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DIFFICULTIES IN OPTIMIZATION OF IMPERFECT STIFFENED CYLINDRICAL SHELLS

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(This is an abridged version. See the full-length paper for more: panda2.papers/2006.difficult.pdf)

ABSTRACT

The PANDA2 computer program generates minimum-weight designs of ring and stringer stiffened flat or cylindrical composite panels subjected to multiple sets of load combinations. PANDA2 is described with emphasis on the many different stress and buckling constraints that can affect the evolution of a design during optimization cycles, on the way that imperfections are treated, on certain difficulties that imperfections may cause during optimization cycles, and on difficulties encountered during attempts to evaluate optimum designs with the use of the STAGS general purpose finite element program. Details are given on how PANDA2 determines the effect of an initial buckling modal imperfection on the load-bearing capability of a ring and stringer stiffened cylindrical shell. Numerical results pertain to a metallic cylindrical shell with external T-shaped stringers and external T-shaped rings subjected to combined axial compression, external pressure and in-plane shear (torque). The maximum allowable stress is set very high so that stress constraints do not affect the evolution of the global optimum design in this example. Minimum-weight designs are determined for this shell with an initial imperfection in the form of the critical general buckling mode. Modifications to PANDA2 are described that overcome some of the difficulties associated with the determination of a global optimum design in the presence of an initial general buckling modal imperfection. Further modifications to PANDA2 are described that lead to less conservative global optimum designs than was previously the case. The optimum designs obtained by PANDA2 are evaluated by comparisons with predictions from STAGS for various finite element models generated automatically with a PANDA2 processor called STAGSUNIT. The agreement between PANDA2 and STAGS predictions for a global optimum design obtained by PANDA2 is good enough to qualify PANDA2 for the optimum design of imperfect stiffened cylindrical panels and shells under combined loads.

1.0 INTRODUCTION

The PANDA2 computer program [1-17] generates minimum-weight designs of ring and stringer stiffened flat or cylindrical composite panels subjected to multiple sets of load combinations. An example of such a structure is shown in Figs. 1-3, which are finite element models from STAGS [27-30], not PANDA2 models. Figs. 1-3 represent an externally T-ring and T-stringer stiffened cylindrical shell that has been optimized by PANDA2. Many of the results presented in this paper are derived from the configuration shown in Fig. 1, which is a finite element model of the shell specified in Column 5 of Table 8 in [16] and in Table 2 in this paper.

In this paper PANDA2 is described with emphasis on the many different stress and buckling constraints that can affect the evolution of a design during optimization cycles, on the way that imperfections are treated, on certain difficulties that imperfections may cause during optimization cycles, and on difficulties encountered during attempts to evaluate the optimum design via STAGS finite element models.

The optimizer incorporated into the PANDA2 system is called ADS, created by Vanderplaats and his colleagues many years ago [18-19]. PANDA2 uses much of the software from an earlier version, PANDA [2], and from BOSOR4 [20-26]. The PANDA2 system includes processors by means of which input files are automatically generated for the computer programs BOSOR4 (2011 NOTE: now BIGBSOSOR4) (shells of revolution [20-26]) and STAGS (general shells [27-30]) for optimum designs previously obtained by PANDA2. Hence, optimum designs obtained by PANDA2 can easily be evaluated by executions of BOSOR4 and STAGS, especially STAGS [7,8,16]. Figures 1-3 are examples of STAGS finite element models generated by a PANDA2 processor called STAGSUNIT [7]. It is emphasized that these STAGS finite element models are NOT used within the optimization process; they are only used after PANDA2 has already obtained an optimum design.

Local and overall buckling and optimization of stiffened panels can be determined with the PANDA2 [1-17], POSTOP [31], VICONOPT [32], and PASCO [33] computer programs. These four programs are capable of obtaining optimum designs, and PANDA2, POSTOP, and VICONOPT can do so including the effect of local postbuckling of the panel skin and/or parts of the stringers. (2011 NOTE: Dr. Riccardo Vescovini and Professor Chiara Bisagni at the Politecnico di Milano, Milan, 20156, Italy, have created a similar computer program, which is described in their paper, “Buckling Optimization of Stiffened Composite Flat and Curved Panels, AIAA Paper 2011-xxxx, 52nd AIAA Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, April 4-7, 2011.)

Other contributions to the field of buckling and postbuckling of panels include works by Weaver and his colleagues [34-36], Hilburger, et al [37], Baruch and Singer [38], the creators of the STAGS general purpose program, Almroth, Rankin, Brogan, and Riks [27-30], Arbocz and his colleagues [39-41], Stein [42], Leissa [43], Arnold and Parekh [44], Starnes, Knight, and Rouse [45], Spier [46,47], Khot and Bauld [48,49], Zhang and Matthews [50], Gurdal and his colleagues [51-56], Haftka and his colleagues [57,58], Librescu and his colleagues [59-61], Sridharan and his colleagues [62,63], Hyer and his colleagues [64-66], Nemeth, Hilburger, and Starnes and colleagues [67-70], Elishakoff and his colleagues [71-73], Weller and his colleagues [74-77], Chamis and Abumeri [78] and Noor, Starnes, and Peters [79], to identify but a few in a vast literature.

2.0 PURPOSES OF THIS PAPER

The purposes of this paper are:

1. to describe briefly what the PANDA2 system consists of,
2. to identify the many different models used in PANDA2,
3. to identify the many different stress and buckling constraints several of which may effect the evolution of a design during optimization cycles,
4. to identify several "knockdown" factors used in PANDA2, not only for imperfection sensitivity but also to compensate for the inherent unconservativeness of some of the approximate models used by PANDA2 (for example "smearing" stiffeners [38]),

5. to emphasize that initial imperfections in stiffened shells give rise to redistribution of stress between skin and stiffener segments that dramatically affects stress and buckling constraints,
6. to list the ways in which the PANDA2 predictions lead to conservative optimum designs,
7. to describe how the effect of imperfections is handled in PANDA2,
8. to identify some difficulties encountered in connection with the optimization of imperfect shells,
9. to describe certain modifications to PANDA2 that overcome some of these difficulties and that lead to less conservative designs than previous versions,
10. to provide comparisons of PANDA2 predictions with results from BOSOR4 [20-26] (2011 NOTE: superseded now by BIGBOSOR4) and STAGS [27-30] for a shell optimized by PANDA2.

Table 14 Optimum design of stiffened cylindrical shell after modification of PANDA2

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DIMENSIONS OF  CURRENT  DESIGN...
VARIABLE   CURRENT
 NUMBER     VALUE          DEFINITION
   1    5.8178E+00     B(STR):stiffener spacing, b: STR seg=NA, layer=NA
   2    5.8178E-01    B2(STR):width of stringer base, b2 (must be > 0, see
   3    3.6633E+00     H(STR):height of stiffener (type H for sketch), h: S
   4    2.8610E+00     W(STR):width of outstanding flange of stiffener, w:
   5    5.6639E-01 T(1 )(SKN):thickness for layer index no.(1 ): SKN seg=1
   6    2.8154E-01 T(2 )(STR):thickness for layer index no.(2 ): STR seg=3
   7    2.2753E-01 T(3 )(STR):thickness for layer index no.(3 ): STR seg=4
   8    2.7273E+01     B(RNG):stiffener spacing, b: RNG seg=NA, layer=NA
   9    0.0000E+00    B2(RNG):width of ring base, b2 (zero is allowed): RNG
  10     7.8659E+00     H(RNG):height of stiffener (type H for sketch), h: R
  11     6.2330E+00     W(RNG):width of outstanding flange of stiffener, w:
  12     6.5922E-01 T(4 )(RNG):thickness for layer index no.(4 ): RNG seg=3
  13     3.5912E-01 T(5 )(RNG):thickness for layer index no.(5 ): RNG seg=4

CURRENT VALUE OF THE OBJECTIVE FUNCTION:
 1.062E+04   WEIGHT OF THE ENTIRE PANEL (180 deg. of cylindrical shell, lbs)
 TOTAL WEIGHT OF SKIN                        =   5.3354E+03
 TOTAL WEIGHT OF SUBSTIFFENERS               =   0.0000E+00
 TOTAL WEIGHT OF STRINGERS                   =   2.7240E+03
 TOTAL WEIGHT OF RINGS                       =   2.5642E+03
 SPECIFIC WEIGHT (WEIGHT/AREA) OF STIFFENED PANEL=   1.1278E-01
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Table 15 Design margins for perfect optimized design listed in Table 14

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MARGINS FOR CURRENT DESIGN: LOAD SET NO.1, SUBCASE NO.1 (midway between rings)
 MAR. MARGIN
 NO.  VALUE            DEFINITION
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1 5.86E-01 Local buckling from discrete model-1.,M=8 axial halfwaves;FS=0.99
2 2.57E-01 Long-axial-wave bending-torsion buckling; M=1 ;FS=0.999
3 7.10E+00 eff.stress:matl=1,STR,Dseg=5,node=11,layer=1,z=0.2832; MID.;FS=1.
4 3.14E-01 (m=1 lateral-torsional buckling load factor)/(FS)-1;FS=0.999
5 5.52E-01 Inter-ring bucklng, discrete model, n=30 circ.halfwaves;FS=0.999
6 7.10E+00 eff.stress:matl=1,SKN,Iseg=1,at:n=1,layer=1,z=0.2832;-MID.;FS=1.
7 8.30E-01 buckling margin stringer Iseg.3 . Local halfwaves=7 .MID.;FS=1.
8 1.23E-01 buckling margin stringer Iseg.4 . Local halfwaves=7 .MID.;FS=1.
9 1.14E-01 buckling stringer Isegs.3+4 together.M=7 ;C=0. ;MID.;FS=1.4
10 2.13E+00 buckling stringer Iseg 4 as beam on foundation. M=223;MID.;FS=1.2
11 7.39E-01 buck.(SAND);simp-support local buck.; (0.95*altsol);FS=0.999
12 1.67E-01 buck.(SAND);simp-support inter-ring; (1.00*altsol);FS=0.999
13 4.13E-01 buck.(SAND);simp-support general buck;M=1;N=3;slope=8.9127;FS=0.999
14 4.06E-01 buck.(SAND);simp-support general buck;(0.85*altsol);FS=0.999
15 1.59E+01 buck.(SAND);rolling with smear rings; M=112;N=1;slope=0.01;FS=0.999
16 9.46E-02 buck.(SAND);rolling only of stringers;M=12;N=0;slope=0.;FS=1.4
17 4.33E-01 buck.(SAND);hiwave roll. of stringers;M=89;N=0;slope=0.;FS=1.2
18 4.31E+02 buck.(SAND);rolling only axisym.rings;M=0;N=0;slope=0.;FS=1.4
19 8.30E-01 buck.(SAND); STRINGERS: web buckling;M=7;N=1;slope=0.;FS=1.
20 2.99E+04 buck.(SAND); RINGS: web buckling;M=1;N=6;slope=0.;FS=1.
21 9.00E+01 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
22 2.33E+00 0.3333 *(Stringer spacing, b)/(Stringer base width, b2)-1;FS=1.
23 5.37E-01 1.-V(3)^1+20.V(6)^1-1
24 6.76E-01 1.-V(10)^1+20.V(12)^1-1
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Table 16 Design margins for the optimized imperfect stiffened cylindrical shell, dimensions for which are listed in Tables 1 and 14. Critical margins are printed in boldface. (NOTE: Only Part 1 of Table 16 is listed here.)

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Part 1: positive imperfection Wimp(general buckling mode) = 1.0 in. midway between rings
MARGINS FOR CURRENT DESIGN: LOAD SET NO 1, SUBCASE NO.1 (midway between rings)
MAR. MARGIN
NO. VALUE DEFINITION
1 2.21E-01 Local buckling from discrete model-1.,M=1 axial halfwaves;FS=0.99
2 2.23E-01 Bending-torsion buckling; M=1 ;FS=0.999
3 6.61E+00 eff.stress:matl=1,SKN,Dseg=2,node=6,layer=1,z=0.2832; MID.;FS=1.
4 2.08E-01 (m=1 lateral-torsional buckling load factor)/(FS)-1;FS=0.999
5 -2.92E-02 Ring flang buckling,discrete model,n=65 circ.halfwaves;FS=0.999
6 -2.88E-02 Lo-n Ring sidesway, discrete model, n=8 circ.halfwaves;FS=0.999
7 6.27E+00 eff.stress:matl=1,RNG,Iseg=3,at:TIP,layer=1,z=0.3296;-MID.;FS=1.
8 6.72E-01 buckling margin stringer Iseg.3 . Local halfwaves=7 .MID.;FS=1.

9 -8.27E-03 buckling margin stringer Iseg.4 . Local halfwaves=7 .MID.;FS=1.
10 4.63E-03 buckling stringer Isegs.3+4 together.M=7 ;C=0. ;MID.;FS=1.4
11 1.77E+00 buckling stringer Iseg 4 as beam on foundation. M=223;MID.;FS=1.2
12 2.42E+00 buckling margin ring Iseg.3 . Local halfwaves=1 .MID.;FS=1.
13 1.27E+00 buckling ring Iseg 4 as beam on foundation. M=139;MID.;FS=1.2
14 7.91E-01 buck.(SAND);simp-support local buck.; (0.95*altsol);FS=0.999
15 9.73E-02 buck.(SAND);simp-support inter-ring; (1.00*altsol);FS=0.999
16 1.21E-02 buck.(SAND);simp-support general buck;M=1;N=3;slope=8.9127;FS=0.999
17 -2.27E-02 buck.(SAND);simp-support general buck;(0.85*altsol);FS=0.999
18 1.60E+01 buck.(SAND);rolling with smear rings; M=112;N=1;slope=0.01;FS=0.999
19 -3.14E-02 buck.(SAND);rolling only of stringers;M=12;N=0;slope=0.;FS=1.4
20 2.68E-01 buck.(SAND);hiwave roll. of stringers;M=89;N=0;slope=0.;FS=1.2
21 6.26E-01 buck.(SAND); STRINGERS: web buckling;M=7;N=1;slope=0.;FS=1.
22 2.64E+00 buck.(SAND); RINGS: web buckling;M=1;N=1;slope=0.1749;FS=1.
23 9.00E+01 (Max.allowable ave.axial strain)/(ave.axial strain) -1; FS=1.
24 2.33E+00 0.3333 *(Stringer spacing, b)/(Stringer base width, b2)-1;FS=1.
25 5.37E-01 1.-V(3)^1+20.V(6)^1-1
26 6.76E-01 1.-V(10)^1+20.V(12)^1-1
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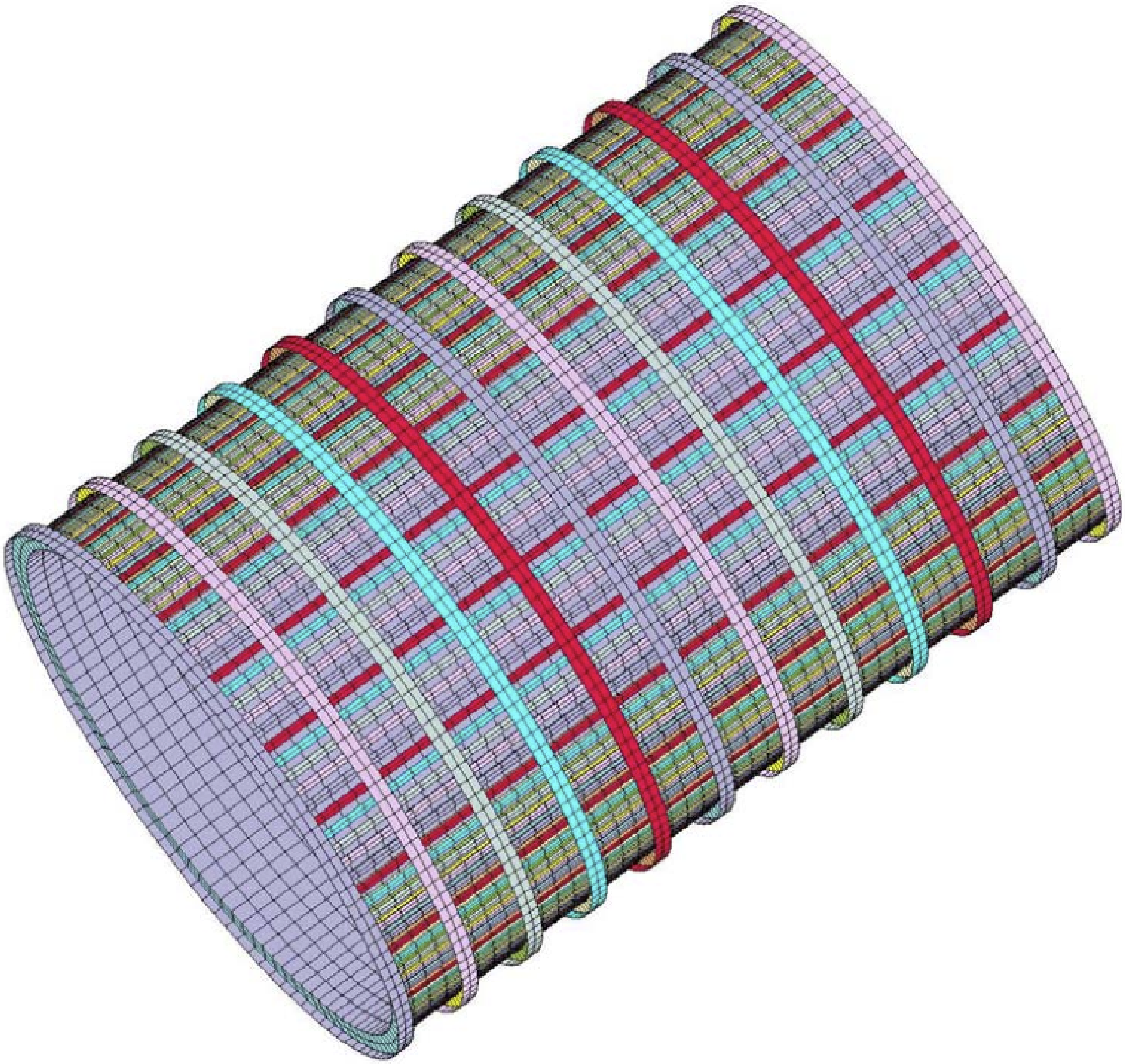

Fig. 1 STAGS model generated by the PANDA2 processor called “STAGSUNIT”. (from the AIAA 47th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2006-1943, 2006)
Loading used for all cases:
Axial Resultant (lb/in), Nx(1) Load Set A = -100000 lb/in
Hoop Resultant (lb/in), Ny(1) Load Set A = -20000 lb/in
In-plane shear (lb/in), Nxy(1) Load Set A = 20000 lb/in
Uniform pressure, (psi),p(1) Load Set A = -200 psi
Zero loading in Load Set B

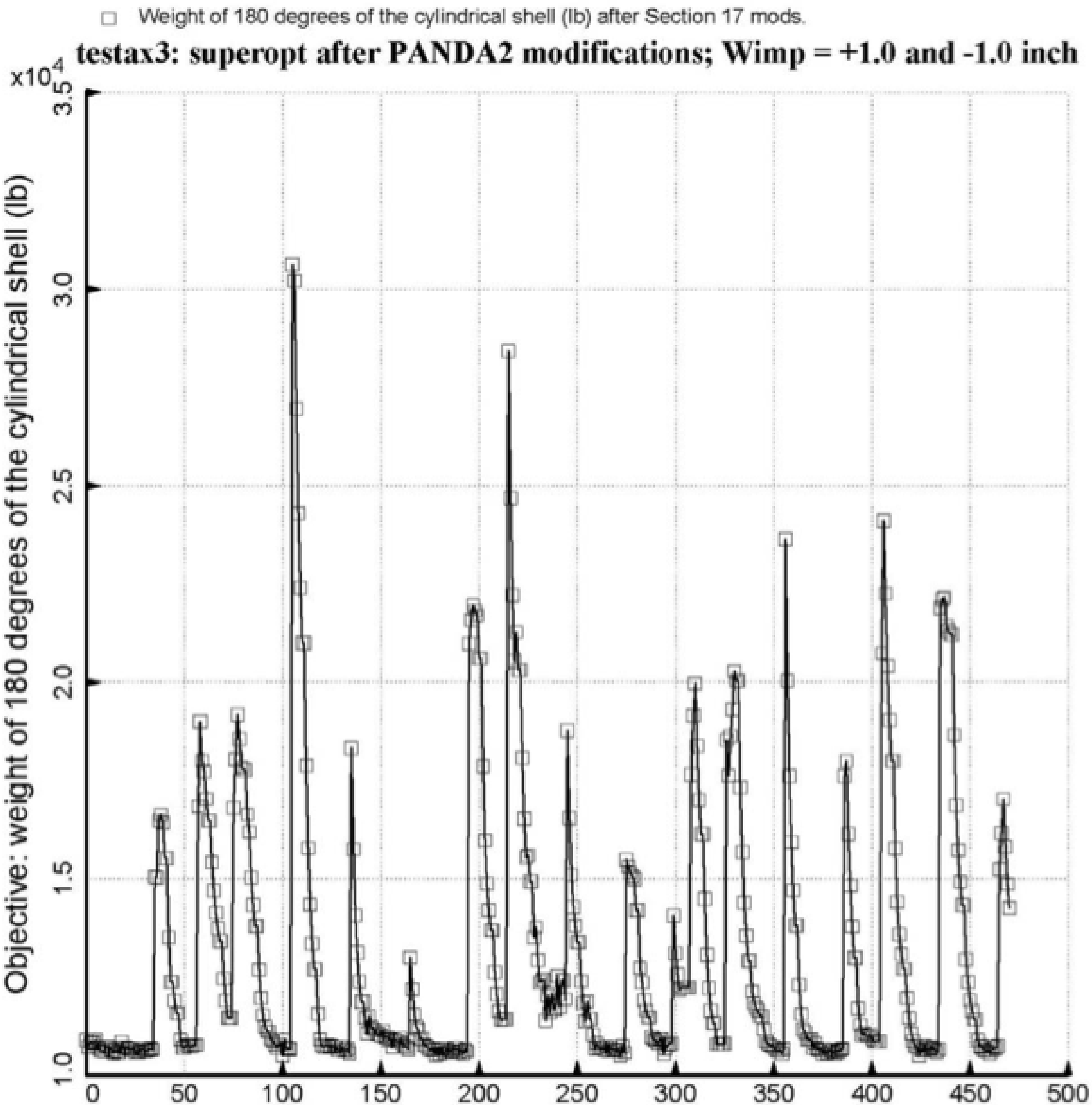

Fig. 34 Design iterations from the SUPEROPT execution made after PANDA2 modifications. Each “spike” in the curve corresponds to a new “starting” design obtained randomly by the PANDA2 processor, AUTOCHANGE. (from the AIAA 47th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2006-1943, 2006)

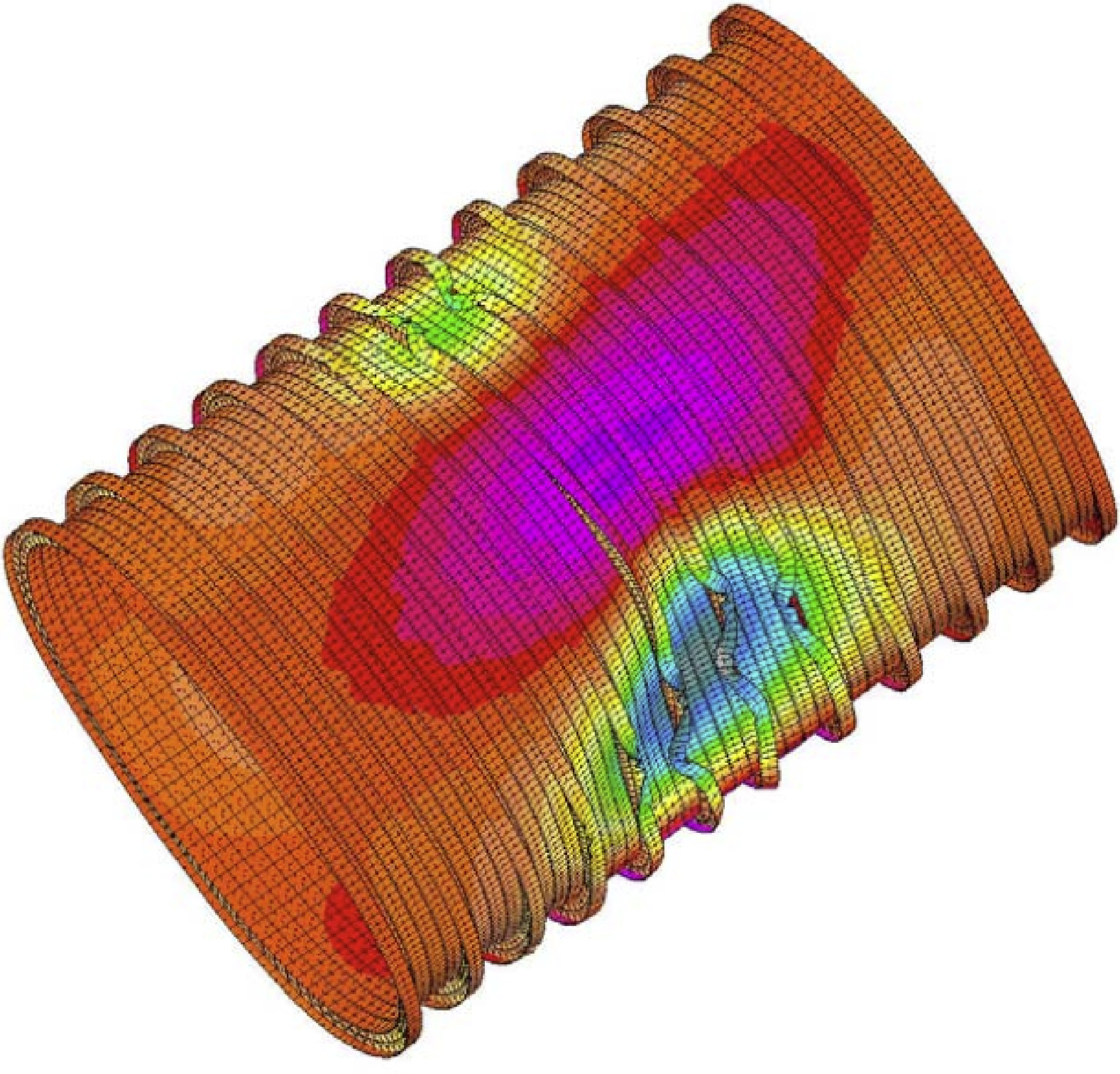

Fig. 49 Nonlinear state of the optimized imperfect shell after the STAGS transient run (INDIC=6). The load factor, PA = 1.118, TIME = 0.02775 seconds (time step no. 180). The optimum design is listed in Table 14. The stringers are smeared out and the rings are modeled with shell units. The STAGS 480 finite element is used. (from the AIAA 47th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2006-1943, 2006)

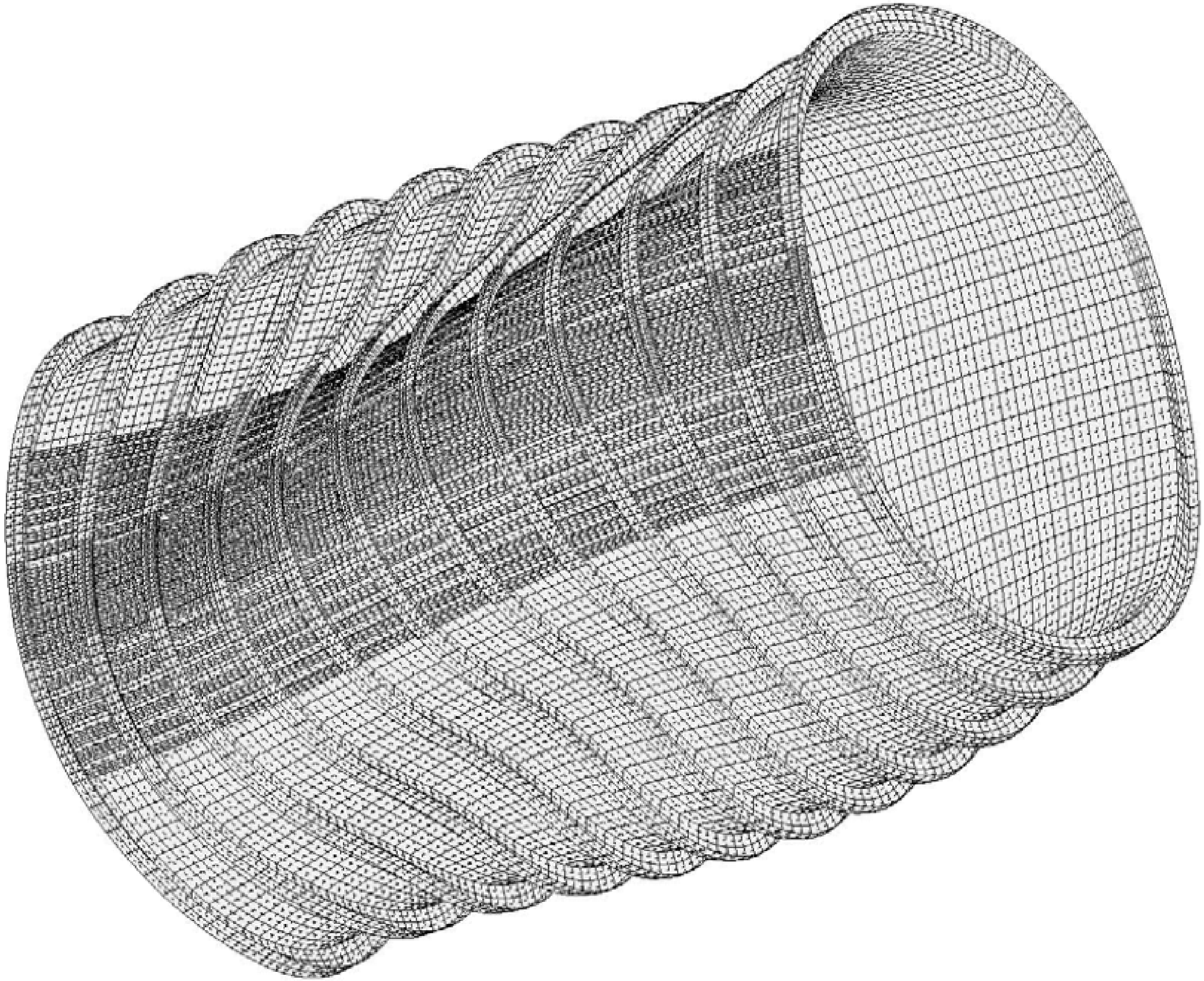

Fig. 62 STAGS model of the optimized shell with the use of a compound model with mesh density that varies over the circumference. The STAGS index, ILIN = 1. This is bifurcation buckling mode 28. The buckling load factor, Pcr = 1.4429. This mode is used as an initial imperfection shape in a following nonlinear equlibrium analysis by STAGS. The optimum design is listed in Table 14. The stringers are smeared out over 300 degrees of circumference and modeled with shell units over the 60-degree sector where the mesh is dense in the circumferential coordinate direction. The rings are modeled as shell units everywhere. (from the AIAA 47th Structures, Structural Dynamics, and Materials Conference, Paper no. AIAA-2006-1943, 2006)