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USE OF GENOPT AND BIGBOSOR4 TO OBTAIN OPTIMUM DESIGNS OF AN AXIALLY COMPRESSED CYLINDRICAL SHELL WITH A COMPOSITE TRUSS-CORE SANDWICH WALL

David Bushnell[1] Retired, 775 Northampton Drive, Palo Alto, CA 94303
Charles Rankin[2] , Rhombus Consultants Group, Inc., Suite B100, 1121 San Antonio Rd., Palo Alto, CA 94303

ABSTRACT

GENOPT/BIGBOSOR4 is applied to the problem of an axially compressed perfect elastic cylindrical shell the wall of which is a composite truss-core sandwich. The truss-core sandwich is constructed of trapezoidal core tubes that are sandwiched between two face sheets. At the junction of the core webs and the face sheets are "noodle" regions that are filled with unidirectional composite material. The design constraints are local buckling, general buckling, and five stress constraints for each material. Local and general buckling are computed from BIGBOSOR4 models in which the "huge torus" prismatic representation of the cylindrical shell is employed. In both the local and general buckling models the "huge torus" representation of the cylindrical shell consists of a number of identical modules of the cross section of the truss-core sandwich wall that are strung together along the curved meridian of the "huge torus". The rather elaborate 22-segment module used for local buckling includes small curved and straight segments that occur at the corners of the trapezoidal tool around which the truss-core is wrapped during the fabrication process. The presence of "noodles" that fill the prismatic triangular-like gaps between adjacent trapezoids is accounted for. BIGBOSOR4 models are included that determine approximately the effect on local buckling of support by each noodle of the little shell segments that enclose it. The six-segment module used in the general buckling is much simpler than the 22-segment module used for local buckling. It consists of six shell segments analogous to those used in the truss-core sandwich model employed in PANDA2. The effect of the "noodles" is accounted for, however, which is not possible in the PANDA2 model. Also, the GENOPT/ BIGBOSOR4 general buckling model retains both face sheets and truss-core webs as flexible shell segments. Therefore, the general buckling model exhibits the correct global transverse shear deformation (t.s.d.) characteristics, whereas in PANDA2 the effect of t.s.d. is simulated approximately by a knockdown factor. The number of modules used in the model for general buckling is determined by the largest circumferential arc that subtends the maximum number of shell segments permitted by BIGBOSOR4: 295 segments. Stress constraints are computed in a way completely analogous to that used in PANDA2 for composite laminates, but calculations are simpler because the pre-buckled state of the "huge torus" is a uniform membrane state whereas local bending due to initial imperfections is permitted in the PANDA2 model. The effect of thermal curing is included in the model. The decision variables for optimization are the width of a single module, the width of the crown of one trapezoid, the height of the trapezoid, two distinct corner radii of the trapezoidal core tube, and lamina thicknesses. Optimum designs are obtained via

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[1] Retired, AIAA Fellow.
[2] AIAA Associate Fellow

SUPEROPT. The objective is the weight per unit area of the cylindrical shell. Predictions from GENOPT/ BIGBOSOR4 are compared with those from PANDA2. Local and general finite element models for processing by STAGS are automatically produced by GENOPT/BIGBOSOR4 for the truss-core sandwich configurations previously optimized by GENOPT/BIGBOSOR4.

SECTION 1 INTRODUCTION AND SUMMARY

Motivation and Previous work done

The effort that resulted in this paper was motivated by work currently being performed at the NASA Langley Reaearch Center (LaRC) on the buckling behavior of cylindrical shells with a truss-core sandwich wall fabricated from laminated composite material [1, 21]. A capability to analyze and efficiently to optimize such a shell has been needed. This paper reports results from a continuation of the work documented in [2] and [3]. Reference [2], derived from a case called "**nasatruss2**", reports results from the use of PANDA2 [4, 13] and BIGBOSOR4 [5]. Reference [3], derived from a generic case called "**trusscomp**" and a specific case called "**test**", reports results from the use of GENOPT [6] and BIGBOSOR4 [5]. A brief overview of the GENOPT program [6] is given here. Extensive details about how to use GENOPT in connection with BIGBOSOR4 are presented in [7] and [8] and will not be repeated here. The GENOPT/BIGBOSOR4 capability has been used to optimize axially compressed cylindrical shells with a number of axially oriented Tee-stiffened weld lands [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. Figure 1a, created by Robert P. Thornburgh [8], demonstrates the concept of the "huge torus" model. The results from GENOPT/BIGBOSOR4 reported in this paper are based on a version of BIGBOSOR4 in which cylindrical shells are modeled as true prismatic assemblages of shell segments [8,10]. Descriptions of the "huge torus" model and of the "true prismatic shell" model are given in [8]. A brief summary is provided 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 behavior constraint gradients is computed from finite differences of the behavior constraints for the perturbed design minus the behavior constraints for the current design in which the decision variables are perturbed one at a time by a certain percentage, usually five per cent. By "behavior" is meant buckling, stress, displacement, vibration frequency, clearance, and any other phenomena that may affect the evolution of a design during optimization cycles.

Purposes of this paper and some geometry

This paper is analogous to [8]. The main purpose of the work reported here is to produce a "quick and dirty" way of optimizing uniformly axially compressed cylindrical shells with a composite truss-core sandwich wall in which the truss-core webs run in the axial direction. An auxiliary purpose of this paper is to provide enough detail so that the reader, with the use of [3], [6], [7] and [8], can employ 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. The name given to the generic case is "**trusscomp**". The specific cases discussed in this paper are called "**nasatruss2**" and "**nasatruss3**". Additional information on these specific cases and on two additional specific cases, "**isotruss**" and "**isotruss2**", that are also members of the generic class, “**trusscomp**”, is contained in the supplemental (unpublished) reports listed in [23].

Figure 1a, produced by Dr. Robert P. Thornburgh for [8], demonstrates the “huge torus” concept. The cylindrical shell that is part of the huge torus has a wall with a truss-core sandwich configuration. The minimum weight per surface area of the axially compressed cylindrical shell is sought. The decision variables of the optimization problem include the height and pitch of the truss-core sandwich, the ply thicknesses in the composite laminates that form the webs and face sheets, and the “corner” radii adjacent to the “noodle gaps” indicated in Fig. 1c.

Figures 1b – 1f show various models used by GENOPT/BIGOBOSR4 for the generic case, “**trusscomp**”. Figure 1b shows the first few modules of the model used for the prediction of general buckling by GENOPT/BIGBOSOR4. The truss-core sandwich cross section is discretized, and variation of the general buckling mode in the direction normal to the plane of the paper is trigonometric. Figures 1c -1f show various models used for the prediction of local buckling. The uniformly axially compressed pre-buckled state of the truss-core sandwich wall is demonstrated by the STAGS model displayed in Fig. 1g. (NOTE: Fig. 1g is included here only to emphasize that the pre-buckled state in the GENOPT/BIGBOSOR4 model is a membrane state (no pre-buckling bending). STAGS and predictions from STAGS are NOT used in the GENOPT/ BIGBOSOR4 optimization loop.)

Figures 2 and 3 present end views of an optimized configuration with **local** buckling modes corresponding to a model consisting of a single module (Fig. 2a,b) and local buckling models consisting of three modules (Fig.3a) and five modules (Fig. 3b). The user of GENOPT/BIGBOSOR4 decides how many modules to use in the local buckling model.

In GENOPT/BIGBOSOR4 models the cross section of a single repeating module of the truss-core sandwich wall of the cylindrical shell is divided into a number of shell segments. Figure 4 shows the BIGBOSOR4 segment numbering scheme, direction of “travel” along each segment, and dimensions used for a single module of the **local** buckling models such as those depicted in Figs. 1c-1f, 2a,b, and 3a,b. Figure 5 shows the critical **general** buckling mode of the optimized configuration. Figure 6 (top) shows the segment numbering scheme and direction of “travel” along each segment used for a single module of the **general** buckling multi-module model such as that depicted in Figs. 1b and 5.

Figure 6 (bottom portion) and Fig. 7 focus on a typical “noodle gap” and “noodle” cross-section area. Typically, a “noodle” is formed by filling the noodle gap with epoxy/adhesive or by inserting unidirectional fibrous composite material with all fibers oriented along the axis of the cylindrical shell. In this paper it is assumed that each noodle consists of unidirectional fibrous composite material with the same properties as those of a single ply oriented at zero degrees, that is, with the composite fibers oriented along the axis of the cylindrical shell. There are four noodle gaps in the single-module cross-sections shown in Figs. 1c, 1e, 1f, 2a,b, and 4.

Figure 8 shows the composite layup used in [3], which is different from that used in this paper, but which represents a typical selection of decision variables for the optimization process in a specific case that is a member of the generic class called “**trusscomp**”. In [3] the specific case is called “**test**”. In this paper the specific cases are called “**nasatruss2**” and “**nasatruss3**”.

The starting design for the specific case, “**nasatruss2**” is listed in Table 3. The cylindrical shell has an inner surface radius of 78.15 inches, is 109 inches long, is simply supported, and is subjected to a total load, 2535000 lb axial compression. The properties of a single ply and the stress allowables are listed in Table 3. In Table 3 the curing "delta-temperature", TEMCUR, is listed as zero because most of the results in this paper pertain to cases in which there is no thermal curing effect. The results listed in Table 6 were obtained with TEMCUR = 200 degrees.

In the laminated composite truss-core wall segments shown in Fig. 4 there are four different layer "types". Each layer "type" has a bundle of three properties: thickness, layup angle, and material type. The layer thicknesses for the four layer "types" are called THICK(1), THICK(2), THICK(3), and THICK(4). These are all decision variable candidates. The corresponding layer layup angles are called ANGLE(1), ANGLE(2), ANGLE(3), and ANGLE(4). These are not decision variable candidates in the formulation used for the production of this paper. The four layup angles are fixed at ANGLE(1) = +45 degrees, ANGLE(2) = -45 degrees, ANGLE(3) = 0 degrees, and ANGLE(4) = 90 degrees, as listed in Table 3 in the section entitled "PARAMETERS WHICH ARE ALWAYS FIXED…". Zero degrees corresponds to the fibers of a unidirectional ply oriented along the axis of the cylindrical shell. Note that in the specific case called "**nasatruss2**" the three decision variable candidates, THICK(2), THICK(3), and THICK(4), are all linked to THICK(1), as seen near the top of Table 3. Hence, in "**nasatruss2**" there is only one independent thickness decision variable in this particular application, THICK(1). [However, note that in the specific case for which results are listed in Table 5 ("**nasatruss3**") there are two independent thickness decision variables, THICK(1) and THICK(4)].

THICK(1) is the thickness of the +45-degree ply in both the laminates, NLAYRC and NLAYRF, two quantities that are defined in Fig. 8; THICK(2) is the thickness of the –45-degree ply in both the laminates, NLAYRC and NLAYRF; THICK(3) is the thickness of a 0-degree ply in the laminate, NLAYRF; and THICK(4) is the thickness of each 90-degree ply in the laminate, NLAYRF. The meanings of NLAYRC and NLAYRF are demonstrated in Fig. 8, which applies to the specific case called "**test**" in [3]. In the specific cases, "**nasatruss2**" and "**nasatruss3**", on which the results of this paper are based, NLAYRC has only two layers, [+45, -45], and NLAYRF has only six layers, [0, 90, 90, 0, -45, +45] (bottom face sheet) or [-45, +45, 0, 90, 90, 0] (top face sheet). The two-layered laminate, NLAYRC, is the laminate that is wrapped around each trapezoidal mandrel during the fabrication process. Two adjacent wrapped trapezoidal mandrels, one with its crown down and the other with its crown up, produce a non-symmetric anisotropic slanted truss-core web with four layers, [+45, -45, +45, -45].

A single 22-segment module of the fabricated truss-core sandwich shell wall, such as that displayed in Fig. 4, has the following laminated segments:

face sheet segments not at the "noodle gaps" (Segments 1, 6, 15 in Fig. 4):
[+45, -45, 0, 90, 90, 0, -45, +45]total

face sheet segment not at the "noodle gaps" (Segment 18 in Fig. 4):
[-45, +45, 0, 90, 90, 0, +45, -45]total

slanted truss-core webs (Segments 7 and 12 in Fig. 4):
[+45, -45, +45, -45]total

curved and short straight segments in Fig. 4 that enclose the "noodle gaps" except the face sheets:
[+45, -45]total

two bottom face sheet segments at the “noodle gaps” (Segments 3 and 8 in Fig. 4):
[0, 90, 90, 0, -45, +45]total

two top face sheet segments at the “noodle gaps” (Segments 17 and 22 in Fig. 4):
[-45, +45, 0, 90, 90, 0]total

Summary of this paper

The objective of the optimization is to minimize the weight per area of the axially compressed composite truss-core sandwich wall subjected to a set of specified requirements (behavior constraints). Next and in SECTIONS 2 and 3 descriptions are given of the "quick and dirty" models of a cylindrical shell with a truss-core sandwich wall. A brief description of GENOPT [6] appears in SECTION 4. SECTION 5 describes how GENOPT is used to produce a user-friendly capability to optimize any cylindrical shell with a truss-core sandwich wall that consists of isotropic or laminated composite segments (the generic class called “**trusscomp**”). SECTION 6 discusses numerical results relating to two specific members, “**nasatruss2**” and “**nasatruss3**”, of the generic class, “**trusscomp**”. SECTION 7 demonstrates the effect of thermal curing on the design margins for the specific case, “**nasatruss2**”. In SECTION 8 predictions from GENOPT/ BIGBOSOR4 and from PANDA2 are compared for cases in which thermal curing is neglected and included in the model. SECTION 9 demonstrates the construction of detailed finite element models for local and general buckling from which predictions from a general-purpose computer program such as STAGS [15-18] can be compared with those from GENOPT/BIGBOSOR4 [1]. SECTION 10 describes the effect on local buckling of support afforded by each noodle to the little shell segments that enclose it. SECTION 11 shows results from a design sensitivity analysis of the previously optimized specific case, “**nasatruss3**”.

Models used

The models used in this paper are much simpler than those constructed for processing by general-purpose finite-element computer programs such as STAGS [15-18, Fig. 1g]. Naturally, the GENOPT/BIGBOSOR4 models used here are approximate. For example, the pre-buckled state is assumed to be a membrane state: there is no pre-buckling bending of the axially compressed cylindrical shell with the composite truss-core sandwich wall. The axial compression, N_x, in the various segments of the model, such as those displayed in Figs. 1b-1f and 2 – 6, is distributed in proportion to the membrane axial stiffness of those segments. This distribution of N_x is prismatic, that is, it does not vary along the axis of the cylindrical shell. There is no axially varying "boundary layer", that is, there is no axisymmetric pre-buckling nonuniformity of radial displacement w in the neighborhoods of the two ends of the axially compressed cylindrical shell caused by restriction of induced Poisson ratio radial expansion there. The pre-buckled state is a uniform membrane state, as if uniform end shortening were applied and the shell were free to expand axisymmetrically and uniformly radially along its entire length. Fig. 1g, which is generated from a STAGS model that consists of three modules of the type shown in Fig. 4, demonstrates the prismatic pre-buckled membrane state that exists in the GENOPT/BIGBOSOR4 models that are used for optimization. (NOTE: A finite element model such as that shown in Fig. 1g is NOT used for optimization. Figure 1g is included here only to demonstrate the membrane pre-buckled state that is assumed to exist in the much simpler GENOPT/BIGBOSOR4 generic “**trusscomp**” model.)

The models used here for the optimization of the composite truss-core sandwich wall are BIGBOSOR4 models

[5,19]. 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 finite-element models such as that displayed in Fig. 1g. This property of one-dimensional discretization leads to efficient optimization.

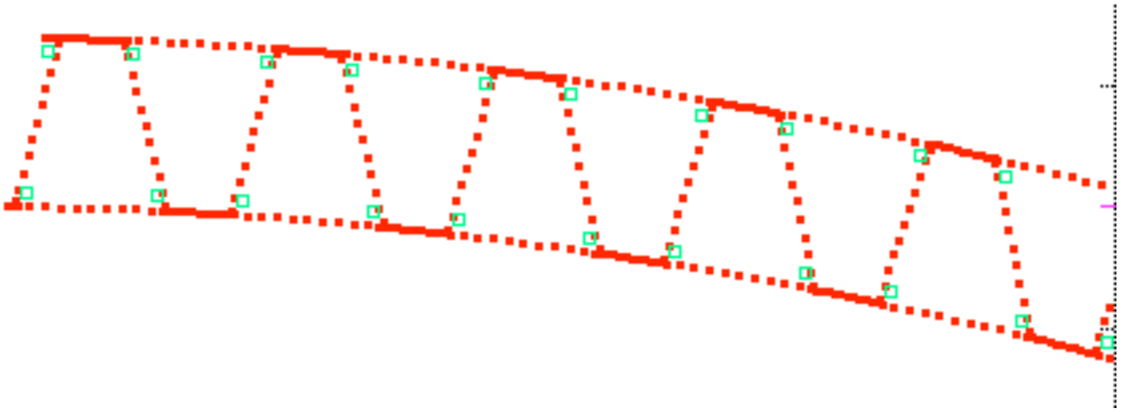


Fig. 1b. Part of the 46-module model used for the prediction of general buckling by GENOPT/BIGBOSOR4. The truss- core sandwich cross section is discretized, and variation of the general buckling displacement in the direction normal to the plane of the paper is trigonometric. The centroid of each noodle is indicated by a small green square. In the general buckling model there are no little curved and flat shell segments that enclose each noodle, as are shown in the next figures that depict various local buckling models. See Figs. 5, 13, 14 for general buckling modes obtained with this type of GENOPT/BIGBOSOR4 model. The segment numbering scheme is for each module is shown in Fig. 6 (top).

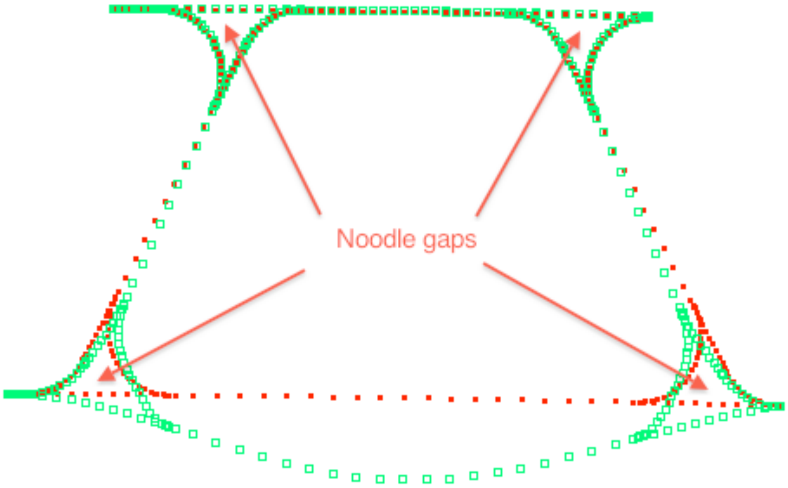


Fig. 1c. Cross section of a single module of the model used for the prediction of local buckling by GENOPT/BIGBOSOR4. In this model the noodles are present (not shown here), but do not support the little shell segments that enclose them. Careful inspection of these little segments, especially those at the bottom of the figure, reveals that they deform in the local buckling mode. This conservative model is generated when the index, ILINKS (defined in Table 1 and fully described at Prompt No. 195 in Table 2) is equal to zero. See Figs. 2, 3, 9 for local buckling modes based on this type of model.

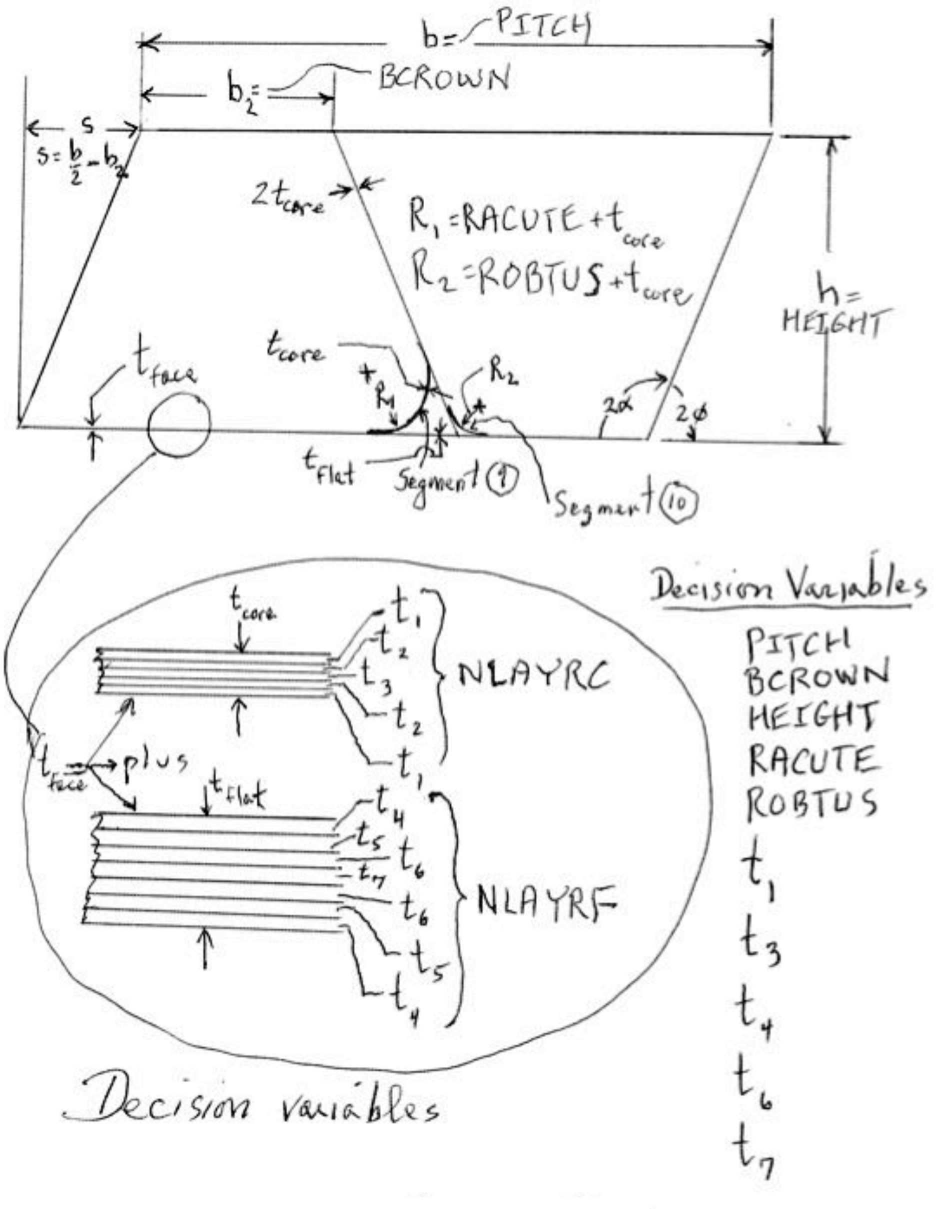


Fig. 8 **Decision variables for a typical specific case** that is a member of the "**trusscomp**" class.. **Note that the composite laminates, NLAYRC ("number of layers in the truss-core laminate") and NLAYRF ("number of layers in each face sheet laminate") are different in this figure from the numbers, NLAYRC and NLAYRF, in the case called** "**nasatruss2**", which one of the specific cases examined in this paper. In the case, **nasatruss2**, NLAYRC = 2 and NLAYRF = 6, and there is only one ply thickness, THICK(1) that is an independent decision variable. The other ply thicknesses in the **nasatruss2** case are all linked to THICK(1), as described in the text. The laminates and decision variables listed in this figure pertain to the specific case called "**test**" in [3], not to the specific case called "**nasatruss2**".

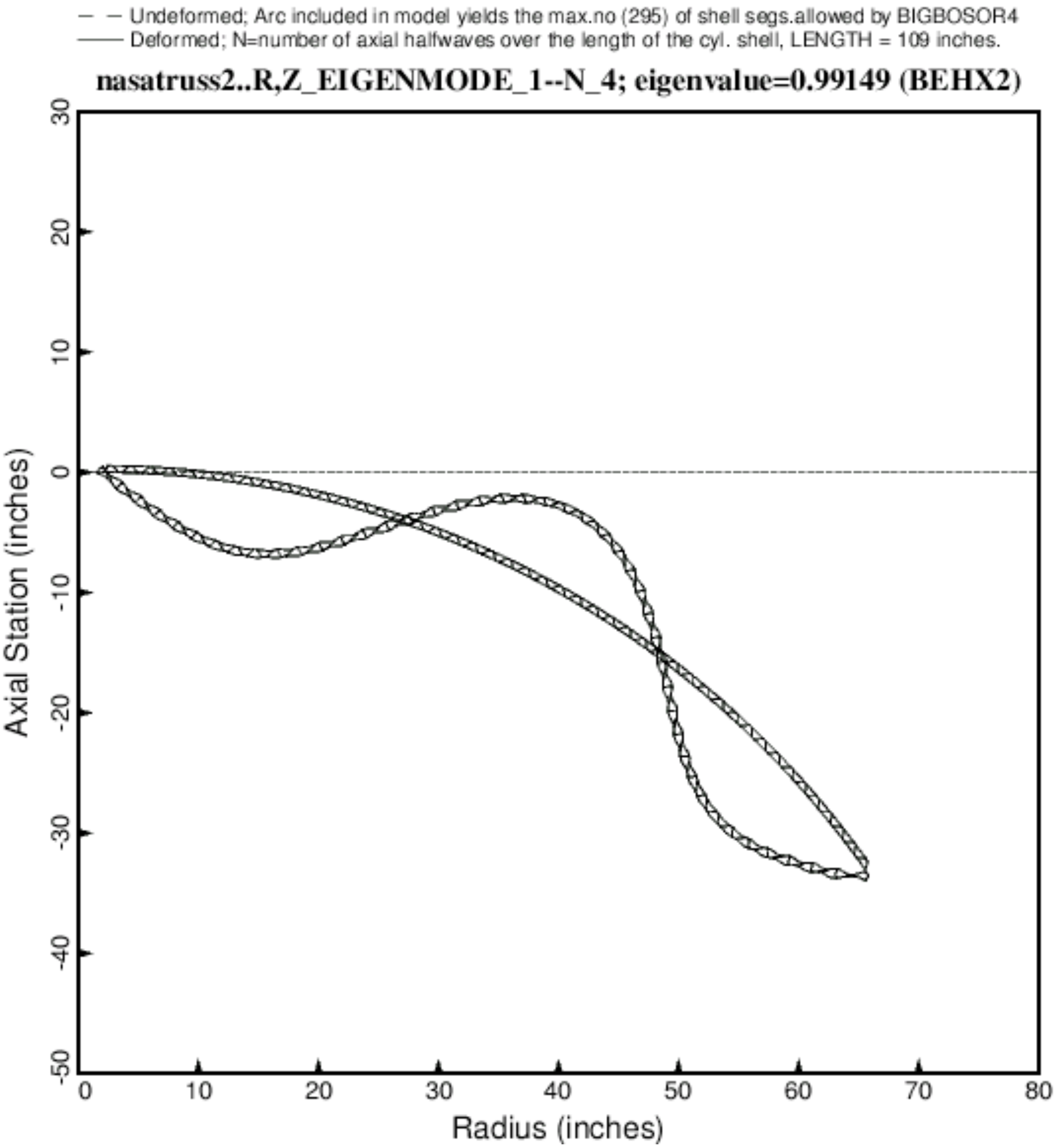
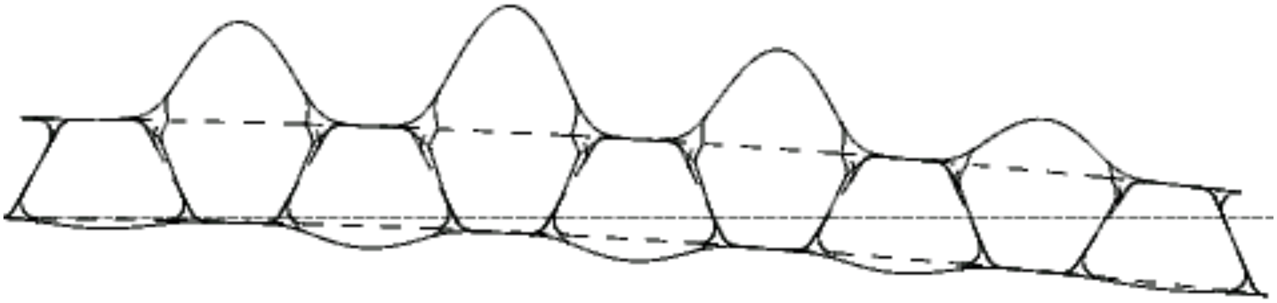


Fig. 5 A multi-module model of the truss-core sandwich shell wall, showing a general buckling mode shape. The single module used for general buckling consists of six BIGBOSOR4 shell segments, numbered as shown in the top part of Fig. 6. There are 46 modules in this model. Fig. 1b shows part of the 46-module model used for general buckling. The general buckling load factor is computed in SUBROUTINE BEHX2. This result is for an optimized truss-core sandwich wall (Table 4). The quantity N is the number of axial half-waves over the length, 109 inches, of the cylindrical shell. The cross-section properties and design margins of the optimized design are listed in Table 4. The arc shown here is the longest portion of the circumference of the cylindrical shell that can be handled by BIGBOSOR4 for this particular geometry. BIGBOSOR4 presently has an upper limit of 295 shell segments. (From the AIAA 52nd Structures, Structural Dynamics, and Materials Conference, 2011, AIAA Paper 2011-1811)



Local buckling of the axially compressed cylindrical shell with a composite truss-core sandwich wall construction. The axial compression is normal to the plane of the figure. (From the AIAA 52nd Structures, Structural Dynamics, and Materials Conference, 2011, AIAA Paper 2011-1811)

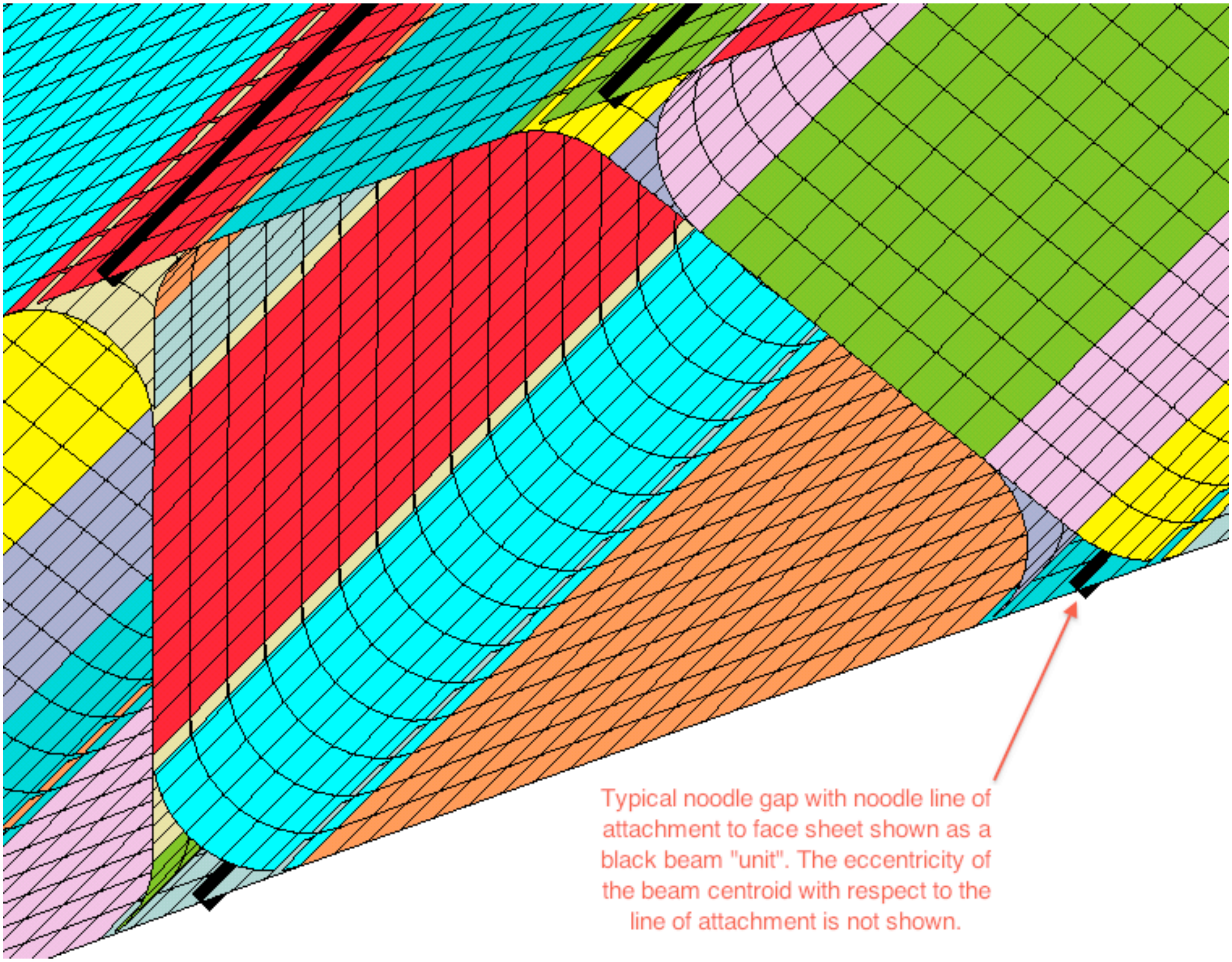

Typical noodle gap with noodle line of attachment to face sheet shown as a black beam "unit". The eccentricity of the beam centroid with respect to the line of attachment is not shown.

Fig. 18 “**nasatruss2**” starting design (Table 3). **Close-up view of a STAGS finite element model of one of the local buckling modules.** Each shell unit is shown in a different color. The black “units” represent the noodles. Unfortunately, STAGS does not show the eccentricity of the noodle centroid with respect to its attachment point of the face sheet. However, this eccentricity is present and accounted for in the STAGS model. The STAGS input file, *.inp, is automatically created by the generic GENOPT/BIGBOSOR4 case called "**trusscomp**". Comparisons between results from GENOPT/BIGBOSOR4 and general purpose computer programs such as STAGS [15-18] are provided in [1].

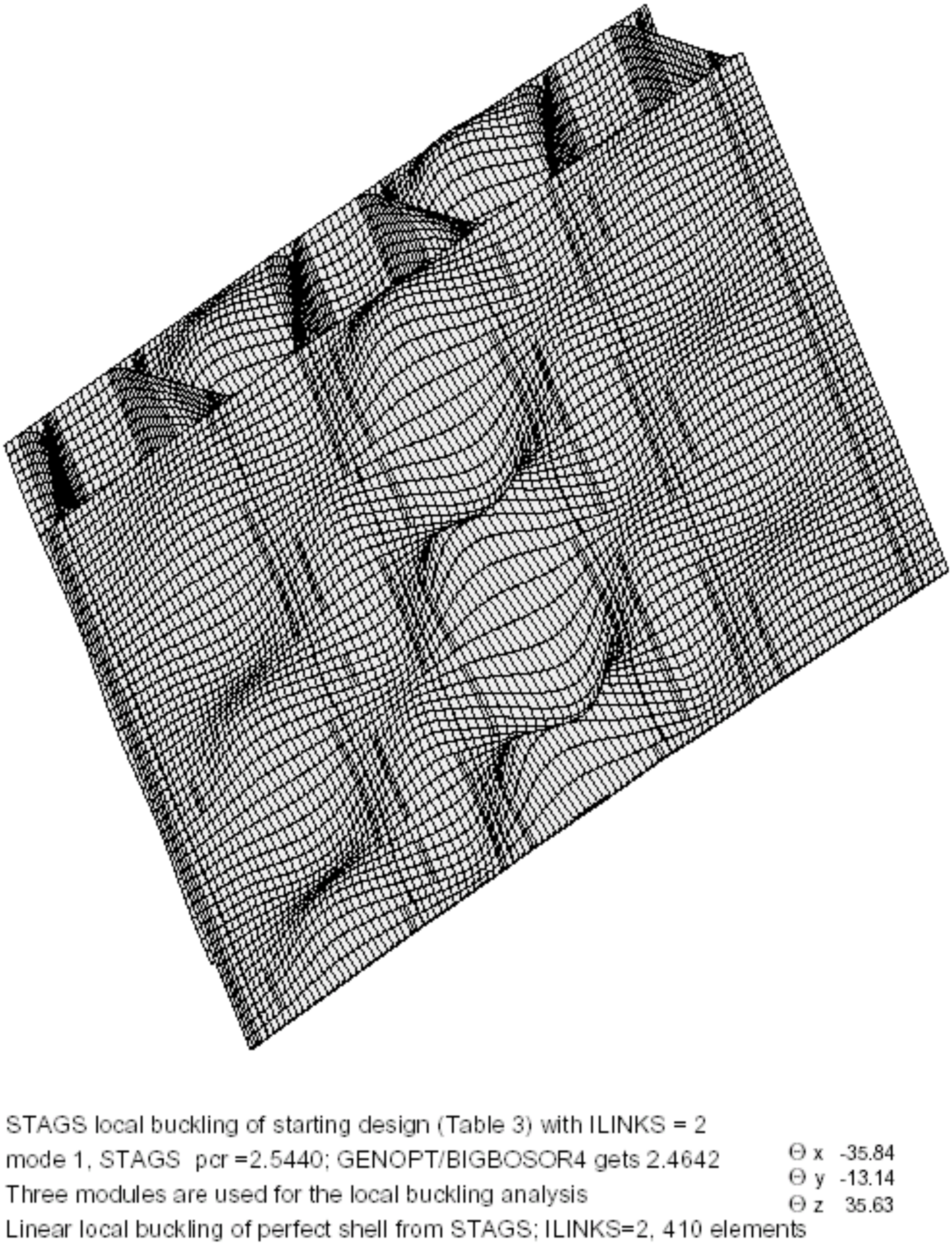


Fig. x STAGS model of local buckling of the axially compressed composite truss-core sandwich cylindrical shell. (Supplemental “trusscomp nasatruss2" report, 2011)