
5.8180E-02 thickness of the cylindrical shell skin: TSKIN
```

---

### PART 3 MARGINS CORRESPONDING TO THE OPTIMIZED DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN CURRENT

| NO. | VALUE             | DEFINITION   |
|-----|-------------------|--|
| 1   | <b>-9.437E-03</b> | (GENBUK(1 )/GENBUKA(1 )) / GENBUKF(1 )-1; F.S.= 2.00 |
| 2   | <b>4.288E-04</b>  | (PANBUK(1 )/PANBUKA(1 )) / PANBUKF(1 )-1; F.S.= 1.50 |
| 3   | 2.006E+00         | (STRESSA(1 )/STRESS(1 )) / STRESSF(1 )-1; F.S.= 1.00 |

---

### PART 4 OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION: VAR. CURRENT

| NO. | VALUE     | DEFINITION   |
|-----|-----------|--|
| 1   | 6.128E-02 | weight of the weld land+"extra" edge stringers: WEIGHT |

NOTE: The objective, 6.128E-02 lb/in, is the weight per unit axial length of the weld land curved plate plus the weight per unit axial length of the two T-shaped stringers that run along each of the two longitudinal edges of the weld land curved plate.

---

**PART 5**

**The previously optimized "acreage" design with the use of ICONSV = 1:**

| VAR. | CURRENT   | DEFINITION                                     |
|------|-----------|--|
| NO.  | VALUE     | DEFINITION                                     |
| 3    | 2.268E+00 | stringer spacing: BSTR                         |
| 4    | 8.646E-02 | stringer thickness: TSTR                       |
| 5    | 9.898E-01 | stringer height: HSTR                          |
| 6    | 1.375E+01 | ring spacing: BRNG                             |
| 7    | 1.858E-01 | ring thickness: TRNG                           |
| 8    | 9.717E-01 | ring height: HRNG                              |
|      | 5.818E-02 | thickness of the cylindrical shell skin: TSKIN |

---

TABLE 7

Optimum design of the "acreage" cylindrical shell with use of the conservativeness index, ICONSV = -1 during optimization. The PANDA2 computer program is used to obtain the optimum design. Dimensions are in inches and lb. See Ref.[13] for information about the conservativeness index, ICONSV. Critical and nearly critical margins are in **boldface**.

---

**PART 1**

**Starting design of "acreage":**

DIMENSIONS OF THE STARTING DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 4.0000E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 1.3330E+00 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 3.0000E-01 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 1.0000E-01 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 1.0000E-01 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 4.0000E+00 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 3.0000E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.0000E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

---

**PART 2**

**Optimum design of the "acreage" cylindrical shell determined with**

**-1 \$ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV:**

**0.125 \$ Initial buckling modal general imperfection amplitude, Wimpg2(1)**

**-0.125 \$ Initial buckling modal general imperfection amplitude, Wimpg2(2)**

DIMENSIONS OF THE OPTIMIZED DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 2.0517E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 6.8494E-01 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 8.5570E-01 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 5.2719E-02 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 8.2445E-02 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 1.3750E+01 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 8.6800E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.6030E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

CURRENT VALUE OF THE OBJECTIVE FUNCTION:

VAR. STR/ SEG. LAYER CURRENT

| NO. | RNG | NO.       | NO.  | VALUE | DEFINITION |
|-----|-----|-----------|--|-------|------------|
| 0   | 0   | 9.575E+01 | WEIGHT OF THE ENTIRE PANEL (180 deg. of circ.) |       |            |

---

**PART 3**

**Design margins for the optimized shell with imperfection amplitude, Wimp = 0.0:**

**-1 \$ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV:**

**0.0 \$ Initial buckling modal general imperfection amplitude, Wimpg2(1)**

MARGINS FOR THE OPTIMIZED DESIGN: LOAD CASE NO.1, SUBCASE NO.1 (PERFECT SHELL)  
MAR. MARGIN

| NO. | VALUE           | DEFINITION  |
|-----|-----------------|---|
| 1   | 2.81E-01        | Local buckling from discrete model-1.,M=6 axial halfwaves;FS=0.99 |
| 2   | 2.93E-01        | Local buckling from Koiter theory,M=6 axial halfwaves;FS=0.999    |
| 3   | 1.80E+00        | eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=-0.0264; MID.;FS=1. |
| 4   | 1.65E+00        | eff.stress:matl=2,STR,Dseg=3,node=11,layer=1,z=0.0412; MID.;FS=1. |
| 5   | 2.95E-01        | (m=5 lateral-torsional buckling load factor)/(FS)-1;FS=0.999      |
| 6   | 6.32E-01        | Inter-ring buckling, discrete model, n=18 circ.halfwaves;FS=0.999 |
| 7   | 1.80E+00        | eff.stress:matl=1,SKN,Iseg=2,at:n=6,layer=1,z=-0.0264;-MID.;FS=1. |
| 8   | 1.66E+00        | eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.      |
| 9   | 1.02E+01        | eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.      |
| 10  | 7.15E-01        | buck.(SAND);simp-support general buck;M=3;N=8;slope=0.;FS=0.999   |
| 11  | 7.07E+00        | buck.(SAND);rolling with smear rings; M=103;N=1;slope=0.;FS=0.999 |
| 12  | 6.71E-01        | Cold-bending ring buckling, closed form soln; N=173;FS=1.1        |
| 13  | 6.57E-01        | Cold-bending ring buckling, "skin"-ring module; N=103;FS=1.1      |
| 14  | <b>1.62E-03</b> | <b>Cold-bending ring buckling, skin-ring module; N=73 ;FS=1.1</b> |
| 15  | 4.39E+02        | (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.     |

---

#### PART 4

Design margins for the optimized shell with imperfection amplitude,Wimp=+0.125:  
 -1 \$ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV  
 0.125 \$ Initial buckling modal general imperfection amplitude, Wimpg2(1)

MARGINS FOR THE OPTIMIZED DESIGN: LOAD CASE NO.1, SUBCASE NO.1 (IMPERFECT SHELL)  
 MAR. MARGIN

| NO. | VALUE           | DEFINITION  |
|-----|-----------------|---|
| 1   | <b>6.92E-02</b> | <b>Local buckling from discrete model-1.,M=5 axial halfwaves;FS=0.99</b>  |
| 2   | <b>6.54E-02</b> | <b>Bending-torsion buckling; M=5 ;FS=0.999</b>                            |
| 3   | <b>8.33E-02</b> | <b>Bending-torsion buckling: Koiter theory,M=5 axial halfwave;FS=0.99</b> |
| 4   | 2.45E+00        | eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=-0.0264; MID.;FS=1.         |
| 5   | 2.28E-01        | eff.stress:matl=2,STR,Dseg=3,node=11,layer=1,z=0.0412; MID.;FS=1.         |
| 6   | 2.39E-01        | (m=5 lateral-torsional buckling load factor)/(FS)-1;FS=0.999              |
| 7   | 6.19E-01        | Inter-ring buckling, discrete model, n=17 circ.halfwaves;FS=0.999         |
| 8   | 1.15E+00        | eff.stress:matl=1,SKN,Iseg=1,at:n=1,layer=1,z=-0.0264;-MID.;FS=1.         |
| 9   | 2.41E-01        | eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.              |
| 10  | 1.19E-01        | eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.              |
| 11  | <b>2.03E-01</b> | <b>buck.(SAND);simp-support general buck;M=3;N=8;slope=0.;FS=0.999</b>    |
| 12  | 7.29E+00        | buck.(SAND);rolling with smear rings; M=106;N=1;slope=0.;FS=0.999         |
| 13  | 3.18E+02        | buck.(SAND);rolling only axisym.rings;M=0;N=0;slope=0.;FS=1.4             |
| 14  | 6.71E-01        | Cold-bending ring buckling, closed form soln; N=173;FS=1.1                |
| 15  | 6.57E-01        | Cold-bending ring buckling, "skin"-ring module; N=103;FS=1.1              |
| 16  | <b>1.62E-03</b> | <b>Cold-bending ring buckling, skin-ring module; N=73 ;FS=1.1</b>         |
| 17  | 5.96E+02        | (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.             |

---

#### PART 5

Design margins for the optimized shell with imperfection amplitude,Wimp=-0.125:  
 -1 \$ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV  
 -0.125 \$ Initial buckling modal general imperfection amplitude, Wimpg2(1)

MARGINS FOR THE OPTIMIZED DESIGN: LOAD CASE NO.2, SUBCASE NO.1 (IMPERFECT SHELL)  
 MAR. MARGIN

| NO. | VALUE            | DEFINITION   |
|-----|------------------|--|
| 1   | <b>3.50E-02</b>  | <b>Local buckling from discrete model-1.,M=7 axial halfwaves;FS=0.99</b> |
| 2   | <b>1.60E-02</b>  | <b>Local buckling from Koiter theory,M=7 axial halfwaves;FS=0.999</b>    |
| 3   | 1.18E+00         | eff.stress:matl=1,STR,Dseg=4,node=11,layer=1,z=0.0264; MID.;FS=1.        |
| 4   | 4.36E+05         | stringer popoff margin:(allowable/actual)-1, web 1 MID.;FS=1.            |
| 5   | 1.29E+00         | eff.stress:matl=2,STR,Dseg=3,node=1,layer=1,z=0.0412; MID.;FS=1.         |
| 6   | <b>1.48E-02</b>  | <b>(m=1 lateral-torsional buckling load factor)/(FS)-1;FS=0.999</b>      |
| 7   | <b>6.37E-02</b>  | <b>Inter-ring buckling, discrete model, n=42 circ.halfwaves;FS=0.999</b> |
| 8   | 1.14E+00         | eff.stress:matl=1,SKN,Iseg=1,at:n=1,layer=1,z=0.0264;-MID.;FS=1.         |
| 9   | 2.48E-01         | eff.stress:matl=2,STR,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.             |
| 10  | 1.24E-01         | eff.stress:matl=3,RNG,Iseg=3,at:TIP,layer=1,z=0.;-MID.;FS=1.             |
| 11  | 8.55E+00         | buckling margin stringer Iseg.3 . Local halfwaves=5 .MID.;FS=1.          |
| 12  | <b>-1.09E-02</b> | <b>buckling margin stringer Iseg.3 . Local halfwaves=5 .NOPO;FS=1.</b>   |

```
13  1.47E-01 buck.(SAND);simp-support general buck;M=3;N=8;slope=0.;FS=0.999
14 -6.60E-02 buck.(SAND);rolling with smear string;M=1;N=44;slope=0.;FS=0.999
15  4.58E+00 buck.(SAND);rolling with smear rings; M=103;N=1;slope=0.;FS=0.999
16  8.40E-01 buck.(SAND);rolling only of stringers;M=50;N=0;slope=0.;FS=1.4
17  7.78E+00 buck.(SAND);rolling only of rings; M=0;N=103;slope=0.;FS=1.4
18  3.20E+02 buck.(SAND);rolling only axisym.rings;M=0;N=0;slope=0.;FS=1.4
19  3.47E+02 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
=====
=====
```

## TABLE 8

Optimized design of the T-stiffened weld land with use of the "acreage" design listed in Table 7. GENOPT/BIGBOSOR4 is used to obtain the optimum design. Dimensions are in inches and lb. See Ref.[13] for information about the conservativeness index, ICONSV. Critical and nearly critical margins are in **boldface**.

---

### Part 1

#### The starting design:

```
4.0000E+00  width of the weld land: WLAND
3.2500E-01  thickness of the weld land: TLAND
1.3340E-01  eccentricity of the weld land: ECLAND
2.0000E-01  web thickness of the weld land edge stringer: TWLAND
1.5000E+00  height of the web of the weld land edge stringer: HWLAND
2.0000E-01  thickness of the outstanding flange of the stringer: TFLAND
1.5000E+00  width of the outstanding flange of the stringer: WFLAND
5.2710E-02  thickness of the cylindrical shell skin: TSKIN
```

NOTE: TSKIN has to be a decision variable because it is involved in a linking expression. In the wcold.DEC file (input data for the GENOPT processor, "DECIDE") very tight lower and upper bounds are established for TSKIN because we do not want it to change materially from its previously optimized value of 0.05271 inch. The relevant lines from the file, wcold.DEC are:

```
y      $ Any more decision variables (Y or N) ?
8      $ Choose a decision variable (1,2,3,...)
0.5271000E-01 $ Lower bound of variable no.( 8)
0.52720000E-01 $ Upper bound of variable no.( 8)
```

---

### PART 2

#### The optimized design:

```
4.0030E+00  width of the weld land: WLAND
1.2350E-01  thickness of the weld land: TLAND
3.5400E-02  eccentricity of the weld land: ECLAND
1.0580E-01  web thickness of the weld land edge stringer: TWLAND
3.4010E+00  height of the web of the weld land edge stringer: HWLAND
5.9760E-02  thickness of the outstanding flange of the stringer: TFLAND
2.1070E+00  width of the outstanding flange of the stringer: WFLAND
5.2710E-02  thickness of the cylindrical shell skin: TSKIN
```

---

### PART 3

MARGINS CORRESPONDING TO THE OPTIMIZED DESIGN (F.S.= FACTOR OF SAFETY)

MARGIN CURRENT

| NO. | VALUE             | DEFINITION   |
|-----|-------------------|--|
| 1   | <b>-9.459E-03</b> | (GENBUK(1 )/GENBUKA(1 )) / GENBUKF(1 )-1; F.S.= 2.00 |
| 2   | <b>4.628E-03</b>  | (PANBUK(1 )/PANBUKA(1 )) / PANBUKF(1 )-1; F.S.= 1.50 |
| 3   | 1.982E+00         | (STRESSA(1 )/STRESS(1 )) / STRESSF(1 )-1; F.S.= 1.00 |

---

### PART 4

OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION:

VAR. CURRENT

| NO. | VALUE     | DEFINITION   |
|-----|-----------|--|
| 1   | 1.416E-01 | weight of the weld land+"extra" edge stringers: WEIGHT |

NOTE: The objective, 1.416E-01 lb/in, is the weight per unit axial length of the weld land curved plate plus the weight per unit axial length of the two T-shaped stringers that run along each of the two longitudinal edges of the weld land curved plate.

---

PART 5

The previously optimized "acreage" design with the use of ICONSV = -1:

| VAR. | CURRENT   |  |
|------|-----------|--|
| 3    | 2.052E+00 | stringer spacing: BSTR                         |
| 4    | 8.245E-02 | stringer thickness: TSTR                       |
| 5    | 8.557E-01 | stringer height: HSTR                          |
| 6    | 1.375E+01 | ring spacing: BRNG                             |
| 7    | 1.603E-01 | ring thickness: TRNG                           |
| 8    | 8.680E-01 | ring height: HRNG                              |
|      | 5.271E-02 | thickness of the cylindrical shell skin: TSKIN |

---

TABLE 9

Run stream for obtaining "weldland/wcold" optimum designs with GENOPT/BIGBOSOR4. The commands that the user types are in **boldface**.

---

(In this case the GENOPT user (the first author) selected "weldland" for the GENERIC case name and "wcold" for the SPECIFIC case name. The case is run in the directory, /home/progs/genoptcase, in which "/home/progs" is the PARENT directory of GENOPT, BIGBOSOR4, PANDA2, etc. at the first author's facility. At your facility, replace the string, "/home/progs" with whatever directory is the PARENT directory of GENOPT, BIGBOSOR4, etc. where you are using GENOPT/BIGBOSOR4.)

```
cd /home/progs/genoptcase
```

```
genoptlog (activate GENOPT command set)
```

(The command, "genoptlog", produces the following screen:)

---

GENOPT commands have been activated.

|             |  |
|-------------|--|
| gentext     | GENOPT user generates a prompt file.   |
| genprograms | GENOPT user generates (makes) executables:<br>begin, decide, mainsetup, optimize,<br>change, chooseplot, and diplot. |
| begin       | End user provides starting data.   |
| decide      | End user chooses decision variables, bounds,<br>linked variables, and inequality constraints.                        |
| mainsetup   | End user sets up strategy parameters.  |
| optimize    | End user performs optimization.  |
| change      | End user changes some parameters.  |
| autochange  | New values for decision variables randomly   |
| superopt    | End user find global optimum (autochange/optimize)...  |
| chooseplot  | End user chooses which variable to plot vs.<br>iterations.   |
| diplot      | End user plots variables vs. iterations.   |
| insert      | GENOPT user adds parameters to the problem.  |
| cleangen    | GENOPT user cleans up GENeric case files.  |
| cleanspec   | End user cleans up SPECIFIC case files.  |

---

```
gentext [provide generic case name ("weldland"),  
variable names, roles, one-line definitions,  
"help" paragraphs, etc. The input data from  
the long GENTEXT interactive session are saved  
in the file, "weldland.INP" (Table 5 of [3]). Also, see  
the files produced by GENTEXT called "weldland.DEF"  
(Table 6 of [3]) and "weldland.PRO" (Table 2 here).]
```

---

\*\*\*\*\* A SMALL DIGRESSION FROM THE RUN STREAM \*\*\*\*\*

After execution of GENTEXT the following "weldland" files exist in the directory where GENTEXT was executed, that is, in the directory, /home/progs/genoptcase :

---

|            |   |      |      |       |        |       |                                   |
|------------|---|------|------|-------|--------|-------|-----------------------------------|
| -rw-r--r-- | 1 | bush | bush | 4529  | Jun 12 | 11:11 | weldland.CHA                      |
| -rw-r--r-- | 1 | bush | bush | 1378  | Jun 12 | 11:11 | weldland.COM (common blocks)      |
| -rw-r--r-- | 1 | bush | bush | 6339  | Jun 12 | 11:11 | weldland.CON                      |
| -rw-r--r-- | 1 | bush | bush | 58128 | Jun 12 | 11:11 | weldland.DAT                      |
| -rw-r--r-- | 1 | bush | bush | 32086 | Jun 12 | 11:11 | weldland.DEF (some documentation) |
| -rw-r--r-- | 1 | bush | bush | 58161 | Jun 12 | 09:57 | weldland.INP (input for GENTEXT)  |

---

```

-rw-r--r-- 1 bush bush 29517 Jun 12 11:11 weldland.NEW
-rw-r--r-- 1 bush bush 21560 Jun 12 11:11 weldland.PRO (prompting file)
-rw-r--r-- 1 bush bush 1882 Jun 12 11:11 weldland.REA
-rw-r--r-- 1 bush bush 45038 Jun 4 10:26 weldland.SAV
-rw-r--r-- 1 bush bush 383 Jun 12 11:11 weldland.SET
-rw-r--r-- 1 bush bush 11357 Jun 12 11:11 weldland.SUB
-rw-r--r-- 1 bush bush 1882 Jun 12 11:11 weldland.WRI
-----

```

The contents of these files is described in the weldland.DEF file. See pages 2 and 3 of Table 6 of [3]. Also, see [7].

Next, create software that computes the design constraints and the objective. In this example create bosdec.weldland (Table 12 of [3]), which generates valid input files for the BIGBOSOR4 preprocessor, B4READ, and "flesh out" the skeletal behavior.new file and the struct.new file that are automatically created by GENOPT. That is, create behavior.weldland (Tables 10 and 11 of [3]) from behavior.new and create struct.weldland from struct.new (Table 8 of [3]). The "fleshing out" of struct.new is very simple in this "weldland" application: only THREE lines are added to the version of struct.new created automatically by GENOPT. These three added lines are indicated below:

The following is part of the "fleshed out" version of the struct.new file:

```

C  USER: YOU MAY WANT TO INSERT SUBROUTINE CALLS FROM SOFTWARE DEVELOPED
C        ELSEWHERE FOR ANY CALCULATIONS PERTAINING TO THIS LOAD SET.
C
C
CALL OPNGEN <--added by the GENOPT user (the writer)
CALL RWDGEN <--added by the GENOPT user (the writer)
C
-----
```

and the following is part of the struct.new file:

```

C  NEXT, EVALUATE THE OBJECTIVE, OBJGEN:
IF (ILOADX.EQ.1) THEN
    PHRASE = 'weight of the weld land+"extra" edge stringers' | Created
    CALL BLANKX(PHRASE,IENDP4) | automatically
    CALL OBJECT(IFILE8,NPRINX,IMODX,OBJGEN,
1      'weight of the weld land+"extra" edge stringers') | by GENOPT
ENDIF
NCONSX = ICONSX
C
CALL CLSGEN | added by the
C
RETURN | GENOPT user
END
-----
```

The three added statements, CALL OPNGEN, CALL RWDGEN, and CALL CLSGEN, open, rewind, and close various files used by BIGBOSOR4. If you plan to optimize some other shell using GENOPT/BIGBOSOR4 you can "flesh out" struct.new in exactly the same way. To find the places in the "skeletal" version of struct.new that is automatically produced by GENTEXT, search for the string, "YOU MAY WANT", in order to find where you should insert the two lines, CALL OPNGEN and CALL RWDGEN. Search for the string, "NCONSX", in order to find where you should insert the line, CALL CLSGEN. If you want to see what struct.new looks like, see Table 8 of [3]. Sometimes, in your other applications of GENOPT, you may want to add more coding to the "skeletal" version of struct.new, as was done in [5] and [7], especially in [7], where all of the computations are done in struct.new and the "skeletal" version of behavior.new produced automatically by GENOPT remains unchanged.

A significant part of the work in this project was the creation by the GENOPT user (the first author of this paper) of

the file, bosdec.weldland. Some effort was also required to "flesh out" the skeletal "behavior.new" file automatically created by GENOPT. The "fleshed out" version is called "behavior.weldland" (Tables 10 and 11 of [3]). There are three "behavior" subroutines: BEHX1, BEHX2, BEHX3. The GENOPT user must also "flesh out" the subroutine that computes the objective, SUBROUTINE OBJECT. The "BEHX<sub>i</sub>",  $i = 1,2,3$ , subroutines compute the following:

SUBROUTINE BEHX1 computes the general buckling load.

SUBROUTINE BEHX2 computes the inter-ring ("panel") buckling load.

SUBROUTINE BEHX3 computes the effective stress.

SUBROUTINE OBJECT computes the objective, which in this case is the weight/axial length of one T-stiffened weld land (the weld land plate + two T-stringers).

If you plan to use GENOPT in combination with BIGBOSOR4 for optimizing other shells of revolution which have buckling behavior, you can use the list of SUBROUTINE BEHX1 or of SUBROUTINE BEHX2 in Tables 10 and 11 of [3] as a guide.

NOTE: make it a habit to develop the "behavior", "struct", and "bosdec" files using different suffices than ".new" or ".src". By this practice you will not lose work should you execute GENTEXT again after you have already added FORTRAN coding to behavior.new and to struct.new, which are over-written by GENTEXT. In this "weldland" case the writer initially copied behavior.new and struct.new (the "skeletal" versions created automatically by GENOPT after completion of the GENTEXT interactive session) to behavior.weldland and struct.weldland, then "fleshed out" the behavior.weldland and struct.weldland files. Also, the writer developed his version of "bosdec" in a file called "bosdec.weldland". Then, just before execution of "genprograms", the writer did the following:

```
-----  
cp behavior.weldland behavior.new  (behavior.weldland and struct.weldland  
cp struct.weldland struct.new      are developed in the directory:  
                                    /home/progs/genoptcase)  
cd /home/progs/bosdec/sources      ("bosdec" is stored in a different  
cp bosdec.weldland bosdec.src      directory)  
cd /home/progs/genoptcase          (return to the "genoptcase" directory  
                                    before executing "genprograms")  
-----  
***** END OF A SMALL DIGRESSION FROM THE RUN STREAM *****
```

**genprograms** (compiles the software created by GENOPT and  
"fleshed out" and added by the GENOPT user)

\*\*\*\*\* ANOTHER SMALL DIGRESSION FROM THE RUN STREAM \*\*\*\*\*  
If compilation is successful, the following is listed on your computer screen:

```
-----  
Congratulations! Your code compiled successfully. You should  
now check to make sure that you get correct results from a  
simple test case with a known answer before attempting a more  
complicated case.
```

Here is a list of all your newly created executables:

```
-rwxr-xr-x 1 bush bush 83839 Jun 12 11:17 autochange.linux  
-rwxr-xr-x 1 bush bush 190917 Jun 12 11:17 begin.linux  
-rwxr-xr-x 1 bush bush 135079 Jun 12 11:17 change.linux  
-rwxr-xr-x 1 bush bush 157882 Jun 12 11:17 chooseplot.linux  
-rwxr-xr-x 1 bush bush 160553 Jun 12 11:17 decide.linux  
-rwxr-xr-x 1 bush bush 105947 Jun 12 11:17 mainsetup.linux  
-rwxr-xr-x 1 bush bush 1603626 Jun 17 14:24 optimize.linux  
-rwxr-xr-x 1 bush bush 124325 Jun 12 11:17 store.linux  
-----
```

NOTE: You may see the lines above even when you still have errors in your newly "fleshed out" and created

FORTRAN coding. You will doubtless discover additional errors when you first execute "OPTIMIZE". Make your corrections to the behavior.weldland, struct.weldland, and bosdec.weldland files, then again copy them to behavior.new, struct.new, and bosdec.src as specified above, and then give the command, "genprograms" again. Keep doing this until you are satisfied that there are no more errors in your FORTRAN coding. Go through this "error elimination loop" before you try to do any optimization. In other words, specify ITYPE = 2 and NPRINT = 2 in the \*.OPT file (input for MAINSETUP, listed below) while you are in this error elimination phase of your work. Only when you are satisfied that behavior.weldland, struct.weldland, and bosdec.weldland are correct should you attempt to do any optimization (ITYPE = 1 and NPRINT = 0 in the \*.OPT file).

Concerning the use of the GENOPT processor called "INSERT":

It may well happen that, after you have already developed behavior.weldland, struct.weldland, and bosdec.weldland as just described, you may want to add one or more variables to your generic case. You can use "INSERT" to do this. However, note that if you add (or take away) any variables, the labelled common blocks (weldland.COM) produced automatically by GENTEXT will change. These new common blocks will be present in the new "skeletal" versions of behavior.new and struct.new generated automatically by your re-run of GENTEXT. Also, if you use "INSERT" to add one or more "behaviors", GENTEXT creates additional FORTRAN coding in the behavior.new and struct.new libraries.

Concerning "behavior" and "struct":

With regard to the "behavior" and the "struct" libraries, You now have a choice between Choice 1 or Choice 2:

Choice 1. You can add your "fleshed out" FORTRAN coding now contained only in behavior.weldland, struct.weldland, to the latest "skeletal" versions, behavior.new and struct.new, then type the commands:

```
cp behavior.new behavior.weldland  (Be careful! you may be destroying  
cp struct.new struct.weldland      your previous work if you have not  
                                     updated behavior.new and/or  
                                     struct.new correctly.)
```

This is almost always the best choice, as explained next in Choice 2.

Choice 2. You can replace the old, GENTEXT-created, common blocks with the new common blocks located in the file, \*.COM (e.g. "\*" = "weldland") in your behavior.weldland and struct.weldland files. This is not generally the best choice because you may have added new "behaviors". In that case it is not just the common blocks that change but also the GENTEXT-created FORTRAN coding in behavior.new and struct.new. Also, you may have changed the wording in one or more of the one-line definitions of the variables. These changes in wording of the one-line definitions of the variables exist only in the new "skeletal" behavior.new and struct.new files. Therefore, it is almost always best to port your "fleshed out" FORTRAN coding from your behavior.weldland and struct.weldland files to the new "skeletal" behavior.new and struct.new files produced automatically by GENTEXT, then (only after you are certain that you have done everything correctly!) copy the "fleshed out" behavior.new into behavior.weldland and the "fleshed out" struct.new into struct.weldland.

Concerning "bosdec":

In the case of the file, /home/progs/bosdec/sources/bosdec.weldland, you have to copy the new GENTEXT-created common blocks, located in weldland.COM, into the proper place in the bosdec.weldland file and then remove the old GENTEXT-created common blocks (if any). Since bosdec.weldland contains only FORTRAN code produced by you, you don't have to worry about any new GENTEXT-created FORTRAN code there.

Concerning modification of only the "help" paragraphs in the file \*.INP (weldland.INP):

After you run BEGIN you will probably come to the conclusion that the end user will need more "help" information than you have provided. You can do this by editing the \*.INP (weldland.INP) file. Just be sure to follow the pattern that exists in the \*.INP file. For example, for each new line of a "help" paragraph there exists a following line:

```
y      $ Are there more lines in the "help" paragraph?
```

As you add new "help" lines make sure in your editing that you follow each new "help" line with the line printed above. The last line in the "help" input is always followed by the line:

```
n      $ Are there more lines in the "help" paragraph?
```

You can, in the same way, add a new "help" paragraph where there was none previously. You would change the line:

```
n      $ Do you want to include a "help" paragraph?
```

to

```
y      $ Do you want to include a "help" paragraph?
```

and then proceed as is done elsewhere in the \*.INP file for variables that have "help" paragraphs.

```
***** END OF SMALL DIGRESSION *****
```

Now, assuming that all the GENOPT-user-inserted FORTRAN coding is correct and that the GENOPT user has played the role of end user by running one or more test cases, the GENOPT user's job is done. The end user now takes over.

Next, type the command BEGIN to provide input data for a specific case that belongs to the generic set, "weldland". In this paper the specific case is called "wcold".

```
begin (provide starting design, material, loading,  
allowables and factors of safety for the  
following "behaviors":  
1. general buckling (computed in SUBROUTINE BEHX1)  
2. inter-ring buckling (computed in SUBROUTINE BEHX2)  
3. effective stress (computed in SUBROUTINE BEHX3)
```

(The command, BEGIN, starts an interactive session, the beginning of which presents the following to your computer screen:)

```
-----  
THE NAME OF THE PROMPT FILE ASKED FOR NEXT  
IS THE NAME OF THE CLASS OF PROBLEMS THAT THE GENOPT-USER  
HAS CHOSEN, NOT THE NAME OF THE PARTICULAR CASE BEING  
STUDIED HERE. IT IS THE "NAME" PART OF "NAME".PRO.
```

ENTER THE GENERIC CASE NAME: **weldland**

FROM HERE ON, WHENEVER THE CASE NAME IS REQUESTED,  
YOU PROVIDE THE NAME OF THE PARTICULAR INSTANCE IN THE CLASS  
OF PROBLEMS THAT YOU ARE NOW STUDYING. THIS NAME MUST BE  
DIFFERENT FROM THE NAME YOU HAVE JUST PROVIDED ABOVE.

ENTER THE SPECIFIC CASE NAME: **wcold**

```
***** BEGIN *****
```

Purpose of BEGIN is to permit you to provide a starting design in an interactive mode. You give starting dimensions, material properties, allowables. The interactive session is stored on a file called wcold.BEG, in which wcold is a name that you have chosen for the specific case. (The name, wcold, must remain the same as you use BEGIN, DECIDE, MAINSETUP, OPTIMIZE, and CHANGE.) In future runs of the same or a slightly modified case, you will find it convenient to use the file wcold.BEG as input. Rather than answer all the questions interactively, you can use wcold.BEG or an edited version of wcold.BEG as input to BEGIN. BEGIN also generates an output file called wcold.OPB. OPB lists a summary of the case, and if you choose the tutorial option, the questions, helps, and your answers for each input datum.

\*\*\*\*\*

---

(When you have completed BEGIN you will have the file, wcold.BEG, which can be used in any future execution of BEGIN. A list of the file, wcold.BEG, follows:)

---

```

n          $ Do you want a tutorial session and tutorial output?
4.000000  $ width of the weld land: WLAND
0.3250000 $ thickness of the weld land: TLAND
0.1334045 $ eccentricity of the weld land: ECLAND
            2 $ index for weld land edge stringer (0 or 1 or 2): KLAND
0.2000000 $ web thickness of the weld land edge stringer: TWILAND
1.500000  $ height of the web of the weld land edge stringer: HWLAND
0.2000000 $ thickness of the outstanding flange of the stringer: TFLAND
1.500000  $ width of the outstanding flange of the stringer: WFLAND
            3 $ number of weld lands in 360 degrees: NLAND
0.0581910 $ thickness of the cylindrical shell skin: TSKIN
            48 $ radius of the cylindrical shell: RADCYL
            68.75 $ length of the cylindrical shell: LENCYL
2.267600  $ stringer spacing: BSTR
0.0864620 $ stringer thickness: TSTR
0.989770  $ stringer height: HSTR
13.75000 $ ring spacing: BRNG
0.185760  $ ring thickness: TRNG
0.971730  $ ring height: HRNG
0.1100000E+08 $ Young's modulus: EMOD
0.3000000 $ Poisson ratio: NU
0.2500000E-03 $ mass density (aluminum = 0.00025 in English units): DENS
            1 $ low end of the M-range for general buckling: MLONG
            10 $ High end of the M-range for general buckling: MHIGHG
           1 $ low end of the M-range for "panel" buckling: MLLOWP
           10 $ high end of the M-range for "panel" buckling: MHIGHP
           1 $ Number NCASES of load cases (environments): NCASES
-669234.63 $ total axial load (2*pi*r*Nx): PX( 1)
            0 $ uniform normal pressure: PY( 1)
            0 $ axial load in Load Set B: PX0( 1)
            0 $ pressure in Load Set B: PY0( 1)
1.000000  $ allowable for general buckling: GENBUKA( 1)
2.000000  $ factor of safety for general buckling: GENBUKF( 1)
1.000000  $ allowable for "panel" buckling: PANBUKA( 1)
1.500000  $ factor of safety for "panel" buckling: PANBUKF( 1)
70000.00  $ maximum allowable stress: STRESSA( 1)
1.000000  $ factor of safety for effective stress: STRESSF( 1)

```

---

**decide** (provide decision variables, bounds, equality constraints (linking expressions), and inequality constraints. DECIDE saves your interactive input in the file, wcold.DEC. A list of the file, wcold.DEC, follows:)

---

```

n      $ Do you want a tutorial session and tutorial output?
    1      $ Choose a decision variable (1,2,3,...)
    4.0     $ Lower bound of variable no.( 1)
    6.0     $ Upper bound of variable no.( 1)
n      $ Do you want especially to restrict variable no.( 1)
y      $ Any more decision variables (Y or N) ?
    2      $ Choose a decision variable (1,2,3,...)
0.1000000     $ Lower bound of variable no.( 2)
0.6000000     $ Upper bound of variable no.( 2)
n      $ Do you want especially to restrict variable no.( 2)
y      $ Any more decision variables (Y or N) ?
    4      $ Choose a decision variable (1,2,3,...)
0.2000000E-01 $ Lower bound of variable no.( 4)
0.4000000     $ Upper bound of variable no.( 4)
n      $ Do you want especially to restrict variable no.( 4)
y      $ Any more decision variables (Y or N) ?
    5      $ Choose a decision variable (1,2,3,...)
0.2000000     $ Lower bound of variable no.( 5)
5.000000      $ Upper bound of variable no.( 5)
n      $ Do you want especially to restrict variable no.( 5)
y      $ Any more decision variables (Y or N) ?
    6      $ Choose a decision variable (1,2,3,...)
0.2000000E-01 $ Lower bound of variable no.( 6)
0.4000000     $ Upper bound of variable no.( 6)
n      $ Do you want especially to restrict variable no.( 6)
y      $ Any more decision variables (Y or N) ?
    7      $ Choose a decision variable (1,2,3,...)
0.2000000     $ Lower bound of variable no.( 7)
5.000000      $ Upper bound of variable no.( 7)
n      $ Do you want especially to restrict variable no.( 7)
y      $ Any more decision variables (Y or N) ?
    8      $ Choose a decision variable (1,2,3,...)
0.5818000E-01 $ Lower bound of variable no.( 8)
0.5819000E-01 $ Upper bound of variable no.( 8)
n      $ Do you want especially to restrict variable no.( 8)
n      $ Any more decision variables (Y or N) ?
y      $ Any linked variables (Y or N) ?
    3      $ Choose a linked variable (1,2,3,...)
    1      $ Choose type of linking (1=polynomial; 2=user-defined)
    2      $ To which variable is this variable linked?
0.5000000     $ Assign a value to the linking coefficient, C(j)
    1      $ To what power is the decision variable raised?
y      $ Any other decision variables in the linking expression?
    8      $ To which variable is this variable linked?
-0.5000000     $ Assign a value to the linking coefficient, C(j)
    1      $ To what power is the decision variable raised?
n      $ Any other decision variables in the linking expression?
n      $ Any constant C0 in the linking expression?
n      $ Any more linked variables (Y or N) ?
n      $ Any inequality relations among variables? (type H)
y      $ Any escape variables (Y or N) ?

```

y \$ Want to have escape variables chosen by default?

---

**mainsetup** (provide strategy, analysis type, etc.. MAINSETUP  
saves your interactive input in the file, wcold.OPT.  
A list of the file, wcold.OPT, follows:

---

n \$ Do you want a tutorial session and tutorial output?  
0 \$ Choose an analysis you DON'T want (1, 2,...), IBEHAV  
0 \$ NPRINT= output index (0=GOOD, 1=ok, 2=debug, 3=too much)  
1 \$ Choose type of analysis (1=opt., 2=fixed, 3=sensit.) ITYPE  
5 \$ How many design iterations in this run (3 to 25)?  
n \$ Take "shortcuts" for perturbed designs (Y or N)?  
2 \$ Choose 1 or 2 or 3 or 4 or 5 for IDESIGN  
1 \$ Choose 1 or 2 or 3 or 4 or 5 for move limits, IMOVE  
y \$ Do you want default (RATIO=10) for initial move limit jump?  
y \$ Do you want the default perturbation (dx/x = 0.05)?  
n \$ Do you want to have dx/x modified by GENOPT?  
n \$ Do you want to reset total iterations to zero (Type H)?  
1 \$ Choose IAUTOF= 1 or 2 or 3 or 4 or 5 or 6 to change X(i)

---

**superopt** (Start the "batch" run that attempts to find a "global"  
optimum design. This run may require several hours [3]  
or even days [8] on the computer.)

(Inspect the wcold.OPP file.)

**chooseplot** (choose what to plot vs design iterations. The  
interactive CHOOSEPLOT session is saved in the  
file, wcold.CPL. An example of the wcold.CPL  
file used in this case follows:

---

n \$ Do you want a tutorial session and tutorial output?  
n \$ Any design variables to be plotted v. iterations (Y or N)?  
n \$ Any design margins to be plotted v. iterations (Y or N)?  
n \$ Do you want to get more plots before your next "SUPEROPT"?  
-----)

**diplot** (obtain the postscript file, wcold.5.ps (objective  
versus design iterations. The plot is shown in Fig. 4.)

(Edit the wcold.OPT file in order to obtain the analysis of a fixed design, that is, change ITYPE from 1 to 2 in the  
wcold.OPT file.)

**mainsetup** (set up a run for the fixed previously optimized design.)

**optimize** (obtain the wcold.OPM file corresponding to the  
optimized design. The optimum design is listed in Table 6.)  
"OPTIMIZE", when executed in the ITYPE = 2 mode in wcold.OPT,  
produces three files that contain valid input for  
BIGBOSOR4:  
wcold.BEHX0 = general buckling, no weld land (Fig. 5)  
wcold.BEHX1 = general buckling, yes weld lands (Figs. 6, 8)  
wcold.BEHX2 = inter-ring ("panel") buckling, yes weld lands  
(Figs. 10, 12, 14)

Just below in this runstream wcold.BEHX1 and wcold.BEHX2 are used, as you will see next.)

**change** (Use the processor, CHANGE, to save the optimum design. The interactive CHANGE session is saved in the file, wcold.CHG. This is the best way to "preserve" the optimum design. In this way you can easily resurrect the optimum design at anytime in the future. A list of the file, wcold.CHG, follows:)

---

```
n      $ Do you want a tutorial session and tutorial output?
y      $ Do you want to change any values in Parameter Set No. 1?
    1  $ Number of parameter to change (1, 2, 3, . .)
4.000000 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    2  $ Number of parameter to change (1, 2, 3, . .)
0.1051000 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    3  $ Number of parameter to change (1, 2, 3, . .)
0.2344000E-01 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    4  $ Number of parameter to change (1, 2, 3, . .)
0.4283000E-01 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    5  $ Number of parameter to change (1, 2, 3, . .)
1.656000 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    6  $ Number of parameter to change (1, 2, 3, . .)
0.3886000E-01 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    7  $ Number of parameter to change (1, 2, 3, . .)
0.9274000 $ New value of the parameter
y      $ Want to change any other parameters in this set?
    8  $ Number of parameter to change (1, 2, 3, . .)
0.5818000E-01 $ New value of the parameter
n      $ Want to change any other parameters in this set?
n      $ Do you want to change values of any "fixed" parameters?
n      $ Do you want to change any loads?
n      $ Do you want to change values of allowables?
n      $ Do you want to change any factors of safety?
```

---

(Next, we want to execute BIGBOSOR4 outside the GENOPT context in order to obtain plots corresponding to the general buckling and inter-ring ("panel") buckling modes of the cylindrical shell with the T-stiffened weld lands. First, copy the two files, wcold.BEHX1 and wcold.BEHX2, into a directory from which you want to execute BIGBOSOR4 in its "stand alone" context:)

```
cp wcold.BEHX1 /home/progs/bigbosor4/workspace/. (GENERAL buckling input)
cp wcold.BEHX2 /home/progs/bigbosor4/workspace/. (INTER-RING buckling input)
```

(Go to the directory where you want to run BIGBOSOR4:)

```
cd /home/progs/bigbosor4/workspace
bigbosor4log (activate BIGBOSOR4 commands)
```

(The command, "bigbosor4log", presents the following to your screen:)

The BIGBOSOR4 commands, in the general order in which you would probably use them (except in GENOPT applications), are:

```
help4      (get information on BOSOR4.)
input       (you provide segment-by-seg. input)
assemble   (concatenates segment data files)
bigbosorall (batch run of pre, main, post proc.)
bosorplot  (batch run for generating plot files)
resetup    (input for restart run, same model)
bigrestart (batch run of main & postprocessors)
cleanup    (delete all except for .DOC file)
getsegs    (generate segment files from .DOC)
modify     (modify a segment file)
```

(Copy the BIGBOSOR4 input file for GENERAL buckling, wcold.BEHX1, into wcold.ALL because BIGBOSOR4 input files must always have the three-letter suffix, ".ALL":)

**cp wcold.BEHX1 wcold.ALL**

**bigbosorall** (Start "batch" run for GENERAL buckling. The output file that you want to inspect is called wcold.OUT. This will be a long file, so search specifically for the string, "EIGENVALUE()", typed with the "(" at the end of the string. You will find the following output there:

```
***** CRITICAL EIGENVALUE AND WAVENUMBER *****
EIGCRT= 1.9811E+00; NO. OF AXIAL HALF WAVES, NWVCRT=      2
*****
***** EIGENVALUES AND MODE SHAPES *****
EIGENVALUE(AXIAL HALF WAVES)
=====
2.0826E+00( 1)
1.9811E+00( 2) (see Fig. 6 -general buckling)
2.2501E+00( 3)
2.0171E+00( 4)
1.9941E+00( 5) (see Fig. 8 -T-stringer rolling)
2.2411E+00( 6)
2.6524E+00( 7)
3.1729E+00( 8)
3.7585E+00( 9)
4.3097E+00( 10)
=====
```

**bosorplot** (obtain a plot of the critical GENERAL buckling mode. The postscript file is called "metafile.ps" (Fig. 6))

(Execution of bosorplot presents the following to your computer screen:)

Please enter the BIGBOSOR4 case name: **wcold**

Do you want to use Xgraph or create a PostScript file? (Choose X or P) **p**

One, maybe Two moments please...

Text file(s) have been created containing plot data. The names of the files explain to a greater or lesser extent what the data represent.  
Some plot files contain data for more than one plot.

```
1)      wcold..R,Z_EIGENMODE_1--N_1
2)      wcold..R,Z_EIGENMODE_1--N_10
3)      wcold..R,Z_EIGENMODE_1--N_2      <--we want to plot this one
4)      wcold..R,Z_EIGENMODE_1--N_3
5)      wcold..R,Z_EIGENMODE_1--N_4
6)      wcold..R,Z_EIGENMODE_1--N_5
7)      wcold..R,Z_EIGENMODE_1--N_6
8)      wcold..R,Z_EIGENMODE_1--N_7
9)      wcold..R,Z_EIGENMODE_1--N_8
10)     wcold..R,Z_EIGENMODE_1--N_9
11)     wcold..R,Z_RingLocation
CR)     to QUIT
Please choose the number of the file you wish to plot: 3
Plotting: Undefomed & Deformed Axial Station as a function of Radius
```

The PostScript file, metafile.ps, has been created.  
Please choose one of the three options below:

- 1) Rename the PostScript file. This is useful if you don't have access to a PostScript printer on your machine, but you wish to save to a file so you can later transfer it to a different machine for printing.

Example: mv metafile.ps plot1.ps

- 2) Enter an "lpr" command. This is useful if your default printer is not PostScript, but there is a PostScript printer available on your system.

Example: lpr -PApplelaser metafile.ps

- 3) Press the return key. This executes the command:

lpr metafile.ps

This assumes that your default printer is a PostScript printer.

Enter your command> <CR> ("CR" means "carriage return")  
Printing PostScript plot on the default printer...

Text file(s) have been created containing plot data. The names of the files explain to a greater or lesser extent what the data represent.  
Some plot files contain data for more than one plot.

```
1)      wcold..R,Z_EIGENMODE_1--N_1
2)      wcold..R,Z_EIGENMODE_1--N_10
3)      wcold..R,Z_EIGENMODE_1--N_2
4)      wcold..R,Z_EIGENMODE_1--N_3
5)      wcold..R,Z_EIGENMODE_1--N_4
6)      wcold..R,Z_EIGENMODE_1--N_5
7)      wcold..R,Z_EIGENMODE_1--N_6
8)      wcold..R,Z_EIGENMODE_1--N_7
```

```

9)      wcold..R,Z_EIGENMODE_1--N_8
10)     wcold..R,Z_EIGENMODE_1--N_9
11)     wcold..R,Z_RingLocation
CR)      to QUIT
Please choose the number of the file you wish to plot: <CR>
-----

```

(In order to view the plot of the local buckling mode, type the command:)

**gv metafile.ps**

("gv" stands for "ghost view" a LINUX utility which presents the postscript file, metafile.ps, as a plot on your screen. If you do not have "ghost view", just send the postscript file to your printer with whatever command is appropriate at your facility for obtaining plots from postscript files.)

(Figure 6 contains the plot corresponding to an edited version of the metafile.ps file.)

[You can execute BOSORPLOT again in the same way as just listed in order to produce a new metafile.ps corresponding to "N\_5" (5 axial half waves), edit the metafile.ps file, and type, "gv metafile.ps" in order to produce Fig. 8]

(Next, "clean up" the BIGBOSOR4 files:)

```

cleanup (deletes unneeded BIGBOSOR4 files and
generates a properly annotated wcold.ALL
file and a properly annotated wcold.DOC file.

```

(Next, we wish to obtain plots of three of the INTER-RING buckling modes (Figs.10,12,14) from execution of BIGBOSOR4 and from three successive executions of BOSORPLOT:)

(Copy the BIGBOSOR4 input file for INTER-RING buckling, wcold.BEHX2, into wcold.ALL because BIGBOSOR4 input files must always have the three-letter suffix, ".ALL":)

**cp wcold.BEHX2 wcold.ALL**

```

bigbosorall (Start "batch" run for INTER-RING buckling. The output
file that you want to inspect is called wcold.OUT.
This will be a very long file, so search specifically
for the string, "EIGENVALUE()", typed with the
"(" at the end of the string. You will find the
following output there:
-----
```

```

***** CRITICAL EIGENVALUE AND WAVENUMBER *****
EIGCRT= 1.5005E+00; NO. OF AXIAL HALF WAVES, NWVCRT= 10
*****
```

```

***** EIGENVALUES AND MODE SHAPES *****
EIGENVALUE(AXIAL HALF WAVES)
=====
```

```

1.8066E+00( 1) (Fig. 10 - T-stringer rolling)
2.0553E+00( 2)
1.5850E+00( 3)
1.5114E+00( 4) (Fig. 12 - weld land skin/T-stringer buckling)
1.5931E+00( 5)
1.7159E+00( 6)
```

```
1.6312E+00(      7)  
1.5469E+00(      8)  
1.5091E+00(      9)  
1.5005E+00(     10) (Fig. 14 - T-stringer crippling)  
=====
```

```
-----  
bosorplot (obtain a plot of the "N_1" INTER-RING buckling mode.  
The postscript file is called "metafile.ps"(Fig. 10).)
```

```
bosorplot (obtain a plot of the "N_4" INTER-RING buckling mode.  
The postscript file is called "metafile.ps"(Fig. 12).)
```

```
bosorplot (obtain a plot of the "N-10" INTER-RING buckling mode.  
The postscript file is called "metafile.ps"(Fig. 14).)
```

(Next, "clean up" the BIGBOSOR4 files:)

```
cleanup (deletes unneeded BIGBOSOR4 files and  
generates properly annotated wcold.ALL  
and wcold.DOC files.)  
=====
```

Table 10

Run stream for using PANDA2 to optimize the "acreage" cylindrical shell called "nasacoldbend", to generate an input file for BIGBOSOR4 for a "huge torus" model of the optimized "nasacoldbend" shell with an embedded optimized T-stiffened weld land, and to execute BIGBOSOR4 to obtain plots such as those in Figs. 7, 9, 11, 13, 15, and 16. User's commands are in **boldface**.

---

The case, "nasacoldbend", is the same as the case called "nasaortho" (...panda2/case/nasaortho) except that design constraints have been introduced into PANDA2 to account for possible buckling of internal rings and internal sub-rings during the cold-bending fabrication process. These new constraints generate a heavier optimum design than for the case, "nasaortho", which was run before the new cold-bending ring buckling constraints existed. Please see Item No. 790 in the file, ...panda2/doc/panda2.news, for details.

With the new cold-bending ring buckling constraints in PANDA2 the optimized design has much stockier rings, as one would expect.

A new PANDA2 processor called "PANEL3" was created during an investigation of weld lands in orthogrid-stiffened cylindrical shells under uniform axial compression. (Please see Item No. 792 in the file, ...panda/doc/panda2.news for details).

In order to optimize the "acreage" cylindrical shell and to produce Figs. 7, 9, 11, 13, 15, and 16 in the paper:

Bushnell, David and Thornburgh, Robert, "Use of GENOPT and BIGBOSOR4 to optimize weld lands in axially compressed stiffened cylindrical shells and evaluation of the optimized designs by STAGS", AIAA Paper xxxx, 1st AIAA Structures, Structural Dynamics, and Materials Conference, Orlando, Florida, April 2010

Execute the following run stream. It is assumed here that the name of the "home" directory is "/home/progs".

---

(First, obtain an optimum "acreage" design. Go to a directory where you want to execute PANDA2:)

**cd /home/progs/work7**

(Obtain the input files for the "nasacoldbend" case from the file: /home/progs/panda2/case/nasacoldbend/nasacoldbend.tar.gz:)

```
cp /home/progs/panda2/case/nasacoldbend/nasacoldbend.tar.gz .
gunzip nasacoldbend.tar.gz
tar xvf nasacoldbend.tar
```

(This sequence of commands produces the following files:

```
6841 Apr 20 2009 nasacoldbend.BEG
1677 Mar  5 05:33 nasacoldbend.CHG
2270 Apr 20 2009 nasacoldbend.DEC
6483 Jan  4 07:53 nasacoldbend.OPT
1039 Dec  9 05:31 nasacoldbend.PAN
6483 Dec  6 08:11 nasacoldbend.imperfect.OPT
200211 Mar  5 07:02 nasacoldbend.optimized.opm
1039 Mar  5 06:56 nasacoldbend.panel3.genbuck.PAN
1039 Mar  5 06:57 nasacoldbend.panel3.genbuck.smearedstringers.PAN
1039 Mar  5 06:58 nasacoldbend.panel3.interrngbuck.PAN
4050 Dec  6 07:47 nasacoldbend.perfect.OPT
```

```
3983 Jan  4 07:58 nasacoldbend.readme
31507 Apr 20 2009 nasacoldbend.superopt1.ps
30380 Apr 20 2009 nasacoldbend.superopt2.ps
```

---

(Execute PANDA2:)

```
panda2log (activate the PANDA2 set of commands)
begin      (use nasacoldbend.BEG as the input file)
setup       (PANDA2 sets up matrix templates)
decide     (use nasacoldbend.DEC as the input file)
mainsetup  (use nasacoldbend.OPT as the input file.
            Make sure that NPRINT = 0 and ITYPE = 1)
superopt   (obtain a "global" optimum design)
```

(Inspect the nasacoldbend.OPP file.)

```
chooseplot(choose to plot only the objective vs design iterations)
diplot    (obtain the nasacoldbend.5.ps file)
gv nasacoldbend.5.ps      (obtain plot of objective versus design
                           iteration on your computer screen)
change    (change the stringer spacing so that there are an
           integral number of stringers over 360 degrees of the
           circumference of the cylindrical shell. Change the
           ring spacing so that there are an integral number of
           rings over the axial length of the cylindrical shell.
           In this particular case, B(STR) = 2.2676 and
           B(RNG) = 13.75. Don't forget to change B2(STR) as
           appropriate.)
setup     (PANDA2 sets up matrix templates)
mainsetup (use a modified form of the nasacoldbend.OPT file:
            change ITYPE from 1 to 2)
pandaopt  (execute the PANDA2 mainprocessor in the "fixed
            design" mode, ITYPE=2, in order to see if you need
            to do more optimization now that you have changed
            the stringer and ring spacings, B(STR) and B(RNG).)
```

(Inspect the nasacoldbend.OPM file to see if there are any unacceptably negative margins or if there are no nearly critical margins. If there are you may want to do more optimization. If you decide to do more optimization, do the following:)

```
decide    (use a modified form of the nasacoldbend.DEC file:
            eliminate the stringer spacing and the ring spacing as
            decision variables.)
mainsetup (use nasacoldbend.OPT with ITYPE = 1)
superopt  (obtain a new "global" optimum design with the
            stringer and ring spacings, B(STR) and B(RNG),
            held at their "integral" values established above
            by the previous execution of "CHANGE")
```

(Inspect the nasacoldbend.OPP file.)

```
chooseplot(choose to plot only the objective vs design iterations)
diplot    (obtain the nasacoldbend.5.ps file)
gv nasacoldbend.5.ps      (obtain plot of objective versus design
                           iteration on your computer screen)
mainsetup (use a modified form of the nasacoldbend.OPT:
            change ITYPE from 1 to 2)
```

```
pandaopt (execute the PANDA2 mainprocessor in the "fixed  
design" mode, ITYPE=2)
```

(Inspect the nasacoldbend.OPM file. The optimum design and the design margins are listed in Table 5.)

```
change (use nasacoldbend.CHG as the input file.  
The purpose here is to preserve the optimized design.)
```

-----  
Next, you want to generate a plot such as that in Fig. 7.

[Do general buckling of the optimized "nasacoldbend" acreage (Table 5) with the embedded optimized T-stiffened weld land (Table 6). Use discrete "acreage" stringers and smeared "acreage" rings in the BIGBOSOR4 model.]

```
cp nasacoldbend.panel3.genbuck.PAN nasacoldbend.PAN
```

```
panel3 (use nasacoldbend.PAN as the input file.  
This "panel3" command generates valid input for  
BIGBOSOR4: nasacoldbend.ALL . This file is not  
properly annotated at this time. See below.)
```

-----  
(Go to a directory where you want to run BIGBOSOR4:)

```
cd /home/progs/work1  
cp /home/progs/work7/nasacoldbend.ALL .
```

(Execute BIGBOSOR4:)

```
bigbosor4log (activate the BIGBOSOR4 set of commands)  
bigbosorall (use nasacoldbend.ALL as the input file)  
cleanup (clean up BIGBOSOR4 files and obtain a  
properly annotated form of the nasacoldbend.ALL  
file.)
```

(Edit the properly annotated nasacoldbend.ALL file as follows:

1. add the string, "ixprism" to the title card so that BIGBOSOR4 will use the kinematic relationships for a true prismatic shell.

2. insert a new record immediately after the title record:

```
68.75 $ AXIALL = axial length of the cylindrical shell
```

For example:

```
nasacoldbend ixprism  
68.75 $ AXIALL= length of the prismatic shell
```

3. Search for the string, "GLOBAL" in the properly annotated nasacoldbend.ALL file.

4. Change the input data, N0B, NMINB, NMAXB, INCRB to values appropriate for the number of half waves along the axis of the cylindrical shell. For example, you might provide the following:

```
1 $ N0B = starting number of axial half waves(buckling analysis)  
1 $ NMINB = minimum number of axial half waves (buckling analysis)  
9 $ NMAXB = maximum number of axial half waves (buckling analysis)  
1 $ INCRB = increment in number of axial half waves (buckling)
```

if you want to search for the critical general buckling load in the range from 1 to 9 axial half waves in the prismatic shell.)

(Execute BIGBOSOR4 again, this time with use of the true prismatic shell model and with the proper values for N0B, NMINB, NMAXB, INCRB.)

**bigbosorall** (use the edited nasacoldbend.ALL as the input file)

(Inspect the nasacoldbend.OUT file: search for "EIGENVALUE(". You will find the following output:)

```
***** CRITICAL EIGENVALUE AND WAVENUMBER *****
EIGCRT= 1.9484E+00; NO. OF AXIAL HALF WAVES, NWVCRT=      5
*****
***** EIGENVALUES AND MODE SHAPES *****
EIGENVALUE(AXIAL HALF WAVES)
=====
2.1287E+00(    1)
2.0079E+00(    2) <-Fig. 7
2.1242E+00(    3)
1.9714E+00(    4)
1.9484E+00(    5) <-Fig. 9
2.1895E+00(    6)
2.5905E+00(    7)
3.0973E+00(    8)
3.6672E+00(    9)
=====

bosorplot (get plot as appropriate, including that in Fig. 7)
bosorplot (get plot as appropriate, including that in Fig. 9)

cleanup (clean up "nasacoldbend" BIGBOSOR4 files)
```

(Follow an analogous procedure in order to obtain Figs. 11, 13, 15, and 16.)

---

#### Some notes on a 9 March, 2010 derivation of an optimum “nasacoldbend” design:

The SUPEROPT run led to a somewhat different optimum design from that listed in Table 5. The optimized design without regard to an integral number of acreage stringers in 360 degrees of circumference and without regard to an integral number of acreage rings over the axial length, 68.75 inches is as follows:

```
Optimum design of the "acreage" cylindrical shell determined with
 1 $ Choose ICONSV = -1 or 0 or 1 or H(elp), ICONSV:
 0.125 $ Initial buckling modal general imperfection amplitude, Wimpg2(1)
 -0.125 $ Initial buckling modal general imperfection amplitude, Wimpg2(2)
```

DIMENSIONS OF THE OPTIMIZED DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 2.5360E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 8.4524E-01 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 1.0515E+00 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 5.9869E-02 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 9.1343E-02 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 1.5535E+01 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 1.0038E+00 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.9375E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

```
OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION:
VAR. STR/ SEG. LAYER CURRENT
NO. RNG NO. NO. VALUE DEFINITION
0      0     1.086E+02 WEIGHT OF THE ENTIRE PANEL (180 deg. of circ.)
```

A second SUPEROPT run in which the acreage ring spacing is set equal to 13.75 inches (exactly five ring bays in the 68.75-inch length of the cylindrical shell), and B(RNG) is no longer included as a decision variable in "DECIDE" yields the following optimized design:

DIMENSIONS OF THE OPTIMIZED DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 2.4999E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 8.3322E-01 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 1.0166E+00 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 6.0351E-02 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 8.9811E-02 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 1.3750E+01 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 9.6843E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.8445E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION:

| VAR. | STR/ SEG. | LAYER     | CURRENT  |            |
|------|-----------|-----------|--|------------|
| NO.  | RNG       | NO.       | NO.  | DEFINITION |
| 0    | 0         | 1.082E+02 | WEIGHT OF THE ENTIRE PANEL (180 deg. of circ.) |            |

A third SUPEROPT run in which the acreage ring spacing is set equal to 13.75 inches, and B(RNG) is no longer included as a decision variable, and the acreage stringer spacing is set equal to 2.4925 (exactly 121 acreage stringers in 360 degrees of circumference), and B(STR) is no longer included as a decision variable, and B2(STR) is set equal to  $0.3333 \times 2.4925 = 0.83075$ , and the linking expression involving B(STR) and B2(STR) is deleted in "DECIDE" yields the following optimized design:

DIMENSIONS OF THE OPTIMIZED DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 2.4925E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 8.3075E-01 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 1.0257E+00 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 6.1682E-02 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 8.8461E-02 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 1.3750E+01 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 9.2656E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |
| 9        | 1.7630E-01 | T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3 |

OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION:

| VAR. | STR/ SEG. | LAYER     | CURRENT  |            |
|------|-----------|-----------|--|------------|
| NO.  | RNG       | NO.       | NO.  | DEFINITION |
| 0    | 0         | 1.083E+02 | WEIGHT OF THE ENTIRE PANEL (180 deg. of circ.) |            |

The optimum design listed in Table 5, that is, the following design:

DIMENSIONS OF THE OPTIMIZED DESIGN...

| VARIABLE | CURRENT    | DEFINITION  |
|----------|------------|---|
| NUMBER   | VALUE      |   |
| 1        | 2.2676E+00 | B(STR):stiffener spacing, b: STR seg=NA, layer=NA       |
| 2        | 7.5902E-01 | B2(STR):width of stringer base, b2 (must be > 0, see    |
| 3        | 9.8977E-01 | H(STR):height of stiffener (type H for sketch), h: S    |
| 4        | 5.8191E-02 | T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1 |
| 5        | 8.6462E-02 | T(2 )(STR):thickness for layer index no.(2 ): STR seg=3 |
| 6        | 1.3750E+01 | B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA       |
| 7        | 0.0000E+00 | B2(RNG):width of ring base, b2 (zero is allowed): RNG   |
| 8        | 9.7173E-01 | H(RNG):height of stiffener (type H for sketch), h: R    |

```
9     1.8576E-01    T(3 )(RNG):thickness for layer index no.(3 ): RNG seg=3
```

```
OPTIMIZED VALUE OF THE OBJECTIVE FUNCTION:  
VAR. STR/ SEG. LAYER CURRENT  
NO. RNG NO. NO. VALUE DEFINITION  
0     0   1.074E+02 WEIGHT OF THE ENTIRE PANEL (180 deg. of circ.)
```

is still feasible. No recent changes in PANDA2 affect that outcome. However, a “global” optimum design is difficult to find because there are abrupt changes in the critical general buckling mode shape during design iterations. This leads to abrupt changes in the number of critical margins from iteration to iteration, as follows, for example:

| Iter-              | Objective  | Design          | Quality | Critical | Margins |
|--------------------|------------|-----------------|---------|----------|---------|
| action             |            |                 | Load    | Load     |         |
| No.                |            |                 | set 1   | set 2    |         |
|                    |            |                 | +0.125  | -0.125   | = Wimp  |
| -----PANDAOPT----- |            |                 |         |          |         |
| 439                | 1.0830E+02 | ALMOST FEASIBLE | ( 5)    | ( 8)     |         |
| 440                | 1.0791E+02 | MOSTLY UNFEASIB | ( 11)   | ( 10)    |         |
| 441                | 1.0955E+02 | MILDLY UNFEASIB | ( 5)    | ( 5)     |         |
| 442                | 1.0892E+02 | FEASIBLE        | ( 2)    | ( 4)     |         |
| 443                | 1.0839E+02 | MOSTLY UNFEASIB | ( 13)   | ( 12)    |         |
| 444                | 1.0968E+02 | MOSTLY UNFEASIB | ( 10)   | ( 10)    |         |
| -----PANDAOPT----- |            |                 |         |          |         |
| 445                | 1.0968E+02 | MOSTLY UNFEASIB | ( 10)   | ( 10)    |         |
| 446                | 1.1155E+02 | ALMOST FEASIBLE | ( 2)    | ( 3)     |         |
| 447                | 1.1073E+02 | FEASIBLE        | ( 2)    | ( 0)     |         |
| 448                | 1.0905E+02 | MOSTLY UNFEASIB | ( 13)   | ( 11)    |         |
| 449                | 1.0971E+02 | FEASIBLE        | ( 2)    | ( 0)     |         |
| 450                | 1.0878E+02 | MOSTLY UNFEASIB | ( 13)   | ( 11)    |         |
| -----PANDAOPT----- |            |                 |         |          |         |
| 451                | 1.0878E+02 | MOSTLY UNFEASIB | ( 13)   | ( 11)    |         |
| 452                | 1.1086E+02 | FEASIBLE        | ( 2)    | ( 0)     |         |
| 453                | 1.0898E+02 | MOSTLY UNFEASIB | ( 13)   | ( 11)    |         |
| 454                | 1.0952E+02 | MOSTLY UNFEASIB | ( 11)   | ( 10)    |         |
| 455                | 1.4238E+02 | FEASIBLE        | ( 1)    | ( 0)     |         |
| 456                | 1.4069E+02 | UNKNOWN FEASIB. | ( 1)    | ( 0)     |         |
| 457                | 1.3936E+02 | FEASIBLE        | ( 1)    | ( 0)     |         |
| -----              |            |                 |         |          |         |

The list just presented is part of a nasacoldbend.OPP file generated from an execution of SUPEROPT.  
=====

Table 11

Run stream for executing STAGS for obtaining linear buckling loads in order to get imperfection shapes followed by nonlinear static runs to get collapse. The user's commands are in **boldface**.

---

PART 1 Use the PANDA2 processor called STAGSUNIT to generate the two input files for STAGS: \*.bin and \*.inp

Suppose you have an optimized "nasacoldbend" acreage design, such as that listed in Table 5, and now you want to generate automatically STAGS models such as those shown in Figs. 18 and 20.

First obtain the optimized "nasacoldbend" acreage as described in the previous table. Then do the following to get the STAGS model displayed in Fig. 18.

The assumption here is that the "home" directory is "/home/progs"

(Go to directory where you want to run PANDA2:)

**cd /home/progs/work7**

(Execute PANDA2:)

```
panda2log      (activate the set of PANDA2 commands)
begin          (use nasacoldbend.BEG as the input file)
change          (use nasacoldbend.CHG as the input file.
                 This resurrects the optimum design with ICONSV = 1)
setup           (PANDA2 gets matrix templates)
decide          (use nasacoldbend.DEC as the input file)
mainsetup       (use nasacoldbend.OPT with ITYPE = 2,
                 with only one load set, and with the amplitudes of
                 all initial imperfections set to zero.)
pandaopt        (execute PANDA2 in the "fixed design" mode.)
```

**cp nasacoldbend.strsmeared.stg nasacoldbend.STG**

(A list of the input for STAGSUNIT corresponding to Fig. 18, the file called "nasacoldbend.STG", follows:)

---

```
n      $ Do you want a tutorial session and tutorial output?
1      $ Choose type of STAGS analysis (1,3,4,5,6), INDIC
0      $ Restart from ISTARTth load step (0=1st nonlinear soln), ISTART
1.300000 $ Local buckling load factor from PANDA2, EIGLOC
y      $ Are the dimensions in this case in inches?
0      $ Nonlinear (0) or linear (1) kinematic relations?, ILIN
1      $ Type 1 for closed (360-deg) cyl. shell, 0 otherwise, ITOTAL
68.75000 $ X-direction length of the STAGS model of the panel: XSTAGS
301.5929 $ Panel length in the plane of the screen, L2
y      $ Is the nodal point spacing uniform along the stringer axis?
101    $ Number of nodes in the X-direction: NODEX
131    $ Number of nodes in the Y-direction: NODEY
-2219.000 $ Resultant (e.g. lb/in) normal to the plane of screen, Nx
0      $ Resultant (e.g. lb/in) in the plane of the screen, Ny
0      $ In-plane shear in load set A, Nxy
0      $ Normal pressure in STAGS model in Load Set A, p
```

```

0 $ Resultant (e.g. lb/in) normal to the plane of screen, Nx0
0 $ Resultant (e.g. lb/in) in the plane of the screen, Ny0
0 $ Normal pressure in STAGS model in Load Set B, p0
1.000000 $ Starting load factor for Load System A, STLD(1)
0.000000 $ Load factor increment for Load System A, STEP(1)
1.000000 $ Maximum load factor for Load System A, FACM(1)
0 $ Starting load factor for Load System B, STLD(2)
0 $ Load factor increment for Load System B, STEP(2)
0 $ Maximum load factor for Load System B, FACM(2)
1 $ How many eigenvalues do you want? NEIGS
480 $ Choose element type: 480 or 410 or 940
n $ Have you obtained buckling modes from STAGS for this case?
133 $ Number of stringers in STAGS model of 360-deg. cylinder
6 $ Number of rings in the STAGS model of the panel
y $ Are there rings at the ends of the panel?
1 $ Number of finite elements between adjacent stringers
5 $ Number of finite elements between adjacent rings
3 $ Stringer model: 1 or 2 or 3 or 4 or 5(Type H(elp))
3 $ Ring model: 1 or 2 or 3 or 4 or 5 (Type H(elp))
0 $ Reference surface of cyl: 1=outer, 0=middle, -1=inner
n $ Do you want to use fasteners (they are like rigid links)?
y $ Are the stringers to be "smeared out"?
n $ Are the rings to be "smeared out"?
5 $ Number of nodes over height of stiffener webs, NODWEB
5 $ Number of nodes over width of stringer flange, NDFLGS
5 $ Number of nodes over width of ring flange, NDFLGR
n $ Do you want stringer(s) with a high nodal point density?
n $ Do you want ring(s) with a high nodal point density?
n $ Is there plasticity in this STAGS model?
y $ Do you want to use the "least-squares" model for torque?
n $ Is stiffener sidesway permitted at the panel edges?
0 $ Edges parallel to screen (0) in-plane deformable; (1) rigid
0 $ Stringer web axial displacement index, IBCX0XL=0 or 1
-----
```

(Execute STAGSUNIT:)

**stagsunit** (use the nasacoldbend.STG just listed as the input file)

(STAGSUNIT generates two files, nasacoldbend.bin and nasacoldbend.inp. The nasacoldbend.bin file follows:)

```

nasacoldbend STAGS INPUT FOR STIFFENED CYL.(STAGSUNIT=SHELL UNITS)
1, $ INDIC=1 is bifur.buckling; INDIC=3 is nonlinear BEGIN B-1
1, $ IPOST=1 means save displacements every IPOSTth step
0, $ ILIST =0 means normal batch-oriented output
0, $ ICOR =0 means projection in; 1 means not in.
1, $ IMPTHE=index for imperfection theory.
0, $ ICHIST=index for crack archive option
0, $ IFLU =0 means no fluid interaction.
-1 $ ISOLVR= 0 means original solver; -1 new solver.END B-1 rec
1.000E+00, $ STLD(1) = starting load factor, System A. BEGIN C-1 rec.
0.000E+00, $ STEP(1) = load factor increment, System A
1.000E+00, $ FACM(1) = maximum load factor, System A
0.000E+00, $ STLD(2) = starting load factor, System B
0.000E+00, $ STEP(2) = load factor increment, System B
0.000E+00, $ FACM(2) = maximum load factor, System B
0 $ ITEMPI =0 means no thermal loads. END C-1 rec.
10000, $ NSEC= number of CPU seconds before run termination
```

```

0., $ DELEV is eigenvalue error tolerance (0=.00001)
0 $ IPRINT=0 means print modes, iteration data, END D-2 rec.
1, $ NEIGS= number of eigenvalues sought. BEGIN D-3 rec.
9.100E-01, $ SHIFT=initial eigenvalue shift
0.000E+00, $ EIGA =lower bound of eigenvalue range
0.000E+00 $ EIGB =upper bound of eigenvalue range. END D-3 rec.
-----
```

(The nasacoldbend.inp file is too long to list here.)

---

## PART 2 Execute STAGS in the linear buckling branch (INDIC = 1)

Next copy the two files, nasacoldbend.bin and nasacoldbend.inp, to a directory where you want to run STAGS. At the writer's facility type the following:

```

ftp feynman
bush
(password)
cd /home/bush
put nasacoldbend.bin
put nasacoldbend.inp
bye
telnet feynman
bush
(password)
cd /home/bush
source /home/weiler/stags5/prc/initialize (this activates STAGS commands)
stags -b nasacoldbend (execute STAGS s1 and s2)
-----
```

(Inspect the nasacoldbend.out2 file. Find the following output:)

---

```

CONVERGENCE HAS BEEN OBTAINED FOR EIGENVALUES 1 THROUGH 1
CRITICAL LOAD FACTOR COMBINATION
NO. EIGENVALUE LOAD SYSTEM A LOAD SYSTEM B @DOF
1 2.227241E+00 2.227241E+00 0.000000E+00 19767
-----
```

(Get a plot of the buckling mode:)

(The following is the input data for the STAGS post-processor called STAPL:)

---

```

linear buckling of perfect shell from STAGS
1 0 1 0 $PL-2 NPILOT,IPREP,IPRS,KDEV
1 0 4 0 1 $PL-3 KPLOT,NUNIT,ITEM,STEP,MODE
0.0 3 $PL-5 DSSCALE,NROTS
1 -0.35840000E+02 $PL-6 IROT,ROT
2 -0.13140000E+02 $PL-6 IROT,ROT
3 0.35630001E+02 $PL-6 IROT,ROT
-----
```

(Execute STAPL:)

```
stapl nasacoldbend
```

(STAPL produces the file, nasacoldbend.pdf. You can see the plot by typing:)

**acoread nasacoldbend.pdf**

(You will see Fig. 18.)

---

PART 3 Obtain nonlinear collapse of the imperfect nasacoldbend acreage, where the imperfection shape is given by nasacoldbend.pdf (Fig. 18) with an amplitude, Wimp = 0.125 inch.

(Start by doing a nonlinear static equilibrium STAGS run (INDIC = 3). The file, nasacoldbend.bin file is as follows:)

---

```
optimized imperfect shell, nonlinear theory (INDIC=3)
3, $ INDIC=1 is bifur.buckling; INDIC=3 is nonlinear BEGIN B-1
1, $ IPOST=1 means save displacements every IPOSTth step
0, $ ILIST =0 means normal batch-oriented output
0, $ ICOR =0 means projection in; 1 means not in.
1, $ IMPTHE=index for imperfection theory.
0, $ IOPTIM=0 means bandwith optimization will be performed
0, $ IFLU =0 means no fluid interaction.
-1 $ ISOLVR= 0 means original solver; -1 new solver.END B-1 rec
0.05, $ STLD(1) = starting load factor, System A. BEGIN C-1 rec.
0.05, $ STEP(1) = load factor increment, System A
1.0, $ FACM(1) = maximum load factor, System A
0.000E+00, $ STLD(2) = starting load factor, System B
0.000E+00, $ STEP(2) = load factor increment, System B
0.000E+00, $ FACM(2) = maximum load factor, System B
0 $ ITEMP =0 means no thermal loads. END C-1 rec.
0, $ ISTART=restart from ISTARTth load step. BEGIN D-1 rec.
3500,$ NSEC= number of CPU seconds before run termination
7,$ NCUT = number of times step size may be cut
-20, $ NEWT = number of refactorings allowed
-1,$ NSTRAT=-1 means path length used as independent parameter
0.0001,$ DELX=convergence tolerance
0. $ WUND = 0 means initial relaxation factor =1.END D-1 rec.
0, 4, 0 $ NPATH=0: Riks method, NEIGS=no.of eigs, NSOL=0: contin. ET-1
```

---

(Edit the nasacoldbend.inp file as follows:)

1. Change NIMPFS from 0 to 1

2. Immediately following the record:

C Begin B-4, B-5 input data, if any...

add the following record:

0.125 0 1 1 \$B-5 WIMPFA, IMSTEP, IMMODE, IMRUN (1st imperf.)

(Execute STAGS:)

**stags -b nasacoldbend**

(The following occurs as part of the nasacoldbend.out2 file:)

---

MAXIMUM NUMBER OF ITERATIONS

CONVERGENCE HAS BEEN OBTAINED FOR EIGENVALUES 1 THROUGH 1  
CONVERGENCE CRITERION HAS NOT BEEN SATISFIED FOR EIGENVALUES 2 THROUGH 4

CRITICAL LOAD FACTOR COMBINATION

| NO. | EIGENVALUE   | LOAD SYSTEM A | LOAD SYSTEM B | @DOF  |
|-----|--------------|---------------|---------------|-------|
| 1   | 1.048585E+00 | 2.048585E+00  | 0.000000E+00  | 5043  |
| 2   | 1.083075E+00 | 2.083076E+00  | 0.000000E+00  | 34005 |

|   |              |              |              |       |
|---|--------------|--------------|--------------|-------|
| 3 | 1.088306E+00 | 2.088306E+00 | 0.000000E+00 | 33813 |
| 4 | 1.096431E+00 | 2.096431E+00 | 0.000000E+00 | 5139  |

(lines skipped to save space)

LIST OF LOAD STEPS AND LOAD FACTORS

| STEP | PA           | PB           | PX |
|------|--------------|--------------|----|
| 0    | 0.500000E-01 | 0.000000E+00 |    |
| 1    | 0.500000E-01 | 0.000000E+00 |    |
| 2    | 0.100000E+00 | 0.000000E+00 |    |
| 3    | 0.137367E+00 | 0.000000E+00 |    |
| 4    | 0.193174E+00 | 0.000000E+00 |    |
| 5    | 0.276271E+00 | 0.000000E+00 |    |
| 6    | 0.399243E+00 | 0.000000E+00 |    |
| 7    | 0.578704E+00 | 0.000000E+00 |    |
| 8    | 0.831045E+00 | 0.000000E+00 |    |
| 9    | 0.100000E+01 | 0.000000E+00 |    |

(Do another nonlinear static run, starting at Step 9 and load level 1.0, etc. etc.)

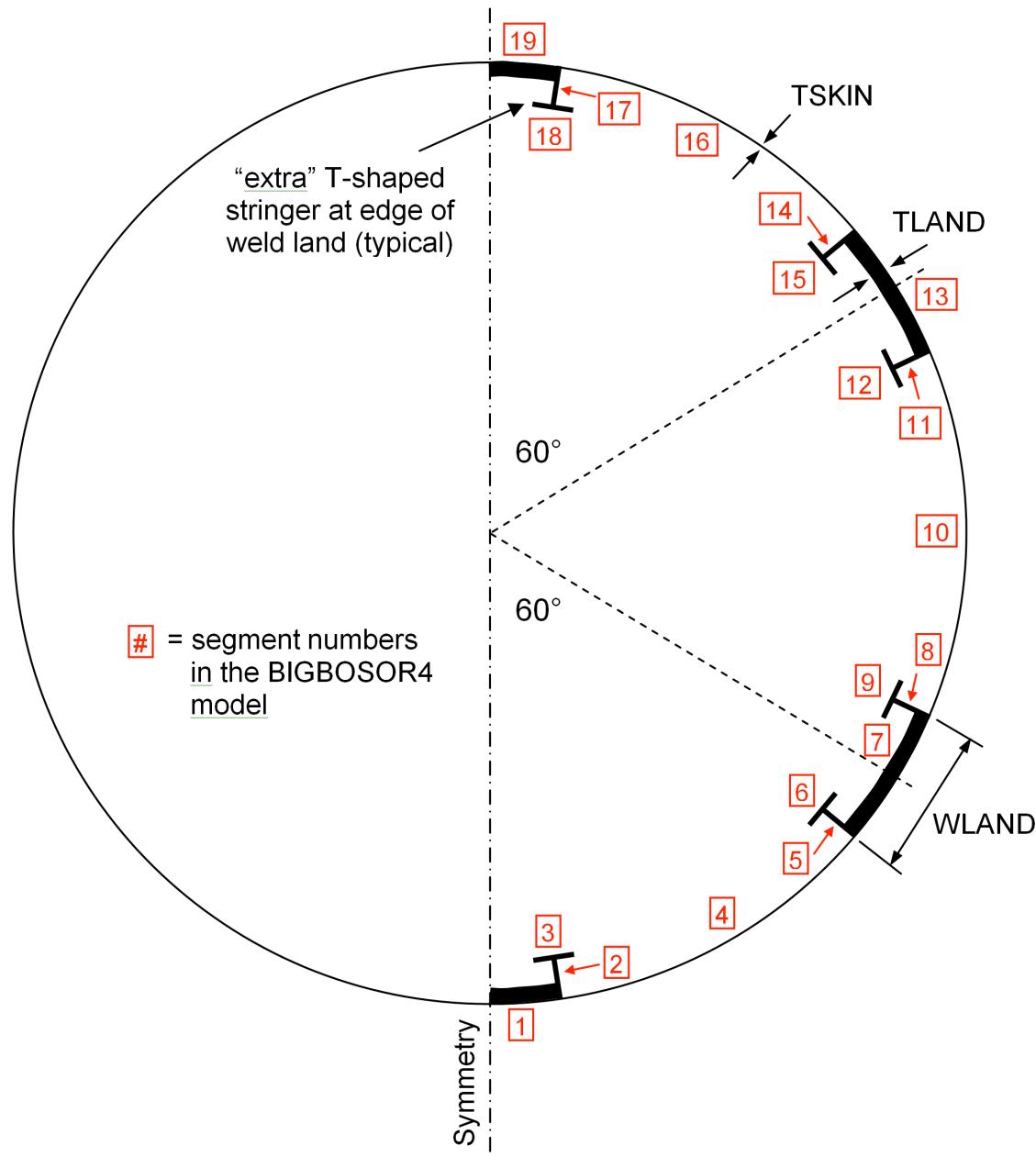


Fig .1 Example in which there are T-stiffened weld lands spaced at intervals of 60 degrees. Results in this paper correspond to weld lands spaced at intervals of 120 degrees.

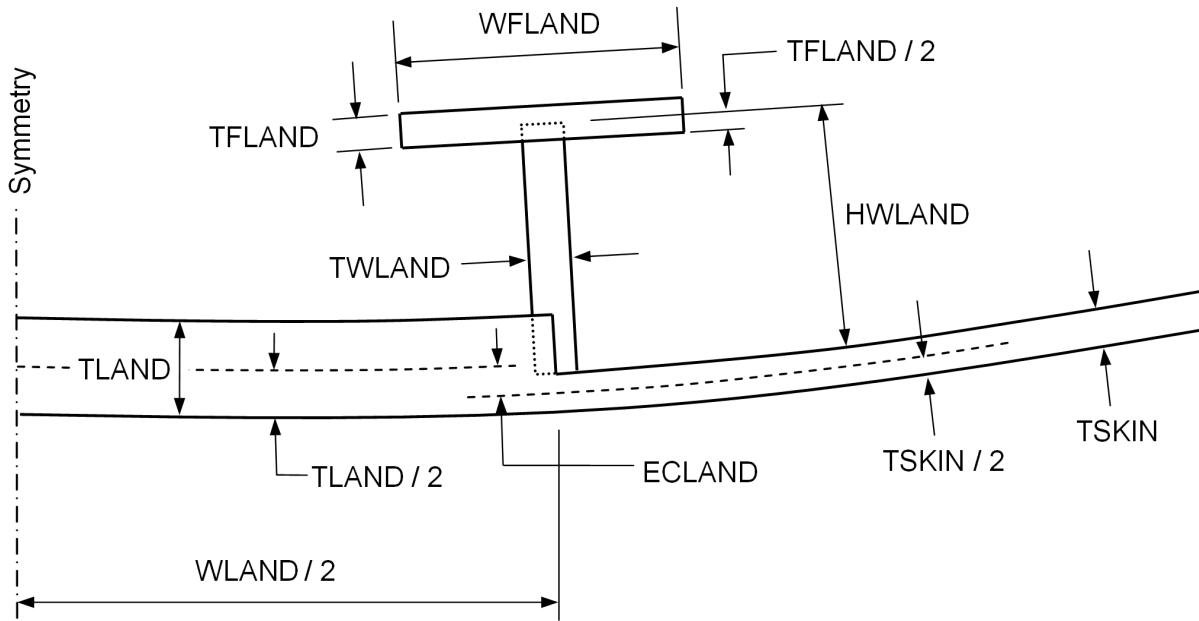


Fig. 2 Half of a T-stiffened weld land showing the decision variables for the “wcold” optimization with the use of GENOPT/BIGBOSOR4 [6,5]. Although  $TSKIN$  is a decision variable, it has very tight lower and upper bounds so that during “wcold” optimization cycles  $TSKIN$  will not differ materially from the optimized value determined during the previous optimization of the “acreage” into which the T-stiffened weld land is embedded.  $ECLAND$  is not a decision variable but is established by a linking expression that forces the outer surfaces of the curved weld land plate of thickness  $TLAND$  and the acreage cylindrical shell of thickness  $TSKIN$  always to be flush during optimization cycles.

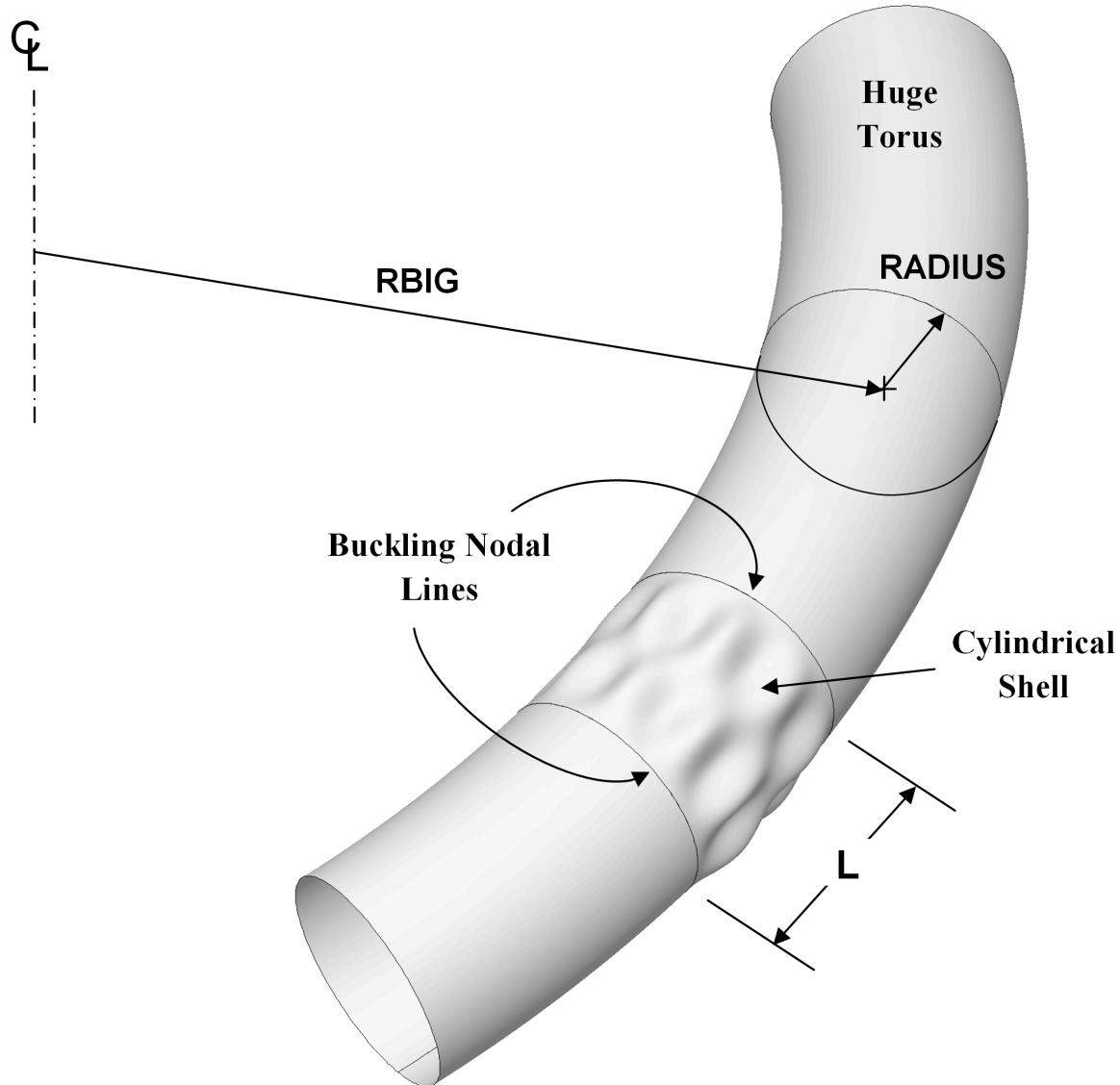


Fig. 3a Schematic of a “huge torus” model. For most “huge torus” models, a good choice of RBIG is  $RBIG = 100xL/\pi$ . The cylindrical shells studied here have  $RADIUS = 48$  inches. For the “true prismatic” shell model the kinematic relationships introduced recently into BIGBOSOR4 correspond essentially to  $RBIG = \infty$ .

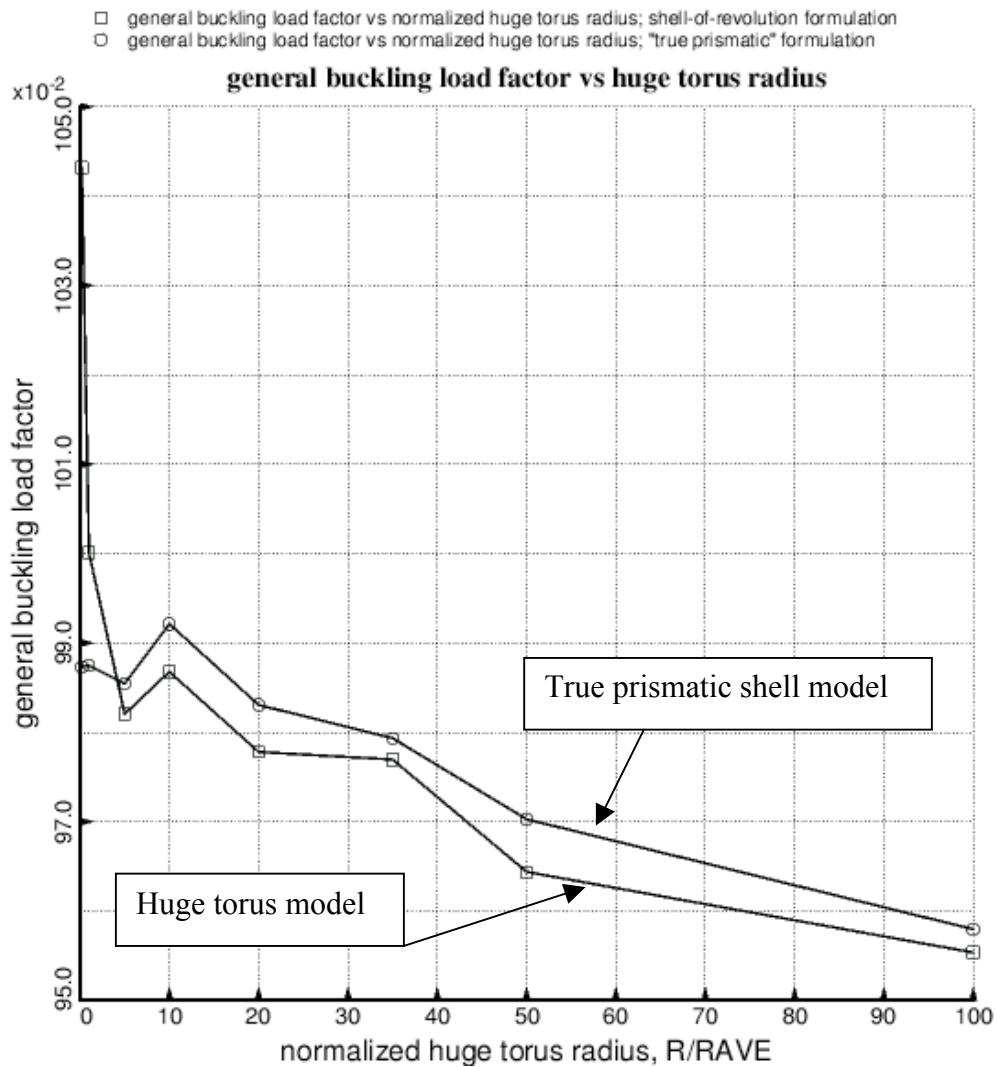


Fig. 3b This figure shows a disadvantage of the “huge torus” model. With  $R/R_{RAVE}$  too small the buckling load factor is unconservative. With  $R/R_{RAVE}$  too large roundoff error prevents the determination of an accurate value. The “true prismatic” formulation is better than the “huge torus” formulation because it behaves well for small  $R/R_{RAVE}$ . Unfortunately, it exhibits the same kind of inaccuracy for large  $R/R_{RAVE}$ . The “true prismatic formulation was used to produce all the “nasacoldbend” and “wcold” results in this paper.

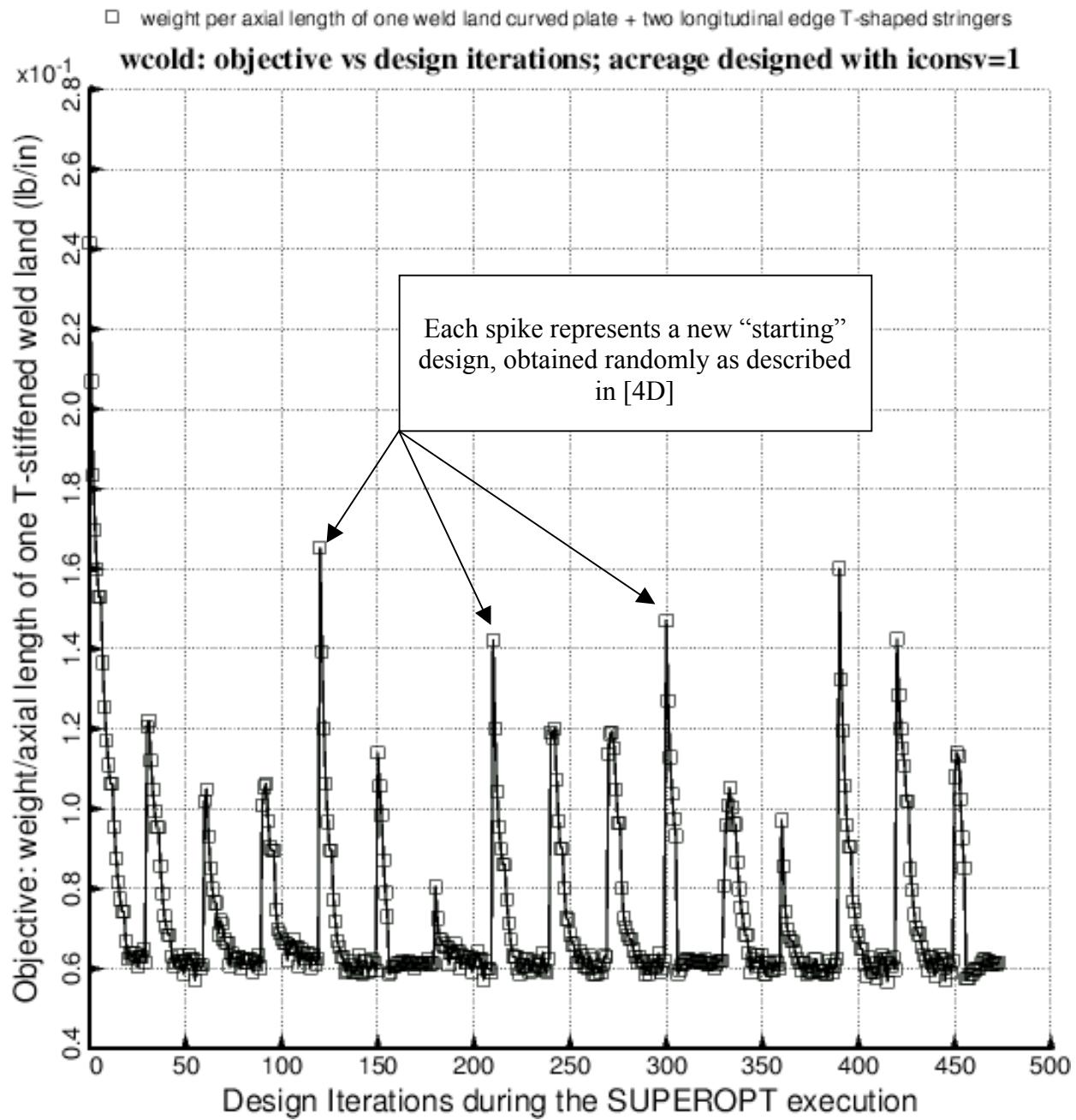


Fig. 4 Evolution of the objective during an execution of SUPEROPT [4D]

-- Undefomed; This is the optimized orthogrid cylindrical shell without weld lands: wcold.BEHX0  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = 1

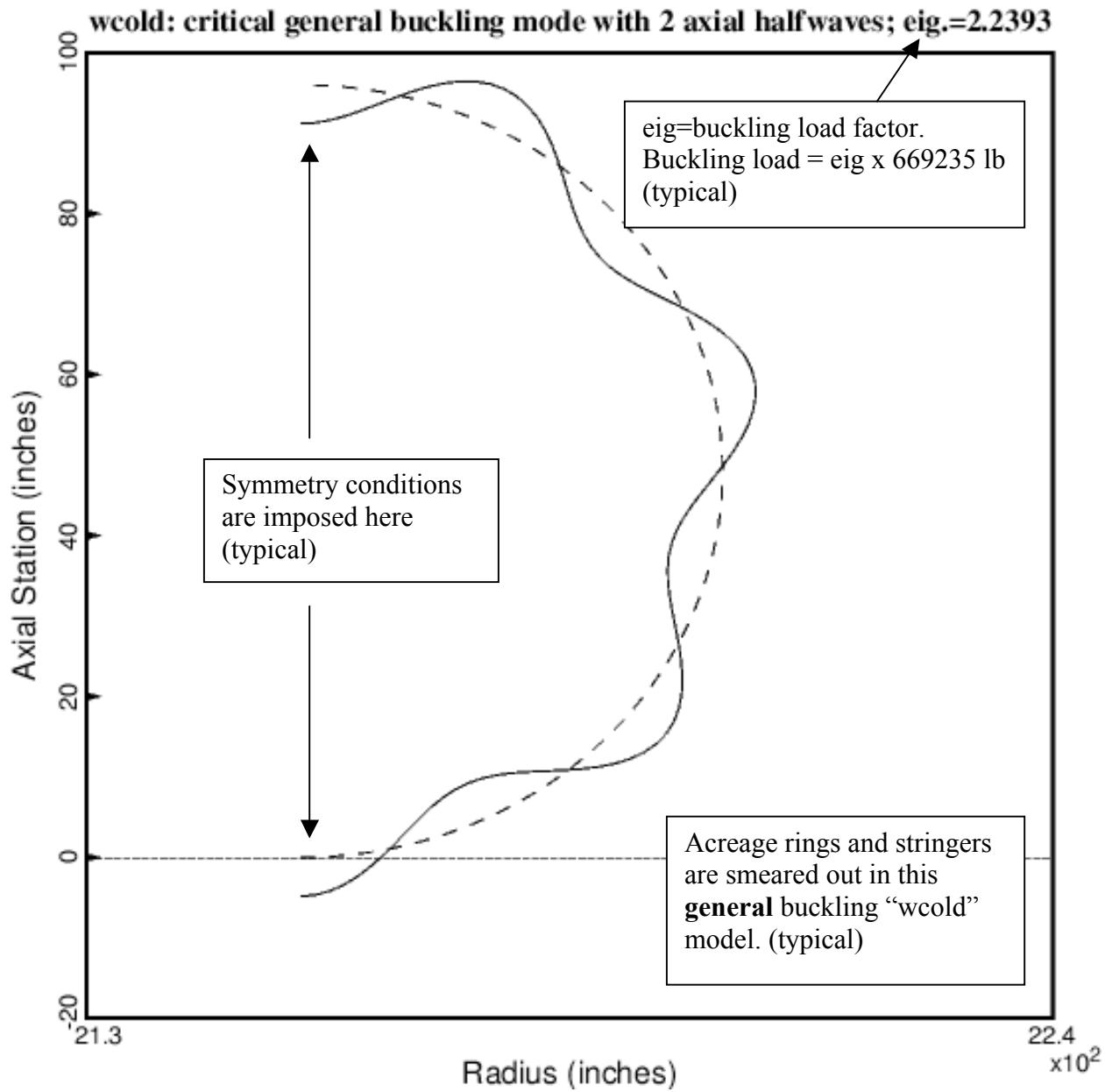


Fig. 5 General buckling of optimized “acreage” without any weld land.

-- Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX1  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = 1

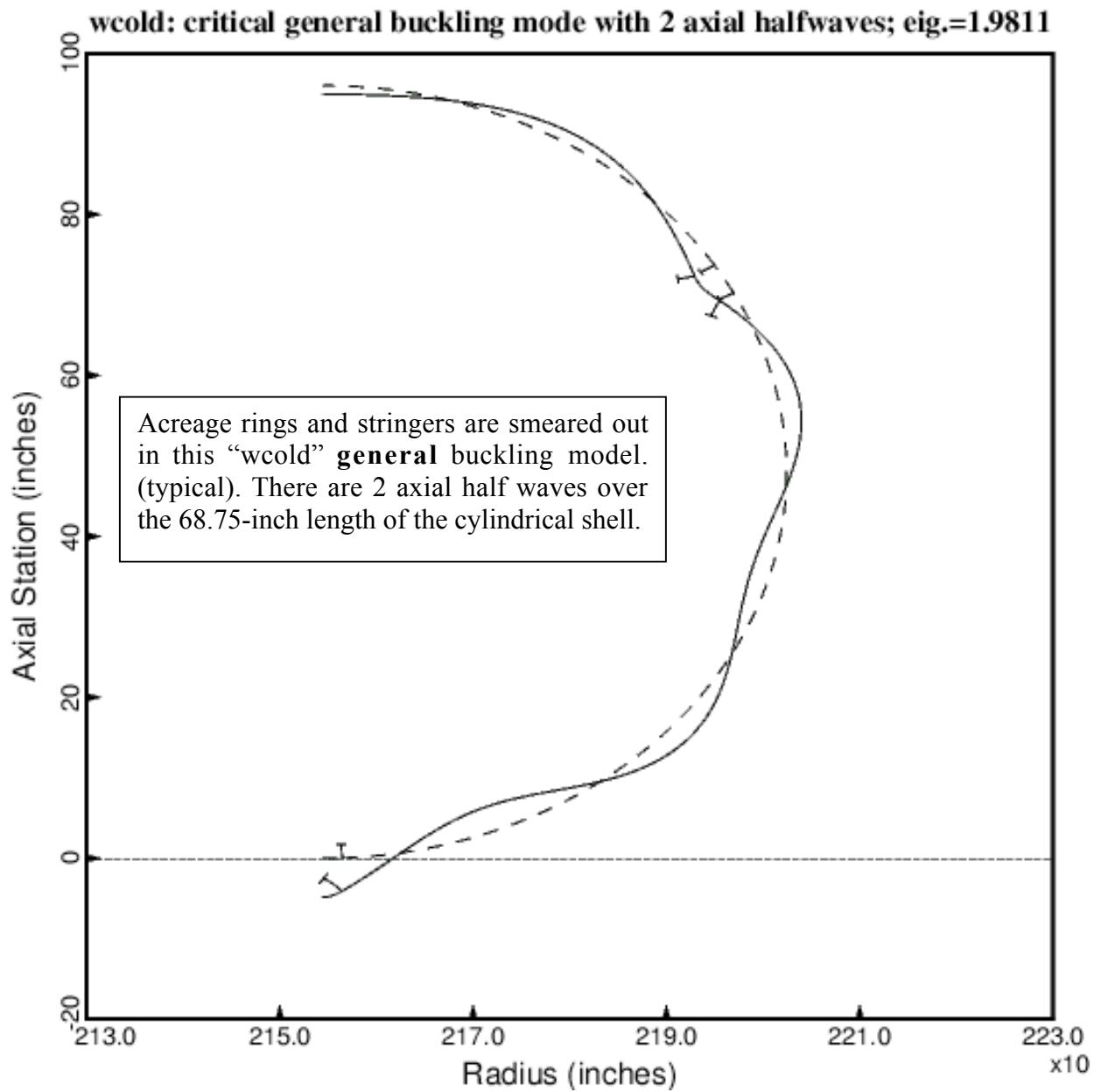


Fig. 6 General buckling of cylindrical shell with 3 T-stiffened weld lands

— — Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: nasacoldbend  
— Deformed: general buckling model; stringers discrete, no rings; conservativeness index, ICONSV=1

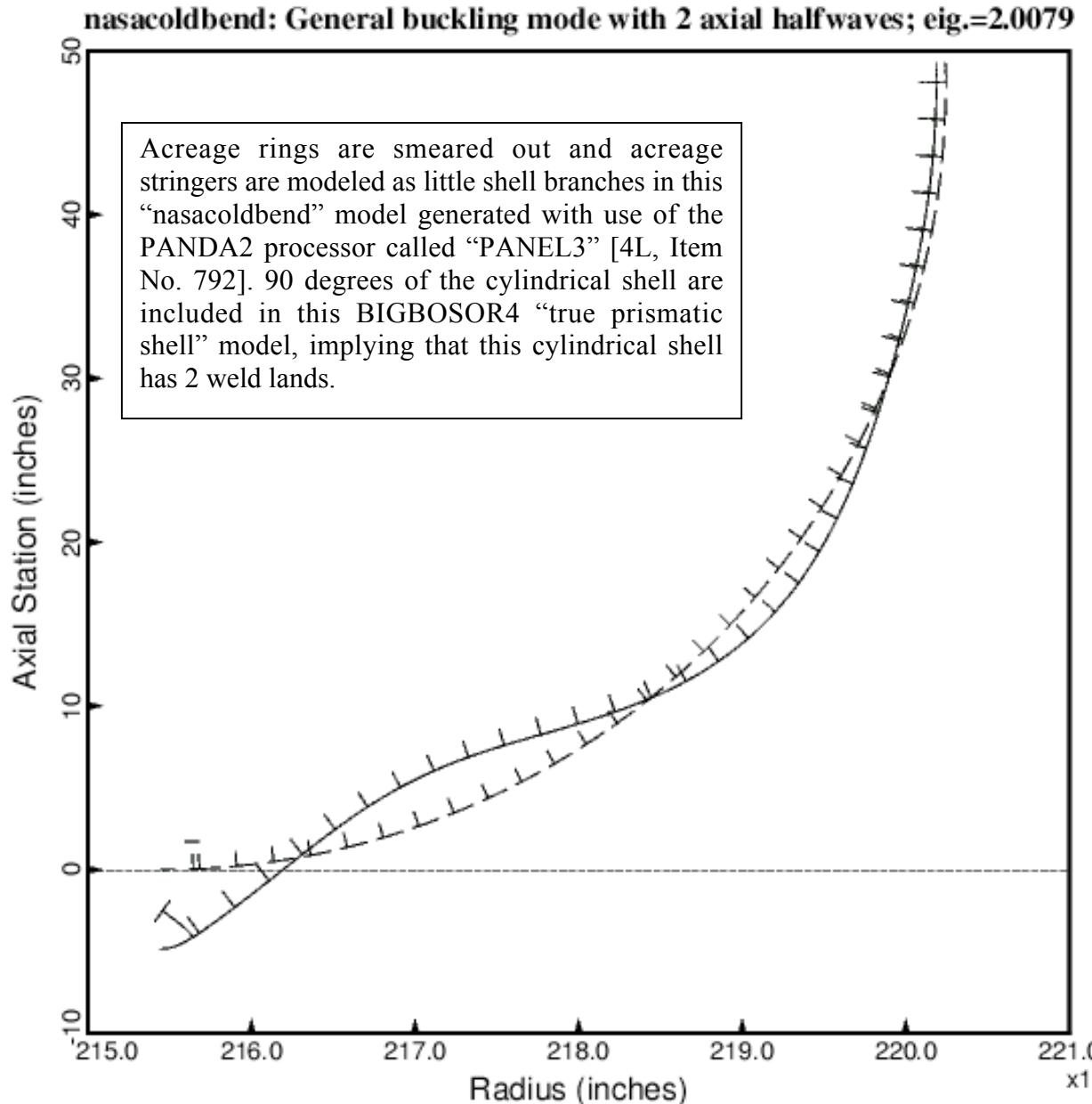


Fig. 7 General buckling of cylindrical shell with two T-stiffened weld lands from the “nasacoldbend PANEL3” model. Compare with Fig. 6.

— Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX1  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = 1

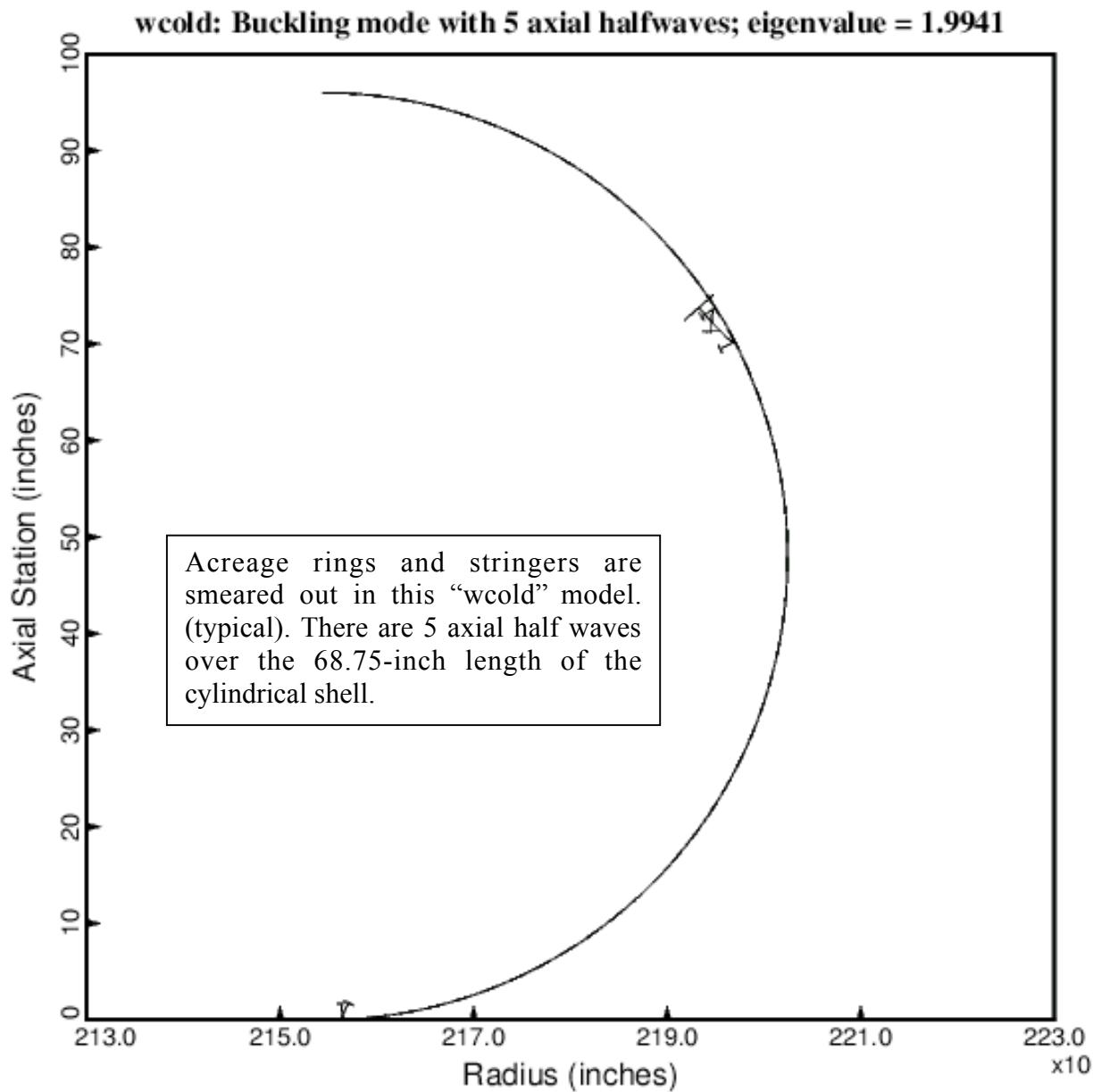


Fig. 8 The general buckling “wcold” model is used here, but 5 axial half waves over the length, 68.75 inches, corresponds to rolling of the T-stringers at the edges of the weld lands rather than to general buckling.

— Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: nasacoldbend  
— Deformed: general buckling model; stringers discrete, no rings; conservativeness index, ICONSV=1

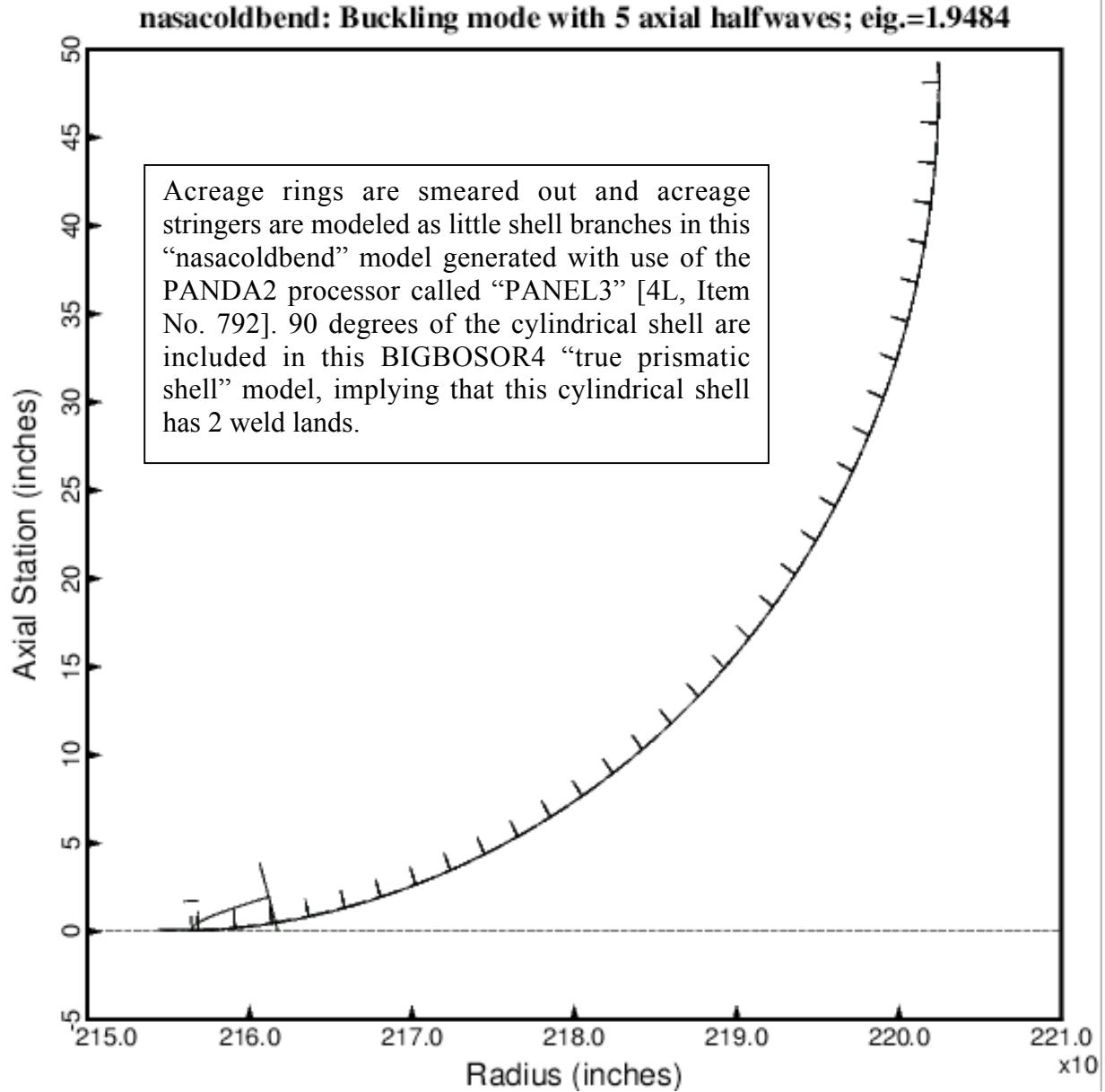


Fig. 9 The general buckling “nasacoldbend PANEL3” model is used here, but 5 axial half waves over the length, 68.75 inches, corresponds to rolling of the T-stringers at the edges of the weld lands rather than to general buckling. Compare with the previous figure.

-- Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX2  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = 1

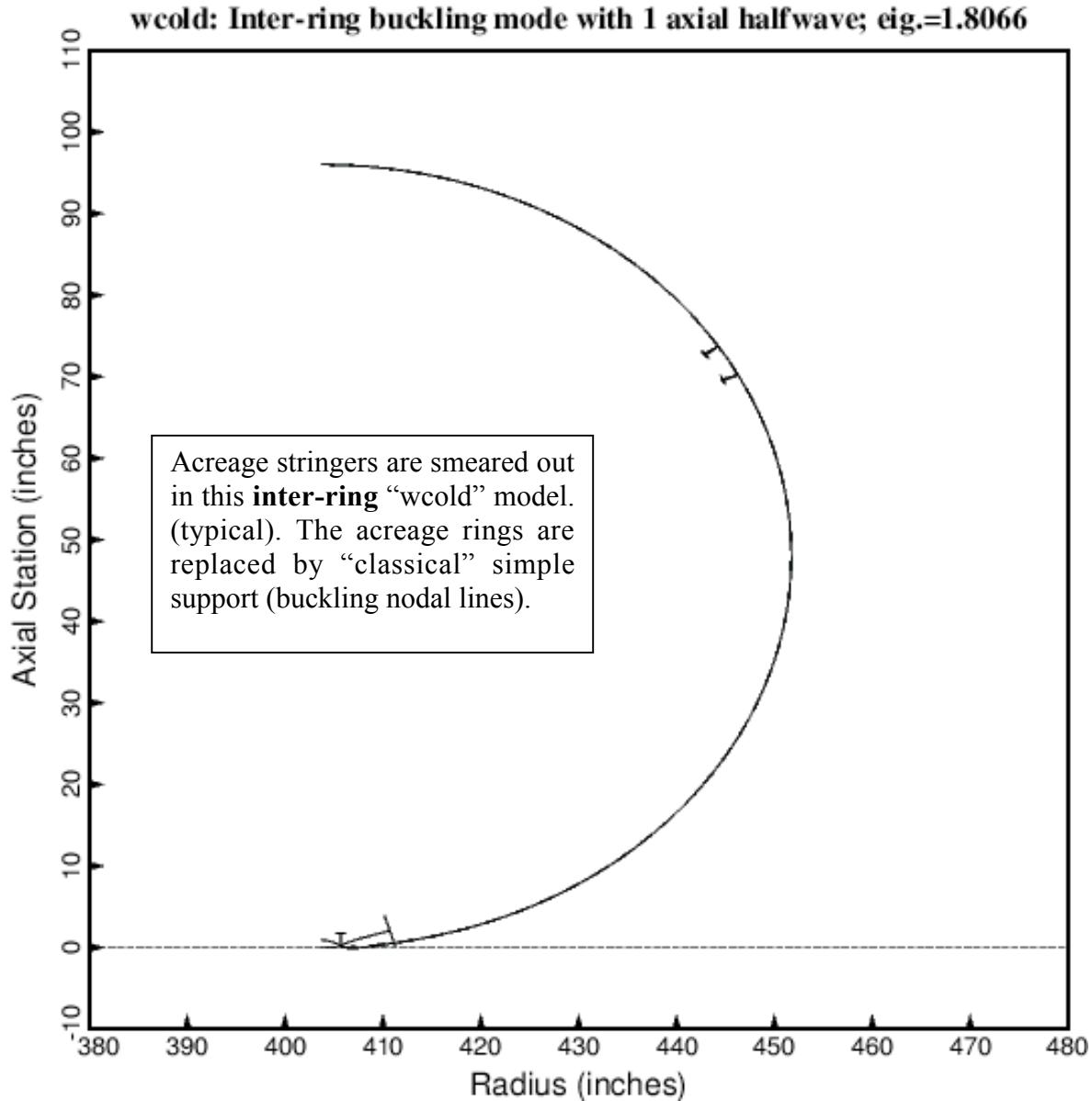


Fig. 10 The inter-ring buckling “wcold” model is used here, and one axial half wave over the length, 13.75 inches, corresponds to rolling of the T-stringers at the edges of the weld lands rather than to acreage buckling between rings.

— — Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: nasacoldbend  
 — Deformed: inter-ring buckling model; stringers discrete, no rings; conservativeness index, ICONSV=1

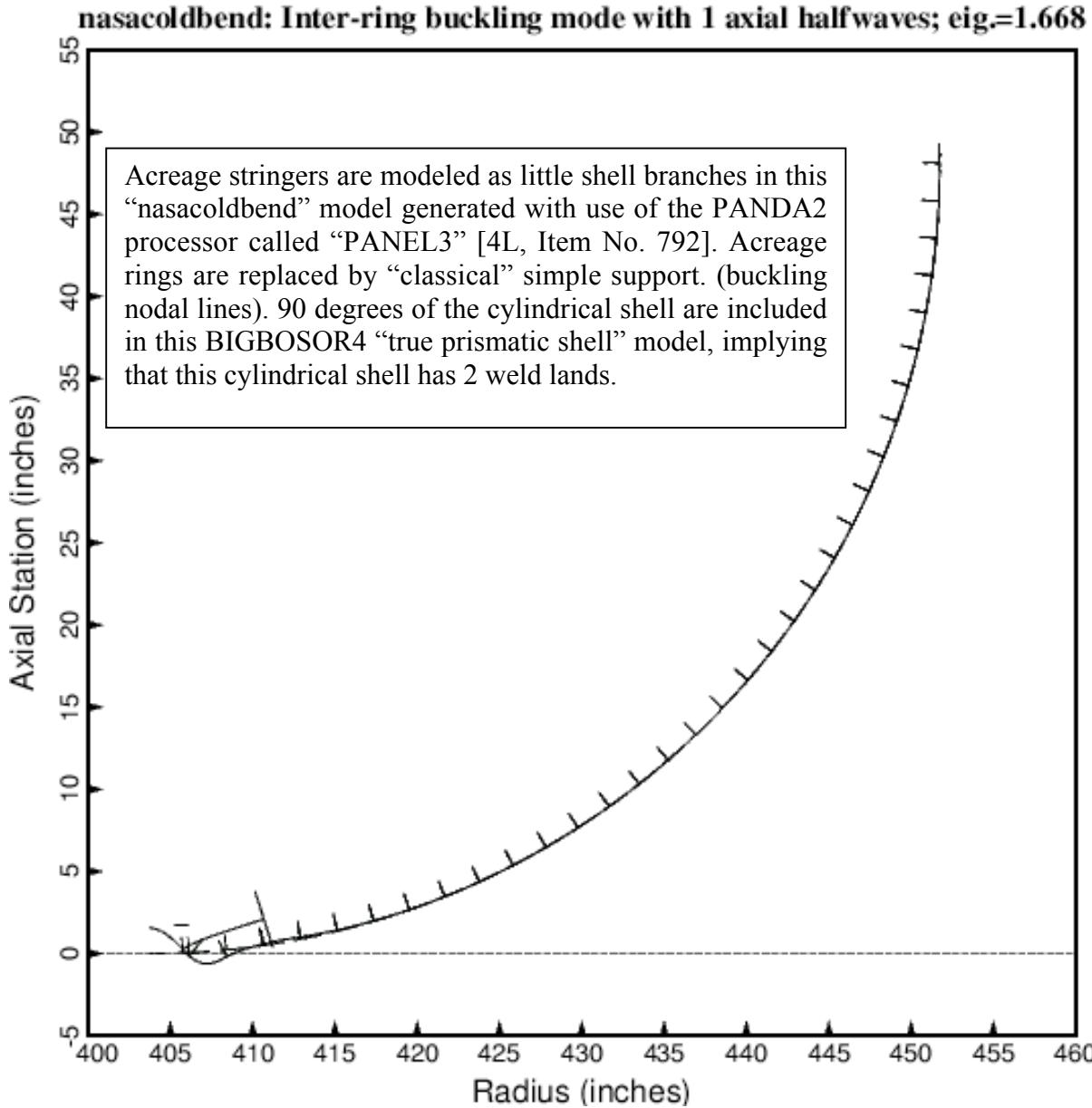


Fig. 11 The inter-ring buckling “nasacoldbend PANEL3” model is used here, and 1 axial half wave over the length, 13.75 inches, corresponds to rolling of the T-stringers at the edges of the weld lands rather than to acreage buckling between rings. Compare with the previous figure.

-- Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX2  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = 1

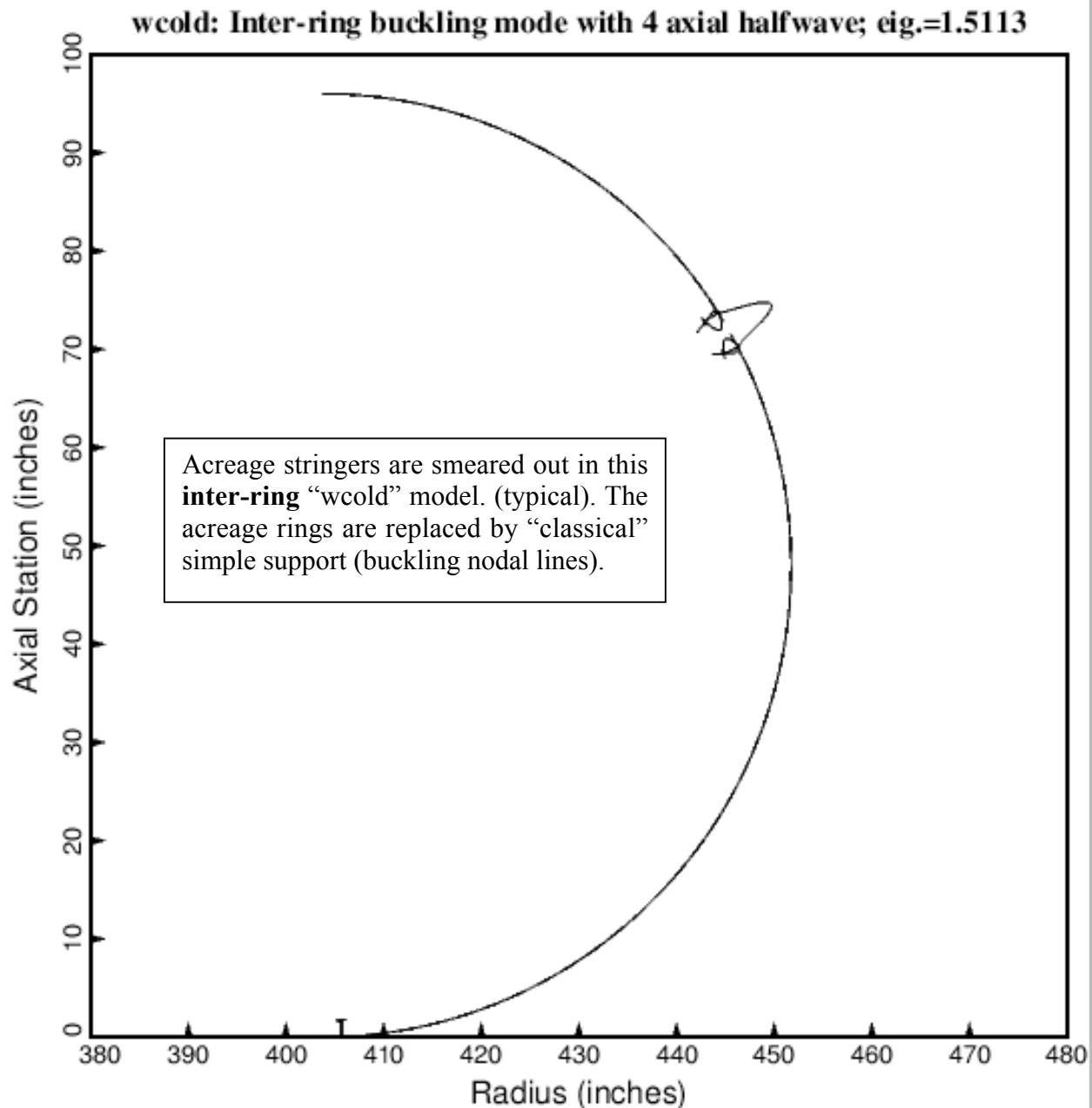


Fig. 12 The inter-ring buckling “wcold” model is used here, and 4 axial half waves over the length, 13.75 inches, corresponds to buckling of the weld land curved plate and T-stringers rather than to acreage buckling between rings.

— — Undefomed; This is the optimized orthogrid cylindrical shell with weld lands: nasacoldbend  
— Deformed: inter-ring buckling model; stringers discrete, no rings; conservativeness index, ICONSV=1

**nasacoldbend: Inter-ring buckling mode with 4 axial halfwaves; eig8=1.4558**

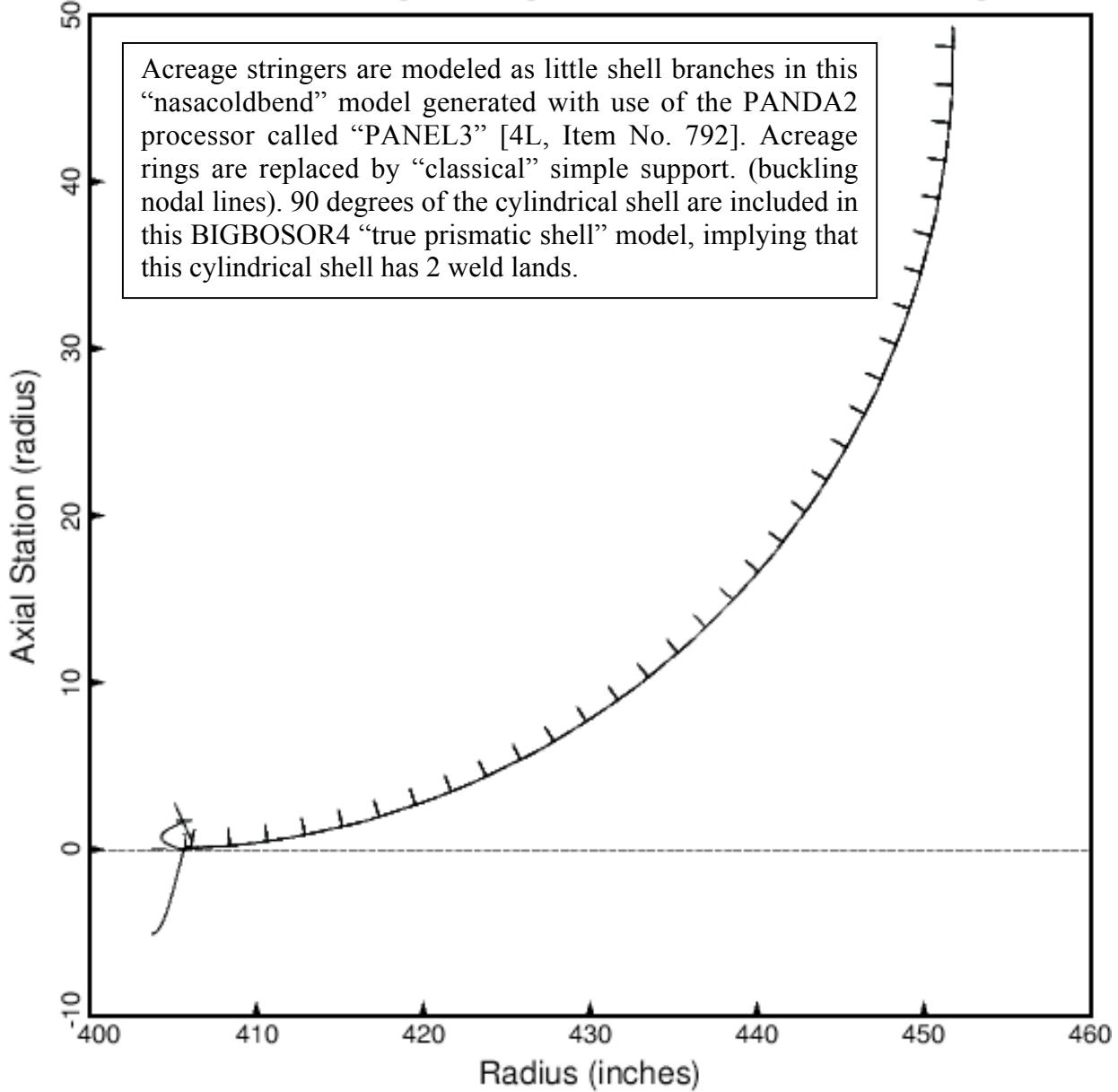


Fig. 13 The inter-ring buckling “nasacoldbend” model is used here, and 4 axial half waves over the length, 13.75 inches, corresponds to buckling of the weld land curved plate rather than to acreage buckling between rings. Compare with the previous figure.

— — Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX2  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = 1

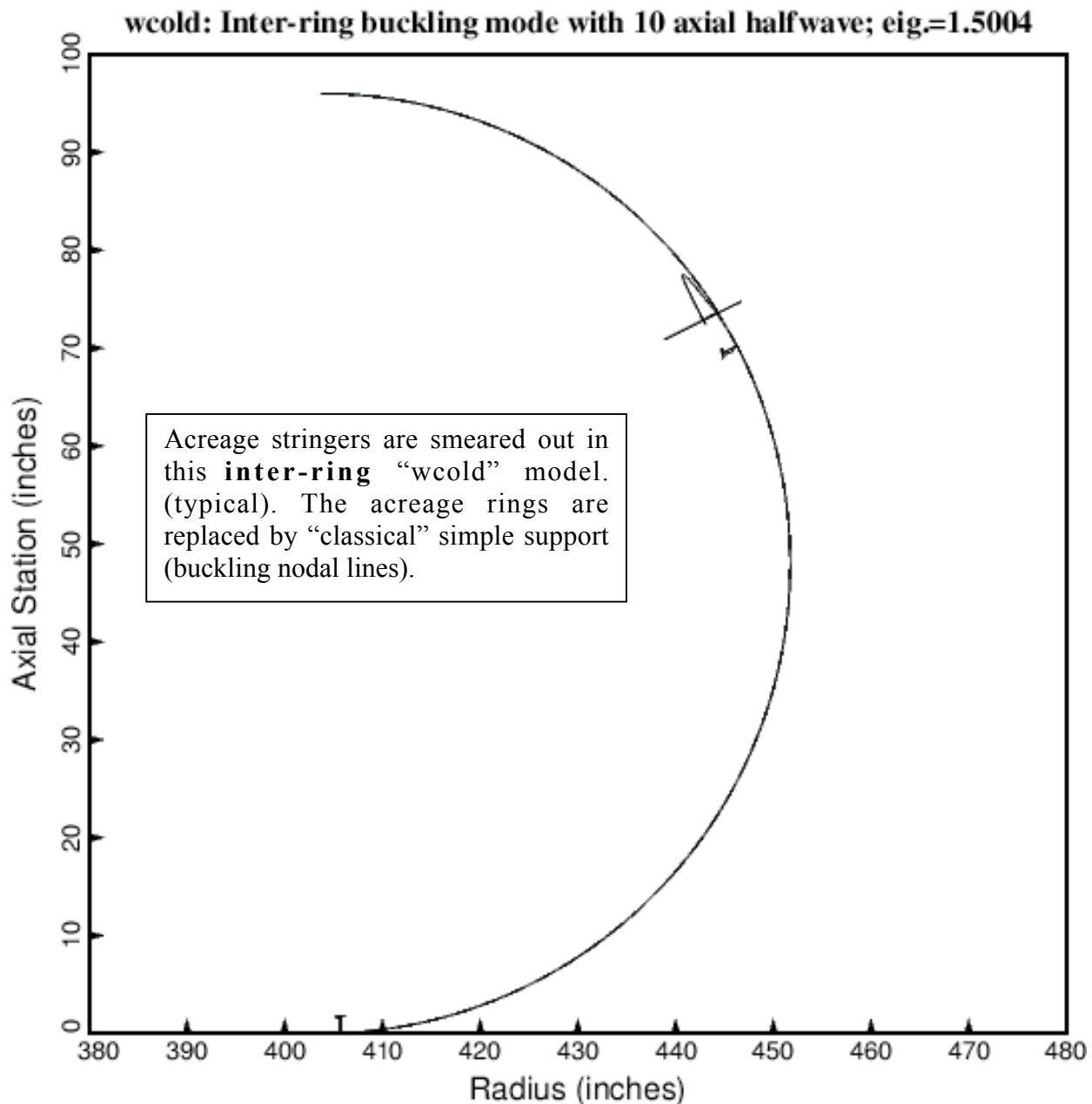


Fig. 14 The inter-ring buckling “wcold” model is used here, and 10 axial half waves over the length, 13.75 inches, corresponds to crippling of the T-stringer web with rolling of T-stringer outstanding flange rather than to acreage buckling between rings.

— — Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: nasacoldbend  
 — Deformed: inter-ring buckling model; stringers discrete, no rings; conservativeness index, ICONSV=1

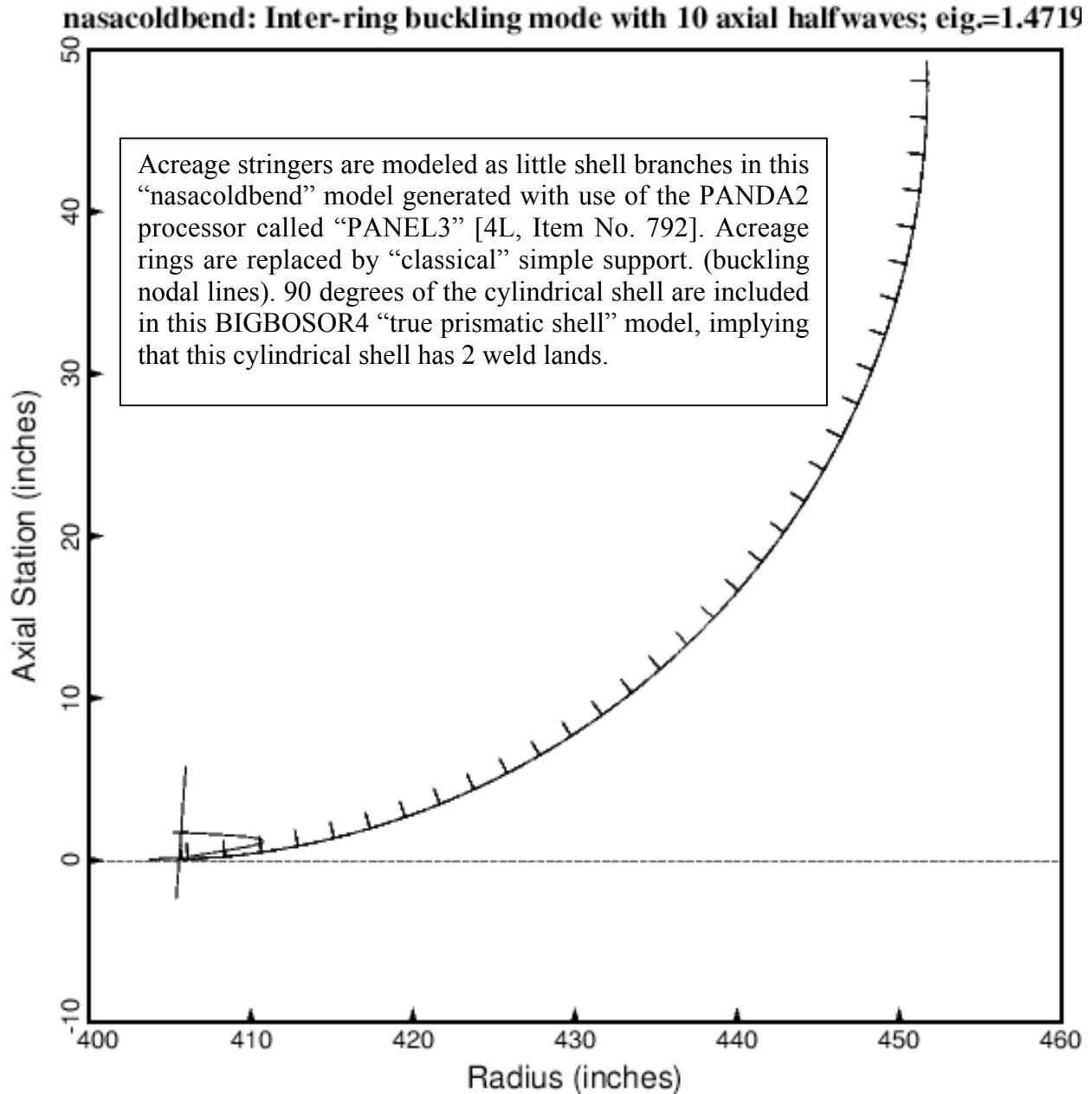


Fig. 15 The inter-ring buckling “wcold” model is used here, and 10 axial half waves over the length, 13.75 inches, corresponds to crippling of the T-stringer web with rolling of the T-stringer outstanding flange rather than to acreage buckling between rings. Compare with the previous figure.

— — Undefomed; This is the optimized orthogrid cylindrical shell with weld lands: nasacoldbend  
— Deformed: inter-ring buckling model; stringers discrete, no rings; conservativeness index, ICONSV=1

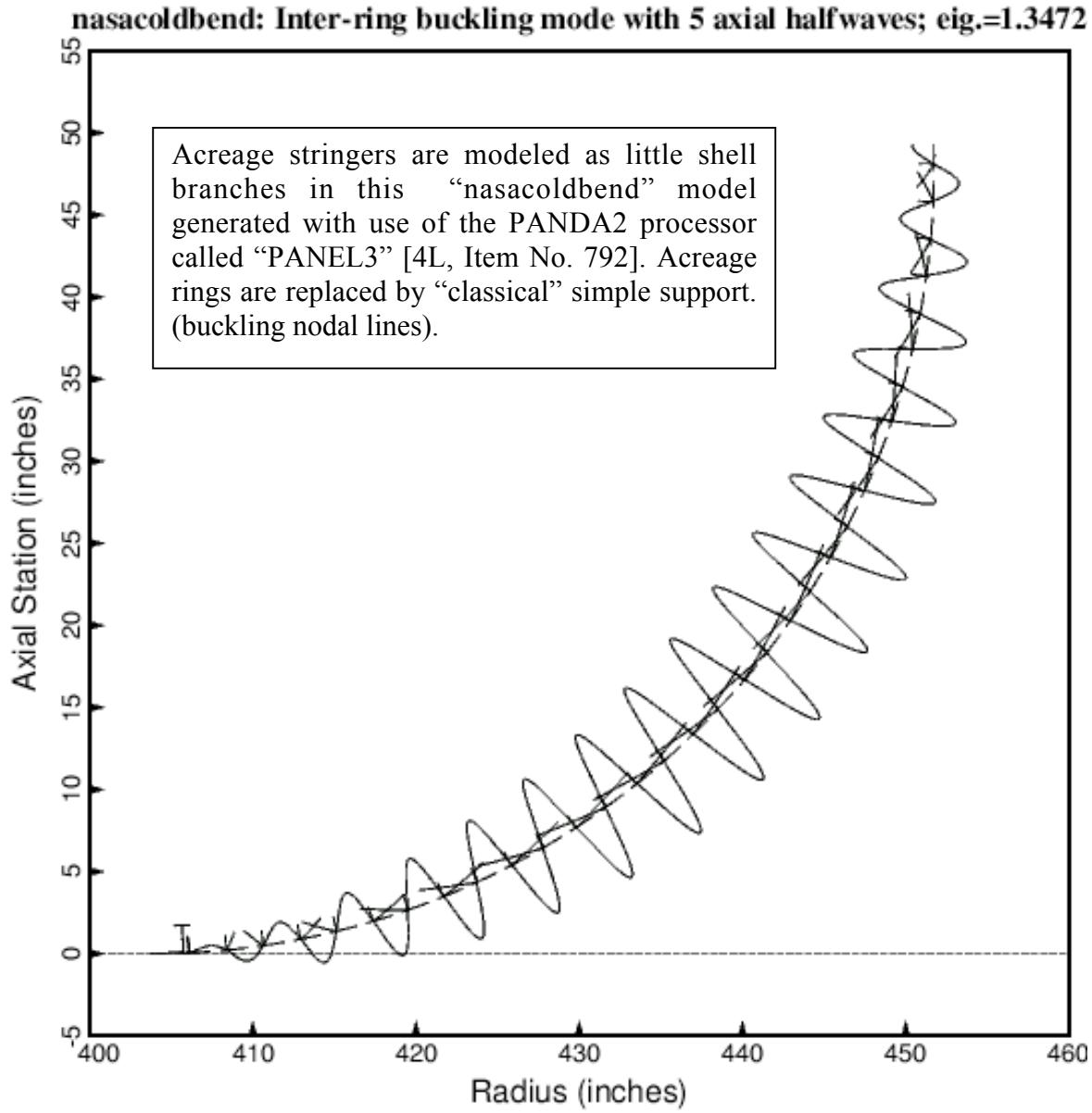
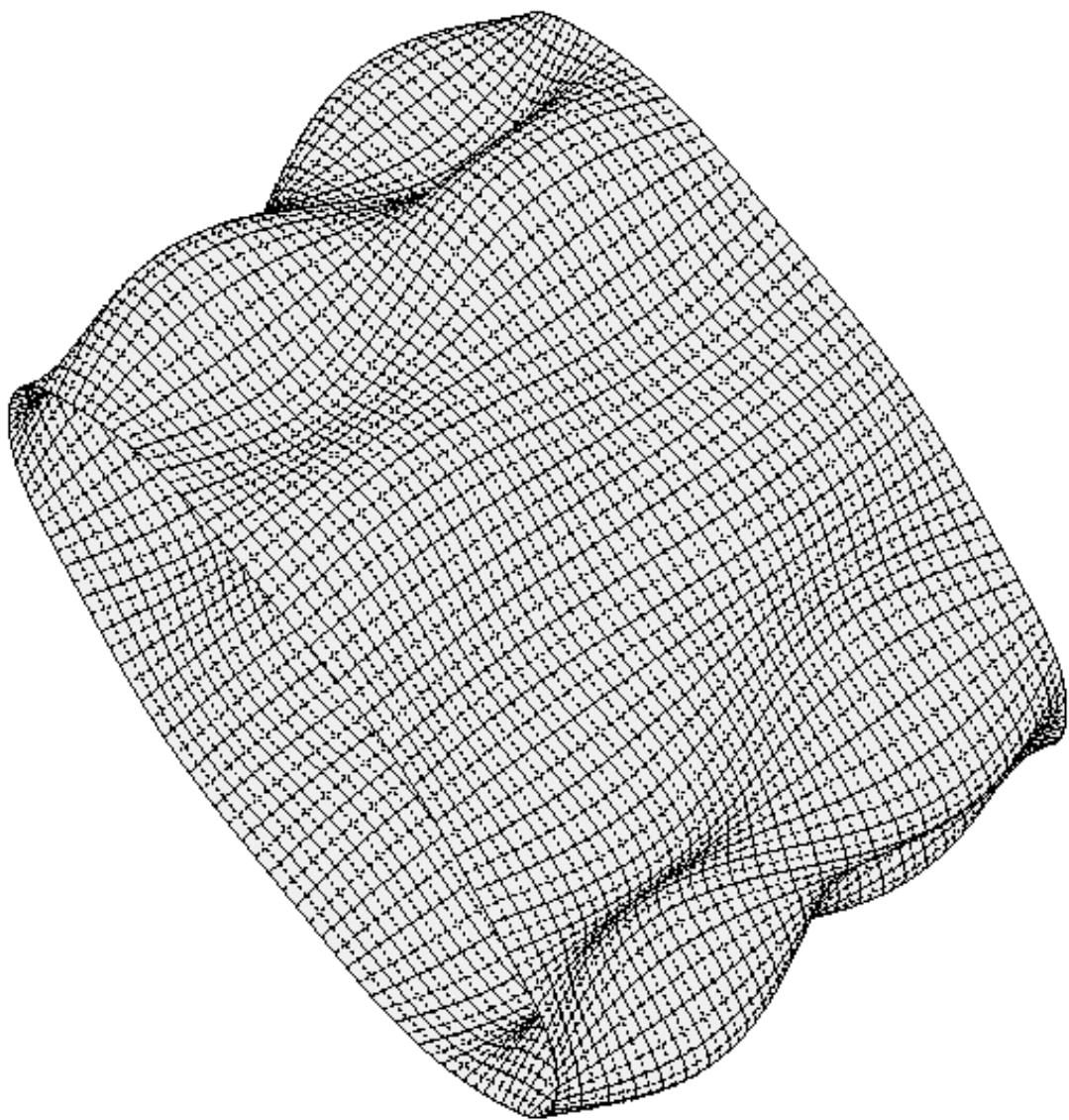


Fig. 16 The inter-ring buckling “nasacoldbend” model is used here, and 5 axial half waves over the length, 13.75 inches, corresponds to local “pocket” buckling between acreage stringers with rolling of the acreage stringers rather than to acreage overall buckling between rings or to buckling of one or more weld land T-stringers.

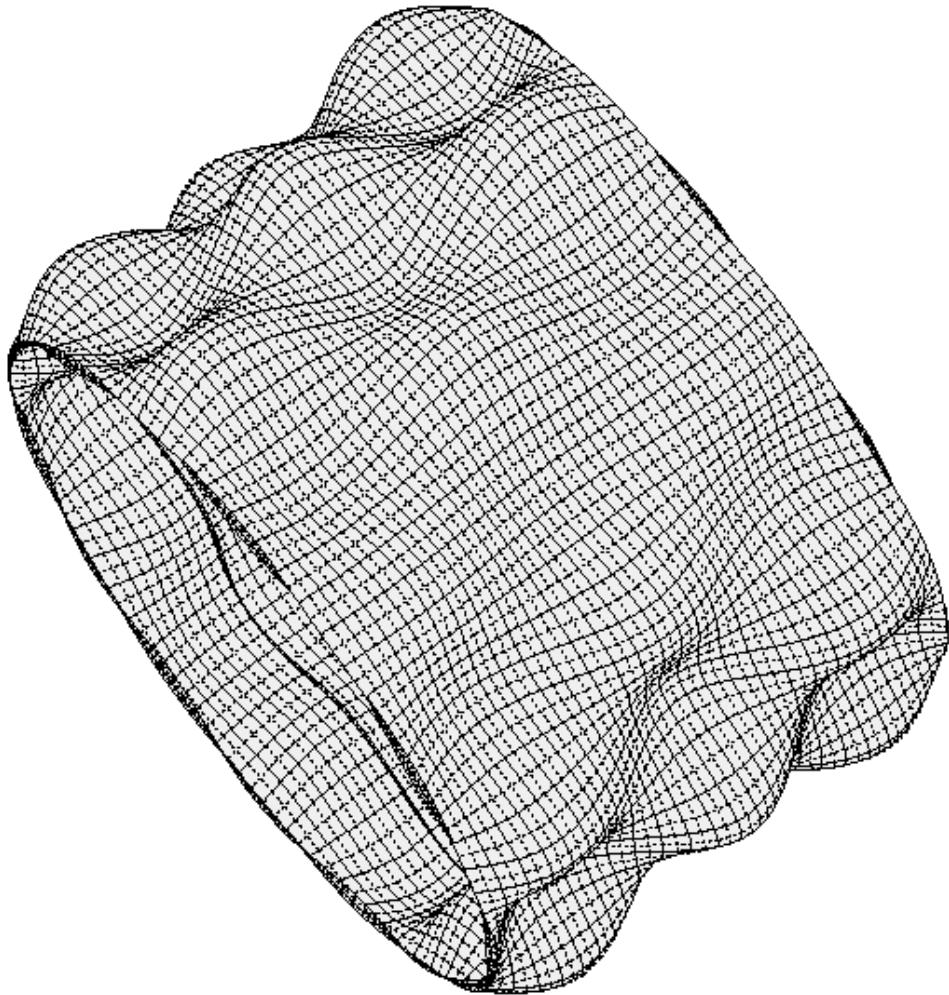


solution scale = 0.6163E+01; PANDA2 gets: pcr = 1.898 for iconsrv=1, pcr = 2.260 for iconsrv=-1  
mode 1, pcr=0.22660E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84       $\Theta_y$  -13.14       $\Theta_z$  35.63

y    z                          x

Fig. 17 General buckling of STAGS “acreage” model with both acreage rings and acreage stringers smeared out. There is no weld land. This buckling mode agrees with that predicted by PANDA2 for the “nasacoldbend” case (Tables 4 and 5). Buckling load factor = 2.266.



solution scale = 0.6112E+01 PANDA2 gets: pcr =1.898 for iconsrv=1, pcr =2.260 for iconsrv=-1

mode 1, pcr = 0.22272E+01

step 0 eigenvector deformed geometry

linear buckling of perfect shell from STAGS

$\Theta$  x -35.84

$\Theta$  y -13.14

$\Theta$  z 35.63

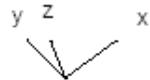
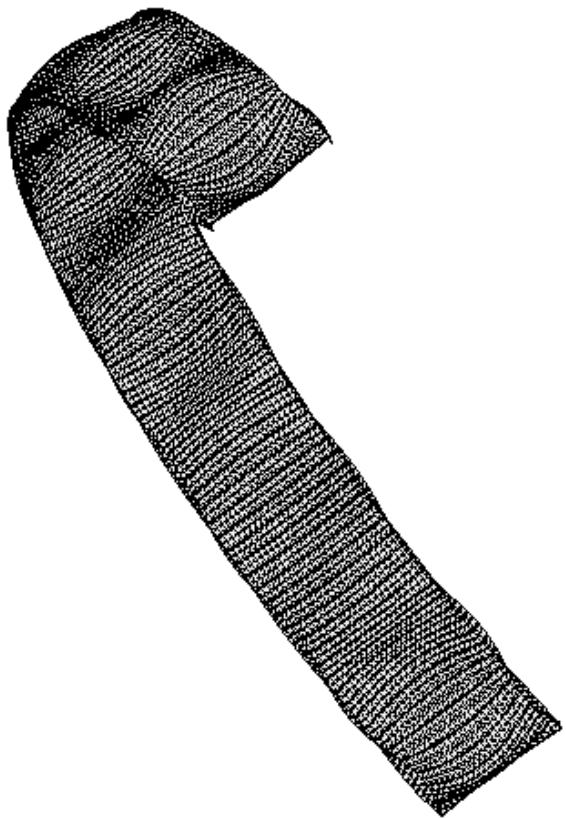


Fig. 18 General buckling of STAGS “acreage” model with the acreage rings modeled as little shell units and the acreage stringers smeared out. There is no weld land. This buckling mode has one more axial half wave than that predicted by PANDA2 for the “nasacoldbend” case (Tables 4 and 5) in which both acreage stringers and acreage rings are smeared out. However, the eigenvalue, pcr = 2.2272, is only slightly less than that displayed in the previous figure: pcr=2.266.



```

solution scale = 0.4327E+01; PANDA2 gets: pcr =1.864 for iconsrv=1, pcr =2.350 for iconsrv=-1
mode 1, pcr = 0.23387E+01; inter-ring buckling from STAGS
step 0 eigenvector deformed geometry
linear buckling of perfect shell from STAGS
          Θ x -35.84      y z
          Θ y -13.14      x
          Θ z 35.63
                                V
                                |
                                1.461E+01

```

Fig. 19 Inter-ring buckling of a one-ring-bay STAGS “acreage” model with the two acreage end rings modeled as little shell units and with the acreage stringers smeared out. There is no weld land. The acreage rings at each end of the short cylindrical shell have half the stiffness and density of the actual rings. This “trick” produces a model that yields the same inter-ring buckling load factor and mode shape that would occur in a multi-ring-bay STAGS model. The buckling mode agrees with that from PANDA2 (Table 4).

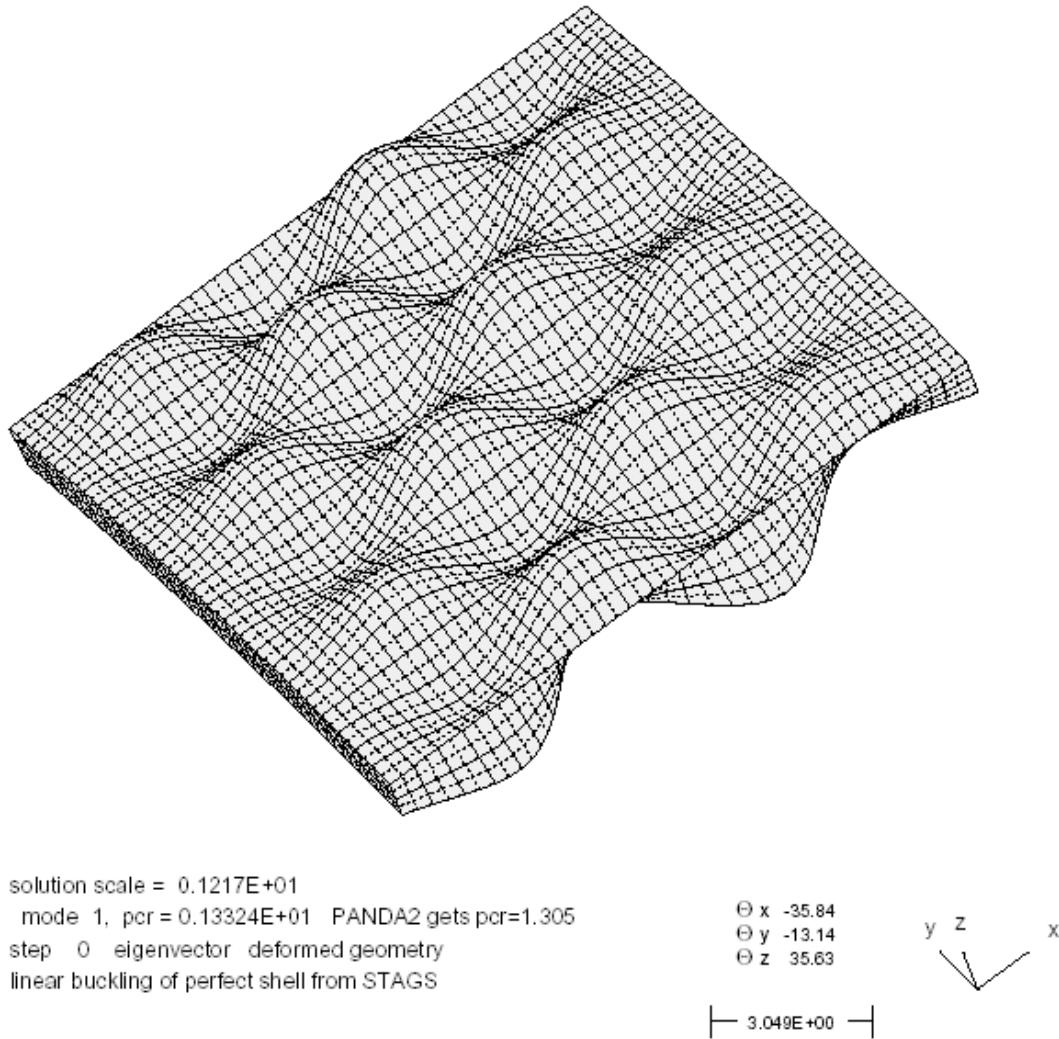
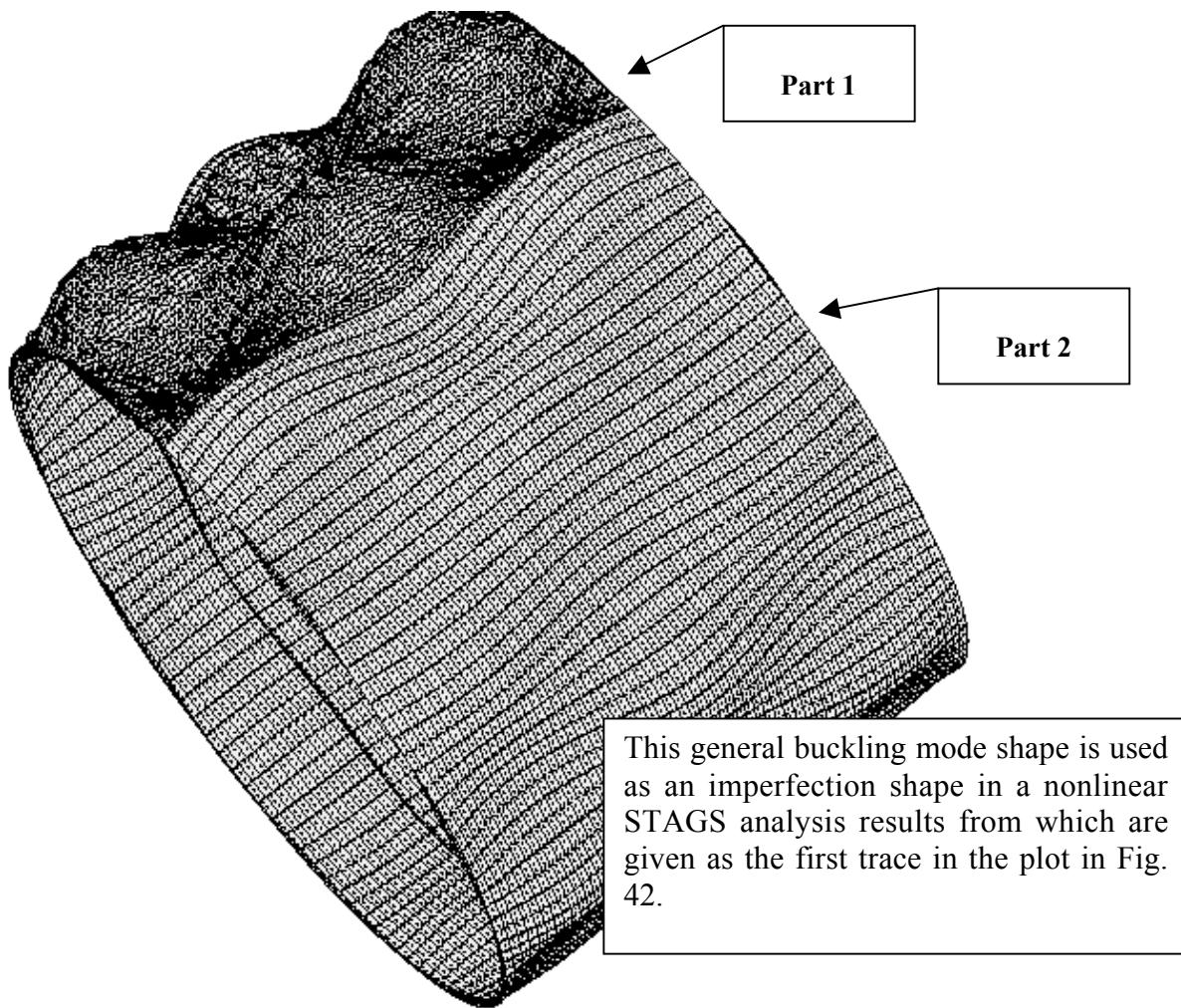


Fig. 20 Local buckling of a one-ring-bay STAGS “acreage” model with all acreage stiffeners modeled as little shell units. There is no weld land. The acreage stiffeners that run along all four edges of this small sub-domain of the entire cylindrical shell have half the stiffness and density of the interior stiffeners. This “trick” produces a model that yields the same local buckling load factor and mode shape that would occur in a much larger multi-ring-bay STAGS model. The buckling mode shown here agrees with that from PANDA2 (Table 4) and that from the “wcold” model (Table 4, Fig.16).



solution scale = 0.7214E+01; nasacoldbend compound model; general buckling mode  
 $p_{cr}=2.3325$ ; PANDA2:  $p_{cr}=1.898$  for  $i_{cons}=1$ ,  $p_{cr}=2.260$  for  $i_{cons}=-1$   
 This is eigenvalue and eigenmode no. 295; STAGS index  $ILIN=1$   
 linear buckling of perfect shell from STAGS; This mode is used as an imperfection shape

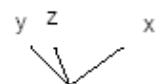
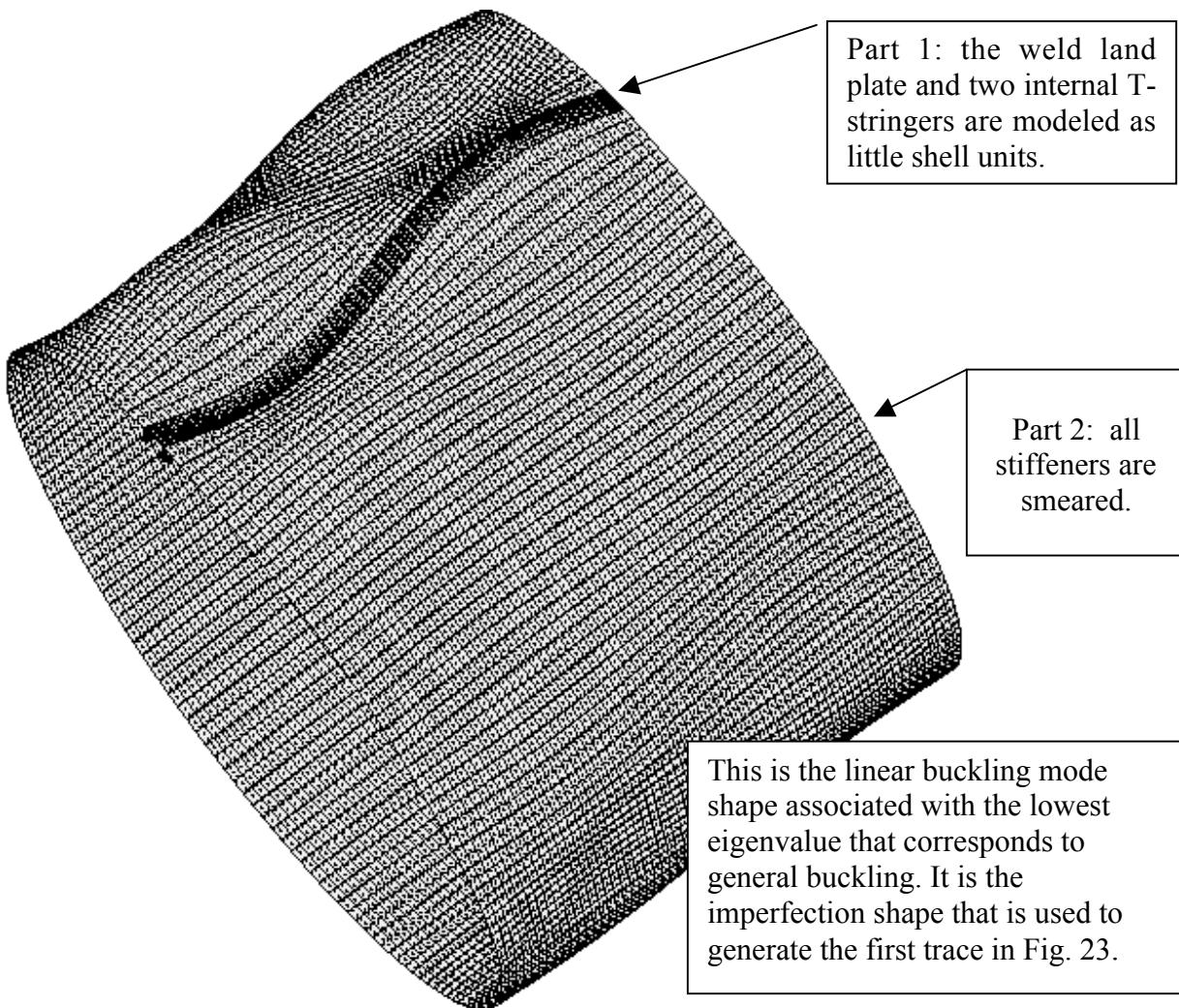


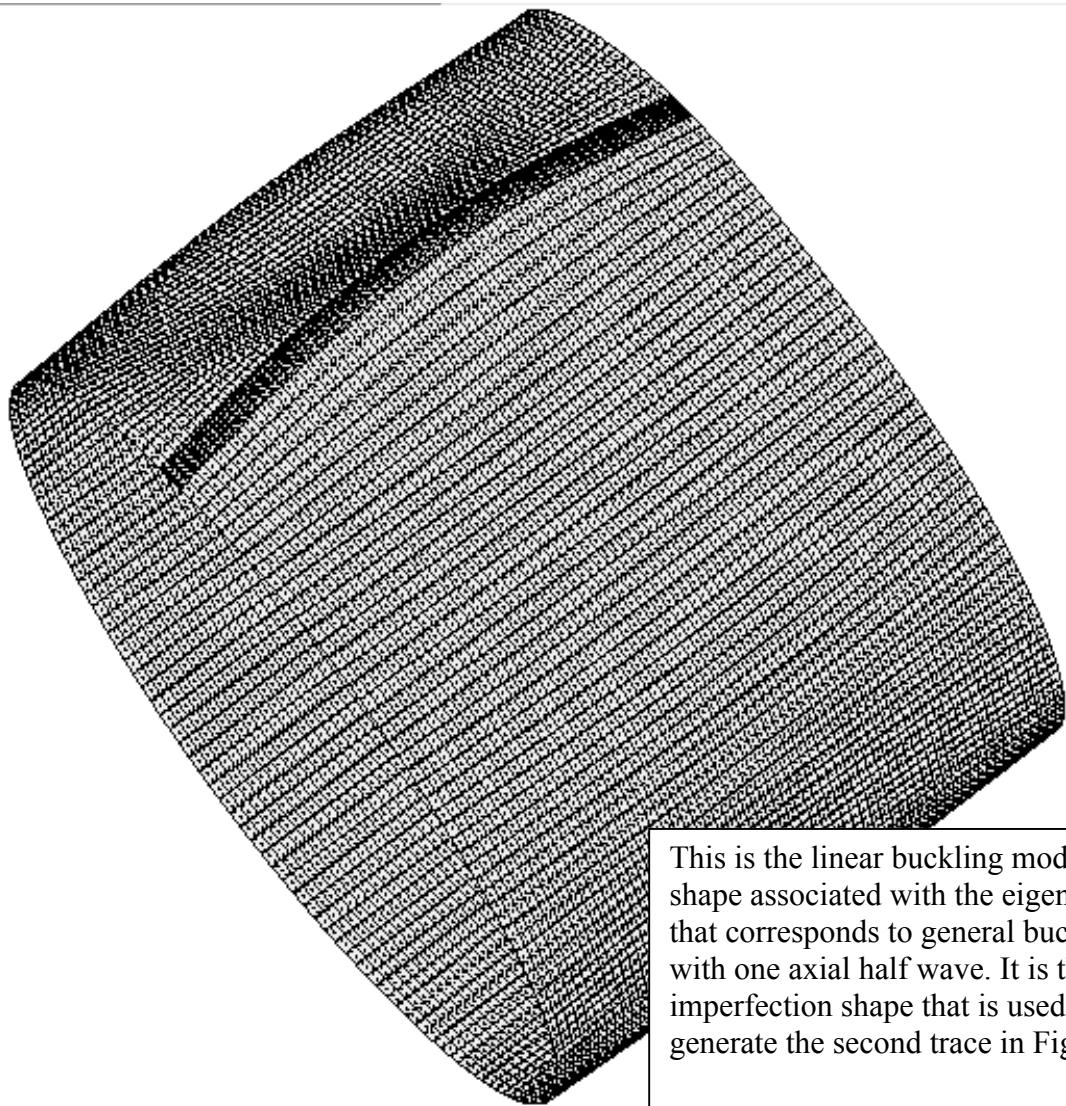
Fig. 21 General buckling from a STAGS “compound” model. The “compound” model has two parts: In Part 1 both the rings and the stringers are modeled as little shell units. In Part 2 the rings are modeled as little shell units but the stringers are smeared out. In this STAGS model the STAGS index,  $ILIN=1$ .  $ILIN=1$  tends to filter out many of the local buckling eigenvalues that interfere with the STAGS user’s ability to find the critical general buckling mode.



```

solution scale = 0.5999E+01; GENOPT/BIGBOSOR4 gets pcr = 1.9811 for general buckling with T-stiffened weld land
mode 1, pcr = 0.20324E+01 from STAGS model with weld land
step 0 eigenvector deformed geometry
linear buckling of perfect shell from STAGS; This compound model includes the T-stiffened weld land
    Θ x -35.84
    Θ y -13.14
    Θ z 35.63
          y   z
          |   |
          v   v
          x   x
  
```

Fig. 22a STAGS compound model with one T-stiffened weld land. This general buckling mode is used as an imperfection shape with amplitude,  $W_{imp} = 0.125$  inch in the nonlinear STAGS analysis to follow (Fig.23). The buckling load factor is 2.0324.



solution scale = 0.7106E+01

mode 114, pcr = 0.21559E+01

This is the second general buckling mode  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

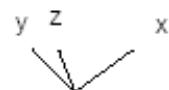


Fig. 22b STAGS compound model with one T-stiffened weld land. This general buckling mode is used as an imperfection shape with amplitude,  $W_{imp} = -0.125$  inch in the nonlinear STAGS analysis to follow (Fig.23). The buckling load factor is 2.1559.

- $\square$  General buckling modal imperfection shape in Fig. 22 with amplitude,  $|W_{imp}| = +0.125$  inch
- $\circ$  General buckling modal imperfection shape in Fig. 49 with amplitude,  $|W_{imp}| = -0.125$  inch
- $\triangle$  General buckling modal imperfection shape in Figs. 32 and 33 with amplitude,  $|W_{imp}| = +0.125$  inch

**End shortening  $u$  versus load factor PA for the design in Table 6**

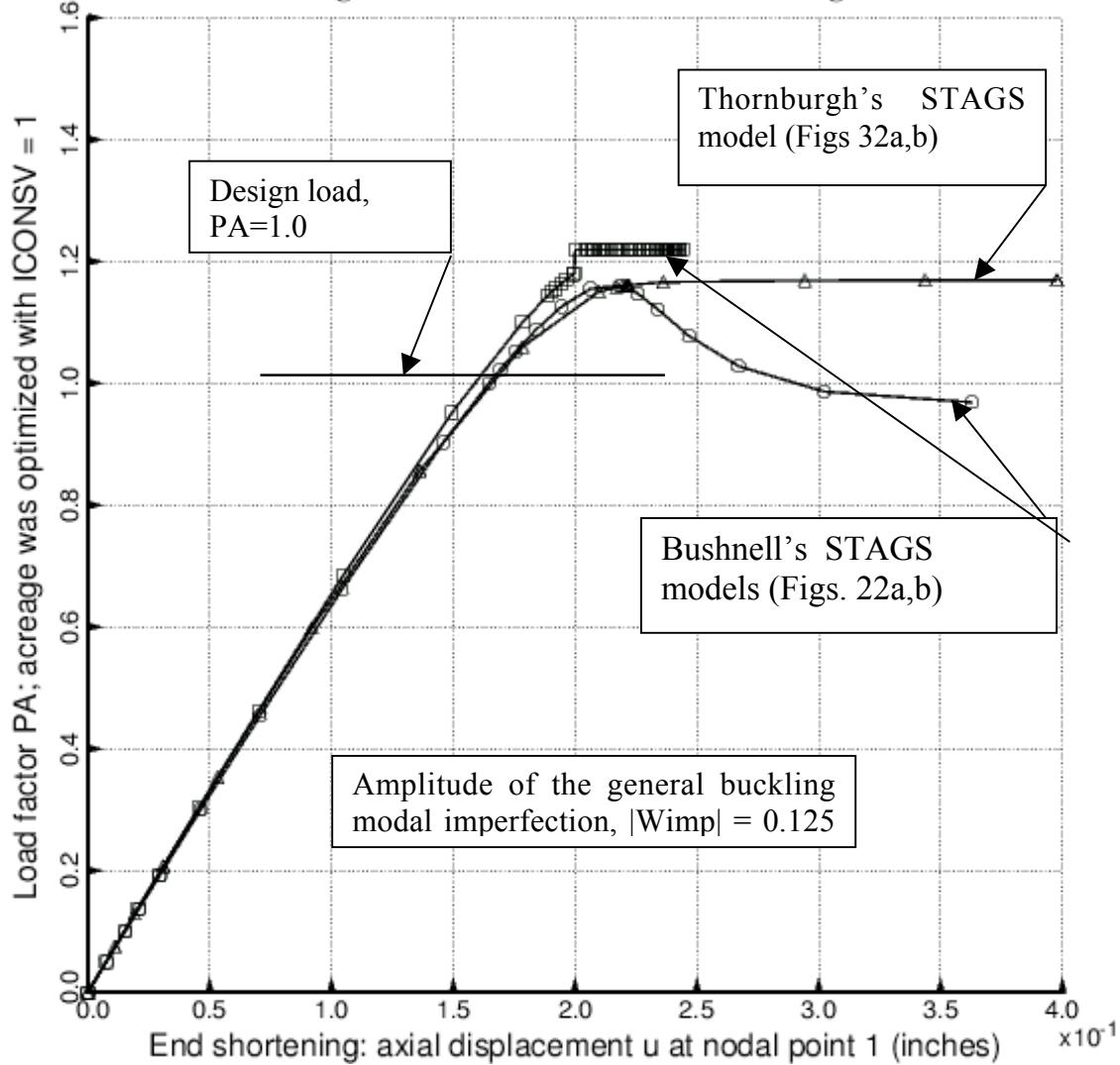


Fig. 23 STAGS nonlinear equilibrium paths of an optimized axially compressed cylindrical shell with weld lands and with various general buckling modal imperfection shapes. Load factor, PA = 1.0, corresponds to the design load: a total axial load of 669235 lb.

□ Kinetic energy versus Time for "compoundweld" model, yes weld land;  $W_{imp} = 0.125$  inch

### Kinetic energy versus Time for "compoundweld" model; PA = 1.22

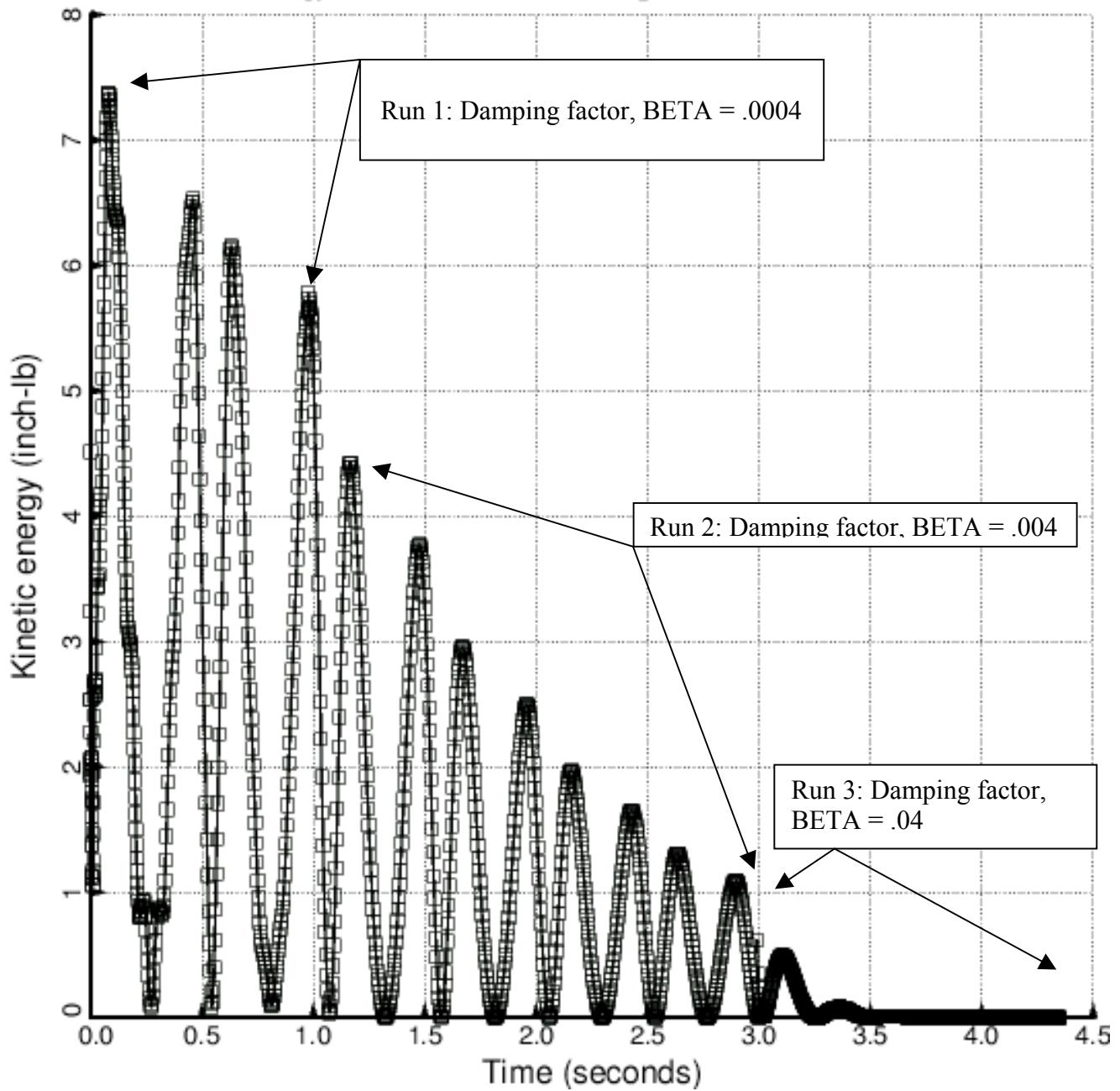
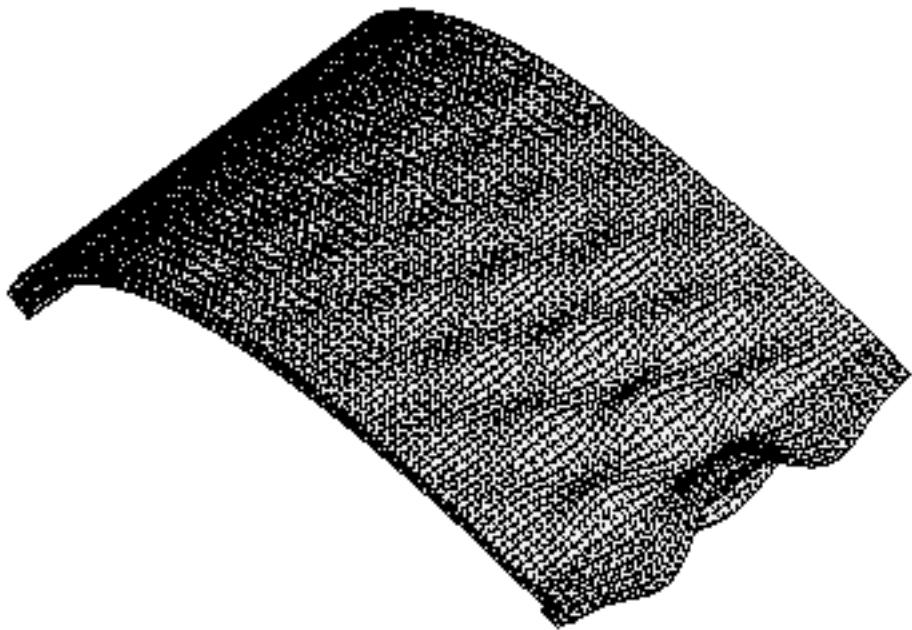


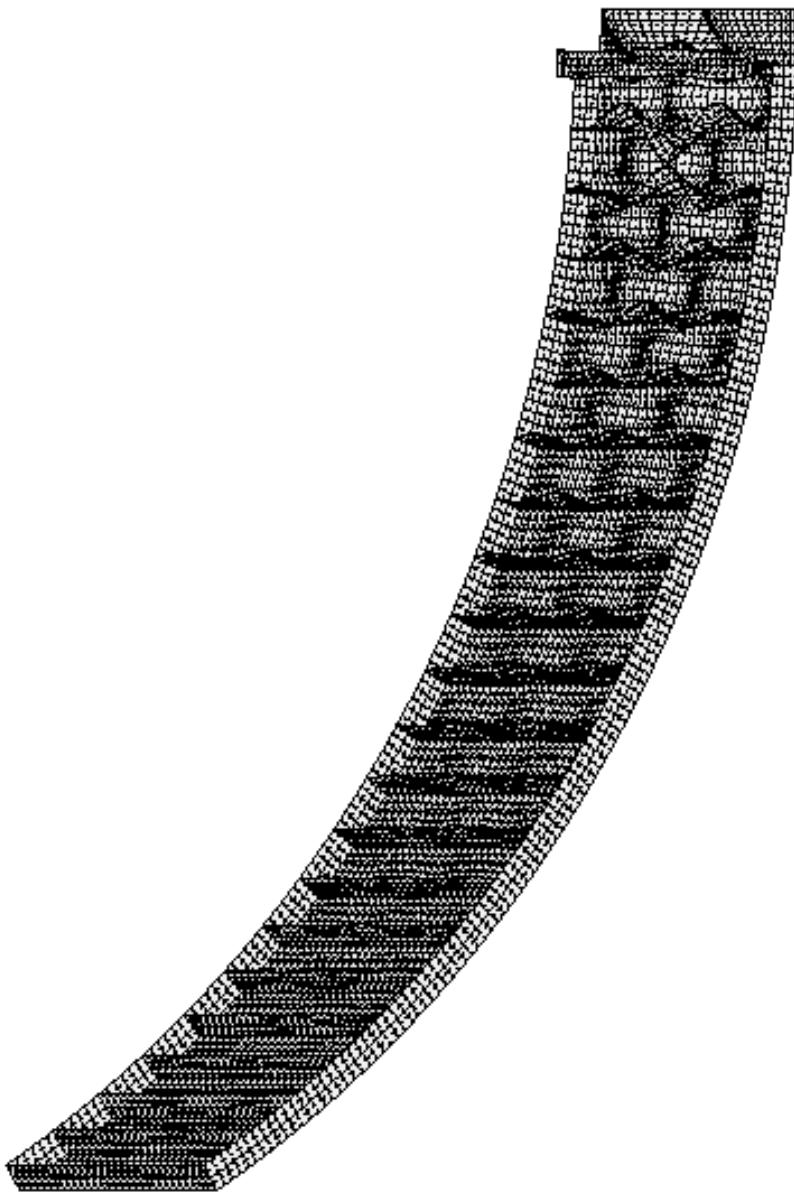
Fig. 24 Results from a sequence of three STAGS nonlinear transient runs at load factor, PA = 1.22. The horizontally arrayed data points at PA = 1.22 in the previous figure are generated by these three transient runs, each with a different damping factor, BETA.



solution scale = 0.1835E+01  
mode 1, pcr = 0.13488E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

Fig. 25 STAGS “60-degree”, one-ring-bay model. Local “pocket” buckling combined with weld land curved plate buckling. This mode corresponds to the first (lowest) eigenvalue (buckling load factor), which is equal to 1.3488. The next two figures show different views of the same buckling mode. Compare with Figs. 12, 13, 16, and 20.



solution scale = 0.2378E+01  
mode 1, pcr = 0.13488E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

Θ x -180.00  
Θ y 60.00  
Θ z -0.00

Fig. 26 STAGS “60-degree”, one-ring-bay model. This is the same buckling mode as that shown in the previous figure.

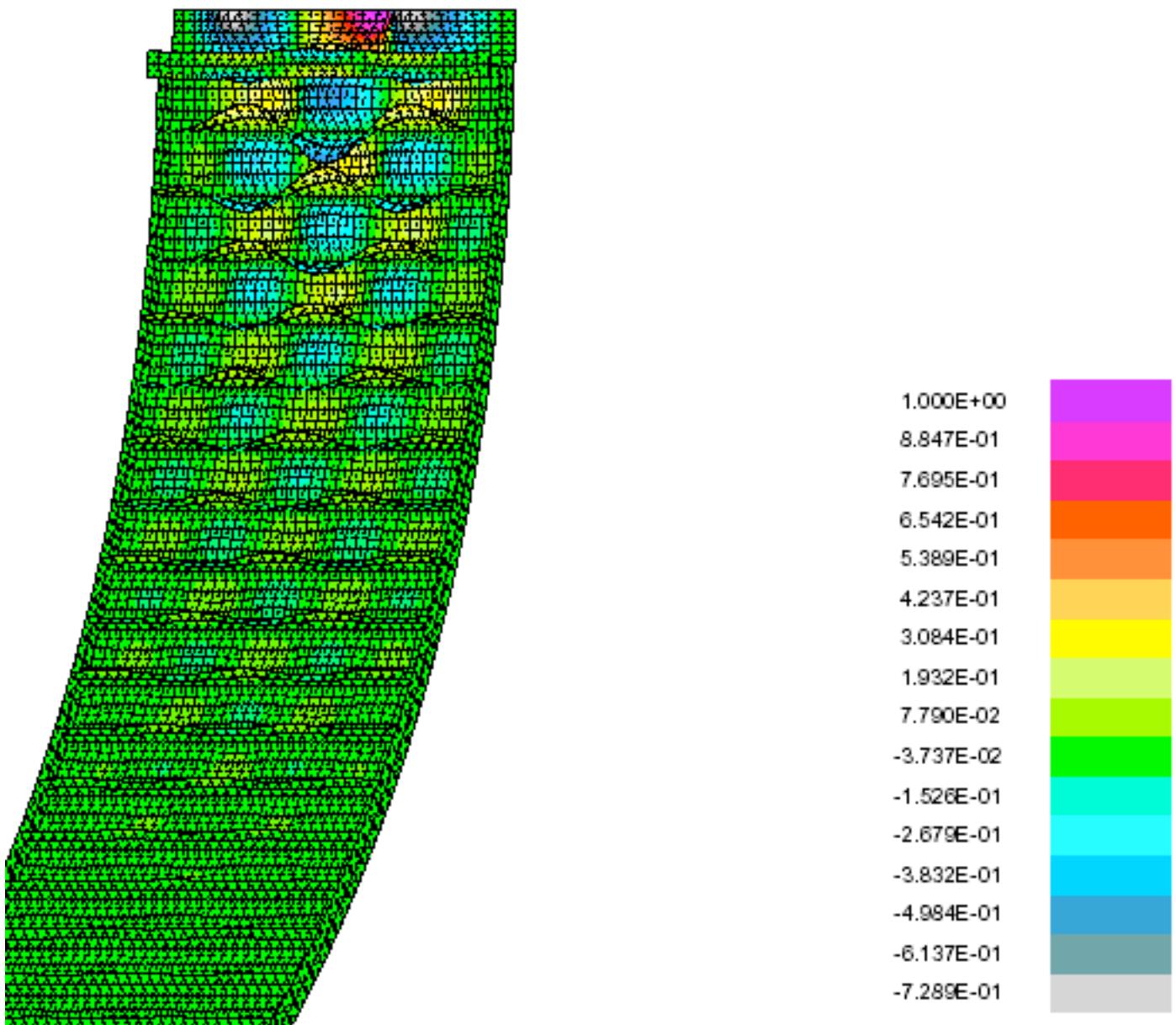
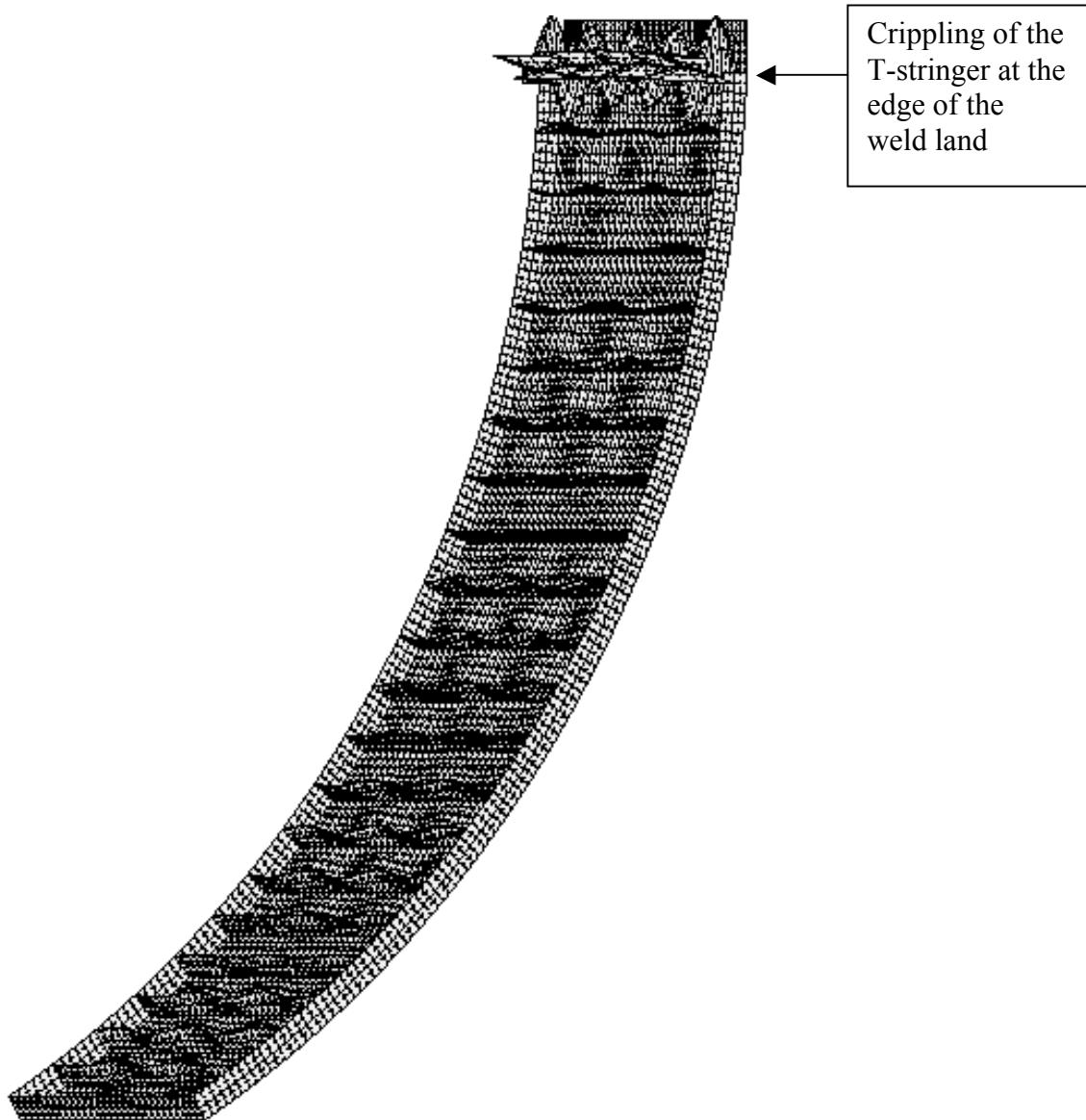


Fig. 27 STAGS “60-degree”, one-ring-bay model. This is the same buckling mode as that shown in the previous two figures.



solution scale = 0.2064E+01  
mode 14, pcr = 0.14278E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -180.00  
 $\Theta_y$  60.00  
 $\Theta_z$  -0.00

Fig. 28a STAGS “60-degree”, one-ring-bay model. This is eigenvector no. 14, which includes crippling of the weld land T-stringer. The buckling load factor is 1.4278. Compare with Figs 14 and 15.

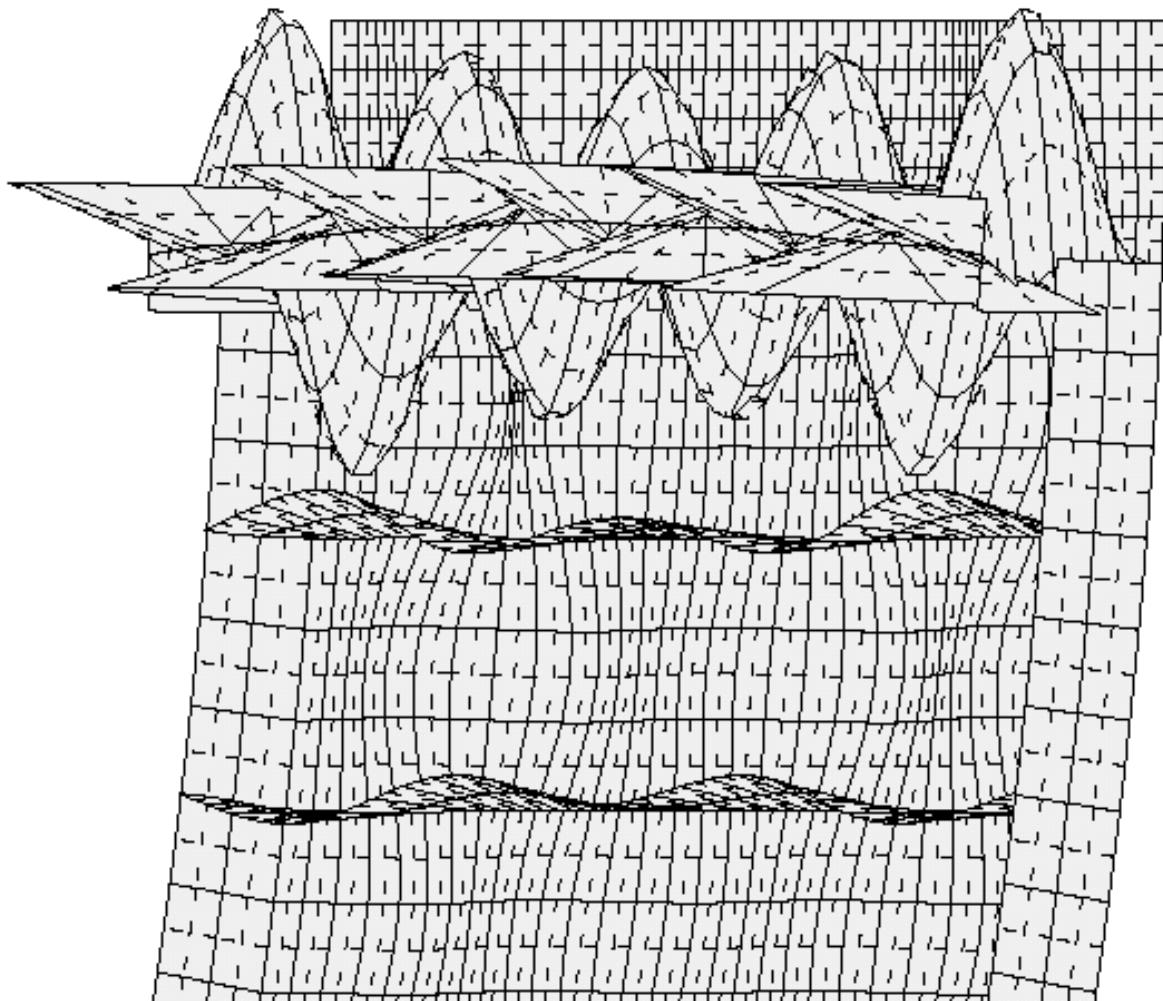


Fig. 28b Close-up of the crippling of the T-stringer at the edge of the weld land that first appears as part of eigenvector no. 14 of the “60-degree”, one-ring-bay STAGS model. The buckling load factor is 1.4278. This figure shows a close-up view of the same mode as that displayed in the previous figure.

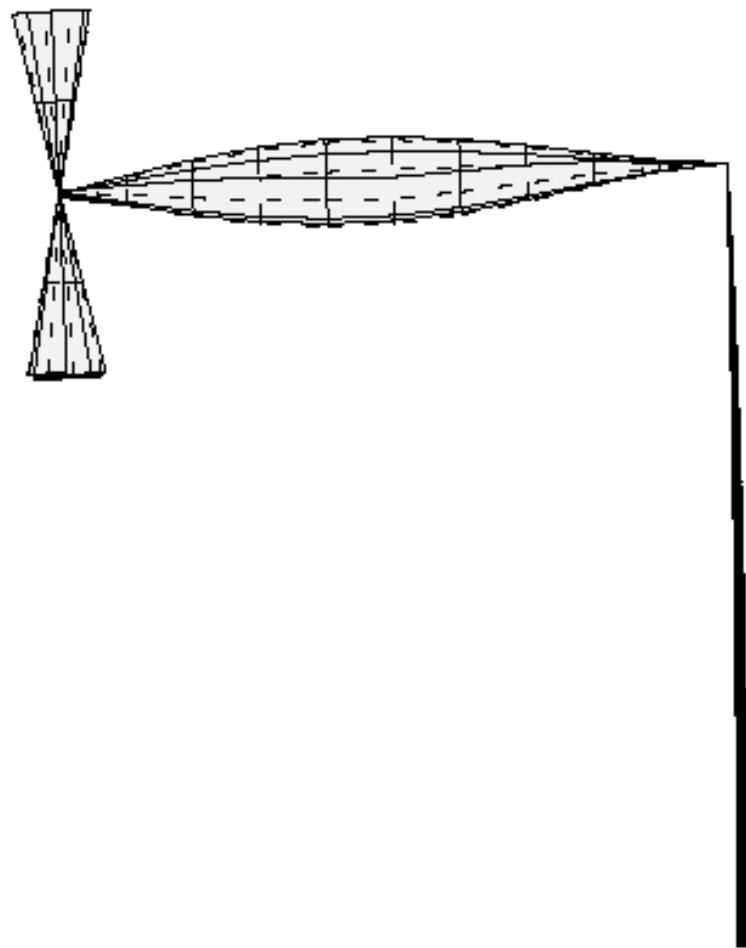


Fig. 28c Close-up end view of the crippling of the T-stringer at the edge of the weld land that first appears as part of eigenvector no. 14 of the “60-degree”, one-ring-bay STAGS model. The buckling load factor is 1.4278. This plot is for the same buckling mode displayed in the previous two figures.

Small component of  
T-stringer rolling. (See  
next figure.)



solution scale = 0.2528E+01  
mode 37, pcr = 0.15450E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

Θ x -180.00  
Θ y 60.00  
Θ z -0.00

Fig. 29a STAGS “60-degree”, one-ring-bay model. This is eigenvector no. 37, in which there is a small component of T-stringer rolling combined with local “pocket” buckling in the acreage shell, buckling of the weld land curved plate, and crippling of the T-stringer. The eigenvalue is 1.5450.

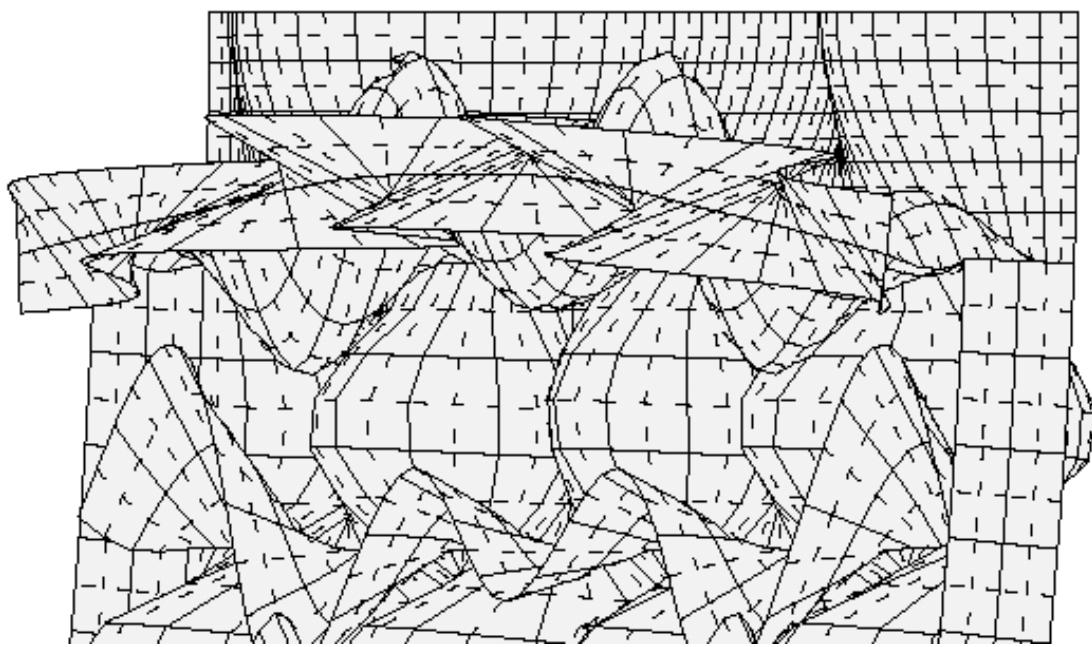
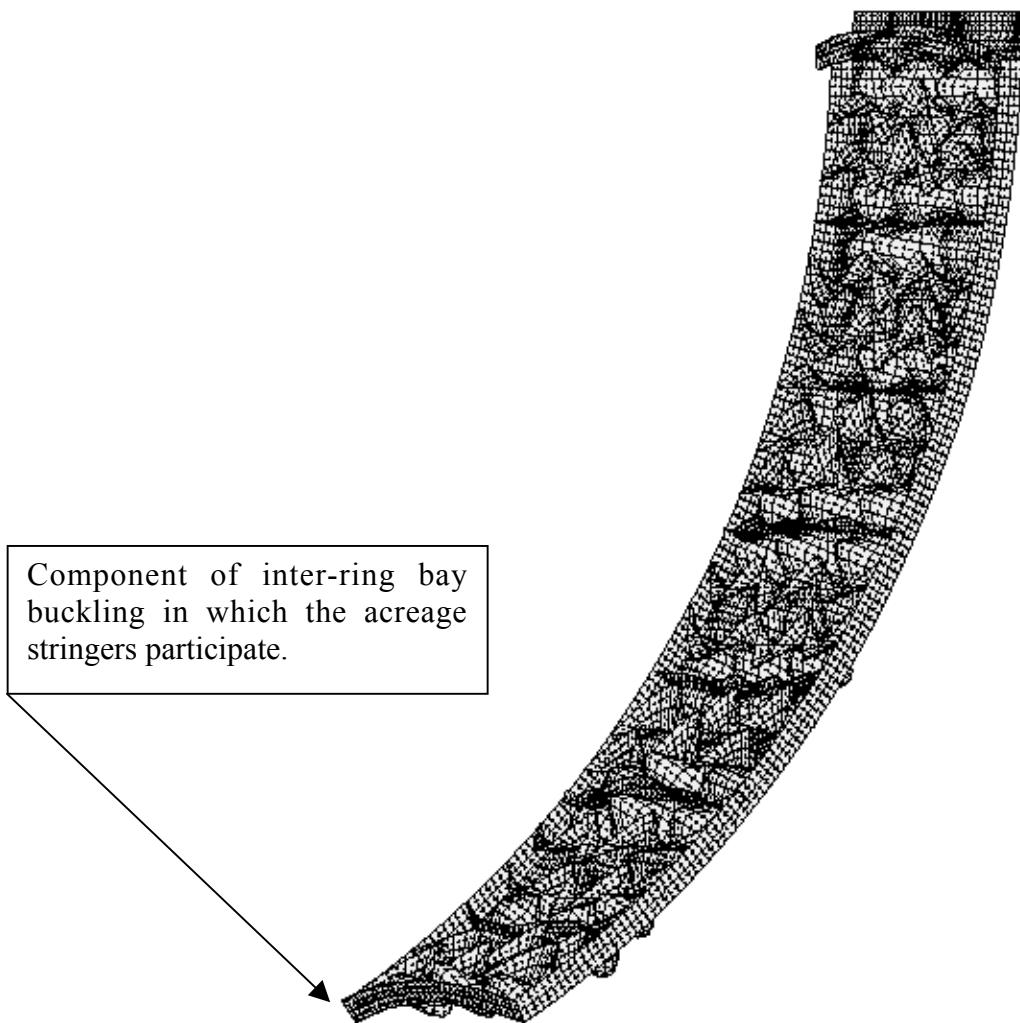


Fig. 29b STAGS “60-degree”, one-ring-bay model. Close-up of eigenvector no. 37, in which there is a small component of T-stringer rolling. The eigenvalue is 1.5450. This is the same buckling mode as that shown in the previous figure. Compare with the next figure.



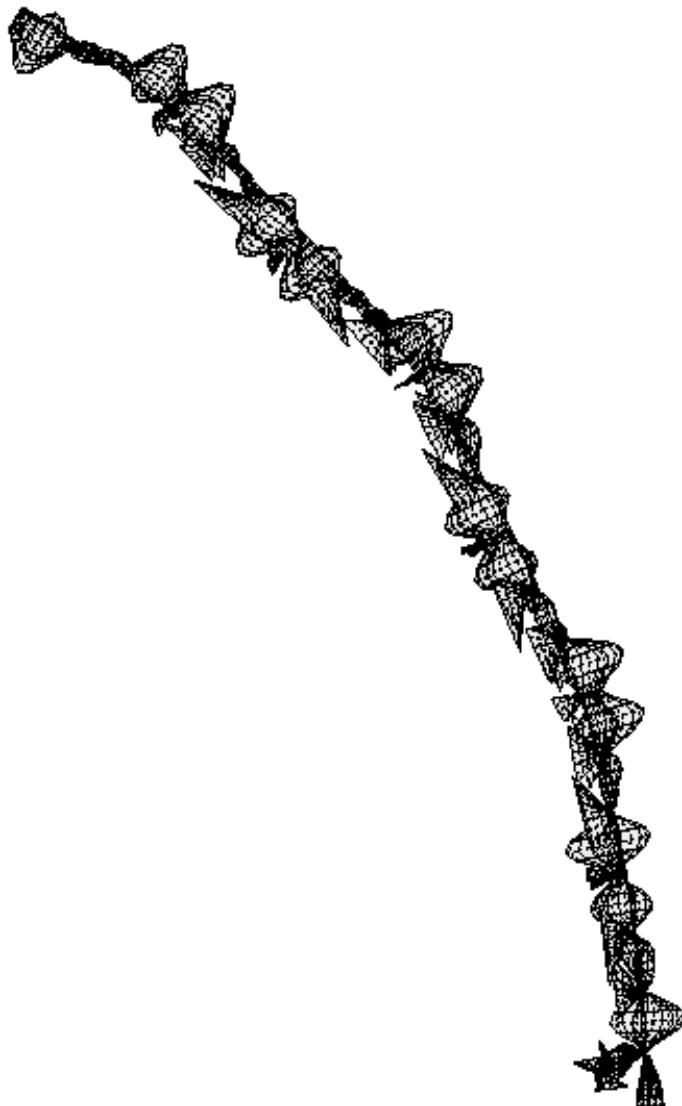
solution scale = 0.4695E+00  
mode 56, pcr = 0.16288E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

Fig. 30 STAGS "60-degree", one-ring-bay model. Close-up of eigenvector no. 56, in which there is a much larger component of T-stringer rolling. The eigenvalue is 1.6288. Compare with the previous figure. Compare with the eigenvalue, 1.668, listed in Table 4 under the "nasacolbend PANEL3" column for the type of buckling called "T-stringer rolling". Compare with Figs. 10 and 11.



solution scale = 0.2374E+01  
mode 102, pcr = 0.21456E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

Fig. 31a STAGS “60-degree”, one-ring-bay model. This is eigenvector no. 102, in which there is a component of inter-ring bay buckling. The eigenvalue is 2.1456. See the next two figures for different views of this same buckling mode. Compare with Fig. 19.



```
solution scale = 0.2372E+01  
mode 102, pcr = 0.21456E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS
```

Fig. 31b STAGS “60-degree”, one-ring-bay model. This is eigenvector no. 102 (same as in the previous figure except this is an end view), in which there is a component of inter-ring bay buckling. The eigenvalue is 2.1456.

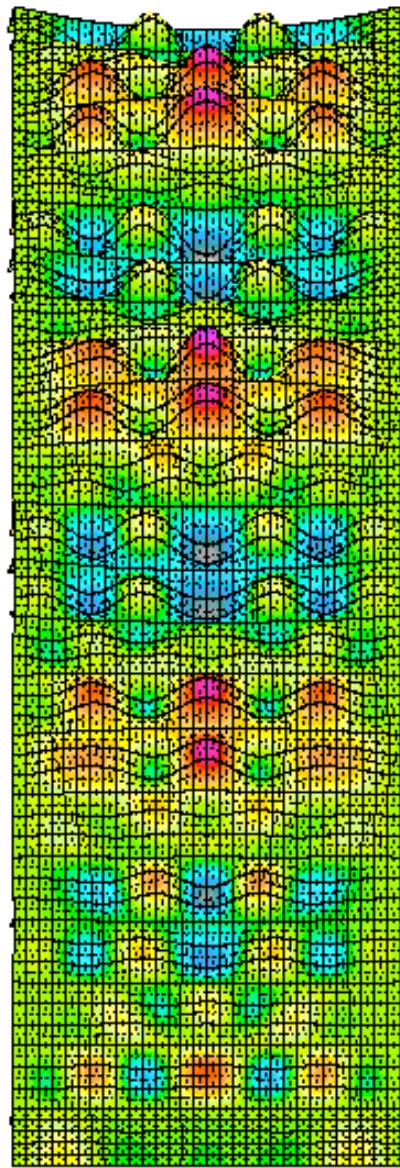


Fig. 31c STAGS “60-degree”, one-ring-bay model. This is eigenvector no. 102 (same as in the previous two figures except this is a plan view fringe plot), in which there is a component of inter-ring bay buckling. The eigenvalue is 2.1456.

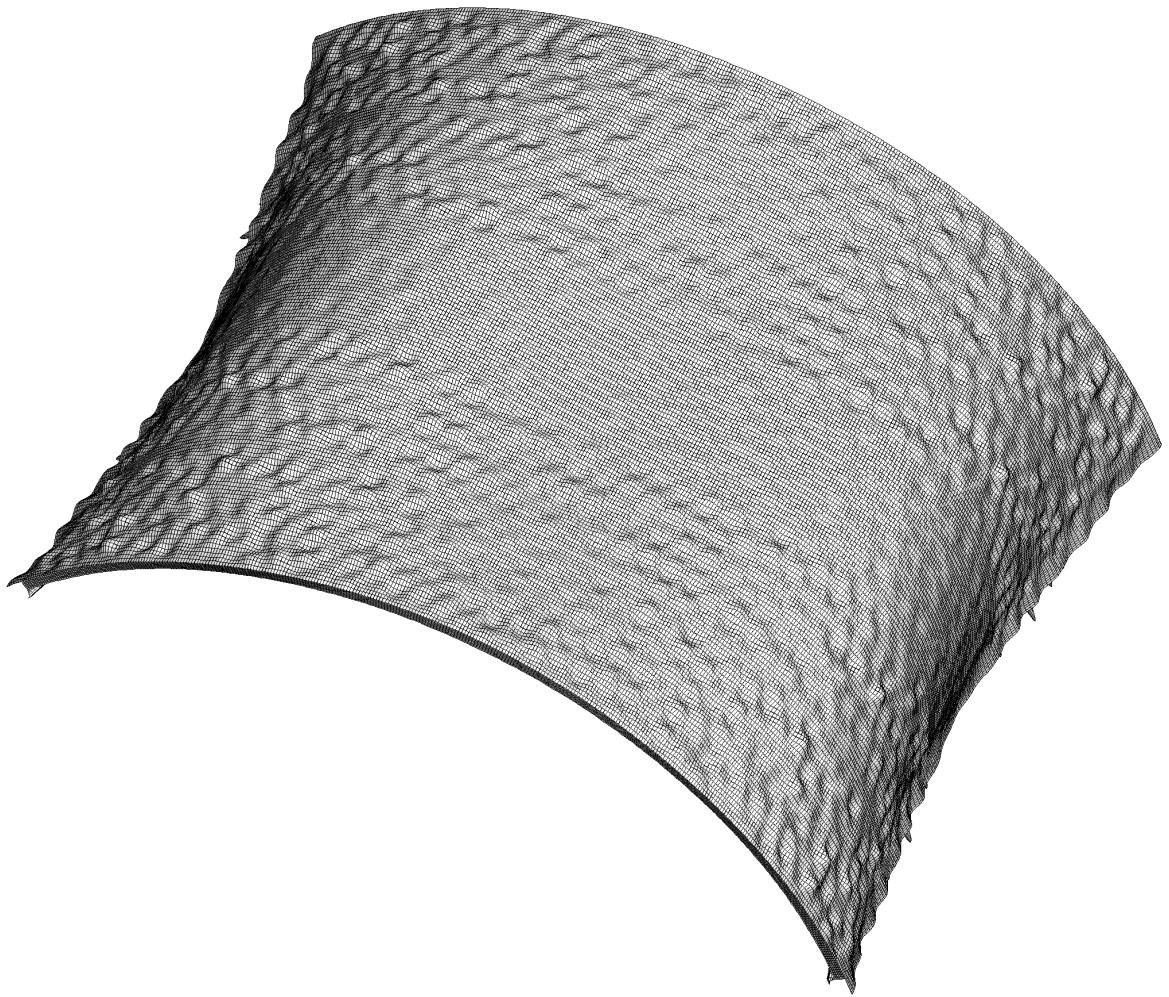


Fig. 32a The critical (lowest) general buckling mode from Thornburgh's elaborate 120-degree STAGS model with T-stiffened weld lands at the symmetry planes at zero and at 120 degrees. The buckling load factor is 2.0599, that is, the total buckling load from linear theory is  $669235 \times 2.0599$  lb. This is the 1147th eigenvector in Thornburgh's model, which has 836514 degrees of freedom. Notice that there is a significant component of local "pocket" buckling as part of this mode shape. This local buckling component gives rise to significant local stress concentrations, as seen from the STAGS nonlinear results plotted in Figs. 35a and 35b.

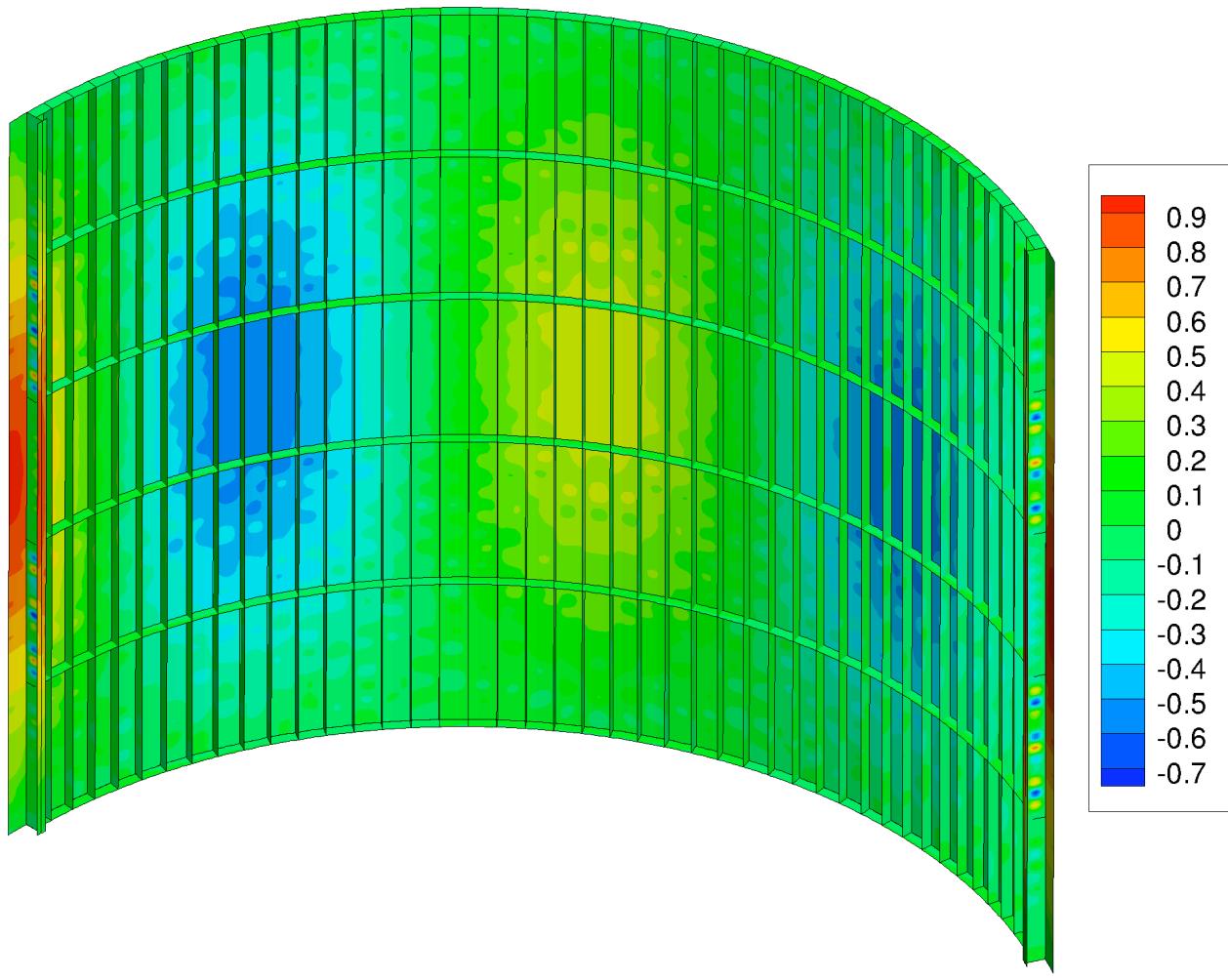


Fig. 32b Another view of the general buckling mode from Thornburgh's 120-degree STAGS model. Symmetry conditions are applied at zero degrees and at 120 degrees where halves of the T-stiffened weld land curved plates have edges. This general buckling mode is used as an initial imperfection with amplitude,  $W_{imp} = 0.125$  inch in Thornburgh's nonlinear STAGS analysis (third trace in Fig. 23).

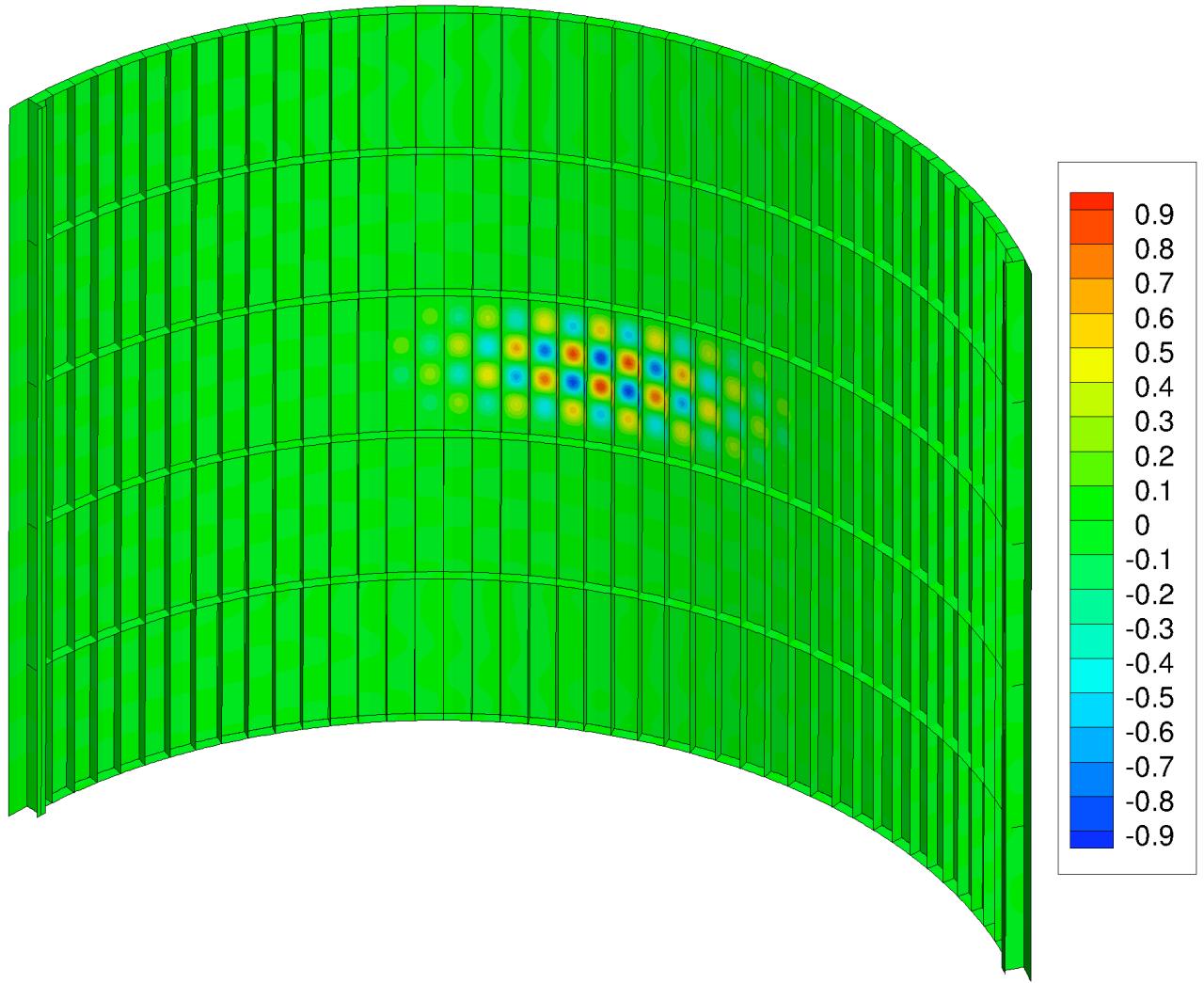


Fig. 33 Local “pocket” buckling in the acreage cylindrical shell from Thornburgh’s elaborate STAGS model. There are 836514 degrees of freedom in Thornburgh’s STAGS model. The STAGS 410 finite element is used. This is the first eigenmode. The buckling load factor is 1.3924. Compare with Figs. 16, 20, and 25-27. See Table 4.

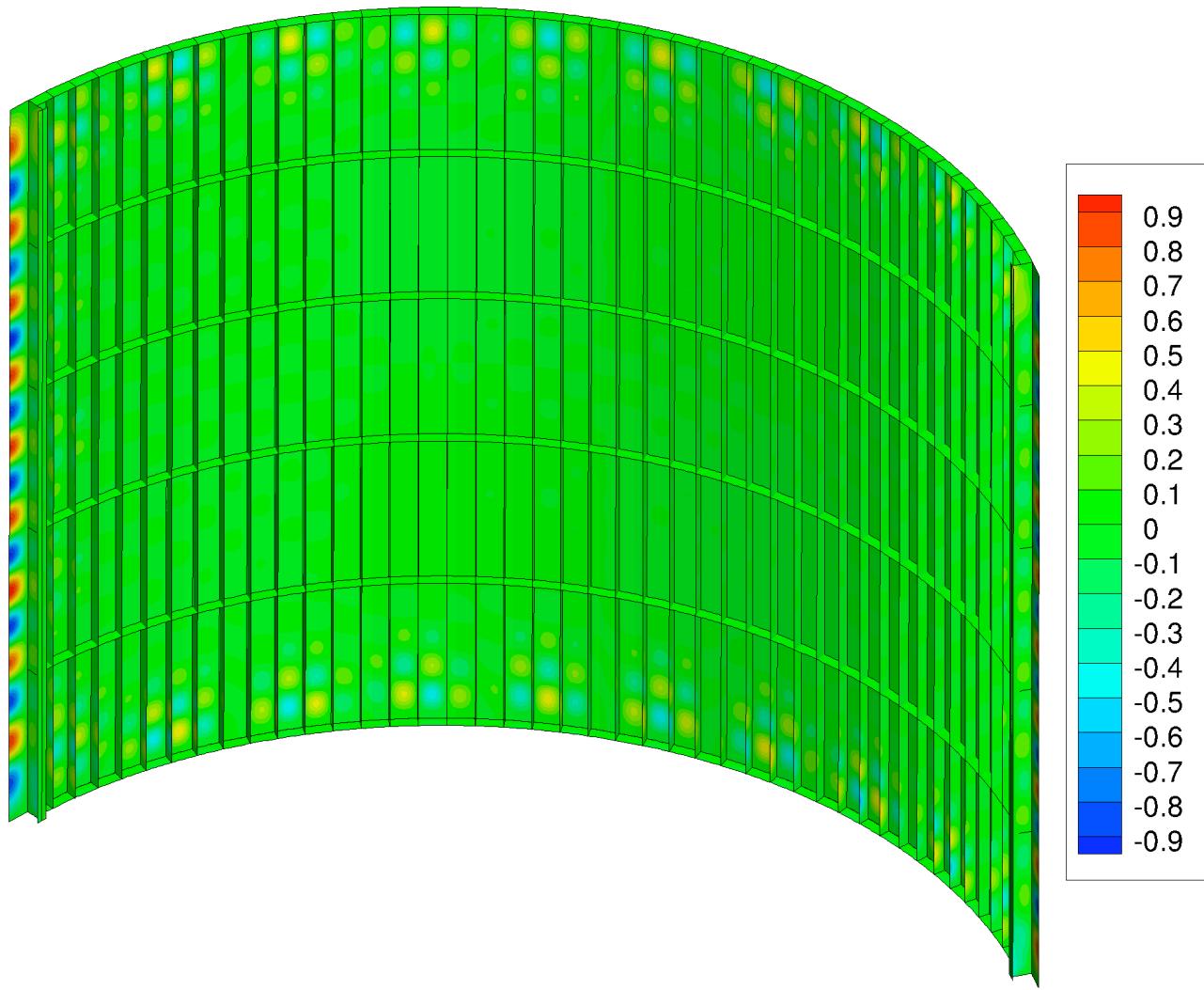


Fig. 34a The critical (lowest) buckling mode in Thornburgh's elaborate STAGS model that corresponds to buckling of the weld land curved plate. The buckling load factor is 1.4345, which gives a total buckling load of  $669235 \times 1.4345$  lb. Compare with the buckling modes shown for the "wcold weld" model in Fig. 12, for the "nasacoldbend PANEL3" model in Fig. 13, and for the "60-degree" STAGS model shown in Figs. 25 – 27. See Table 4.

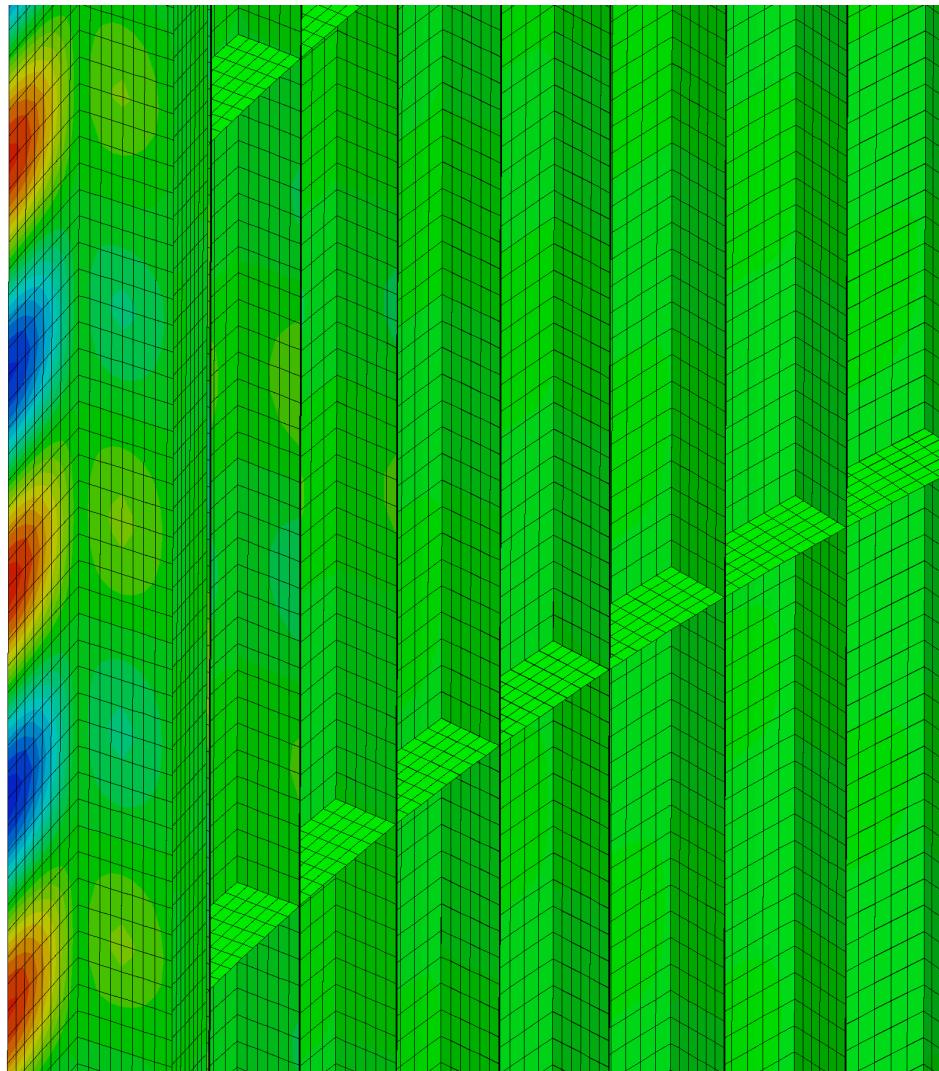
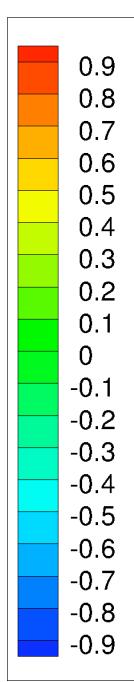


Fig. 34b Close-up of the same buckling mode as that shown in Fig. 34a. From this close-up view it can be seen that the web of the weld land T-stringer participates somewhat in the buckling mode in which the weld land curved plate predominates. Also, the rather dense array of STAGS 410 finite elements used in Thornburgh's very large STAGS model (836514 degrees of freedom) is now visible.

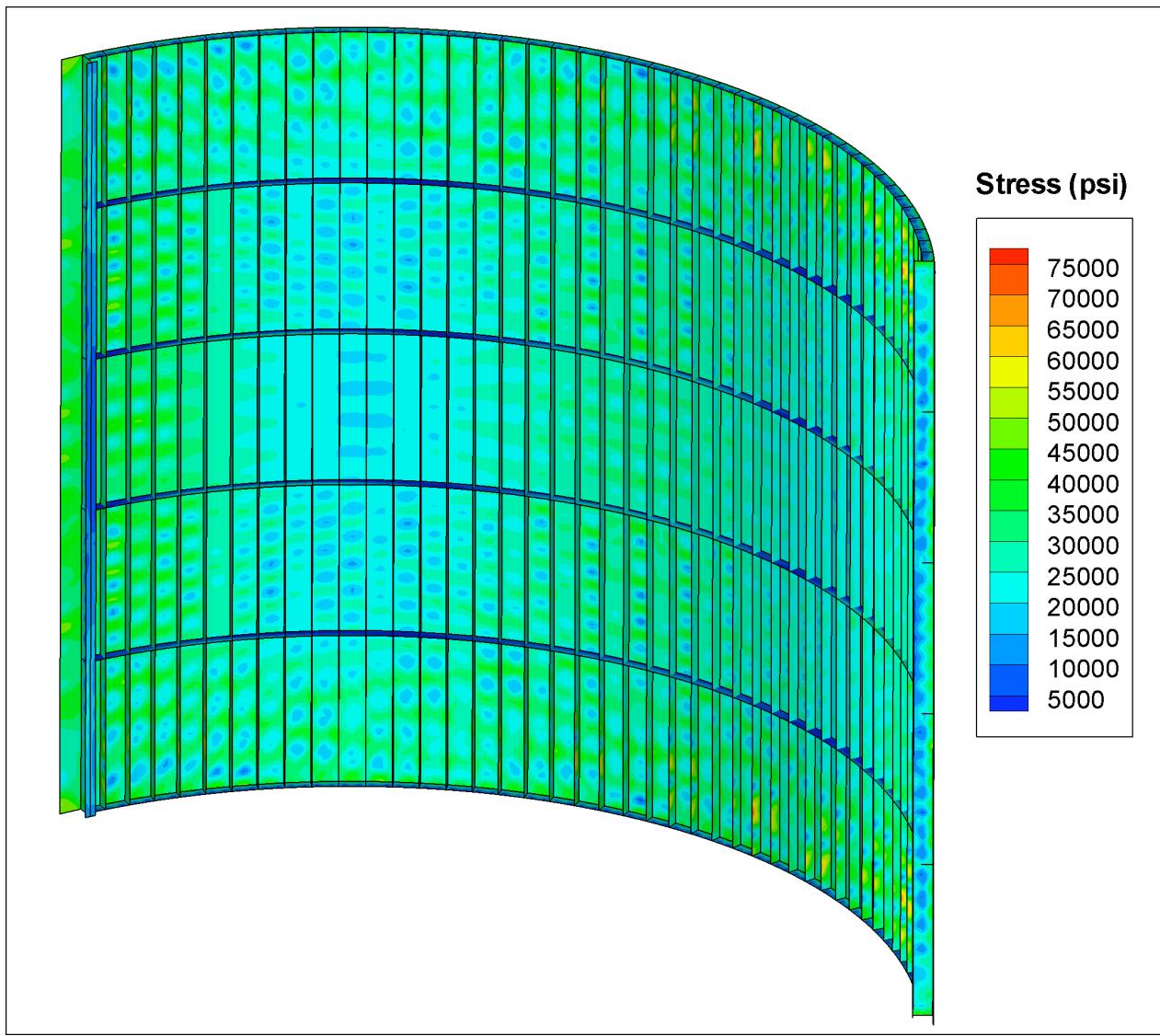


Fig. 35a Effective stress distribution in Thornburg's STAGS model of the axially compressed shell with the linear buckling modal imperfection shape shown in Figs. 32a and 32b at the load factor,  $PA = 1.16$ , which is the static limit load (just before collapse). The maximum allowable stress of the material is specified as 70000 psi in Table 3.

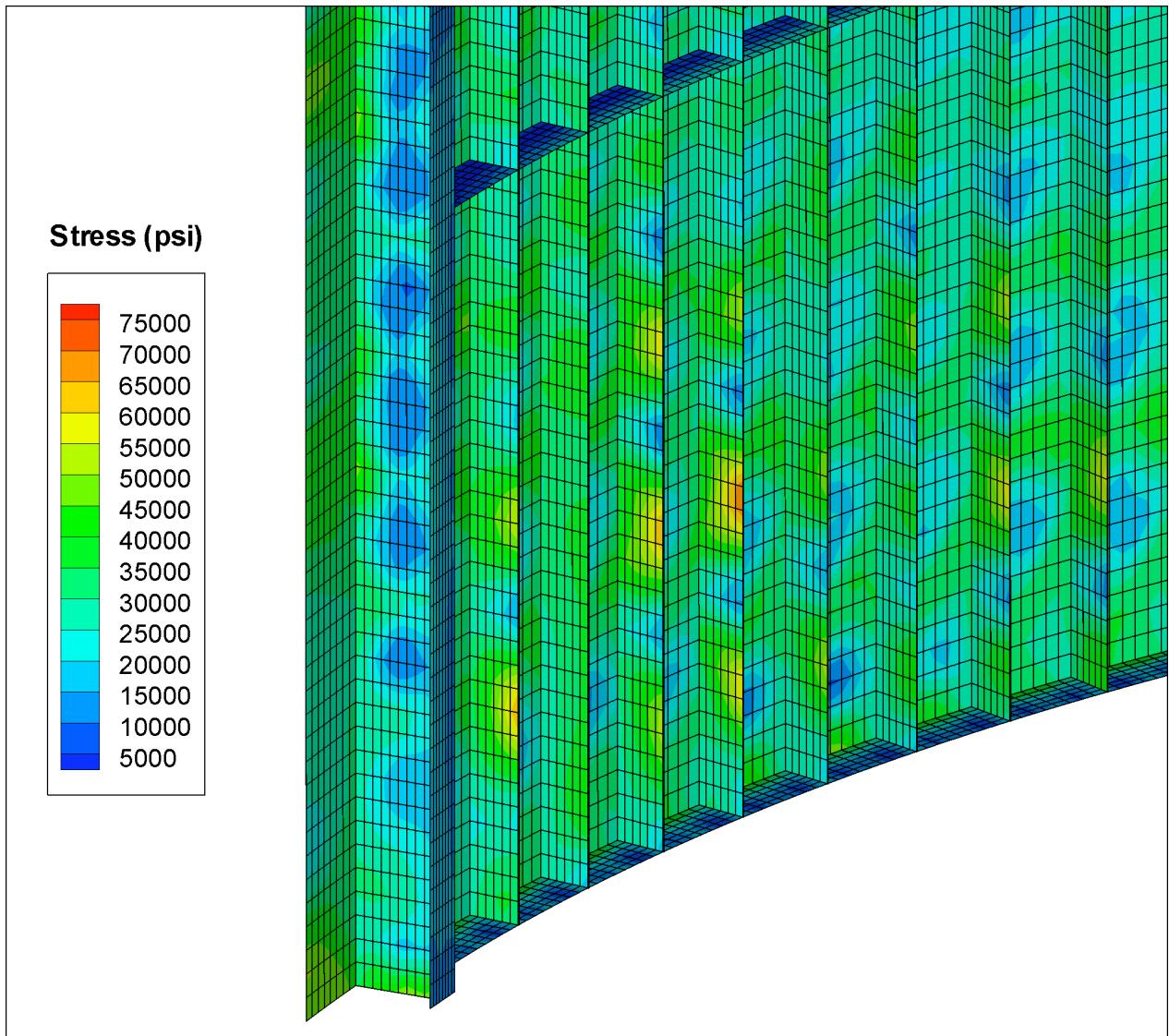


Fig. 35b Close-up view of the effective stress in part of the shell shown in the previous figure. The local stress concentrations exist because the general buckling imperfection shape displayed in Figs. 32a and 32b has small short-wavelength components.

— — Undeformed; This is the optimized orthogrid cylindrical shell without weld lands: wcold.BEHX0  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = -1

**wcold: critical general buckling mode with 3 axial halfwaves; eig.=1.7007**

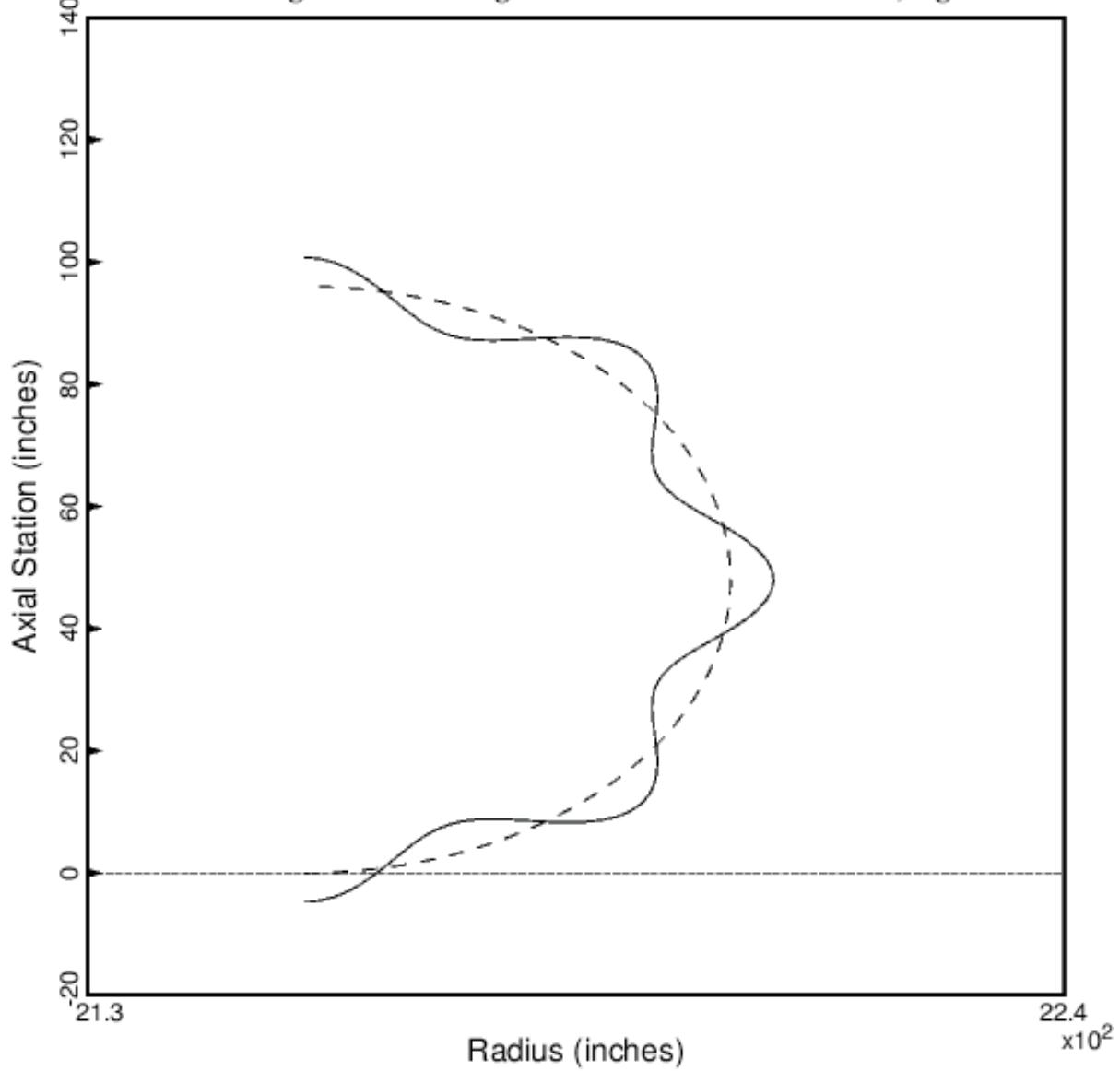


Fig. 36 “wcold” model of general buckling of the acreage cylindrical shell with no weld lands. The “nasacoldbend” acreage cylindrical shell was optimized by PANDA2 with ICONSV = -1. This figure is analogous to Fig. 5.

— Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX1  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = -1

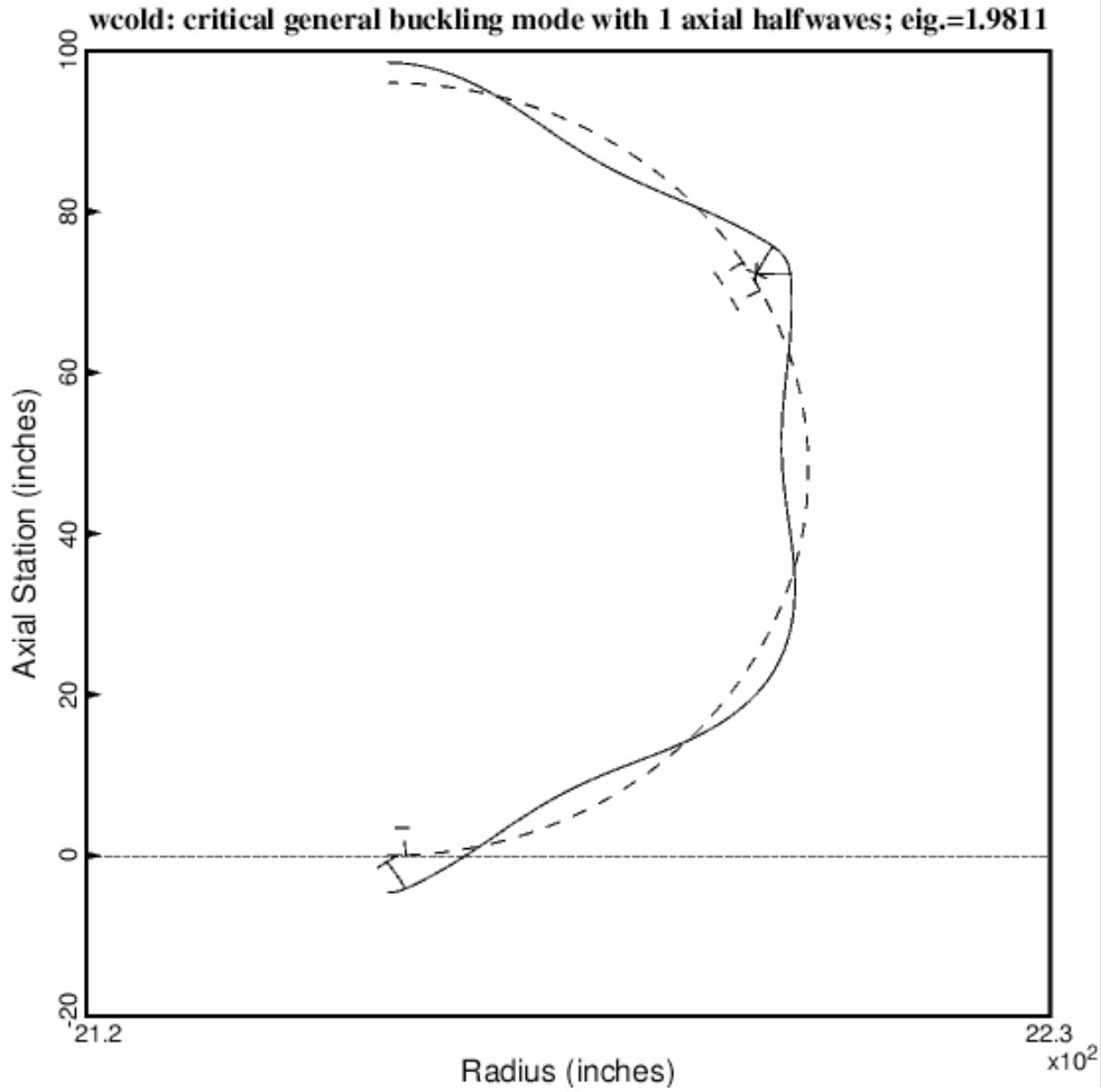


Fig. 37 Optimized “wcold” model of general buckling of a cylindrical shell with three T-stiffened weld lands. This figure is analogous to Fig. 6. The acreage was designed with the PANDA2 conservativeness index, ICONSV = -1.

-- Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX1  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = -1

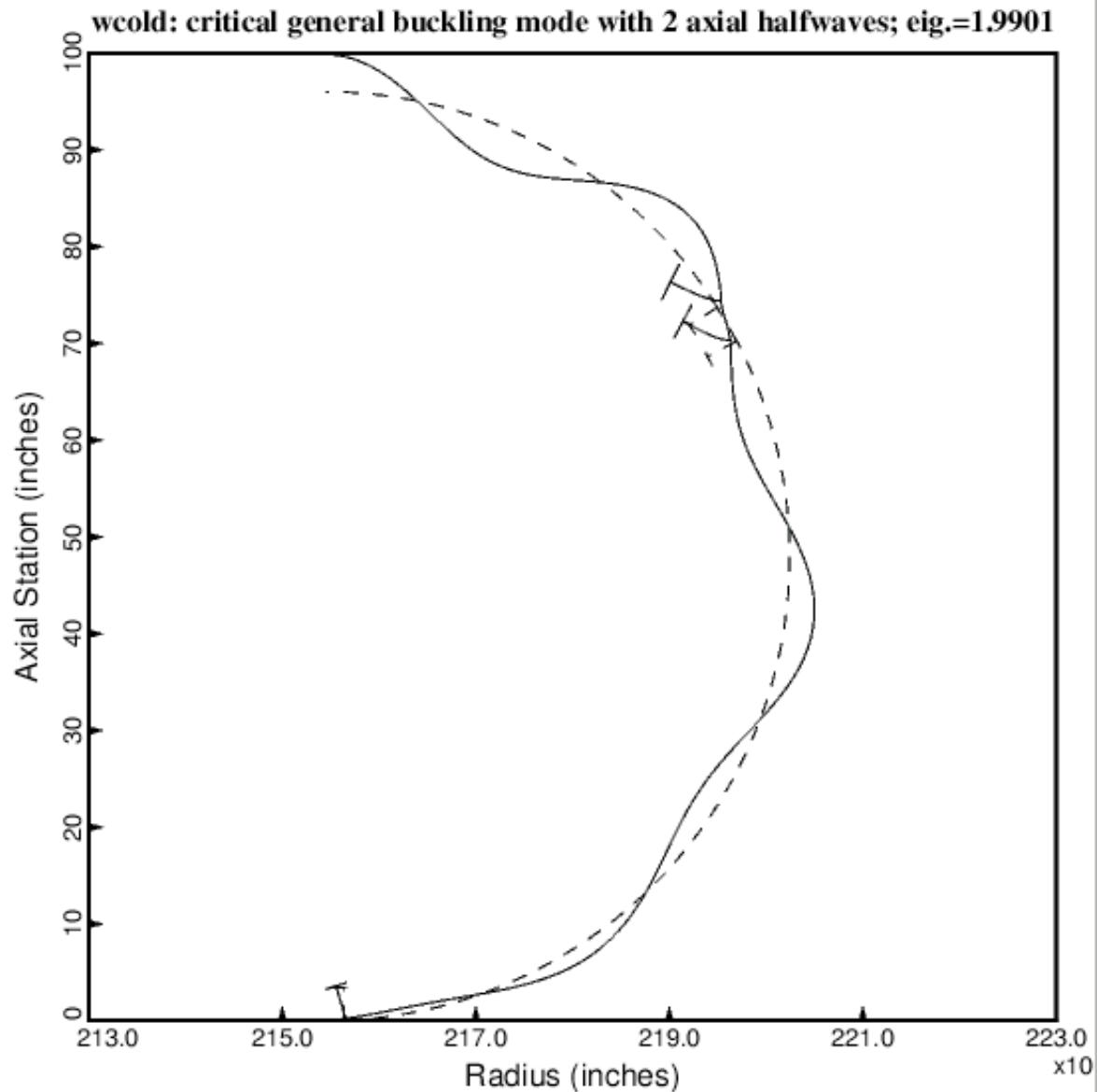


Fig. 38 A second “wcold” general buckling mode for the optimized shell with three T-stiffened weld lands. The acreage was designed with the PANDA2 conservativeness index, ICONSV = -1.

— Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX1  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = -1

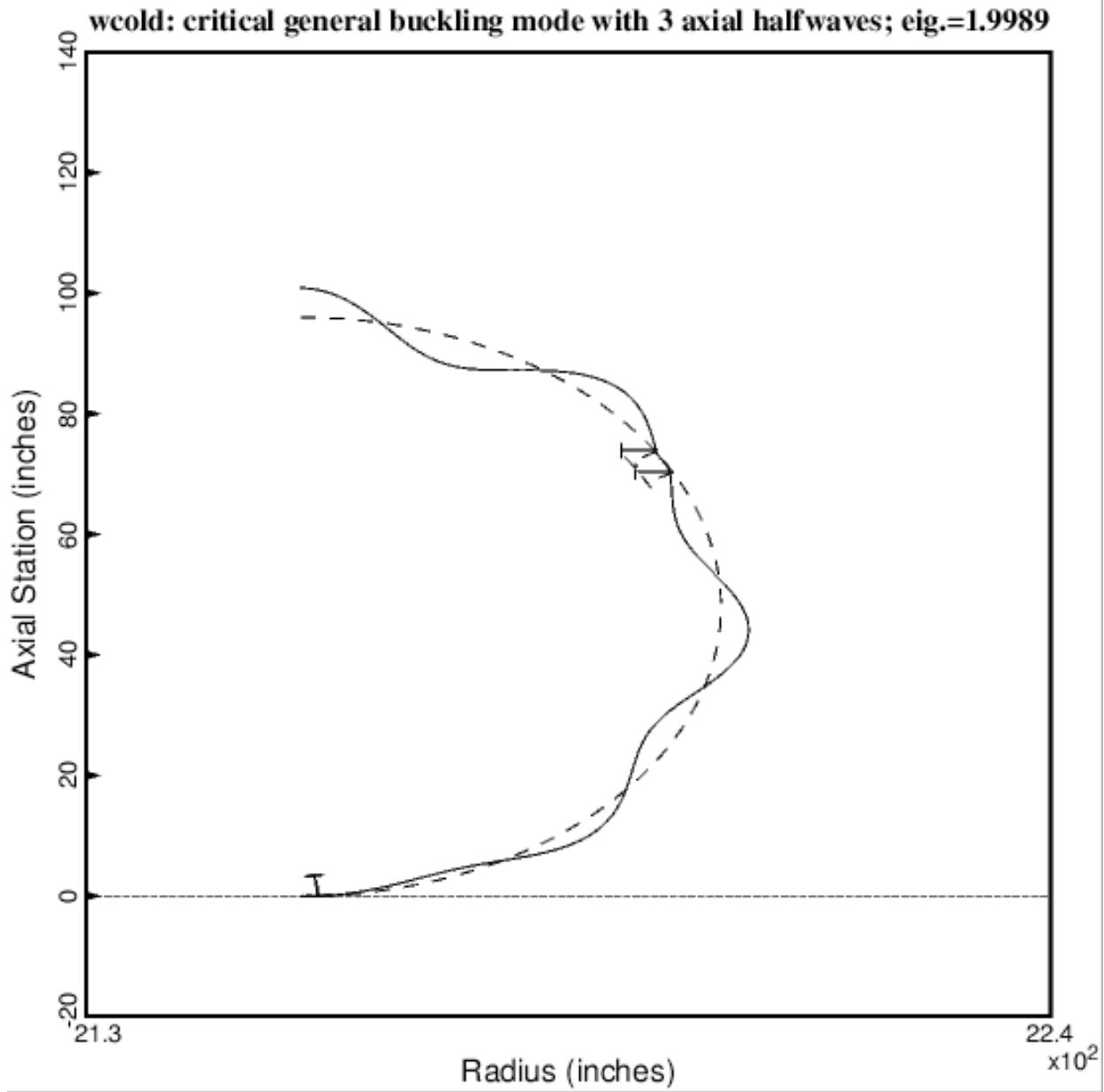


Fig. 39 A third “wcold” general buckling mode for the optimized shell with three T-stiffened weld lands. The acreage was designed with the PANDA2 conservativeness index, ICONSV = -1.

-- Undeformed; This is the optimized orthogrid cylindrical shell with weld lands: wcold.BEHX2  
— Deformed: The shell acreage was optimized with the conservativeness index, ICONSV = -1

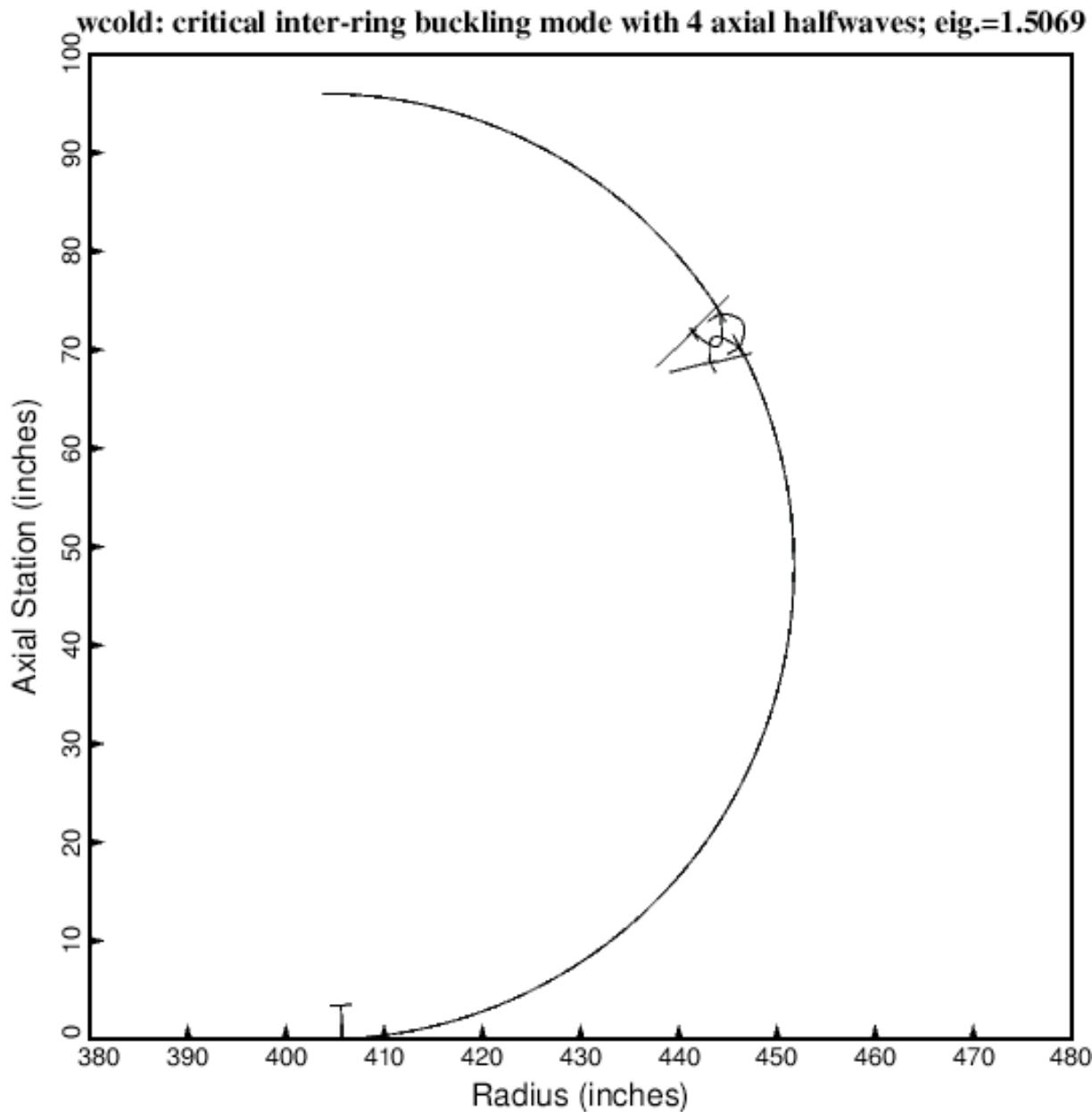
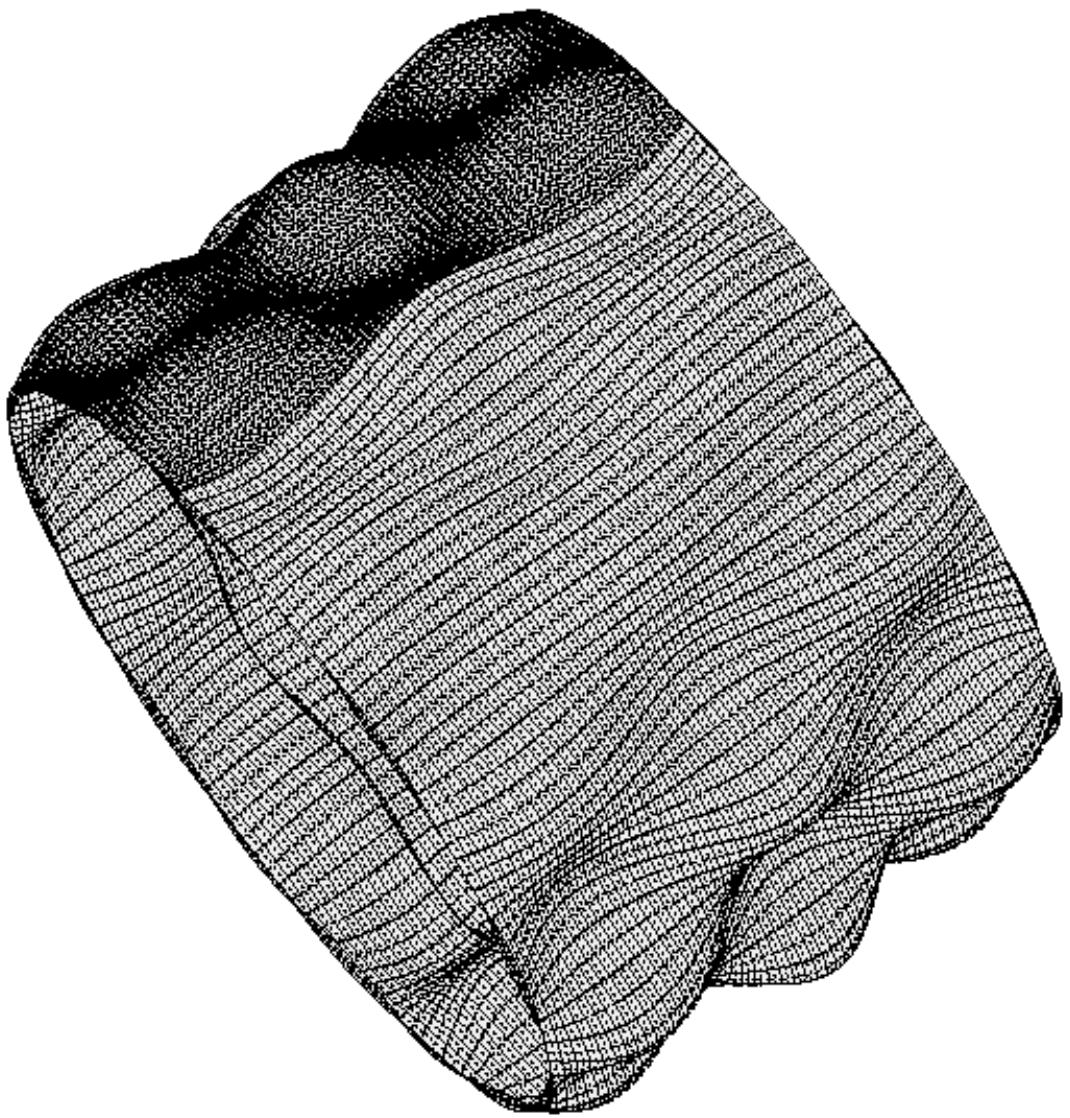


Fig. 40 Inter-ring buckling of the optimized “wcold” cylindrical shell with three T-stiffened weld lands. This figure is analogous to Fig. 12. The acreage was designed with the PANDA2 conservativeness index, ICONSV = -1.



solution scale = 0.6727E+01; re-optimized nasacoldbend, ICONSV=-1; compound model; general buckling mode  
pcr=1.8061; PANDA2 gets pcr=1.715 for ICONSV = -1  
This is eigenvalue and eigenmode no. 119; STAGS index ILIN = 1  
linear buckling of perfect shell from STAGS; This mode is used as an imperfection shape

$\Theta_x$  -35.84       $\Theta_y$  -13.14       $\Theta_z$  35.63  
y z x

Fig. 41 Compound STAGS model of general buckling of the optimized “nasa coldbend” acreage shell without any weld lands. The shell was optimized with  $ICONSV = -1$ . This figure is analogous to Fig. 21.

- End shortening  $u$  at nodal point 1 for "compound" model, no weld land, acreage optimized with ICONSV=1
- End shortening  $u$  at nodal point 1 for "compound" model, no weld land, acreage optimized with ICONSV=-1

### End shortening $u$ at nodal point 1 for acreage "compound" model

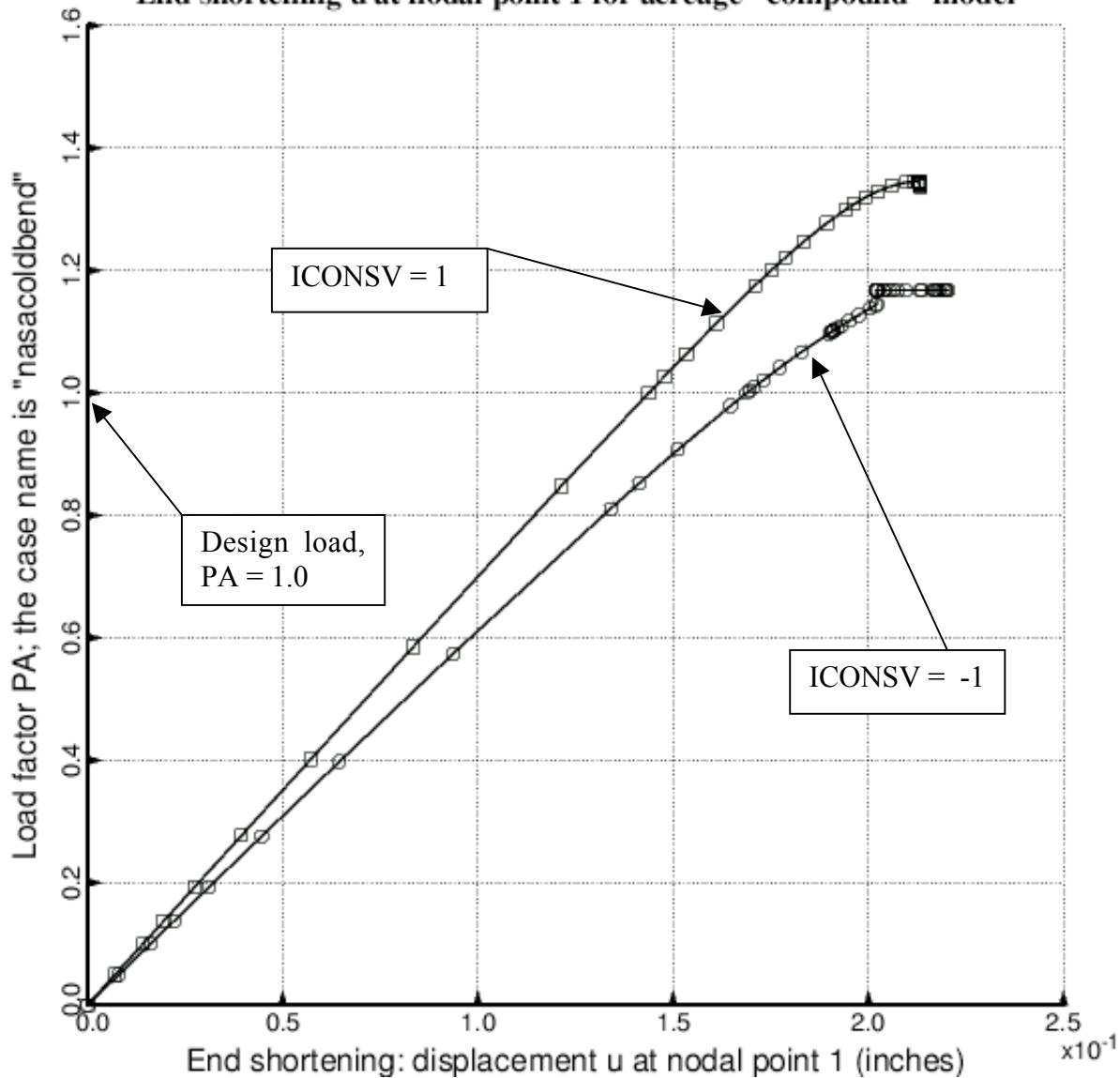


Fig. 42 Load displacement curves from STAGS for the optimized "nasacoldbend" acreage cylindrical shells without weld lands, showing the effect of the PANDA2 conservativeness index, ICONSV. The design load, 669235 lb corresponds to the STAGS load factor, PA = 1.0.

— — Undeformed; T-stringer web height must be less than 10 x web thickness; same with flange  
— Deformed; General buckling of the cylindrical shell with T-stiffened weld lands

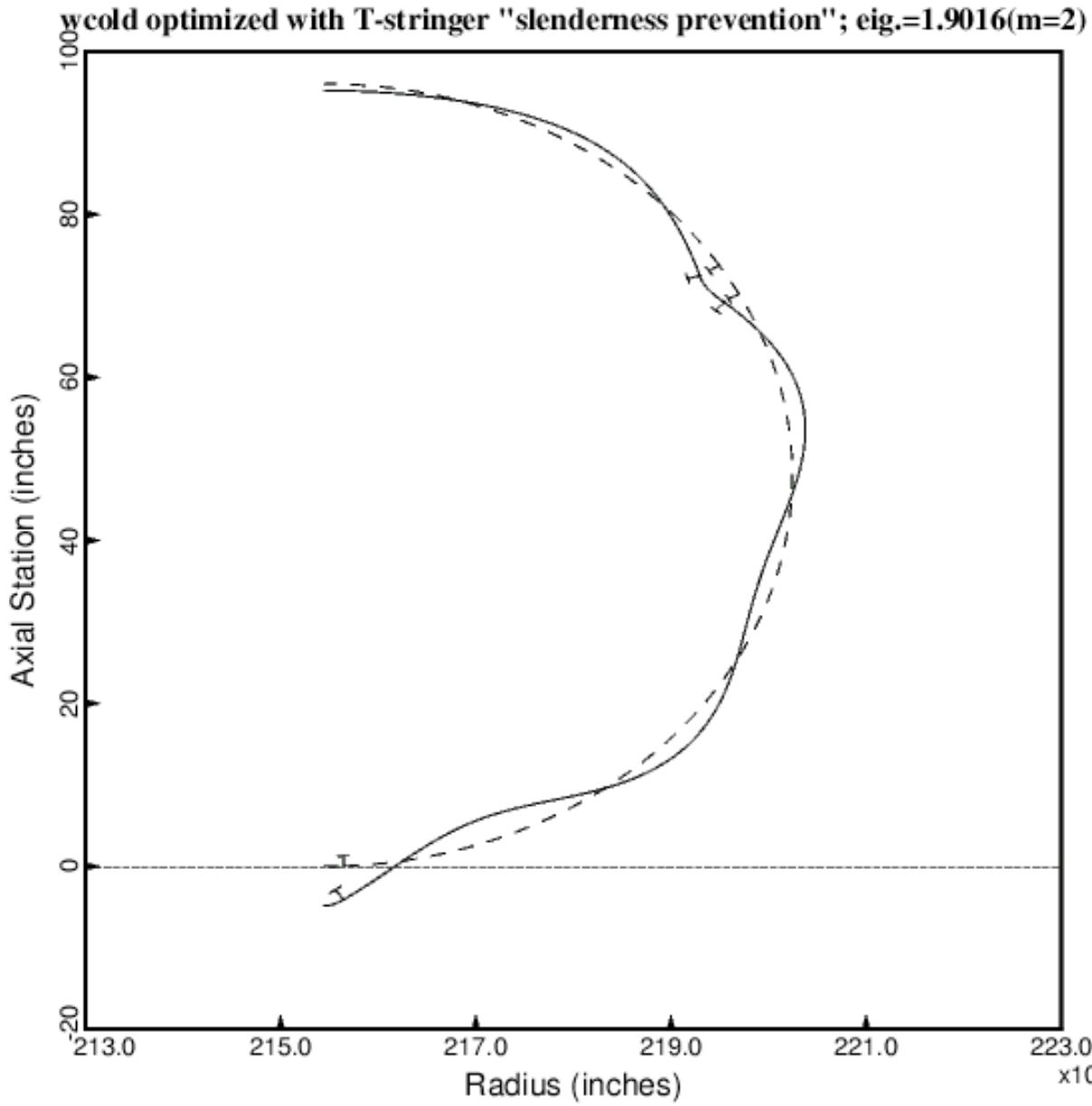
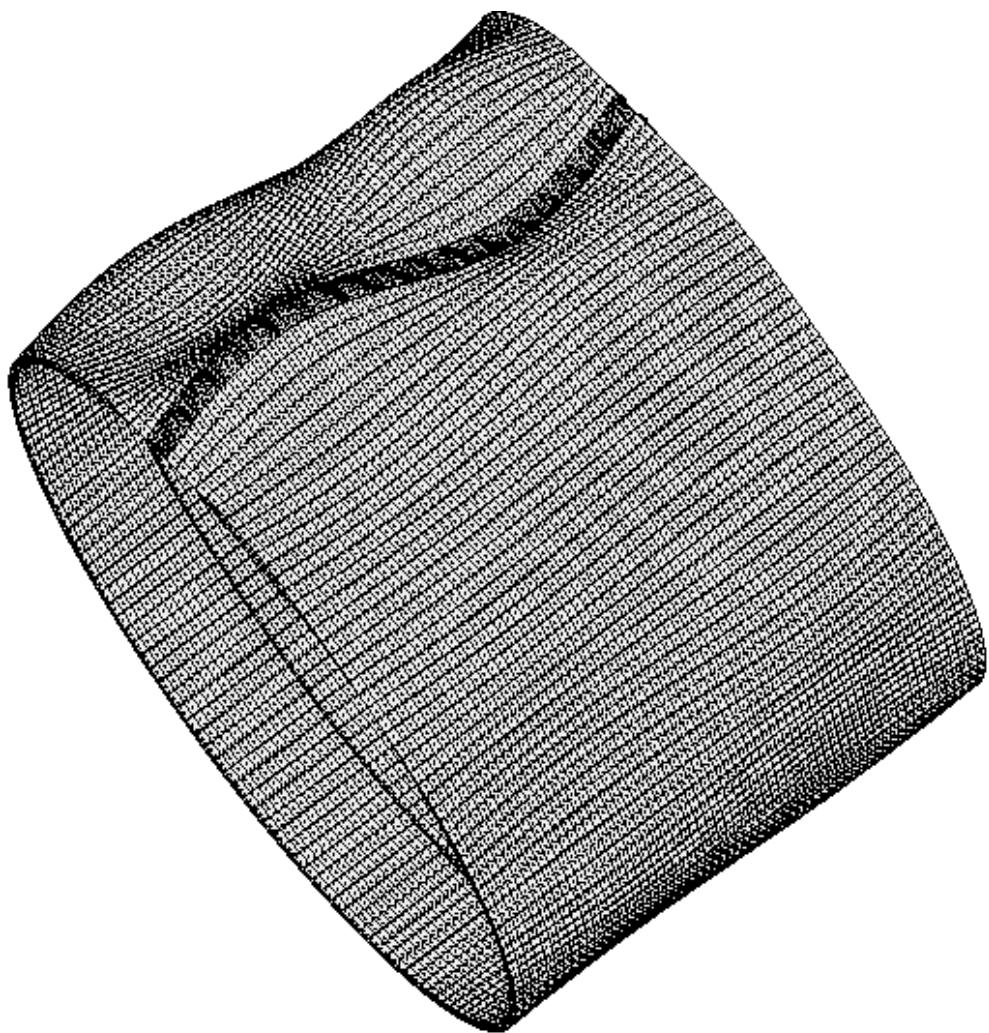


Fig. 43 General buckling of optimized “wcold” cylindrical shell with constraints placed upon the web and outstanding flange slenderness during optimization cycles. (HWLAND < 10 x TWLAND and WFLAND < 10 x TFLAND). This figure is analogous to Fig. 6



solution scale = 0.7668E+01  
mode 15, pcr = 0.19022E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

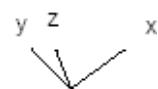


Fig. 44 Compound STAGS model of the “wcold” cylindrical shell optimized with constraints on the T-stringer web and outstanding flange slenderness ratios. This figure is analogous to Fig. 22. The critical (lowest) general buckling load factor is 1.9022, which corresponds to the 15th eigenvalue.

-- Undeformed; T-stringer web height must be less than 10 x web thickness; same with flange  
— Deformed; Inter-ring buckling of the cylindrical shell with T-stiffened weld lands

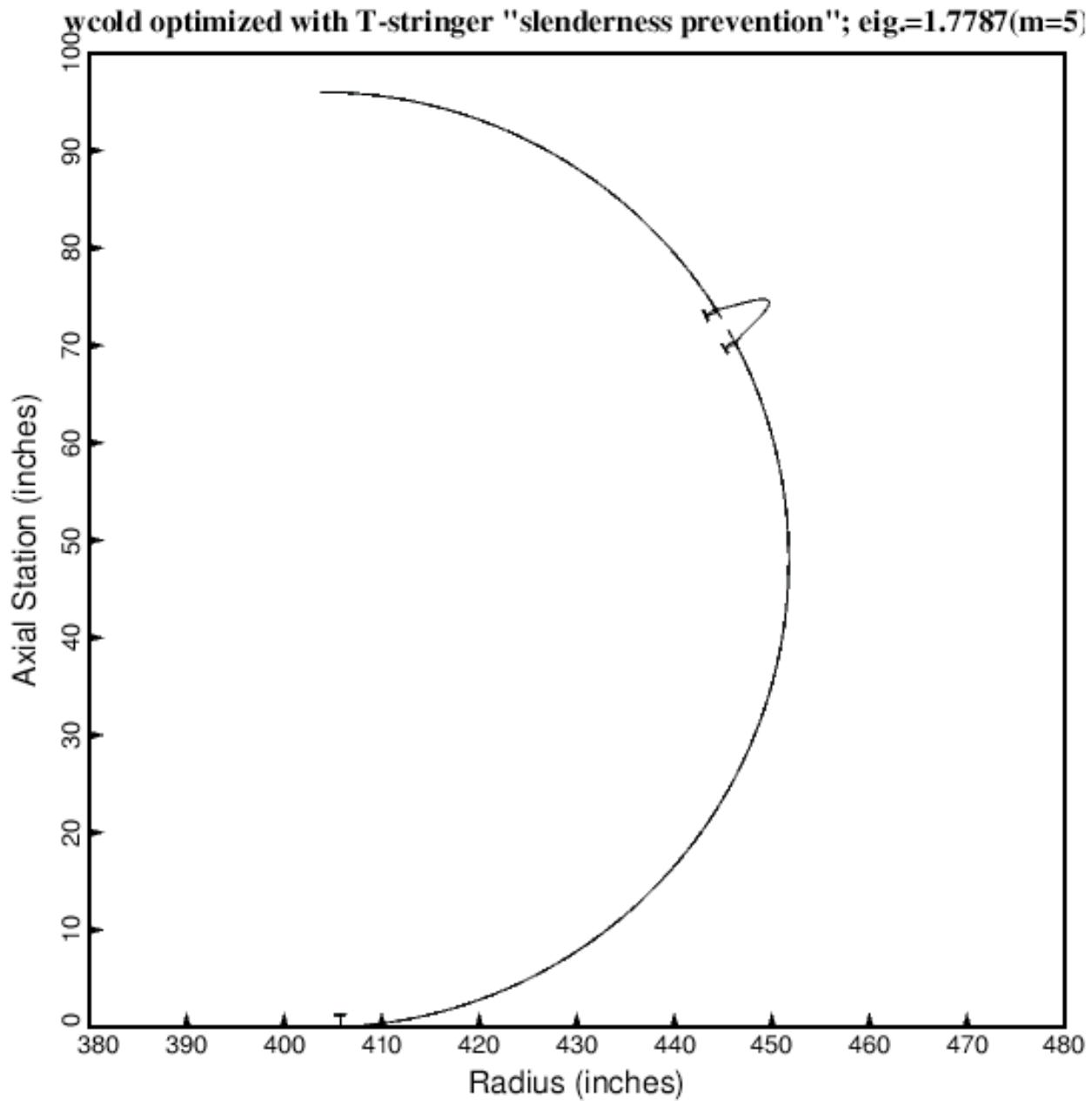
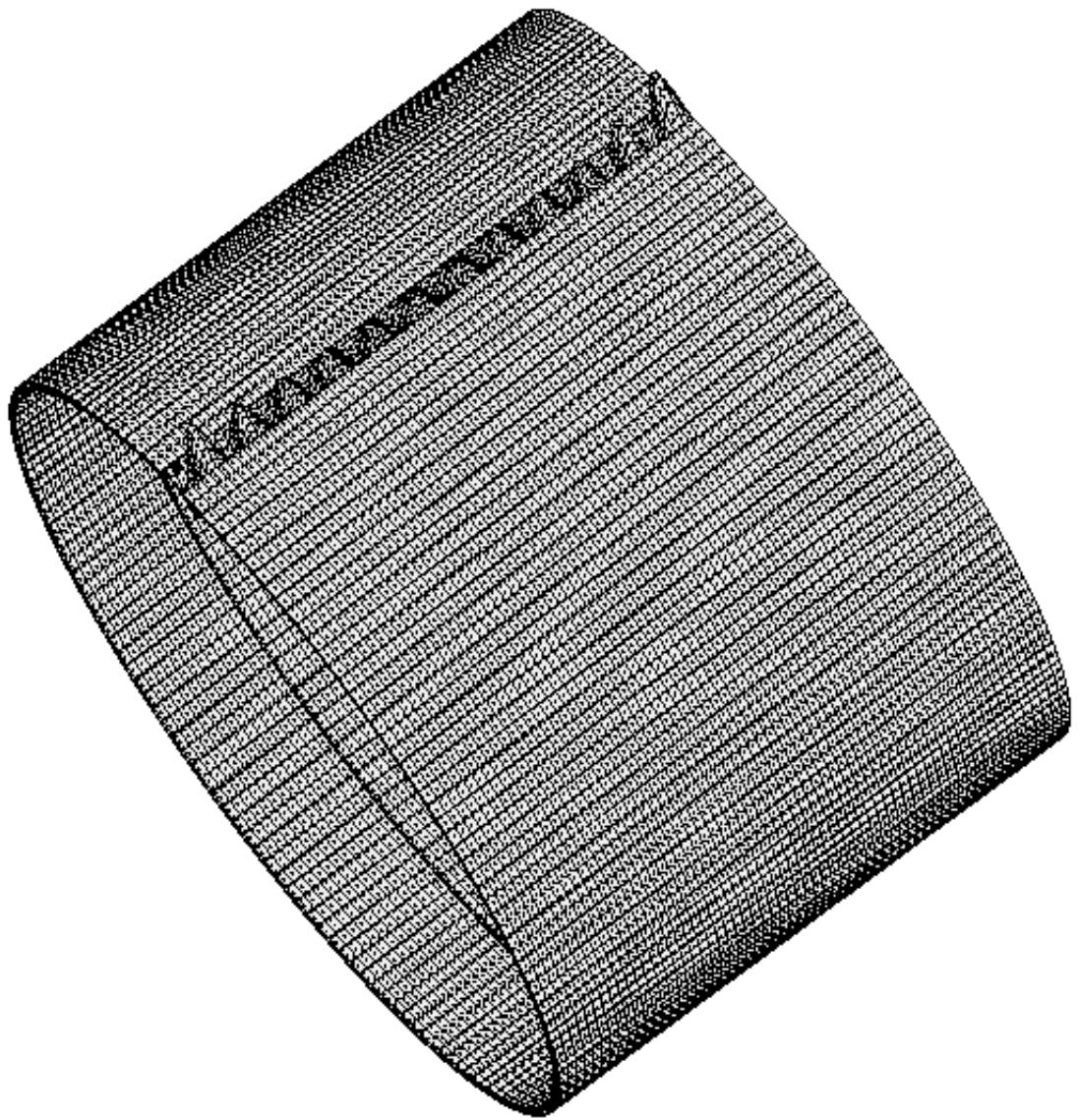


Fig. 45 Inter-ring buckling of optimized “wcold” shell with constraints on the slenderness ratios of the T-stringer web and outstanding flange. This figure is analogous to Fig. 12.



solution scale = 0.7717E+01  
mode 1, pcr = 0.17112E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

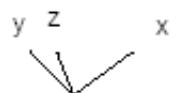


Fig. 46 Compound STAGS model 1 of the "wcold" cylindrical shell optimized with constraints on the T-stringer web and outstanding flange slenderness ratios. This figure is analogous to the previous figure. The buckling load factor is 1.7112, which is the first (lowest) eigenvalue for the STAGS model 1.

- Imperfection shape has 2 axial half waves (Fig.44);  $W_{imp}=+0.125$  inch; there is one weld land
- Imperfection shape has 1 axial half wave (Fig.49);  $W_{imp}=-0.125$  inch; there is one weld land
- △ Imperfection shape has 1 axial half wave (Fig.54);  $W_{imp}=-0.125$  inch; elaborate 180-degree model
- + Imperfection shape has 2 axial half waves; antisymmetric (Fig.50);  $W_{imp}=+0.125$  inch; there is one weld land
- × Imperfection shape has 3 axial half waves (Fig.51);  $W_{imp}=+0.125$  inch; there is one weld land
- ◊ Imperfection shape has 1 axial half wave (Fig.54);  $W_{imp}=+0.125$  inch; elaborate 180-degree model

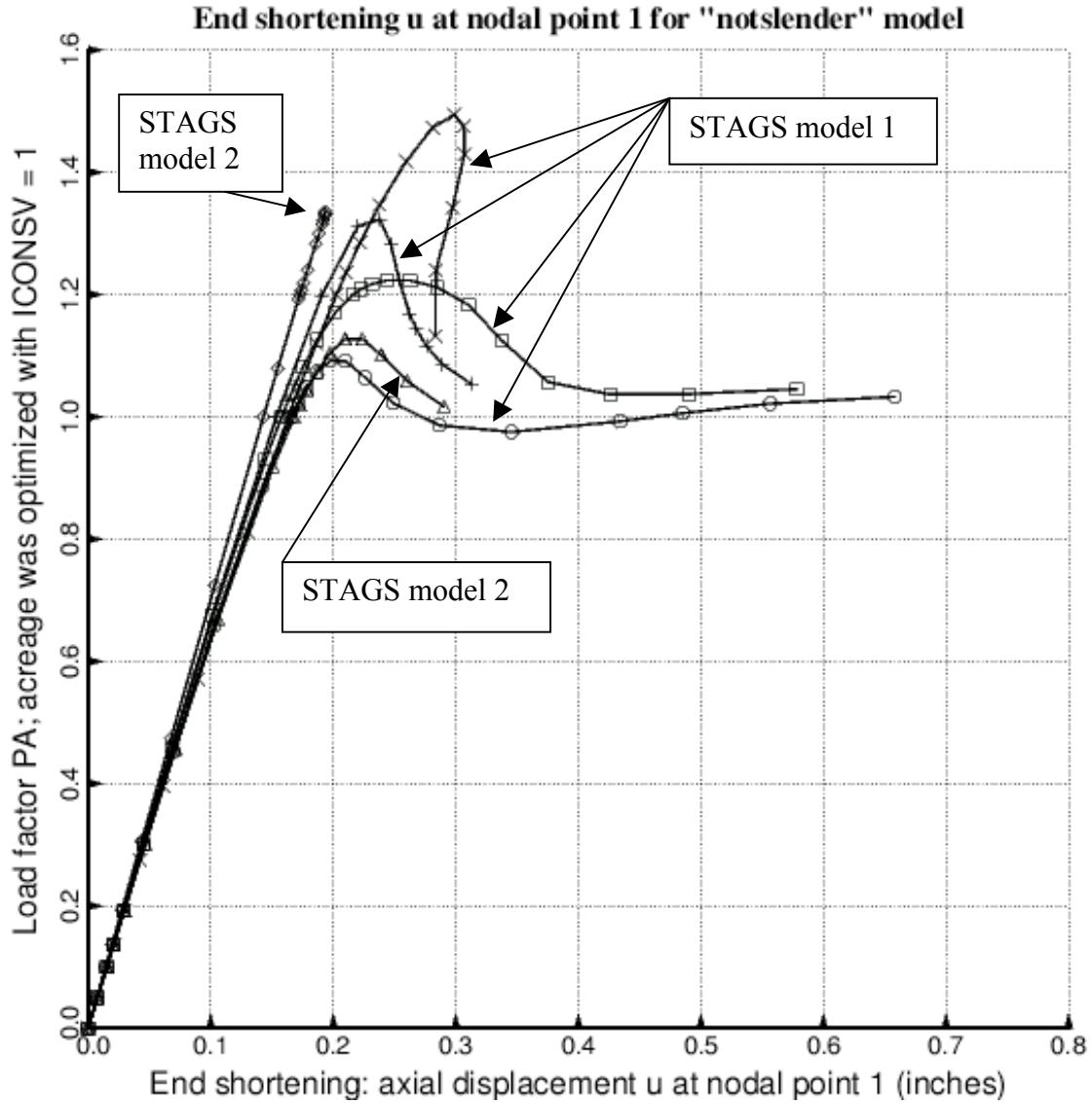


Fig. 47 Load-deflection curves from STAGS compound models of imperfect optimized “wcold” cylindrical shells with constraints on the slenderness ratios of T-stringer web and outstanding flange. The various general buckling modal imperfection shapes are shown in Figs. 44, 49 – 51, and 54. The design load, 669345 lb, corresponds to  $PA = 1.0$ .

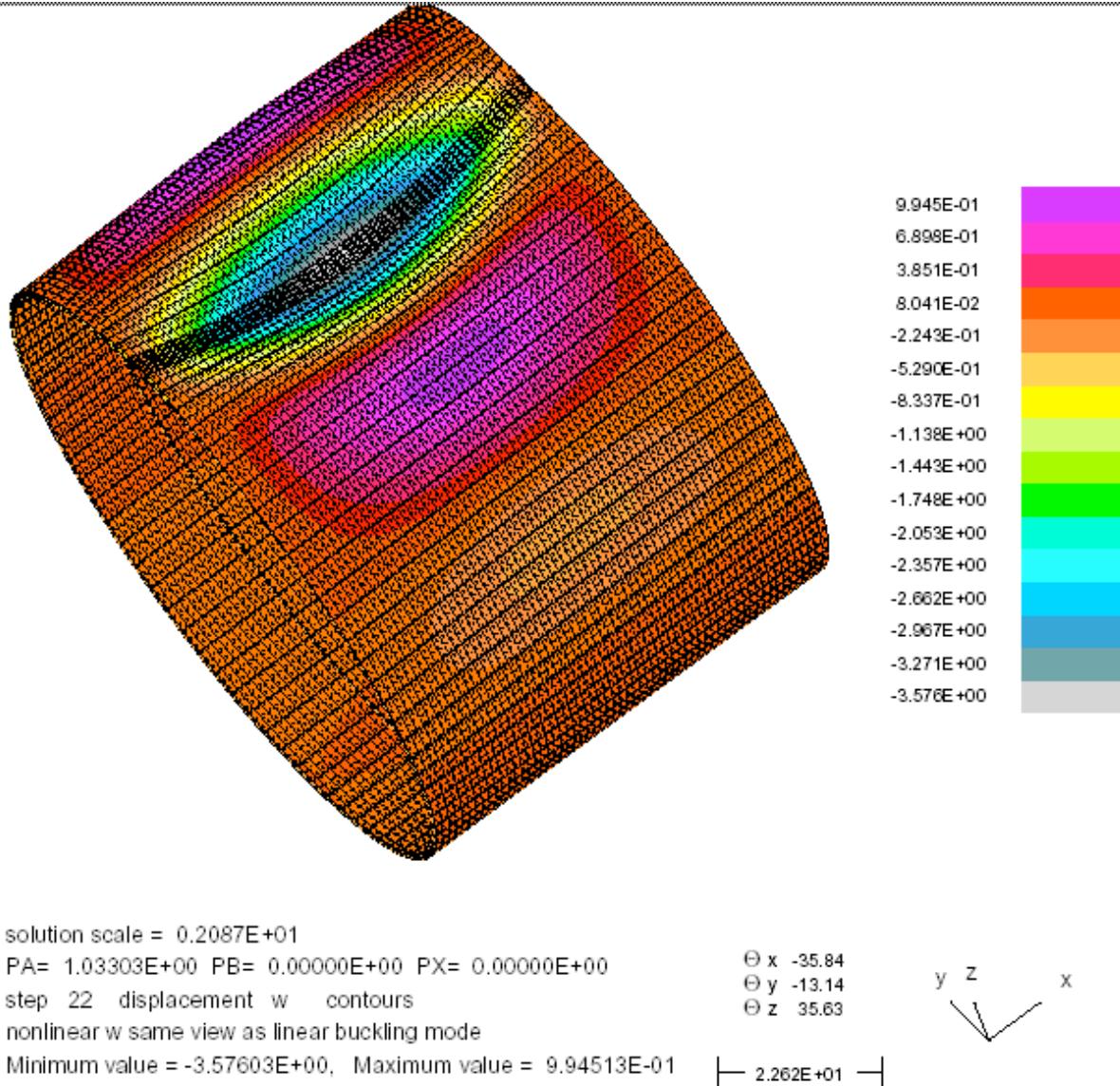
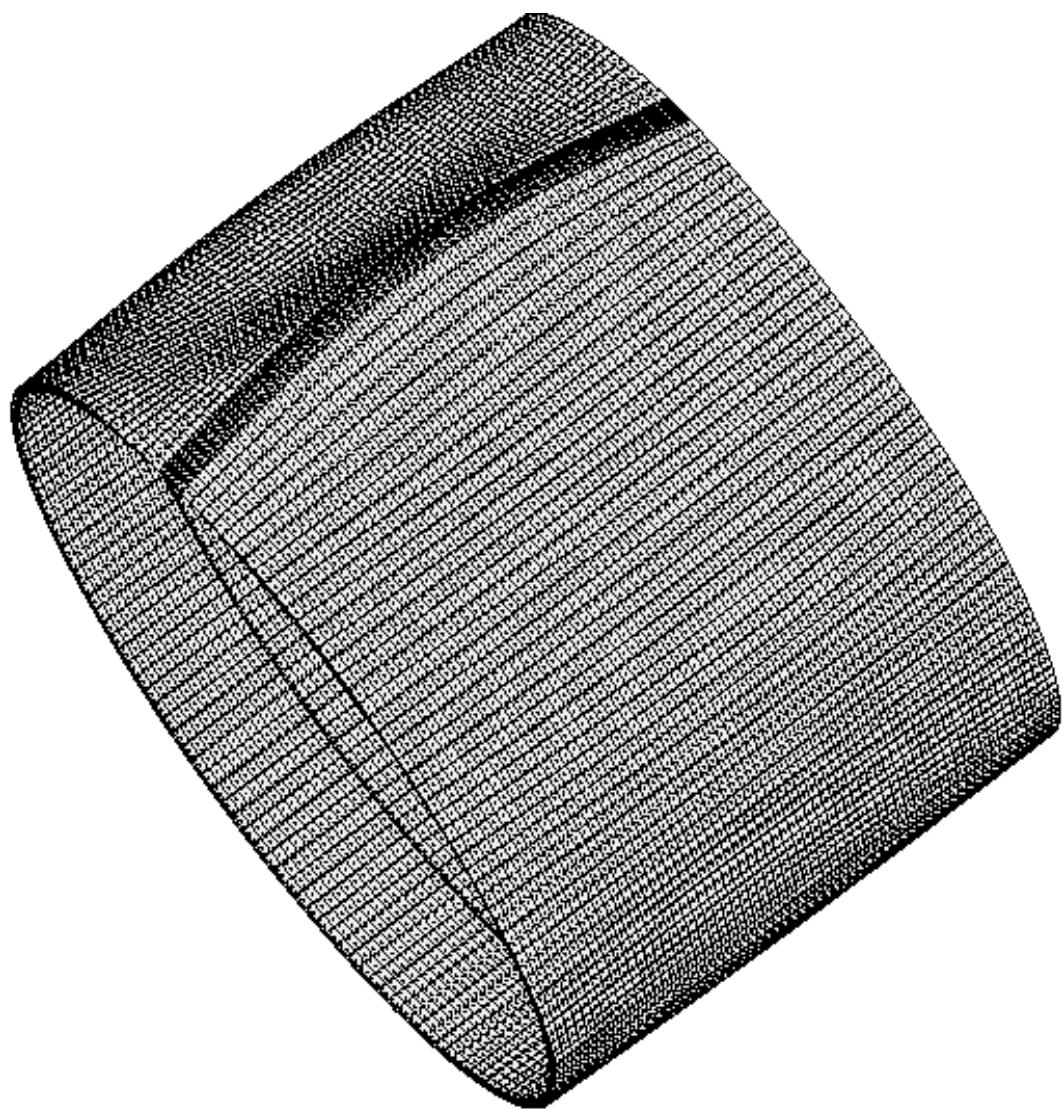


Fig. 48 Mode of collapse of the optimized “wcold” shell with constraints on the T-stringer web and outstanding flange slenderness ratios. The imperfection shape is shown in Fig. 44. The mode of nonlinear deformation changes from one with 2 axial half waves to one with one axial half wave as the imperfect shell collapses, suggesting that a general buckling modal imperfection with one axial half wave would be more harmful than the imperfection shape displayed in Fig. 44.



solution scale = 0.7354E+01  
mode 20, pcr = 0.20080E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

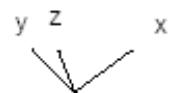


Fig. 49 2nd general buckling mode from the STAGS compound model 1 of the "wcold" cylindrical shell optimized with constraints on the slenderness ratios of the T-stringer web and outstanding flange. The negative of this mode is the most harmful buckling modal imperfection shape (second trace in Fig. 47).



solution scale = 0.5511E+01  
mode 22, pcr = 0.20179E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

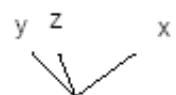
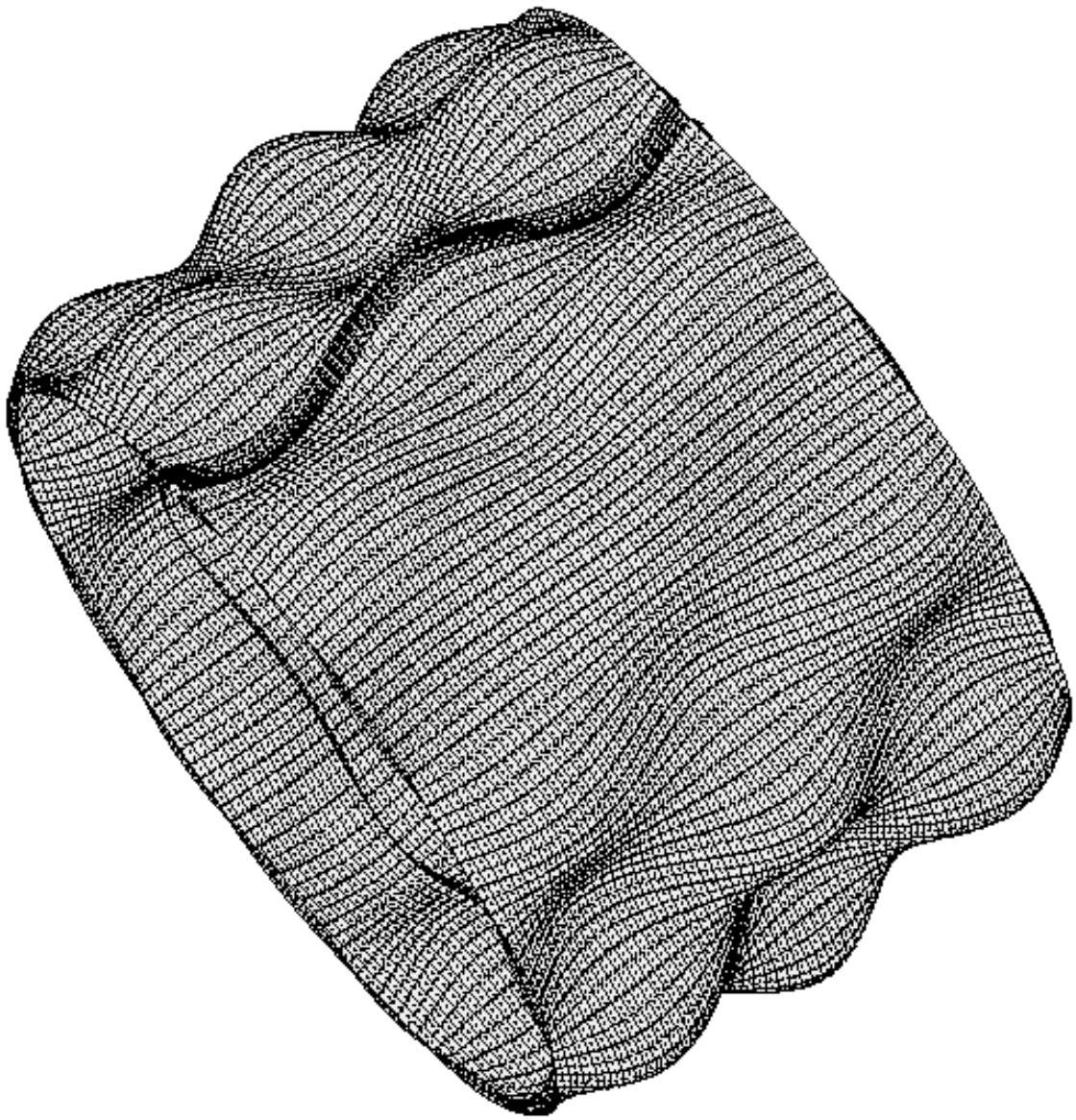


Fig. 50 3rd general buckling mode from the STAGS compound model 1 of the "wcold" cylindrical shell optimized with constraints on the slenderness ratios of the T-stringer web and outstanding flange. This imperfection shape yields the 4th trace in Fig. 47.



solution scale = 0.6654E+01

mode 29, pcr = 0.22280E+01

step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

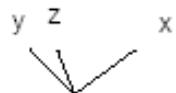


Fig. 51 4th general buckling mode from the STAGS compound model 1 of the "wcold" cylindrical shell optimized with constraints on the slenderness ratios of the T-stringer web and outstanding flange. This imperfection shape yields the 5th trace in Fig. 47.

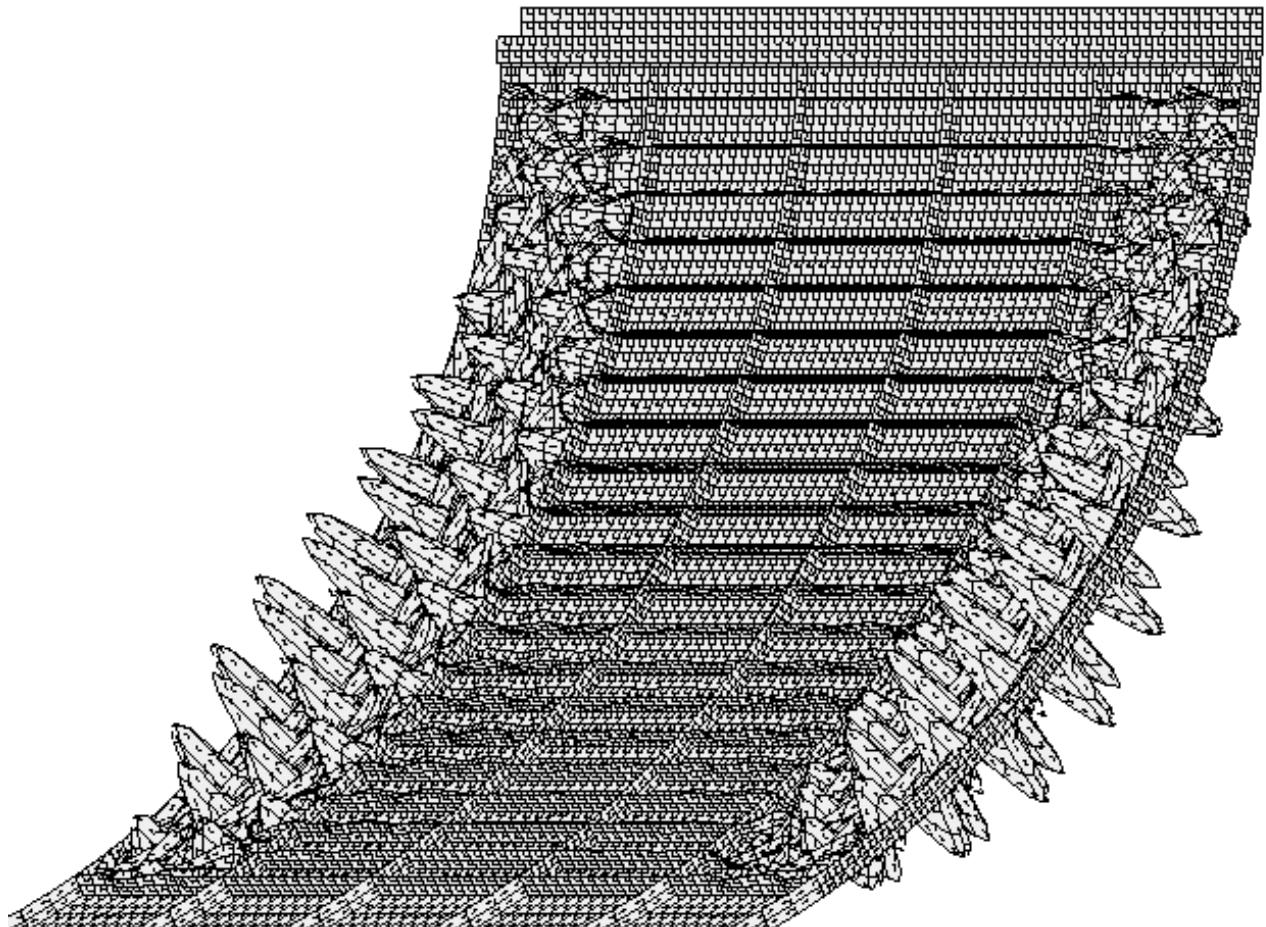
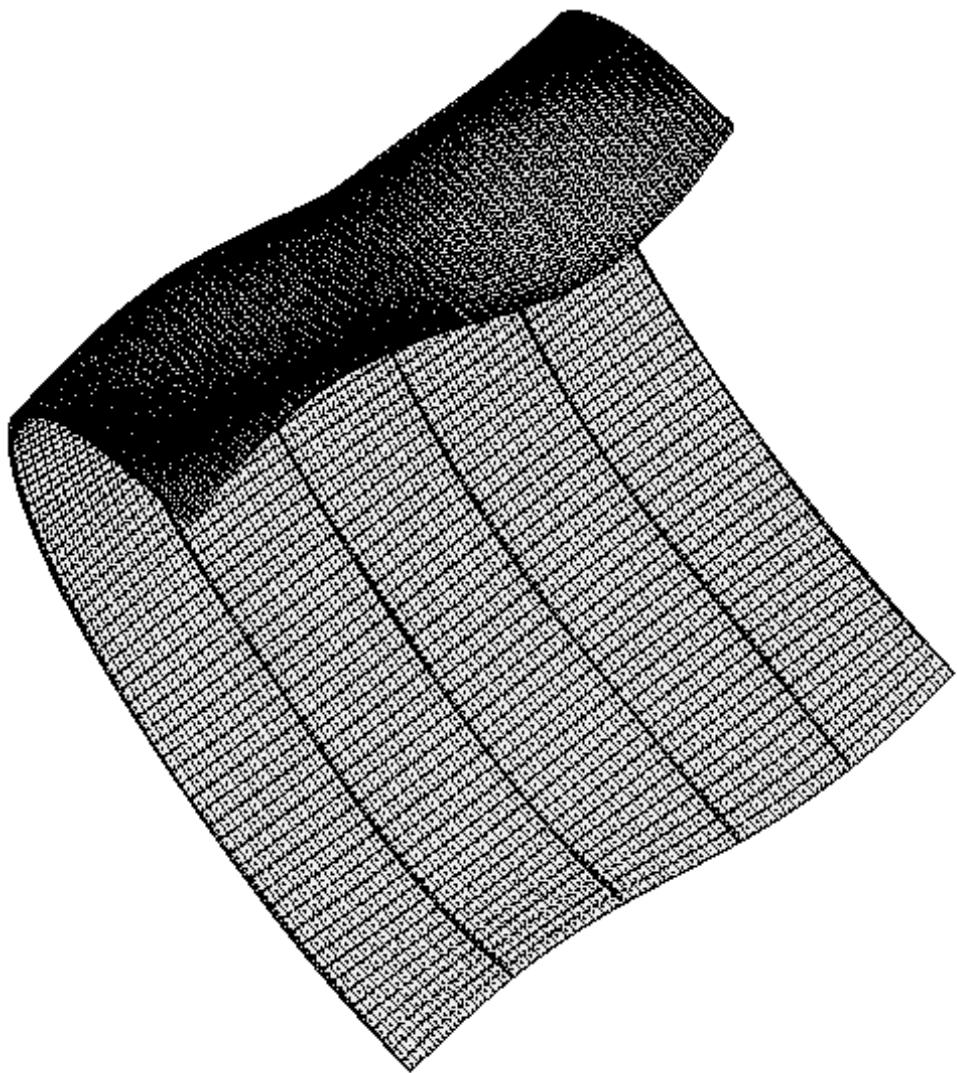


Fig. 52 First buckling mode from the 180-degree STAGS model 2 for the optimized shell in which the T-stringer web and outstanding flange slenderness ratios are constrained to be less than 10. The buckling load factor for this local “pocket” buckling mode is 1.3524. See Table 4 for comparison with other local “pocket” buckling predictions.



solution scale = 0.6357E+01  
mode 499, pcr = 0.19339E+01  
step 0 eigenvector deformed geometry  
linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

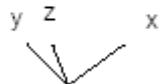
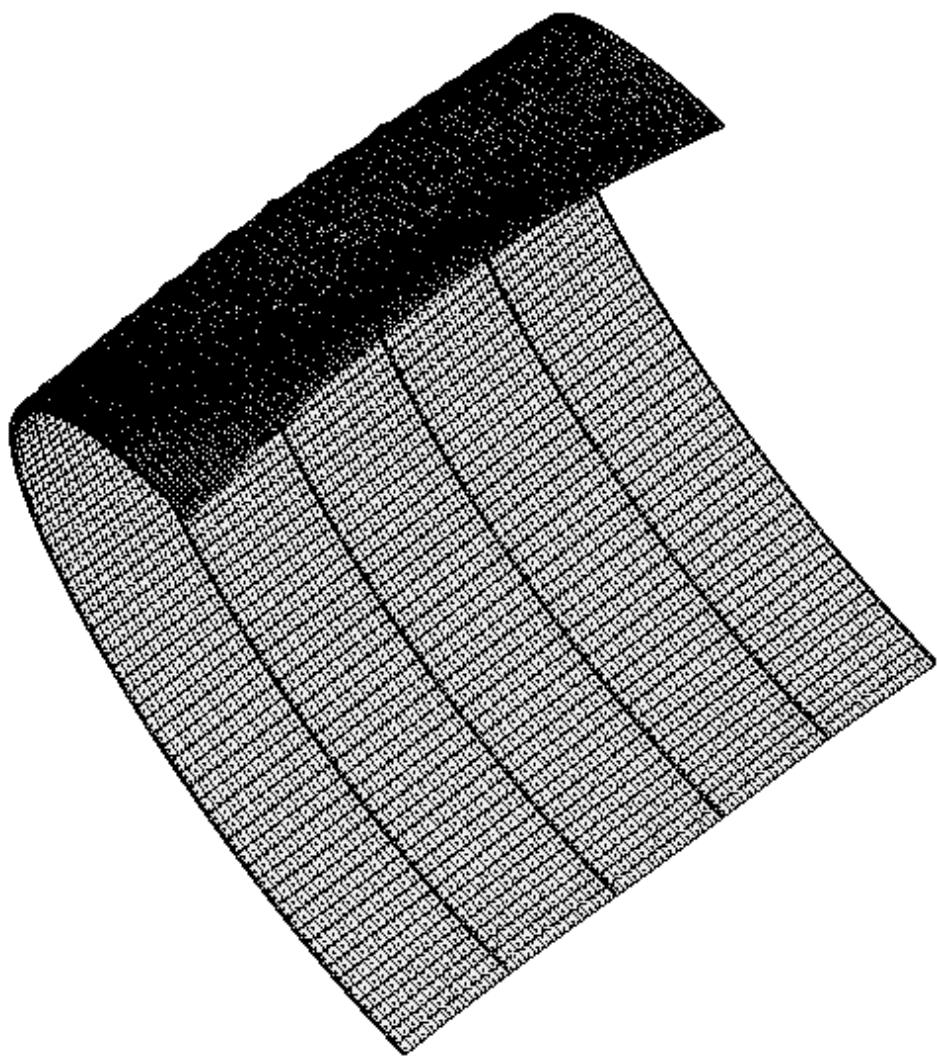


Fig. 53 First general buckling mode from the STAGS 180-degree model 2 for the optimized shell in which the T-stringer web and outstanding flange slenderness ratios are constrained to be less than 10. This is the eigenvector corresponding to the 499th eigenvalue. The buckling load factor is 1.9339.



solution scale = 0.6514E+01  
 mode 651, pcr = 0.20495E+01  
 step 0 eigenvector deformed geometry  
 linear buckling of perfect shell from STAGS

$\Theta_x$  -35.84  
 $\Theta_y$  -13.14  
 $\Theta_z$  35.63

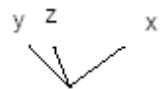


Fig. 54a Second general buckling mode from the STAGS 180-degree model 2 for the optimized shell in which the T-stringer web and outstanding flange slenderness ratios are constrained to be less than 10. This is the eigenvector corresponding to the 651st eigenvalue. The buckling load factor is 2.0496. This imperfection shape yields the 3rd trace (with Wimp = -0.125 inch) and the 6th trace (with Wimp = +0.125 inch) in Fig. 47.

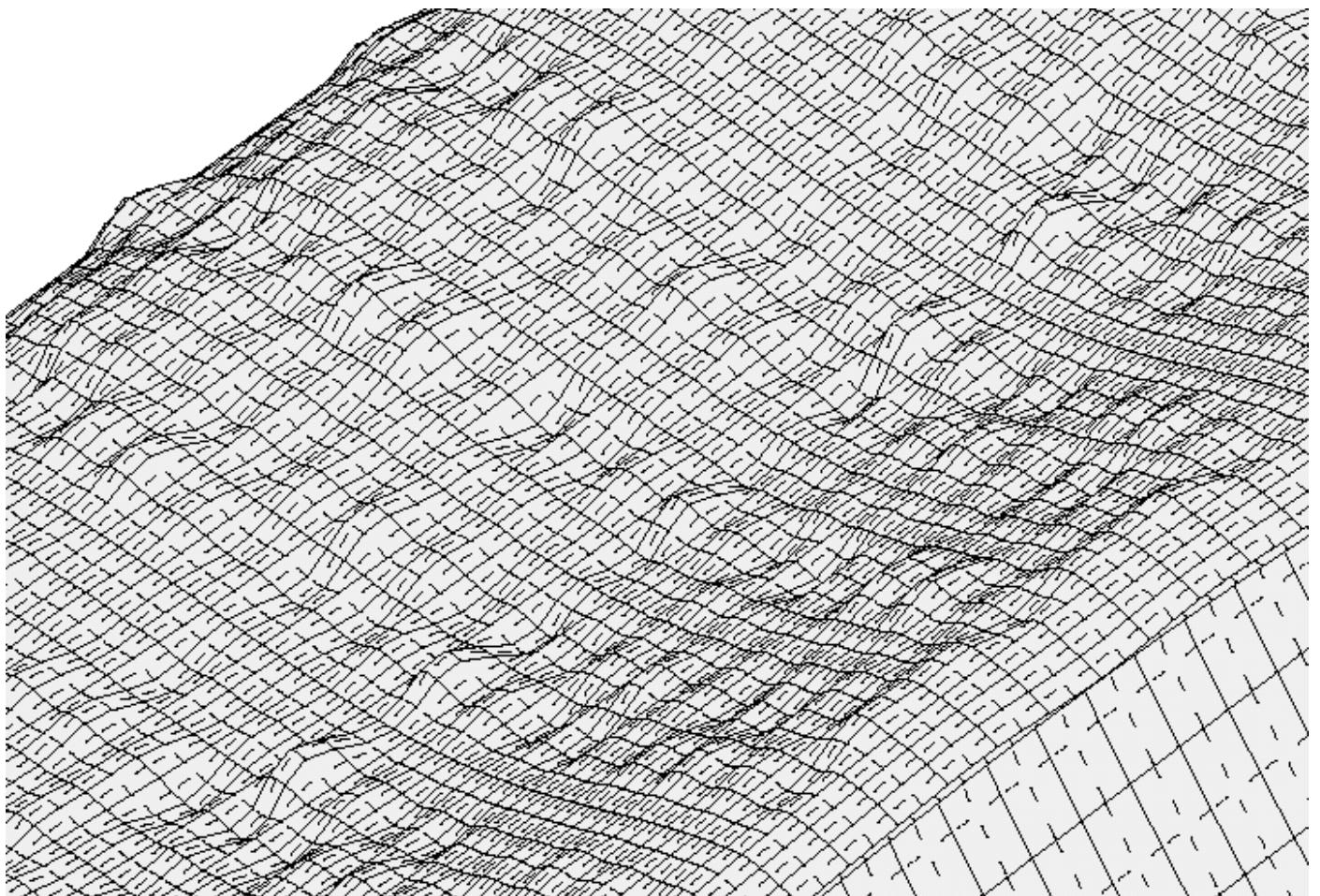


Fig. 54b Close-up view of second general buckling mode from the STAGS 180-degree model 2 for the optimized shell in which the T-stringer web and outstanding flange slenderness ratios are constrained to be less than 10. This view shows the short-wavelength component of the general buckling mode displayed in the previous figure.

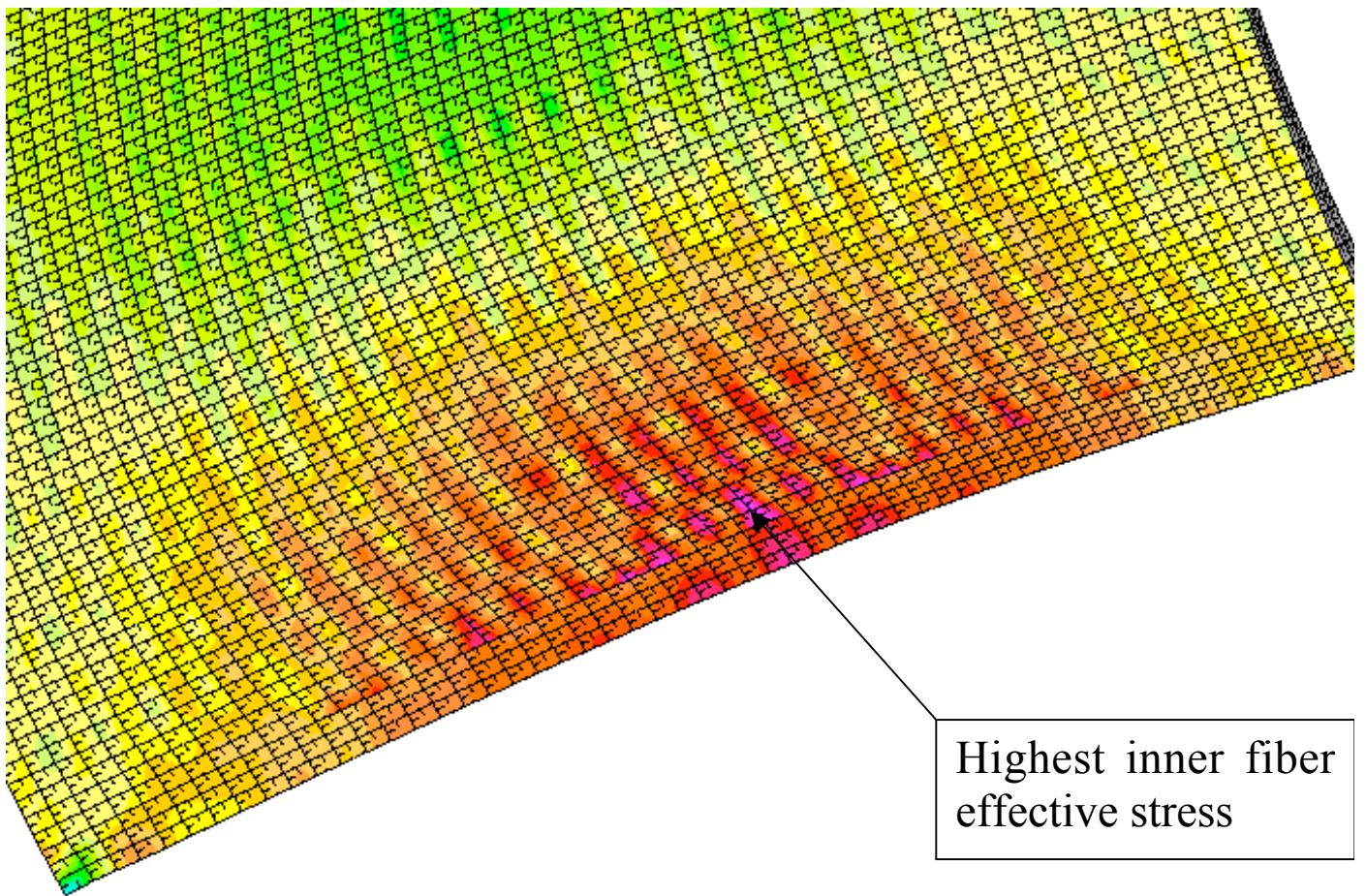


Fig. 55 Inner fiber effective stress in the weld land and its neighborhood from the STAGS model 2 for the optimized shell in which the T-stringer web and outstanding flange slenderness ratios are constrained to be less than 10. The initial general buckling modal imperfection is the negative of the shape displayed in the previous figure with amplitude = -0.125 inch. The STAGS load factor is PA = 1.127, which is the collapse load (third trace in Fig. 47). The highest (pink) inner fiber effective stress at this load is 45351 psi.

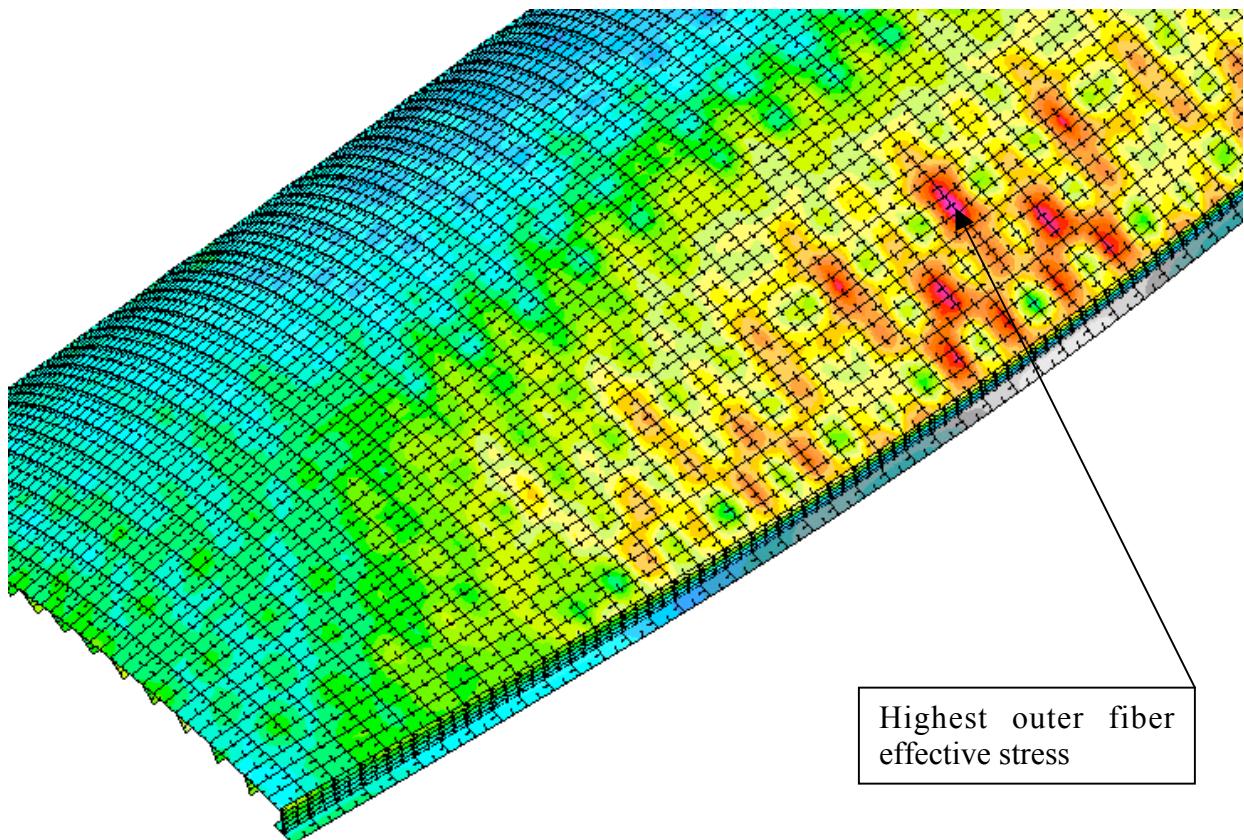


Fig. 56 Outer fiber effective stress in the neighborhood of the weld land from the STAGS model 2 for the optimized shell in which the T-stringer web and outstanding flange slenderness ratios are constrained to be less than 10. The initial general buckling modal imperfection is the negative of the shape displayed in Figs. 54a,b with amplitude,  $W_{imp} = -0.125$  inch. The STAGS load factor is  $PA = 1.127$ , which is the collapse load (third trace in Fig. 47). The highest (pink) outer fiber effective stress at this load is 47955 psi. (The weld land curved plate is not included in this plot. Also, the acreage ring along the curved edge at  $x = 0$  is omitted from the plot so that the ends of the acreage stringers can be seen. The shell is viewed from a different angle in this figure from that corresponding to the previous figure.)