'BIG-BOSOR4

AUTOMATED OPTIMUM DESIGN OF SHELLS OF REVOLUTION WITH APPLICATION TO RING-STIFFENED CYLINDRICAL SHELLS WITH WAVY WALLS

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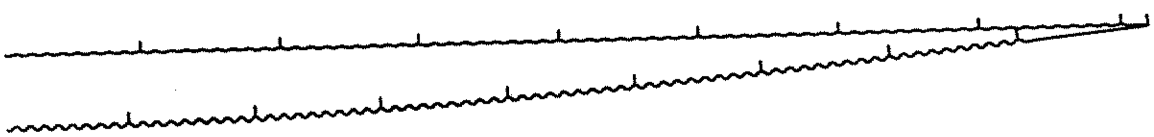
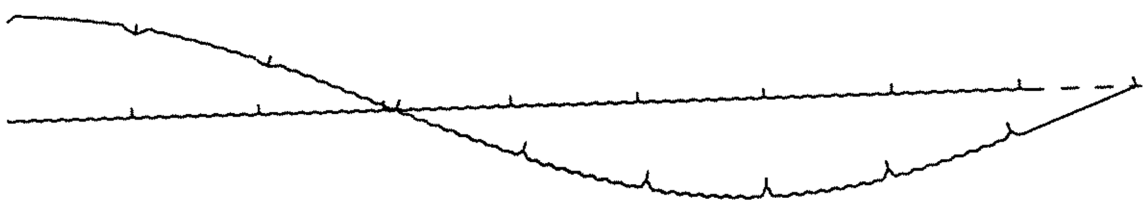
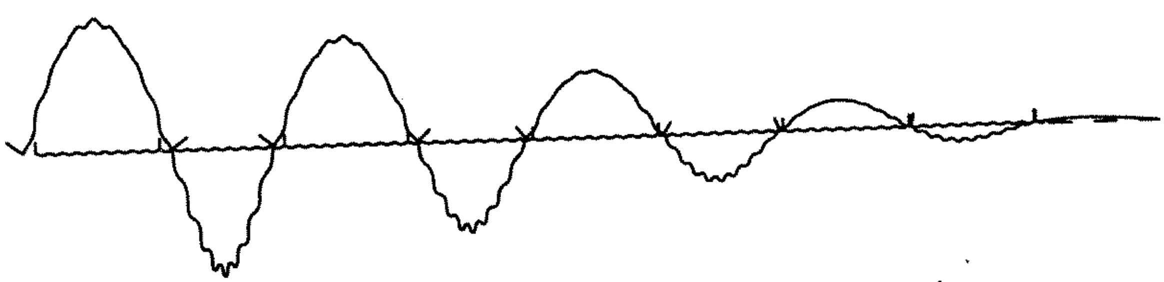
Starting Design



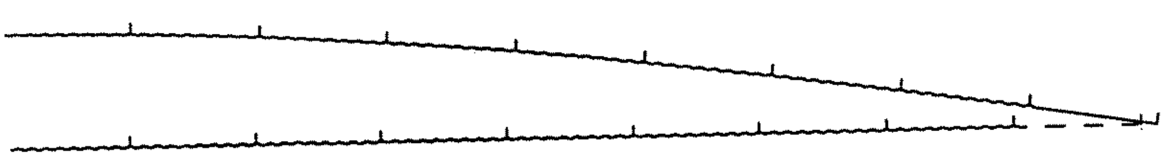
Optimum Design - Prebuckled State



Optimum Design - General Buckling



Optimum Design - Local Buckling



Optimum Design - Modal Vibration

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ABSTRACT

GENOPT, a program that writes user-friendly optimization code, and BOSOR4, a program for stress, buckling, and vibration analysis of segmented, branched, stiffened shells of revolution, are combined to create a capability to optimize specific classes of shells of revolution. Examples are provided of aluminum cylindrical shells with wavy walls with and without ring stiffeners and a laminated composite cylindrical shell without rings. GENOPT and BOSOR4 and recent improvements to them are described. In the examples the objective of the optimization is minimum weight and the design constraints involve stress, buckling, modal vibration, and random response to base excitation. An Appendix is provided in which a very simple example is used to demonstrate in detail how a user can create a capability to optimize any shell of revolution.

1.0 INTRODUCTION

About 10 years ago Cohen and Haftka [1] took a step toward creating a capability for automated design of shells of revolution. In this paper a further step is taken by combination of two computer program systems, GENOPT [2] and BOSOR4 [3]. GENOPT and BOSOR4 are combined to permit optimization of a certain class of shell of revolution, called here "WAVYCYL". This class includes ring-stiffened cylindrical shells with a "wavy" wall. The waviness is in the axial direction, that is the cylindrical shell is corrugated with the axis of the corrugations running around the circumference. This "wavy" cylindrical shell, if perfect, is axisymmetric. The rings may be rectangular or Tee-shaped, external or internal. They are modeled as consisting of little shell segments, as in [4].

Figure 1 shows an example studied intensively here, and Figs. 2 - 6 display additional members of the class called "WAVYCYL". Classical simple support or clamping is imposed at the bottom of the models (z = 0). Prebuckling symmetry and buckling symmetry or antisymmetry are imposed at the top of the models (z=90 in), which represents the midlength of the entire cylindrical tube. In the computer models the material stiffness and density of the ring at the symmetry plane, if any, are half those of the rings elsewhere in the models.

In the models shown in Figs. 1 - 3 the wavy portion is a multi-segmented model consisting entirely of joined toroidal frustra, that is, segments within each of which the meridional curvature is constant and fixed by the amplitude and axial halfwavelength of the waviness. The meridional slope is continuous at junctions between adjacent toroidal frustra. In the model shown in Fig. 4 the wavy portion consists of very short toroidal segments connected by little conical segments. The model depicted in Fig. 5 is of the same class: The "little conical segments" have become annular segments. The model shown in Fig. 6 is simply a ring-stiffened cylindrical shell.

Note that the models shown in Figs. 1 - 5 all have a straight cylindrical segment near the bottom. This is Segment 1 of the multi-segmented model. Its wall properties are derived by a "smearing" of the waviness as described in Item 10 of Section 5.

One of the input data defined by the GENOPT user is called "MAXDOF" (maximum allowable number of degrees of freedom in the BOSOR4 model). The WAVYCYL system uses this datum, MAXDOF, to determine the axial extent of the wavy portion of the model. The user can do initial optimizations setting MAXDOF to a relatively low number, such as 1500 - 3000. In such a model there may be a relatively long straight segment, such as is shown in Fig. 3, for which MAXDOF was set equal to 1500.

The results obtained with such a model are approximate because less than half of the BOSOR4 model consists of explicit waviness and the behavior of the straight segment only approximates the behavior of the actual wavy shell. After optimizing with the "rough" model, the WAVYCYL user can increase MAXDOF and re-optimize. This strategy was used in the studies reported here, for example, to determine that the best ring stiffeners have no outstanding flanges, given the applied loading and lower bounds of 10 inches on ring spacing and 0.03 inches on the thickness of the wavy wall.

Note that, given MAXDOF, the extent of the wavy portion of the BOSOR4 model depends on the axial halfwavelength, WAVLEN, of the waviness and on how many nodal points, NMESHC, are used in each of the little toroidal segments that form the explicitly wavy part of the BOSOR4 model. Results from convergence studies with respect to MAXDOF and NMESHC are presented later.

The WAVYCYL models can be loaded by arbitrary combinations of axisymmetric axial load, N_x, uniform internal or external pressure, p, lateral and axial accelerations, g(lateral) and g(axial), and random lateral excitation of the support at axial station, z = 0.

Decision variables in the optimization of "WAVYCYLs" are the wall thickness of the "wavy" cylindrical shell (or ply thicknesses if the wall is laminated), the axial halfwavelength and amplitude of the "waviness", the spacing of the rings, and the thicknesses and heights of the web and outstanding flange of a ring. (All rings are identical.)

In this paper the capabilities of GENOPT and BOSOR4 are summarized, with details given where these computer programs have been modified from the versions described in [2] and [3]. Then instructions are given on the use of GENOPT and on the use of the system of computer programs created by GENOPT, called "WAVYCYL". The flow of computations for each design evaluation is described. Finally, numerical results are given for several examples. A long appendix is provided in which a simple example is used to demonstrate how a user can set up a user-friendly system of programs to optimize any shell of revolution.

2.0 GENOPT (GENeral OPTimization)

2.1 Summary of capabilities and properties of GENOPT [2]

The purpose of GENOPT [2] is to enable an engineer to create a user-friendly system of computer programs for analyzing and/or optimizing anything. The application of

GENOPT is not limited to the field of structural mechanics. In [2] the purpose, properties and operational details of GENOPT are described. The reader is advised to read [2] and the appendix provided here in order to obtain a better understanding of the work described in this paper. GENOPT is executed via the following commands:

GENOPTLOG (The GENOPT command set is activiated.)

GENTEXT (The GENOPT user responds interactively to GENOPT prompts in order to provide names, definitions, and roles of variables to be used during execution of the user-friendly system of programs described next.)

GENPROGRAMS (GENOPT compiles and creates executable elements, BEGIN, DECIDE, OPTIMIZE, CHOOSEPLOT, CHANGE, AUTOCHANGE, described next.)

During the execution of "GENTEXT", GENOPT creates a system of computer programs consisting of the following independently executable processors:

BEGIN (The user supplies starting design, material properties, loads, allowables, factors of safety, etc.)

DECIDE (The user chooses decision variables, lower and upper bounds, linked variables, inequality constraints.)

MAINSETUP (The user chooses analysis type: fixed design, optimization, design sensitivity, and which design constraints to ignore during program execution.)

OPTIMIZE (The program system performs the analysis type specified by the user in MAINSETUP.)

SUPEROPT (The program system attempts to find a global optimum design.)

CHOOSEPLOT (The user chooses which variables to plot vs design iterations or vs value of design sensitivity variable.)

DIPLOT (The user obtains plots of objective, margins, decision variables vs design iterations or vs design sensitivity variable.)

CHANGE (The user changes selected problem variables.)

AUTOCHANGE (The program system changes all decision variables randomly, in a manner consistent with user-specified bounds, equality constraints, and inequality constraints.)

Certain parts of some of these processors (BEGIN, OPTIMIZE, CHANGE) are written by the GENOPT program system during the interactive "GENTEXT" execution. For example, certain subroutines called by the processor OPTIMIZE are partly written by GENOPT. These subroutines are named SUBROUTINE STRUCT, SUBROUTINE BEHXi, i = 1, 2, 3..., and SUBROUTINE OBJECT. As written by GENOPT, these subroutines are "skeletons": they have argument lists, labelled common blocks, and "RETURN" and "END" statements. The labelled common blocks contain all the variables that define the class of objects to be optimized. The body of each of the "skeletal" subroutines must be supplied by the GENOPT user. See [2] and the appendix provided here for examples of how this is done.

SUBROUTINE STRUCT calls SUBROUTINE BEHXi, i=1, 2, 3,... and SUBROUTINE OBJECT. SUBROUTINE BEHXi, i = 1, 2, 3, when completed by the GENOPT user, yield values of "behaviors" (responses such as maximum stress, critical buckling load factor, modal vibration frequency, maximum displacement, etc.). SUBROUTINE OBJECT computes the objective function. In the rather complex examples in the class, "WAVYCYL", to be described later, there are 18 "behavior" subroutines, BEHXi, i = 1, 18. In the much simpler example provided in the appendix, called "CYLINDER", there are only four "behavior" subroutines, BEHXi, i = 1,4. It might be best for the reader to gain a clear understanding of how GENOPT works by reading the appendix before proceeding further.

During each optimization cycle, SUBROUTINE STRUCT is called to evaluate the "current" design and each "perturbed" design. A "perturbed" design is the same as the "current" design except that one of the decision variables has been perturbed a small amount in order to obtain gradients of responses, which are needed by the optimization software embedded in the GENOPT system.

The optimizer embedded in GENOPT is ADS, written many years ago by Vanderplaats and his colleagues [5,6]. As installed in GENOPT, the ADS software is "hardwired" in the "0-5-7" mode, which is the modified-method-of-feasible-directions branch of this widely used code. ADS is a gradient-based optimizer, that is, the objective and design constraints are considered to be continuous, differentiable functions.

There are two types of user referred to in [2] and in this paper:

1. the GENOPT user

2. the "end" user (in this paper called the "WAVYCYL" user and in the appendix called the "CYLINDER" user)

The roles of the two types of user are defined in [2]. In brief, the GENOPT user "sets up" the processors just listed (BEGIN, DECIDE, OPTIMIZE, CHANGE, etc.) for the "end" user to use. The "end" user (called "WAVYCYL user" here and "CYLINDER user" in the appendix because "WAVYCYL" and "CYLINDER" are the names of the program systems created by the GENOPT user in the particular examples explored here and in the appendix) establishes the starting design, decision variables and bounds, and analysis type for the class (WAVYCYL, CYLINDER) of object to be optimized. Then the "WAVYCYL user" or "CYLINDER user" performs the optimization.

2.2 Recent improvements to GENOPT

In 1998 and 1999 the GENOPT system was improved as follows:

1. A new process (script) called SUPEROPT was introduced. SUPEROPT, a process that attempts to find a GLOBAL optimum design, is described in [7]. In the GENOPT environment it consists of multiple automatic executions of the OPTIMIZE and AUTOCHANGE processors as follows:

OPTIMIZE(Perform several design iterations)

OPTIMIZE (Perform several more iterations)

OPTIMIZE (Perform several more iterations)

OPTIMIZE (Perform several more iterations)

OPTIMIZE (Perform several more iterations)

AUTOCHANGE (Obtain a new "starting" design by randomly changing all of the decision variables.)

OPTIMIZE(Perform several design iterations)

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OPTIMIZE (perform several more iterations)

AUTOCHANGE (Obtain new "starting" design.)

OPTIMIZE (Perform several iterations.)

OPTIMIZE(Perform several more iterations.)

and so on, until a total of about 275 design iterations have been executed. The new processor, AUTOCHANGE, described in [7], obtains a new starting design by a random process in which all of the user-selected decision variables are changed in a manner consistent with user-specified bounds, equality constraints, and inequality constraints. The WAVYCYL user chooses how many "OPTIMIZEs" to perform for each "AUTOCHANGE".

2. A new control index, IBEHV(i,j) has been introduced that can "turn off" execution of any SUBROUTINE BEHXi for any load set j. This new flexibility is especially useful in the WAVYCYL example because so much computer time is required for execution of some of the software and many of the "behaviors" are seldom critical or are almost always less critical than others. One can first perform optimization with the less critical of the SUBROUTINE BEHXi "turned off". Then after an optimum design has been obtained, one can turn them on for a fixed design analysis to make sure that the formerly "turned off" responses do not create any negative margins for the configuration that represents the optimum design. In order to obtain BOSOR4 plots of the types shown in Figs. 26- 32, for example, the WAVYCYL user must execute MAINSETUP and OPTIMIZE for a fixed design (ITYPE = 2) with all "behaviors" turned off except one.

3.0 BOSOR4 PROGRAM

3.1 Summary of capabilities of BOSOR4

BOSOR4 [3] is a program for the static and dynamic analysis of any shell of revolution. The shell may be loaded axisymetrically or non-axisymetrically by line loads, distributed loads, temperature, and acceleration. BOSOR4 computes static equilibrium states, buckling, modal vibration, and response to base excitation.

In BOSOR4 a complex, branched, stiffened shell of revolution is treated as an assemblage of shell segments or branches, each with its own geometry (flat, conical, cylindrical, spherical, toroidal, etc.), loading, wall construction, and linear elastic material properties. The user of BOSOR4 provides input data in an interactive mode on a segment-by-segment basis. These input data are automatically stored in a fully annotated file, one input datum and a phrase defining it on each record of the file. (See Table A.7 in the appendix for an example of such a file.) The meridian of each segment is discretized. Variation in the circumferential coordinate direction is assumed to be trigonometric, For more details about BOSOR4 see [3].

In BOSOR4 the type of analysis to be performed is controlled by an index called INDIC, as follows:

INDIC =

-2= stability determinant calculated for increasing load,

-1= bifurcation buckling with nonlinear axisymmetric prebuckling analysis,

0= nonlinear axisymmetric stress (and collapse) analysis,

1= bifurcation buckling with "linear" axisymmetric prebuckling analysis, (Actually the prebuckling analysis is the same as for INDIC = -1. However, the applied load is never changed during a case. Linear behavior is exhibited as long as the user applies a load that is very small compared to the design load.)

2= modal vibration with axisymmetric nonlinear prestress,

3= linear axisymmetric and non-axisymmetric stress analysis,

4= bifurcation buckling with linear non-axisymmetric prebuckling. (In the INDIC=4 branch of BOSOR4 the user selects the circumferential coordinate of the meridian and BOSOR4 uses the prebuckled stress state along that meridian in a bifurcation buckling analysis that is identical to the INDIC = 1 branch, that is, the fact that the prebuckled state is non-axisymmetric is ignored. This is usually a conservative approximation provided the user has chosen the meridian for which the prebuckling state is most destabilizing.)

BOSOR4 will also compute peak response to loads that vary either harmonically or randomly in time. Buckling under harmonic or random base excitation can also be calculated.

BOSOR4 will also calculate body forces corresponding to rigid body dynamics of free-free complex shell structures subjected to non-self- equilibrating loads. These body forces are automatically included in Load Sets A ("eigenvalue" loads) and B ("constant prestress" loads) if the user indicates that rigid body motions are possible under the boundary conditions supplied.

3.2 Modification of BOSOR4 software to yield correct predictions for buckling and modal vibration for a bellows-type ("wavy") cylindrical shell

The shell equations (Sanders type [8]) on which the BOSOR4 computer program is based [3] are not adequate to predict buckling of a bellows-type of cylindrical shell, that is, a shell that is very soft in the axial direction compared to the hoop direction so that it buckles like a column (n=1 circumferential wave). This type of buckling of bellows and springs is called "squirm" [9-15]. Marlowe [16] developed general equations, that when modified for application to shells of revolution, yield the correct bifurcation loads for bellows-type cylindrical shells under internal or external pressure. In particular the expressions for work done by the prebuckling stress field during buckling modal deformations and the work done by normal pressure during buckling modal deformations were changed as described next.

3.2.1 Work done by prebuckling stress resultants during buckling

For shells of revolution Marlowe [16] gives the following relationships for reference surface strains:

$$\begin{aligned} e_s &= \gamma_s + \frac{1}{2}\left(\gamma_s^2 + \chi^2 + \gamma_{ys}^2\right) \\ e_y &= \gamma_y + \frac{1}{2}\left(\gamma_y^2 + \psi^2 + \gamma_{sy}^2\right) \\ e_{sy} &= \frac{1}{2}\left(\gamma_{sy} + \gamma_{ys}\right) + \frac{1}{2}\left(\gamma_y \gamma_{ys} + \gamma_s \gamma_{sy} + \chi\psi\right) \end{aligned} \qquad (3.1)$$

in which

$$\begin{aligned} \gamma_s &= u,_s + w/R_1 \\ \gamma_y &= v,_y + w/R_2 + ur,_s/r \\ \chi &= w,_s - u/R_1 \\ \psi &= w,_y - v/R_2 \\ \gamma_{sy} &= u,_s - vr,_s/r \\ \gamma_{ys} &= v,_s \end{aligned} \qquad (3.2)$$

where s is the coordinate along the meridian of the shell of revolution and y is the circumferential coordinate and $()_{,s}$ and $()_{,y}$ denote differentiation of () with respect to s and y, respectively. Subscripts s and y signify "meridional" and "circumferential" and subscripts sy and ys signify in-plane shear or component of rotation about a normal to the shell surface. The buckling modal displacement components, u, v, and w, are meridional, circumferential, and outward normal, respectively, and r is the radius of the parallel circle at the reference surface at the coordinate s. The quantities R_1 and R_2 are the meridional and normal circumferential radii of curvature of the shell of revolution.

Corresponding to Eqs. (3.1), the integrand of the energy expression for bifurcation buckling of axisymmetrically loaded shells of revolution with zero prebuckling torque contains the terms

$$\frac{N_{s0}}{2}\left(\gamma_s^2+\chi^2+\gamma_{ys}^2\right)+\frac{N_{y0}}{2}\left(\gamma_y^2+\psi^2+\gamma_{sy}^2\right) \tag{3.3}$$

These terms represent the work done by the prebuckling meridional and circumferential stress resultants, N_{so}, N_{yo}, during the buckling process. The analogous terms for a buckling analysis based on Sanders' equations [8] are

$$\frac{N_{s0}}{2}\left(\chi^2+\gamma^2\right)+\frac{N_{y0}}{2}\left(\psi^2+\gamma^2\right) \tag{3.4}$$

in which γ, the "average" rotation about the normal to the shell surface, is defined as

$$\gamma=\left(\gamma_{sy}+\gamma_{ys}\right)/2 \tag{3.5}$$

3.2.2 Effect of uniform normal pressure acting on shell surface

Marlowe [17] gives

$$W=\iint_{ys} p\left\{w(1+\gamma_s/2+\gamma_y/2)-(u\chi+v\psi)/2\right\}dsdy \tag{3.6}$$

for the work done by the uniform normal pressure during the buckling process. Equation (3.6) is to be compared with an analogous expression given by Cohen [18], which for uniform pressure simplifies to

$$W=\iint_{ys} p\begin{Bmatrix} w(1+\gamma_s+\gamma_y) \\ -w^2(1/R_1+1/R_2)/2 \\ +(u^2/R_1+v^2/R_2)/2 \end{Bmatrix}dsdy \tag{3.7}$$

Use in BOSOR4 [3] of expressions (3.4) and (3.7) yields incorrect values for the buckling load of a very, very long cylindrical shell loaded by internal pressure acting on the curved wall only (not acting on the ends in such a way as to create prebuckling axial tension). For example, a cylinder with modulus $E = 10^7$ psi, Poisson ratio $\mu = 0.3$, thickness $t = 1.0$ in., radius $R = 10$ in. and length $L = 600$ in. should buckle at $p_{cr} = 2741$ psi, according to Euler's formula,

$$\pi r^2 p_{cr}=P_{cr}=\pi^2 EI/L^2$$

$$p_{cr}=\pi^2 ERt/L^2 \tag{3.8}$$

The BOSOR4 program, as based on Eqs. (3.4) and (3.7), yields p_{cr}=-6.9 psi for this problem. After modification of BOSOR4 such that the analysis is based on Eqs. (3.3) and (3.6), the predicted critical pressure is 2739 psi.

3.3 Modification of BOSOR4 software to compute response to base excitation and buckling due to base excitation

This capability was added in 1984 to BOSOR4 but never before published. The following description occurs in the file, "bosor4.news", which is distributed with the BOSOR4 computer program:

BOSOR4 computes the response to base excitation as follows:

(i) harmonic excitation at a series of natural frequencies

(ii) random excitation

(iii) shock excitation

Depending on which analysis type, i, ii, or iii, the user is asked by the BOSOR4 system to provide load factors, damping factors, and spectral densities as functions of the frequency. Details are listed in Table 3.1, which is part of the PROMPT3.DAT file that contains prompts and "help" paragraphs for the interactive BOSOR4 user.

3.4 Modification of BOSOR4 software to work in the context of automated optimization

The version of BOSOR4 that has been widely distributed consists of a number of processors that are separate computer programs executed in a prescribed sequence, as described in [3] (preprocessor, B4READ, mainprocessor, B4MAIN, postprocessor, B4POST). This software was modified by conversion of the BOSOR4 "main programs" into subroutines that are called from SUBROUTINE STRUCT and SUBROUTINEs BEHXi, i = 1,...18. All of the FORTRAN statements dealing with the opening and closing of files were moved to SUBROUTINES OPNGEN, RWDGEN, and CLSGEN, which open, rewind, and close the various files needed for execution of BOSOR4. The "GASP" routines, which transfer data to and from random access mass storage, were modified by Frank Weiler (see Acknowledgments) in order to avoid unlimited expansion of the random access file size as optimization cycles proceed.

New subroutines were written by means of which the GENOPT data (dimensions, loads, material properties, boundary and junction conditions between segments, etc.) are used to generate input files that the BOSOR4 software can process. These new subroutines are called PUTWAV and BOSDEC. The output of SUBROUTINE BOSDEC is a standard input file for BOSOR4. (See the appendix for an example of a relatively simple BOSDEC routine. In the simple example used in the Appendix there is no need of a "PUTWAV" routine.)

3.5 Increase of maximum problem size that can be handled by BOSOR4

Previously, the maximum number of segments in a BOSOR4 model had to be less than or equal to 95, and the maximum number of degrees of freedom had to be less than 3000. These limits have been raised to 195 and 15000, respectively, in the version of BOSOR4 used for optimization.

4.0 INSTRUCTIONS FOR THE USE OF GENOPT/WAVYCYL

In the following it is assumed that GENOPT is being applied to problems involving a certain class of ring-stiffened shells of revolution called "WAVYCYL". However, it is emphasized that the GENOPT system can be applied to any field, not just that of structural analysis and not just that involving shells of revolution such as "WAVYCYL". For more details see [2] and the appendix supplied here.

4.1 Things for the GENOPT user to do before working with the computer

a. The GENOPT user must decide what shell of revolution or class of shells of revolution he or she wants to optimize. Questions such as the following must be answered by the GENOPT user:

1 Is the shell wall stiffened?

2 What types of shell wall are to be included (e.g. isotropic, laminated composite)?

3 What boundary conditions are to be used?

4 What are the loadings? Are there multiple load sets? Do both Load Set A and Load Set B exist?

b. The GENOPT user must identify what computer coding (presumably already written and working) he or she will need to perform the various structural analyses that will be "looped through" during optimization cycles. In this example the structural analysis coding is a modified form of the BOSOR4 computer program [3] plus translators called PUTWAV and BOSDEC that convert "WAVYCYL" input for a specific class of shells of revolution to standard BOSOR4 input data. (See the appendix for a simpler case for which PUTWAV is not needed).

c. The GENOPT user must identify various models of the structure to be used in his/her application:

1 global models

2 local models

3 Are rings to be modelled as branched shell segments?

d. The GENOPT user must decide what the objective is:

1 minimum weight

2 minimum cost

3 other

e. The GENOPT user must identify what behaviors may constrain the design:

1 stress

2 displacement

3 buckling

i. local buckling

ii. general buckling

4 modal frequency

5 thermal expansion

6 clearances

7 other

f. The GENOPT user must identify all variables in the problem, think of names for these variables (6 characters or less), think of user-friendly one-line definitions (less than 60 characters in length) for each of the variables, and think of possible supporting "HELP" paragraphs for each of the variables. The one-line definitions are especially important because they appear in the output data and therefore should be easy to understand. They are what make the system of programs created by GENOPT "user friendly".

As described in [2], GENOPT requires that each of the variables be categorized as one of the following types:

f.1 a possible decision variable for optimization, typically a dimension of a structure.

f.2 a constant parameter (cannot vary as design evolves), typically a control integer or material property, but not a load, allowable, or factor of safety, which are asked for later. For examples, a table of material properties vs temperature or a table of knockdown factors for buckling loads vs amplitude of initial imperfection would fit into this category.

f.3 a parameter characterizing the environment, such as a load component or a temperature.

f.4 a quantity that describes the response of the structure, (e.g. stress, buckling load, modal frequency)

f.5 an allowable, such as maximum allowable stress, minimum allowable frequency, etc.

f.6 a factor of safety

f.7 the quantity that is to be minimized or maximized, called the "objective function" (e.g. weight).

NOTE 1: Variables of types 4, 5, 6 are always "bundled" together. For example, if the GENOPT user selects a variable of Type 4 (for example, call it STMAX for "maximum stress") he/she will next be asked to provide information about STMAX (maximum actual stress), STMAXA (maximum allowable stress), and STMAXF (factor of safety for stress). STMAX, STMAXA and STMAXF are names that the GENOPT user chooses. All "responses" (often called "behaviors"), such as stress, buckling, displacement, etc., are treated in this manner.

NOTE 2: GENOPT requires the user to provide all input relative to variables of Types 1 and 2 before variables of Type 3. All variables of Type 3 must be provided before variables of Types 4. 5, 6. All "4, 5, 6" "bundles" must be provided before the objective (Type 7).

4.2 Things for the GENOPT user to do on the computer

a. Execute GENTEXT. "GENTEXT" is the command that causes execution of the GENOPT program called GENPROMPT. The "GENTEXT" command initiates the interactive session in which the GENOPT user is asked to provide the information just described in Section 4.1f. During this interactive session the GENOPT system writes FORTRAN code fragments that it later inserts into processors called BEGIN and CHANGE and subroutine libraries called STRUCT, BEHAVIOR, and STOGET. These entities, plus others (processors called DECIDE, MAINSETUP, OPTIMIZE, AUTOCHANGE, STORE, CHOOSEPLOT, and subroutine libraries called CONMAN, ADS, PROMPTER, and UTIL, which are NOT modified by GENOPT) constitute the computer program system by means of which ordinary "fixed design" structural analyses, such as an ordinary BOSOR4 analysis, are automatically converted into a computer program system that can optimize something, such as "WAVYCYL". (NOTE: as mentioned above, GENOPT is not restricted to the field of structural analysis.) In this paper the computer program system created by GENOPT and the GENOPT user is called "WAVYCYL". In the much simpler example featured in the appendix the computer program system created by GENOPT and the GENOPT user is called "CYLINDER".

b. It will usually happen sometime after the GENOPT user has completed a possibly very long "GENTEXT" interactive session, or even after the "end" user (WAVYCYL user) has made several optimization runs, that the GENOPT user will think of additional variables that must be included. Since GENOPT demands that the various classes of variables listed in Section 4.1f be supplied in a certain order, this seems to require that the GENOPT user start over from the beginning. However, the GENOPT system contains a processor called INSERT by means of which the GENOPT user can easily supply additional variables in any of the categories listed in Section 4.1f except f.7, the objective.

c. The subroutine libraries called STRUCT and BEHAVIOR are "shells" that contain places for the GENOPT user to insert computer coding that performs the structural analysis for each optimization cycle in which the design constraints (e.g. stress, buckling, displacement, natural frequency) and objective (e.g. weight) are computed and in which the gradients of the design constraints and objective with respect to each of the decision variables are computed. By far most of the effort in generating a working optimization tool for the class of problem selected by the GENOPT user (in this case the optimization tool called "WAVYCYL" and in the appendix the optimization tool called "CYLINDER") is the derivation of completed subroutine libraries STRUCT and BEHAVIOR and the many modifications to them that will doubtless be required before a final working and thoroughly checked version of "WAVYCYL" or "CYLINDER" (or other system) exists.

Table 4.1 summarizes the activities of the GENOPT user and the "end" ("WAVYCYL", "CYLINDER") user that lead to the capability to optimize any of a class of objects.

Tables 4.2 - 4.5 list information that is created by the GENOPT user for the "WAVYCYL" class of shells and organized by the GENOPT system. Table 4.2 lists the beginning of the wavycyl.INP file, which contains input data for "GENTEXT" provided by the GENOPT user. Table 4.3 lists the first part of the prompt file, wavycyl.PRO, which is automatically created as the GENOPT user proceeds with the interactive "GENTEXT" session. The part of the wavycyl.PRO file listed in Table 4.3 corresponds to the part of the wavycyl.INP file listed in Table 4.2. Table 4.4 is part of the wavycyl.DEF file, created by the GENOPT system upon completion of the "GENTEXT" interactive session. Table 4.5 lists the labelled common blocks created by GENOPT during the interactive "GENTEXT" session. These common blocks contain all the data that characterize the class, "wavycyl". The labelled common blocks appear in the skeletal STRUCT and BEHXi and OBJECT subroutines, which must be "fleshed out" by the GENOPT user. See [2] and the appendix for examples of how this is done.

Tables 4.6 - 4.8 list input data, provided by the WAVYCYL user for the specific case called "testnew6", for the WAVYCYL processors, BEGIN, DECIDE, and MAINSETUP/OPTIMIZE, respectively. The data in Table 4.6 correspond to the starting design depicted in Fig. 1.

5.0 FLOW OF COMPUTATIONS FOR EACH DESIGN EVALUATION

5.1 Introduction

Within an outer loop over the number of different load sets (up to 20 are permitted but only one is used in the examples provided here and in the appendix), the computations described next are performed for each "current" design and each "perturbed" design, for each load set and within each optimization cycle. A "perturbed" design is the same as the "current" design except that one of the decision variables has been perturbed by a small amount. (The perturbation is usually five per cent of the "current" value of the decision variable). For each load set and optimization cycle there are NDEC "perturbed" designs, in which NDEC is the number of decision variables used during optimization. Results from the "perturbed" designs are used to compute gradients of the design constraints, which are needed by the optimizer, ADS. The value of each constraint gradient is given by:

(constraint gradient(i,j)) = [(constraint value(i,j) for perturbed design(j)) -(constraint value(i) for current design)] /DX(j) (5.1)

in which the index i refers to the constraint (behavior) number, the index j refers to the decision variable number, and DX(j) is the perturbation in the jth decision variable. NOTE: In Eq. (5.1) there should actually be an additional "outer loop" index, such as k, denoting load set number. It is omitted here for clarity. In all the optimization runs from which the results presented here were derived, there is only one load set.

5.2 Definitions of "margin" and "constraint"

"margin" = "constraint" - 1.0 (5.2)

in which, for buckling load factors and modal vibration frequencies or any behavior for which the "response" must be greater than the "allowable" (e.g. buckling load factor must be greater than 1.0; frequency must be greater than 10 Hz),

"constraint" = "response"/ ("allowable"*factor-of-safety) (5.3)

and for stress and displacement or any behavior for which the "response" must be less than the "allowable" (e.g. maximum stress must be less than the maximum allowable stress).

"constraint" = 2.0-("response"/"allowable") *(factor-of-safety) (5.4)

5.3 Flow of computations in SUBROUTINE STRUCT

The entire design evaluation occurs in SUBROUTINE STRUCT, which is partly written by the GENOPT system during the "GENTEXT" interactive session (as described in [2]) and partly written by the GENOPT user after he or she completes the "GENTEXT" session. In the "WAVYCYL" example SUBROUTINE STRUCT calls 18 subroutines with names BEHX1 through BEHX18. BEHX1 through BEHX18 generate the values of the 18 constraints (called "behaviors" herein) identified by the GENOPT user during the long "GENTEXT" interactive session as playing a role in possibly constraining the design for each load set during optimization cycles. These 18 behaviors are listed near the end of Table 4.4 and in Table 6.1. (In the much simpler "CYLINDER" example described in detail in the appendix there are only four "behaviors", BEHXi, i = 1, 4.)

In addition, SUBROUTINE STRUCT performs the following computations listed next. In the following list reference is made to "BOSOR4 MODEL 1" and "BOSOR4 MODEL 2". These two different BOSOR4 models are characterized as follows:

MODEL 1: No rings, only wavy segments included in the model; symmetry conditions applied at both ends of MODEL 1, which simulates a wavy shell of infinite length.

MODEL 2: Yes rings (modeled as thin shell branches as described in [4] (see Fig. 1); wavy segments plus straight segment in which the waviness is "smeared out" by representation of the material by its 6 x 6 matrix of coefficients of the integrated constitutive law, C(i,j). Boundary conditions are classical simple support at bottom and symmetry or antisymmetry at top.

The following computations are carried out in the part of SUBROUTINE STRUCT written by the GENOPT user:

1. Open files (call OPNGEN).

2. Rewind files (call RWDGEN).

3. Initialize the 18 behaviors, that is, set STRMAX through WWWRAN to zero. (See table 6.1 for the GENOPT-user-provided definitions of the 18 behaviors.)

4. Reset the number of axial halfwaves, NWAVES, in the axially "wavy" cylindrical shell such that:

a. NWAVES*WAVLEN is less than or equal to 0.9*AXIAL.

b. MOD(NWAVES-2,4) = 0 (NWAVES-2 is divisible by 4) where WAVLEN = axial halfwavelength of waviness and AXIAL = total length of the cylindrical shell (AXIAL = twice the length shown in Fig. 1, for example.)

5. Check to see if the maximum allowable number of degrees of freedom, MAXDOF, is exceeded. (IREDUC = 1?). If so, reduce NWAVES and do 4 again.

6. If there is no waviness (NWAVES=0), compute the constitutive coefficients C(i,j) and mass density per area of the cylindrical shell wall.

7. Compute the maximum effective stress, STRMAX, from nonlinear theory from MODEL 1. (MODEL 1 contains the wavy portion only, and no rings). This is accomplished by running BOSOR4 for the configuration called MODEL 1 with the BOSOR4 analysis type, INDIC = 0. By "running BOSOR4" is meant execution of several subroutines as follows:

a. CALL PUTWAV( ) (create input file, *.WAV, for BOSDEC).

b. CALL BOSDEC (create standard input file, *.ALL, for the BOSOR4 preprocessor, B4READ).

c. CALL B4READ (execute BOSOR4 preprocessor).

d. CALL B4MAIN (execute BOSOR4 mainprocessor).

e. CALL B4POST (execute BOSOR4 postprocessor).

The output needed here is the maximum effective stress in the wavy portion of the cylindrical tube, called STRMAX. The "*" in Items a and b above represents the WAVYCYL user's chosen name for the case (e.g. "testnew6").

8. Compute the axial stiffness of the wavy portion of the cylindrical tube. As in Item 7, MODEL 1 is used (wavy portion only) and the BOSOR4 analysis type index, INDIC = 0. All external loads in the current load case are set to zero except the axial resultant, N_x, which is set to -1.0 lb/in. SUBROUTINES PUTWAV() and BOSDEC and the three BOSOR4 processors are executed as listed in a-e in Item 7. The output needed here is the axial end shortening, called ENDUV. Figure 7 shows an example of the "axial stiffness" model. The end shortening, ENDUV, is the axial displacement at the bottom of the BOSOR4 MODEL 1. This end shortening is caused by the unit axial resultant, N_x = -1.0 lb/in, applied at the bottom of the model.

9. Perform linear modal vibration analysis with n = 2 circumferential waves. All loads in the current load case are set to zero. Again MODEL 1 is used. The BOSOR4 analysis type index, INDIC = 2. SUBROUTINES PUTWAV() and BOSDEC and two of the three BOSOR4 processors, B4READ and B4MAIN, are executed as listed in a-d in Item 7. The output needed here is the fundamental natural frequency corresponding to n = 2 circumferential waves, called FREQ2. This frequency is used to establish the effective hoop bending stiffness of the "wavy" wall of the cylindrical shell, as described next. Figure 8 shows an example of a wavy section of tube vibrating in an n = 2 mode.

10. From the results just obtained, especially those listed in Items 8 and 9, determine the effective stiffnesses, $C_{eff}(i,j)$, i=1,6, j=1,6 for the equivalent "orthotropic" cylindrical shell that represents the portion of BOSOR4 MODEL 2 treated as a perfect cylindrical shell segment with straight generators. (See Fig. 3 for an example.) In this straight cylindrical segment of MODEL 2 the axial waviness is "smeared out", that is, it is represented as a sort of "orthotropic" material. (Actually, the material is not strictly orthotropic but somewhat more complex because the relationships between extensional and bending stiffnesses of the shell wall are more complex than those of a monocoque orthotropic shell wall. The approximated shell wall is more like a sandwich with orthotropic core and face sheets.) The proper 6x6 integrated constitutive matrix, $C_{eff}(i,j)$, i=1,6, j=1,6, is provided in the BOSOR4 input file as listed in Table 5.1, which is FORTRAN coding taken from SUBROUTINE STRUCT.

In Table 5.1 a formula is given for the in-plane modal vibration of a ring:

$$\omega^2 = C_{55EFF}(36/5)(1/R^4)(1/m) \qquad (5.5)$$

in which ω is the natural frequency in radians/sec, C_{55EFF} is the hoop bending stiffness "EI" of the ring, R is the radius of the ring and m is the mass per unit area for width of ring equal to unity. This formula is derived from energy minimization as follows. The strain and kinetic energies of the ring of unit width are given by:

$$\text{strain energy} = U = \frac{1}{2}\int_y EI\kappa^2 dy \qquad (5.6)$$

$$\text{kinetic energy} = T = \frac{1}{2}\int_y \left\{\left(\frac{\partial v}{\partial t}\right)^2 + \left(\frac{\partial w}{\partial t}\right)^2\right\} dy \qquad (5.7)$$

in which the change in hoop curvature, kappa, is

$$\kappa = -w,_{yy} + v,_y / R \qquad (5.8)$$

and the tangential and normal displacement components, v and w, are given by

$$v = V\cos(2y/R)\sin(\omega t) \qquad (5.9)$$

$$w = W\sin(2y/R)\sin(\omega t) \qquad (5.10)$$

From Eqs. (5.9, 5.10) one sees that it is assumed that the lowest in-plane modal vibration frequency corresponds to $n = 2$ circumferential waves. It is also assumed that the in-plane modal vibration of the ring is inextensional, that is, the hoop strain of the reference surface is zero:

$$e_y = v,_y + w/R = 0 \qquad (5.11)$$

Eq. (5.11) with Eqs.(5.9) and (5.10) yields

$$V = W/2 \qquad (5.12)$$

Use of Eqs. (5.12), (5.9), and (5.10) in Eqs. (5.6-5.8) and minimization of the total potential energy, $U - T$, with respect to W leads to the formula given in Eq. (5.5).

11. Compute the CIJEFF, RHOEFF, for a cylindrical shell without waviness (NWAVES = 0).

12a. Discussion

All fabricated shells are imperfect. Bushnell and Bushnell [19] describe an approximate method in which the effects of general and local buckling modal initial imperfections are accounted for in the optimum design of stiffened cylindrical panels and shells. The method described in [19] is used here in a simplified form: it is assumed that the only initial imperfection present is in the shape of the general buckling mode. In that mode the cylindrical shell wall and rings deform together, as shown, for example in Fig. 26(b). Because the shell is imperfect (for example, in the mode with two circumferential waves, $n = 2$, it is slightly oval rather than perfectly circular) it bends as soon as any loading is applied. This primarily hoop bending occurs about the neutral axis of combined cylindrical shell skin and rings, which is some distance from the middle surface of the skin. Therefore, additional hoop tension and compression, $N_y(add)$, are induced in the skin of the cylindrical shell. The additional hoop load, $N_y(add)$, varies around the circumference as $sin(n\theta)$. In this application we are concerned only with maximum additional hoop compression, which is destabilizing and will therefore diminish the buckling load factor for inter-ring (local) buckling and increase the maximum effective stress in the shell wall.

The additional hoop compression, N_y(add), in the skin of the cylindrical shell between adjacent rings is derived next. We assume that for the skin there is no coupling between bending and stretching. Hence, in the skin the axial and hoop stress resultants are given by

$$N_x(add) = C_{11}e_x(add) + C_{12}e_y(add) \qquad (5.13)$$

$$N_y(add) = C_{12}e_x(add) + C_{22}e_y(add) \qquad (5.14)$$

in which $e_x(add)$ and $e_y(add)$ are the additional (imperfection induced) axial and hoop strains of the middle surface of the skin of the cylindrical shell. The qualifer, "*add*", denotes "quantity generated only from inextensional prebuckling bending of the initially imperfect shell", that is, prebuckling bending caused only by the presence of the initial general buckling modal imperfection. The membrane strain components from the applied loading (e.g. $e_x = pr/2$; $e_y = pr$) are not included here.

It is assumed for simplicity that no axial resultant $N_x(add)$ develops as a result of prebuckling hoop bending of the cylindrical skin. Therefore, the additional axial strain, $e_x(add)$, is given by

$$e_x(add) = -C_{12}e_y(add)/C_{11} \qquad (5.15)$$

and therefore,

$$N_y(add) = (C_{22} - C_{12}^2 / C_{11}) e_y(add) \qquad (5.16)$$

in which the constitutive coefficients, C_{11}, C_{22} C_{12}, are for the skin only (with "smeared" waviness, as listed in Item 10; the "eff" is omitted from the C_{ij} for simplicity.)

During loading the globally imperfect shell bends; especially it undergoes hoop bending as the amplitude of the initial general buckling modal imperfection grows under increasing external pressure. The rate of growth is hyperbolic, approaching infinity as the load approaches the general instability buckling load. (See Eq. (7), p 494 of [19]). This hoop bending is assumed to be inextensional at the neutral plane for hoop bending. The change in hoop curvature is given by

$$\kappa_y = w,_{yy} = W_0 (n/R)^2 \sin(ny/R)/(\lambda - 1) \qquad (5.17)$$

in which w is the normal displacement, W_0 is the amplitude (half peak-to-peak) of the initial buckling modal imperfection, n is the number of circumferential waves in the general buckling mode, R is the nominal radius of the cylindrical shell, y is the circumferential coordinate and λ is the buckling load factor corresponding to general instability.

The additional hoop strain, $e_y(add)$, at the middle surface of the skin of the cylindrical shell, generated from just the prebuckling bending of the initially imperfect shell, is given by

$$e_y(add) = z\kappa_y \qquad (5.18)$$

where z is the distance from the neutral axis for hoop bending to the middle surface of the skin. In the absence of refinement of the theory to account for the fact that the "effective length" of skin (that stretches in the hoop direction as each ring on the imperfect shell undergoes prebuckling in-plane bending) is in general considerably shorter than the spacing between rings, the distance z is given by

$$ABS(z) = ABS(C_{s25} / C_{s22}) \qquad (5.19)$$

in which C_{s25} and C_{s22} are coefficients in the 6x6 constitutive matrix for the shell with smeared rings. C_{s22} is the (hoop stiffness)/(axial length) and C_{s25} represents the bending-stretching coupling in the hoop direction. C_{s22} and C_{s25} are given by Eqs(40) in [21]:

$$C_{s22} = C_{22skin} + (EA/b)_{ring} \qquad (5.20)$$

$$C_{s25} = C_{25} + (eEA/b)_{ring} \qquad (5.21)$$

where E, A, b are the elastic modulus, cross section area, and spacing of the rings (or "effective length" of skin; see below) and e is the ring eccentricity, that is, the distance from the middle surface of the skin of the cylindrical shell to the shear center of the ring.

If we insert the right-hand sides of Eqs. (5.20, 5.21) into Eq. (5.19) and the right-hand sides of Eqs. (5.17) and (5.19) into the right-hand side of Eq. (5.18), and the result into the right-hand side of Eq. (5.16), we obtain for the additional hoop stress resultant in the skin of the cylindrical shell, the following:

$$N_y(add) = -(C_{22} - C_{12}^2 / C_{11})(C_{s25} / C_{s22})(n/R)^2 W_0 / (\lambda - 1) \qquad (5.22)$$

(valid only for lambda > 1).

We have replaced $sin(ny/R)$ in Eq. (5.17) with -1 and the imperfection amplitude, W_0, is assumed to be positive.

In the investigation of the effects of the initial general buckling modal imperfection on inter-ring buckling and effective stress, we introduce two models, the first (used later in the analysis of inter-ring buckling) leading to FN2ADD(1) in which the eigenvalue, λ (call it λ_1) is derived from a general buckling model where the rings are "smeared" as prescribed by Baruch and Singer [23] and the second (used later in the derivation of maximum effective stress) leading to FN2ADD(2) in which the eigenvalue, λ (call it λ_2), is derived from a general buckling model in which rings are modeled as discretized shell segments. In both general instability models the waviness of the wall of the cylindrical shell is "smeared" as described in Item 10.

There is another difference in the two models leading to FN2ADD(1) and FN2ADD(2). In the computation of the coefficient for hoop bending-stretching coupling, C_{s25}, the "effective length", b, of skin in the model leading to FN2ADD(1) is taken as the ring spacing BRINGS, as recorded in Eq. (5.21). In the computation of C_{s25} the "effective length", b, of skin in the model leading to FN2ADD(2) is taken as

$$b = BRINGS(\lambda_2 / \lambda_1)^2 \qquad (5.23)$$

The eigenvalue λ_2 is smaller than λ_1 because the general buckling model in which the rings are modeled as discrete is less stiff than the model in which the rings are smeared out.

12b COMPUTATIONS

Two values of FN2ADD must be computed:

FN2ADD(1) = Additional hoop resultant, $N_y(add)$, from a model in which the rings are smeared out. This is used for the analysis of inter-ring buckling later. For buckling modes judged by the WAVYCYL program to represent local buckling between rings, the imperfection-induced increment of hoop compression, FN2ADD(1), is added to the hoop compression computed in the BOSOR4 buckling models executed later via the "BEHXi" routines described in the next section.

FN2ADD(2) = Additional $N_y(add)$ from a model in which the rings are treated as discrete. FN2ADD(2) is used in the linear non-axisymmetric stress analysis (BOSOR4 analysis type INDIC = 3; see Item 16 below). An additional external pressure, $p(add)$ = FN2ADD(2)/RADIUS, is applied in order to represent the additional, imperfection-induced hoop compression in the cylindrical shell skin in the neighborhood of each ring.

Compute hoop compression increments, FN2ADD(1) and FN2ADD(2), in the wall of the cylindrical tube caused by amplification of a general buckling modal initial imperfection with n circumferential waves and an amplitude W_0 corresponding to the "ASME one per cent rule", that is

$$\text{(maximum diameter) - (minimum diameter)} = 0.01\text{*(diameter)} \qquad (5.24)$$

For an initial imperfection given by $w(imp) = W_0 sin(n\theta)$, the "ASME one per cent rule" leads to amplitude

$$W_0 = 0.005R \qquad (5.25)$$

The imperfection amplitude, W_0, is "built in" to the WAVYCYL system; it is NOT an input datum to be provided by the WAVYCYL user.

13. Compute local (inter-ring) buckling load factors vs number of circumferential waves n via an INDIC = 1 BOSOR4 type of buckling analysis of a small (computer-efficient) model. A BOSOR4 MODEL 2 of length equal to the ring spacing, BRINGS, is used with only 31 nodes in the part of the model that represents the cylindrical shell of length BRINGS. The waviness in the wall of the cylindrical shell is "smeared" as described in Item 10. At each end of the short cylindrical shell there is a discrete ring with modulus equal to half of the actual ring modulus because these rings are at planes of symmetry in the prebuckling analysis and planes of

antisymmetry in the buckling analysis. The end rings are represented as little flexible shell branches, as with the models shown in Figs. 1 and 6.

This approximate local (inter-ring) buckling analysis is used to determine the minimum number of circumferential waves n for which the WAVYCYL program can, in the later much larger buckling analyses conducted in subroutines BEHXi, i = 6, 7, 8, 9, 10, 11, 16, and 17, conclude that the buckling mode is a local one and not a general one. The WAVYCYL program adds the imperfection-induced hoop compression resultant, FN2ADD(1), to the hoop resultants derived in the BOSOR4 prebuckling analysis only if the buckling mode is judged by WAVYCYL to be local and not general. The "minimum number of circumferential waves corresponding to local buckling is called NWAVLC in the program, and is given by

NWAVLC = 0.7*FLOAT(NWVCRT) + 0.5 (5.26)

in which NWVCRT is the number of circumferential waves that corresponds to the minimum buckling load factor found for all circumferential wavenumbers in the search over n for the critical eigenvalue with use of the small, local buckling model of length BRINGS just described.

14. Compute the total mass, TOTMAS, of the shell with use of BOSOR4 MODEL 2. Only the BOSOR4 preprocessor (Items 7a-c) is executed. The weight of half of the length of the shell (from the simply supported end to the symmetry plane at the midlength) is printed as output. It is called WEIGHT and it is given by WEIGHT = TOTMAS*GRAVTY, in which GRAVTY is the acceleration of gravity in the units of the case.

15. The wavy tube is supported in the axial direction at much more widely spaced intervals than is the case for support against lateral motion. In SUBROUTINE STRUCT an additional (quasi-static) axial compression, FNXADD, is computed as follows:

FNXADD = -WEIGHT*GAXIAL(ILOADX)
*(LGAXL/AXIAL)/(2.*3.141593*RADIUS) (5.27)

in which

GAXIAL(ILOADX) = axial g-loading in Load Case ILOADX

LGAXL = length of wavy tube between supports that prevent axial motion.

AXIAL = length of wavy tube between supports that prevent lateral motion.

RADIUS= nominal (average) radius of wavy cylindrical shell.

In SUBROUTINE PUTWAV the quantity FNXADD is added to the externally applied axial load, FNX(ILOADX) = p*RADIUS/2, in which p represents the uniform external pressure (p is negative for external pressure).

16. Two linear non-axisymmetric static responses are computed from BOSOR4 MODEL 2 for the wavy ring-stiffened tube as loaded by uniform axial compression, FNX + FNXADD, uniform external pressure p = PRESS + FN2ADD(2)/RADIUS, and lateral g-loading, GLATRL. The BOSOR4 analysis index is INDIC = 3 for both of these analyses. The BOSOR4 models are larger than those described previously, containing many, many little curved (toroidal) segments, a straight cylindrical segment in which the waviness is "smeared" as described in Item 10, and the discrete rings spaced at axial intervals, BRINGS, as shown in Fig 1, for example. The discrete rings (either rectangular or Tee-shaped) are modeled as small, flexible shell branches, as in [4].

The purpose of the first linear static stress analysis is to obtain the response (maximum lateral displacement and maximum effective stress) along the generator corresponding to circumferential angle, $\theta = 0$ degrees. The purpose of the second linear static analysis is to obtain the same quantities along the generator corresponding to the circumferential angle, $\theta = 180$ degrees. In these computations all the loads from Load Set B (non-eigenvalue loads, if any) are added to all the loads from Load Set A (eigenvalue loads) and the Load Set B loads are then temporarily set equal to zero.

These two linear nonaxisymmetric stress analyses lead to the behavioral constraint conditions involving maximum effective stress and lateral displacement, STR0 and WWW0, respectively, on the θ=0 degree generator and maximum effective stress and lateral displacement, STR180 and WWW180, respectively, on the θ=180 degree generator. The maximum effective stress at circumferential angles, $\theta = 0$ and 180 degrees, are "fed" to SUBROUTINES BEHX4 and BEHX5, respectively. The maximum lateral displacements at $\theta = 0$ and 180 degrees are "fed" to SUBROUTINES BEHX12 and BEHX13, respectively. (See Table 6.1).

17. Compute the 18 behavioral constraint conditions and corresponding margins from SUBROUTINES BEHX1 through BEHX18. The "GENTEXT" interactive session produces subroutine "shells" named "BEHX1, BEHX2,. ..BEHX18. The GENOPT user must complete these "shells" by supplying code by means of which the various structural responses are computed. Table 6.1 lists the various "behaviors" corresponding to which design constraints and margins are computed. (See the next section for more details).

18. The objective (e.g. weight) is computed. In this paper the total mass of the BOSOR4 model (half of the cylindrical shell: from one simply supported or clamped end to the midlength, which is a plane of symmetry in prebuckling analyses and sometimes a plane of symmetry and other times a plane of antisymmetry in bifurcation buckling analyses) is called TOTMAS and is computed as described in Item 14. The weight of the BOSOR4 model is given by TOTMAS*GRAVTY, in which GRAVTY is the value of the acceleration of gravity in the units of the case.

19. Close files (CLSGEN).

6.0 COMPUTATIONS IN THE "BEHAVIOR" SUBROUTINES, BEHX1 - BEHX18

6.1 Introduction

Table 6.1 lists the 18 "behaviors" (responses) that the WAVYCYL program can possibly evaluate for each "current" design and each design perturbation for each load set during optimization cycles. The values in Table 6.1 under the heading, "CURRENT VALUE" correspond to the optimized design of the wavy cylindrical shell with external rings, for which complete results appear in Table 7.8. "Behavior" numbers for which the "CURRENT VALUE" is either 1.000E+10 or 1.000E-10 have been previously "marked" by the WAVYCYL user during the interactive MAINSETUP session to be skipped in this case. (See Table 4.8, for example) In the example provided in Table 6.1, the WAVYCYL user has indicated that he/she does NOT want to generate design constraints corresponding to "behaviors" 2 and 3 (nonlinear buckling) and 15 - 18 (responses to random excitation). "Behaviors" 2 and 3 are too conservative in this example because they are generated from BOSOR4 MODEL 1 in which the rings are ignored and the shell is of infinite length, and "Behaviors" 15 - 18 are judged unnecessary in this case because the minimum natural frequency allowable, 10 hertz (see "Behavior" no. 14), is set at a level for which it is thought that no significant response occurs at higher frequencies. Also, spectral density and damping coefficients were not available at the time these computer runs were made.

During optimization, in order to save computer time, only "behaviors" 4, 5, 6, 7, 8 and 14 were included. Preliminary explorations revealed that all buckling constraints corresponding to conditions along the meridian at θ = 180 degrees ("Behaviors" 10 and 11) were less severe than those along the meridian at θ = 0 degrees ("Behaviors" 6, 7, 8, 9) and there is no maximum displacement constraint ("Behaviors" 12 and 13) for the particular loading set used during optimization cycles. It was decided to check "Behavior" no. 9 only after completion of optimization cycles because it is very expensive in terms of computer time, requiring exploration of buckling load factors for a model with a large number of degrees of freedom (BOSOR4 MODEL 2) over a wide range of number of circumferential waves in the buckling mode.

The design margins corresponding to the "CURRENT VALUES" of "behaviors" listed in Table 6.1 appear in Table 6.2. Please note that the "MARGIN NOs" do NOT correspond to the "Behavior" numbers. For correspondance of values, inspect the WAVYCYL-user-specified names used in the various margins listed in Table 6.2 and compare with the "behavior" names listed in Table 6.1.

All of the "behaviors" listed in Table 6.1 are either "presented" or computed in SUBROUTINES BEHX1 - BEHX18. By "presented" is meant the behavior is computed earlier in SUBROUTINE STRUCT and its value is simply printed out from the BEHXi routine. It is uneconomical to compute ALL behaviors entirely within the BEHXi routines because certain computations yield more than one quantity that is involved in a design constraint condition. For example, the linear nonaxisymmetric stress analysis computed earlier in SUBROUTINE STRUCT (see Item No. 16 in Section 5) yields both maximum stress and maximum lateral displacement.

As mentioned previously, skeletal forms of SUBROUTINES BEHX1 - BEHX18 are written by the GENOPT computer program for the problem class called WAVYCYL by the GENOPT user. These skeletal subroutines are included in the library called BEHAVIOR.NEW. The GENOPT user must "flesh out" each of these BEHXi subroutines with computer code that generates a value for the corresponding "behavior" (response). In this case, the GENOPT user is the author of this paper. See the appendix for a more complete explanation of this process in the case of a much simpler example.

6.2 Flow of computations in each of the subroutines BEHXi, i = 1,18

SUBROUTINE BEHX1: Print the maximum effective stress corresponding to the ILOADXth load set, STRMAX(ILOADX). This stress is computed from nonlinear theory (BOSOR4 analysis type indicator, INDIC = 0) in SUBROUTINE STRUCT as described in Item No. 7 in Section 5.

SUBROUTINE BEHX2: Compute buckling load factors corresponding to axisymmetric and non-axisymmetric buckling modes for a range of circumferential wavenumbers from n = N0B to n = NMAXB from BOSOR4 analysis type INDIC = 1 and from BOSOR4 MODEL 1 (rings neglected and symmetry of buckling mode assumed at both ends of cylindrical shell, that is, the shell is of infinite length). Identify the lowest buckling load factor, BUCFAC(ILOADX), and corresponding number of circumferential waves, NWAV3. The range limits, N0B and NMAXB are set by the WAVYCYL program user during the "BEGIN" interactive session; see Table 4.6.

SUBROUTINE BEHX3: Perform the same kinds of computations as in SUBROUTINE BEHX2 for the high-n range of number of circumferential waves in the buckling mode. Identify the lowest buckling load factor, BUCHIW(ILOADX), and corresponding number of circumferential waves, NWAV4.

SUBROUTINE BEHX4: Print the maximum effective stress, STR0(ILOADX), from the linear nonaxisymmetric stress analysis branch of BOSOR4 (INDIC = 3) in which BOSOR4 MODEL 2 is used. STR0(ILOADX) corresponds to the maximum effective stress along the meridian at circumferential coordinate, θ = 0 deg. It is computed in SUBROUTINE STRUCT, as described in Item 16 in Section 5.

SUBROUTINE BEHX5: Same as for SUBROUTINE BEHX4, except that BEHX5 applies to the maximum effective stress, STR180(ILOADX), along the meridian at circumferential coordinate, θ = 180 degrees.

SUBROUTINE BEHX6: Compute buckling load factors corresponding to axisymmetric and non-axisymmetric buckling modes that are SYMMETRIC about the midlength plane of symmetry in the cylindrical shell (axial station = 90 inches in Fig. 1), for a range of circumferential wavenumbers from n = N0B to n = NMAXB/2 (low-n range) from BOSOR4 analysis type INDIC = 4 and from BOSOR4 MODEL 2 (rings included, Fig. 1). The prebuckling state is that computed from linear analysis (INDIC=3) and buckling corresponds to the prebuckled state along the meridian with circumferential coordinate, θ = 0 degrees. Identify the lowest buckling load factor, BUC0(ILOADX), and corresponding number of circumferential waves, NWAV7.

In the BOSOR4 MODEL 2 the number of axial halfwaves used in the "wavy" portion of MODEL 2 is established such that the wavy portion is as close to 0.9*AXIAL/2 in axial length as possible without exceeding the WAVYCYL-user-established limit on degrees of freedom, MAXDOF. (MAXDOF is set by the WAVYCYL user in the "BEGIN" interactive session: see Table 4.6.)

If IMODX = 0 (analysis of current design), ILOADX = 1 (first load set), and ITYPEX = 2 (analysis of fixed design), perform the same analysis again with BOSOR4 MODEL 2 in which the waviness is "smeared" over the entire axial length, AXIAL/2, of BOSOR4 MODEL 2, as described in Item 10 in Section 5. An example of such a BOSOR4 model is displayed in Fig. 6.

SUBROUTINE BEHX7: The same as BEHX6, except that BEHX7 explores the low-n range for buckling that is ANTISYMMETRIC about the symmetry plane at the midlength of the cylindrical shell. The critical buckling load factor is stored in B0ANTI(ILOADX) and corresponding number of circumferential waves is stored in NWAV7A. Again, the prebuckled state corresponds to conditions along the meridian at circumferential coordinate, θ = 0.

SUBROUTINE BEHX8: The same as BEHX6 and BEHX7, except that BEHX8 searches for the lowest buckling load factor in the mid-n range (n = NMAXB/2+1 to NMAXB) corresponding to buckling both SYMMETRIC and ANTISYMMETRIC with respect to the midlength symmetry plane of the ring-stiffened wavy cylindrical shell. The critical buckling load factor is called BUC0MD(ILOADX) and corresponding number of circumferential waves NWAV7M. Again, the prebuckling state is for the meridian at the circumferential coordinate, θ = 0 degrees.

SUBROUTINE BEHX9: The same as for BEHX8, except that only buckling that is ANTISYMMETRIC with respect to the symmetry plane is considered and buckling load factors are sought for the high-n range of circumferential waves, with the starting number of circumferential waves n = NMAXB + INCRBX and the highest number of circumferential waves n = 3*NAVE, with the increment in number of circumferential waves given by INCRBX = 0.1*FLOAT(NAVE) + 1, in which NAVE (average wavenumber) = pi*RADIUS/WAVLEN, where RADIUS = nominal radius of the cylindrical shell and WAVLEN = axial halfwavelength of the waviness. Again, the prebuckling state is that along the meridian at circumferential coordinate, θ = 0 degrees. The lowest buckling load factor is stored in

BUC0HI(ILOADX) and the corresponding number of circumferential waves is stored in NWAV8. This analysis is expensive because the search over the number of circumferential waves n in the buckling mode is extensive.

SUBROUTINE BEHX10: Same as BEHX8, except that the prebuckling state is that along the meridian at circumferential coordinate, θ = 180 degrees and the range of circumferential wavenumbers explored is n = NOB to n = NMAXB, which includes both the low-n and mid-n ranges explored separately in BEHX6, BEHX7, and BEHX8. Buckling both SYMMETRIC and ANTISYMMETRIC about the midlength symmetry plane are explored in separate searches for the critical buckling load factor. The smallest buckling load factor is stored in BUC180(ILOADX) and the corresponding number of circumferential waves is stored in NWAV9.

SUBROUTINE BEHX11: Same as BEHX9, except that the prebuckling state is that along the meridian at circumferential coordinate, θ = 180 degrees. The smallest buckling load factor is stored in B180HI(ILOADX) and the corresponding number of circumferential waves is stored in NWAV10.

SUBROUTINE BEHX12: The maximum lateral displacement at circumferential coordinate, θ=0, called WWW0(ILOADX), is printed. WWW0(ILOADX) is computed in SUBROUTINE STRUCT as described in Item 16 in Section 5.

SUBROUTINE BEHX13: Same as BEHX12 except that the maximum lateral displacement, WWW180(ILOADX), at circumferential coordinate, θ = 180 degrees, is printed.

SUBROUTINE BEHX14: Modal vibration frequencies (in hertz) are computed from a BOSOR4 analysis type, INDIC = 2 (axisymmetric prestress, axisymmetric or non-axisymmetric modal vibration) for BOSOR4 MODEL 2. The lowest natural frequency is sought for in the range of circumferential wavenumbers from N0V to NMAXV, in which N0V and NMAXV are specified by the WAVYCYL program user in the interactive "BEGIN" session; see Table 4.6. Only vibration modes that are symmetric with respect to the midlength of the ring-stiffened cylindrical shell are sought. A modal vibration frequency corresponding to "pogo" (n = 0 axial) vibration is also computed corresponding to a BOSOR4 MODEL 2 which is of length equal to the spacing, LGAXL, between axial restraints on the ring-stiffened wavy cylindrical tube. The length LGAXL can be much greater than the spacing, AXIAL, between lateral supports. As with the buckling computations conducted in BEHX6 and BEHX7, if IMODX=0 and ILOADX = 1 and ITYPEX = 2, modal vibration frequencies are also computed from a BOSOR4 MODEL 2 in which the waviness over the entire length of the shell is "smeared". The lowest natural frequency is stored in FREQ(ILOADX) and the corresponding number of circumferential waves (usually n = 1 for a wavy cylindrical shell) is stored in NWAV13.

SUBROUTINE BEHX15: Compute the response to random lateral (n = 1 circumferential wave) excitation at the "base" (the simply supported end of BOSOR4 MODEL 2, that is, the bottom end of the model shown in Fig. 1, for example). The stated purpose of BEHX15, as written in a comment at the beginning of the subroutine, is, " Obtain maximum stress from random excitation". However, BEHX15 also computes the buckling response from random excitation and the maximum lateral displacement from random excitation, which are merely printed out in SUBROUTINEs BEHX16 and BEHX18, respectively. There are several major steps in the computations carried out in SUBROUTINE BEHX15:

STEP1: Compute the nonlinear static response to the axisymmetric (n=0) portion of the applied loading (axial loading, N_x, external pressure, p, and quasi-static axial acceleration, GAXIAL. This is done for BOSOR4

MODEL 2 from an INDIC = 0 analysis type. The maximum effective stress, called STRMXX, must be added later to the maximum stress from lateral (n=1) random excitation.

STEP2: Add Load Set B loads to Load Set A loads and temporarily reset Load Set B loads to zero.

STEP3: Find "several" vibration modes and frequencies corresponding to $n = 1$ circumferential wave, from BOSOR4 MODEL 2 as loaded by the axisymmetric components of the sum of Load Set A and Load Set B. (NOTE: Lateral deformations of the cylindrical tube under lateral excitation at the supports correspond to $n = 1$ circumferential wave.) In the WAVYCYL application "several modes" = 5 modes. The BOSOR4 analysis type INDIC = 2 is used for this step. Compute the generalized mass and participation factor for each mode shape. The important output from this step is listed in Table 6.3. (This output appears in the file, testnew6.OUT, in which "testnew6" is the WAVYCYL program user's name for the case. The testnew6.OUT file is deleted upon successful execution of a processor. Therefore, a temporary "call exit" statement had to be inserted at the end of SUBROUTINE BEHX15 in order to save the testnew6.OUT file.) The results listed in Table 6.3 correspond to the optimized design of the wavy cylindrical shell with external rings, complete results for which are listed in Table 7.8.

STEP4: Use the "RESETUP" (restart) BOSOR4 capability to compute the $n = 1$ response to random excitation, given the WAVYCYL-user-provided spectral densities and damping factors as functions of frequency provided in the "BEGIN" interactive session. (See Table 4.6) In this "optimization" application of BOSOR4, the BOSOR4 processor formerly called "RESETUP" is now a subroutine called "RESET". The purpose of RESET is to read a file called testnew6.RES created by SUBROUTINE PUTWAV. The testnew6.RES file contains input data needed for the RESTART branch of BOSOR4 in which response to base excitation is to be computed. A list of the file testnew6.RES appears in Table 6.4. The information in the testnew6.RES file plus the modal vibration information generated from STEP2 and listed in Table 6.3 is sufficient to compute multipliers for each vibration mode that are listed in the right-most column of Table 6.5. These multipliers appear as the product, m(i)*P(i)/2, in the equation for the response to random excitation,

w(response) = SQRT{ sum from 1 to 5 of [m(i)*(P(i)/2)*phi(i)]**2} (6.1)

In Eq. (6.1) the quantity, phi(i), represents the ith vibration mode. The output listed in Table 6.5 appears in the testnew6.OUT file.

STEP5: With use of the amplitude factors listed in the right-most column of Table 6.5, compute the n=1 prebuckling quasi-static response to random excitation. This response yields the maximum effective stresses along the meridians at circumferential coordinates, $\theta = 0$ and $\theta = 180$ degrees.

STEP6: Use the quasi-static prebuckling response along the meridian at circumferential coordinate, $\theta = 0$ degrees in a linear bifurcation buckling analysis in which the smallest buckling load factor is sought over the range of circumferntial wavenumbers, $n = 2$ to n = NMAXB. Only buckling SYMMETRIC about the midlength symmetry plane of the wavy, ring-stiffened cylindrical shell is considered. With the BOSOR4 coding in its present form it is not possible to have different boundary conditions in prebuckling and bifurcation phases of the analysis for the case of random excitation of the supports.

STEP7: Add the maximum effective stresses from STEP1 and STEP5 to obtain the total maximum effective stress caused by the axisymmetric static components of Load Sets A and B and the $n = 1$ random components of Load Sets A and B (lateral g-loading only, in this WAVYCYL application). The maximum effective stress is called STRRAN(ILOADX). The maximum lateral displacement, WWWRNX, is also computed.

The results from SUBROUTINE BEHX15 for the optimized wavy cylindrical shell with external rings are listed in Table 6.6. Note that the smallest buckling load factor is far less than 1.0, indicating that the design is unfeasible. However, the "tables" of spectral density and damping factors vs frequency listed in Tables 4.6 and 6.4 represent an example for the purpose of demonstration only, not an actual loading case. Actual values of spectral density and damping factors were not available when this paper was written. Therefore, SUBROUTINE BEHX15 (and BEHX16 - BEHX18) were NOT "turned on" during any optimization runs, results for which are reported here.

SUBROUTINE BEHX16: The minimum buckling load factor, BUCRAN(ILOADX), as computed in STEP6 in SUBROUTINE BEHX15 (response to random lateral excitation of the lateral supports) is printed. This is the minimum buckling load factor in the range of circumferential wavenumbers n = 2 to n = NMAXB.

SUBROUTINE BEHX17: In a second BOSOR4 "restart" run, the minimum buckling load factor (random lateral excitation of the lateral supports) over the high-n range of circumferential wavenumber is sought. The high-n range is established in the same way as described for SUBROUTINE BEHX9. The minimum buckling load factor in this high-n range is stored in BRANHI(ILOADX) and the corresponding number of circumferential waves is stored in NWAV16.

SUBROUTINE BEHX18: The maximum lateral displacement under random lateral excitation of the supports, computed in SUBROUTINE BEHX15, is printed. It is called WWWRAN(ILOADX).

7.0 NUMERICAL RESULTS: ALUMINUM WAVY CYLINDRICAL SHELL WITH RINGS

7.1 Summary

Results pertaining to the wavy cylindrical shell with rings are listed in Tables 7.1 - 7.9 and plotted in Figs. 9 - 39. Table 4.6 lists input data for the BEGIN processor of the WAVYCYL system, which contains the starting design, material properties, loading, etc. The name assigned to the case by the WAVYCYL user (the writer) is "testnew6". Note that in Table 4.6 there is rather a lot of input pertaining to spectral density and damping factor vs frequency. These data are present only for the purpose of demonstration. As mentioned in the subsection entitled "SUBROUTINE BEHX15" in Section 6, the "behaviors" relating to response to random excitation (BEHX15, BEHX16, BEHX17, BEHX18) were never turned on during optimization runs.

This section contains descriptions of the starting design, an initial optimization, the final runstream used for development of the final optimum design, results from convergence studies with respect to the maximum allowable number of degrees of freedom, MAXDOF, in the BOSOR4 model and with respect to the number of nodal points, NMESHC, used in each small toroidal segment of the wavy portion of the model, and design sensitivity studies at the optimum design with respect to all of the decision variables used during optimization.

7.2 Starting design, choice of decision variables, choice of "behaviors"

The starting design, material properties, loading, etc. are listed in Table 4.6, to which Fig. 1 corresponds. The English system of units is used (in., lbs). Decision variables and their bounds are listed in Table 4.7 and input data for MAINSETUP is listed in Table 4.8. As revealed indirectly by Table 4.8, optimization was carried out with only "behaviors" 4 - 8 and 14 "active". (See Table 6.1 for definition of the 18 possible "behaviors" accounted for in the WAVYCYL system.)

7.3 Initial optimization of "testnew6" with the WAVYCYL system

The maximum number of degrees of freedom, MAXDOF, was initially set to 3000, not 15000 as listed in Table 4.6. The following WAVYCYL runstream was executed:

GENOPTLOG (activate the GENOPT/WAVYCYL command set)

BEGIN (establish a starting design, etc.; input file = testnew6.BEG; Table 4.6)

DECIDE (choose decision variables, bounds: input file = testnew6.DEC; Table 4.7)

MAINSETUP (choose "behaviors", analysis type; input file = testnew6.OPT; Table 4.8)

SUPEROPT (launch "global" optimizer; see Section 2.2 for description)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript files of plots, testnew6.i.ps, i = 3, 4, 5)

The SUPEROPT run required about 60 hours of computer time on a very fast SGI workstation. The run was especially long because there were eight decision variables:

1. thickness of wavy wall of cylindrical shell, THICK

2. ring spacing, BRINGS

3. ring web thickness, TWEB

4. ring web height, HWEB

5. thickness of outstanding flange of ring, TFLANG

6. width of outstanding flange of ring, HFLANG

7. axial halfwavelength of waviness, WAVLEN

8. amplitude (peak-to-peak/2) of waviness, AMPLIT

The initial optimization run for the configuration with the Tee-shaped rings, such as shown in Fig. 1, demonstrated that the size of the outstanding flange of the ring dwindled to small lower bounds. Therefore, further investigations were made with rectangular rings rather than with Tee-shaped rings. The input data for "BEGIN" (Table 4.6) was modified by setting the thickness and width of the outstanding flange, TFLANG and HFLANG, respectively, to zero.

Also, because of the long computer time required for execution of SUPEROPT, a decision was made to use PANDA2 [7, 19-22] to determine optimum values for the ring spacing, BRINGS, and the thickness and height, TWEB and HWEB, of the rectangular rings.

NOTE: Results for the initial optimization with SUPEROPT as just described are not included in this paper because at the time those runs were made the effect of initial imperfections had not yet been incorporated into the WAVYCYL system.

7.4 A more refined run stream to develop the optimum design.

A typical run stream leading to an optimum design follows. PANDA2 is first used to obtain optimum values for the ring spacing, BRINGS, and ring thickness and height, TWEB and HWEB, respectively. Then the WAVYCYL system is used to obtain the thickness, THICK, of the wavy wall of the cylindrical shell, the axial halfwavelength, WAVLEN, and the amplitude, AMPLIT, of the waviness. The wavy cylindrical shell has an initial imperfection in the shape of the general buckling mode, with imperfection amplitude, W_0 = 0.005*R = 0.045 in. The run stream is:

------ begin optimization with PANDA2. The PANDA2 case name is "cyl" --------

PANDA2LOG (activate the command set for PANDA2 [7, 19-22])

BEGIN (provide starting design for PANDA2 execution, Table 7.1 = cyl.BEG)

SETUP (PANDA2 system sets up matrix templates [22])

DECIDE (choose decision variables, bounds, inequality constraints, Table 7.2. Inequality constraint: the ring thickness, TWEB cannot be less than one tenth the ring height, HWEB; file=cyl.DEC)

MAINSETUP (provide loading, imperfections, strategy parameters, type of analysis, etc., Table 7.3 = cyl.OPT)

SUPEROPT (launch "global" optimizer [7]. Execution of SUPEROPT required about 20 minutes of computer time on the super-fast SGI workstation. output=cyl.OPP)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (obtain postscript plots for PANDA2 phase of optimization; see Figs. 9 - 14)

(See Table 7.4 for output from PANDA2 corresponding to the optimized design. The optimum ring spacing is 10 in.; the ring thickness and height are 0.067398 and 0.67398 inches, respectively.)

--- end of optimization with PANDA2 ---

--- begin optimization with WAVYYCL ---

GENOPTLOG (activate the WAVYCYL system command set)

BEGIN (provide starting design for WAVYCYL optimization, Table 4.6 with BRINGS = 10 in., TWEB = 0.067398 in., HWEB = 0.67398 in., TFLANG = 0, HFLANG = 0; MAXDOF = 15000; input = testnew6.BEG)

DECIDE (choose decision variables and bounds. Only THICK, WAVLEN, and AMPLIT are now decision variables. See Table 7.5 = testnew6.DEC)

MAINSETUP (choose "behaviors", analysis type; Table 4.8 = testnew6.OPT)

SUPEROPT (launch "global" optimizer; output file = testnew6.OPP)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript files of plots, testnew6.i.ps, i = 3, 4, 5; see Figs. 15 - 17)

--- end of first SUPEROPT optimization ---

(Reduce upper bound of WAVLEN in Table 7.5 from 3.0 to 0.8 in.)

DECIDE (run DECIDE with updated file, input = testnew6.DEC [Table 7.5 with upper bound of WAVLEN reduced from 3.0 to 0.8 in.])

SUPEROPT (launch "global" optimizer; output = testnew6.OPP)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript files of plots, testnew6.i.ps, i = 3, 4, 5; see Figs. 18 - 22)

--- end of 2nd SUPEROPT optimization ---

(Find out why the objective (Fig. 18) and the margins (Fig. 19) are so "jumpy" during optimization cycles. To do this, run a design sensitivity analysis [ITYPE=3 in Table 4.8; see Table 7.6]. Use very "tight" starting and ending values of WAVLEN, with the value from the optimum design near the center of the range, 0.545 in. < WAVLEN < 0.564 in.)

MAINSETUP (choose "behaviors" and use analysis type ITYPE=3; Table 7.6)

OPTIMIZE (run the WAVYCYL processor OPTIMIZE in the design sensitivity mode [ITYPE=3])

CHOOSEPLOT (select which margins to plot for 0.545 < WAVLEN < 0.564 in.)

DIPLOT (get postscript file of plot, testnew6.3.ps [margins v WAVLEN]; see Fig. 23)

---- end of design sensitivity run with respect to WAVLEN -----

(get plots of critical buckling modes corresponding to the minimum and maximum design margins for BUC0 and B0ANTI, which occur at WAVLEN = 0.55060 in. and WAVLEN = 0.55555 in., respectively, as can be seen from Fig. 23.)

(first, get critical buckling mode corresponding to WAVLEN=0.55060)

CHANGE (change WAVLEN to 0.5506 in.)

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 7 [B0ANTI = antisymmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to WAVLEN = 0.55060 and THICK and AMPLIT = values obtained after the 2nd SUPEROPT run. This run yields a file called testnew6.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the critical buckling mode, see Fig. 24)

(next, get critical buckling mode corresponding to WAVLEN=0.55555)

GENOPTLOG (activate the WAVYCYL system command set)

CHANGE (change WAVLEN to 0.55555 in.)

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 7 [B0ANTI = antisymmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to WAVLEN = 0.55555 and THICK and AMPLIT = values obtained after the 2nd SUPEROPT run. This run yields a file called testnew6.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the critical buckling mode, see Fig. 25)

----- end of fixed design WAVYCYL runs and BOSOR4 runs for mode shapes -----

(next, do more optimizing. From the last use of CHANGE, the axial halfwavelength of waviness, WAVLEN, is now set to 0.55555 in., which corresponds to the maxima of BUC0 and B0ANTI vs WAVLEN in the range 0.545 < WAVLEN < 0.564 in. as plotted in Fig. 23. Maintain WAVLEN=0.55555 in. and remove WAVLEN from the list of decision variables; optimize with respect to THICK and AMPLIT only [Table 7.7])

DECIDE (choose as decision variables only THICK and AMPLIT [Table 7.7])

MAINSETUP (use the input in Table 4.8 again.)

OPTIMIZE (perform optimization. Only one "OPTIMIZE" is enough to get the global optimum design now, since we are so close to it from all the previous computations. output = testnew6.OPP)

------ end of final optimization -----

MAINSETUP (input is same as Table 4.8, except analysis type, ITYPE = 2, that is, fixed design analysis and fewer "behaviors" are turned off. [See the beginning of Table 7.8 for testnew6.OPT])

OPTIMIZE (perform fixed design analysis with fewer "behaviors" turned off. The results from this run, stored in the file, testnew6.OPM, are listed in Table 7.8)

------- end of fixed design analysis of optimized design --------

7.5 Discussion about optimization of wavy cylindrical shell with rings

7.5.1 PANDA2 optimization

Tables 7.1 - 7.3 list the input files, cyl.BEG, cyl.DEC, cyl.OPT, for the PANDA2 processors, BEGIN, DECIDE, and MAINSETUP/PANDAOPT, respectively. The shell optimized with PANDA2 has a general buckling modal imperfection of amplitude, W_0= 0.005*R = 0.045 in. (See Table 7.3). PANDA2 handles complete (360 degree) cylindrical shells as simply supported panels that span 180 degrees. That is why the "panel length in the plane of the screen" (circumferential length), the third entry in Table 7.1, is given as 28.274 in. (pi*R = 28.274 in.). The loading in the PANDA2 model is uniform axial compression and external pressure only. (The hoop resultant, N_y = p*R = -106.2 lb/in). PANDA2 cannot handle nonuniform loading, such as occurs with lateral g-loading, for example. Therefore, the loading in the PANDA2 model is slightly different from that imposed in the WAVYCYL model. Also, PANDA2 cannot account for the waviness in the wall of the cylindrical shell. In spite of these shortcomings, it is felt that for the cases studied here the similarity in capabilities of PANDA2 and WAVYCYL justify the use of PANDA2 as a "shortcut" for obtaining optimum values of ring spacing, BRINGS, ring thickness, TWEB, and ring height, HWEB. If one wants, one can re-introduce BRINGS, TWEB, HWEB as decision variables in other WAVYCYL optimizations.

The SUPEROPT processor in PANDA2 is used to obtain the optimum design. This processor, by means of which a global optimum design can be obtained, is described in [7]. It works in a manner completely analogous to that described for the WAVYCYL processor SUPEROPT, a brief description of which appears in Section 2.2.

Figures 9 - 14 show results from the PANDA2 run, SUPEROPT. At the initiation of the SUPEROPT run the user chose the option of 6 PANDAOPTs per AUTOCHANGE. (PANDAOPT is the name of PANDA2's main processor, analogous to the processor called OPTIMIZE in the WAVYCYL system) The spikes in Fig. 9 correspond to iterations for which a new starting design is generated randomly by automatic execution of the PANDA2 processor called AUTOCHANGE [7] (similar but not the same as the WAVYCYL system processor also called AUTOCHANGE). For all of the 11 random "restarts" (re-executions of AUTOCHANGE) that permitted the full six successive executions of PANDAOPT before the next execution of AUTOCHANGE, PANDA2 yields the same optimum design. (The 12th random "restart", at Iteration No. 269 approximately, was not permitted to converge to an optimum design because the SUPEROPT process reached the specified maximum permitted total number of design iterations first.) It can be concluded, therefore, that the optimum design is very likely to be the global optimum design. As will be seen later, the SUPEROPT process used with the WAVYCYL model does not usually lead to such "clean" plots.

As seen from Figs. 10 and 11, the most critical margins are general buckling, inter-ring buckling, rolling with local buckling (same as inter-ring buckling, just a different model of the same phenomenon), and the geometrical (inequality-condition-based) constraint, Margin No. 3 in Fig. 10, by means of which the thickness of the ring must be greater than one tenth the height of the ring if the design is to be feasible. Figures 12 - 14 show the values of the decision variables, BRINGS, THICK, TWEB, and HWEB, vs the design iterations during the SUPEROPT run. The best optimized design obtained by PANDA2 during the approximately 275 iterations is listed in Table 7.4.

NOTE: It is emphasized that with use of a SUPEROPT process the best, that is, lightest design is rarely the last design obtained during the total number of iterations. During the SUPEROPT process, PANDA2 keeps track of the best design obtained for all iterations since the beginning of the SUPEROPT process. The user can perform multiple SUPEROPT optimizations provided he/she executes at least one CHOOSEPLOT/DIPLOT between successive SUPEROPTs. These characteristics also hold for the WAVYCYL SUPEROPT process.

It was necessary to modify PANDA2 in a significant way in order to obtain the results plotted in Figs. 9 - 14 and listed in Table 7.4. In cases such as this, for which the lower bound on ring spacing (10 inches in this case) is much greater than would naturally occur if the rings were free to approach eachother more closely during design iterations, it is necessary to account for the fact that the "effective length" of cylindrical shell working efficiently with each ring during buckling modal deformation is much shorter than the ring spacing. Until now no "effective length" strategy had been introduced into PANDA2. In the present case, for a perfect shell, without any "effective length" strategy, PANDA2 yielded a general instability load factor of 1.25, whereas BOSOR4 [3] yielded a general instability load factor of 0.79 for the same ring-stiffened shell and loading. Now a new "effective length" strategy has been introduced into PANDA2 for ring-stiffened shells. It is described fully in ITEM 509 of the file, ...panda2/doc/panda2.news [25], which is a log of all PANDA2 modifications since 1987 and which is distributed with the PANDA2 program system. A brief summary is given next.

The new "effective length" strategy in PANDA2 introduces a new knockdown factor, RNGKNK = EIG(discrete)/EIG(smeared), in which RNGKNK is the knockdown factor, EIG(discrete) is the general buckling modal load factor (eigenvalue) obtained from a single discretized skin-ring module [20] permitted to buckle like a ring (see Fig. 33e on p. 345 of [20], for example), and EIG(smeared) is the buckling load of a ring with certain hoop bending stiffness, "EI". EIG(smeared) is given by:

EIG(smeared)

$$= \left(3EI / R^3\right) / p = \left(3(C_{s55} - C_{s25}^2 / C_{s22}) / R^3\right) / p \qquad (7.1)$$

in which C_{s22} is the hoop extensional stiffness, C_{s55} is the hoop bending stiffness, and C_{s25} is the hoop bending-stretching coupling for the cylindrical shell with rings smeared as prescribed by Baruch and Singer [23]. Eq. (7.1) is valid if the reference surface is the middle surface of the skin of the cylindrical shell. The new knockdown factor, RNGKNK, is used to reduce the buckling load factor computed in PANDA2 from what is called "the PANDA-type" model, that is, the model in which the buckling load factors are given in "closed form" by Eq. (57) in [21]. With the new "effective length" strategy in place the predictions of PANDA2 and BOSOR4 are now in good agreement for this case.

7.5.2 WAVYCYL optimization

The optimum ring spacing, BRINGS = 10 in., and optimum ring thickness, TWEB = 0.067398 in. and ring height, HWEB = 0.67398 in. determined from applcation of PANDA2 are fixed during the WAVYCYL optimization. The amplitude of the initial general buckling modal imperfection is W_0=0.005*R = 0.045 in. The upper bound on axial halfwavelength of the waviness, WAVLEN, was set equal to 3.0 inches. Figure 15 shows the results of the first SUPEROPT run conducted with use of the maximum allowable number of degrees of freedom, MAXDOF, set at its largest possible value, 15000. (A previous SUPEROPT, the results from which are not included in this paper, had been executed with MAXDOF = 3000). Figure 15 is analogous to Fig. 9. Notice that, unlike the results from the PANDA2 SUPEROPT run, the objective does not return consistently to the same minimum-weight design. In fact, as design iterations proceed, the SUPEROPT process never finds a design as good as that determined during the first approximately 35 iterations, that is, before the first execution of AUTOCHANGE. This phenomenon, explained later in more detail, is caused by the extremely "noisy" shape of the boundary between feasible and unfeasible regions in design space. A hint of this "noisiness" is provided by plots of the design margins vs iterations shown in Fig. 16. The buckling margins for BUCO, BOANTI, and BUCOMD are especially "spiky".

Figure 17 shows the evolution of axial halfwavelength, WAVLEN during the SUPEROPT run. The general tendency is for WAVLEN to approach its upper bound, 3.0 in., in this case.

After completion of the first SUPEROPT run and execution of CHOOSEPLOT/ DIPLOT in order to obtain plots, the input file for "DECIDE" (testnew6.DEC; Table 7.5) was edited to reduce drastically the upper bound of WAVLEN from 3.0 to 0.8 in. The WAVYCYL processors, DECIDE, SUPEROPT, CHOOSEPLOT and DIPLOT were executed again. With restriction on the possible excursions of WAVLEN, Figures 18 - 22 show much more consistent behavior than that depicted in Fig. 15. However, the objective, for example, is still much, much more jagged than that from the optimization with PANDA2, displayed in Fig. 9. The "spikiness" of the margins (Fig. 19), especially those for BUCO and BOANTI, remains. The WAVYCYL SUPEROPT process does not seem to be able to determine a consistent value for WAVYCYL (Fig. 21) at all, and the amplitude of the waviness, AMPLIT, wanders in the region from 0.6 to 0.8 inches, as one can see from Fig. 22. An explanation of this behavior is given next.

In the WAVYCYL/GENOPT system design sensitivity can be determined with respect to any user-selected decision variable. This is done here. The decision variable, WAVLEN, is chosen as the independent variable because intuition tells us that there may be an important interaction between the ring spacing, BRINGS, and the axial halfwavelength, WAVLEN, of the waviness. New input data for MAINSETUP/OPTIMIZE are generated (Table 7.6). A very small range, 0.545 < WAVLEN < 0.564, is chosen, with the center of the range corresponding to the value obtained as optimum after the second SUPEROPT run. The values of wavy wall thickness, THICK, and amplitude of the waviness, AMPLIT, are held at the optimum values obtained after the second SUPEROPT run.

Figure 23 shows the results of this design sensitivity analysis. As can be seen from the plots in Fig. 23, the margins for BUCO (low-circumferential-wave symmetric buckling at θ=0 degrees) and for BOANTI (low-circumferential-wave antisymmetric buckling at θ=0 degrees), are especially sensitive to small changes in WAVLEN. This explains, from a mathematical point of view, why the results from execution of SUPEROPT tend to wander: very small changes in WAVLEN lead to very large changes in the gradients of the BUC0 and B0ANTI margins with respect to WAVLEN. We still need an explanation from a physical point of view of why these particular margins "oscillate" so much with very small changes in WAVYCYL.

In order to determine the cause of the extreme sensitivity of the critical buckling load factors, BUC0 and B0ANTI, to changes in WAVLEN in the neighborhood of WAVLEN = 0.55 in., we wish to obtain plots of the configuration and the critical buckling modes corresponding to the minimum and maximum values of the BUC0 and B0ANTI margins in Fig. 23. Therefore, we must do two "fixed design" analyses (ITYPE = 2 in Table 4.8, for example): the first with the value of WAVLEN set at 0.55060 in.(minimum BUC0 and B0ANTI margins in Fig. 23) and the second with the value of WAVLEN set at 0.55555 in. (maximum BUC0 and B0ANTI margins in Fig. 23). Each of these two "fixed design" analyses is performed with only the Behavior No. 7 "turned on" in the testnew6.OPT file (MAINSETUP). Behavior No. 7 is low-circumferential-wave buckling antisymmetric with respect to the cylindrical shell midlength. After each WAVYCYL "fixed design" analysis is complete, we copy the testnew6.PLT2 file to a directory from which BOSOR4 processors are generally executed. Then we activate the BOSOR4 command set (BOSOR4LOG) and execute the BOSOR4 plotting processor, BOSORPLOT. These operations lead to Figs. 24 and 25.

Figure 24 shows the critical buckling mode shape corresponding to WAVLEN = 0.55060 in.. The buckling load factor (eigenvalue) is 1.1397. (Remember, the factor of safety for all kind of buckling in this study is 1.25, as listed in Table 4.6. Therefore, the buckling load factor of 1.1397 leads to a negative margin as shown in Fig. 23 for WAVLEN = 0.55060.)

Figure 25 shows the critical buckling mode corresponding to WAVLEN = 0.55555 in. The buckling load factor is 1.3894, about 18 per cent higher than that for WAVLEN = 0.55060 in., which is less than one per cent different. Both buckling modes correspond to general instability.

Close inspection of the plots of the undeformed meridians reveals why there is such a big difference in the buckling load factors. With WAVLEN = 0.55555 in. (Fig. 25) the root of every ring corresponds to the outward-directed peak of a wave in the cylindrical shell. Since the ring spacing is 10 inches and the axial halfwavelength of the waviness, WAVLEN, is 0.55555 inches, there are exactly 18 halfwaves of waviness between rings, with the ring at the plane of symmetry, z = 90 in. being located at an outward-directed peak "by definition", that is in all wavy models. With the very slightly lower value, WAVLEN = 0.55060 in., several of the rings located in the bottom half of the shell depicted in Fig. 24 have their roots in "valleys" rather than peaks of the waviness. The effective overall circumferential bending stiffness for general instability is therefore considerably greater with WAVLEN = 0.55555 in. than is the case with WAVLEN = 0.55060 in.

One might well ask, "Why not ALWAYS place the rings at outward-directed peaks in the waviness and make that part of the definition of the structure to be optimized?" It is true that the WAVYCYL system could have been constructed in this way. However, such a system might work well only in cases for which the axial halfwavelength of the waviness, WAVLEN, is small compared to the ring spacing.

As listed near the end of the run stream, a final optimization was conducted with WAVLEN fixed at its optimum value, 0.55555 in., and with only the thickness, THICK, of the wavy wall and the amplitude, AMPLIT, of the waviness, permitted to change during optimization cycles. In this case SUPEROPT was not needed. A single execution of OPTIMIZE was adequate to yield the final optimum design, which is listed in Table 7.8.

7.5.3 Discussion of output listed in Table 7.8

Table 7.8 lists results corresponding to the ring-stiffened cylindrical shell with a wavy wall, optimized as described in the run stream listed in Section 7.4 and in this section. These results were obtained by "turning on" additional behaviors (9 - 13) for the "fixed design" analysis option, ITYPE = 2, that were previously "turned off" during the optimization process (ITYPE = 1). As seen from the echo of the input file, testnew6.OPT, listed at the beginning of Table 7.8, only behaviors 2 and 3 (nonlinear buckling analysis of the shell without rings) and behaviors 15 - 18 (random response behaviors) were "turned off" in the "fixed design" run leading to Table 7.8.

Table 7.8 represents an edited version of the testnew6.OPM file. Annotations have been added primarily on the right-hand side of the table to give further explanation of the meaning of the WAVYCYL output.

The dimensions of the optimized design are listed near the beginning of Table 7.8. In SUBROUTINEs BEHX6, BEHX7, and BEHX14, buckling load factors (BEHX6, BEHX7) and modal vibration frequencies (BEHX14) are listed for two models, the first in which the axial waviness of the wall is included explicitly, such as shown in Figs. 24 and 25, and the second in which the axial waviness is "smeared out" in the manner described in Item 10 of Section 5.3, such as shown in Fig. 26a-f. The "smeared waviness" models are not used during optimization. They are included in the "fixed design" analysis option (ITYPE=2) because they convey an idea of the quality of the "smeared waviness" model used for the straight portion of the "explicitly" wavy cylindrical shell such as that shown in the bottom portion of Fig. 3. As one can see from Table 7.8, the "smeared waviness" model provides a good estimate of general instability corresponding to $n = 2$ circumferential waves and modal vibration with $n = 1$ circumferential wave. As one would expect, the "smeared waviness" model is not nearly as good for predicting local (inter-ring) buckling, which corresponds to $n = 4$ or 5 circumferential waves in this case.

7.6 Convergence studies

7.6.1 Introduction

Table 7.9 and Figures 26 - 32 give the results of convergence studies with respect to MAXDOF, the user-specified maximum allowable number of degrees of freedom in the BOSOR4 model, and NMESHC, the user-specified number of nodal points in each of the little toroidal segments in the BOSOR4 model.

The WAVYCYL model works as follows: For all stress, buckling, and vibration models except those in BEHX1 (nonlinear axisymmetric stress analysis, rings and boundary conditions neglected, that is, an infinite tube), BEHX2 (low-circumferential-wave nonlinear buckling with rings and boundary conditions neglected), and BEHX3 (high-circumferential-wave nonlinear buckling with rings and boundary conditions neglected), the WAVYCYL system computes twice the number of axial halfwaves to appear explicitly in the BOSOR4 model, NWAVES, as:

NWAVES = minimum of

[(0.9*AXIAL/WAVLEN),

(value that corresponds to d.o.f.= MAXDOF)]

(7.2)

in which AXIAL is the axial length of the cylindrical tube (twice the axial length shown in Fig. 1), WAVLEN is the axial halfwavelength of the waviness, and "d.o.f." denotes the actual number of degrees of freedom in the BOSOR4 model. Figures 1 and 2 show examples in which the number of axial halfwaves in the BOSOR4 model is governed by the first element, 0.9*AXIAL/WAVLEN, and Fig. 3 shows a model in which the number of axial halfwaves is governed by the second element, MAXDOF. (MAXDOF corresponding to Fig. 3 was set to a lower number than that corresponding to Fig. 2.) In general, if the second element in Eq. (7.2) governs, the number of degrees of freedom in the BOSOR4 model, d.o.f., is not exactly equal to the user-specified MAXDOF, but is a per cent or so less than MAXDOF. The number of axial halfwaves computed from Eq.(7.2) depends on how many nodal points, NMESHC, are specified by the WAVYCYL user to exist for each of the little toroidal segments in the BOSOR4 model, how many nodal points, NMESH1, are to be used in Segment 1 (the straight segment with "smeared" waviness), and the number of mesh points NMESHR to be used in each segment of each ring.. As mentioned in Section 3, in order to accommodate models with many, many axial waves the capacity of the BOSOR4 program to handle large problems was increased by a factor of 5 over that reported in [3].

7.6.2 Results from convergence studies

Figures 26 - 32 show the prebuckling deflected shape, symmetric and antisymmetric general and local buckling modes, and the fundamental vibration mode corresponding to several BOSOR4 models with increasing values of the user-specified maximum allowable number of degrees of freedom, MAXDOF, and the number of nodal points, NMESHC, used in each of the little toroidal segments in the explicitly wavy part of the BOSOR4 model. All results are for a PERFECT tube that has been optimized via SUPEROPT (Section 2.2).

Figure 26 displays results from a BOSOR4 model in which the axial waviness has been "smeared" over the entire length of the cylindrical shell. For this model the local (inter-ring) buckling load factors are overestimated by about 35 per cent (1.79 vs the converged value of about 1.33 for n = 5 circumferential waves; compare Figs. 26e and 30e).

Figures 27 - 30 show results for user-specified MAXDOF = 3000, 6000, 9000, and 15000, respectively. All of these figures were produced from a model in which the number of nodal points in each little toroidal segment is NMESHC = 21. One can see that the higher the value of MAXDOF, the more little waves in the BOSOR4 model. (Inspect especially Figs. 27a, 28a, 29a, and 30a; the little "wiggles" show up most clearly in those figures).

Figures 31 and 32 depict the critical local buckling modes for MAXDOF = 9000 and NMESHC = 11 and 5, respectively. Even though the mode shapes are identical for all practical purposes, the buckling load factors, 1.3039 and 1.1792, are quite different. The corresponding buckling load factor for NMESHC = 21 (Fig. 29e) is 1.3271. This is probably very close to a converged value.

Table 7.9 Lists results from the convergence models shown in Figs. 26 - 32.

7.7 Design sensitivity studies at the optimum design

Figures 33 - 39 display the results of design sensitivity studies with respect to all of the decision variables used for the wavy cylindrical shell with ring stiffeners. The nominal design is the optimum design obtained for the IMPERFECT shell (See Table 7.8), and all of the design sensitivity studies reported here are for the IMPERFECT shell.

In each figure notice that for the value on the abscissa corresponding to the optimum for that decision variable, there exists a cluster of critical design margins. This is typical for optimized designs. An exception appears to occur in Fig. 38. However, the apparently negative margins corresponding to the optimum ring spacing, BRINGS = 10, is merely an artifact of the relatively sparse spacing of the computed points on the abscissa. Figure 39 shows how the margins look when plotted for very closely spaced values of BRINGS in the immediate neighborhood of the optimum value, BRINGS = 10 in. The relatively sparse spacing of points on the BRINGS axis in Fig. 38 is insufficient to capture the true variation of buckling margins corresponding to BUC0 (low-circumferential-wave symmetric buckling along the meridian at circumferential coordinate, $\theta = 0$ degrees) and B0ANTI (low-circumferential-wave antisymmetric buckling along the meridian at $\theta = 0$ degrees).

In Figs. 33 - 35 the plots of maximum effective stress at circumferential coordinates, $\theta = 0$ and 180 degrees, curve steeply downward for the weaker (sub-optimal) structures (smaller values of THICK, TWEB, and HWEB) because the IMPERFECT shell experiences stresses that approach infinity as the buckling load factor corresponding to general instability approaches unity. Because all the factors of safety for the various types of buckling were set equal to 1.25, a buckling load factor of unity corresponds to a design margin of -0.2 in this case. In Figure 33 the lowest buckling load factors (small triangles and small crosses) correspond to local buckling, not general instability. Therefore, the curves for stress margin are less steep in the neighborhood of margin = -0.2 in Fig. 33 than in Figs. 34 and 35, for which the lowest buckling curves correspond to general instability, not local buckling in that neighborhood of margin.

Notice the extreme sensitivity of margin gradient to variation of WAVLEN and BRINGS in the neighborhood of the optimum value. This phenomenon has already been discussed. The optimum value of WAVLEN and BRINGS corresponds to each of the rings occurring at an outward "peak" in the axial waviness.

8.0 NUMERICAL RESULTS: ALUMINUM WAVY CYLINDRICAL SHELL WITHOUT RINGS

8.1 Summary

This case is called "testnew7". The same sorts of runs described in Section 7.4 are executed in this case also. Results are listed in Table 8.1 and plotted in Figs. 40 - 63.

8.2 Run stream used to obtain the optimum design

The following run stream was used to produce the optimum design and plots of objective, etc. vs design iterations (Figs. 40 - 53), the BOSOR4 plots of the prebuckled state and critical buckling modes of the optimized tube (Figs. 54 - 56), and the plots from the design sensitivity analysis (Figs. 57 - 63):

--- set up the problem to be solved ---

GENOPTLOG (activate the GENOPT/WAVYCYL command set)

BEGIN (establish a starting design, etc.; input file = testnew7.BEG)

DECIDE (choose decision variables, bounds: input file = testnew7.DEC)

MAINSETUP (choose "behaviors", analysis type; input file = testnew7.OPT)

------ begin global optimization -----

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 5.0 in.)

CHOOSEPLOT(choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testnew7.i.ps, i = 5, 3, 4, Figs. 40-42)

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 3.0 in.)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testnew7.i.ps, i = 5, 3, 4, Figs. 43-45)

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 2.0 in.)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testnew7.i.ps, i = 5, 3, 4, Figs. 46-48)

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 1.0 in.)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testnew7.i.ps, i = 5, 3, 4, Figs. 49-53)

-------- end of optimization --------

----- Obtain data corresponding to the optimized design ------

MAINSETUP (input is same as Table 4.8, except analysis type, ITYPE = 2, that is, fixed design analysis and fewer "behaviors" are turned off. [See the beginning of Table 8.1 for testnew7.OPT])

OPTIMIZE (perform fixed design analysis with fewer "behaviors" turned off. The results from this run, stored in the file, testnew7.OPM, are listed in Table 8.1)

----- end of fixed design analysis of optimized design -----

---- get BOSOR4 plots of critical buckling modes ----

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 6 [BUC0 = symmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to Behavior No. 6 (BUC0) of the optimized design. This run yields a file called testnew7.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the prebuckling displacement of the meridian at circumferential coordinate, θ=0, and the critical buckling mode; see Figs. 54 (prebuckling state) and 55 (buckling mode))

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 7 [B0ANTI = antisymmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to Behavior No. 7 (B0ANTI) of the optimized design. This run yields a file called testnew7.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the critical buckling mode; see Fig. 56)

---- end of section of run stream to get BOSOR4 plots ----

----- begin design sensitivity study -----

MAINSETUP (choose "behaviors" and use analysis type ITYPE=3; The input data are analogous to those listed in Table 7.6)

OPTIMIZE (run the WAVYCYL processor OPTIMIZE in the design sensitivity mode [ITYPE=3]. WAVLEN is the independent variable.)

CHOOSEPLOT (select which margins to plot for the range 0.5 < WAVYCYL < 1.2)

DIPLOT (get postscript file of plot, testnew7.3.ps [margins v WAVLEN]; See Fig. 57)

(Repeat the above with use of THICK and AMPLIT as independent variables, thereby obtaining Figs. 58 - 63. Several different ranges of AMPLIT are used to obtain good plots of the margin corresponding to FREQ vs AMPLIT (Figs. 59 - 63))

---- end of design sensitivity runs for optimum design ----

8.3 Discussion

8.3.1 Optimization

Figures 40 - 53 show results from the four SUPEROPT runs required in this csse to obtain a global optimum design. The value of MAXDOF was set to 15000. Several days of computer time on a super-fast SGI workstation were required for the four SUPEROPT runs.

Figure 40 displays the objective vs design iterations during the first SUPEROPT run. The upper bound on axial halfwavelength of the waviness, WAVLEN, was set equal to 5.0 inches. The lower bound on WAVLEN was set equal to 0.5 inch in all four SUPEROPT runs. It is clear from Fig. 40 that the WAVYCYL mainprocessor has a very difficult time settling on a "global" optimum. The minimum weight of 90 inches of the wavy tube is about 35 lbs. This minimum weight is obtained during the first set of executions of OPTIMIZE, before the first execution of AUTOCHANGE. For this design the axial halfwavelength of the waviness, WAVLEN, is equal to about 2.3 inches (Fig. 42). From Figure 41 one sees that the margins are very jagged, which is why WAVYCYL has a hard time settling on a global minimum weight. Figure 42 resembles Fig. 17. There is no particular stable value of WAVLEN over the approximately 275 design iterations during the first SUPEROPT run.

The same strategy was used in this example as for the wavy cylindrical shell with rings: Additional SUPEROPT runs were made with more and more restriction on the upper bound of WAVLEN. Figures 43 - 45 show results from the second SUPEROPT run, for which the upper bound of WAVLEN was reduced to 3.0 inches. From this run a minimum weight of about 32 lbs was found (near Iteration 200). The corresonding value of WAVLEN is about 2.0 inches. The plot of the objective vs design iterations (Fig. 43) is much more "organized" than that for the first SUPEROPT run (Fig. 40), and the plot of margins (Fig. 44) is a bit less jagged. In the third SUPEROPT run the upper bound on WAVLEN was further reduced to 2.0 inches. Figures 46 - 48 show the results from this run. A "global" minimum weight of about 26 lbs was found (Fig. 46, Iteration 240). Corresponding to this feasible design the axial halfwavelength, WAVLEN, is slightly less than 1.0 inch (Fig. 48). The jagged nature of the margins has almost disappeared (Fig. 47). In the final SUPEROPT run the upper bound on WAVLEN was reduced to 1.0 inch. The behavior during design iterations, except for the value of WAVLEN (Fig. 51), is very stable. The "global" minimum weight of about 26 lbs is returned to repeatedly during the SUPEROPT run (Fig. 49). The margins are not at all jagged (Fig. 50). Figures 52 and 53 show respectively the evolution of the thickness, THICK, of the wall of the wavy cylindrical shell and the amplitude, AMPLIT, of the waviness. The amplitude converges to several different levels (Fig. 53), corresponding to the different values to which the much less stable WAVLEN converges (Fig. 51).

8.3.2 The optimized design

Figures 54 - 63 and Table 8.1 correspond to the optimized design. Figures 54 - 56 are BOSOR4 plots of the prebuckled state (Fig. 54) and the critical buckling modes symmetric (Fig. 55) and antisymmetric (Fig. 56) with respect to the midlength symmetry plane of the wavy cylindrical tube.

8.3.3 Design sensitivity of the optimized design

Figures 57 - 63 display results from the design sensitivity analysis of the optimized design. The optimum values of wavy wall thicknees, THICK, axial halfwavelength of waviness, WAVLEN, and amplitude of waviness, AMPLIT, are 0.05025, 0.76725, and 0.12856 in., respectively. As expected, for an optimized design, and as can be seen from Figs. 57 - 59, the critical margins cluster in the neighborhood this optimum set of dimensions.

Figures 57 and 59 exhibit very marked interruptions in the otherwise smooth curves of critical modal frequency (FREQ) vs WAVLEN (Fig. 57) and vs AMPLIT (Fig. 59). The smooth curves correspond to beam-type (n = 1 circumferential wave) vibration symmetric about the midlength symmetry plane of the tube. The gross interruptions correspond to vibration in which the cross section of the tube ovalizes (n = 2) in a mode similar to the buckling mode displayed in Fig. 55. The interruptions in the smooth curve corresponding to n = 1 first occur in regions for which the buckling margin corresponding to buckling symmetric about the midlength is less than -0.2, which is the margin value that corresponds to a buckling load factor, BUC0 = 1.0. (Remember, the factor of safety for buckling is 1.25).

The fundamental frequency of a vibrating structure approaches zero as destabilizing loads on that structure approach the buckling load. Figures 60 - 63 display the same behavior for more and more restrictive ranges of AMPLIT. According to the theory, the fundamental vibration frequency of the shell in this case should be zero at the point where the curve for the "BUC0" margin first descends through a margin value of -0.2. (Since the factor of safety for buckling is 1.25, the buckling margin of -0.2 corresponds to a buckling load factor of 1.0).

According to Fig. 61 this occurs approximately at AMPLIT = 0.114 in. Why then does the smooth (n=1) curve continue to the left until AMPLIT = 0.1113, where the "BUC0" curve is well below the critical value of -0.2?

It is because the vibration frequencies are computed in the BOSOR4 analysis with inclusion only of the axisymmetric components of loading. (That is a limitation of the BOSOR4 computer program). In contrast, the buckling load factors, BUC0 and B0ANTI, are computed including the nonaxisymmetric (n = 1) loading component represented by lateral g-loading as well as the axisymmetric external pressure and axial compression. Hence, the "dip" in the curve of FREQ vs AMPLIT, displayed with increasing refinement of range of AMPLIT in Figs. 60 - 63, occurs for smaller values of AMPLIT than it would if there were no lateral g-loading.

9.0 NUMERICAL RESULTS: COMPOSITE WAVY CYLINDRICAL SHELL WITHOUT RINGS

9.1 Summary

This case is called "testcomp". The same sorts of runs described in Section 8.0 are executed in this case also. Results are listed in Tables 9.1 - 9.9 and plotted in Figs. 64 - 86.

9.2 Run stream used to obtain the optimum design with [90, 45, -45, 0]s

The 90-degree ply is on the outside and the 0-degree plies are in the middle. The following run stream was used to produce the optimum design and plots of objective, etc. vs design iterations (Figs. 64 - 68) and the BOSOR4 plots of the prebuckled state and critical buckling modes of the optimized tube (Figs. 69 - 72), and tabulated results correponding to the optimized design evaluated with use of MAXDOF = 3000 (Table 9.4) and with MAXDOF = 15000 (Table 9.5).

-----set up the problem to be solved -----

GENOPTLOG (activate the GENOPT/WAVYCYL command set)

BEGIN (establish a starting design, etc.; input file = testcomp.BEG, Table 9.1. Use MAXDOF = 3000)

DECIDE (choose decision variables, bounds: input file = testcomp.DEC, Table 9.2)

MAINSETUP (choose "behaviors", analysis type; input file = testcomp.OPT, first part of Table 9.4)

----- begin global optimization with MAXDOF = 3000 ----

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 1.0 in., MAXDOF = 3000 degrees of freedom. The SUPEROPT run was terminated at 90 iterations because it was taking a lot of computer time and the behavior was very stable (Fig. 64), so it was strongly felt that a global optimum had already been determined.)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testcomp.i.ps, i = 5, 3, 4, Figs. 64-68)

---- end of optimization [90,45,-45,0]s with MAXDOF = 3000 ----

---- Obtain data corresponding to the optimized design, MAXDOF = 3000 ----

CHANGE (reset values of WAVLEN, AMPLIT, and thicknesses TLAYER(i), i = 1,4 (thicknesses of [90,45,-45,0]-degree layers) to the values corresponding to the optimum found for the 90 iterations during the SUPEROPT run. See Table 9.3)

MAINSETUP (input is same as Table 4.8, except analysis type, ITYPE = 2, that is, fixed design analysis. [See the beginning of Table 9.4 for listing of testcomp.OPT])

OPTIMIZE (perform fixed design analysis (ITYPE=2). The results from this run, stored in the file, testcomp.OPM, are listed in Table 9.4)

---- end of fixed design analysis of optimized design, MAXDOF = 3000 ----

---- get BOSOR4 plots of critical buckling mode, MAXDOF = 3000 ----

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 6 [BUC0 = symmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to Behavior No. 6 (BUC0) of the optimized design. This run yields a file called testcomp.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the prebuckling displacement of the meridian at circumferential coordinate, θ=0, and the critical buckling mode; see Fig. 69 (prebuckling state) and Fig. 70 (symmetric buckling mode))

----- end of section of run stream to get BOSOR4 plots, MAXDOF = 3000 -----

----- begin evaluation of optimized design with use of MAXDOF = 15000 -----

CLEANSPEC (delete all testcomp.* files except *.BEG, *.DEC, *.OPT, *.CHG)

BEGIN (establish a starting design, etc.; input file = testcomp.BEG, Table 9.1, except MAXDOF has been increased from 3000 to 15000)

DECIDE (choose decision variables, bounds: input file = testcomp.DEC, Table 9.2)

CHANGE (reset values of WAVLEN, AMPLIT, and thicknesses TLAYER(i), i = 1,4 (thicknesses of [90,45,-45,0]-degree layers) to the values corresponding to the optimum found for the 90 iterations during the SUPEROPT run. See Table 9.3)

MAINSETUP (input is same as Table 4.8, except analysis type, ITYPE = 2, that is, fixed design analysis. [See the beginning of Table 9.4 for listing of testcomp.OPT])

OPTIMIZE (perform fixed design analysis (ITYPE=2). The results from this run, stored in the file, testcomp.OPM, are listed in Table 9.5)

----- end of fixed design analysis of optimized design, MAXDOF = 15000 -----

-----get BOSOR4 plots of critical buckling mode, MAXDOF = 15000 -----

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 6 [BUC0 = symmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to Behavior No. 6 (BUC0) of the optimized design. This run yields a file called testcomp.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the prebuckling displacement of the meridian at circumferential coordinate, θ=0, and the critical buckling mode; see Fig. 71 (prebuckling state) and Fig. 72 (symmetric buckling mode))

----- end of section of run stream to get BOSOR4 plots, MAXDOF = 15000 -----

9.3 Run stream used to obtain the optimum design with [0, 45, -45, 90]s

The zero-degree and ninety-degree layers have been exchanged. The following run stream was used to produce the optimum design and plots of objective, etc. vs design iterations (Figs. 73 - 81), the BOSOR4 plots of the prebuckled state and critical buckling modes of the optimized tube (Figs. 82 - 84), and the plots from the design sensitivity analysis (Figs. 85 and 86).

-----set up the problem to be solved -----

GENOPTLOG (activate the GENOPT/WAVYCYL command set)

BEGIN (establish a starting design, etc.; input file = testcomp.BEG, Table 9.1, except the 0-degree and 90-degree layers are exchanged. Use MAXDOF = 3000)

DECIDE (choose decision variables, bounds: input file = testcomp.DEC, Table 9.2)

MAINSETUP (choose "behaviors", analysis type; input file = testcomp.OPT, same as testcomp.OPT file listed as the first part of

Table 9.4)

------begin global optimization with MAXDOF = 3000 -----

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 1.0 in., MAXDOF = 3000 degrees of freedom. The SUPEROPT run was terminated at 92 iterations because it was taking a lot of computer time and the behavior was very stable (Fig. 73), so it was strongly felt that a global optimum had already been determined.)

CHOOSEPLOT(choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testcomp.i.ps, i = 5, 3, 4, Figs. 73-77)

-------end global optimization with MAXDOF = 3000 -------

------begin global optimization with MAXDOF = 15000 ------

CHANGE (reset values of WAVLEN, AMPLIT, and thicknesses TLAYER(i), i = 1,4 (thicknesses of [0,45,-45,90]-degree layers) to the values corresponding to the optimum found for the 92 iterations during the SUPEROPT run. See Table 9.6)

CLEANSPEC (delete all testcomp.* files except *.BEG, *.DEC, *.OPT, *.CHG)

BEGIN (establish a starting design, etc.; input file = testcomp.BEG, Table 9.1, except the 0-degree and 90-degree layers are exchanged. Use MAXDOF = 15000)

CHANGE (reset values of WAVLEN, AMPLIT, and thicknesses TLAYER(i), i = 1,4 (thicknesses of [0,45,-45,90]-degree layers) to the values corresponding to the optimum found for the 92 iterations during the SUPEROPT run. See Table 9.6)

DECIDE (choose decision variables, bounds: input file = testcomp.DEC, Table 9.2)

MAINSETUP (choose "behaviors", analysis type; input file = testcomp.OPT, same as testcomp.OPT file listed as the first part of Table 9.4)

OPTIMIZE (perform optimization analysis (ITYPE=1). OPTIMIZE converges to a local optimum after only 2 iterations. (See Iteration No. 2 in Fig. 78.)

CHANGE (reset values of WAVLEN, AMPLIT, and thicknesses TLAYER(i), i = 1,4 (thicknesses of [0,45,-45,90]-degree layers) to the following: WAVLEN = 1.0, AMPLIT = 0.176, TLAYER(i),i=1,3=0.005; TLAYER(4) = 0.0075 in. All except TLAYER(4) are the optimum values determined after the 2 iterations in the previous OPTIMIZE. TLAYER(4) (the 90-degree layer) is set equal to 1.5 ply thicknesses (1.5 x 0.005 = 0.0075) because the TOTAL laminate will then contain three 90-degree plies at its center. See Table 9.7)

DECIDE (choose only WAVLEN and AMPLIT as decision variables. From now on the ply thicknesses are fixed. See Table 9.8)

SUPEROPT (launch "global" optimizer; Upper bound of WAVLEN = 2.0 in., MAXDOF = 15000 degrees of freedom. The SUPEROPT run was terminated at 58 iterations because it was taking a lot of computer time and the behavior was considered to be stable enough (Figs. 78,79), so it was felt that a global optimum had already been determined.)

CHOOSEPLOT (choose what to plot vs design iterations during SUPEROPT)

DIPLOT (get postscript plots, testcomp.i.ps, i = 5, 3, 4, Figs. 78-81)

----end of optimization [0,45,-45,90]s with MAXDOF = 15000 -----

---- get BOSOR4 plots of critical buckling modes, MAXDOF = 15000 ----

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 6 [BUC0 = symmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to Behavior No. 6 (BUC0) of the optimized design. This run yields a file called testcomp.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the prebuckling displacement of the meridian at circumferential coordinate, θ=0, and the critical buckling mode; see Fig. 82 (prebuckling state) and Fig. 83 (symmetric buckling mode))

MAINSETUP (choose all behaviors "turned off" except for Behavior no. 7 [BOANTI = antisymmetric low-n buckling at θ=0 deg.; choose analysis type, ITYPE = 2 [fixed design analysis])

OPTIMIZE (perform the fixed design analysis to obtain output corresponding to Behavior No. 7 (BOANTI) of the optimized design. This run yields a file called testcomp.PLT2, which is a standard BOSOR4 file, legal for input to the BOSOR4 procesor called BOSORPLOT.)

BOSOR4LOG (activate the BOSOR4 command set)

BOSORPLOT (obtain postscript file for plotting the critical antisymmetric buckling mode; see Fig. 84)

----- end of section of run stream to get BOSOR4 plots, MAXDOF = 15000 -----

------begin design sensitivity study -----

MAINSETUP (choose "behaviors" and use analysis type ITYPE=3; The input data are analogous to those listed in Table 7.6)

OPTIMIZE (run the WAVYCYL processor OPTIMIZE in the design sensitivity mode [ITYPE=3]. WAVLEN is the independent variable.)

CHOOSEPLOT (select which margins to plot for the range 0.5 < WAVYCYL < 2.05)

DIPLOT (get postscript file of plot, testcomp.3.ps [margins v WAVLEN]; see Fig. 85)

(Repeat the above with use of AMPLIT as the independent variable, in the range 0.1 < AMPLIT < 0.25 in, thereby obtaining Fig. 86.)

-------end of design sensitivity runs for optimum design -------

9.3 Discussion

9.3.1 Optimization with layup = [90,45,45,0]s

The maximum allowable number of degrees of freedom, MAXDOF, was set equal to 3000 and the upper bound on the axial halfwavelength of the waviness, WAVLEN, was set equal to 1.0. Figures 64 - 68 show results from the truncated SUPEROPT run required in this case to obtain a global optimum design. The SUPEROPT run was deliberately terminated after about 18 hours of computer time on a super-fast SGI workstation because it was obvious from the results computed until then that a stable, global optimum design had already been found (Fig. 64). Table 9.4 lists the optimum design and the various behaviors corresponding to that design. Figure 69 shows the prebuckled deformed state of the meridian at circumferential coordinate, θ = 0 degrees, and Fig. 70 shows the critical buckling mode and load factor.

The optimum design was then evaluated with use of a much larger BOSOR4 model: The maximum allowable number of degrees of freedom in the BOSOR4 model was increased from 3000 to 15000 and a fixed design analysis (ITYPE = 2) was run. Table 9.5 lists results from this run, which yielded critical margins about five per cent lower than those with the somewhat stiffer model with MAXDOF = 3000 d.o.f. (Table 9.4). Figures 71 and 72 show BOSOR4 plots of prebuckling state and critical buckling mode of the model with MAXDOF = 15000.

9.3.2 Optimization with layup = [0,45,45,90]s

The maximum allowable number of degrees of freedom in the BOSOR4 model was set to MAXDOF = 3000. Figures 73 - 77 display the results of the deliberately truncated SUPEROPT run after about 18 hours of computer time on the SGI workstation. Notice that the optimum design has a weight of about 13 lbs., significantly lighter than than obtained with the 90-degree ply on the outside (WEIGHT = 17.7 lb from Table 9.4).

The number of plies in each layer was reset so that the TOTAL laminate would have an integral number of plies of thickness 0.005 in. in each of seven layers, [0, 45, -45, 90, -45, 45, 0]total, with thickness (in inches) [0.005, 0.005, 0.005, 0.015, 0.005, 0.005, 0.005]total. Then ply thicknesses were removed from the list of decision variables (Table 9.8). The upper bound of axial halfwavelength of waviness, WAVLEN, was increased from 1.0 to 2.0 inches. The maximum allowable number of degrees of freedom, MAXDOF, was set equal to 15000. SUPEROPT was executed again and the long run (approximately 18 hours) was deliberatly terminated after 58 iterations. The results from this truncated SUPEROPT run are displayed in Figs. 78 - 81. The final optimum design and behaviors are listed in Table 9.9.

Figures 82 - 84 show the prebuckling deflected shape and the critical symmetric and antisymmetric buckling modes and corresponding load factors for the optimized design.

Figures 85 and 86 show results from design sensitivity anslyses with respect to WAVLEN and AMPLIT, respectively for the optimized design. In each of these figures the point on the abscissa where the margins corresponding to symmetric buckling (BUC0), antisymmetric buckling (B0ANTI), and natural frequency (FREQ), are all very nearly zero corresponds to the optimum design determined in the last SUPEROPT run. Notice that, as with the aluminum shell (Figs. 57 and 59), the curves for margins corresponding to the modal frequency, FREQ, deteriorate in the regions where buckling margins are significantly less than -0.2.

10.0 CONCLUSIONS

Two computer programs, GENOPT [2] and BOSOR4 [3], have been combined to create a capability to optimize classes of shells of revolution. One class, called "WAVYCYL", can optimize isotropic or laminated composite ring stiffened cylindrical shells with "wavy" walls.

Another class, explored in the appendix as a demonstration, can optimize simple isotropic monocoque cylindrical shells. Enough details are given, especially in the simple example given in the appendix, so that the reader can use GENOPT and BOSOR4 to set up a user-friendly system of programs to optimize any shell of revolution that can be handled by BOSOR4.

The capability of BOSOR4 was increased to handle much larger problems than was previously possible in order to permit the analysis of long cylindrical tubes with many, many axial halfwaves along their lengths.

Also, the accuracy of BOSOR4 predictions for buckling of bellows-type shells was significantly improved by incorporation of the equations of Marlowe [16].

Global optimum designs are obtained for an isotropic ring-stiffened cylindrical shell with a "wavy" wall, an isotropic "wavy-walled" cylindrical shell without rings, and a laminated composite "wavy-walled" cylindrical shell without rings. Decision variables include the thickness of the "wavy" cylindrical shell wall (or ply thicknesses if the wall is laminated), amplitude and axial halfwavelength of the waviness, and thicknesses and widths of the segments of the ring stiffeners. Design constraints include maximum stress, maximum lateral displacement, local buckling, general buckling, modal vibration frequency, and response to random base excitation. The loading is uniform axial compression, uniform external pressure, lateral acceleration, and axial acceleration.

Results from convergence studies on the number of axial halfwaves included explicitly in the BOSOR4 models and on the number of nodal points in each of the shell segments that form an axial halfwave of the waviness are presented, as well as results from design sensitivity analyses carried out for the optimized designs.

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APPENDIX

A.0 A SIMPLE CASE FOR THE PURPOSE OF DEMONSTRATION

A.1 Introduction

The wavy cylindrical shell cases described in the body of the paper are rather complicated. The purpose of this appendix is to provide a demonstration of how to use GENOPT to set up a user-friendly system of computer processors to optimize a simple shell of revolution: a monocoque cylindrical shell. The generic name of the case (the name chosen by the GENOPT user) is "CYLINDER". The specific case processed by the CYLINDER system is called "cyl" by the "CYLINDER" user. Data pertaining to this example are listed in Tables A.1 - A.19 and plotted in Figs. A.1 - A.8.

A.2 Problem formulation

Section 4.1 contains a description of several things the GENOPT user must think about before working on the computer. In this example the results of this "thinking phase" are:

a. The shell of revolution is a monocoque cylindrical shell made of isotropic material. The shell can be either simply supported or clamped at its ends. One half the length is to be modeled, with symmetry conditions being applied at the midlength for prebuckling stress analysis and modal vibration analysis and both symmetry and antisymmetry conditions to be applied at the midlength for bifurcation buckling analysis. The shell can be subjected to any combination of uniform (axisymmetric) axial load, N_x, and normal pressure, p. There is to be only one load set.

b. The following "external" computer software is to be used:

b1. addbosor4.src = BOSOR4 preprocessor, B4READ, and mainprocessor, B4MAIN, and postprocessor, B4POST, and the subroutines called by B4READ, B4MAIN, and B4POST, modified as described in Section 3 for use in an automated optimization context.

b2. b4util.src = BOSOR4 utilities, modified as above.

b3. b4plot.src = BOSOR4 plotting software.

b4. bosdec.src = a subroutine that produces a "legal" BOSOR4 input file, *.ALL, given input pertaining to the specific item to be optimized.

b5. prompter.src = the software that can read and write a "legal" BOSOR4 input file.

b6. opngen.src = software by means of which BOSOR4 files are opened, rewound, and closed.

b7. gasp, bio = software (originally written by F. Weiler to be used with STAGS [24] and modified by Weiler to work well in an optimization context) by means of which files can be stored and retrieved efficiently (block I/O) to and from random access mass storage.

b8. computer coding added to the GENOPT-written "skeletal" forms of the libraries, STRUCT.NEW and BEHAVIOR.NEW, which, when "fleshed out" will compute the various responses ("behaviors") required to evaluate each current design and each design perturbation within each design cycle.

c. Global models are to be used for buckling and vibration. (There are no stiffeners, so there is no local buckling or local vibration). A local model is to be used for computation of the maximum effective stress. This local model is to capture accurately the bending stresses in the neighborhood of a clamped end that decay to the pure membrane stress state within an axial distance ("boundary layer") of length equal to approximately 2.7*SQRT(RADIUS*THICK).

d. The objective is to be minimum weight.

e. The behaviors (responses) that may constrain the design are:

e1. Maximum effective stress.

e2. Buckling that is symmetric about the midlength symmetry plane.

e3. Buckling that is antisymmetric about the midlength symmetry plane.

e4. The minimum modal frequency of the prestressed shell, corresponding to a mode that is symmetric about the midlength symmetry plane, must exceed a user-specified allowable.

In this example the maximum effective stress is to be computed from a nonlinear axisymmetric stress analysis (BOSOR4 analysis type, INDIC = 0). The buckling load factors are to be computed from an INDIC = 1 analysis, which is "quasi-linear" [3]: The axisymmetric prebuckled state from the applied loads is obtained from nonlinear theory (geometric nonlinearity only. In the BOSOR4 universe the material remains elastic). In order to maintain linear behavior during optimization cycles, the buckling load factors are computed from applied loads that are set equal to 1/1000th of the applied loads specified by the CYLINDER user in "BEGIN". Then the "allowable" buckling load factor is set equal to 1000. Remember, the buckling constraint is given by:

(buckling load factor)/[(allowable buckling load factor)*(f.s.)]

in which "f.s." denotes factor of safety for buckling. By means of this "trick" we avoid problems associated with possible non-convergence of the prebuckling computations for designs that are in the unfeasible region.

The minimum modal frequency is determined for the shell as loaded by the user-specified applied loads. Only vibration modes symmetric with respect to the midlength symmetry plane are computed in this particular example, although it would have been easy to add another "behavior" in order to capture antisymmetric model vibrations also.

f. The variable names and one-line definitions appear in Tables A.1 - A.3. The only decision variable is the thickness of the shell, THICK

A.3 The GENOPT user sets up the user-friendly "CYLINDER" program system

The user-friendly "CYLINDER" program system has the usual command set, BEGIN, DECIDE, MAINSETUP, OPTIMIZE, SUPEROPT, CHANGE, AUTOCHANGE, CHOOSEPLOT, DIPLOT. The GENOPT user performs the activities listed in Items 1 - 6 of Table 4.1 in order to accomplish this task. Once the problem has been formulated and variable names and definitions have been decided upon, the GENOPT user executes the following run stream:

GENOPTLOG (Activate the GENOPT set of commands.)

GENTEXT (Interactively provide variable names and definitions and roles [seven roles as defined in Items f.1 - f.7 in Section 4]. This interactive session produces the file called cylinder.INP listed in Table A.1, the file called cylinder.PRO listed in Table A.2, the file called cylinder.DEF from which Table A.3 is taken, the file called cylinder.COM listed in Table A.4, the file called struct.new which is a "skeletal" version of that listed in Table A.5, the file called behavior.new which is a "skeletal" version of that listed in Table A.6, and several other files which contain FORTRAN fragments that are incorporated into the programs and subroutines called begin.new, change.new, and stoget.new, struct.new, and behavior.new.)

The GENOPT user next assembles all the external software to be included in the CYLINDER program system. The external software for CYLINDER is listed in Item b of Section A.2. The "fleshed out" versions of the libraries struct.new and behavior.new are listed in Tables A.5 and A.6, respectively. The subroutine that produces the "legal" BOSOR4 input files that will be needed during execution, SUBROUTINE BOSDEC, is listed in Table A.10. The script,

"usermake.<MACHINE>"

by means of which all the program elements are compiled and the executable elements are created is listed in Table A.11. After all external coding has been gathered and the libraries, STRUCT.NEW and BEHAVIOR.NEW, have been "fleshed out", the GENOPT user gives the command:

GENPROGRAMS (The user-friendly CYLINDER program system elements, BEGIN, DECIDE, MAINSETUP, OPTIMIZE, STORE, CHANGE, AUTOCHANGE, CHOOSEPLOT, are created via the script, "usermake.<MACHINE>", in which the string, <MACHINE>, denotes a UNIX workstation [SGI, DEC-ALPHA, etc.].)

If there are no compilation or assembly errors in GENPROGRAMS, then the GENOPT user's job is done. It is next the job of the "CYLINDER" user to process a specific example of the generic class "CYLINDER". In this example the "CYLINDER" user named the specific example "cyl".

A.4 The best way to create SUBROUTINE BOSDEC

The purpose of SUBROUTINE BOSDEC is to generate "legal" BOSOR4 input files given "CYLINDER"-user-provided data such as dimensions, material properties, loading, boundary conditions, etc. and CYLINDER-system-provided control indices such as analysis type indicator, INDIC.

The best way to create SUBROUTINE BOSDEC is to first run BOSOR4 in the usual way for a sample case or cases that represent typical members of the class, "CYLINDER". Table A.7 lists the cyl.ALL file generated during such a preliminary run. SUBROUTINE BOSDEC will have to create "legal" input files such as that listed in Table A.7 for use by the BOSOR4 software incorporated into the file, addbosor4.src (in particular, the BOSOR4 preprocessor, B4READ). An example or examples of such files, which the GENOPT user employs as "templates" from which to generate the appropriate "WRITE" statements in SUBROUTINE BOSDEC, are very helpful.

Corresponding to the various values of BOSOR4 analysis type, INDIC (see the list involving INDIC near the beginning of Section 3), BOSOR4 requires slightly different input data, especially the "global" data that lie between the line, "GLOBAL DATA BEGINS..." and the line, "CONSTRAINT CONDITIONS FOLLOW...." in Table A.7. In the example described in this appendix, BOSOR4 input files corresponding to three values of INDIC (INDIC = 0, 1 and 2) must be created. Table A.7 lists "legal" BOSOR4 input data for INDIC = 1 (bifurcation buckling analysis). The "GLOBAL DATA" must be changed from those listed in Table A.7 to those listed in Table A.8 for INDIC = 0 (nonlinear axisymmetric stress analysis) and to those listed in Table A.9 for INDIC = 2 (modal vibration of prestressed shell). Inspection of Table A.10, which contains a list of SUBROUTINE BOSDEC, reveals that there are "IF statement" branches corresponding to the various values of INDIC used in this simple example. The data listed in Tables A.8 and A.9 were created by running the BOSOR4 processor called "MODIFY" with the "MODIFY" choice that leads to a file called GLOBAL2.QUE.

NOTE: The differences between BOSOR4 *.ALL files corresponding to INDIC = 3 and 4 (nonaxisymmetric loading) vs *.ALL files corresponding to INDIC = 0, 1, 2 (axisymmetric loading) are more substantial because the input for loading in each segment of the BOSOR4 model is very different for nonaxisymmetric vs axisymmetric loading. If one wants to create a SUBROUTINE BOSDEC valid for both nonaxisymmetric and axisymmetric loading, then one should first run BOSOR4 for both of these types of cases in order to obtain useful "templates" (*.ALL files) upon which to base the correct "WRITE" statements to be inserted into SUBROUTINE BOSDEC.

A.5 Some comments about "fleshing out" of the STRUCT.NEW and BEHAVIOR.NEW libraries

A.5.1 STRUCT.NEW library

Table A.5 lists the library STRUCT.NEW after it has been "fleshed out" by the GENOPT user. In this case the STRUCT.NEW library is modified by the GENOPT user from that created automatically by GENOPT in three places:

a. A BOSOR4 labelled common block is added near the beginning, as follows

COMMON/TOTMAX/TOTMAS

b. A section of code is added after the message, "USER, YOU MAY WANT TO INSERT...", as follows:

CALL OPNGEN (Open BOSOR4 files.)

CALL RWDGEN (Rewind BOSOR4 files.)

C initialize behaviors:

STRESS(ILOADX) = 0.

BSYM(ILOADX) = 0.

BANTI(ILOADX) = 0.

FREQ(ILOADX) = 0.

C Find mass of cyl. shell from boundary to mid-length symmetry plane. The mass is stored in TOTMAS, which is one of the BOSOR4 labelled common blocks.

INDIC = 0

CALL BOSDEC(5,ILOADX,INDIC)

CALL B4READ

CALL GASP (DUM1,DUM2,-2,DUM3)

GRAVTY = 386.4

WEIGHT = GRAVTY*TOTMAS

c. The following statement is added at the end of SUBROUTINE STRUCT:

CALL CLSGEN (Close BOSOR4 files.)

The rest of the STRUCT.NEW library was written by GENOPT during the interactive GENTEXT session.

The weight of the shell, WEIGHT, is computed early in SUBROUTINE STRUCT rather than in SUBROUTINE OBJECT, which is part of the BEHAVIOR.NEW library, because each call to the BOSOR4 preprocessor, B4READ, destroys an old *.DOC file and creates a new *.DOC file. If one wishes to obtain BOSOR4 plots corresponding to individual behaviors (responses), such as is done later in this case (see Figs. A.4 - A.7), one must compute the total mass, TOTMAS, and weight, WEIGHT, first so that the appropriate *.DOC file (to be copied into *.ALL and used later as input in a direct execution of BOSOR4) will exist at the end of the "CYLINDER" run.

A.5.2 BEHAVIOR.NEW library

The "fleshed out" version of the library, BEHAVIOR.NEW, is listed in Table A.6. For example, the part of SUBROUTINE BEHX1 written by the GENOPT user is:

COMMON/INSTAB/INDIC

COMMON/ENDUVX/ENDUV,STRMAX,ARCLEN (STRMAX is computed in B4POST)

INDIC = 0

CALL BOSDEC(1,ILOADX,INDIC)

CALL B4READ

CALL B4MAIN

CALL B4POST

CALL GASP(DUM1, DUM2, -2, DUM3) (GENOPT user has to reset GASP)

STRESS(ILOADX) = STRMAX
(STRMAX is computed in B4POST)

WRITE(IFILE,'(A,1P,E12.4)')' Maximum effective stress from BEHX1: STRESS=',STRMAX

In the coding fragment above, "BOSDEC" creates the "legal" input file for BOSOR4 for the analysis type, INDIC = 0 (axisymmetric nonlinear stress analysis). The three calls, CALL B4READ, CALL B4MAIN, CALL B4POST, represent the same computations that follow the command, "BOSORALL", in a normal execution of BOSOR4 [3]. After each execution of the BOSOR4 preprocessor, B4READ, mainprocessor, B4MAIN, and postprocessor, B4POST, the random access file, called *.RAN, must be reinitialized via the statement, CALL GASP(DUM1, DUM2, -2, DUM3). The variable, STRMAX, is the maximum effective stress contained in a BOSOR4 labelled common block, /ENDUVX/ in the BOSOR4 software (addbosor4.src). STRESS(ILOADX) is the maximum effective stress corresponding to Load Set No. ILOADX. The quantity, STRESS(ILOADX) is used by SUBROUTINE STRUCT to build a design constraint via SUBROUTINE CONX, as listed in Table A.5 in the section of SUBROUTINE STRUCT written automatically by the GENOPT system. See the part of Table A.5 immediately following the line,

'Start of the final portion of STRUCT written by "GENTEXT"'

The subroutines for symmetric buckling with respect to the midlength symmetry plane (BEHX2), antisymmetric buckling with respect to the midlength symmetry plane (BEHX3), and modal vibration of the axisymmetrically prestressed shell (BEHX4), are similar to eachother. For example, the GENOPT-user-written portion of SUBROUTINE BEHX2 follows:

```
COMMON/INSTAB/INDIC

COMMON/EIGB4M/EIGCOM(200),IWAVEB
                (These are computed in B4MAIN)

COMMON/WVEB4M/NWVCOM(200)
                (This is computed in B4MAIN))

COMMON/EIGBUK/EIGCRT
                (This is computed in B4MAIN)

COMMON/NWVBUK/NWVCRT
                (This is computed in B4MAIN)

COMMON/BUCKN/N0BX,NMINBX,NMAXBX,
INCRBX      (These are used in B4MAIN)

COMMON/PRMOUT/IFILE3,IFILE4,IFILE8,
IFILE9,IFIL11

COMMON/EIGALL/EIG2,EIG3,EIG4

COMMON/WAVALL/NWAV2,NWAV3,NWAV4
      (These must be saved for perturbation)

INDIC = 1

N0B = 2          (NOTE: In this example the
                  range of circ. waves over
NMAXB = 10        which to search for the
                  critical buckling load is
                  "hard-wired". N0B and
                  NMAXB could have been
                  variables introduced by the
                  GENOPT user during
                  "GENTEXT", as they were in the
                  more complex WAVYCYL
                  example.)

CALL BOSDEC(2,ILOADX,INDIC)

CALL B4READ

IF (IMODX.EQ.0) THEN
                (IMODX = 0 means "current
                design")

  N0BX = N0B

  NMINBX = N0B

  NMAXBX = NMAX B

  INCRBX = 1

ELSE            (IMODX = 1 means "perturbed
                design")
```

```
  NOBX = NWAV2     (lots of computer time is
  NMINBX=NWAV2   saved by not searching
  NMAXBX=NWAV2   over a range of circ.
  INCRBX = 1          waves for the perturbed
                          design, which is very
                          close to the current
                          design.)

ENDIF

REWIND IFILE9

CALL STOCM1(IFILE9)

CALL STOCM2(IFILE9)

CALL B4MAIN

CALL GASP(DUM1,DUM2,-2,DUM3)
(GENOPT user has to reset GASP)

IF (IMODX.EQ.0) THEN

  EIG2 = EIGCRT

  NWAV2= NWVCRT

ENDIF

WRITE(IFILE,'(/,A)') 'SYMMETRIC
BUCKLING LOAD FACTORS AND MODES
(BEHX2)'

DO 10    I = 1,IWAVEB

     WRITE(IFILE,'(A,1P,E12.4,A,I4,A)')
     '        ',EIGCOM(I),'(',NWVCOM(I),')'

10 CONTINUE

WRITE(IFILE,'(A,1P,E12.4)')           '
Critical buckling load factor, BSYM=',EIGCRT
WRITE(IFILE,'(A,I5)')                 '
Critical number of circumferential waves,
NWVCRT=',NWVCRT

BSYM(ILOADX) = EIGCRT
```

The first seven BOSOR4 labelled common blocks, /INSTAB/ - /PRMOUT/, appear in BOSOR4 (addbosor4.src, b4util.src). The index, IMODX, is zero for the "current design" and one for the "perturbed design", in which "perturbed" signifies the design that is the same as the "current design" except that one decision variable has been perturbed by a small amount (usually about five per cent). Evaluation of each perturbed design is required in order to be able to compute the gradient of each behavioral constraint with respect to a small change in each decision variable. These gradients are needed by the optimizer, ADS [5,6]. In the coding fragment just listed, The BOSOR4 labelled common block, /BUCKN/, which contains circumferential wavenumbers, etc., is filled with appropriate values just before execution of the BOSOR4 mainprocessor, B4MAIN. The role of SUBROUTINEs STOCM1 and STOCM2 is to store the BOSOR4 labelled common blocks in sequential mass storage for use by the various BOSOR4 processors, B4READ, B4MAIN, and B4POST.

A strategy is used here that saves computer time: For the PERTURBED design (IMODX = 1), a single buckling load factor is sought, that which corresponds to the same number of circumferential waves, NWAV2, determined as critical for the CURRENT design. It would be wasteful to search the entire range of n, NMINBX < n < NMAXBX, for the minimum buckling load for each perturbed design because the perturbed design is only slightly different from the current design. Therefore, it is safe to assume that the critical buckling mode for each perturbed design will have the same number of circumferential waves as that for the current design. (NOTE: this assumption was not a good one for the "wavy" cylindrical shells because of the great sensitivity of buckling load factor with respect to very small changes in certain of the decision variables, WAVLEN and BRINGS).

A.6 Optimization and evaluation by the "CYLINDER" user

A.6.1 Summary

Tables A.12 - A.19 and Figs. A.1 - A.8 pertain to this section. First the run stream used to produce the results from a specific example, called "cyl" by the "CYLINDER" user, is given. Then the results are discussed briefly.

A.6.2 Run Stream used by the "CYLINDER" user

The following run stream was used to generate the optimum design and other information pertaining to the specific case, "cyl":

GENOPTLOG (activate the GENOPT/CYLINDER commands, BEGIN, DECIDE, etc.)

BEGIN (provide the starting design. cyl.BEG listed in Table A.12)

DECIDE (choose decision variables and bounds. cyl.DEC; Table A.13)

MAINSETUP (choose behaviors, etc. cyl.OPT listed in Table A.14. In this case all of the four behaviors, BEHX1, BEHX2, BEHX3, BEHX4, are processed.)

OPTIMIZE (launch "batch" run for first set of design iterations)

OPTIMIZE (launch "batch" run for second set of design iterations)

(We have obtained an optimum design. Inspect the files, cyl.OPP in Table A.15 and cyl.OPM in Table A.16.)

CHOOSEPLOT (choose what to plot)

DIPLOT (obtain postcript plot files, cyl.i.ps, i = 5, 3, 4. See Figures A.1 - A.3, respectively.

(Next, obtain BOSOR4 plots corresponding to each "behavior".)

MAINSETUP (choose one behavior and use fixed design, ITYPE = 2)

OPTIMIZE (obtain results for the one behavior (BEHX2: symmetric buckling. See Table A.17.)

(The cyl.DOC file, created by this run, contains "legal" BOSOR4 input data for symmetric buckling about the midlength symmetry plane. See Table A.18 for a list of cyl.DOC.)

(Next, run BOSOR4 to obtain a BOSOR4 plot of the critical buckling mode for symmetric buckling with respect to the midlength symmetry plane. Go to a directory where you want to run BOSOR4. Copy the file, cyl.DOC, from the "genoptcase" directory into cyl.ALL in the directory from which you want to execute BOSOR4.)

BOSOR4LOG (activate the BOSOR4 set of commands)

BOSORALL (run BOSOR4. Inspect the cyl.OUT file to see the eigenvalues.)

BOSORPLOT (get postcript plot files from the cyl.PLT2 file. See Fig. A.4.)

(Next, repeat the sequence, MAINSETUP, OPTIMIZE, BOSORALL, BOSORPLOT for BEHX3: antisymmetric buckling at midlength symmetry plane. See Fig. A.5.)

(Next, repeat the sequence, MAINSETUP, OPTIMIZE, BOSORALL, BOSORPLOT for BEHX4: modal vibration of prestress shell. See Fig. A.6.)

(Next, repeat the sequence, MAINSETUP, OPTIMIZE, BOSORALL, BOSORPLOT for BEHX1: axisymmetric nonlinear stress analysis. In the cyl.ALL file, change the index, NLAST, from 0 to 1. See Fig. A.7.)

(Next, perform a design sensitivity analysis with respect to the only decision variable in this problem, the wall thickness, THICK.)

MAINSETUP (Choose behaviors and range of THICK. See Table A.19)

OPTIMIZE (Obtain the design sensitivity results.)

CHOOSEPLOT (choose which margins to plot vs THICK)

DIPLOT (obtain postscript plot file. See Fig. A.8)

A.7 Discussion of results for the specific case, "cyl"

Results from this simple case are listed in Tables A.15 - A.17 and plotted in Figs. A.1 - A.8.

Figures A.1 - A.3 display results from the optimization phase of the analysis. Design iterations 0 - 5 correspond to results obtained during the first execution of OPTIMIZE. Design iterations 6 and 7 correspond to results obtained during the second execution of OPTIMIZE. Results for Iterations 5 and 6 are identical because the starting design for the second OPTIMIZE is the same as the last design obtained after the first OPTIMIZE.

Figures A.4 - A.7 were generated by ordinary BOSOR4 runs in which the input data are contained in cyl.DOC files such as that listed in Table A.18, which corresponds to the BOSOR4 input data that leads to Fig. A.4.

NOTE: In this and the other examples presented in this paper the postcript plot files produced by CHOOSEPLOT/DIPLOT and by BOSORPLOT were edited in order to provide more information in the title, legends, and axes labels.

Figure A.8 shows the results of the design sensitivity analysis. (Input data for MAINSETUP/OPTIMIZE are listed in Table A.19). Note that the shape of the curve for fundamental modal frequency has dips analogous to those shown in Figs. 57, 59, 60-63, 85, and 86. The explanation for these dips is given in the paper.

```
Table 3.1  Section of the file ../bosor4/execute/PROMPT3.DAT that is
about response of a shell of revolution to base excitation
=========================================================================
750.1 Do you want response at resonance to base excitation?
750.2
You can type Y only if you have just run an INDIC = 2 (modal vibration
case) with n = 0 only or n = 1 only. (n is the number of circumferential
waves.)  This program estimates the response by RSS (square root of the
sum of the squares). The sum is over the number of modes calculated in the
previous (INDIC = 2) run.  This program will handle response to harmonic
excitation, response to random excitation, and response to shock. You will
be asked to provide input data such as load factor (number of g's
acceleration), damping factor, and/or spectral density.

770.0
To use this branch you must just have run a modal vibration analysis for a
single number of circumferential waves: either n = 0 or n = 1. The purpose
here is to find the response of the structure to either:
1. sinusoidal excitation    or
2. random excitation        or
3. shock

780.1 Want more information?
790.0
There are four kinds of information that must be supplied in order to
perform all of the three types of analysis just listed:
a.  gravity in the units of this case (e.g. 386.4 in/sec**2)
b.  a table of load factors or shock levels (g's) vs.
    frequency in hertz:                               [N = N(f)]
c.  a table of damping factor vs. frequency in hertz: [B = B(f)]
d.  a table of spectral density vs. frequency in hertz:[W = W(f)],
    in which W is in units of g's-squared-per-hertz (N**2/hertz).
For harmonic excitation you must supply a., b., and c.
For random   vibration  you must supply a., c., and d.
For shock    response   you must supply a. and b.

800.1 Want more information?
810.0
Suppose you calculated the first five vibration frequencies and modes for
n = 1 circumferential wave in your previous run, call it run no. 1.
Suppose you now want to calculate the response to random excitation.  In
the present run, call it run no. 2, the state of the shell from random
lateral or axial excitation [no rotational excitation (pitching) allowed!]
is estimated by superposition of quantities calculated for each resonance:

 w(response) =SQRT{sum from 1 to 5 of [m(i)*P(i)*phi(i)]**2}  (3.9)

in which m(i) is a frequency-dependent multiplier, P(i) is a modal
participation factor, and phi(i) is the ith vibration mode, including
modal stresses derived from appropriate differentiations of the modal
displacements. For response to harmonic excitation, each mode is treated
separately; the responses from the various modes are not superposed.

812.1 Want more information?
813.0
For all of the three types of analysis listed above an amplitude factor is
derived which is a product of the modal participation factor, P(i), and
the multiplier, m(i). The frequency-dependent multiplier, m(i), is given
for each of the three analysis types by:

For harmonic excitation (analysis type 1):
```

```
  m(i) = N(i)*g/[OMEGA**2*BETA(i)]                              (3.10)

For random excitation   (analysis type 2):

  m(i) = SQRT[OMEGA*SPECD/(2*BETA)]*g/OMEGA**2                  (3.11)

For shock response      (analysis type 3):

  m(i) = 2*N(i)*g/OMEGA**2                                      (3.12)

[ N(i)=load factor, g = acceleration of gravity,
  OMEGA=freq.(rad/sec), BETA=damping, SPECD=spectral density]

815.1 Type of response analysis (1 or 2  or 3)
815.2
1 means response to sinusoidal excitation
2 means response to random excitation
3 means response to shock

820.1 Value of acceleration of gravity in the units of this case
830.0
Next, provide number of g's (N) vs. frequency (f) in hertz. If N varies
with f, make sure that the data span the range of frequencies for which
you calculated vibration modes in your previous INDIC = 2 run.
NOTE: MAXIMUM OF 20  (N,f)  PAIRS IS ALLOWED.

840.1 Does N (no. of g's) vary with f (frequency)?
850.1 Number of g's, N
860.1 Frequency, f, corresponding to N
870.1 Want more entries in the N = N(f) table?
880.0
Next, provide damping factor (B) vs. frequency (f) in hertz.
NOTE: MAXIMUM OF 20  (B,f)  PAIRS IS ALLOWED.

890.1 Does B (damping factor) vary with f (frequency)?
900.1 Damping factor, B
910.1 Frequency, f, corresponding to B
920.1 Want more entries in the B = B(f) table?
930.0
Next, provide spectral density (W) vs. frequency (f) in hertz.
NOTE: MAXIMUM OF 20  (W,f)  PAIRS IS ALLOWED.

940.1 Does W (spectral density) vary with f (frequency)?
950.1 Spectral density (N**2/hertz), W
960.1 Frequency, f, corresponding to W
970.1 Want more entries in the W = W(f) table?
980.1 Do you want to find buckling load factors?
982.0
For horizontal (lateral) base motion, maximum compressive stress
resultants are either at circumferential coordinate THETA = 0 degrees or
THETA = 180 degrees. Print out meridional distributions of prebuckling
membrane resultants along both the meridian at THETA = 0 deg. and at THETA
= 180 deg; then decide which meridian to choose for the buckling analysis.
It may be a good idea to do buckling analyses corresponding to the stress
states at both THETA = 0 and THETA = 180 deg.
=========================================================================
```

Table 4.1 A log of activities and computer runs to determine the optimum design of a "wavy" cylindrical tube stiffened by external rings.

ACTIVITY	NATURE AND PURPOSE OF ACTIVITY
PART 1: Activity by the GENOPT user leading to creation of a capability to optimize a fairly broad class of shells of revolution: ring stiffened cylindrical shells with straight or "wavy" walls made of isotropic or laminated composite material.	
1 Formulate problem.	This must be done before ANY computer runs.
2. Choose and classify constants, variables. Choose names and definitions. These will appear in output.	This must be done before ANY computer runs. Properties, indices, dimensions, loadings, responses (e.g. stress, buckling, vibration, displacement), allowables, factors of safety, objective, must all be identified.
3. Run "GENTEXT". Provide names, definitions, "help" paragraphs, etc. that will later play various roles in the optimization problem to be solved.	The items decided on in Item 2 are provided interactively, leading to the *.INP file and GENOPT-written computer code some of which will be modified by the GENOPT user. The "*" in *.INP is the GENOPT-user-selected name for the class of problems to be solved later. In this particular case, this "generic" name, "*", equals "wavycyl".
4. Any quantities left out? Add them now.	Run the GENOPT processor "INSERT" as needed.
5. Provide whatever FORTRAN code is needed to compute buckling, stress, vibration, displacement, etc. for a design with given properties, dimensions.	This is the hardest part of the job. The FORTRAN subroutine skeletons, STRUCT.NEW and BEHAVIOR.NEW, generated during the "GENTEXT" interactive session (Item 3), must be "fleshed out" by the GENOPT user so that the various "behaviors" can be computed. In this case most of the code consists of BOSOR4 software, modified as described in Section 3.
6. Run "GENPROGRAMS".	This compiles the sofware generated automatically by GENOPT and modified as in Item 5 by the GENOPT user. When this step has been successfully completed, there exists a reasonably user-friendly system of programs, BEGIN, DECIDE, MAINSETUP, OPTIMIZE, SUPEROPT, CHOOSEPLOT, etc. for optimizing a user-provided member of the class, "wavycyl". In this case the class, "wavycyl", includes ring-stiffened cylindrical shells with straight or "wavy" walls, made of isotropic or laminated composite material. The "waviness" can be of very large amplitude, such as is so with bellows.
PART 2: Activity of the WAVYCYL user leading to the optimum designs of specific members of the class, "wavycyl".	
7. Run PANDA2 [7,19-22] to determine ring cross section and approximate spacing, as well as the effect of ini-	PANDA2 runs much faster than "wavycyl" because it is based of the use of models with many fewer degrees of freedom (d.o.f.). See Refs. [7,19-22] for details about PANDA2. PANDA2 can handle ring-stiffened cylindrical shells with straight

tial imperfections[19].	walls.
8. Run the BEGIN, DECIDE, MAINSETUP, SUPEROPT, CHOOSEPLOT processors.	Optimize a member of the class, "wavycyl": an externally ring-stiffened cylindrical shell with a "wavy" wall. Fig. 1 shows a typical starting design.
9. Investigate convergence with respect to number of d.o.f. in the BOSOR4 model.	Check the accuracy of the model.
10 Perform sensitivity analyses, especially with respect to the axial halfwavelength of the "waviness".	Experience shows that it is difficult to obtain a "global" minimum weight design. This is because there is extreme sensitivity of general buckling load factor to small changes in the axial half-wavelength of the "waviness" in the cyl. wall.

===

Table 4.2 Example of input data for the "GENTEXT" interactive session.
This table is a list of the first part of the "wavycyl.INP" file, created
as the GENOPT user executes the GENOPT process called "GENTEXT".

```
==========================================================================
       5  $ starting prompt index in the file wavycyl.PRO
       5  $ increment for prompt index
       0  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 This is wavycyl
 n        $ Are there more lines in the "help" paragraph?
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt

 AXIAL    $ Name of a variable in the users program (defined below)
       2  $ Role of the variable in the users program
       2  $ type of variable:  1 =integer,  2 =floating point
 n        $ Is the variable  AXIAL  an array?
 length of cylindrical shell
 y        $ Do you want to include a "help" paragraph?
 Give nominal length in units of your case.
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?   $10
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 RADIUS   $ Name of a variable in the users program (defined below)
       2  $ Role of the variable in the users program
       2  $ type of variable:  1 =integer,  2 =floating point
 n        $ Is the variable  RADIUS  an array?
 Average nominal radius of cylindrical shell
 y        $ Do you want to include a "help" paragraph?
 The waviness oscillates about RADIUS
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?   $15
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 THICK    $ Name of a variable in the users program (defined below)
       1  $ Role of the variable in the users program
 n        $ Is the variable  THICK  an array?
 Total wall thickness
 y        $ Do you want to include a "help" paragraph?
 This is a decision variable only for an isotropic wall.
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?   $20
       1  $ Type of prompt: 0="help" paragraph, 1=one-line prompt
 IRING    $ Name of a variable in the users program (defined below)
       2  $ Role of the variable in the users program
       1  $ type of variable:  1 =integer,  2 =floating point
 n        $ Is the variable  IRING  an array?
 Location of T-ring: -1=internal, 0=none, 1=external
 y        $ Do you want to include a "help" paragraph?
 Use IRING=-1 for internal rings; 1 for external rings; 0 for no rings.
 n        $ Any more lines in the "help" paragraph?
 y        $ Any more variables for role types  1  or  2   ?   $25
==========================================================================
```

Table 4.3 The portion of the "wavycyl.PRO" file corresponding to the input data listed in the previous table "wavycyl.INP". This file contains the prompts and "help" paragraphs that will be seen by the WAVYCYL user. The "wavycyl.PRO" file is created by the GENOPT system. The GENOPT user creates the prompting phrases and "help" phrases and variable names during the "GENTEXT" interactive session.

```
==========================================================================
    5.0
        This is wavycyl

   10.1 length of cylindrical shell: AXIAL
   10.2
        Give nominal length in units of your case.

   15.1 Average nominal radius of cylindrical shell: RADIUS
   15.2
        The waviness oscillates about RADIUS

   20.1 Total wall thickness: THICK
   20.2
        This is a decision variable only for an isotropic wall.

   25.1 Location of T-ring: -1=internal, 0=none, 1=external: IRING
   25.2
        Use IRING=-1 for internal rings; 1 for external rings; 0 for no rings.
==========================================================================
```

```
Table 4.4 Glossary of variables used in "wavycyl". This table is created
by the GENOPT system and is located in the "wavycyl.DEF" file.
===========================================================================
ARRAY NUMBER OF        PROMPT  VARIABLE                                BEHAV.
 ?   (ROWS,COLS) ROLE  NUMBER    NAME       DEFINITION OF VARIABLE     BEHXi
                    (wavycyl.PRO)                                          i
---------------------------------------------------------------------------
 n    (  0,  0)    2      10     AXIAL   = length of cylindrical shell
 n    (  0,  0)    2      15     RADIUS  = Average nominal radius of cylindri
 n    (  0,  0)    1      20     THICK   = Total wall thickness
 n    (  0,  0)    2      25     IRING   = Location of T-ring: -1=internal, 0
 n    (  0,  0)    1      30     BRINGS  = ring spacing (use zero if no rings
 n    (  0,  0)    1      35     TWEB    = thickness of web of T-ring
 n    (  0,  0)    1      40     HWEB    = height of web of T-ring
 n    (  0,  0)    1      45     TFLANG  = thickness of outstanding flange of
 n    (  0,  0)    1      50     HFLANG  = width of outstanding flange of T-r
 n    (  0,  0)    2      55     ERING   = Average modulus of ring material
 n    (  0,  0)    2      60     FNURNG  = Average Poisson ratio of ring mate
 n    (  0,  0)    2      65     DENRNG  = Average mass density of ring mater
 n    (  0,  0)    2      70     NMESHR  = Number of nodal points in each rin
 n    (  0,  0)    2      75     GRAVTY  = Acceleration of gravity (e.g. 386.
 n    (  0,  0)    2      80     LGAXL   = Length of tube unrestrained by axi
 n    (  0,  0)    2      85     NWAVES  = Number (EVEN) of axial halfwaves i
 n    (  0,  0)    1      90     WAVLEN  = Axial halfwavelength of the wavine
 n    (  0,  0)    1      95     AMPLIT  = Amplitude of waviness
 n    (  0,  0)    2     105     IWAVE   = Type of waviness (IWAVE=2 or 3)
 n    (  0,  0)    1     115     RADSML  = Local meridional radius of curvatu
 n    (  0,  0)    2     125     NMESHS  = Number of nodal points in STRAIGHT
 n    (  0,  0)    2     130     NMESHC  = Number of nodal pts. in each curve
 n    (  0,  0)    2     135     NMESH1  = Number of nodal pts. in "smeared"
 n    (  0,  0)    2     140     MAXDOF  = Maximum number of d.o.f. of buckli
 n    (  0,  0)    2     145     IBOUND  = Boundary condition index: 1 = s.s.
 n    (  0,  0)    2     150     IWALL   = Type of shell wall (1=isotropic, 2
 n    (  0,  0)    2     155     ESTIFF  = Youngs modulus
 n    (  0,  0)    2     160     FNU     = Poisson ratio
 n    (  0,  0)    2     165     DENS    = Material mass density (e.g. alum.=
 n    (  0,  0)    2     175     NLAYER  = Number of layers in the wall
 n    (  0,  0)    2     180     ILTYPE  = ILTYPE=layer type in LTYPE(ILTYPE)
 y    ( 90,  0)    2     185     LTYPE   = Layer index
 y    ( 90,  0)    2     190     NEWLAY  = NEWLAY: 0=not new layer type; 1=ne
 n    (  0,  0)    2     195     ITLAYE  = position in TLAYER array in TLAYER
 y    ( 20,  0)    1     200     TLAYER  = thickness of layer type
 y    ( 20,  0)    1     205     ANGLE   = layup angle (deg.) for layer type
 y    ( 20,  0)    2     210     MTYPE   = Material index (1,2...) for layer
 y    ( 20,  0)    2     215     NEWMAT  = NEWMAT: 0=not new matl; 1=new matl
 y    ( 20,  0)    2     225     E1      = modulus in the fiber direction
 y    ( 20,  0)    2     230     E2      = modulus transverse to fibers
 y    ( 20,  0)    2     235     G       = in-plane shear modulus
 y    ( 20,  0)    2     240     NU      = small Poisson ratio
 y    ( 20,  0)    2     245     A1      = coeff. thermal expansion along fib
 y    ( 20,  0)    2     250     A2      = coeff. thermal expansion transvers
 y    ( 20,  0)    2     255     CURETP  = residual stress temperature
 y    ( 20,  0)    2     260     RHO     = mass density (e.g. alum.=.00025 lb
 y    ( 20,  0)    2     270     S1TEN   = maximum tensile stress long fibers
 y    ( 20,  0)    2     275     S1COMP  = max compressive stress along fiber
 y    ( 20,  0)    2     280     S2TEN   = max tensile stress normal to fiber
 y    ( 20,  0)    2     285     S2COMP  = max compressive stress normal to f
 y    ( 20,  0)    2     290     TAU12   = max shear stress
 n    (  0,  0)    2     295     NRS     = control (0 or 1) for smeared stiff
 n    (  0,  0)    2     300     NDAMP   = number of entries in table of damp
 n    (  0,  0)    2     305     IBDAMP  = position in BDAMP array in BDAMP(I
 y    ( 20,  0)    2     310     BDAMP   = damping factor
```

y	(20, 0)	2	315	BFREQ	= frequency (hertz) corresponding to	
n	(0, 0)	2	320	NSPECT	= number of entries in table of spec	
n	(0, 0)	2	325	ISPTDE	= position in BDAMP array in SPTDEN(	
y	(20, 0)	2	330	SPTDEN	= spectral density	
y	(20, 0)	2	335	SFREQ	= frequency (hertz) corresponding to	
n	(0, 0)	2	340	N0B	= starting number of circumferential	
n	(0, 0)	2	345	NMAXB	= ending number of circumferential w	
n	(0, 0)	2	350	INCRB	= Increment in number of circumferen	
n	(0, 0)	2	355	N0V	= starting no. of circ. waves for vi	
n	(0, 0)	2	360	NMAXV	= ending no. of circ. waves for vibr	
n	(0, 0)	2	365	INCRV	= increment in no. circ. waves for v	
n	(0, 0)	2	370	NVE	= Number of eigenvalues for each cir	
n	(0, 0)	2	375	NCASES	= Number of load cases (number of en	
y	(20, 0)	3	380	FNX	= Axial resultant (neg. for compress	
y	(20, 0)	3	385	FNXB	= Axial resultant (neg. for compress	
y	(20, 0)	3	390	GAXIAL	= number of g's acceleration along c	
y	(20, 0)	3	395	GLATRL	= Number of g's perpendicular to axi	
y	(20, 0)	3	400	PRESS	= pressure (negative for external),	
y	(20, 0)	3	405	PRESSB	= pressure (negative for external),	
y	(20, 0)	4	410	STRMAX	= maximum stress in wall from nonlin	1
y	(20, 0)	5	415	STRALW	= maximum allowable vonMises stress,	
y	(20, 0)	6	420	STRFS	= factor of safety for vonMises stre	
y	(20, 0)	4	425	BUCFAC	= buckling load factor from nonlinea	2
y	(20, 0)	5	430	BUCALW	= allowable for buckling factor (use	
y	(20, 0)	6	435	BUCFS	= factor of safety for buckling, non	
y	(20, 0)	4	440	BUCHIW	= hi-wave buckling load factor, nonl	3
y	(20, 0)	5	445	BUCHIA	= allowable for hi-wave buckling fac	
y	(20, 0)	6	450	BUCHIF	= factor of safety for hi-wave buckl	
y	(20, 0)	4	455	STR0	= max. vonMises stress at 0 deg., li	4
y	(20, 0)	5	460	STR0A	= max. allowable vonMises stress, li	
y	(20, 0)	6	465	STR0F	= factor of safety for vonMises stre	
y	(20, 0)	4	470	STR180	= max. vonMises stress at 180 deg.,	5
y	(20, 0)	5	475	ST180A	= max. allowable vonMises stress, li	
y	(20, 0)	6	480	ST180F	= factor of safety for vonMises stre	
y	(20, 0)	4	485	BUC0	= buckling load factor at 0 deg., li	6
y	(20, 0)	5	490	BUC0A	= allowable for buckling factor (use	
y	(20, 0)	6	495	BUC0F	= factor of safety for buckling fact	
y	(20, 0)	4	500	B0ANTI	= load factor for antisymmetric buck	7
y	(20, 0)	5	505	B0ANTA	= allowable (use 1) for antisymmetri	
y	(20, 0)	6	510	B0ANTF	= factor of safety for antisymmetric	
y	(20, 0)	4	515	BUC0MD	= load factor for mid-wave-range buc	8
y	(20, 0)	5	520	BUC0MA	= allowable (use 1) for mid-wave-ran	
y	(20, 0)	6	525	BUC0MF	= factor of safety for mid-wave-rang	
y	(20, 0)	4	530	BUC0HI	= hi-wave buckling load factor at 0	9
y	(20, 0)	5	535	BUC0HA	= allowable for hi-wave buckling (us	
y	(20, 0)	6	540	BUC0HF	= factor of safety for hi-wave buckl	
y	(20, 0)	4	545	BUC180	= buckling load factor at 180 deg, l	10
y	(20, 0)	5	550	BU180A	= allowable buckling factor at 180 d	
y	(20, 0)	6	555	BU180F	= factor of safety for buckling at 1	
y	(20, 0)	4	560	B180HI	= hi-wave buckling load factor 180 d	11
y	(20, 0)	5	565	B180HA	= allowable (use 1) hi-wave buckling	
y	(20, 0)	6	570	B180HF	= factor of safety for hi-wave buckl	
y	(20, 0)	4	575	WWW0	= maximum normal displacement at 0 d	12
y	(20, 0)	5	580	WWW0A	= maximum allowable normal displacem	
y	(20, 0)	6	585	WWW0F	= factor of safety for max. normal d	
y	(20, 0)	4	590	WWW180	= maximum normal displacement at 180	13
y	(20, 0)	5	595	WW180A	= max. allowable normal displacment,	
y	(20, 0)	6	600	WW180F	= factor of safety for normal displa	
y	(20, 0)	4	605	FREQ	= modal frequency (hertz)	14
y	(20, 0)	5	610	VIBALW	= minimum allowable modal frequency	
y	(20, 0)	6	615	VIBFS	= factor of safety for modal frequen	
y	(20, 0)	4	620	STRRAN	= max. effective stress from random	15

```
 y   ( 20,  0)    5      625     STRRNA  = max. allowable stress from random
 y   ( 20,  0)    6      630     STRRNF  = factor of safety for stress from r
 y   ( 20,  0)    4      635     BUCRAN  = buckling load factor from random e  16
 y   ( 20,  0)    5      640     BUCRNA  = allowable buckling load factor (us
 y   ( 20,  0)    6      645     BUCRNF  = factor of safety for buckling from
 y   ( 20,  0)    4      650     BRANHI  = hi-wave buckling factor from rando  17
 y   ( 20,  0)    5      655     BRANHA  = allowable (use 1) for buckling fac
 y   ( 20,  0)    6      660     BRANHF  = factor of safety for hi-wave buckl
 y   ( 20,  0)    4      665     WWWRAN  = max. normal displacement from rand  18
 y   ( 20,  0)    5      670     WWWRNA  = max. allowable normal displ. from
 y   ( 20,  0)    6      675     WWWRNF  = factor of safety for max. normal d
 n   (  0,  0)    7      680     WEIGHT  = weight of the cylindrical shell
==============================================================================
```

Table 4.5 Labelled common blocks created by the GENOPT system. These labelled common blocks contain all the variables created by the GENOPT user during the "GENTEXT" interactive session. They appear in SUBROUTINE STRUCT, in each of the SUBROUTINEs BEHXi, i = 1, 2, ...18, and in SUBROUTINE OBJECT. (They also appear in SUBROUTINE PUTWAV, which was written by the GENOPT user for the WAVYCYL system).

```
=================================================================================
      COMMON/FV01/AXIAL,RADIUS,THICK,BRINGS,TWEB,HWEB,TFLANG,HFLANG
      REAL AXIAL,RADIUS,THICK,BRINGS,TWEB,HWEB,TFLANG,HFLANG
      COMMON/FV09/ERING,FNURNG,DENRNG,GRAVTY,LGAXL,WAVLEN,AMPLIT,RADSML
      REAL ERING,FNURNG,DENRNG,GRAVTY,LGAXL,WAVLEN,AMPLIT,RADSML
      COMMON/IV01/IRING,NMESHR,NWAVES,IWAVE,NMESHS,NMESHC,NMESH1,MAXDOF
      INTEGER IRING,NMESHR,NWAVES,IWAVE,NMESHS,NMESHC,NMESH1,MAXDOF
      COMMON/IV12/LTYPE(90),ILTYPE
      INTEGER LTYPE
      COMMON/IV13/NEWLAY(90)
      INTEGER NEWLAY
      COMMON/FV20/TLAYER(20),ITLAYE
      REAL TLAYER
      COMMON/IV14/MTYPE(20)
      INTEGER MTYPE
      COMMON/IV15/NEWMAT(20)
      INTEGER NEWMAT
      COMMON/FV21/ANGLE(20)
      REAL ANGLE
      COMMON/FV22/E1(10),IE1
      REAL E1
      COMMON/FV23/E2(10),G(10),NU(10),A1(10),A2(10),CURETP(10)
      REAL E2,G,NU,A1,A2,CURETP
      COMMON/FV29/RHO(10),S1TEN(10),S1COMP(10),S2TEN(10),S2COMP(10)
      REAL RHO,S1TEN,S1COMP,S2TEN,S2COMP
      COMMON/FV34/TAU12(10)
      REAL TAU12
      COMMON/FV35/BDAMP(20),IBDAMP
      REAL BDAMP
      COMMON/FV36/BFREQ(20)
      REAL BFREQ
      COMMON/FV37/SPTDEN(20),ISPTDE
      REAL SPTDEN
      COMMON/IV09/IBOUND,IWALL,NLAYER,NRS,NDAMP,NSPECT,N0B,NMAXB,INCRB
      INTEGER IBOUND,IWALL,NLAYER,NRS,NDAMP,NSPECT,N0B,NMAXB,INCRB
      COMMON/FV38/SFREQ(20)
      REAL SFREQ
      COMMON/FV39/FNX(20)
      REAL FNX
      COMMON/FV40/FNXB(20),GAXIAL(20),GLATRL(20),PRESS(20),PRESSB(20)
      REAL FNXB,GAXIAL,GLATRL,PRESS,PRESSB
      COMMON/FV47/STRMAX(20),STRALW(20),STRFS(20)
      REAL STRMAX,STRALW,STRFS
      COMMON/FV50/BUCFAC(20),BUCALW(20),BUCFS(20)
      REAL BUCFAC,BUCALW,BUCFS
      COMMON/FV53/BUCHIW(20),BUCHIA(20),BUCHIF(20)
      REAL BUCHIW,BUCHIA,BUCHIF
      COMMON/FV56/STR0(20),STR0A(20),STR0F(20)
      REAL STR0,STR0A,STR0F
      COMMON/FV59/STR180(20),ST180A(20),ST180F(20)
      REAL STR180,ST180A,ST180F
      COMMON/FV62/BUC0(20),BUC0A(20),BUC0F(20)
      REAL BUC0,BUC0A,BUC0F
      COMMON/FV65/B0ANTI(20),B0ANTA(20),B0ANTF(20)
      REAL B0ANTI,B0ANTA,B0ANTF
      COMMON/FV68/BUC0MD(20),BUC0MA(20),BUC0MF(20)
```

```
      REAL BUC0MD,BUC0MA,BUC0MF
      COMMON/FV71/BUC0HI(20),BUC0HA(20),BUC0HF(20)
      REAL BUC0HI,BUC0HA,BUC0HF
      COMMON/FV74/BUC180(20),BU180A(20),BU180F(20)
      REAL BUC180,BU180A,BU180F
      COMMON/FV77/B180HI(20),B180HA(20),B180HF(20)
      REAL B180HI,B180HA,B180HF
      COMMON/FV80/WWW0(20),WWW0A(20),WWW0F(20)
      REAL WWW0,WWW0A,WWW0F
      COMMON/FV83/WWW180(20),WW180A(20),WW180F(20)
      REAL WWW180,WW180A,WW180F
      COMMON/FV86/FREQ(20),VIBALW(20),VIBFS(20)
      REAL FREQ,VIBALW,VIBFS
      COMMON/FV89/STRRAN(20),STRRNA(20),STRRNF(20)
      REAL STRRAN,STRRNA,STRRNF
      COMMON/FV92/BUCRAN(20),BUCRNA(20),BUCRNF(20)
      REAL BUCRAN,BUCRNA,BUCRNF
      COMMON/FV95/BRANHI(20),BRANHA(20),BRANHF(20)
      REAL BRANHI,BRANHA,BRANHF
      COMMON/FV98/WWWRAN(20),WWWRNA(20),WWWRNF(20)
      REAL WWWRAN,WWWRNA,WWWRNF
      COMMON/IV22/N0V,NMAXV,INCRV,NVEC
      INTEGER N0V,NMAXV,INCRV,NVEC
      COMMON/FV17/ESTIFF,FNU,DENS,WEIGHT
      REAL ESTIFF,FNU,DENS,WEIGHT
===========================================================================
```