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Optimum design of isotropic monocoque and
ring-stiffened circular cylindrical shells subject to
external hydrostatic pressure

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OPTIMUM DESIGN OF ISOTROPIC
MONOCOQUE AND RING-STIFFENED
CIRCULAR CYLINDRICAL SHELLS
SUBJECT TO EXTERNAL HYDROSTATIC PRESSURE

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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ABSTRACT

The objective of this research is to create a flexible code which is to be used in the investigation of optimum (minimum weight) shell designs. A shell analysis/design program (DAPS3) and a general purpose numerical optimization program (ADS) are incorporated into a single code (THESIS). This code provides the user great flexibility in changing the design variables and constraints which model the optimization problem. The optimum designs produced by this code are compared to DAPS3 optimum designs in order to identify any improvements made by the numerical optimization technique.

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I. INTRODUCTION

A. DEVELOPING A MATHEMATICAL MODEL FOR OPTIMIZATION

Design optimization is a powerful tool available to the design engineer. While it is not a new concept, only recently has numerical design optimization become a technique which is routinely applied by practicing engineers to the myriad of design tasks. This trend can be attributed to recent technological advances in high-speed digital computers, which are necessary to solve the multitude of equations modeling the optimization problem.

One area particularly suited for design optimization applications is structural design. The design of a structure requires a great deal of forethought by the design engineer. Several restrictions (constraints) on the design, such as environmental effects, geometry, and material selection, must first be determined. Then, these restrictions are applied to the design process to produce a specific output (objective), such as maximum structural response or minimum cost. The goal of the design engineer is to design the best possible structure, in terms of a specific desired output, while adhering to several expected constraints on the final design. That is, the final structure must be the optimum design for anticipated conditions.

In order to achieve this optimum design, the design optimization process requires that the design task be defined as a mathematical model. This model consists of an objective function, constraint functions, and side constraint functions.

These three functions are mathematical equations expressed in terms of design variables and state variables. State variables are fixed quantities in the mathematical equations. Design variables are those quantities which are allowed to vary during the optimization process. The objective function, which contains every design variable, is a single equation representing the quantity to be optimized (such as weight, displacement, cost, etc.). Constraint functions are one or more equations which restrict the design variables; one or more design variables are contained in each constraint function. Side constraint functions are equations which limit the upper and lower bound ranges of each design variable. Simply stated, the model describes, mathematically, what is to be optimized (objective) and the limitations (constraints and side constraints) on design variables.

Having converted the design task into a mathematical model, the design engineer can program the model. Using his own optimization code, or, more likely, available software, the design engineer may now execute the process of optimizing the objective function and the associated design variables.

B. MODELING A CYLINDRICAL SHELL FOR MINIMUM WEIGHT DESIGN

The design optimization task is to design a minimum weight thin cylindrical shell subjected to external hydrostatic pressure. The shell can be either monocoque or ring-stiffened (by internal rectangular cross-section rings placed at equidistant intervals within the shell). A single isotropic shell and ring material will be used in either case. A more complex orthotropic material or a hybrid construction material

could have been used (and supported by the DAPS3 analysis mode). However, due to time limitations, only an isotropic material will be investigated. This simpler material should still credibly serve the purpose of demonstrating the application of numerical optimization techniques to a minimum weight shell design. The optimized design is also constrained by buckling, strength, and geometry considerations. This design task is applicable to the design of submerged cylindrical structures under a static pressure load. Examples might include submarine pressure hulls and torpedo cases.

In order to model the above design task, a shell analysis program, DAPS3 (Design and Analysis of Plastic Shells version 3), was used to evaluate the buckling and strength constraint functions of a thin shell under external hydrostatic pressure. Development of these constraint functions is discussed in Chapter II (Shell Buckling and Strength). The optimization problem was evaluated by the general purpose numerical optimization program ADS (Automated Design Synthesis version 1.10). Development of the mathematical model for optimization is discussed in Chapter III (Optimization Problem). Both programs, which are written in the FORTRAN language, are incorporated into a single FORTRAN code named THESIS.

The THESIS code produces a minimum weight shell design, and it indicates the shell dimension design variables (thickness, ring height, and ring width) associated with that optimum design. Therefore, the design task is modeled and optimized within the THESIS code.

C. THESIS OBJECTIVES

DAPS3 uses an iterative technique to optimize the shell design variables. The variables are manipulated (in a "DO" loop sense) until a design is produced which does not buckle under the input hydrostatic pressure. When all possible buckling loads are greater than the hydrostatic pressure, DAPS3 terminates the iterations. The DAPS3 generated optimum design is produced from the last design iteration. It was felt that incorporation of the more sophisticated numerical optimization technique should improve upon the DAPS3 iterative design technique.

In pursuit of the above hypothesis, this thesis will investigate optimum designs generated by the THESIS code over a wide range of geometry configurations (L/OD ratios) and loads (external hydrostatic pressures). These designs will then be compared to the optimum designs generated by DAPS3 (when used in the "design" mode). Specifically, the following design elements will be compared: 1) objective (shell weight), 2) design variables (thickness, ring height, and ring width), and 3) constraints (buckling, strength, and geometry). Any design improvements made by use of the numerical optimization technique will be identified. Results are presented in Chapter IV. Conclusions as to the advantages and disadvantages of incorporating a numerical optimization technique are presented in Chapter V.

II. SHELL BUCKLING AND STRENGTH

The purpose of this chapter is to explain the formulation of the buckling and strength (or stress) terms used by the THESIS code. A detailed derivation of the buckling equations is provided by Renzi [Refs. 1,2].

A. BUCKLING EQUATIONS

Structural failure by buckling is associated with an "unstable" design. Material, geometry, and load factors contribute to this instability. The THESIS code designs the geometry of a "stable" cylindrical shell based on material and load factors which are input by the user. Within the THESIS code, DAPS3 is used as a subroutine analysis program to calculate the buckling loads on either a monocoque or ring-stiffened shell. These buckling loads are then returned to the numerical optimization program (ADS), which is incorporated in the THESIS code, to be considered in buckling constraints on the optimum shell design. Of course, other constraints (strength and geometry) are also considered before the THESIS code produces the optimum shell design.

The three types of shell buckling loads considered are:

1. Axisymmetric Collapse Pressure (PC)
2. Elastic Monocoque Shell Instability Pressure or Elastic Interbay Instability Pressure (PIB)

3. Elastic General Instability Pressure (PGEN)

Note that the above buckling terms are expressed in terms of pressure rather than in terms of force. The specific unit of pressure used in the THESIS code is (lb_f/in^2). The use of buckling pressures, rather than buckling forces, allows easy comparison of the buckling loads to the applied load, which is the external hydrostatic pressure (PSTR), also in (lb_f/in^2). The comparison of buckling load to applied load will quickly reveal whether the shell will buckle under the specified applied load. From herein, any use of the term "load" will mean pressure in units of (lb_f/in^2).

Since this thesis examines both monocoque and ring-stiffened shells, the type of shell also determines which particular buckling loads are present. For the monocoque shell and ring-stiffened shells, two buckling loads are present: axisymmetric collapse pressure (PC) and elastic shell monocoque shell instability pressure (PIB). When the shell is ring-stiffened, a third buckling load, elastic general instability pressure (PGEN), is also present.

Note that the buckling term PIB is associated with two different names. If the shell is monocoque, then PIB is called the elastic shell monocoque instability pressure. Otherwise, the same term is called the elastic interbay instability pressure if the shell is ring-stiffened. This distinction is discussed in the subsection concerning development of the PIB term.

1. Axisymmetric Collapse Pressure (PC)

This buckling load is present in both monocoque and ring-stiffened shells.

It describes local axisymmetric buckling of the shell in between two ring-stiffeners (or in between the end frames for a monocoque shell). An example of axisymmetric buckling between two rings is illustrated in Figure 1.

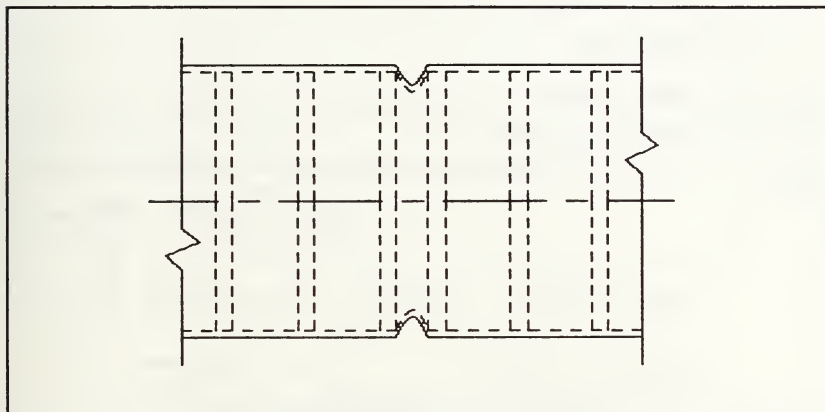


Figure 1. Local Axisymmetric Buckling of a Ring-Stiffened Shell Between Adjacent Rings.

To find an explicit expression for the axisymmetric collapse pressure (PC), first consider the differential element of a thin cylindrical shell shown in Figure 2. After establishing equilibrium of forces and moments on the element, it is found that the governing differential equation of the isotropic shell is:

$$\left[\frac{ET^3}{12(1-\nu^2)} \right] \frac{d^4 w}{dx^4} + \left[\frac{(PSTR)(R)\alpha^2}{2} \right] \frac{d^2 w}{dx^2} + \left[\frac{ET}{R^2} \right] w = -(PSTR) \left(1 - \frac{\nu\alpha^2}{2} \right)$$

where:

T = Thickness of Shell

$$\alpha = \frac{R_o}{R}; R_o = \frac{1}{2}(\text{Outside Diameter}), R = R_o - \frac{1}{2}(T)$$

ν = Poisson Ratio

E = Elastic Modulus

w = Radial Displacement

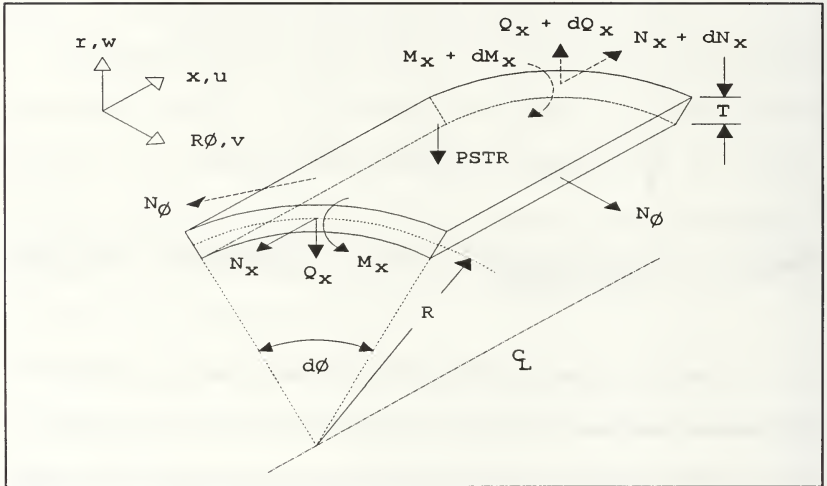


Figure 2. Differential Element of an Isotropic Thin Shell Subjected to External Hydrostatic Pressure (PSTR).

The coefficient of the second order term, in this fourth order ordinary differential equation, renders the solution $w(x)$ to be nonlinear with respect to the

external hydrostatic pressure (PSTR). This same coefficient also makes it possible to extract the axisymmetric collapse pressure (PC) from the solution $w(x)$.

The solution of the governing differential equation is found to be:

$$w(x) = A \sinh(\lambda_1 x) + B \cosh(\lambda_1 x) + C \sinh(\lambda_3 x) + F \cosh(\lambda_3 x) - \frac{(PSTR)R^2}{ET} \left(1 - \frac{\nu}{2} \alpha^2\right)$$

However, due to selection of the axial coordinate x (or u) origin at a point midway between ring-stiffeners, two of the arbitrary constants are found to be $A = C = 0$.

So, the general solution reduces to:

$$w(x) = B \cosh(\lambda_1 x) + F \cosh(\lambda_3 x) - \frac{(PSTR)R^2}{ET} \left(1 - \frac{\nu}{2} \alpha^2\right)$$

where:

λ_1, λ_3 are characteristic roots

The arbitrary constants B and F are solved using two boundary conditions which require that:

1. The shell span in between ring-stiffeners behaves like a beam fixed at both ends.
2. Radial continuity exists at the ring-stiffener and shell junction.

These boundary conditions are applied, and it is found that the arbitrary constants B and F are algebraically quite complex. However, both constants possess the same

denominator quantity.¹ This denominator quantity is found to be a function of shell material variables, shell geometry variables, and the characteristic roots. Since the variables of shell material and geometry are independent of the PC term, the axisymmetric collapse pressure (PC) must be extracted from the characteristic roots.

The PC term may be extracted from the solution $w(x)$ by requiring that, upon collapse, the radial displacement of the shell tend to infinity. That is, the common denominator (which is a function of the characteristic roots) of the arbitrary constants B and F is equal to zero when the external hydrostatic pressure (PSTR) exceeds the axisymmetric collapse pressure (PC). Thus:

The characteristic roots λ_1 and λ_3 correspond to:

$$\frac{PSTR}{PC} > 1.0$$

Then, it is found that the characteristic roots are pure imaginary numbers:

$$\lambda_1 = i \frac{\sqrt[4]{3(1-\nu^2)}}{\sqrt{RT}} \left[\sqrt{\frac{PSTR}{PC} - 1} + \sqrt{\frac{PSTR}{PC} + 1} \right]$$

$$\lambda_3 = i \frac{\sqrt[4]{3(1-\nu^2)}}{\sqrt{RT}} \left[\sqrt{\frac{PSTR}{PC} - 1} - \sqrt{\frac{PSTR}{PC} + 1} \right]$$

¹ For brevity, the algebraically complex expression of this common denominator is omitted. See [Ref. 2: p. A-11] for details.

When these characteristic roots are placed into the common denominator, which is then set equal to zero, a transcendental equation results. This equation is a function of PC and can be solved for the same.

The DAPS3 subroutine, in the THESIS code, calculates the PC term for each change in the shell geometry design variables (thickness, T, for monocoque shells; thickness, T, ring height, HEIGHT, and ring width, WIDTH, for ring-stiffened shells). Recall that the other terms (shell material and geometry properties and external hydrostatic pressure) used to extract the PC term are user-specified and remain constant throughout the process. The PC term is then returned to the ADS optimization program, incorporated in the THESIS code, to be evaluated as a buckling constraint term.

2. Elastic Interbay Instability Pressure (PIB)

Recall that the PIB term is associated with two different names:

- Elastic Monocoque Shell Instability Pressure (for the monocoque shell).
- Elastic Interbay Instability Pressure (for the ring-stiffened shell).

This buckling load describes local non-symmetric collapse of a ring-stiffened shell in between any two rings. Similarly, this describes non-symmetric collapse of a monocoque shell in between its two rigid bulkheads (end-rings). An example of interbay buckling is illustrated in Figure 3. Regardless of shell type, from hereon, the PIB term will be called Elastic Interbay Instability Pressure, which describes the more general case of a ring-stiffened shell.

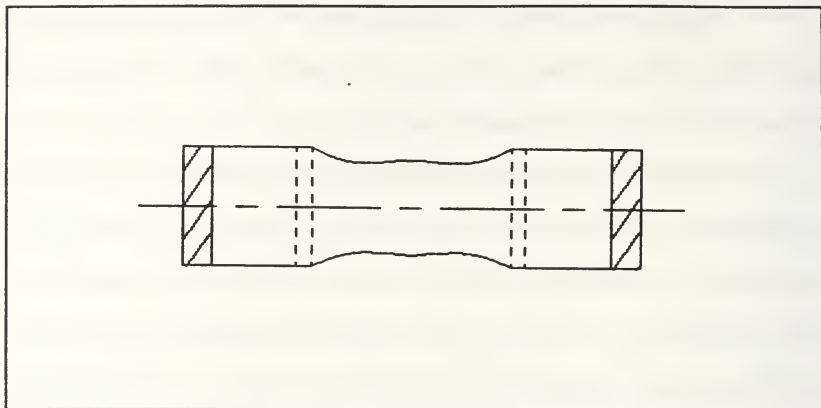


Figure 3. Local Non-symmetric Buckling of a Ring-Stiffened Shell Between Adjacent Rings.

Interbay buckling differs from the type of buckling described by the PC term in subsection (a) in that inward and outward lobes are formed alternately around the circumference. That is, the collapse is not axisymmetric. The number of circumferential waves formed by these lobes is known as the buckling mode, which is designated by the variable (n). This buckling mode term will be discussed in more detail during development of the equations necessary to find the elastic interbay instability pressure (PIB).

The first step in finding PIB is to establish the equilibrium equations for a thin shell differential element, as shown in Figure 4. The differential equilibrium equations -- in terms of forces (N), moments (M), and radial displacement (w) -- in the x , ϕ , and r directions are, respectively:

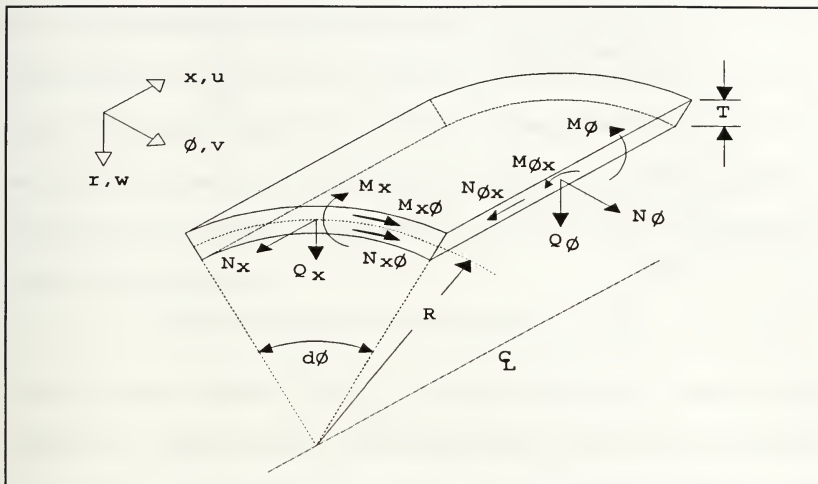


Figure 4. Differential Element of an Isotropic Thin Shell

$$R^2 \frac{\partial^2 N_x}{\partial x^2} + R \frac{\partial^2 N_{x\phi}}{\partial \phi \partial x} = 0$$

$$-R \frac{\partial^2 N_x}{\partial x^2} + \frac{\partial N_\phi}{\partial \phi^2} + \frac{\partial^2 M_{x\phi}}{\partial \phi \partial x} - \frac{\partial^2 M_\phi}{R \partial \phi^2} = 0$$

$$R \frac{\partial^2 M_x}{\partial x^2} - \frac{\partial^2 M_{x\phi}}{\partial x \partial \phi} - R^2 \frac{\partial^2 N_x}{\partial x^2} + \frac{\partial^2 N_\phi}{\partial \phi^2} + N_\phi = (PIB) \left(w + \frac{\partial^2 w}{\partial \phi^2} + \frac{R^2}{2} \frac{\partial^2 w}{\partial x^2} \right)$$

Next, a solution for the displacement terms -- u(axial), v(circumferential), and w(radial) -- is assumed:²

² In [Ref. 1, p.2-7], Renzi notes that this is the same displacement pattern used by Von Mises for isotropic shells. It is a well accepted solution which is somewhat conservative.

$$u = A \sin(n\phi) \sin \frac{\beta x}{R}$$

$$v = B \cos(n\phi) \cos \frac{\beta x}{R}$$

$$w = \sin(n\phi) \cos \frac{\beta x}{R}$$

where:

$$\beta = \frac{\pi R}{L_s} ; L_s = \text{Unsupported shell length between rings}$$

These assumed displacements account for the sinusoidal nature of the circumferential waves which form upon collapse. As noted earlier, the buckling mode (n) is the number of waves formed.

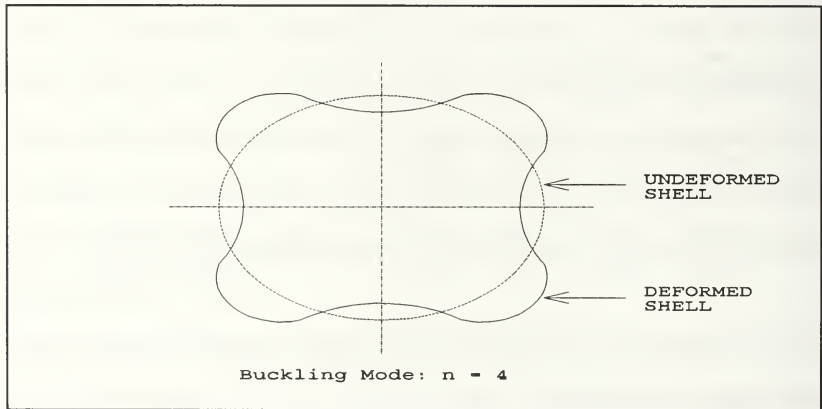


Figure 5. Buckling Mode (n) under Elastic Interbay Instability Pressure.

Next, strain and curvature expressions are generated in terms of the assumed displacements. Then, the forces (N) and moments (M) are expressed in

terms of the generated strain and curvature expressions. Subsequently, the force and moment expressions in the established differential equilibrium equations are now in terms of the assumed displacements. That is, the three equilibrium equations are now in terms of known shell material properties, known shell geometry properties, unknown arbitrary constants A and B, and the unknown term PIB. The following system of equations results:

$$\begin{bmatrix} a_1 & a_2 \\ a_4 & a_5 \\ a_7 & a_8 \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} a_3 \\ a_6 \\ a_9 + (PIB)a_{10} \end{bmatrix}$$

Note that the above a_i terms are expressions in terms of known shell geometry properties, known shell material properties, and buckling mode (n). To insure that the last equation in the above system is a consistent linear combination of the other two, the determinant of the following augmented matrix must equal zero:

$$\det \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 + (PIB)a_{10} \end{bmatrix} = 0$$

Thus, the elastic interbay instability pressure (PIB) is given by the following explicit expression:

$$PIB = \frac{1}{a_{10}} \left[\frac{a_7(a_3a_5 - a_2a_6) + a_8(a_1a_6 - a_3a_4)}{a_1a_5 - a_2a_4} - a_9 \right]$$

The only remaining unknown in the expression is the buckling mode (n). The DAPS3 subroutine in the THESIS code iterates the variable n over an integer range from 2 to 20. The minimum PIB calculated within this range is the elastic interbay instability pressure, and the corresponding n is the number of circumferential waves in which the shell will buckle. The value of PIB is returned to the ADS optimization program, which is incorporated into the THESIS code, for evaluation as a buckling constraint term.

3. Elastic General Instability Pressure (PGEN)

The third buckling load considered describes the overall or general instability of a ring-stiffened shell, whereas the previously described PC and PIB buckling loads described local instabilities (in between any two ring-stiffeners) for both monocoque and ring-stiffened shells. Collapse under elastic general instability pressure (PGEN) is somewhat similar to collapse under elastic interbay instability pressure (PIB) in that the shell does not collapse axisymmetrically. That is, the shell collapses in inward and outward lobes around the circumference as was seen in Figure 5. However, the buckling effect is not isolated between any two ring-stiffeners. Instead, the entire length of the shell (between its rigid bulkheads) collapses with a discernible buckling mode (n), as seen in Figure 6.

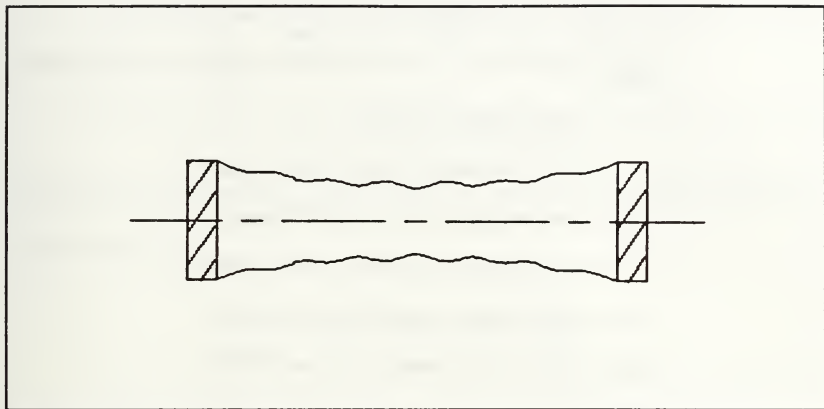


Figure 6. General Non-symmetric Buckling of a Ring-Stiffened Shell

In deriving the previous local buckling loads, PC and PIB, differential equations were used to find a closed form exact solution. However, use of a differential equation method in deriving PGEN would be quite difficult without making simplistic, perhaps unrealistic, assumptions. So, an alternative method is needed to obtain an expression for PGEN.

The approach used is the Ritz energy method. Consider a system consisting of a ring-stiffened shell under external hydrostatic pressure (PSTR). Pre-buckling displacements and post-buckling (collapse) displacements (in the shell and in the rings) contribute strain energy to the system. In addition, work is done by the applied load (PSTR) to cause these displacements. Thus, the system possesses some total potential energy, which is the sum of these strain potential energies and the work done by external pressure:

$$U_t = U_{s,e} + U_{s,b} + U_{r,e} + U_{r,b} + W_{PSTR}$$

where:

$$U_t = \text{Total Potential Energy}$$

$$U_{s,e} = \text{Shell Extensional Strain Potential Energy}$$

$$U_{s,b} = \text{Shell Bending Strain Potential Energy}$$

$$U_{r,e} = \text{Ring Extensional Strain Potential Energy}$$

$$U_{r,b} = \text{Ring Bending Strain Potential Energy}$$

$$W_{PSTR} = \text{Work of the External Pressure(PSTR)}$$

Under the Ritz energy method, this total potential energy must be a minimum. This requirement ultimately leads to a solution for the elastic general instability pressure (PGEN), which is the critical PSTR at which the ring-stiffened shell buckles.

After a long series of derivations, it can be shown that the potential energy, U_t , is a function of: known shell/ring material and geometry properties; the unknown elastic general instability pressure (PGEN); and the variable displacements u, v , and w . The displacements due to buckling are assumed to be of the form:

$$u = A_1 \cos(n\phi) \cos\left(\frac{\pi x}{L}\right)$$

$$v = B_1 \sin(n\phi) \sin\left(\frac{\pi x}{L}\right) + B_2 \sin(n\phi) \left[1 - \cos\left(\frac{2\pi x}{L_f}\right)\right]$$

$$w = C_1 \cos(n\phi) \sin\left(\frac{\pi x}{L}\right) + C_2 \cos(n\phi) \left[1 - \cos\left(\frac{2\pi x}{L_f}\right)\right]$$

By substituting the above displacements into the U_t expression, the total potential energy becomes a function of the five arbitrary constants:

$$U_t = U_t(A_1, B_1, C_1, B_2, C_2)$$

Recall that the total potential energy must be a minimum to satisfy equilibrium requirements, thus:

$$\frac{\partial U_t}{\partial A_1} = \frac{\partial U_t}{\partial B_1} = \frac{\partial U_t}{\partial C_1} = \frac{\partial U_t}{\partial B_2} = \frac{\partial U_t}{\partial C_2} = 0$$

The result is five symmetrical linear homogeneous equations in the unknown arbitrary constants. These equations can be expressed in form $[A_{ij}]\{x_i\} = 0$, or:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ C_1 \\ B_2 \\ C_2 \end{bmatrix} = 0$$

The terms in the above 5 X 5 coefficient matrix are given by:

$$A_{ij} = a_{ij} - (PGEN)b_{ij} \quad ; \quad i,j = 1,5$$

where:

$$a_{ij}, b_{ij} = \text{expressions in terms of known material and geometry properties and the buckling mode variable}(n)$$

Provided that the 5 X 5 coefficient matrix is symmetric and positive definite, it has five positive eigenvalues, $(PGEN)_p$, and five corresponding eigenvectors, $\{x\}_i$. The minimum eigenvalue is the external pressure (PGEN) at which the ring-stiffened shell will buckle.

However, the buckling mode (n) still remains a variable quantity to consider when establishing the minimum eigenvalue. The DAPS3 subroutine iterates (n) in the integer range from 2 to 12, and it saves the minimum eigenvalue (of the five possible eigenvalues) for each corresponding mode. The array of these eigenvalues is examined, and the absolute minimum is chosen as the elastic general instability pressure (PGEN). This is the value which is returned to the ADS optimization program to be considered as a buckling constraint term for a ring-stiffened shell.

B. STRENGTH (STRESS) EQUATIONS

Another type of failure to consider is that of strength limitation. By this, it is meant that the shell fails when resultant Von Mises stresses, at specific locations, exceed the yield strength of the shell/ring material. Since material properties (such as elastic modulus, Poisson's ratio, yield strength, etc.) are input by the THESIS code user and remain fixed, some constraints must be placed on the optimum design to

account for material limitations. These limitations are the strength (or stress) constraints.³

Since these strength constraints compare specific stresses to the material yield strength, it is important to select appropriate locations at which stresses are to be analyzed. There are four shell locations chosen as representative points most likely to fail by yield:

1. The middle fiber of the shell at mid-bay (half way between any two ring-stiffeners or the two rigid bulkheads of a monocoque shell). This stress is designated by the variable STR.
2. The outer fiber of the shell at the shell and ring junction. This stress is designated by the variable SIGVOF.
3. The inner fiber of the shell at the shell and ring junction. This stress is designated by the variable SIGVIF.
4. The center fiber of a rectangular cross-section ring. This stress is designated by the variable SRF.

The above locations, shown in a cross-section view of a ring-stiffened circular cylindrical shell, are illustrated in Figure 7.

The following subsections will briefly explain the development of the equations necessary to calculate the above Von Mises stresses. The effects of stress concentration are not considered in the calculation of these stresses. Note that both material yield strength and calculated stresses are in units of (lb/in²).

³ Although the terms "strength constraint" and "stress constraint" are interchangeable, the single term "strength constraint" will be used throughout this discussion for the sake of consistency.

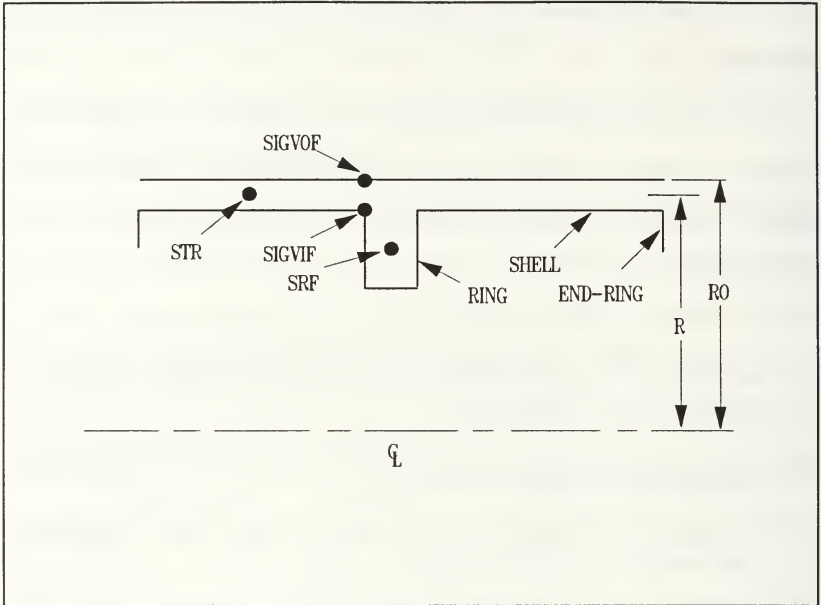


Figure 7. Locations of Stress Values STR, SIGVOF, SIGVIF, and SRF Shown in a Shell Cross-section View.

1. Middle Fiber Shell Stress at Mid-bay (STR)

The effects of the radial stress component are ignored in the calculation of this Von Mises stress. In fact, the radial component is ignored in the calculation of the Von Mises stress at all four locations since the shell is assumed to be thin. (A side constraint is included in the THESIS code to insure that the thickness, T , is less than or equal to 20 percent of the mean radius, R . This insures that the optimum design has negligible radial stress components.)

Calculation of the middle fiber stress value, STR, begins with a definition of the Von Mises stress at the inner and outer fibers (at mid-bay). The Von Mises stress of these fibers is:

$$\sigma_{VM,m}^o = \sqrt{(\sigma_{\phi,m}^o)^2 - (\sigma_{\phi,m}^o)(\sigma_{X,m}^o) + (\sigma_{X,m}^o)^2}$$

where:

$\sigma_{VM,m}$ = Von Mises stress at mid-bay

$\sigma_{X,m}$ = Axial stress at mid-bay

$\sigma_{\phi,m}$ = Circumferential stress at mid-bay

The subscript "i" and the superscript "o" correspond, respectively, to inner and outer fiber locations.

Next, the mid-bay Von Mises stresses at inner and outer fiber locations are each divided by the material yield strength to obtain two percentage values. The middle fiber stress value, STR, is an average of these two percentages:

$$STR = \frac{1}{2} \left[\frac{\sigma_{VM,m}^i}{\sigma_y} + \frac{\sigma_{VM,m}^o}{\sigma_y} \right]$$

where:

σ_y = Material yield strength

The superscripts "i" and "o" correspond, respectively, to inner and outer fiber locations.

The stress value STR is calculated by the DAPS3 subroutine in a much more complex scheme than described above; the process of calculating the hoop and

axial stresses is quite involved.⁴ The STR value is returned to the ADS optimization program to be considered as the first of four strength constraints on the optimum design.

2. Outer Fiber Shell Stress at a Ring Junction (SIGVOF)

This Von Mises stress is calculated by a method similar to that of the STR value calculation. The only difference being that outer fiber shell stress components (at the shell/ring junction) are used, instead of the outer and inner fiber shell stress components (at mid-bay). The Von Mises outer fiber shell stress at the junction is:

$$\sigma_{VMj}^o = \sqrt{(\sigma_{\phi_j}^o)^2 - (\sigma_{\phi_j}^o)(\sigma_{x_j}^o) + (\sigma_{x_j}^o)^2}$$

where:

σ_{VMj} = Von Mises stress at shell/ring junction

σ_{x_j} = Axial stress at shell/ring junction

σ_{ϕ_j} = Circumferential stress at shell/ring junction

The "o" superscript indicates an outer fiber location.

The strength constraint requires that this Von Mises stress be compared to the material yield strength. Thus, the value of SIGVOF is:

⁴ See Chapter 1 of [Ref. 1] for details.

$$SIGVOF = \frac{\sigma_{VMj}^o}{\sigma_y}$$

This is the value returned to the optimization program for consideration as the second of four strength constraints.

3. Inner Fiber Shell Stress at a Ring Junction (SIGVIF)

The development of this value is identical to that of the SIGVOF value except that inner fiber shell stress components are used. The Von Mises inner fiber shell stress is defined as:

$$\sigma_{VMj}^i = \sqrt{(\sigma_{\phi j}^i)^2 - (\sigma_{\phi j}^i)(\sigma_{xj}^i) + (\sigma_{xj}^i)^2}$$

where:

σ_{VMj} = Von Mises stress at shell/ring junction

σ_{xj} = Axial stress at shell/ring junction

$\sigma_{\phi j}$ = Circumferential stress at shell/ring junction

Then, this Von Mises stress is compared to the material yield strength:

$$SIGVIF = \frac{\sigma_{VMj}^i}{\sigma_y}$$

This is the value returned to the optimization program for consideration as the third of four strength constraints.

4. Center Fiber Ring Stress (SRF)

The last of the four strength constraints is the Von Mises stress at the centroid of a ring-stiffener. Note that this is not a shell stress, but rather a stress inside the internally located rectangular cross-section ring. Since the ring-stiffener does not bear an axial load, the Von Mises stress inside the ring reduces to the circumferential stress, which is defined as:

$$\sigma_{VM,r}^c = \sigma_{\phi,r}^c = \frac{Q^*R}{A_{eff} + (WIDTH)(T)} \left(\frac{R}{RR} \right)$$

where:

Q^* = Total load on ring per unit circumference length

$$A_{eff} = (HEIGHT)(WIDTH) \left(\frac{R}{RR} \right)^2$$

RR = Radius from shell centerline to ring centroid

$HEIGHT$ = Height of rectangular ring-stiffener

$WIDTH$ = Width of rectangular ring-stiffener

The "c" superscript indicates a center fiber location, which is the centroid of the ring. Perhaps, the above shell geometry terms are best illustrated by Figure 8.

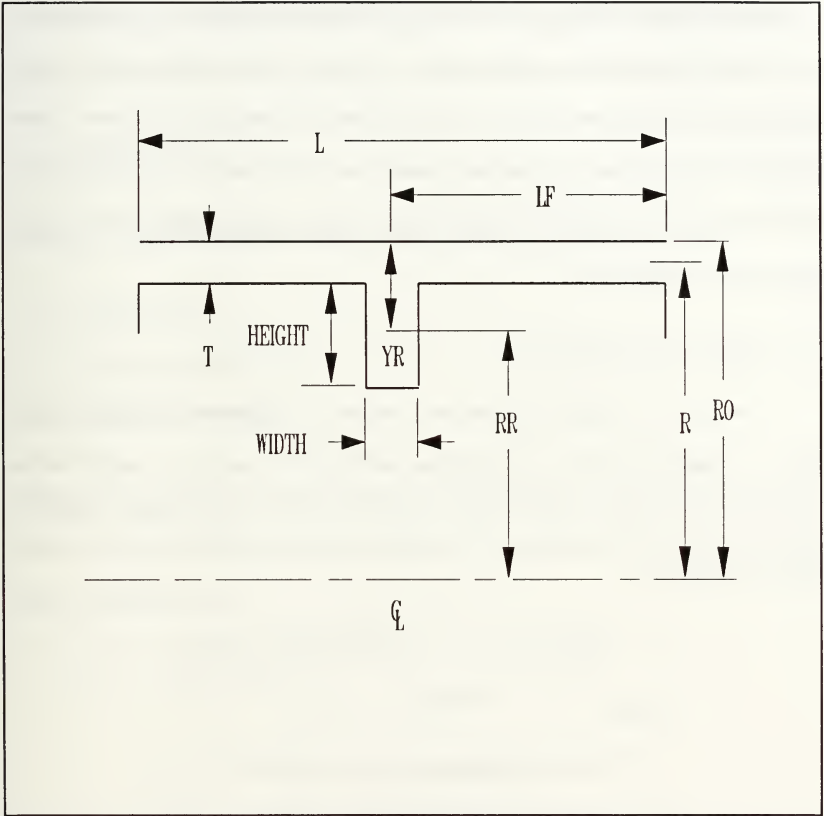


Figure 8. Illustration of Various Shell Geometry Terms.

III. OPTIMIZATION PROBLEM

Now that the buckling and strength terms have been defined, a mathematical model of the optimization problem can be defined. The model consists of an objective function (F), constraint functions (g_j), and side constraint functions. These functions will be defined in subsequent subsections of this chapter. A description of the Sequential Linear Programming (SLP) technique used to optimize the model follows those subsections.

A. OBJECTIVE FUNCTION

Recall that the objective of the optimization is to design a minimum weight circular cylindrical shell. The objective function (F), then, is a mathematical expression of the shell weight. For the general case of a ring-stiffened shell, the objective function is:

$$F = \frac{24\pi}{L} \left[(R)(T)(L)(\rho) + (RO-YR)(AR) \left(\frac{L}{LF} - 1 \right) (\rho_f) \right]$$

where:

ρ = Specific weight [lb_f/ft³] of the shell(skin)

ρ_f = Specific weight [lb_f/ft³] of the ring(s)

Figure 8 best illustrates the above variable terms. The first quantity represents the shell(skin) weight, while the second quantity represents the ring(s) weight. Note that

the weight is expressed on a (lb/ft) basis. The above expression is also valid for the more specific case of a monocoque shell. In that case, the AR (ring cross-section area) term would just be zero.

The objective function contains all the design variables of the optimization problem. Recall that the single design variable for the monocoque shell is:

1. Thickness (T)

In contrast, the ring-stiffened shell has three design variables, which are:

1. Thickness (T)
2. Ring height (HEIGHT)
3. Ring width (WIDTH)

The design variable T is explicitly expressed in the objective function. The objective function (F) also contains indirect expressions which incorporate the design variables.

These expressions are:

$$R = RO - \frac{T}{2}$$

$$YR = T + \frac{HEIGHT}{2}$$

$$AR = (HEIGHT)(WIDTH)$$

Now that the objective has been defined in terms of the design variable(s), the first step in defining the optimization model is complete. Next, constraints on the design variables will be defined.

B. CONSTRAINT FUNCTIONS

The constraints on the design variables are divided into three groups: 1) buckling, 2) strength, 3) geometry. As noted in Chapter II, the number and type of constraints placed on the design variables depends upon the particular shell being designed: monocoque or ring-stiffened. The next two subsections define the specific constraints placed on monocoque and ring-stiffened shell designs.

1. Monocoque Shell Constraints

The monocoque shell is subject to two buckling loads (PC,PIB); four stress loads (STR,SIGVOF,SIGVIF,SRF); and no geometry constraints.⁵ Accordingly, the six constraints on the monocoque shell design are:

$$g_1 = 1 - (PC/PSTR) \leq 0$$

$$g_2 = 1 - (PIB/PSTR) \leq 0$$

$$g_3 = (STR/100) - 1 \leq 0$$

$$g_4 = (SIGVOF/100) \leq 0$$

$$g_5 = (SIGVIF/100) - 1 \leq 0$$

$$g_6 = (SRF/100) - 1 \leq 0$$

In the above expressions, $g_j(j=1,2)$ represent the buckling constraints and $g_j(j=3,4,5,6)$ represent the strength constraints on the monocoque shell design.

⁵ Actually, the monocoque shell is subject to a type of geometry constraint which limits the range of the design variable, thickness (T), between an upper and lower bound. However, it will be seen that this is actually a side constraint on the design variable.

2. Ring-stiffened Shell Constraints

The ring-stiffened shell is subject to three buckling loads (PC, PIB, PGEN), four stress loads (STR, SIGVOF, SIGVIF, SRF), and one geometry constraint which limits the ring aspect ratio (HEIGHT/WIDTH) to be less than 4:1.⁶

This geometry constraint is necessary to ensure that the resultant ring design is not "flimsy", that is, unstable. The predominate mode of instability for rectangular ring-stiffeners is the tendency to rotate about the ring-stiffener base [Ref. 3: pp. 23-24]. This rotation causes the ring-stiffener to deform in a sinusoidal pattern which crosses in and out of the ring's vertical plane of symmetry. Since DAPS3 does not check for this instability when designing a ring-stiffened shell, this particular constraint keeps the ring aspect ratio low enough that the ring instability mode is adequately addressed (by the THESIS produced shell design).⁷ Inclusion of this constraint may result in a weight penalty since a "flimsy" ring may weigh less than a short and thick, but inherently stable, ring.

The resulting eight constraints on the ring-stiffened shell design are given by the following g_j expressions:

⁶ As explained in the previous footnote, side constraints on the design variables (T, HEIGHT, WIDTH) also apply for the ring-stiffened shell.

⁷ DAPS3 does attempt to prevent a "flimsy" ring. If intermediate designs have an aspect ratio greater than 4:1 and a ring width less than 0.125 inch, a minimum ring width of 0.125 inch is then forced. However, this does not necessarily prevent the aspect ratio from increasing to an unreasonable number ($\gg 4:1$).

$$\begin{aligned}
g_1 &= 1 - (PC/PSTR) \leq 0 \\
g_2 &= 1 - (PIB/PSTR) \leq 0 \\
g_3 &= 1 - (PGEN/PSTR) \leq 0 \\
g_4 &= (STR/100) - 1 \leq 0 \\
g_5 &= (SIGVOF/100) \leq 0 \\
g_6 &= (SIGVIF/100) - 1 \leq 0 \\
g_7 &= (SRF/100) - 1 \leq 0 \\
g_8 &= [(HEIGHT]WIDTH)/4] - 1 \leq 0
\end{aligned}$$

In the above expressions, $g_j(j=1,2,3)$ represent the buckling constraints, $g_j(j=4,5,6,7)$ represent the strength constraints, and $g_j(j=8)$ represents the geometry constraint.

C. SIDE CONSTRAINTS

Side constraints directly impose bounds on the design variables. The ADS optimization program incorporated into the THESIS code requires that the user specify lower and upper bounds on all declared design variables. The optimization search will then only occur in that portion of the design space delineated by the side constraints.

The monocoque shell has only one design variable, T , and it is directly constrained by the following bounds:

$$0.10 \text{ IN} \leq T \leq 1.818 \text{ IN}$$

The lower bound was chosen as an arbitrarily low number to permit a broad design space, knowing that the lower bound would not be approached at the higher external hydrostatic pressure shell loads. The upper bound was chosen such that the shell thickness (T) would not exceed the ratio:

$$\frac{T}{R} \leq 0.20$$

where:

$$\begin{aligned} R &= \frac{1}{2} (\text{Shell Outside Diameter}) - \frac{T}{2} \\ &= RO - \frac{T}{2} \end{aligned}$$

Since the shell outside diameter is fixed input (OD = 20 IN), the outside radius remained fixed (RO = 10 in). Thus, the value of T = 1.818 IN was calculated such that the shell thickness never exceeded 20% of the mean radius. Recalling that the objective is to design a thin circular cylindrical shell, a T/R value less than 20% assures that the shell remains "thin". That is, radial stress is much smaller than axial or circumferential stresses and can be ignored.

The design variables of a ring-stiffened shell are assigned the following side constraints:

$$0.10 \text{ IN} \leq T \leq 1.818 \text{ IN}$$

$$0.05 \text{ IN} \leq \text{HEIGHT} \leq 10.0 \text{ IN}$$

$$0.05 \text{ IN} \leq \text{WIDTH} \leq 5.0 \text{ IN}$$

Again, the lower bounds are chosen to be arbitrarily low. The upper bounds are chosen such that: HEIGHT does not exceed the physical dimension of the shell outside diameter, and WIDTH does not become so wide that the resulting HEIGHT is negligible (in other words, the ring would be virtually flat, and a monocoque shell would probably be more appropriate).

D. SUMMARY

The mathematical models of the monocoque and the ring-stiffened shell are summarized below. These are the models programmed into the THESIS code to solve the optimization problem.

1. Monocoque Shell

Minimize:

$$F = \frac{24\pi}{L} \left[(R)(T)(L)(\rho) + (RO-YR)(AR) \left(\frac{L}{LF} - 1 \right) (\rho_f) \right]$$

Subject to:

$$\begin{aligned} g_1 &= 1 - (PC/PSTR) \leq 0 \\ g_2 &= 1 - (PIB/PSTR) \leq 0 \\ g_3 &= (STR/100) - 1 \leq 0 \\ g_4 &= (SIGVOF/100) \leq 0 \\ g_5 &= (SIGVIF/100) - 1 \leq 0 \\ g_6 &= (SRF/100) - 1 \leq 0 \end{aligned}$$

Side constraints:

$$0.10 \text{ IN} \leq T \leq 1.818 \text{ IN}$$

2. Ring-Stiffened Shell

Minimize:

$$F = \frac{24\pi}{L} \left[(R)(T)(L)(\rho) + (RO-YR)(AR) \left(\frac{L}{LF} - 1 \right) (\rho_f) \right]$$

Subject to:

$$\begin{aligned} g_1 &= 1 - (PC/PSTR) \leq 0 \\ g_2 &= 1 - (PIB/PSTR) \leq 0 \\ g_3 &= 1 - (PGEN/PSTR) \leq 0 \\ g_4 &= (STR/100) - 1 \leq 0 \\ g_5 &= (SIGVOF/100) \leq 0 \\ g_6 &= (SIGVIF/100) - 1 \leq 0 \\ g_7 &= (SRF/100) - 1 \leq 0 \\ g_8 &= [(HEIGHT]WIDTH)/4] - 1 \leq 0 \end{aligned}$$

Side constraints:

$$\begin{aligned} 0.10 \text{ IN} &\leq T \leq 1.818 \text{ IN} \\ 0.05 \text{ IN} &\leq HEIGHT \leq 10.0 \text{ IN} \\ 0.05 \text{ IN} &\leq WIDTH \leq 5.0 \text{ IN} \end{aligned}$$

E. OPTIMIZATION TECHNIQUE

The mathematical models are now structured for application of an optimization technique. The general purpose numerical optimization program, Automated Design

Synthesis (ADS), is used in conjunction with the analysis mode of the DAPS3 to produce optimum shell designs. An excellent reference on numerical optimization techniques is found in [Ref. 4].

The procedure to obtain the optimum shell design involves a mathematical search from an initial design, X^0 , to the optimum design, X^* . A gradient method is used to search for X^* within the design space specified by the side constraints. Search limitations within this design space are imposed by the constraint functions. The objective function, F , when evaluated at the optimum design, X^* , is the minimized objective: shell weight.

The above optimization procedure is described in more detail by the following general steps [Ref. 5: p. 15]:

1. User inputs an initial design, X^0 , for the q^{th} iteration; $q = 0$.
2. Iteration number, q , is updated to $q = q + 1$.
3. Objective function, $F(X)$, and the constraint functions, $g_j(X)$, are evaluated at the design X^{q-1} .
4. Active constraints, J , are identified. These are the g_j constraints which are very close to zero, within a specified tolerance, say ≈ 0.003 .
5. The objective function gradient, $\nabla F(X^{q-1})$ is evaluated, and critical constraint function gradients, $\nabla g_j(X^{q-1})$ are evaluated for $j \in J$.
6. Search direction, S^q , is determined from the evaluations in step 5.
7. A one-dimensional search is performed to find the step length α^* .
8. The design, X^{q-1} , is updated by: $X^q = X^{q-1} + \alpha^* S^q$.

9. Convergence criteria are examined. If design has converged, then X^* has been found. Otherwise, the procedure is reiterated from step 2.

Execution of the above general procedure may be accomplished by a variety of methods, especially at steps 3, 6, and 7. Step 3 is termed the "strategy" (ISTRAT); step 6 is termed the "optimizer"(IOPT); and step 7 is termed the "one-dimensional search"(IONED). These are the three basic levels at which the ADS numerical optimization program can be controlled to produce an optimum design.

ADS offers a great number of combinations of these basic levels. In fact, version 1.10 offers nine strategies, five optimizers, and eight one-dimensional search methods [Ref. 6]. Selecting an appropriate combination of ISTRAT, IOPT, and IONED is a matter of experience, since not all possible combinations are suitable to particular kinds of optimization problems.

The specific combination chosen for this study is:

- ISTRAT = 6: Sequential Linear Programming
- IOPT = 5: Modified Method of Feasible Directions
- IONED = 6: Golden Section + Polynomial 1-D Search

The Sequential Linear Programming (SLP) method is an optimization strategy that approximates a nonlinear problem as a linear problem. This is done by creating a first order Taylor Series approximation of the objective and constraint functions. Now that the problem is linear, an evaluation of the objective and constraint functions are easily and inexpensively calculated, in terms of computer time. Then,

the Modified Method of Feasible Directions is used to determine a search direction S^q . This is also easily obtained since the gradients of the objective and constraint functions are directly available from the Taylor Series expression. Next, the Golden Section + Polynomial one-dimensional search method is used to find the step length, α^* . This step length is how far the search direction vector, S^q , will traverse from design point X^{q-1} . An optimum design, X^q , to this linear approximation is then obtained. The original nonlinear problem is again linearized about this design. The process is repeated until an optimum solution is obtained, as determined by specific convergence criteria.

This combination using the SLP method is a very fast optimization technique since the original nonlinear problem is approximated as a linear problem. Speed represents the major advantage in using this method. Possible disadvantages include: 1) the optimum design may be infeasible and 2) the method may perform poorly for an underconstrained problem [Ref. 4: pp. 156-157]. The first disadvantage means that X^* , though very close to the true optimum, may have a small degree of constraint violation. The second disadvantage means that if there are fewer active constraints at the optimum than there are design variables, the method may not rapidly or accurately converge to the true optimum. ADS deals with this difficulty by imposing finite move limits on the linear approximation so that the true optimum will be approached within the tolerance of the move limits. These possible disadvantages are not considered severe enough to preclude use of the SLP method for this optimization problem. In fact, all methods within the ADS program have

certain advantages and disadvantages which must be accepted when that method is applied to a particular optimization problem.

The optimization combination chosen for this study was compared against other direct and indirect methods.⁸ It was found that the array of optimum designs produced by the SLP method were almost identical to the other strategies. The speed advantage offered by the SLP method was the principal reason that this particular optimization combination was chosen. The next chapter presents the results of applying SLP to the mathematical models defined in this chapter.

⁸ An "indirect" method involves converting a constrained problem into an unconstrained problem; the constraints are accounted for by a penalty function method, and the objective function is converted into a pseudo-objective function which includes the penalty function. By contrast, a "direct" method involves dealing with the objective and constraint functions individually during the optimization process.[Ref. 4: pp.54-58]

IV. RESULTS

A. MONOCOQUE SHELL

The elements of an optimum design are derived from the optimization model.

Accordingly, the results are presented in three parts:

1. Objective: DAPS3 vs. THESIS
2. Design Variables: DAPS3 vs. THESIS
3. Constraints: DAPS3 vs. THESIS

The first part will compare the optimum shell weights achieved by each program (DAPS3 and THESIS). The second part then compares the optimum shell thickness' (T) which correspond to these optimum shell weights. The last part will compare constraint activity (buckling and strength violations) of the two optimum designs.

1. Objective: DAPS3 vs. THESIS

A graphical comparison of the optimum weights achieved by DAPS3 and THESIS is shown in Figures 9 and 10. The graphs are set up such that the optimum monocoque shell weights are shown over a range of external hydrostatic pressure (PSTR) loads and over a range of shell geometries (L/OD ratios, which were varied from 9:1 to 1:1). It can be seen that the weight curves (of each L/OD ratio) is essentially the same for both programs. The one noticeable difference is seen in the 1:1 (L/OD ratio) weight curves. The THESIS objective (weight) is somewhat higher

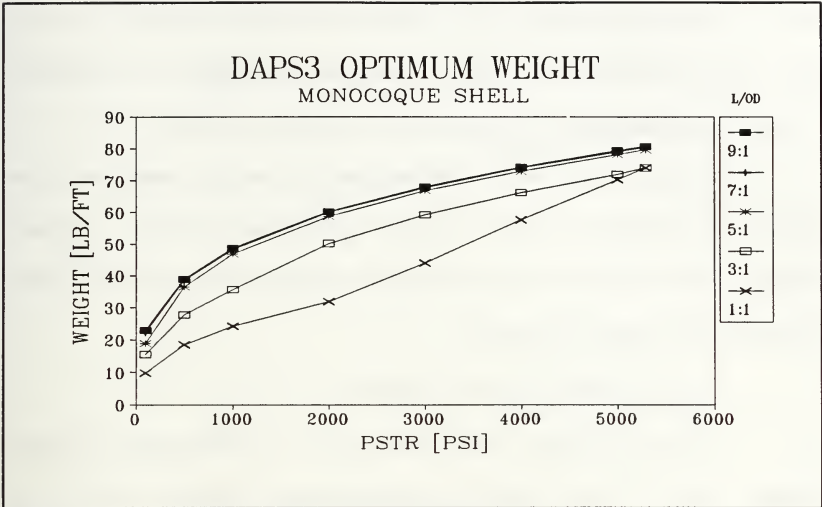


Figure 9. DAPS3 Optimum Shell Weight

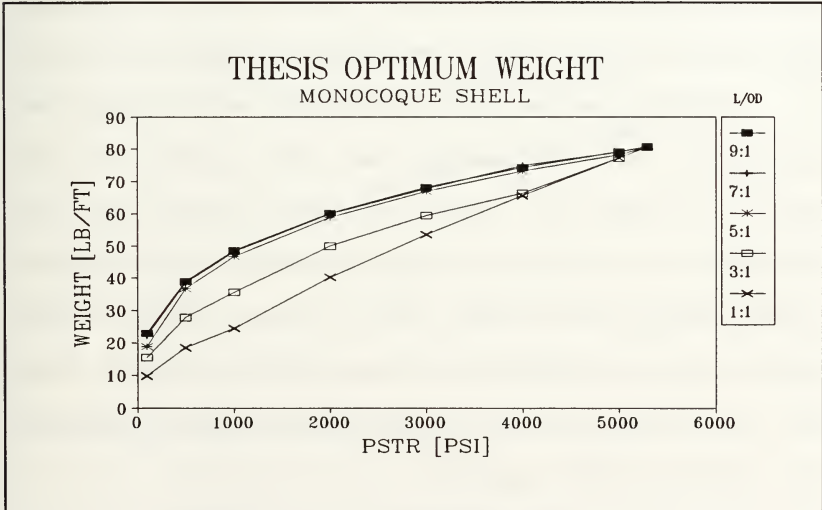


Figure 10. THESIS Optimum Shell Weight

than the DAPS3 objective after $PSTR = 1000$ psi. This will be accounted for in part three of these results. It will be seen that the increase in weight was necessary due to an increase in thickness to compensate for a constraint violation.

At this point, the results of an optimum shell weight comparison do not indicate the advantage of using a numerical optimization technique. The next optimum design element to be examined is the single design variable of the monocoque shell: shell thickness (T).

2. Design Variables: DAPS3 vs. THESIS

The design variable, shell thickness (T), is a monotonically increasing variable. That is, as the external hydrostatic pressure (PSTR) increases, the thickness also increases. This results in the shell weight being directly proportional to the shell thickness, as would be expected. Accordingly, the optimum thickness curves look like the optimum weight curves. This can be seen in Figures 11 and 12.

Since the monocoque shell only has one design variable, the design space is quite simple. There is only one design variable which corresponds to the global optimum in this design space. Even the simple iterative technique employed by DAPS3 will converge quite close to the unique design variable which corresponds to the global optimum (minimum weight). Thus, the advantage of using a numerical optimization technique to find the optimum design variable is not realized. The last part of these results will indicate the advantage of using numerical optimization in even a simple one variable design space.

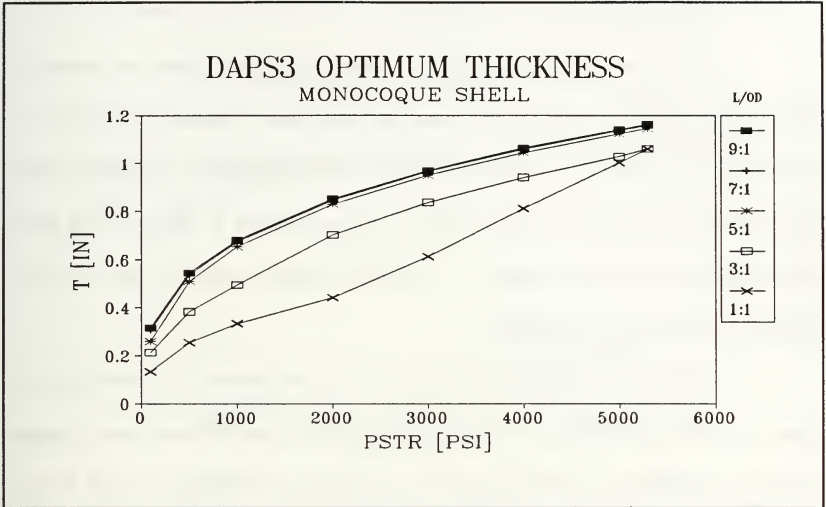


Figure 11. DAPS3 Optimum Shell Thickness (T)

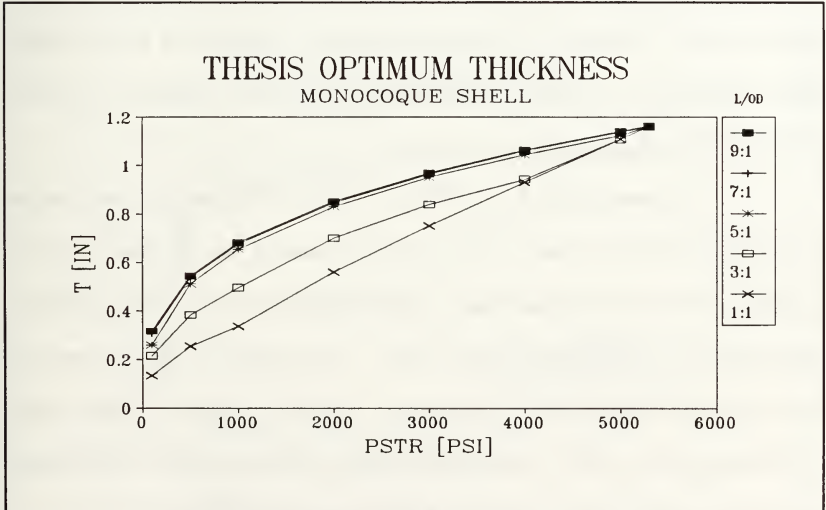


Figure 12. THESIS Optimum Shell Thickness (T)

3. Constraints: DAPS3 vs. THESIS

The six constraints imposed on a monocoque shell design are shown in Figures 13 through 18. The graphs are set up such that a violated constraint is a positive g_j ($j = 1,6$) value; a satisfied constraint is represented by a negative value; and an active constraint is a zero value. If the constraint is violated, this is an indication of an infeasible design. A feasible design is indicated by an active constraint or a satisfied constraint.

The purpose of showing graphs of each constraint is to identify, at a glance, any violations which the "optimum" design may have. The optimum designs produced by DAPS3 and THESIS may be a minimum weight shell design for the input load (PSTR) and geometry (L/OD). However, the code user must be able to verify that the produced optimum, in fact, satisfies the original constraints imposed upon the design. If there are violations, the design produced is not a valid design. That is, the design is infeasible: the objective may have been minimized, but at the expense of violated constraints.

In comparing DAPS3 and THESIS objective values, one program's design may weigh less than the other (when load and geometry are the same for each program). Before accepting the lesser weight design as the true optimum, constraint activity must be verified as outlined above. An example of this was seen in monocoque shell designs of 1:1 L/OD ratios. DAPS3 appears to produce lesser weight designs above PSTR = 1000 psi than THESIS, however, these DAPS3 designs violate the strength (stress) constraints g_3 (STR) and g_5 (SIGVIF).

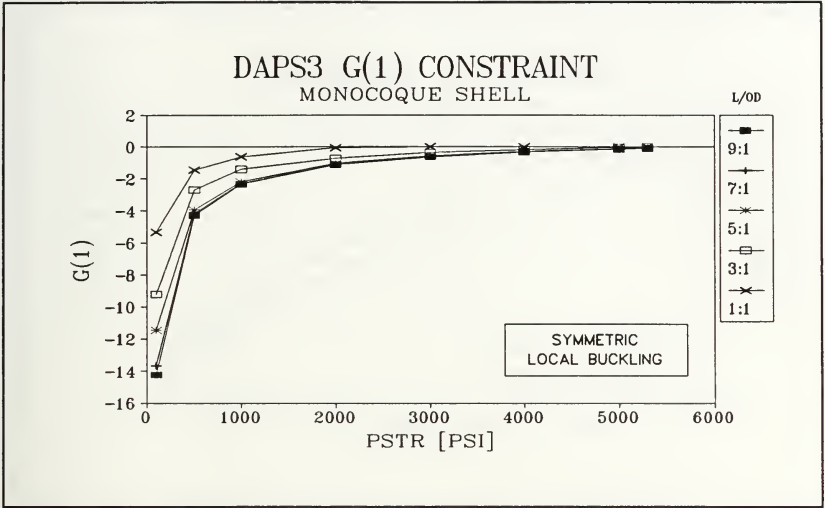


Figure 13. DAPS3 Constraint: Symmetric Local Buckling (PC)

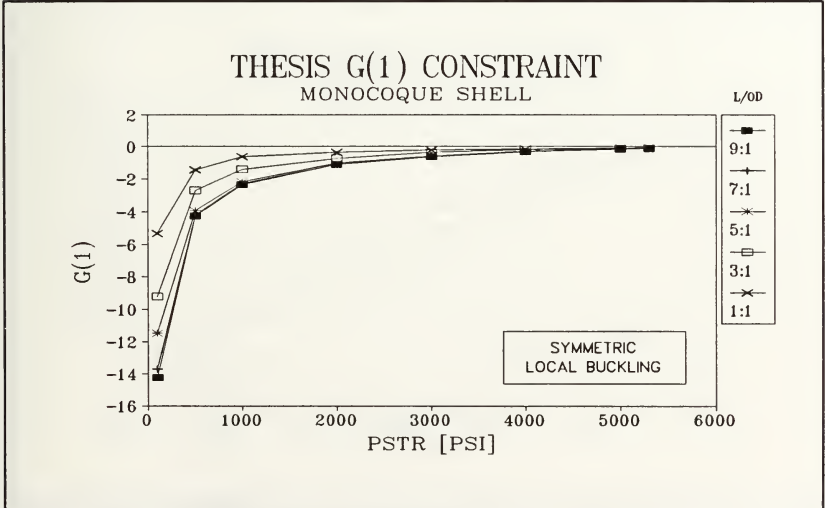


Figure 14. THEISIS Constraint: Symmetric Local Buckling (PC)

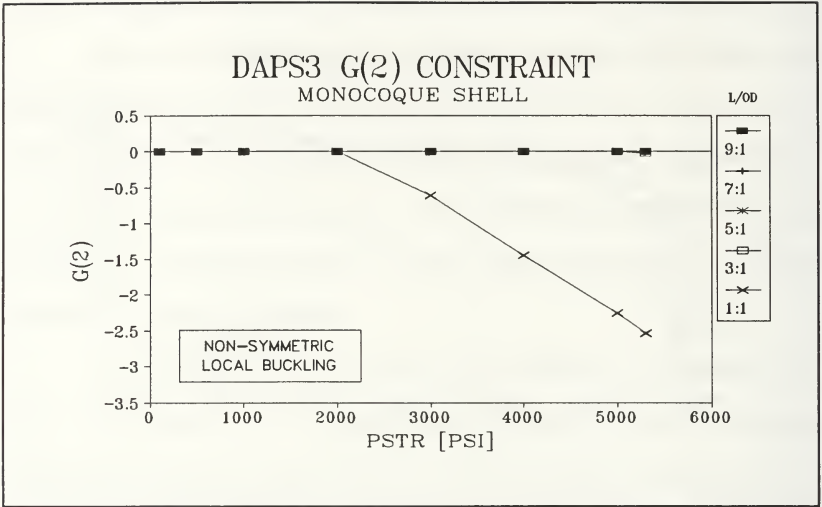


Figure 15. DAPS3 Constraint: Non-Symmetric Local Buckling (PIB)

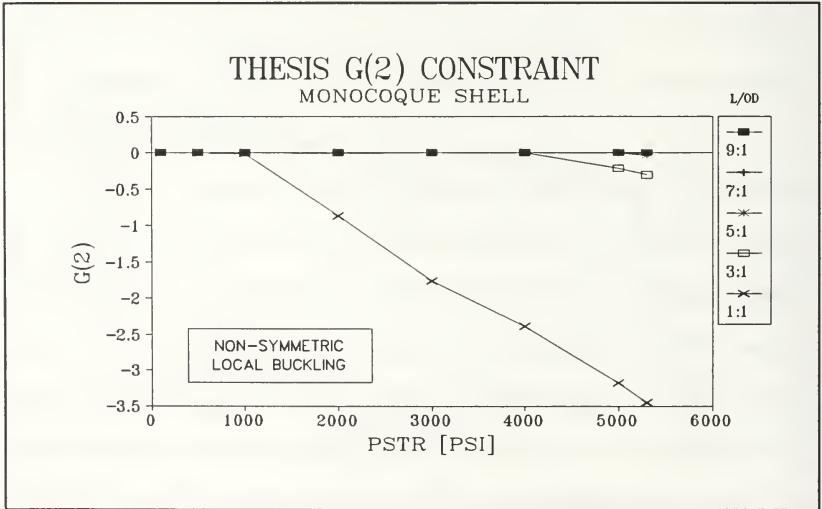


Figure 16. THESIS Constraint: Non-Symmetric Local Buckling (PIB)

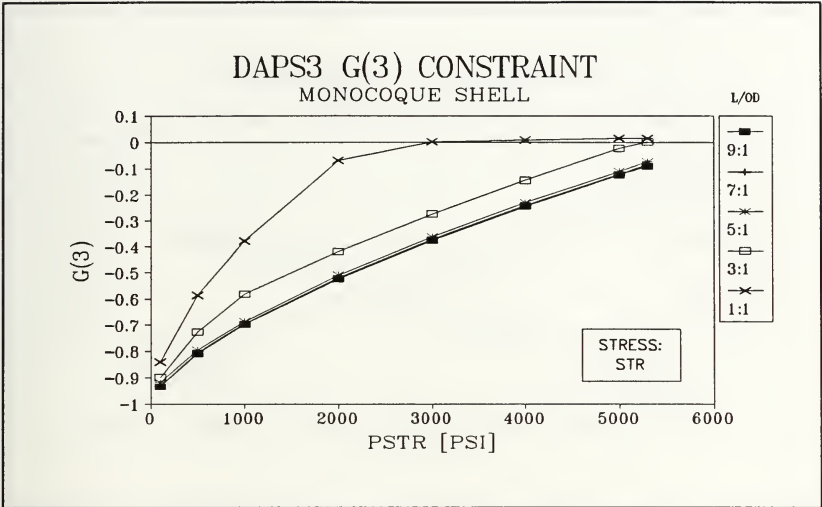


Figure 17. DAPS3 Constraint: Stress (STR)

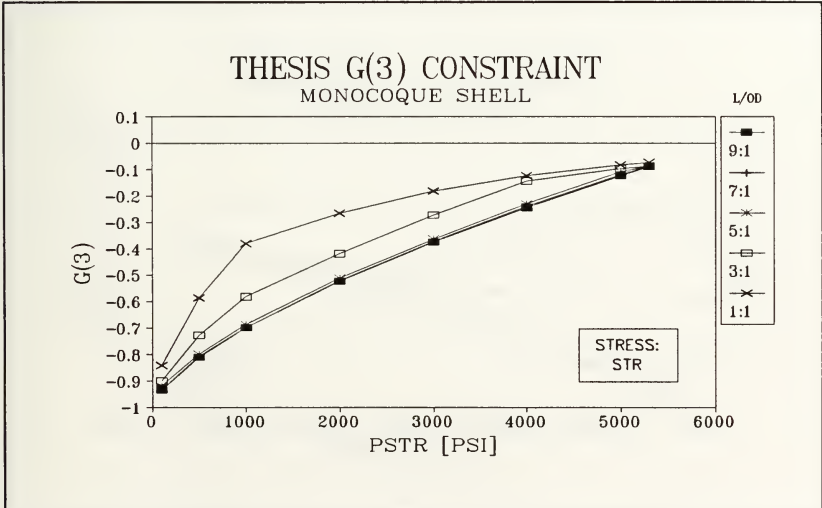


Figure 18. THEISIS Constraint: Stress (STR)

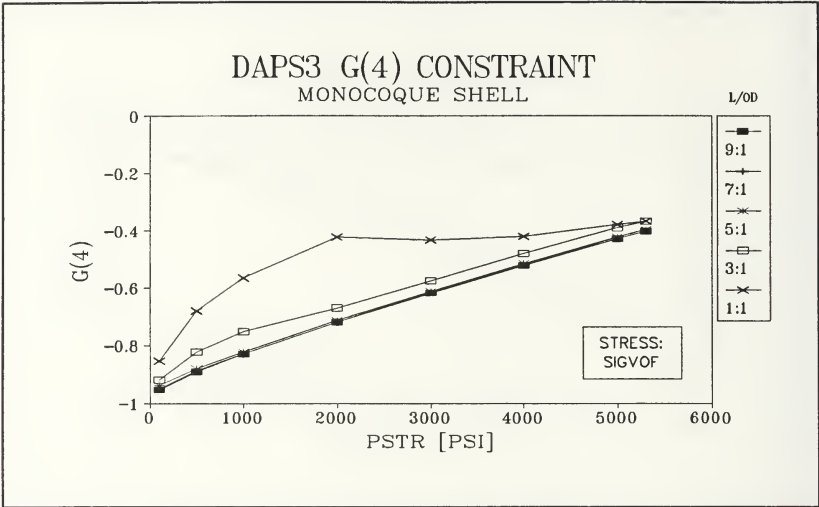


Figure 19. DAPS3 Constraint: Stress (SIGVOF)

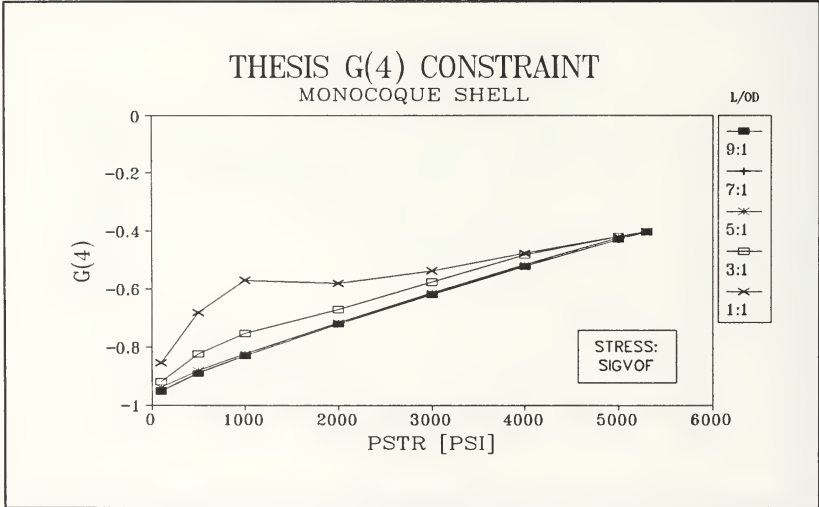


Figure 20. THESIS Constraint: Stress (SIGVOF)

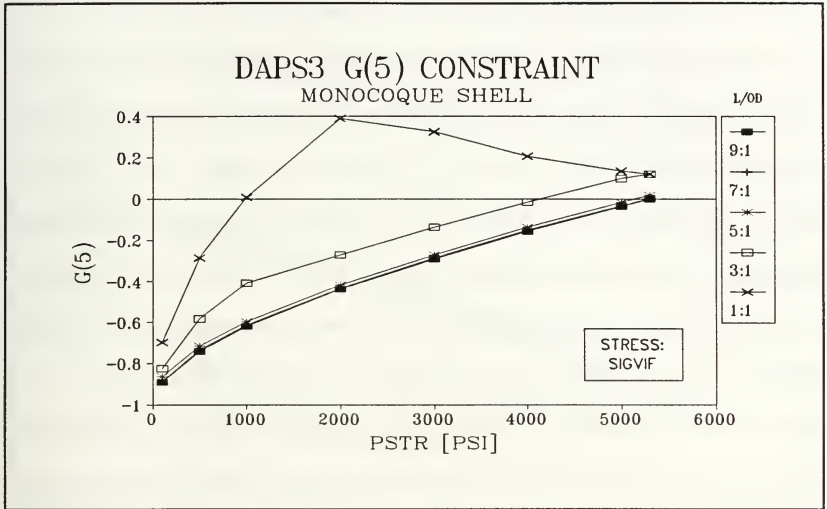


Figure 21. DAPS3 Constraint: Stress (SIGVIF)

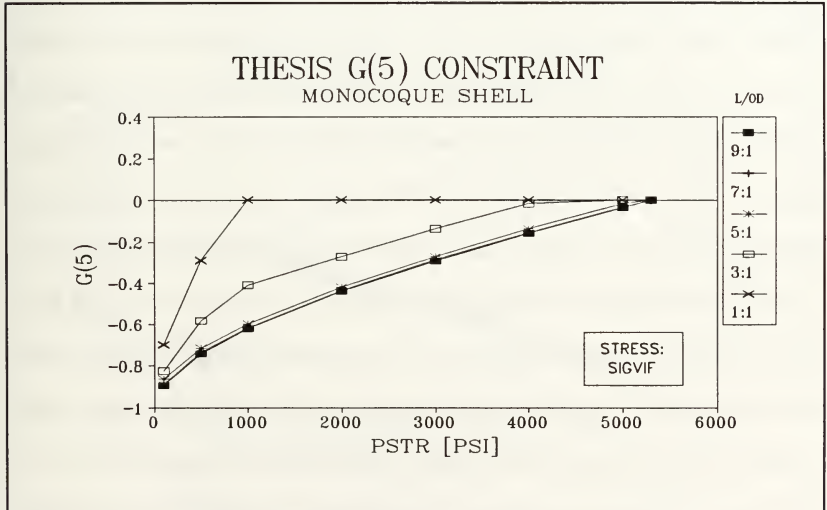


Figure 22. THESIS Constraint: Stress (SIGVIF)

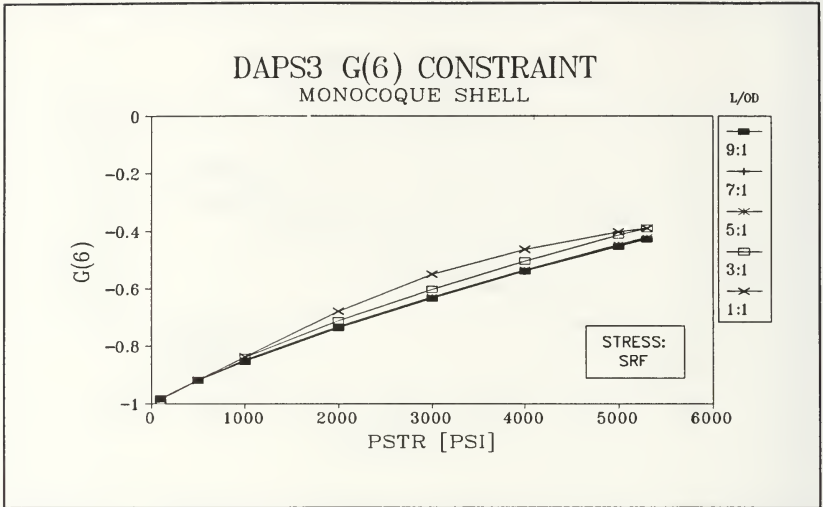


Figure 23. DAPS3 Constraint: Stress (SRF)

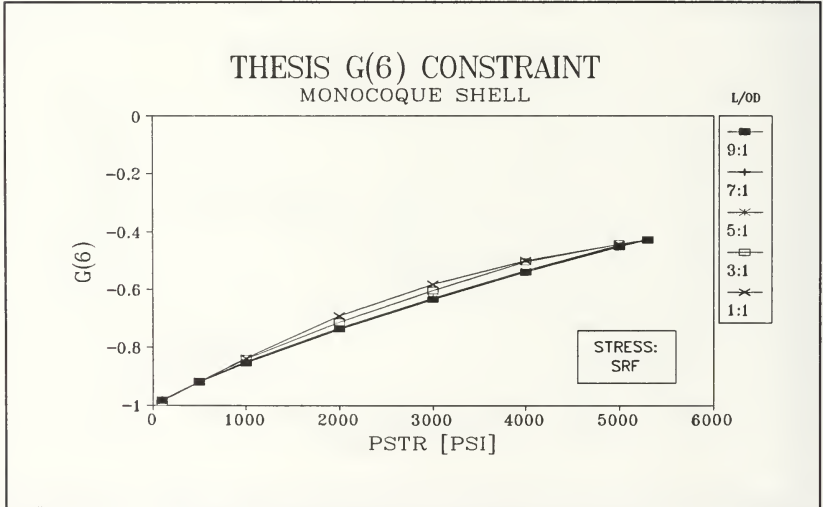


Figure 24. THESIS Constraint: Stress (SRF)

The DAPS3 strength constraint violations are seen in Figures 17 and 21. This is especially noticeable in Figure 21. The g_5 strength constraint (SIGVIF) remains violated at all pressures above 1000 psi (for 1:1 L/OD) and above 4000 psi (for 3:1 L/OD). Thus, all 1:1 and 3:1 (L/OD) DAPS3 designs above the aforementioned pressures are infeasible due to material failure by yield. By contrast, the THESIS designs, which include strength constraints, designs monocoque shells which satisfy all strength constraints. This can be seen in Figures 18, 20, 22, and 24.

The DAPS3 iterative technique is only constrained by buckling considerations. As seen in Figures 13 and 15, the DAPS3 designs do not violate either monocoque shell buckling constraint throughout the range of applied loads. DAPS3 designs a minimum weight shell with the consideration being that a shell which just exceeds buckling loads will be the absolute minimum design required to withstand the external hydrostatic pressure. All monocoque designs thicker than this absolute minimum will also not buckle. These designs will also withstand greater structural stresses due to the added thickness, but an additional weight penalty is imposed upon these stronger designs. Because DAPS3 does not consider strength constraints, the smaller L/OD ratio DAPS3 designed shells are limited by stresses which exceed the material yield strength. In contrast, the THESIS code considers both strength and buckling constraints. As can be seen in Figures 14, 16, 18, 20, 22, and 24, both types of constraints remain satisfied throughout the range of pressures for all L/OD ratios. The THESIS shell weight may be heavier, but the design is feasible throughout the range of pressures.

B. RING-STIFFENED SHELL

The results for the ring-stiffened shell are presented in the same format as the monocoque shell: objective, design variables, and constraints. There are now three design variables (instead of one) and eight constraints (instead of six). This results in a more complex optimization problem since the design space is now three-dimensional (due to three design variables). The simple iterative technique employed by DAPS3 produced nearly the same objective (shell weight) as the THESIS program, which used a numerical optimization technique. However, the optimum design variables for DAPS3 and THESIS differed. Specifically, the HEIGHT and WIDTH of the ring-stiffener varied considerably. A graphical summary of the results are seen in Figures 25 through 48.

1. Objective: DAPS3 vs. THESIS

The first optimum design element examined is the objective: optimum shell weight. Inspection of Figures 25 and 26 show that essentially the same objective was achieved by DAPS3 and THESIS. Some slight weight reduction is seen in the 1:1 and 3:1 THESIS weight curves, which can be attributed to a lesser weight ring design (that is, design variables of HEIGHT and WIDTH). This will be discussed in the design variable results. In general, it can be concluded that the iterative design technique essentially achieves the same objective as the numerical optimization technique. The other design elements (design variables and constraints) must be examined to reveal if numerical optimization provides any advantage.

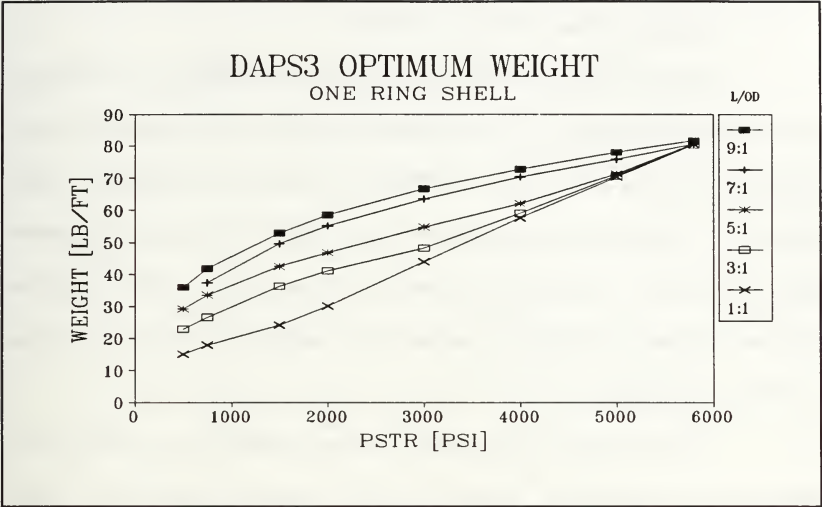


Figure 25. DAPS3 Optimum Weight (Ring-Stiffened Shell)

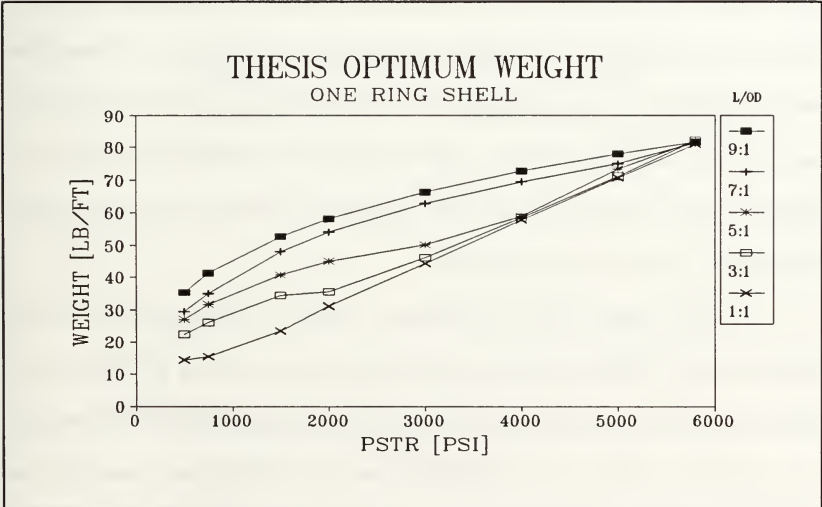


Figure 26. THESIS Optimum Weight (Ring-Stiffened Shell)

2. Design Variables: DAPS3 vs. THESIS

The three optimum design variables produced by DAPS3 and THESIS are seen in Figures 27 through 32. The first design variable, T, is compared in Figures 27 and 28. There is not an apparent difference between the two programs. Shell thickness, T, remains a monotonically increasing variable with increasing external hydrostatic pressure. Since shell thickness is the primary source of shell weight, the optimum thickness curves look very similar to the weight curves, as was seen in the monocoque shell case.

The addition of a single ring-stiffener also contributes to the weight curves, although not very noticeably. Within the surveyed pressure range (500 psi to 5800 psi), both DAPS3 and THESIS design a relatively small single ring-stiffener into the shell design. The small size of this ring-stiffener, in relation to the entire shell, is the reason that the weight curves resemble only the shell thickness curves. However, this small ring-stiffener increases the allowable external hydrostatic pressure by about 500 psi. That is, compared to a similar L/OD ratio monocoque shell, the ring-stiffened shell design can withstand a load of 5800 psi (instead of 5300 psi for the monocoque shell) before the material fails by yield.

The design of this ring-stiffener consists of optimizing the variables HEIGHT and WIDTH such that the shell weight, which includes the weight of the ring, is minimized and all constraints are satisfied. As seen in Figures 29 through 32, the optimized variables of ring HEIGHT and ring WIDTH are quite different between the DAPS3 and THESIS codes.

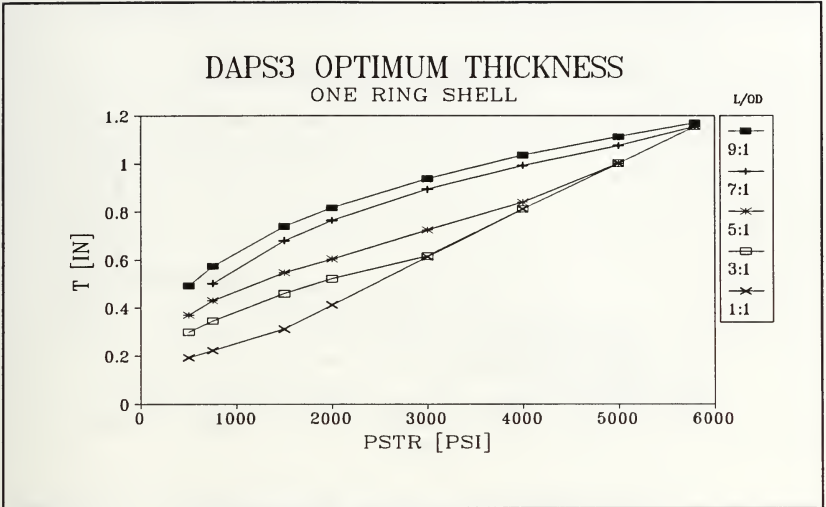


Figure 27. DAPS3 Optimum Shell Thickness (T)

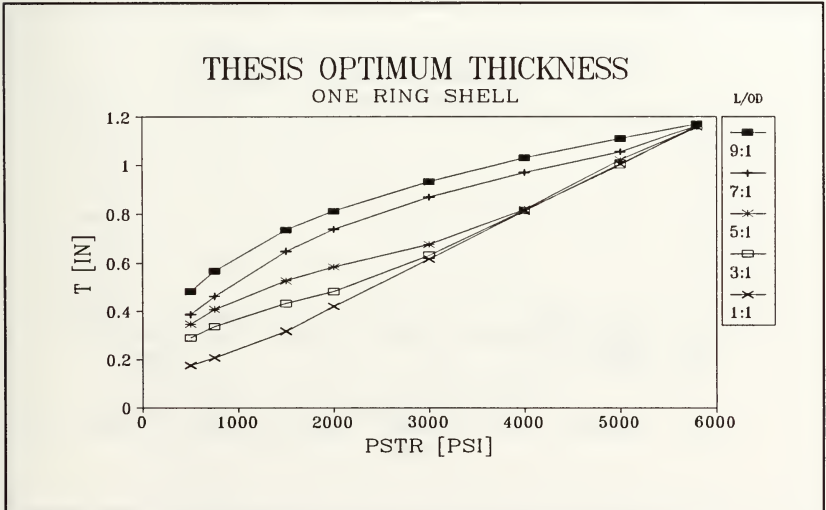


Figure 28. THESIS Optimum Shell Thickness (T)

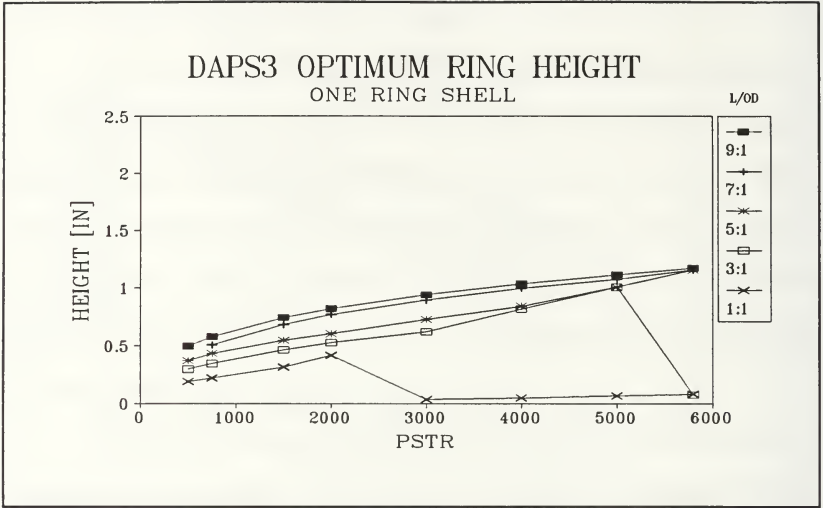


Figure 29. DAPS3 Optimum Ring Height (HEIGHT)

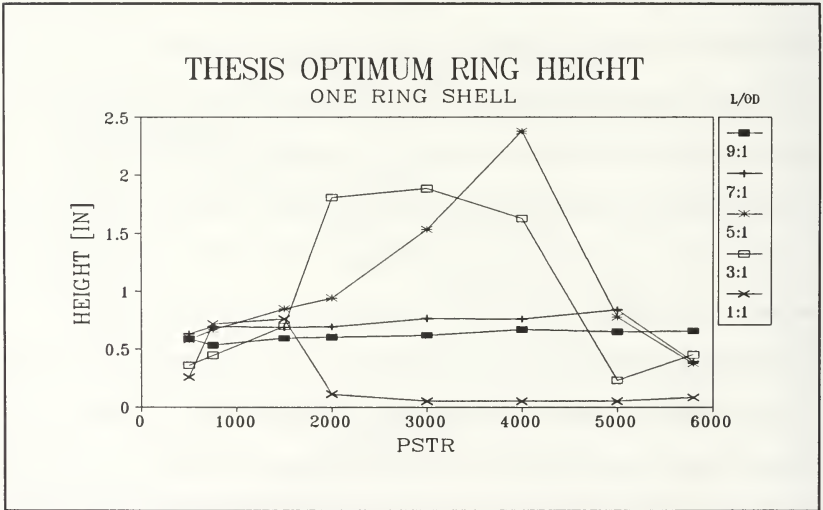


Figure 30. THESIS Optimum Ring Height (HEIGHT)

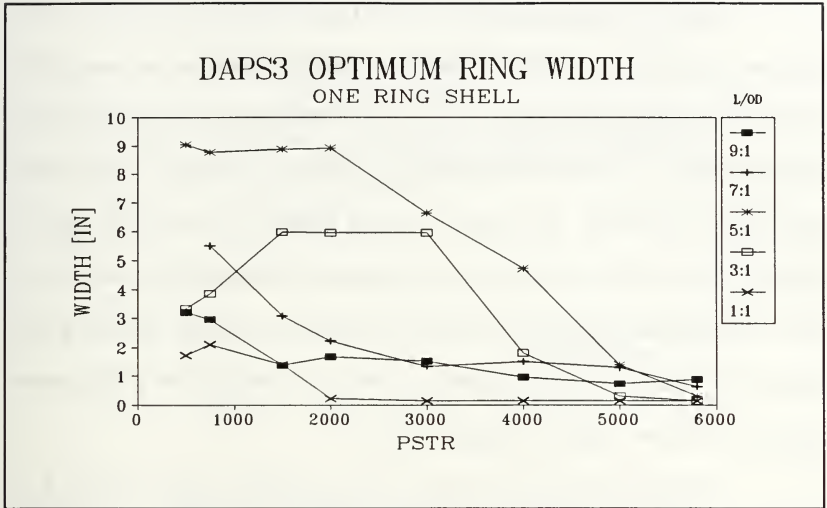


Figure 31. DAPS3 Optimum Ring Width (WIDTH)

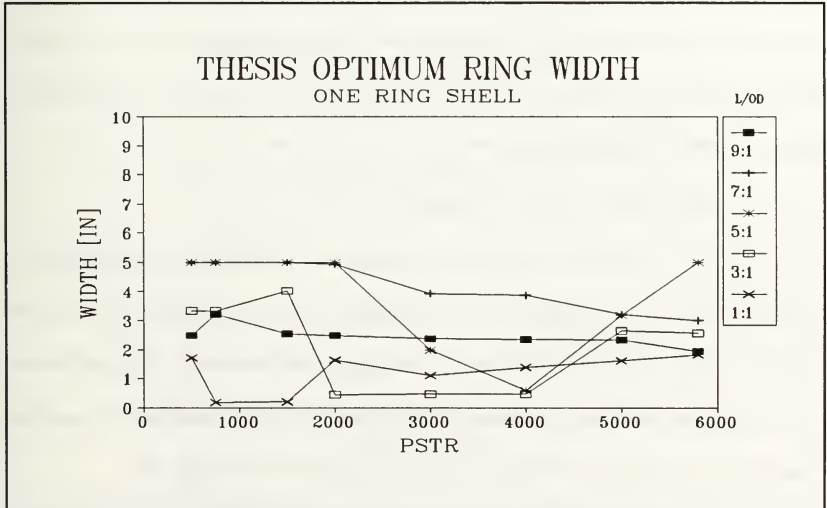


Figure 32. THESIS Optimum Ring Width (WIDTH)

Because the design variables HEIGHT and WIDTH are non-linear in the objective function, neither variable is monotonically increasing or decreasing with respect to the external hydrostatic pressure load. This accounts for the wide array of ring heights and widths for each L/OD ratio, as designed by the THESIS code (see Figures 30 and 32). By contrast, the ring heights for each L/OD ratio, as designed by the DAPS3 code, are generally increasing with increasing pressure (see Figure 29), and the ring widths for each L/OD ratio are generally decreasing (see Figure 31). Thus, a noticeable difference exists in the way that the two programs optimize non-linear design variables.

At this point, it is seen that the same objective may be achieved by different design variables. The selection of these optimum design variables depends on the particular technique employed: iterative (DAPS3) or numerical optimization (THESIS). As in the case of monocoque shell design, an examination of constraint activity by the two different programs may reveal if the numerical optimization technique yields any advantages.

3. Constraints: DAPS3 vs. THESIS

The ring-stiffened shell, as designed by THESIS, has eight design constraints: three for buckling, four for strength, and one for geometry. Recall that DAPS3 designs are only constrained by buckling considerations. This difference results in noticeable strength constraint violations by DAPS3 designs. A graphical comparison of all eight constraints is shown in Figures 33 through 48.

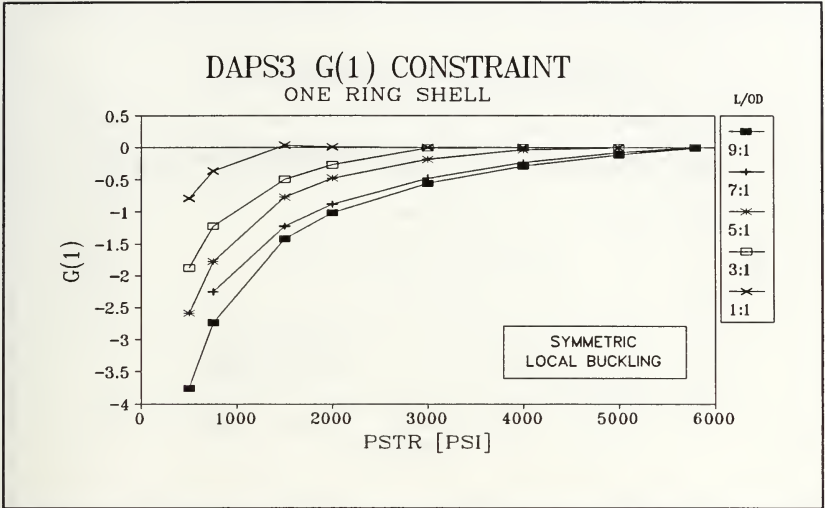


Figure 33. DAPS3 Constraint: Symmetric Local Buckling (PC)

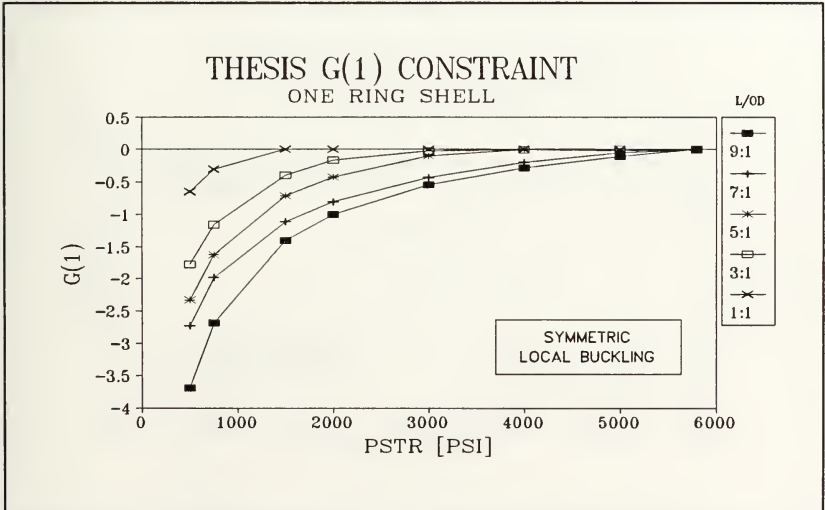


Figure 34. THESIS Constraint: Symmetric Local Buckling (PC)

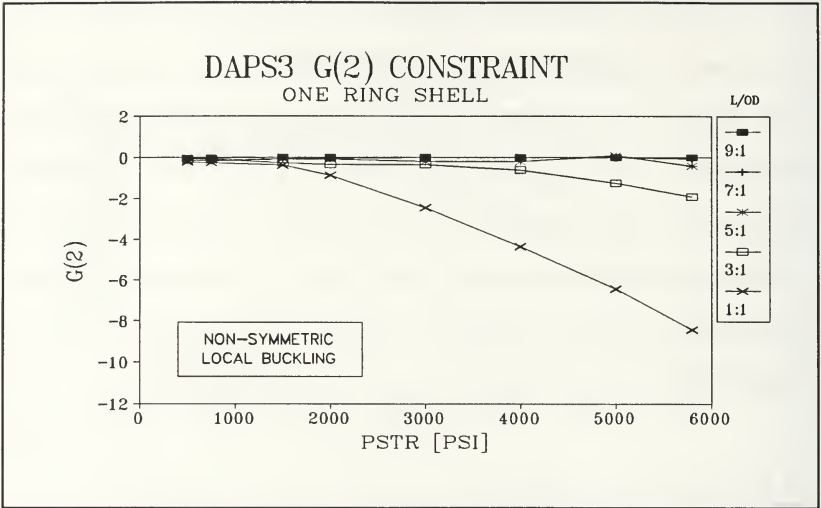


Figure 35. DAPS3 Constraint: Non-Symmetric Local Buckling (PIB)

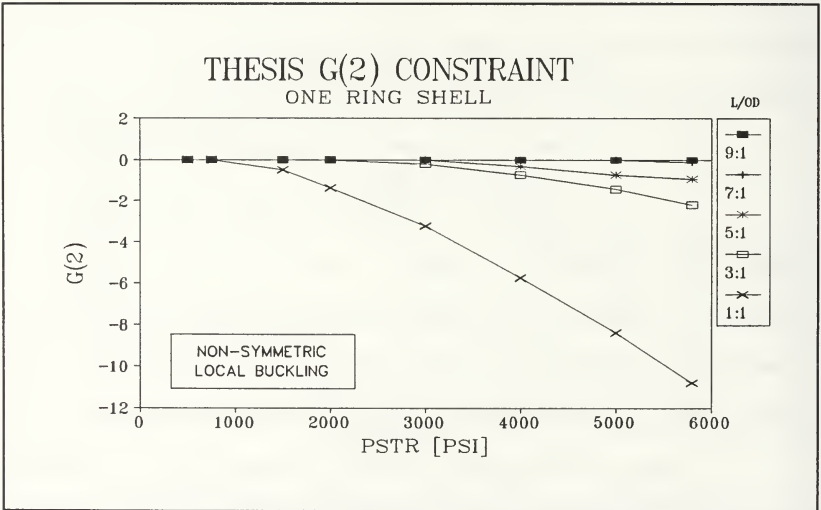


Figure 36. THESIS Constraint: Non-Symmetric Local Buckling (PIB)

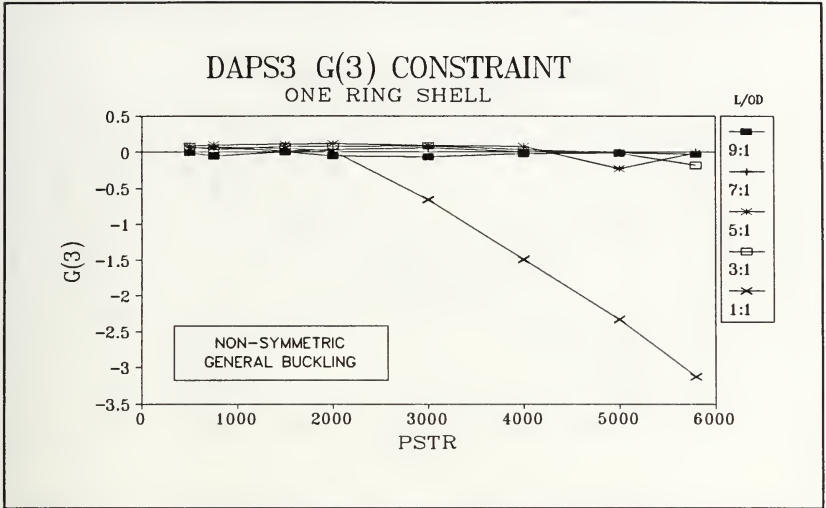


Figure 37. DAPS3 Constraint: Non-Symmetric General Buckling (PGEN)

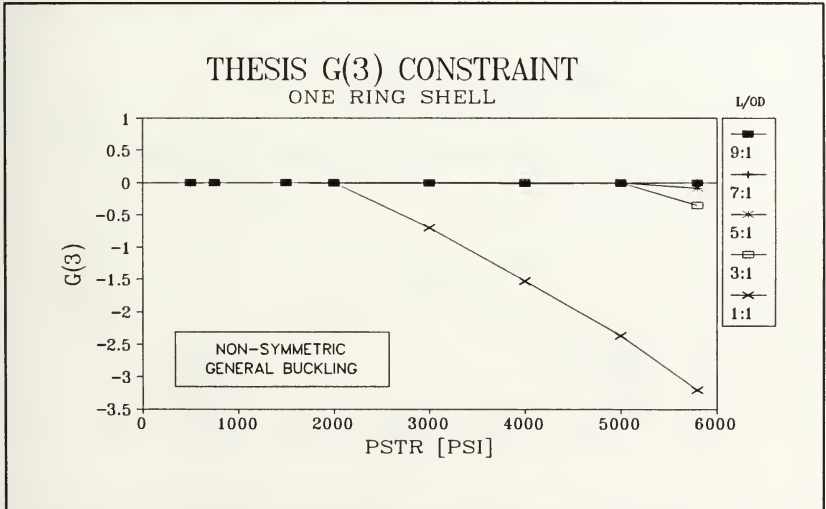


Figure 38. THEISIS Constraint: Non-Symmetric General Buckling (PGEN)

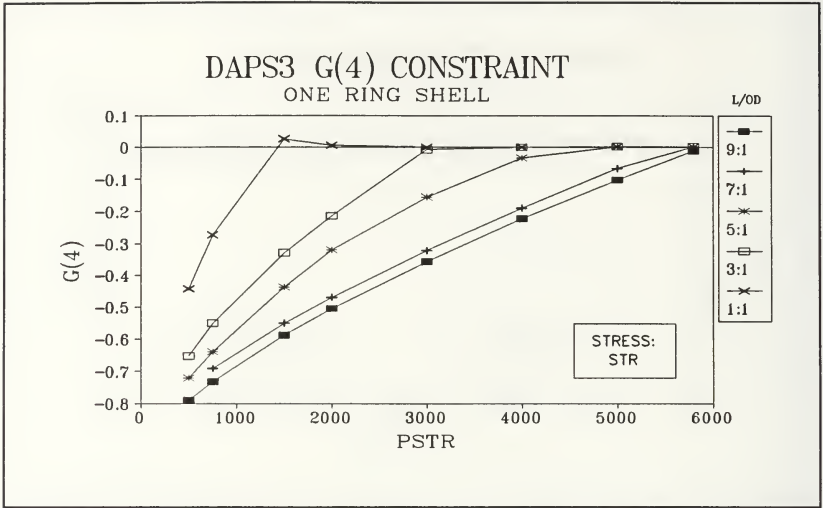


Figure 39. DAPS3 Constraint: Stress (STR)

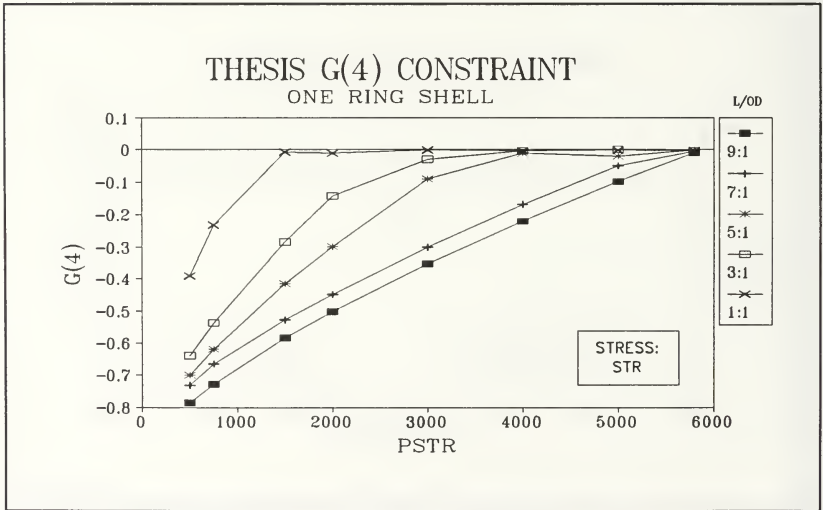


Figure 40. THESIS Constraint: Stress (STR)

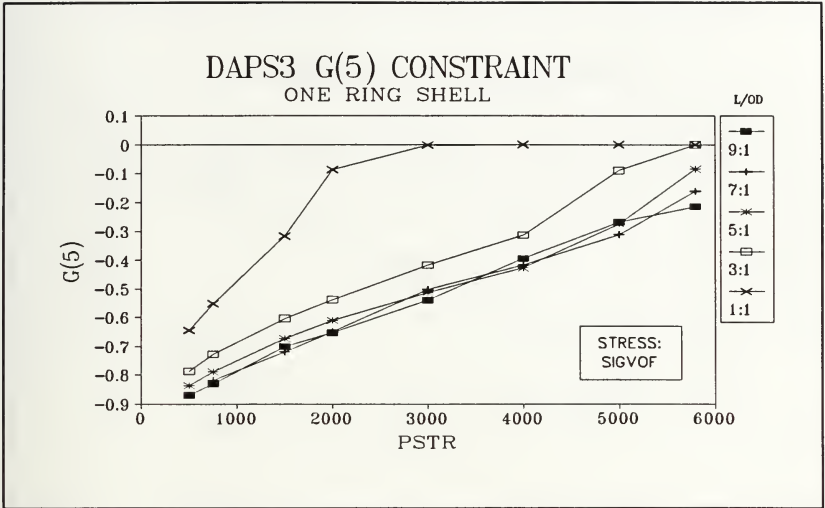


Figure 41. DAPS3 Constraint: Stress (SIGVOF)

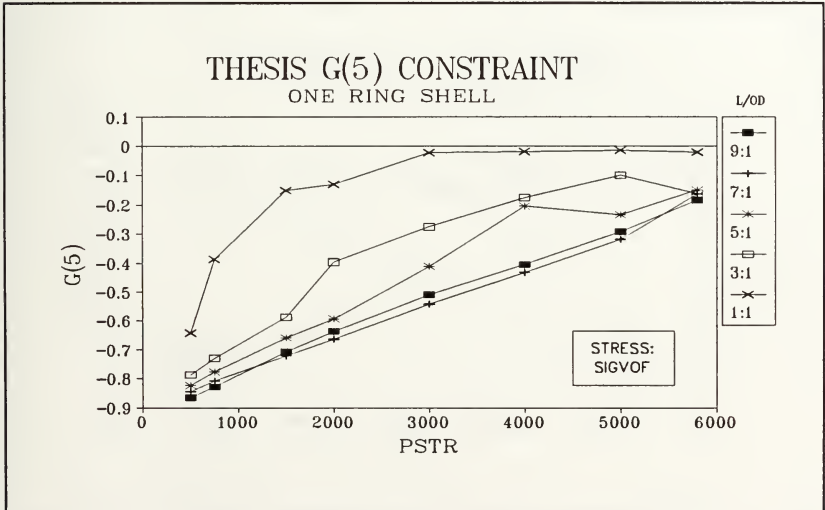


Figure 42. THEISIS Constraint: Stress (SIGVOF)

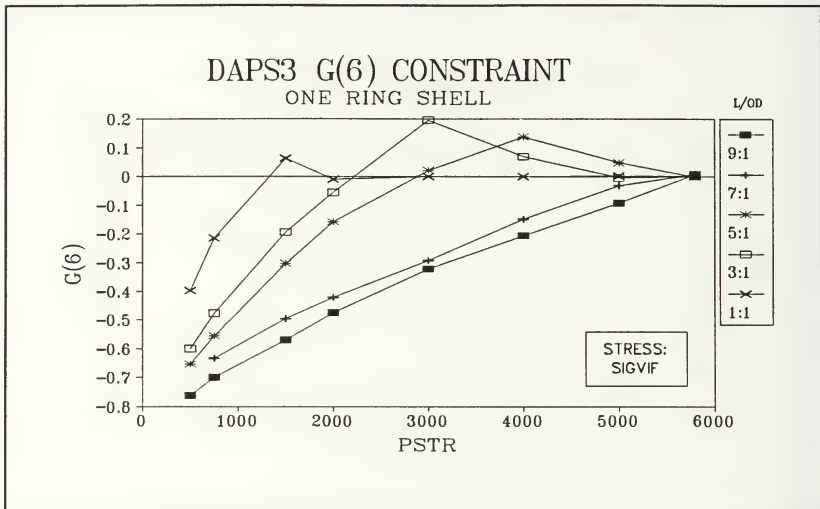


Figure 43. DAPS3 Constraint: Stress (SIGVIF)

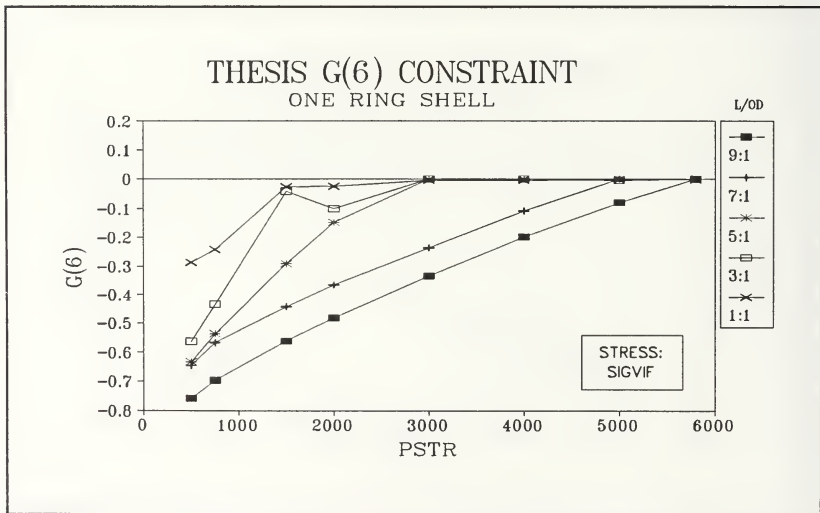


Figure 44. THESIS Constraint: Stress (SIGVIF)

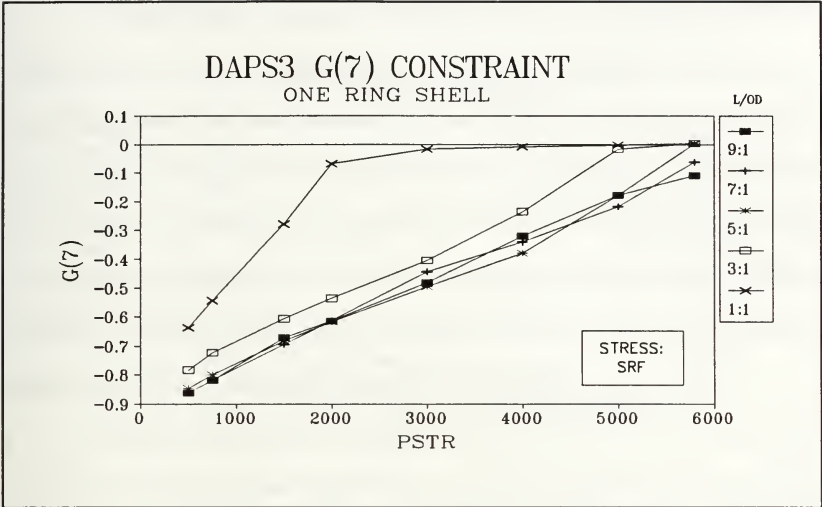


Figure 45. DAPS3 Constraint: Stress (SRF)

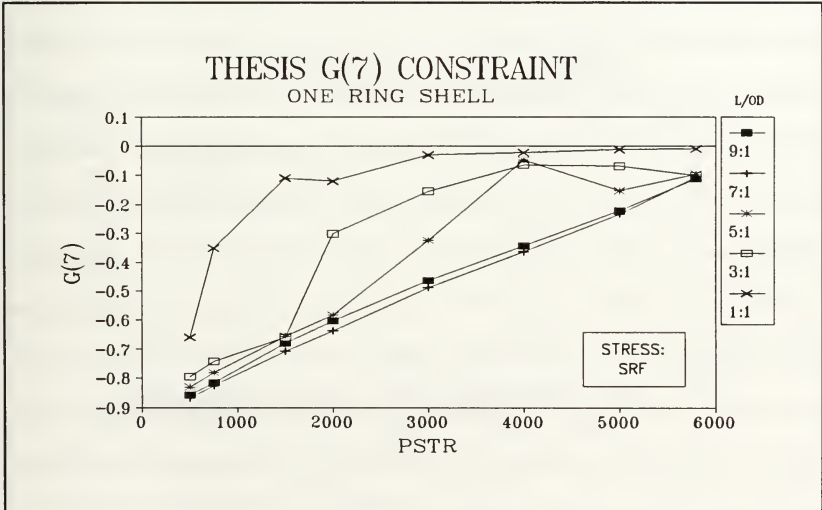


Figure 46. THESIS Constraint: Stress (SRF)

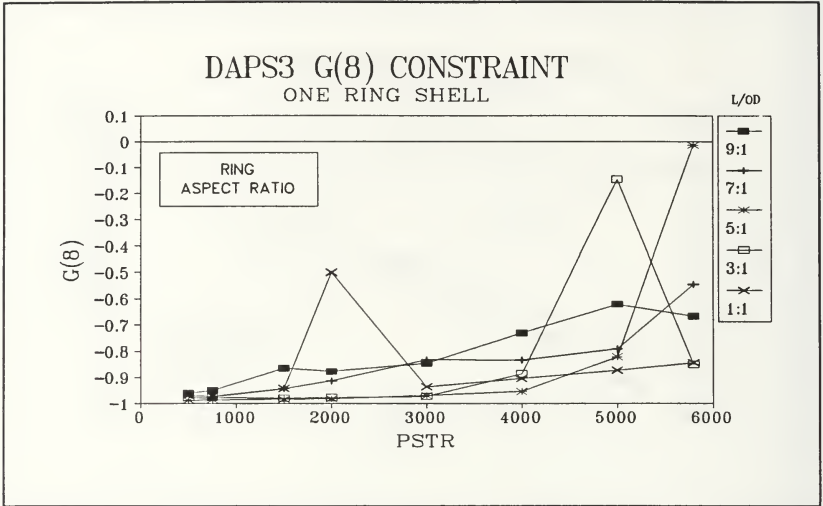


Figure 47. DAPS3 Constraint: Ring Aspect Ratio

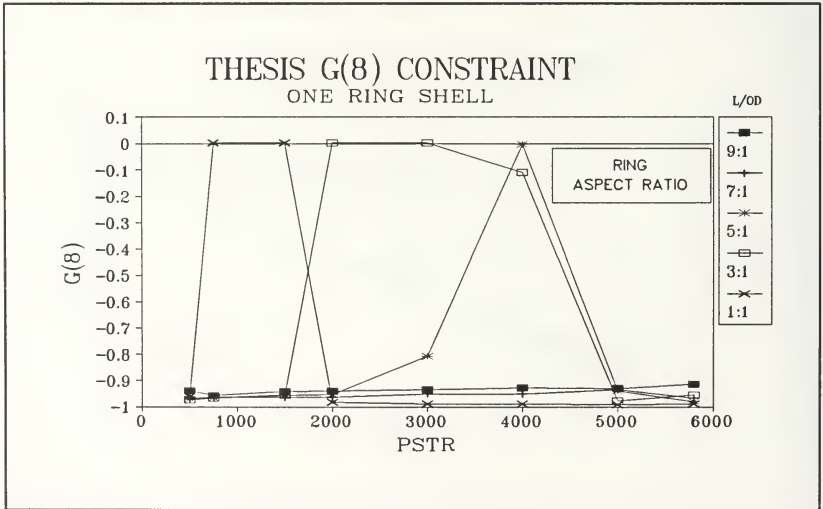


Figure 48. THESIS Constraint: Ring Aspect Ratio

An inspection of Figures 33 through 38 shows that both DAPS3 and THESIS generally satisfy all three buckling constraints. A visible improvement is seen in the g_3 constraint, non-symmetric general buckling. A comparison of Figure 37 with Figure 38 shows that this constraint is better adhered to by the THESIS code. In Figure 37, the DAPS3 g_3 constraint shows slight violations (just above the zero line) but is generally active or satisfied. In contrast, Figure 38 shows that the THESIS g_3 constraint is always active or satisfied. Some improvement is realized by using the numerical optimization technique.

Strength constraints are considered next. These are shown in Figures 39 through 46. Notice that the THESIS $g_j(j = 4,5,6,7)$ constraints do not show any violations: all designs insure that stresses do not exceed the material yield strength. In contrast, the same DAPS3 constraints show violations in two cases. The first violation is seen in Figure 39, which is the g_4 constraint (stress at mid-bay). This constraint is rather small in comparison with the g_6 constraint (stress at the shell and ring junction inner fiber) seen in Figure 43. This constraint was identified as the limiting stress location, which means that it is the first location where the shell would fail by yield. At higher pressures, the g_6 constraint is always active in the THESIS designs, but some large violations occur in DAPS3 designs at these same pressures (see Figure 43). Thus, use of a numerical optimization technique, which easily incorporates strength constraints, has shown an advantage over the DAPS3 technique which does not concurrently consider strength constraints and buckling constraints.

By considering both strength and buckling constraints, the THESIS codes sometimes designs a thicker (and heavier) shell than the DAPS3 code. The result is that the strength constraints become more active (since, at higher pressures, the material yield strength is the limiting design factor) and some buckling constraints become less active. An example of this is seen in Figures 36 and 38, which show the g_2 and g_3 constraints falling below the zero line (becoming less active). The corresponding pressures where the g_2 and g_3 constraints become less active are also the pressures where all the strength constraints, $g_j(j = 4,5,6,7)$, approach the zero line (become more active). This is seen in Figures 40, 42, 44, and 46. Thus, the THESIS code may design a slightly heavier shell, but this shell design does not violate any buckling or strength constraints.

Geometry is the last type of constraint considered. The g_8 constraint limits the maximum aspect ratio of the ring-stiffener to 4:1. This was done to prevent design of a "flimsy" ring. This constraint is shown in Figures 47 and 48. Except for a few of the smaller L/OD ratio designs, this constraint was generally not active. Initial ring-stiffened shell designs by the THESIS code showed this constraint to be active at higher pressures, however these earlier designs were made with a different material (AISI 1060 steel, instead of the Al alloy 6061-T6 used in this study). In summary, this constraint was not active, and all ring-stiffeners could be considered "stable".

V. CONCLUSIONS

The primary goal of this research was to identify any improvements, in monocoque and ring-stiffened shell designs, due to incorporation of a numerical optimization technique into the DAPS3 program. The design elements compared in this study were: 1) objective (shell weight), 2) design variables (shell thickness, ring height, and ring width), 3) constraints (buckling, strength, and geometry).

The results show that the objective (shell weight) was not further minimized by use of the numerical optimization technique. Both DAPS3 and THESIS arrive at about the same optimum shell weight, although the design variable(s) which contribute to this shell weight may differ.

In the case of the monocoque shell, it was found that the design variable, shell thickness (T), was about the same for both DAPS3 and THESIS. This was due to the simple one-variable design space in which either the DAPS3 iterative technique or the THESIS numerical optimization technique could easily achieve the single optimum thickness which corresponds to the minimum monocoque shell weight. In just a few cases, the thickness (T) differed between the two programs. In these cases, the THESIS design variable T was thicker than the same DAPS3 design variable because a thicker shell was necessary to satisfy strength constraints.

In the case of the ring-stiffened shell, the design variable T was also found to be about the same for both DAPS3 and THESIS designs. However, the ring-

stiffener designed by the two programs differed in ring HEIGHT and ring WIDTH. This difference in design variables is not significant with respect to minimizing the shell weight. That is, the optimum design variables produced by DAPS3 and THESIS, although different, still result in the same shell weights. In the more complex three-variable design space of this optimization problem, it was found that HEIGHT and WIDTH are nonlinear variables in the objective function. This accounted for the "up and down" range of values, seen in Figures 30 and 32, for HEIGHT and WIDTH. Although HEIGHT and WIDTH do not significantly contribute to shell weight (due to the relatively small size of the ring-stiffener), these design variables made a difference in complying with the design constraints.

The primary advantage of using a numerical optimization technique for shell design was realized by an examination of the constraints. In general, both DAPS3 and THESIS satisfied the buckling constraints for both monocoque and ring-stiffened shells. However, a significant difference was seen in the strength constraints.

In the monocoque shell case, it was found that some DAPS3 strength constraints (especially at the ring and shell junction inner fiber location) are violated (see Figure 21). In contrast, the same THESIS strength constraints were satisfied due to an increase in shell thickness, as discussed above.

In the ring-stiffened shell case, it was found that similar strength constraint violations occurred in DAPS3 designs. These constraint violations were absent from THESIS designs. Since THESIS shell designs consider strength constraints, while DAPS3 designs do not, the THESIS code was able to optimize the design variables

(especially ring HEIGHT and ring WIDTH) such that there were no strength constraint violations.

In summary, incorporation of a numerical optimization technique into DAPS3 proved to be a worthwhile venture. The primary advantage realized is that constraints can easily be added and tailored to fit a more constrained shell design problem. This is simply done by adding a mathematical constraint function, g_j , to the optimization model. DAPS3 is an excellent shell design program, but it somewhat lacks user flexibility in specifying additional constraints (such as strength constraints). Another advantage realized is that additional design variables, such as shell length (L) and shell outside diameter (OD), may be optimized when the flexible numerical optimization technique is used.

The THESIS code was not written to refine the solutions produced by DAPS3, but rather to supplement the number of solutions available. In this age of high-speed digital computer technology, the ease of employing numerical optimization techniques could be the key to discovering alternative, possibly more effective, solutions to traditional problems.

VI. RECOMMENDATIONS

The THESIS code was a first endeavor into incorporating numerical optimization with the DAPS3 program. Several possibilities exist for more sophisticated optimization research. The following are suggested for any successive research:

1. New design variables. Investigate optimum: number of rings, shell diameter, or shell length.
2. New constraints. One example is maximum allowable shell deflection.
3. New materials. Composite (orthotropic) materials and/or hybrid construction materials. Dramatic shell weight reductions may be realized by use of these materials. The DAPS3 "analysis" and "design" modes fully supports research of these materials.
4. New optimization strategies. Several optimization strategies exist in the ADS program which may improve upon the SLP strategy used in this study. Additionally, a parametric optimization technique such as the homotopy method using an envelope function may be investigated [Ref. 7].

APPENDIX A: THESIS CODE LISTING

This appendix provides a complete listing of the THESIS code. It is written in FORTRAN to be compatible with the DAPS3 code, which is also written in FORTRAN. Also included is the modified DAPS3 code, which is used as a subroutine (DAPS3 SUB) by THESIS.


```

C *****
C
C          THESIS
C (AN INTEGRATED FORTRAN CODE FOR OPTIMUM DESIGN OF ISOTROPIC
C MONOCOQUE AND RING-STIFFENED CIRCULAR CYLINDRICAL SHELLS
C SUBJECT TO EXTERNAL HYDROSTATIC PRESSURE USING A NUMERICAL
C OPTIMIZATION TECHNIQUE)
C *****
C
C THIS FORTRAN CODE INTEGRATES THE PROGRAMS:
C   1) DESIGN AND ANALYSIS OF PLASTIC SHELLS, VERSION 3 (DAPS3)
C     BY J.R. RENZI
C   2) AUTOMATED DESIGN SYNTHESIS, VERSION 1.10 (ADS)
C     BY G.N. VANDERPLAATS
C PROGRAM (1) IS A SHELL ANALYSIS/DESIGN PROGRAM WHICH IS USED TO
C CALCULATE THE BUCKLING AND STRENGTH TERMS CONTAINED IN THE
C DESIGN CONSTRAINTS, G(I).
C PROGRAM (2) RECEIVES THE TERMS EVALUATED BY PROGRAM (1) AND
C EVALUATES THE DESIGN CONSTRAINTS AS PART OF THE OVERALL
C NUMERICAL OPTIMIZATION PROCESS.
C THE OBJECTIVE OF THIS NUMERICAL OPTIMIZATION PROCESS IS TO
C DESIGN AN OPTIMUM (MINIMUM WEIGHT) RING-STIFFENED OR
C MONOCOQUE SHELL.

```

```

C -----
C PROGRAM THESIS
C -----

```

```

INTEGER NPLOT,NCURVE,NDESIGN,ORTHO,IPRINT,ISTRAT,IOPT,IONED
REAL ITHICK,IHEIGHT,IWIDTH

```

```

OPEN (20,FILE='DAPS3 INP A1',STATUS='OLD')

```

```

READ (20,'(4(I5))') NPLOT,NCURVE,NDESIGN,ORTHO
IF ((NPLOT.EQ.0).AND.(NDESIGN.EQ.-1))
: READ (20,'(/////F10.3)') AR
IF ((NPLOT.EQ.0).AND.(NDESIGN.NE.-1))
: READ (20,'(/////F10.3)') AR
IF ((NPLOT.NE.0).AND.(NDESIGN.EQ.-1))
: READ (20,'(/////F10.3)') AR
IF ((NPLOT.NE.0).AND.(NDESIGN.NE.-1))
: READ (20,'(/////F10.3)') AR

```

```

CLOSE(20,STATUS='KEEP')

```

```

C INPUT ADS OPTIMIZATION PARAMETERS:
C IPrint = 2020
C ISTRAT = 6
C IOPT = 5
C IONED = 6

```

```

C INPUT INITIAL DESIGN FOR OPTIMIZATION SEARCH:
IF (AR.LE.0) THEN
  ITHICK = 1.1589
  CALL MONO (IPRINT,ISTRAT,IOPT,IONED,ITHICK)
ELSE
  ITHICK = 0.191
  IHEIGHT = 0.191
  IWIDTH = 1.730
  CALL RING (IPRINT,ISTRAT,IOPT,IONED,ITHICK,IHEIGHT,IWIDTH)
ENDIF

END

```

```

C -----
SUBROUTINE MONO (IPRINT,ISTRAT,IOPT,IONED,ITHICK)
C -----

REAL L,OD,T,PC,PIB,R,RO,RHO,RHOF,AR,YR,LF,MOS1,MOS2,MOS
REAL MSS1,MSS2,MSS3,MSS4,MSS,LS,IR,ITHICK
INTEGER NPLOT,NCURVE,NDESIGN,ORTHO,NSAVE,ISEC,NXPNT,NYPNT,NFPNT
INTEGER IPRINT,ISTRAT,IOPT,IONED
CHARACTER*70 TITLE
PARAMETER (PI = 3.141593)

DIMENSION X(21), VLB(21), VUB(21), G(100), IDG(100), IC(30),
: DF(100), A(21,30), WK(10000), IWK(5000)

COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R,
: PSTR,STR,SIGX,SIGY,SIGX1,SIGY1,HEIGHT,WIDTH,OD

COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
: INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
: NPLOT,NOKM,NRINGS,NEGLAM,INDIC7

COMMON /EMOD/ STRESX(10),STRINX(10),STRESY(10),STRINY(10),
: STRESF(10),STRINF(10),RATIOX,RATIOY,NXPNT,NYPNT,NFPNT

COMMON /GRAPH/ET(28),SIG(28),PB(28),PS(28),ES(28),AAA(6),
: BBB(6),CCC(8),DDD(6),EEE(5),FFF(7),GGG(4),HHH(7),OOO(8),ER(28),
: SIGF(28),SHAPEG(5),SHAPEI(3),WX(101)

COMMON /LAYER/ A11,A22,D11,D22

COMMON /STRESS/ STRX,STRY,PIB,NSAVEI,PGEN,NSAVEG

COMMON /HENRY/ SRF,WM,WF

OPEN (8,FILE='/THESIS OUT A1',STATUS='OLD')

```

```

C   COMMENCE READING INPUT VARIABLES FROM (20,FILE='/DAPS3 INP A1'):
    OPEN (20,FILE='/DAPS3 INP A1',STATUS='OLD')

    READ (20,500) NPLOT,NCURVE,NDESIGN,ORTHO
    READ (20,50) TITLE
    WRITE(6,'(A/A)') 'COMMENCING OPTIMIZATION OF:', TITLE
    IF (NPLOT.EQ.0)
:   READ (20,50) HHH
    IF (NDESIGN.EQ.-1)
:   READ (20,51) A11,A22,D11,D22
    READ (20,51) EX,VYX,VPLAS,SIGX,GXY,EY,EF
    READ (20,53) PSTR,SIGY,SIGX1,SIGY1,PEL,STRX,STRY,NSAVE
    READ (20,51) L,OD,T,RHO,RHOF
    IF (PEL.LE.0.)
:   READ (20,51) AR,IR,YR,LF,LS,ARM
    IF (NDESIGN.GT.0)
:   READ (20,53) RINGS,SECDEP,DW,DASP,RINGSI,RINGSF,DRINGS,ISEC
    IF (NCURVE.EQ.4) GOTO 2
    READ (20,52) SIGXNOM,SIGYNOM,NXPNT,NYPNT,NFPNT
    READ (20,55) (STRESX(I), I = 1,NXPNT)
    READ (20,55) (STRINX(I), I = 1,NXPNT)
    IF (NCURVE.EQ.1) GOTO 2
    READ (20,55) (STRESY(I), I = 1,NYPNT)
    READ (20,55) (STRINY(I), I = 1,NYPNT)
    IF (NCURVE.EQ.2) GOTO 2
    READ (20,55) (STRESF(I), I = 1,NFPNT)
    READ (20,55) (STRINF(I), I = 1,NFPNT)

500  FORMAT (BZ,10I5)
50   FORMAT (BZ,A)
51   FORMAT (BZ,8F10.3)
52   FORMAT (BZ,2F10.3,3I5)
53   FORMAT (BZ,7F10.3,I5)
55   FORMAT (BZ,10F8.0)

2    CONTINUE

    CLOSE(20,STATUS='KEEP')

    NRA = 21
    NCOLA = 30
    NRWK = 10000
    NRIWK = 5000

    IGRAD = 0
    NDV = 1
    NCON = 6

C   THE LOWER BOUND IS THE MIN ALLOWED SHELL THICKNESS (INCHES)
    VLB(1) = 0.10

```

C THE UPPER BOUND IS SET TO 1.818 IN. SO THAT THE MAX ALLOWED
 C T/R RATIO IS 20%. (THIS VALUE IS VALID FOR THE FIXED VALUE
 C 10 IN. OUTSIDE SHELL DIAMETER USED IN THIS STUDY.)
 VUB(1) = 1.818

DO 3 I = 1,6
 IDG(I) = 0

3 CONTINUE

WRITE (8,(A)') '-----'
 WRITE (8,(5X,A,I1,T20,A,I1,T32,A,I1)')
 : 'ISTRAT = ',ISTRAT,'IOPT = ',IOPT,'IONED = ',IONED
 WRITE (8,(A)') '-----'

X(1) = ITHICK

WRITE (8,(/1X,A,T20,A,F7.3,T50,A)') 'INITIALIZED AT:',
 : 'THICKNESS(IN) = ',X(1),'(DESIGN VARIABLE #1)'
 WRITE (8,(1X,A,T30,A,F7.2,2X,A,F7.2)')
 : 'BOUNDARY CONSTRAINTS ----',
 : 'VARIABLE #1:', VLB(1), 'TO', VUB(1)

INFO = -2

CALL ADS (INFO,ISTRAT,IOPT,IONED,IPRINT,IGRAD,NDV,NCON,X,VLB,
 : VUB,OBJ,G,IDG,NGT,IC,DF,A,NRA,NCOLA,WK,NRWK,IWK,NRIWK)
 IWK(2) = 0

10 CALL ADS (INFO,ISTRAT,IOPT,IONED,IPRINT,IGRAD,NDV,NCON,X,VLB,
 : VUB,OBJ,G,IDG,NGT,IC,DF,A,NRA,NCOLA,WK,NRWK,IWK,NRIWK)
 IF (INFO.EQ. 0) GOTO 20

T = X(1)
 RO = OD/2.
 R = RO - T/2.

CALL DAPS3 (PC,RHO,RHOF,TITLE,SIGVOF,SIGVIF,USEVOL,CL)

OBJ = (24.*PI/L) * (R*T*L*RHO + (RO-YR)*AR*(L/LF-1.)*RHOF)

C THE G(1) CONSTRAINT INSURES AXISYMMETRIC COLLAPSE PRESSURE IS
 C LESS THAN ANALYSIS PRESSURE
 G(1) = 1. - (PC/PSTR)

C THE G(2) CONSTRAINT INSURES ELASTIC MONOCOQUE INSTABILITY
 C OR INTER-BAY INSTABILITY PRESSURE IS LESS THAN ANALYSIS PRESSURE
 G(2) = 1. - (PIB/PSTR)

C THE G(3) CONSTRAINT INSURES MID-BAY MEMBRANE STRESS LEVEL
 C (VON MISES STRESS, FROM SIGXM AND SIGTM, PER YIELD) IS LESS
 C THAN 100% (OF MATERIAL YIELD STRENGTH SIGX)
 G(3) = (STR/100.) - 1.

```

C   THE G(4) CONSTRAINT INSURES VON MISES STRESS IN MEMBER AT
C   OUTSIDE FRAME IS LESS THAN 100% OF MATERIAL YIELD STRENGTH
G(4) = (SIGVOF/100.) - 1.

C   THE G(5) CONSTRAINT INSURES VON MISES STRESS IN MEMBER AT
C   INSIDE FRAME IS LESS THAN 100% OF MATERIAL YIELD STRENGTH
G(5) = (SIGVIF/100.) - 1.

C   THE G(6) CONSTRAINT INSURES THAT HOOP STRESS IN THE FRAME (RING)
C   IS LESS THAN MATERIAL YIELD STRENGTH
IF (ORTHO.EQ.0) THEN
    G(6) = ABS(SRF/SIGX) - 1.
    ELSEIF ((ORTHO.EQ.1).AND.(SRF.LT.0)) THEN
        G(6) = ABS(SRF/SIGY) - 1.
    ELSEIF ((ORTHO.EQ.1).AND.(SRF.GT.0)) THEN
        G(6) = (SRF/SIGY1) - 1.
ENDIF
GOTO 10
20  CONTINUE

C   DEFINE LIMITING MARGIN OF STABILITY (MOS)
MOS1 = PC/PSTR
MOS2 = PIB/PSTR
MOS = MIN(MOS1,MOS2)
C   DEFINE LIMITING MARGIN OF STRENGTH (MSS)
MSS1 = STR/100.
MSS2 = SIGVOF/100.
MSS3 = SIGVIF/100.
IF (ORTHO.EQ.0) THEN
    MSS4 = ABS(SRF/SIGX)
    ELSEIF ((ORTHO.EQ.1).AND.(SRF.LT.0)) THEN
        MSS4 = ABS(SRF/SIGY)
    ELSEIF ((ORTHO.EQ.1).AND.(SRF.GT.0)) THEN
        MSS4 = SRF/SIGY1
ENDIF
MSS = MAX(MSS1,MSS2,MSS3,MSS4)

WRITE (8,'(1X,20H*** OPTIMIZATION OF:/1X,A)') TITLE
WRITE (8,'(T6,A,F7.0,1X,A)') '@ ANALYSIS PRESSURE = ',PSTR,'PSI'
IF (ORTHO.EQ.0) THEN
    WRITE (8,'(T6,A)') 'ISOTROPIC MATERIAL PROPERTIES:'
    ELSE
        WRITE (8,'(T6,A)') 'ORTHOTROPIC MATERIAL PROPERTIES:'
ENDIF
WRITE (8,'(T11,A)') '>>> SHELL:'
IF (ORTHO.EQ.0) THEN
    WRITE (8,'(T14,A,2PE9.2,1X,A)')
: 'EX    = 'EX,'PSI'
ELSE
    WRITE (8,'(2(T14,A,2PE9.2,1X,A),T14,A,E9.2,1X,A)')

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: 'EX = 'EX,'PSI',
: 'EY = 'EY,'PSI',
: 'EF = 'EF,'PSI'
ENDIF
WRITE (8,'(T14,A,1PE9.2,1X,A)')
: 'GXY = 'GXY,'PSI'
IF (ORTHO.EQ.0) THEN
WRITE (8,'(T14,A,F8.0,1X,A)')
: 'YIELD = ',SIGX,'PSI'
ELSE
WRITE (8,'(T14,A/3(T14,A,F8.0,1X,A/),T14,A,F8.0,1X,A)')
: 'YIELD:',
: 'AXIAL(C)= ',SIGX,'PSI',
: 'AXIAL(T)= ',SIGX1,'PSI',
: 'HOOP (C)= ',SIGY,'PSI',
: 'HOOP (T)= ',SIGY1,'PSI'
ENDIF
WRITE (8,'(T14,A,F5.3,1X,A)')
: 'DENSITY = ',RHO,'LB/CU.IN.'
WRITE (8,'(T14,A,F6.1,1X,A)')
: ' = ',RHO*(12*3),'LB/CU.FT.'
WRITE (8,'(3(T14,A,F6.3))')
: 'VXY = ',VXY,
: 'VYX = ',VYX,
: 'VPLAS = ',VPLAS
WRITE (8,'(3(1X,A,F9.4/),1X,A,F9.4,T50,A/2(1X,A,F9.4/))')
: 'CRITICAL LENGTH(IN) = ', CL,
: 'LENGTH(IN) = ', L,
: 'OUT.DIAMETER(IN) = ', OD,
: 'THICKNESS(IN) = ', X(1),'(OPTIMIZED VARIABLE #1)',
: 'RING SPACING(IN) = ', LF,
: 'INTERBAY WIDTH(IN) = ', LS
WRITE (8,'(2(1X,A,F6.4,1X,A/))')
: 'SHELL RADIAL DEFLECTION @ MIDBAY = ', WM, 'IN',
: ' @ FRAME = ', WF, 'IN'
IF (MOS.EQ.MOS1) THEN
WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STABILITY (PC/PSTR) = ', MOS
ELSEIF (MOS.EQ.MOS2) THEN
WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STABILITY (PIB/PSTR) = ', MOS
ENDIF
IF (MSS.EQ.MSS1) THEN
WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STRENGTH (STR/YIELD) = ', MSS
ELSEIF (MSS.EQ.MSS2) THEN
WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STRENGTH (SIGVOF/YIELD) = ', MSS
ELSEIF (MSS.EQ.MSS3) THEN
WRITE (8,'(1X,A,F6.4)')

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:   'LIMITING MARGIN OF STRENGTH (SIGVIF/YIELD) = ', MSS
ELSEIF ((MSS.EQ.MSS4).AND.(ORTHO.EQ.0)) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SRF/SIGX) = ', MSS
ELSEIF ((MSS.EQ.MSS4).AND.(ORTHO.EQ.1).AND.(SRF.LT.0)) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SRF/SIGY) = ', MSS
ELSEIF ((MSS.EQ.MSS4).AND.(ORTHO.EQ.1).AND.(SRF.GT.0)) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SRF/SIGY1) = ', MSS
ENDIF

WRITE (8,'(6(1X,A,1PE10.3,T25,A))')
: 'G(1) = ',G(1),'AXISYMMETRIC COLLAPSE PRESSURE      : PC',
: 'G(2) = ',G(2),'MONOCOQUE/INTERBAY INSTABILITY PRESURE : PIB',
: 'G(3) = ',G(3),'VON MISES MIDBAY MEMBRANE STRESS      : STR',
: 'G(4) = ',G(4),'VON MISES OUTSIDE FRAME MEMBRANE STRESS: SIGVOF',
: 'G(5) = ',G(5),'VON MISES INSIDE FRAME MEMBRANE STRESS : SIGVIF',
: 'G(6) = ',G(6),'HOOP STRESS IN THE FRAME              : SRF'
WRITE(8,'(2(1X,A,F10.3),1X,A,F10.3,T50,A/1X,A,F10.3//1X,A,16//)')
: 'INTERNAL VOLUME(CU.FT./FT.) = ', USEVOL,
: 'INTERNAL VOLUME(CU.FT)      = ', USEVOL*L/12.,
: 'WEIGHT(LB/FT)               = ', OBJ,'(OPTIMIZED OBJECTIVE)',
: 'WEIGHT(LB)                  = ', OBJ*L/12.,
: 'ADS ITERATIONS              = ', IWK(28)
IF (L.LT.CL) THEN
  WRITE (8,'(3(1X,A))')
: 'NOTE: SHELL LENGTH IS LESS THAN MINIMUM CRITICAL LENGTH.',
: 'END PLATE EFFECTS MAY AFFECT REPRESENTATIVE STATES OF STRESS',
: 'AT MID-SPAN OF THE SHELL.'
ENDIF

CLOSE (8,STATUS='KEEP')

END

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C -----
C SUBROUTINE RING (IPRINT,ISTRAT,IOP,T,IONED,ITTHICK,IHEIGHT,IWIDTH)
C -----

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REAL  L,OD,T,PC,PIB,R,RO,RHO,RHOF,AR,YR,LF,MOS1,MOS2,MOS3,MOS
REAL  MSS1,MSS2,MSS3,MSS4,MSS,LS,IR,ITTHICK,IHEIGHT,IWIDTH
INTEGER NPLOT,NCURVE,NDESIGN,ORTHO,NSAVE,ISEC,NXPNT,NYPNT,NFPNT
INTEGER NOR,IPRINT,ISTRAT,IOP,T,IONED
CHARACTER*70  TITLE
PARAMETER (PI = 3.141593)

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DIMENSION  X(21), VLB(21), VUB(21), G(100), IDG(100), IC(30),

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:      DF(100), A(21,30), WK(10000), IWK(5000)

COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R,
: PSTR,STR,SIGX,SIGY,SIGX1,SIGY1,HEIGHT,WIDTH,OD

COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
: INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
: NPLOT,NOKM,NRINGS,NEGLAM,INDIC7

COMMON /EMOD/ STRESX(10),STRINX(10),STRESY(10),STRINY(10),
: STRESF(10),STRINF(10),RATIOX,RATIOY,NXPNT,NYPNT,NFPNT

COMMON /GRAPH/ET(28),SIG(28),PB(28),PS(28),ES(28),AAA(6),
: BBB(6),CCC(8),DDD(6),EEE(5),FFF(7),GGG(4),HHH(7),OOO(8),ER(28),
: SIGF(28),SHAPEG(5),SHAPEI(3),WX(101)

COMMON /LAYER/ A11,A22,D11,D22

COMMON /STRESS/ STRX,STRY,PIB,NSAVEI,PGEN,NSAVEG

COMMON /HENRY/ SRF,WM,WF

OPEN (8,FILE='/'/THESIS OUT A1',STATUS='OLD')

C  COMMENCE READING INPUT VARIABLES FROM (20,FILE='/'/DAPS3 INP A1'):
OPEN (20,FILE='/'/DAPS3 INP A1',STATUS='OLD')

READ (20,500) NPLOT,NCURVE,NDESIGN,ORTHO
READ (20,50) TITLE
WRITE(6,('/A/A')) 'COMMENCING OPTIMIZATION OF:', TITLE
IF (NPLOT.EQ.0)
: READ (20,50) HHH
IF (NDESIGN.EQ.-1)
: READ (20,51) A11,A22,D11,D22
READ (20,51) EX,VYX,VPLAS,SIGX,GXY,EY,EF
READ (20,53) PSTR,SIGY,SIGX1,SIGY1,PEL,STRX,STRY,NSAVE
READ (20,51) L,OD,T,RHO,RHOF
IF (PEL.LE.0)
: READ (20,51) AR,IR,YR,LF,LS,ARM
IF (NDESIGN.GT.0)
: READ (20,53) RINGS,SECDEP,DW,DASP,RINGSI,RINGSF,DRINGS,ISEC
IF (NCURVE.EQ.4) GOTO 2
READ (20,52) SIGXNOM,SIGYNOM,NXPNT,NYPNT,NFPNT
READ (20,55) (STRESX(I), I = 1,NXPNT)
READ (20,55) (STRINX(I), I = 1,NXPNT)
IF (NCURVE.EQ.1) GOTO 2
READ (20,55) (STRESY(I), I = 1,NYPNT)
READ (20,55) (STRINY(I), I = 1,NYPNT)
IF (NCURVE.EQ.2) GOTO 2
READ (20,55) (STRESF(I), I = 1,NFPNT)

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READ (20,55) (STRINF(I), I = 1,NFPNT)

500 FORMAT (BZ,10I5)
50  FORMAT (BZ,A)
51  FORMAT (BZ,8F10.3)
52  FORMAT (BZ,2F10.3,3I5)
53  FORMAT (BZ,7F10.3,I5)
55  FORMAT (BZ,10F8.0)

2  CONTINUE

CLOSE(20,STATUS='KEEP')

NRA  = 21
NICOLA = 30
NRWK  = 10000
NRIWK = 5000

IGRAD = 0
NDV  = 3
NCON = 8

C  THE LOWER BOUNDS ON (1) THICKNESS, (2) RING HEIGHT, AND
C  (3) RING WIDTH ARE ESTABLISHED (INCHES)
VLB(1) = 0.10
VLB(2) = 0.05
VLB(3) = 0.125

C  THE UPPER BOUNDS ON (1) THICKNESS, (2) RING HEIGHT, AND
C  (3) RING WIDTH ARE ESTABLISHED (INCHES)
VUB(1) = 1.818
VUB(2) = 10.
VUB(3) = 5.

DO 3 I = 1,8
  IDG(I) = 0
3  CONTINUE

WRITE (8,'(A)') '-----'
WRITE (8,'(5X,A,11,T20,A,11,T32,A,11)')
: 'ISTRAT = ',ISTRAT,'IOPT = ',IOPT,'IONED = ',IONED
WRITE (8,'(A)') '-----'

X(1) = ITHICK
X(2) = IHEIGHT
X(3) = IWIDTH

WRITE (8,'(1X,A,3(T20,A,F7.3,T50,A))') 'INITIALIZED AT:',
: 'THICKNESS(IN) = ',X(1),'(DESIGN VARIABLE #1)',
: 'RING HEIGHT(IN) = ',X(2),'(DESIGN VARIABLE #2)',

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: 'RING WIDTH(IN) = ',X(3),'(DESIGN VARIABLE #3)'
WRITE (8,'(1X,A,3(T30,A,F7.2,2X,A,F7.2))')
: 'BOUNDARY CONSTRAINTS ----',
: 'VARIABLE #1:', VLB(1), 'TO', VUB(1),
: 'VARIABLE #2:', VLB(2), 'TO', VUB(2),
: 'VARIABLE #3:', VLB(3), 'TO', VUB(3)

INFO = -2
CALL ADS (INFO,ISTRAT,IOPT,IONED,IPRINT,IGRAD,NDV,NCON,X,VLB,
: VUB,OBJ,G,IDG,NGT,IC,DF,A,NRA,NCOLA,WK,NRWK,IWK,NRIWK)
IWK(2) = 0
10 CALL ADS (INFO,ISTRAT,IOPT,IONED,IPRINT,IGRAD,NDV,NCON,X,VLB,
: VUB,OBJ,G,IDG,NGT,IC,DF,A,NRA,NCOLA,WK,NRWK,IWK,NRIWK)
IF (INFO .EQ. 0) GOTO 20

T = X(1)
HEIGHT = X(2)
WIDTH = X(3)
RO = OD/2.
R = RO - T/2.
YR = T + HEIGHT/2.
AR = HEIGHT * WIDTH

CALL DAPS3 (PC,RHO,RHOF,TITLE,SIGVOF,SIGVIF,USEVOL,CL)

OBJ = (24.*PI/L) * (R*T*L*RHO + (RO-YR)*AR*(L/LF-1.)*RHOF)

C THE G(1) CONSTRAINT INSURES AXISYMMETRIC COLLAPSE PRESSURE IS
C LESS THAN ANALYSIS PRESSURE
G(1) = 1. - (PC/PSTR)

C THE G(2) CONSTRAINT INSURES ELASTIC MONOCOQUE INSTABILITY
C OR INTER-BAY INSTABILITY PRESSURE IS LESS THAN ANALYSIS PRESSURE
G(2) = 1. - (PIB/PSTR)

C THE G(3) CONSTRAINT INSURES THAT EGI PRESSURE (RING-STIFFENED
C SHELL) IS LESS THAN ANALYSIS PRESSURE
G(3) = 1. - (PGEN/PSTR)

C THE G(4) CONSTRAINT INSURES MID-BAY MEMBRANE STRESS LEVEL
C (VON MISES STRESS, FROM SIGXM AND SIGTM, PER SIGX) IS LESS
C THAN 100% (OF MATERIAL YIELD STRENGTH SIGX)
G(4) = (STR/100.) - 1.

C THE G(5) CONSTRAINT INSURES VON MISES STRESS IN MEMBER AT
C OUTSIDE FRAME IS LESS THAN 100% OF MATERIAL YIELD STRENGTH
G(5) = (SIGVOF/100.) - 1.

C THE G(6) CONSTRAINT INSURES VON MISES STRESS IN MEMBER AT
C INSIDE FRAME IS LESS THAN 100% OF MATERIAL YIELD STRENGTH

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G(6) = (SIGVIF/100.) - 1.

C THE G(7) CONSTRAINT INSURES THAT HOOP STRESS IN THE FRAME (RING)
C IS LESS THAN MATERIAL YIELD STRENGTH
IF (ORTHO.EQ.0) THEN
  G(7) = ABS(SRF/SIGX) - 1.
  ELSEIF ((ORTHO.EQ.1).AND.(SRF.LT.0)) THEN
    G(7) = ABS(SRF/SIGY) - 1.
  ELSEIF ((ORTHO.EQ.1).AND.(SRF.GT.0)) THEN
    G(7) = (SRF/SIGY1) - 1.
ENDIF

C THE G(8) CONSTRAINT LIMITS RING ASPECT TO 4:1 HEIGHT/WIDTH RATIO
G(8) = (HEIGHT/WIDTH)/4. - 1.

GOTO 10
20 CONTINUE

C DEFINE LIMITING MARGIN OF STABILITY (MOS)
MOS1 = PC/PSTR
MOS2 = PIB/PSTR
MOS3 = PGEN/PSTR
MOS = MIN(MOS1,MOS2,MOS3)
C DEFINE LIMITING MARGIN OF STRENGTH (MSS)
MSS1 = STR/100.
MSS2 = SIGVOF/100.
MSS3 = SIGVIF/100.
IF (ORTHO.EQ.0) THEN
  MSS4 = ABS(SRF/SIGX)
  ELSEIF ((ORTHO.EQ.1).AND.(SRF.LT.0)) THEN
    MSS4 = ABS(SRF/SIGY)
  ELSEIF ((ORTHO.EQ.1).AND.(SRF.GT.0)) THEN
    MSS4 = SRF/SIGY1
ENDIF
MSS = MAX(MSS1,MSS2,MSS3,MSS4)
C DEFINE NUMBER OF RINGS (NOR)
NOR = INT((L/LF)-1.)

WRITE (8,'(1X,20H*** OPTIMIZATION OF:(1X,A)') TITLE
WRITE (8,'(T6,A,F7.0,1X,A)') '@ ANALYSIS PRESSURE = ',PSTR,'PSI'
IF (ORTHO.EQ.0) THEN
  WRITE (8,'(T6,A)') 'ISOTROPIC MATERIAL PROPERTIES:'
  ELSE
    WRITE (8,'(T6,A)') 'ORTHOTROPIC MATERIAL PROPERTIES:'
ENDIF
WRITE (8,'(T11,A,T43,A)') '>>>SHELL:','>>>RING:'
WRITE (8,'(T14,A,2PE9.2,1X,A,T46,A,E9.2,1X,A)')
: 'EX = ',EX,'PSI', 'EF = ',EF,'PSI'
IF (ORTHO.EQ.1)
:WRITE (8,'(T14,A,2PE9.2,1X,A)') 'EY = ',EY,'PSI'

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WRITE (8,'(T14,A,1PE9.2,1X,A,T46,A,E9.2,1X,A)')
: 'GXY = ',GXY,'PSI', 'GXY = ',GXY,'PSI'
IF (ORTHO.EQ.0) THEN
  WRITE (8,'(T14,A,F8.0,1X,A,T46,A,F8.0,1X,A)')
: 'YIELD = ',SIGX,'PSI','YIELD = ',SIGX,'PSI'
  ELSE
  WRITE (8,'(T14,A,T46,A)')
: 'YIELD:','YIELD:'
  WRITE (8,'(T14,A,F8.0,1X,A,T46,A,F8.0,1X,A/
: T14,A,F8.0,1X,A,T46,A,F8.0,1X,A)')
: 'HOOP(C) = ',SIGY,'PSI','HOOP(C) = ',SIGY,'PSI',
: 'HOOP(T) = ',SIGY1,'PSI','HOOP(T) = ',SIGY1,'PSI'
  WRITE (8,'(T14,A,F8.0,1X,A/T14,A,F8.0,1X,A)')
: 'AXIAL(C) = ',SIGX,'PSI','AXIAL(T) = ',SIGX1,'PSI'
ENDIF
WRITE (8,'(T14,A,F5.3,1X,A,T46,A,F5.3,1X,A)')
: 'DENSITY = ',RHO,'LB/CU.IN.',
: 'DENSITY = ',RHOF,'LB/CU.IN.'
WRITE (8,'(T14,A,F6.1,1X,A,T46,A,F6.1,1X,A)')
: ' = ',RHO*(12**3),'LB/CU.FT.',
: ' = ',RHOF*(12**3),'LB/CU.FT.'
WRITE (8,'(3(T14,A,F6.3,T46,A,F6.3))')
: 'VXY = ',VXY, 'VXY = ',VXY,
: 'VYX = ',VYX, 'VYX = ',VYX,
: 'VPLAS = ',VPLAS, 'VPLAS = ',VPLAS
WRITE (8,'(3(1X,A,F9.4),3(1X,A,F9.4,T50,A),
: 1X,A,F9.4,1X,1H,(12,1X,6HRINGS)/1X,A,F9.4)')
: 'CRITICAL LENGTH(IN) = ', CL,
: 'LENGTH(IN) = ', L,
: 'OUT.DIAMETER(IN) = ', OD,
: 'THICKNESS(IN) = ',X(1),'(OPTIMIZED VARIABLE #1)',
: 'RING HEIGHT(IN) = ',X(2),'(OPTIMIZED VARIABLE #2)',
: 'RING WIDTH(IN) = ',X(3),'(OPTIMIZED VARIABLE #3)',
: 'RING SPACING(IN) = ',LF,NOR,
: 'INTERBAY WIDTH(IN) = ',LF - X(3)
C NOTE: INTERBAY WIDTH (LS) HAS BEEN REDEFINED AS LS = LF - X(3)
C SO THAT THE ORIGINAL DAPS3 INP VALUE OF LS IS NOT USED.
WRITE (8,'(2(1X,A,F6.4,1X,A))')
: 'SHELL RADIAL DEFLECTION @ MIDBAY = ', WM, 'IN',
: ' @ FRAME = ', WF, 'IN'
IF (MOS.EQ.MOS1) THEN
  WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STABILITY (PC/PSTR) = ', MOS
  ELSEIF (MOS.EQ.MOS2) THEN
  WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STABILITY (PIB/PSTR) = ', MOS
  ELSEIF (MOS.EQ.MOS3) THEN
  WRITE (8,'(1X,A,F6.4)')
: 'LIMITING MARGIN OF STABILITY (PGEN/PSTR) = ', MOS
ENDIF

```

```

IF (MSS.EQ.MSS1) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (STR/YIELD) = ', MSS
ELSEIF (MSS.EQ.MSS2) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SIGVOF/YIELD) = ', MSS
ELSEIF (MSS.EQ.MSS3) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SIGVIF/YIELD) = ', MSS
ELSEIF ((MSS.EQ.MSS4).AND.(ORTHO.EQ.0)) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SRF/YIELD) = ', MSS
ELSEIF ((MSS.EQ.MSS4).AND.(ORTHO.EQ.1).AND.(SRF.LT.0)) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SRF/SIGY) = ', MSS
ELSEIF ((MSS.EQ.MSS4).AND.(ORTHO.EQ.1).AND.(SRF.GT.0)) THEN
  WRITE (8,'(1X,A,F6.4)')
:   'LIMITING MARGIN OF STRENGTH (SRF/SIGY1) = ', MSS
ENDIF
WRITE (8,'(8(1X,A,1PE10.3,T25,A))')
: 'G(1) = ',G(1),'AXISYMMETRIC COLLAPSE PRESSURE      : PC',
: 'G(2) = ',G(2),'MONOCOQUE/INTERBAY INSTABILITY PRESURE : PIB',
: 'G(3) = ',G(3),'ELASTIC GENERAL INSTABILITY PRESSURE : PGEN',
: 'G(4) = ',G(4),'VON MISES MIDBAY MEMBRANE STRESS      : STR',
: 'G(5) = ',G(5),'VON MISES OUTSIDE FRAME MEMBRANE STRESS: SIGVOF',
: 'G(6) = ',G(6),'VON MISES INSIDE FRAME MEMBRANE STRESS : SIGVIF',
: 'G(7) = ',G(7),'HOOP STRESS IN THE FRAME              : SRF',
: 'G(8) = ',G(8),'RING ASPECT RATIO(HT/WDT) .LE. 4:1'
WRITE(8,'(2(1X,A,F10.3),1X,A,F10.3,T50,A/1X,A,F10.3//1X,A,I6//)')
: 'INTERNAL VOLUME(CU.FT/FT.) = ', USEVOL,
: 'INTERNAL VOLUME(CU.FT)      = ', USEVOL*L/12.,
: 'WEIGHT(LB/FT)              = ', OBJ,'(OPTIMIZED OBJECTIVE)',
: 'WEIGHT(LB)                  = ', OBJ*L/12.,
: 'ADS ITERATIONS              = ', IWK(28)
IF (L.LT.CL) THEN
  WRITE (8,'(3(1X,A))')
: 'NOTE: SHELL LENGTH IS LESS THAN MINIMUM CRITICAL LENGTH.',
: 'END PLATE EFFECTS MAY AFFECT REPRESENTATIVE STATES OF STRESS',
: 'AT MID-SPAN OF THE SHELL.'
ENDIF
CLOSE (8,STATUS='KEEP')
END

```

```

C *****
C SUBROUTINE DAPS3 (PC,RHO,RHOF,TITLE,SIGVOF,SIGVIF,USEVOL,CL)
C *****
C (THIS SUBROUTINE IS ESSENTIALLY THE SAME AS THE ORIGINAL DAPS3
C PROGRAM. SOME MODIFICATIONS WERE NECESSARY TO INTEGRATE THIS
C CODE WITH THE THESIS CODE. SUCH MODIFICATIONS ARE NOTED IN
C COMMENT LINES.)

DIMENSION RSAVE(99),WSAVE(99)
INTEGER OK,OKM,OKG,ORTHO,RCOUNT,OKR
REAL IR,L,LS,LF
CHARACTER*70 TITLE(1)
COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R,
: PSTR,STR,SIGX,SIGY,SIGX1,SIGY1,HEIGHT,WIDTH,OD
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
: INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
: NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
COMMON /EMOD/ STRESX(10),STRINX(10),STRESY(10),STRINY(10),
: STRESF(10),STRINF(10),RATIOX,RATIOY,NXPNT,NYPNT,NFPNT
COMMON /GRAPH/ET(28),SIG(28),PB(28),PS(28),ES(28),AAA(6),
: BBB(6),CCC(8),DDD(6),EEE(5),FFF(7),GGG(4),HHH(7),OOO(8),ER(28),
: SIGF(28),SHAPEG(5),SHAPEI(3),WX(101)
COMMON /LAYER/ A11,A22,D11,D22
COMMON /STRESS/ STRX,STRY,PIB,NSAVEI,PGEN,NSAVEG
COMMON /HENRY/ SRF,WM,WF

PI = 4.*ATAN(1.)
ITERAT = 0
RINGSI = 0.
RINGSF = 0.
DRINGS = 0.
3 IF (RINGSI.GT.0.) GO TO 4

C UNIT= 6, FILE =/THESIS DAPSOUT T1: IS DEFINED BY THE THESIS EXEC
C UPON EXECUTION OF THE MAIN PROGRAM (THESIS FORTRAN A1)

100 CONTINUE
10000 CONTINUE

4 IF (NDESIGN.EQ.2) GO TO 5
WRITE (6,60) TITLE(1)
IF (NDESIGN.EQ.1) WRITE (6,64)
5 IF (NDESIGN.EQ.2) WRITE (6,60) TITLE(1)
IF (NDESIGN.EQ.2) WRITE (6,645)
OK = -1
ITERAM= 0
ITERAG= 0
OKM= 0
OKG= 0
RCOUNT= 0

```

```

NOKM= 0
NOKG = 0
NEGLAM = 0
PEL = 0.
IF (RINGSI.GT.0.) GO TO 6
NXPNT = 0
NYPNT = 0
NFPNT = 0
DO 7 I = 1,10
STRESX(I)= 0.
STRINX(I)= 0.
STRESY(I)= 0.
STRINY(I)= 0.
STRESF(I)= 0.
STRINF(I)= 0.
7 CONTINUE
C AR IS COMMENTED OUT TO PREVENT CHANGING INPUT VALUE FM DAPS3 INP
C AR = 0.
RINGS = 0.

10007 IF (NCURVE.EQ.4) GO TO 6

10014 IF (NCURVE.GT.1 .AND. NYPNT.EQ.0) WRITE (6,6100)
IF (NCURVE.EQ.3 .AND. NFPNT.EQ.0) WRITE (6,6110)

6 CONTINUE

IF (PEL.GT.0..AND.NDESIGN.NE.0) WRITE (6,6000)
IF (PEL.GT.0..AND.NDESIGN.NE.0) GO TO 999
IF (NDESIGN.EQ.2) WRITE (6,646) PSTR
EFSAVE = EF
IF (NCURVE.EQ.2) EF = EY
IF (ORTHO.EQ.1) GO TO 8
EY = EX
EF = EX
SIGY1 = SIGX
SIGX1 = SIGX
SIGY = SIGX
STRY = STRX
SIGYNOM = SIGXNOM
GXY = EX/(2.*(1.+VYX))
IF (VPLAS.GT. 0.5) VPLAS = 0.5
8 CONTINUE
IF (ORTHO.EQ.0 .AND. NCURVE.EQ.3) EF = EFSAVE
IF (ORTHO.EQ.0 .AND. NCURVE.LT.3) RHOF = RHO
STRY = ABS(STRY)
STRX = ABS(STRX)
C IF PEL .GT. 0., THEN AT THIS POINT BOTH STRX AND STRY MUST BE
C GREATER THAN ZERO.
IF (EX.LT.10.) EX = 10.

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IF (EY.LT.10.) EY = 10.
VXY = VYX*EX/EY
IF (NDESIGN.EQ.-1) VXY = VYX*A22/A11
IF (NDESIGN.EQ.-1) GO TO 14
IF (VXY.GT.SQRT(EX/EY)/2.) VXY = SQRT(EX/EY)/2.
VYX = VXY*EY/EX
IF (VYX.GT.SQRT(EY/EX)/2.) VYX = SQRT(EY/EX)/2.
VXY = VYX*EX/EY
14 CONTINUE
IF (NDESIGN.GT.-1) GO TO 16
IF (VXY.GT.SQRT(A22/A11)/2.) VXY = SQRT(A22/A11)/2.
VYX = VXY*A11/A22
IF (VYX.GT.SQRT(A11/A22)/2.) VYX = SQRT(A11/A22)/2.
VXY = VYX*A22/A11
16 CONTINUE
IF (VPLAS.LE.0.) VPLAS = VYX
IF (SIGXNOM.LE.0.) SIGXNOM = SIGX
IF (SIGYNOM.LE.0.) SIGYNOM = SIGY
RATIOX = SIGX/SIGXNOM
RATIOY = SIGY/SIGYNOM
DO 9 I = 1,40
WSAVE(I) = 0.
9 RSAVE(I) = 0.
IF (NDESIGN.GT.0 .AND. PSTR.LE.0.) WRITE (6,6300)
IF (NDESIGN.GT.0 .AND. PSTR.LE.0.) GO TO 997
RINGS = AINT(RINGS)
IF (NDESIGN.LT.2) GO TO 10
C REMEMBER, IN NDESIGN = 2 OPTION, NDESIGN IS RESET FROM 2 TO 1
C AFTER SEARCHING. RMAX IS THE MAXIMUM NUMBER OF RINGS CONSIDERED.
IRING = 0
IF (RINGSI.GT.0 .AND.RINGSF.GT.0 .AND.(RINGSF-RINGSI).GT.0)
: IRING = 1
RINGS = RINGSI
RMAX = RINGSF
IF (IRING.EQ.1) GO TO 17
RINGS = 1.
RINGSI = 1.
RMAX = AINT(L/1.5)
IF (RMAX.GT.66.) RMAX = 66.
RINGSF = RMAX
17 CONTINUE
DRINGS = AINT(RMAX/15.)
IF (DRINGS.LT.3.) DRINGS = 3.
IF ((RINGSF-RINGSI).LT.3. .AND.IRING.EQ.1) DRINGS = 1.
10 CONTINUE
C IF (NDESIGN.GT.0) PRINT *, " CALL RIBBIT FROM DAPS3 NEAR LABEL 10"
IF (NDESIGN.GT.0) CALL RIBBIT(RINGS,SECDEP,DW,DASP)
1 OK = OK + 1
IF (NCURVE.EQ.4) OK = 1
INDIC = 0

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```

INDIC3 = 0
INDIC5 = 0
INDIC7 = 0
RO = OD/2.
R = RO - T/2.
RR = RO - YR
IF (NDESIGN.EQ.-1) EXOEY = A22/A11
IF (NDESIGN.GT.-1) EXOEY = EX/EY
CL = PI*(R**2 * T**2 /(3.*(1. - VXY*VYX))*EXOXY)**.25
IF (AR.LE.0.) THEN
  LS = L
  LF = L
END IF
IF (LF.GT.0. .AND. NDESIGN.LE.0) RINGS = L/LF - 1.
IF (RINGS.GT.0. .AND. (RINGS-AINT(RINGS)).GT.5) RINGS = RINGS + 1.
RINGS = AINT(RINGS)
NRINGS = RINGS
IF (PSTR.LE.0.) OK = 1
IF (NDESIGN.GT.0 .AND. OK.EQ.0) INDIC5 = 1
IF (INDIC5.EQ.1) GO TO 15
INDIC7 = 1
C  SETTING INDIC7 = 1 ALLOWS THE FULL FIFTH ORDER SET OF EQUATIONS TO
C  BE USED IN GENERL IN THE FINAL SET OF CALCULATIONS AFTER THE
C  DESIGN ITERATIONS.
IF (NDESIGN.NE.-1) WRITE (6,61) EX,EY,EF,GXY,VXY,VYX,VPLAS
IF (NDESIGN.EQ.-1) WRITE (6,612) A11,A22,D11,D22,GXY,EF,VXY,VYX
IF (PEL.GT.0.) GO TO 11
VOLF = 0.
IF (YR.GT.0.) VOLF = 2.*PI*(RO-YR)*AR*(L/LF-1.)
VOLS = 2.*PI*R*T*L
WEIGHT = 24.*PI/L * (R*T*L*RHO + (RO-YR)*AR*(L/LF-1.)*RHOF)
USEVOL = (L*PI*OD**2/4. - (VOLF+VOLS))/(L*144.)
WRITE (6,615) WEIGHT,USEVOL,RHO,RHOF
11 IF (PEL.GT.0.) WRITE (6,605)
IF (PEL.GT.0.) GO TO 12
IF (AR.GT.0.) WRITE (6,62) OD,L,CL,T,LF
IF (AR.LE.0.) WRITE (6,67) OD,L,CL,T
IF (AR.GT.0.) WRITE (6,625) LS
IF (AR.GT.0.) WRITE (6,63) IR,AR,RR
12 CONTINUE
IF (RINGS.GT.0..AND.NDESIGN.GT.0) WRITE (6,65) HEIGHT,WIDTH,NRINGS
SECTION = T + HEIGHT
IF (WIDTH.GT.0.) ASPECT = HEIGHT/WIDTH
IF (RINGS.GT.0. .AND. NDESIGN.GT.0) WRITE (6,66) SECTION,ASPECT
IF (PEL.LE.0.) GO TO 13
WRITE (6,672) OD,L,CL,T,PEL
WRITE (6,673) STRY,STRX,PSTR
GO TO 40
13 CALL RENSALP(PC,0,SIGVOF,SIGVIF)
IF (PSTR.LE.0.) GO TO 997

```

```

15 CONTINUE
   INDIC = 1
C   PROGRAM CONTROL (GENERAL, INTERBAY, AND AXISYMMETRIC BUCKLING.)
   IF (AR.LE.0.) GO TO 70
   INDIC3 = 1
C   PRINT *, " CALL RENKEN FROM DAPS3 NEAR LABEL 70"
   CALL RENKEN(PINELG)
   IF (NCURVE.EQ.4) WRITE (6,655) PGEN,NSAVEG
   IF (NCURVE.EQ.4) WRITE (6,662) SHAPEG
   IF (NCURVE.EQ.4 .AND. NEGLAM.EQ.1) WRITE (6,663)
70 CONTINUE
C   PRINT *, " CALL RENVON FROM DAPS3 NEAR LABEL 70 "
   CALL RENVON(PINELB)
   IF (NCURVE.EQ.4.AND.AR.GT.0.) WRITE (6,692) PIB,NSAVEI
   IF (NCURVE.EQ.4.AND.AR.LE.0.) WRITE (6,693) PIB,NSAVEI
   IF (NCURVE.EQ.4) WRITE (6,694) SHAPEI
C   IF (NCURVE.EQ.4) GO TO 100
40 CONTINUE
   IF (INDIC3.EQ.0) OKG = 1
   I = 0
   IF (INDIC.EQ.0) CALL REDUCE(PEL,NSAVE,I)
   IF (INDIC.EQ.0) GO TO 997
   IF (INDIC5.NE.1) GO TO 90
C   FROM HERE TO 90 IS ONLY SEEN IN A DESIGN OPTION.
   OKR = 1
   CALL RENSALP(PC,1,SIGVOF,SIGVIF)
   PDUM = AMINI(PC,PINELB)
   CALL ITERM(PDUM)
   IF (OKM.EQ.1 .AND. INDIC3.EQ.0) GO TO 90
   IF (INDIC3.EQ.1) CALL ITERG(PINELG,SECDEP,DW,DASP)
   OKM = 0
   OKG = 0
   IF (INDIC3.EQ.0) OKG = 1
75 ITERAT = ITERAT + 1
   CALL RENSALP(PC,1,SIGVIF,SIGVOF)
C   PRINT *, " CALL RENVON FROM DAPS3 NEAR LABEL 75 "
   CALL RENVON(PINELB)
   PDUM = AMINI(PC,PINELB)
   CALL ITERM(PDUM)
   IF (NOKM.EQ.2) WRITE (6,6200)
   IF (NOKM.EQ.2) THEN
     OKM = 1
     OKG = 1
   END IF
   IF (OKM.EQ.0) GO TO 75
   IF (INDIC3.EQ.0) GO TO 90
76 ITERAT = ITERAT + 1
C   PRINT *, " CALL RENKEN FROM DAPS3 NEAR LABEL 76"
   CALL RENKEN(PINELG)
   CALL ITERG(PINELG,SECDEP,DW,DASP)

```

```

IF (NOKG.EQ. 2) WRITE (6,6200)
IF (NOKG.EQ. 2) THEN
  OKM = 1
  OKG = 1
END IF
IF (OKG.EQ.0) THEN
  OKM = 0
  ITERAM = 0
END IF
IF (OKG.EQ.0) GO TO 76
IF (OKM.EQ.0) THEN
  OKG = 0
  ITERAG = 0
END IF
IF (OKM.EQ.0) GO TO 75
C  WHEN NDESIGN = 1 (WHICH INCLUDES THE FINAL DESIGN OF NDESIGN = 2
C  WHERE NDESIGN WAS RESET TO 1), INDIC7 SERVES THE SOLE PURPOSE OF
C  CAUSING FIRST THE SHELL TO BE DESIGNED USING CUBIC AND THEN
C  REFINED FURTHER TO THE FINAL OPTIMUM DIMENSIONS USING EIGZF (SEE
C  GENERL). THEREFORE ALL FINAL DESIGNS USE EIGZF.
INDIC7 = INDIC7 + 1
IF (INDIC7.EQ.1 .AND. NOKG.LT.2 .AND. NOKM.LT.2) THEN
  OKM = 0
  OKG = 0
  ITERAM = 0
  ITERAG = 0
END IF
IF (OKM.EQ.0 .AND. NDESIGN.EQ.1) GO TO 75
C  INDIC7 DOES NOTHING WHILE NDESIGN IS STILL 2 .
C  PRINT *, " DAPS3 ",RO,T,AR,YR,HEIGHT,WIDTH,LS
IF (NDESIGN.EQ.1) GO TO 90
C  SEARCH FOR OPTIMUM WEIGHT (NDESIGN = 2) IS CONTROLLED HERE.
OKM= 0
ITERAM= 0
OKG= 0
ITERAG= 0
NOKM= 0
NOKG = 0
RCOUNT = RCOUNT + 1
IF (RCOUNT.EQ.99) GO TO 997
WEIGHT = 24.*PI/L * (R*T*L*RIIO + (RO-YR)*AR*(L/LF-1)*RHOF)
RSAVE(RCOUNT) = RINGS
WSAVE(RCOUNT) = WEIGIIT
C  A=SECOND() ---- CALCULATES CPU SECONDS
WRITE (6,666) RINGS,WEIGIIT,ITERAT,A
84  RINGS = RINGS + DRINGS
NRINGS = RINGS
IF (RINGS.GT.RMAX) GO TO 85
CALL RIBBIT(RINGS,SECDEP,DW,DASP)
GO TO 75

```

```

85  CONTINUE
    CALL RCLOSE(RSAVE,WSAVE,RINGS,WEIGHT,RINGSI,DRINGS,RMAX,
1  RCOUNT,OKR)
    IF (OKR.EQ.1) GO TO 84
    ITERAT = 0
    NDESIGN = 1
    RINGSI = RINGS
    RINGSF = RINGS
    DRINGS = 1.
    NRINGS = RINGS
    WRITE (6,6400) NRINGS
    GO TO 3
90  CONTINUE
    NOKM = 0
    NOKG = 0
    C   FOR AN ANALYSIS OF A MONOCOQUE SHELL, OKG = 1 HERE SINCE INDIC3 =
    C   (ABOVE AFTER 40) AND OK = 0 (FIRST TIME THRU) BUT OKM .NE. 1 SO
    C   THE PROGRAM STILL DOES NOT GO TO 1 .
    IF (OKM.EQ.1.AND.OKG.EQ.1.AND.OK.EQ.0) GO TO 1
60  FORMAT (/5H*****,A70)
605 FORMAT (1H0)
61  FORMAT ( /5X,'ELASTIC MODULI' / 7X,'EX = ',2PE10.3,3X,'EY = ',
: E10.3, 3X,'EF = ',E10.3, 3X,'GXY = ',1PE10.3 / 5X,'POISSON RATIO
: S' ,3X,'VXY = ', 0PF5.3, 3X,'VYX = ',F5.3,3X,'VPLAS = ',F5.3)
612 FORMAT ( /5X,'A11 = ',1PE10.3,3X,'A22 = ',E10.3,3X,'D11 = ',E10.3,
: 3X,'D22 = ',E10.3/ 5X,'GXY = ',1PE10.3,3X,'EF = ',E10.3,3X,
: 'VXY = ',0PF5.3,3X,'VYX = ',F5.3)
615 FORMAT (5X,'SHELL WEIGHT = ',F7.2,' LB/FT , INTERNAL VOLUME = ',
: F8.4,' CU.FT./FT./ 5X,'(SKIN DENSITY = ',F6.3,7X,
: 'RING DENSITY = ',F6.3,')/')
62  FORMAT(5X,'OUTSIDE DIAMETER = ',F7.3,' LENGTH = ',F8.3,' CRITI
: CAL LENGTH = ',F5.2/5X,'BAY THICKNESS = ',F5.3,' RING SPACING =
: ',F6.3)
625 FORMAT (5X,'UNSUPPORTED BAY WIDTH = ',F6.3,2X,'(USED FOR INTERBAY
: BUCKLING)')
63  FORMAT (5X,'RING PROPERTIES' /8X,'IX = ',1PE10.3,3X, 'AREA = ',
: E10.3,3X, 'RADIUS TO C.G. = ',0PF7.3)
64  FORMAT(21X,'THIS SHELL IS DESIGNED BY THE PROGRAM. ')
645 FORMAT (4X,'THE DAPS3 SEARCH11 OPTION FOR THE OPTIMUM NUMBER OF RIN
: GS GOES AS FOLLOWS. ')
646 FORMAT ( 25X,'(DESIGN PRESSURE = ',F6.0,' PSI)''' / 8X,
: 'NUMBER OF RINGS',5X,'WEIGHT (LB/FT)',5X,'ITERATIONS',5X,
: 'CP SECONDS' / )
65  FORMAT (8X,'RING HEIGHT = ',F7.3,' RING WIDTH = ',F7.3,4X,'( ,
: I3,' RINGS)')
655 FORMAT ( / 5X,'ELASTIC GENERAL INSTABILITY PRESSURE = ',1PE10.3,
: 3X,'MODE = ',I2)
66  FORMAT(8X,'SECTION DEPTH = ',F7.3,' ASPECT RATIO = ',F7.3)
662 FORMAT ( 5X,'A1=,1PE10.3,' B1=,E10.3,' C1=,E10.3,' B2=,
: E10.3,' C2=,E10.3)

```

```

663  FORMAT ( 5X,'(A NEGATIVE EIGENVALUE WAS IGNORED.)' )
666  FORMAT (13X,F4.0,13X,F8.3,10X,I7,6X,F10.3)
67   FORMAT(5X,'OUTSIDE DIAMETER = ',F7.3,' LENGTH = ',F8.3,' CRITI
:CAL LENGTH = ',F5.2/5X,'SKIN THICKNESS = ',F5.3/5X,'(ANALYSIS IS F
:OR A MONOCOQUE SHELL.')
```

```

672  FORMAT(5X,'OUTSIDE DIAMETER = ',F6.3,' LENGTH = ',F8.3,' CRITI
:CAL LENGTH = ',F5.2/5X,'SKIN THICKNESS = ',F5.3/5X,'THE ELASTIC B
:UCKLING PRESSURE (PRECALCULATED) = ',IPE10.3,' PSI.')
```

```

673  FORMAT (5X,'THE PRECALCULATED STRESS LEVELS IN THE SHELL = ',IPE1
:0.3,' PSI (HOOP) AND ',/5X,IPE10.3,' PSI (AXIAL) FOR AN APPLIED PR
:ESSURE OF ',E10.3,' PSI.')
```

```

692  FORMAT (/5X,'ELASTIC INTER-BAY INSTABILITY PRESSURE = ',IPE10.3,
:3X,'MODE = ',I2)
```

```

693  FORMAT ( /5X,'ELASTIC MONOCOQUE SHELL INSTABILITY PRESSURE = ',
:IPE10.3,2X,'MODE = ',I2)
```

```

694  FORMAT (5X,'BUCKLED SHAPE ... ',2X,'A = ',IPE10.3,2X,' B = ',
:E10.3,2X,' C = ',0PF5.3)
```

```

699  FORMAT (/5X,'(THIS SHELL REQUIRED ',I7,' NUMERICAL ITERATIONS.)')
```

```

6000 FORMAT (5X,'USER WARNING -- YOU CANNOT USE THE DESIGN OPTION WHEN
: PEL IS GREATER THAN 0.')
```

```

6100 FORMAT ( 5X,'NOTE -- NO POINTS ON THE Y-CURVE WERE READ IN SINCE N
:YPNT = 0.')
```

```

6110 FORMAT ( 5X,'NOTE -- NO POINTS ON THE F-CURVE WERE READ IN SINCE N
:FPNT = 0.')
```

```

6200 FORMAT ( 5X,'* ATTEMPTS AT CONVERGENCE FOR THIS DESIGN ARE DISCON
:TINUED.')
```

```

6300 FORMAT (/5X,'USER MESSAGE -- NDESIGN MUST BE 0 OR -1 WHEN PSTR IS
:NEGATIVE.')
```

```

6400 FORMAT ( // 8X,'ALTHOUGH ',I3,' RINGS GIVES THE MINIMUM WEIGHT DES
:IGN, THIS TABLE MAY ',/5X,'SHOW THAT FROM A PRACTICAL DESIGN STAND
:POINT CONSIDERABLY FEWER RINGS ',/5X,'WILL RESULT IN ONLY A SLIGHT
:WEIGHT PENALTY.')
```

```

      IF (DRINGS.LT.1) DRINGS = 1.
      IF (RINGSI.GT.0) RINGSI = RINGSI + DRINGS
      RINGS = RINGSI
      NRINGS = RINGS
      WRITE (6,699) ITERAT
      ITERAT = 0
```

```

C ***** NOTE! *****
C THE NEXT LINE IS USED TO FORCE RETURN TO MAIN PROGRAM.
  IF (ITERAT.GE.0) GO TO 999
C OTHERWISE, AN INFINITE LOOP RESULTS AND FILE =/THESIS DAPSOUT T1
C IS FILLED TO CAPACITY WITHOUT EVER RETURNING TO MAIN THE PROGRAM.
C ***** NOTE! *****
```

```

      IF (RINGSI.LE.RINGSF) GO TO 3
997  RINGSI = 0.
      GO TO 100
999  CONTINUE
```

```

C   CLOSE (UNIT=5,STATUS='KEEP')
C   CLOSE (UNIT=6,STATUS='KEEP')
END

```

```

SUBROUTINE CUBIC(P,A11,B11,A12,B12,A13,B13,A22,B22,A23,B23,
1 A33,B33)
PI = 4.*ATAN(1.)
E1 = -B11*B22*B33 + B23**2*B11 + B33*B12**2 - 2.*B12*B13*B23
1 + B13**2*B22
F1 = A11*B22*B33 + A22*B11*B33 + A33*B11*B22 - 2.*A23*B23*B11
1 - A11*B23**2 - 2.*A12*B12*B33 - A33*B12**2 + 2.*(A12*B13*B23
2 + A13*B12*B23 + A23*B12*B13) - 2.*A13*B22*B13 - A22*B13**2
G1 = -A22*A33*B11 - A11*A33*B22 - A11*A22*B33 + A23**2*B11
1 + 2.*A23*A11*B23 + A12**2*B33 + 2.*A12*A33*B12 - 2.*(A12
2 *A13*B23 + A12*A23*B13 + A23*A13*B12) + A13**2*B22 + 2.*A13
3 *A22*B13
H1 = A11*A22*A33 - A11*A23**2 - A12**2*A33 + 2.*A12*A13*A23
1 - A13**2*A22
B1 = F1/E1
C1 = G1/E1
R1 = SQRT(ABS(C1 - B1**2/3.))**3/27.)
TH1 = ACOS((B1*C1/3.-2.*B1**3 /27.-H1/E1)/2./R1)
X1 = 2.*R1**(1./3.)*COS(TH1/3.) - B1/3.
X2 = 2.*R1**(1./3.)*COS((TH1 + 2.*PI)/3.) - B1/3.
X3 = 2.*R1**(1./3.)*COS((TH1 + 4.*PI)/3.) - B1/3.
P = AMIN1(ABS(X1),ABS(X2),ABS(X3))
RETURN
END

```

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SUBROUTINE CURVE(STRESS,STRAIN,NPNTS,Y,DYDX,E)

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```

C   THIS SUBROUTINE CALCULATES THE TANGENT MODULUS FOR ANY
C   VALUE OF STRESS ON A CURVE AS REQUESTED BY SUBROUTINE MODULI.
DIMENSION STRESS(NPNTS),STRAIN(NPNTS)
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
ISAVE = NPNTS
DO 100 I = 1,NPNTS
ITERAT = ITERAT + 1
IF (Y.LE.STRESS(I)) ISAVE = I
IF (ISAVE.EQ.I) GO TO 150
100 CONTINUE
150 CONTINUE
IF (ISAVE.GT.1) GO TO 200
DYDX = E
RETURN
200 CONTINUE
C   AT THIS POINT, ISAVE IS AT LEAST 2 AND AT MOST 10 .
ERIGHT = (STRESS(ISAVE) - STRESS(ISAVE-1)) / (STRAIN(ISAVE)
1 - STRAIN(ISAVE-1))
IF (ISAVE.EQ.NPNTS .AND. Y.GE.STRESS(NPNTS))DYDX=AMAX1(ERIGHT,10.)

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IF (ISAVE.EQ.NPNTS .AND. Y.GE.STRESS(NPNTS)) RETURN
C   AT THIS POINT, DYDX HAS BEEN CALCULATED AND RETURNED FOR ANY
C   STRESS VALUE .LT. THE FIRST POINT OR .GT. THE LAST POINT ON THE
C   INPUT STRESS-STRAIN CURVE.
IF (ISAVE.EQ.2) ELEFT = E
IF (ISAVE.GT.2) ELEFT = (ERIGHT + (STRESS(ISAVE-1) - STRESS(ISAVE-
1 2)) / (STRAIN(ISAVE-1) - STRAIN(ISAVE-2))) / 2.
IF (ISAVE.LT.NPNTS) ERIGHT = (ERIGHT + (STRESS(ISAVE+1) -
1 STRESS(ISAVE)) / (STRAIN(ISAVE+1) - STRAIN(ISAVE))) / 2.
IF (ERIGHT.GT.ELEFT) GO TO 300
C   ELEFT AND ERIGHT DEFINE A STRAIGHT LINE WITH DYDX ON THIS LINE.
SLOPE = (ERIGHT - ELEFT) / (STRESS(ISAVE) - STRESS(ISAVE-1))
DYDX = ERIGHT + SLOPE*(Y - STRESS(ISAVE))
IF (DYDX.LT.10.) DYDX = 10.
RETURN
300 CONTINUE
WRITE (6,60) STRESS(1),STRAIN(1)
60 FORMAT ( /// 7X,'DAPS3 USER FATAL ERROR MESSAGE ...' // 7X,
1 'THE SLOPE OF THE STRESS-STRAIN CURVE BEGINNING ' // 7X,
2 'WITH THE POINT ( ',IPE10.3, ', ',E10.3, ' ) IS ' // 7X,
3 'NOT MONOTONICALLY DECREASING EVERYWHERE. ' )
STOP 1000
END
SUBROUTINE GENERL(ETX,ETY,EF,VLT,VTL,PGEN,NSAVEP)
C   THIS SUBROUTINE USES THE RENKEN (RENZI-KENDRICK) EQUATIONS TO
C   CALCULATE THE GENERAL INSTABILITY PRESSURE.
C   FOR THE DERIVATION, SEE RENZI, JOHN R., "AXISYMMETRIC STRESSES
C   AND DEFLECTIONS, INTERBAY BUCKLING, AND GENERAL INSTABILITY OF
C   ORTHOTROPIC, HYBRID, RING-STIFFENED CYLINDRICAL SHELLS UNDER
C   EXTERNAL HYDROSTATIC PRESSURE," NAVAL SURFACE WEAPONS
C   CENTER,NSWC
C   TR 80-269, 19 APRIL 1981.
C   EFE, VXI, AND VYX ARE ALWAYS ELASTIC VALUES HERE. EF, VLT, AND
C   VTL ARE PLASTIC VALUES HERE UNLESS THIS ROUTINE IS CALLED DIRECTLY
C   BY RENKEN.
REAL L,IR,K1,K2,K3,KPRIME,N,N2,L2,LF,LF2,LS,A(5,5),B(5,5),
1 BETA(5),WK(50),RALFA(10),RZ(50),RLAM(10),PLAM(11),VRZ(55),JAY
COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GLT,EX,EY,EFE,VXI,VYX,VPLAS,R
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
COMMON /GRAPH/ET(28),SIG(28),PB(28),PS(28),ES(28),AAA(6),
1 BBB(6),CCC(8),DDD(6),EEE(5),FFF(7),GGG(4),HHH(7),OOO(8),ER(28),
2 SIGF(28),SHAPEG(5),SHAPEI(3),WX(101)
COMMON /LAYER/ A11,A22,D11,D22
COMPLEX ALFA(5),Z(5,5),LAMBDA(5)
EQUIVALENCE (ALFA(1),RALFA(1)),(Z(1,1),RZ(1)),(LAMBDA(1),RLAM(1))
double precision da(5,5), db(5,5), dbeta(5)
complex*16 dz(5,5), dalfa(5)
PI = 4.*ATAN(1.)

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```

PI2 = PI**2
PI3 = PI**3
R = RO - T/2.
R2 = R**2
R3 = R**3
ALPHA = RO/R
AL2 = ALPHA**2
T2 = T**2
T3 = T**3
ECC = YR - T/2.
RN = NRINGS
K1 = 4.*(RN + 1.)**2/((2.*RN + 3.)*(2.*RN + 1.))
K2 = 1. + T2/(12.*R2)
K3 = 2. - K2
V2 = VXY*VYX
IF (NDESIGN.EQ.-1) GO TO 200
CYE = EY*T/(1.-V2)
DXE = EX*T3/(12.*(1.-V2))
VT2 = VLT*VTL
CX = ETX*T/(1.-VT2)
CY = ETY*T/(1.-VT2)
DX = ETX*T3/(12.*(1.-VT2))
DY = ETY*T3/(12.*(1.-VT2))
200 CONTINUE
IF (NDESIGN.NE.-1) GO TO 210
CX = A22
CYE = A11
CY = A11
DXE = D22
DX = D22
DY = D11
210 CONTINUE
C PRINT *, " GENERL ",ETX,ETY,EF,VLT,VTL,GLT,T
C PRINT *, "      ",EX,EY,EFE,VXY,VYX,RO,L
C PRINT *, "      ",AR,IR,YR,LF,LS,RN
L2 = L**2
LF2 = LF**2
BB = LF - LS
C FROM HERE THRU GAMFE, ELASTIC PROPERTIES MUST ALWAYS BE USED.
C REMEMBER THAT V2 IS ELASTIC.
THETA = SQRT(SQRT(CYE*(1.- V2))/(4.*DXE*R2)))*LS
RR = RO - YR
AEFF = AR*(R/RR)**2
KPRIME = EFE/R2*(AEFF + BB*T)
APRIME = KPRIME*R2/(CYE*(1.- V2))*(1. - VYX*AL2/2.) -
1 BB*(1. - VXY*ALPHA/2.)
DPRIME = SINH(THETA) + SIN(THETA)
FPRIM1 = 2./(THETA*DPRIME)*(COSH(THETA) - COS(THETA))
GAMSE = CYE*(1.- V2)*APRIME/(R*(KPRIME/FPRIM1 +
1 4.*THETA**4*DXE/LS**3))

```


BET = EFE*(AEFF + BB*T)*(1.- VYX*AL2/2.)/CYE/(1.- V2) -
 1 BB*(1. - VXY*ALPHA/2.)
 GAMFE = -T/CYE/(1.- V2)*((VYX*AL2/2. - 1.) +
 1 BET/(EFE*(AEFF + BB*T)/CYE/(1.- V2) + LS*FPRIM1))
 EOR = ECC/R
 NODICE = 0
 IF (NSAVEP.EQ.-100 .OR. (INDIC7.EQ.0 .AND. NDESIGN.GT.0))
 1 NODICE = 1
 NSAVEP = 2
 DO 81 K = 2,12
 ITERAT = ITERAT + 1
 N = K
 N2 = N**2
 C SETTING JAY = 0. IS THE SAME AS ELIMINATING THE EIGHTH INTEGRAL IN
 C EQUATION (3-56) ON P. 3-23 OF NSWC TR 80-269 BY RENZI. KENDRICK'S
 C ISOTROP SOLUTION DID NOT HAVE THIS ANALOGOUS INTEGRAL. NOR DID
 C HE HAVE THE EXACT DEFINITIONS FOR GAMSE AND GAMFE DEFINED ABOVE
 C AND BY EQUATIONS (3-30) AND (3-44). IN ADDITION, THIS IS THE MOST
 C EXACT CLOSED FORM ORTHOTROPIC SOLUTION PRESENTLY KNOWN.
 JAY = 1.
 A(1,1) = CX*PI3*R/4./L + GLT*PI*T*L*N2*K2/4./R
 B(1,1) = PI*L*N2/4.*(1. - GAMSE/R) + EF*PI*AR*GAMFE*(RN -
 1 1.)*N2/4./T*(1. + EOR)
 A(1,2) = -PI2*N/4.*(GLT*T*K3 + VTL*CX)
 A(2,1) = A(1,2)
 B(1,2) = PI2*R*N/8.
 B(2,1) = B(1,2)
 A(1,3) = PI2/4.*(VTL*CX - GLT*T3*N2/6./R2)
 A(3,1) = A(1,3)
 B(1,3) = -PI2*R/4.
 B(3,1) = B(1,3)
 A(2,2) = CY*PI*L*N2/4./R + GLT*PI3*T*R*K2/4./L +
 1 EF*PI*AR*(RN + 1.)*N2/4./R
 B(2,2) = PI3*R2*AL2/8./L + EF*PI*AR*GAMFE*(RN + 1.)*N2/2./T*JAY
 A(2,3) = -PI*N/4./R*(CY*L + GLT*PI2*T3/6./L +
 1 EF*AR*(RN + 1.)*(1. + EOR*(1. - N2)))
 A(3,2) = A(2,3)
 B(2,3) = PI*N/4./R/T*(L*T*GAMSE +
 1 EF*AR*R*GAMFE*(RN + 1.)*(JAY*(EOR*(N2-1.)-1.)-1.-EOR))
 B(3,2) = B(2,3)
 A(3,3) = PI*L/4./R*(CY + DY/R2*(N2 - 1.))**2 + DX*PI2/L2*(PI2*R2/L2
 1 + 2.*VTL*(N2 - 1.)) + GLT*PI3*T3*N2/12./R/L + EF*PI*AR*(RN + 1.)
 2 /4./R*(1.+EOR*(EOR*(N2 - 1.))**2 + 2.*(1. - N2))) + EF*PI*IR*(RN +
 3 1.)*(N2 - 1.))**2/4./R3
 B(3,3) = PI*L/4.*(EF*AR*GAMFE*N2/T/L*(1. + EOR)*(RN + 1.) - 1.
 1+ PI2*R2*AL2/2./L2 + N2/R*(R - GAMSE))
 IF (NDESIGN.EQ.2.OR.NODICE.EQ.1) GO TO 10
 C ALWAYS USES THE CUBIC WIEN NDESIGN = 2.
 A(1,4) = -PI*N*K1*(GLT*T*K3 + VTL*CX)
 A(4,1) = A(1,4)

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B(1,4) = PI*R*N*K1/2.
B(4,1) = B(1,4)
A(1,5) = PI*K1*(VYX*CX - GLT* T3*N2/6./R2)
A(5,1) = A(1,5)
B(1,5) = -PI*R*K1
B(5,1) = B(1,5)
A(2,4) = CY*L*N2*K1/R + GLT*PI2*T*R*K1*K2/L
A(4,2) = A(2,4)
B(2,4) = K1*PI2*R2*AL2/2./L
B(4,2) = B(2,4)
A(2,5) = -CY*L*N*K1/R -
1 GLT*PI2*T3*N*K1/6./R/L
A(5,2) = A(2,5)
A(3,4) = A(2,5)
A(4,3) = A(2,5)
B(2,5) = L*N*K1*GAMSE/R
B(5,2) = B(2,5)
B(3,4) = B(2,5)
B(4,3) = B(2,5)
A(3,5) = PI2*K1/L/R*(VTL*DX*(N2 - 1.) + DX*PI2*R2/L2 +
1 GLT*T3*N2/3.) + K1*L/R*(CY + DY*(N2 - 1.)*((N2 - 1.)/R2 +
2 VLT*PI2/L2))
A(5,3) = A(3,5)
B(3,5) = K1*PI2*R2*AL2/2./L + K1*L*(N2*(1. - GAMSE/R)-1.)
B(5,3) = B(3,5)
A(4,4) = GLT*PI3*T*R*L*K2/LF2 + 0.75*CY*PI*L*N2/R
B(4,4) = PI3*L/2.*R2*AL2/LF2
A(4,5) = -PI*L*N/2./R*(1.5*CY + GLT*PI2*T3/3./LF2)
A(5,4) = A(4,5)
B(4,5) = 0.75*PI*L*N/R*GAMSE
B(5,4) = B(4,5)
A(5,5) = PI*L/2./R*(1.5*CY + 4.*DX*PI2/LF2*(2.*PI2*R2/LF2 + VTL*(
1 N2 - 1.)) + 1.5*DY/R2*(N2 - 1.)**2) + GLT*PI3*T3*L*N2/3./R/LF2
B(5,5) = PI3*L*R2*AL2/2./LF2 - 0.75*PI*L*(1. + N2*(GAMSE/R - 1.))
C DATA LDA,LDB,IN,LDEVEC/5,5,5,5/ NEW IMSL NAMES
DATA IA,IB,IN,IZ/5,5,5,5/
C
C * * * THE IMSL ROUTINE GVCRG (EIGZF) IS REQUIRED HERE. * * *
do 8833 i = 1, 5
DO 8833 J = 1, 5
DA(I,J) = A(I,J)
DB(I,J) = B(I,J)
8833 continue

CALL dGVCRG(IN,dA,IA,dB,IB,dALFA,dBETA,dZ,IZ)

do 8834 i = 1, 5
ALFA(I) = DALFA(I)
BETA(I) = DBETA(I)
DO 8834 J = 1, 5

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C  SUBROUTINES RIBDW, RIBAR, AND RIBII. (HERE, AR = AREA.)
COMMON AR,IR,YR,LF,LS,DUM1(3),T,GXY,EX,EY,EF,VXY,VYX,VPLAS,
1 DUM2(7),H,W,OD
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
REAL IR,IE,LF,LE,IS,LS
AR = W * H
IR = AR/12.*H**2
YR = T + H/2.
LS = LF - W
RO = OD/2.
R = RO-T/2.
C  IF (T.LE.0.) PRINT *, "IECAL ",H,W,LF,LS,T,ITERAT,RO,R
B = SQRT(SQRT(3.*(1.-VXY*VYX)*EY/EX)/(R*T))*LF
LE = (2.*(LF/B)*(COSH(B)-COS(B)))/(SINH(B)+SIN(B))
AS=LE*T
IS=(AS/12.)*T**2
YBAR=(T/2.*AS+YR*AR)/(AS+AR)
RCG=RO-YBAR
RR=RO-YR
IE = EY/EF*(IS + AS*(R - RCG)**2) + IR + AR*(RR - RCG)**2
RETURN
END
SUBROUTINE ITERG(PIN,SECDEP,DW,DASP)
C  THIS SUBROUTINE PERFORMS THE DESIGN ITERATIONS ON THE RING
C  HEIGHT, WIDTH, ASPECT RATIO, AND SECTION DEPTH AS REQUIRED.
COMMON AREA,IR,YR,LF,LS,DUM1(3),T,DUM2(8),P,DUM3(5),HEIGHT,WIDTH
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
INTEGER OKG
REAL IR,LF,LS
ITERAT = ITERAT + 1
C  PRINT *," ITERG1 ",DUM1(3),T,AREA,YR,HEIGHT,WIDTH,LS
Q = (P-PIN)/AMAX1(P,PIN)
IF (ABS(Q).LT..001) OKG = 1
C  PRINT *," ITERGQ ",P,PIN,Q,OKG
IF (OKG.EQ.1) RETURN
ITERAG = ITERAG + 1
HEIGHT = HEIGHT/(1. - Q/3.)
C  IF (T.LE.0.) PRINT *, "ITERG ",HEIGHT,WIDTH,LF,LS,T,ITERAT,Q,
C  1 ITERAG
IF (ISEC.EQ.1) CALL RIBII(SECDEP)
C  PRINT *," RIBII O ",DUM1(3),T,AREA,YR,HEIGHT,WIDTH,LS
IF (ISEC.EQ.0 .AND. DW.GT.0 .AND. WIDTH.GT.DW) CALL RIBDW(DW)
AR = HEIGHT/WIDTH
IF (AR.LT.DASP) CALL RIBAR(DASP)
C  PRINT *," RIBARO ",DUM1(3),T,AREA,YR,HEIGHT,WIDTH,LS
AR = HEIGHT/WIDTH

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IF (AR.GT.4..AND.WIDTH.LT..125) CALL RIBDW(0.125)
IF (ITERAG.EQ.100) OKG = 1
IF (ITERAG.EQ.100) NOKG = NOKG + 1
AREA = WIDTH * HEIGHT
IR = AREA/12.*HEIGHT**2
YR = T + HEIGHT/2.
LS = LF - WIDTH
C PRINT *, " ITERG2 ",DUM1(3),T,AREA,YR,HEIGHT,WIDTH,LS
RETURN
END
SUBROUTINE ITERM(PIN)
C THIS SUBROUTINE PERFORMS THE DESIGN ITERATIONS ON THE SKIN
C THICKNESS AS CALLED FROM THE MAIN PROGRAM.
COMMON AREA,IR,YR,DUM1(4),RO,T,DUM2(7),R,P,DUM3(5),HEIGHT,WIDTH
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
INTEGER OKM
REAL IR
C PRINT *, " ITERM1 ",RO,T,AREA,YR,HEIGHT,WIDTH,DUM1(2)
ITERAT = ITERAT + 1
Q = (P-PIN)/AMAX1(P,PIN)
IF (ABS(Q).LT..0008) OKM = 1
C PRINT *, " ITERMQ ",P,PIN,Q,OKM
IF (OKM.EQ.1) RETURN
ITERAM = ITERAM + 1
H1 = T
T = T/(1. - Q/3.)
R = RO - T/2.
C IF (T.LE.0.) PRINT * , " ITERM ",HEIGHT,WIDTH,DUM1(1),DUM1(2),
C 1 T,ITERAT,Q,ITERAM
IF (ITERAM.EQ.100) OKM = 1
IF (ITERAM.EQ.100) NOKM = NOKM + 1
IF (AREA.LE.0.) RETURN
HEIGHT = HEIGHT + H1 - T
AREA = WIDTH*HEIGHT
IR = AREA/12.*HEIGHT**2
YR = T + HEIGHT/2.
C PRINT *, " ITERM2 ",RO,T,AREA,YR,HEIGHT,WIDTH,DUM1(2)
RETURN
END
SUBROUTINE LOCAL(ETX,ETY,VXY,VYX,PREN,NSAVE)
C THIS SUBROUTINE USES THE RENVON (RENZI-VON MISES) EQUATIONS TO
C CALCULATE THE INTERBAY OR MONOCOQUE SHELL INSTABILITY PRESSURE.
C THE DERIVATION OF THE EQUATIONS CAN BE FOUND IN NSWC TR 80-269.
C (SEE THE REFERENCE IN SUBROUTINE GENERL.) VXY AND VYX ARE PLASTIC
C VALUES HERE UNLESS THIS ROUTINE IS CALLED DIRECTLY BY RENVON.
COMMON DUM1(4),LS,DUM2(2),RO,T,GXY,DUM3(6),R
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,

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2 NPLO,T,NOKM,NRINGS,NEGLAM,INDIC7
COMMON /GRAPH/ET(28),SIG(28),PB(28),PS(28),ES(28),AAA(6),
1 BBB(6),CCC(8),DDD(6),EEE(5),FFF(7),GGG(4),HHH(7),OOO(8),ER(28),
2 SIGF(28),SHAPEG(5),SHAPEI(3),WX(101)
COMMON /LAYER/ A11,A22,D11,D22
REAL N,N2,N3,N4,LS
PI = 4.*ATAN(1.)
PSAVE = 1000000.
R = RO - T/2.
R2 = R**2
AA = PI*R/LS
AA2 = AA**2
T3 = T**3
V2 = VXY*VYX
IF (NDESIGN.EQ.-1) GO TO 200
CX = ETX*T/(1.-V2)
CY = ETY*T/(1.-V2)
DX = ETX*T3/(12.*(1.-V2))
DY = ETY*T3/(12.*(1.-V2))
200 CONTINUE
IF (NDESIGN.GT.-1) GO TO 210
CX = A22
CY = A11
DX = D22
DY = D11
210 CONTINUE
A3 = VYX*CX*AA
DO 80 NN = 2,20
ITERAT = ITERAT + 1
N = NN
N2 = N**2
N3 = N**3
N4 = N**4
A1 = CX*AA2 + GXY*T*N2
A2 = -VYX*CX*AA*N - GXY*T*AA*N
A4 = CX*AA*(AA2 - VYX*N2)
A5 = CY*N3 - VYX*CX*AA2*N + GXY/6./R2*AA2*T3*N + DY/R2*N3
A6 = CY*(VXY*AA2 - N2) - GXY/6./R2*AA2*T3*N2 - DY/R2*N4
A7 = CX*AA*(VYX*(N2 - 1.) - AA2)
A8 = VYX*DX/R2*AA2*N + GXY/6./R2*AA2*T3*N + CY*N*(VXY*AA2 - N2+1.)
A9 = CY*(N2-VXY*AA2-1.)-DX/R2*AA2*(AA2+VYX*N2)-GXY/6./R2*AA2*T3*N2
A10 = R*(AA2/2. + N2 - 1.)
PREN=((A7*(A3*A5-A2*A6)+A8*(A1*A6-A3*A4))/(A1*A5-A2*A4)-A9)/A10
IF (PREN.GT.PSAVE) GO TO 81
PSAVE = PREN
NSAVE = NN
DEN = A1*A5 - A2*A4
SHAPEI(1) = (A3*A5 - A2*A6)/DEN
SHAPEI(2) = (A1*A6 - A3*A4)/DEN
80 CONTINUE

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81 CONTINUE
  PREN = PSAVE
  SHAPE(3) = 1.
  RETURN
  END
  SUBROUTINE MIDBAY(PSTR,SIGXM,SIGTM,SIGHOT)
C   THIS SUBROUTINE USES SOME OF THE RENSALP EQUATIONS TO CALCU-
C   LATE THE MIDBAY MIDPLANE STRESSES DUE TO A PRESSURE PSTR, AS
C   CALLED FROM REDUCE.
  REAL IR,LF,LS,NETA1,NETA2,N1,N2,L
  COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R
  COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
  1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
  2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
  COMMON /LAYER/ A11,A22,D11,D22
  T3 = T**3
  V2 = VXY*VYX
  R2 = R**2
  IF (NDESIGN.EQ.-1) GO TO 200
  CY = EY*T/(1.-V2)
  DX = EX*T3/(12.*(1.-V2))
200 CONTINUE
  IF (NDESIGN.GT.-1) GO TO 210
  CY = A11
  DX = D22
210 CONTINUE
  B = LF - LS
  RR = RO - YR
  RATIO = RO/R
  IF (PSTR.LT.0.) RATIO = (RO-T)/R
  THETA = LS*(CY*(1.-V2)/(4.*DX*R2))**.25
  GAMMA = PSTR*R2*RATIO**2/(4.*SQRT(DX*CY*(1.-V2)))
  IF (GAMMA.GE.1.) GAMMA = .999
  NETA1 = .5*SQRT(1. - GAMMA)
  NETA2 = .5*SQRT(1. + GAMMA)
  AEFF=AR*(R/RR)**2
  IF (AR.LE.0.) AEFF = ARM
  BETA = EF*(AEFF + B*T)*(1.-VYX/2.*RATIO**2)/(CY*(1.-V2)) -
  1 B*(1.-VXY/2.*RATIO)
  SIGMAU = -PSTR*R/T
  N1 = NETA1*THETA
  N2 = NETA2*THETA
  DEN = COSH(N1)*SINH(N1)/NETA1 + COS(N2)*SIN(N2)/NETA2
  F1 = (COSH(N1)**2 - COS(N2)**2)*4./THETA/DEN
  F2 = (COSH(N1)*SIN(N2)/NETA2 + SINH(N1)*COS(N2)/NETA1)/DEN
  F4 = (+COSH(N1)*SIN(N2)/NETA2 - SINH(N1)*COS(N2)/NETA1)/DEN
  DELTA = EF*(AEFF + B*T) + CY*(1.-V2)*LS*F1
  SIGXBM = 6.*SIGMAU*BETA*F4/(T*DELTA)*SQRT(DX*CY*(1.-V2))
  SIGTMF = SIGMAU*BETA/DELTA*CY*(1.-V2)
  SIGXO = .5*SIGMAU*RATIO**2 + SIGXBM

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SIGXI = .5*SIGMAU*RATIO**2 - SIGXBM
SIGTO = SIGMAU - SIGTMF*F2 + VYX*SIGXBM
SIGTI = SIGMAU - SIGTMF*F2 - VYX*SIGXBM
SIGXM = ABS((SIGXO + SIGXI)/2.)
SIGTM = ABS((SIGTO + SIGTI)/2.)
QSTAR = -PSTR*B*(1.-VXY/2.*RATIO) + SIGTMF*T*LS*F1/R
SIGHOT = ABS(QSTAR*R/(AEFF + B*T)*(R/RR))
RETURN
END
SUBROUTINE MODULI(X,Y,F,ETX,ETY,ETF,VLT,VTL,NCURVE)
C THIS SUBROUTINE, WITH THE HELP OF CURVE, CALCULATES THE TANGENT
C MODULI AS REQUIRED BY SUBROUTINE REDUCE. THE PLASTIC POISSON
C RATIOS ARE ALSO CALCULATED HERE FOR USE IN THE STABILITY ROUTINES.
COMMON DUM1(10),EX,EY,EF,VXY,VYX,VPLAS,DUM2(4),SIGY
COMMON /EMOD/ STRESX(10),STRINX(10),STRESY(10),STRINY(10),
1STRESF(10),STRINF(10),RATIOX,RATIOY,NXPNT,NYPNT,NFPNT
ETX = EX
ETY = EY
ETF = EF
X = X/RATIOX
YSAVE = X
IF (X.LT.STRESX(1)) GO TO 10
CALL CURVE(STRESX,STRINX,NXPNT,X,ETX,EX)
10 X = X*RATIOX
IF (NCURVE.EQ.1) ETY = ETX
IF (NCURVE.EQ.1 .AND. F.GT.STRESX(1)) CALL CURVE(STRESX,
1 STRINX,NXPNT,F,ETF,EX)
IF (NCURVE.EQ.1) GO TO 30
Y = Y/RATIOY
YSAVE = Y
IF (Y.LT.STRESY(1)) GO TO 20
IF (NCURVE.GT.1) CALL CURVE(STRESY,STRINY,NYPNT,Y,ETY,EY)
20 Y = Y*RATIOY
IF (NCURVE.EQ.2 .AND. F.GT.STRESY(1)) CALL CURVE(STRESY,
1 STRINY,NYPNT,F,ETF,EY)
IF (NCURVE.EQ.2) GO TO 30
IF (F.LT.STRESF(1)) GO TO 30
IF (NCURVE.EQ.3) CALL CURVE(STRESF,STRINF,NFPNT,F,ETF,EF)
30 CONTINUE
IF (ETX.GT.EX) ETX = EX
IF (ETY.GT.EY) ETY = EY
IF (ETF.GT.EF) ETF = EF
C Y1 IS THE PROPORTIONAL LIMIT STRESS IN THE HOOP DIRECTION.
Y1 = 0.
IF (NCURVE.EQ.1) Y1 = STRESX(1)
IF (NCURVE.GT.1) Y1 = STRESY(1)
SLOPEV = 0.
IF (Y1.LT.SIGY) SLOPEV = (VPLAS - VYX)/(SIGY - Y1)
B = VYX - SLOPEV*Y1
C LINEAR VARIATION OF VTL FROM Y1 TO SIGY.

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VTL = SLOPEV*YSAVE + B
IF (YSAVE.LT.Y1) VTL = VYX
C BEYOND YIELD, VTL IS HELD CONSTANT AT VPLAS.
IF (YSAVE.GT.SIGY) VTL = VPLAS
VLT = VTL*ETX/ETY
C WORDS OF WISDOM ... THE PRODUCT OF A STRESS COMPONENT AND THE
C CORRESPONDING STRAIN COMPONENT REPRESENTS WORK DONE BY THE
STRESS.
C THE SUM OF THE WORK DONE BY ALL STRESS COMPONENTS MUST BE POSITIVE
C IN ORDER TO AVOID THE CREATION OF ENERGY. ... (P. 42, JONES)
IF (VLT.GT.SQRT(ETX/ETY)/2.) VLT = SQRT(ETX/ETY)/2.
VTL = VLT*ETX/ETX
IF (VTL.GT.SQRT(ETY/ETX)/2.) VTL = SQRT(ETY/ETX)/2.
VLT = VTL*ETX/ETY
C PRINT *, " MODULI ",X,Y,F,ETX,ETY,ETF,VLT,VTL
RETURN
END
SUBROUTINE RCLOSE(RSAVE,WSAVE,RINGS,WEIGHT,RINGSI,DRINGS,RMAX,
1 RCOUNT,OKR)
C THIS SUBROUTINE AIDS IN CLOSING IN ON THE OPTIMUM NUMBER OF
C RINGS IN THE NDESIGN = 2 OPTION.
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
INTEGER RCOUNT,OKR
DIMENSION RSAVE(RCOUNT),WSAVE(RCOUNT)
IMIN = 0
RMIN = 50000.
WMIN = 50000.
DO 100 I = 1,RCOUNT
ITERAT = ITERAT + 1
IF (WSAVE(I) .GE. WMIN) GO TO 100
IMIN = I
RMIN = RSAVE(I)
WMIN = WSAVE(I)
100 CONTINUE
RINGS = RMIN
WEIGHT = WMIN
IF (DRINGS.LE. 1.) GO TO 300
IF (RMIN .LE. RINGSI) GO TO 200
RINGS = RMIN - DRINGS
RSAVE(1) = RINGS
WEIGHT = WSAVE(IMIN-1)
WSAVE(1) = WEIGHT
200 RMAX = RINGS + 2.*DRINGS - 1.
IF (RMIN .LE. RINGSI) RMAX = RINGS + DRINGS - 1.
DRINGS = AINT(DRINGS/2.)
IF (DRINGS .LT. 1.) DRINGS = 1.
RCOUNT = 1
RETURN

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300 OKR = 2
  RETURN
  END
  SUBROUTINE REDUCE(PINEL,NSAVE,J)
C   THIS SUBROUTINE CALCULATES A REDUCED BUCKLING PRESSURE BASED ON
C   THE STRESS LEVEL EXISTING IN THE SHELL AT THE SAME PRESSURE.
  INTEGER OK,OKM,OKG,ORTHO
  REAL L,N,LF,IR,LS
  COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R,
  1 PSTR,STR,SIGX,SIGY,SIGX1,SIGY1,DUM(2),OD
  COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
  1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
  2 NPLOTT,NOKM,NRINGS,NEGLAM,INDIC7
  COMMON /GRAPH/ET(28),SIG(28),PB(28),PS(28),ES(28),AAA(6),
  1 BBB(6),CCC(8),DDD(6),EEE(5),FFF(7),GGG(4),HHH(7),OOO(8),ER(28),
  2 SIGF(28),SHAPEG(5),SHAPEI(3),WX(101)
  COMMON /STRESS/ STRX,STRY,PIB,NSAVEI,PGEN,NSAVEG
  COMMON /HENRY/ SRF,WM,Wf

  PI = 4.*ATAN(1.)
  INDIC6 = 0
  IF (NCURVE .EQ. 4 .AND. NPLOTT .EQ. -2) INDIC6 = 1
C  PRINT *, " REDUCE ",RO,T,AR,YR,DUM(1),DUM(2),LS
C  IF (INDIC6.EQ.1) GO TO 93
  PSI = 0.
  SLOPES = 0.
  SLOPEF = 0.
  PBI = 0.
  PB(1) = 0.
  IF (J.EQ.0) PEL = PINEL
  IF (J.EQ.0) J = 1
C  FOR PROGRAM OPTION 1.B, RESORT TO THE FOLLOWING EFFECTIVE MODULUS
C  MUST BE USED. (IN OPTION 1.A, EX = EY = E.)
  E = SQRT(EX*EY)
  IF (INDIC.EQ.1) CALL MIDBAY(PSTR,STRX,STRY,SF)
C  SF HAS AN INFLUENCE ON THE REDUCTION OF BOTH ISOTROPIC AND ORTHO-
C  TROPIC RING STIFFENED SHELLS SINCE ETF IS USED IN THE RING TERMS.
  IF (NDESIGN.GT.0 .AND. OK.EQ.0) INDIC5 = 1
  IF (ORTHO.EQ.0) THEN
    STRX = SQRT(STRX**2 + STRY**2 - STRX*STRY)
    STRY = STRX
  END IF
  IF (ORTHO.EQ.0) THEN
    YIELDX = SIGY
    YIELDY = SIGY
    SIGX = SIGY
  END IF
  IF (ORTHO.EQ.0) GO TO 47
C  ALPHA IS A MEASURE OF PERCENT YIELD CAUSED BY STRESSES STRX AND
C  STRY. YIELDX AND YIELDY ARE THE STRESSES WHICH WILL CAUSE YIELD.

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S1 = STRX/SIGX
S2 = STRY/SIGY
ALPHA = AMAX1(S1,S2)
YIELDX = STRX/ALPHA
YIELDY = STRY/ALPHA
47 CONTINUE
C (THE NEXT EQUATION COULD EQUALLY BE SLOPES = PSTR*YIELDX/STRX.)
IF(INDIC.EQ.0.OR.INDIC5.EQ.1) SLOPES = 2.*PSTR/(STRX/YIELDX +
1 STRY/YIELDY)
C (INDIC CANNOT = 0 IF INDIC5 = 1.)
IF(INDIC5.EQ.1) SLOPEF = SF*YIELDX/STRX
N = 0.
DS = 0.04
S = -0.04
DO 90 I = 1,28
ITERAT = ITERAT + 1
S = S + DS
SIG(I) = S*100.
C THE VALUES AS CALCULATED IN THE NEXT THREE LINES WILL BE RETAINED
C IF (INDIC.EQ.0 .OR. INDIC5 .EQ. 1) .
PS(I) = SLOPES*S
SX = S*YIELDX
SY = S*YIELDY
SF = S*SLOPEF
IF(INDIC.EQ.0 .OR. INDIC5.EQ.1) GO TO 957
C P1 IS AN ESTIMATE OF THE PRESSURE REQUIRED TO PRODUCE S PERCENT
C YIELD.
P1 = 2.*T/R/SQRT(3.)*S*SQRT(YIELDX**2 + YIELDY**2 - YIELDX*YIELDY)
IF (S.EQ.0.) GO TO 956
955 IF (P1.LE.0.) P1 = PB(I)
ITERAT = ITERAT + 1
CALL MIDBAY(P1,SX,SY,SF)
X1 = SQRT(SX**2 + SY**2 - SX*SY)/SIGX
S1 = SX/SIGX
S2 = SY/SIGY
IF (ORTHO.EQ.1) X1 = AMAX1(S1,S2)
ERO = (S-X1)/AMAX1(S,X1)
P1 = P1/(1.-ERO/2.)
IF (ABS(ERO).GT..001) GO TO 955
C P1 IS NOW EXACTLY (WITHIN .1 PERCENT) THE PRESSURE REQUIRED TO
C PRODUCE S PERCENT YIELD AT MIDBAY, MID-PLANE OF THE SHELL. SF IS
C THE STRESS IN THE FRAME AT P1.
956 CONTINUE
PS(I) = P1
SIGF(I) = SF
957 CONTINUE
IF (ORTHO.EQ.0) THEN
SX = SQRT(SX**2 + SY**2 - SX*SY)
SY = SX
END IF

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CALL MODULI(SX,SY,SF,ETX,ETY,ETF,VLT,VTL,NCURVE)
C  ARRAY ET(I) IS AXIAL MODULUS.  ARRAY ES(I) IS HOOP MODULUS.
C  ER(I) IS RING MODULUS.
  ET(I) = ETX
  ES(I) = ETY
  ER(I) = ETF
C  THE EFFECTIVE MODULUS IS ONLY USED FOR OPTION 1.B .
  ETI = SQRT(ETX*ETY)
  IF (INDIC.EQ.0) PB(I) = PEL*ETI/E
  INDICM = 0
  INDICG = 0
  IF (I.EQ.1) GO TO 30
  IF (ET(I).EQ.ET(I-1) .AND. ES(I).EQ.ES(I-1)) INDICM = 1
  IF (INDICM.EQ.1 .AND. ER(I).EQ.ER(I-1)) INDICG = 1
30 CONTINUE
  IF (INDIC.EQ.1 .AND. J.EQ.1 .AND. INDICM.EQ.0)
1 CALL LOCAL(ETX,ETY,VLT,VTL,PB(I),NSAVE)
  IF (INDIC.EQ.1 .AND. J.EQ.1 .AND. INDICM.EQ.1) PB(I) = PB(I-1)
  IF (J.EQ.2 .AND. INDICG.EQ.0)
1 CALL GENERAL(ETX,ETY,ETF,VLT,VTL,PB(I),NSAVE)
  IF (J.EQ.2 .AND. INDICG.EQ.1) PB(I) = PB(I-1)
  IF (I.EQ.28) PB(I) = 0.
C  PRINT *, " REDUCEP ",ETX,ETY,ETF,VLT,VTL,PS(I),PB(I),NSAVE,J
  IF (N.EQ.1..OR.PB(I).GT.PS(I)) GO TO 90
  N = 1.
  SSAVE = SIG(I-1)/100.
  IF (INDIC5.EQ.1) GO TO 95
90 CONTINUE
95 CONTINUE
  IF (INDIC.EQ.0) THEN
    ETSAVE = E
    ESSAVE = E
  END IF
  DS = 0.004
  S = SSAVE - 2.*DS
  N = 0.
  DO 89 I=1,13
  ITERAT = ITERAT + 1
  IF (N.EQ.1.) GO TO 86
  S = S + DS
  PSI = SLOPES*S
  SX = S*YIELDX
  SY = S*YIELDY
  SF = S*SLOPEF
  IF (INDIC.EQ.0 .OR. INDIC5.EQ.1) GO TO 857
  P1 = 2.*T/R/SQRT(3.)*S*SQRT(YIELDX**2 + YIELDY**2 - YIELDX*YIELDY)
855 IF (P1.LE.0.) P1 = PBI
  ITERAT = ITERAT + 1
  CALL MIDBAY(P1,SX,SY,SF)
  X1 = SQRT(SX**2 + SY**2 - SX*SY)/SIGX

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S1 = SX/SIGX
S2 = SY/SIGY
IF (ORTHO.EQ.1) X1 = AMAX1(S1,S2)
ERO = (S-X1)/AMAX1(S,X1)
P1 = P1/(1. - ERO/2.)
IF (ABS(ERO).GT..001) GO TO 855
PS1 = P1
857 CONTINUE
IF (ORTHO.EQ.0) THEN
  SX = SQRT(SX**2 + SY**2 - SX*SY)
  SY = SX
END IF
C PRINT *, " CALL MODULI FROM REDUCE NEAR LABEL 857"
CALL MODULI(SX,SY,SF,ETX,ETY,ETF,VL,VTL,NCURVE)
C THE EFFECTIVE MODULUS IS ONLY USED FOR OPTION 1.B .
ETI = SQRT(ETX*ETY)
ETSAVE = ETX
ESSAVE = ETY
EFSAVE = ETF
IF (INDIC.EQ.0) PBI = PEL*ETI/E
INDICM = 0
INDICG = 0
IF (1.EQ.1) GO TO 40
IF (ETX.EQ.ETSAVE .AND. ETY.EQ.ESSAVE) INDICM = 1
IF (INDICM.EQ.1 .AND. ETF.EQ.EFSAVE) INDICG = 1
40 CONTINUE
IF (INDIC.EQ.1 .AND. J.EQ.1 .AND. INDICM.EQ.0)
1 CALL LOCAL(ETX,ETY,VL,VTL,PBI,NSAVE)
IF (J.EQ.2 .AND. INDICG.EQ.0)
1 CALL GENERL(ETX,ETY,ETF,VL,VTL,PBI,NSAVE)
IF (1.EQ.13) PBI = 0.
IF (N.EQ.1..OR.PBI.GT.PSI) GO TO 87
N = 1.
SLOPEB = (PBI - PSAVE)/DS
SSLOPE = (PSI - SSAVE)/DS
BINTER = PBI - SLOPEB*S
SINTER = PSI - SSLOPE*S
SIGMA = (SINTER - BINTER)/(SLOPEB - SSLOPE)
PINEL = SSLOPE*SIGMA + SINTER
87 PSAVE = PBI
SSAVE = PSI
89 CONTINUE
86 CONTINUE
C IF (T.LE.0.) PRINT *, " REDUCE ",T,ITERAT,PINEL,ITERAM,ITERAG
IF (INDIC5.EQ.1) GO TO 99
IF (INDIC.EQ.1.AND.AR.GT.0..AND.J.EQ.1) WRITE (6,692) PIB,NSAVEI
IF (INDIC.EQ.1.AND.AR.LE.0..AND.J.EQ.1) WRITE (6,693) PIB,NSAVEI
IF (J.EQ.2) WRITE (6,655) PGEN,NSAVEG
SIGMA = SIGMA*100.
WRITE (6,698) PINEL,NSAVE,SIGMA

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IF (INDIC.EQ.1 .AND. J.EQ.1) WRITE (6,694) SHAPE1
IF (J.EQ.2) WRITE (6,662) SHAPEG
IF (J.EQ.2 .AND. NEGLAM.EQ.1) WRITE (6,663)
C * * * * * P L O T O U T P U T R E M O V E D * * * * *
IF (NPLOT.GT.0) GO TO 99
655 FORMAT ( / 5X,'ELASTIC GENERAL INSTABILITY PRESSURE = ',1PE10.3,
15X,'MODE = ',I2)
662 FORMAT ( 5X,'A1=',1PE10.3,' B1=',E10.3,' C1=',E10.3,' B2=',
1 E10.3,' C2=',E10.3)
663 FORMAT ( 5X,'(A NEGATIVE EIGENVALUE WAS IGNORED.) ' )
692 FORMAT ( /5X,'ELASTIC INTER-BAY INSTABILITY PRESSURE = ',1PE10.3,
13X,'MODE = ',I2)
693 FORMAT ( /5X,'ELASTIC MONOCOQUE SHELL INSTABILITY PRESSURE = ',
1 1PE10.3,2X,'MODE = ',I2)
694 FORMAT (5X,'BUCKLED SHAPE ... ',2X,'A = ',1PE10.3,2X,' B = ',
1 E10.3,2X,' C = ',0PF5.3)
698 FORMAT ( 5X,'** INELASTIC BUCKLING PRESSURE = ',1PE10.3,1X,'PSI
1,',4X,'MODE = ',I2/ 5X,'THE STRESS LEVEL IN THE SHELL = ',
2 0PF10.4,' PERCENT YIELD.')
801 FORMAT(' INELASTIC BUCKLING PRESSURE = ',1PE10.3,' PSI, MODE = ',
1 I2)
802 FORMAT(' THE REPRESENTATIVE STRESS LEVEL = ',F10.4,' PERCENT YIELD
1 ')
803 FORMAT(' YIELD STRESSES LC = ',F7.0,' LT = ',F7.0,' HC = ',
1 F7.0,' HT = ',F7.0,' PSI ')
804 FORMAT(' SHELL LENGTH = ',F8.3,' IN, OD = ',F7.3,' T = ',F5.3)
805 FORMAT(' ELASTIC BUCKLING PRESSURE = ',1PE10.3,' PSI')
806 FORMAT(' MIDBAY, MIDPLANE STRESSES = ',1PE10.3,' (HOOP) AND ',
1 E10.3,' (AXIAL) ')
807 FORMAT(' UNDER A PRESSURE OF ',1PE10.3,' PSI.')
808 FORMAT(' YIELD STRESSES LC = ',F7.0,' LT = ',F7.0,' HC = ',
1 F7.0,' HT = ',F7.0,' PSI ')
99 CONTINUE
RETURN
END
SUBROUTINE RENKEN(PINELG)
C THIS SUBROUTINE DIRECTLY CALLS GENERL TO CALCULATE THE ELASTIC
C GENERAL INSTABILITY PRESSURE WHEN INDIC5 = 0 . WHEN NCURVE .NE. 4
C REDUCE IS CALLED WHICH CALLS GENERL TO CALCULATE THE INELASTIC
C VALUE BY USING TANGENT MODULI.
COMMON DUM(10),EX,EY,EF,VXY,VYX
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTI10,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
COMMON /STRESS/ STRX,STRY,PIB,NSAVEI,PGEN,NSAVEG
J = 2
IF (INDIC5.EQ.0) CALL GENERL(EX,EY,EF,VXY,VYX,PGEN,NSAVEG)
IF (NCURVE.EQ.4 .AND. NPLOT.EQ.-2) CALL REDUCE(PINEL,NSAVE,J)
C PINEL AND NSAVE IN THE ABOVE CALL IS DUMMY SINCE PGEN AND NSAVEG
C IS IN COMMON WITH REDUCE.

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IF (NCURVE.EQ.4) RETURN
C PRINT *, " CALL REDUCE FROM RENKEN"
CALL REDUCE(PINEL,NSAVE,J)
PINELG = PINEL
RETURN
END
SUBROUTINE RENSALP(PC,OKT,SIGVOF,SIGVIF)
C THIS SUBROUTINE USES NONLINEAR STRESS EQUATIONS (WHICH INCLUDE
C THE BEAM-COLUMN NONLINEARITY PRODUCED BY AXIAL COMPRESSION WITH
C AXIAL BENDING) TO CALCULATE THE AXISYMMETRIC ELASTIC DEFORMATIONS
C AND STRESSES IN A RING-STIFFENED CIRCULAR CYLINDRICAL SHELL UNDER
C HYDROSTATIC PRESSURE. THESE SAME EQUATIONS ARE USED TO CALCULATE
C THE AXISYMMETRIC COLLAPSE PRESSURE. THE RENSALP (RENZI-SALERNO-
C PULOS) EQUATIONS ARE GOOD FOR ORTHOTROPIC HYBRID SHELLS AS WELL
C AS ISOTROPIC SHELLS.
C FOR THE DERIVATION, SEE RENZI, JOHNSON R., "OPTIMIZATION OF
C ORTHOTROPIC, NON-LINEAR, RING-STIFFENED CYLINDRICAL SHELLS UNDER
C EXTERNAL HYDROSTATIC PRESSURE AS APPLIED TO MMC MATERIALS", NSWC
C TR 79-305, 30 SEPTEMBER 1979. SEE ALSO RENZI, NSWC TR 80-269.
INTEGER OKT,ORTHO
REAL IR,LF,LS,NETA1,NETA2,N1,N2,L,KSI(10)
COMMON AR,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R,
: PSAV,STR,SIGX,SIGY,SIGX1,SIGY1
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
: INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
: NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
COMMON /EMOD/ STRESX(10),STRINX(10),STRESY(10),STRINY(10),
: STRESF(10),STRINF(10),RATIOX,RATIOY,NXPNT,NYPNT,NFPNT
COMMON /LAYER/ A11,A22,D11,D22
COMMON /HENRY/ SRF,WM,WF
C WHEN OKT = 1, RENSALP IS EXPRESSLY USED TO QUICKLY CALCULATE THE
C AXISYMMETRIC COLLAPSE PRESSURE.
C PRINT *, " RENSALP ",RO,T,AR,YR,LS
T3 = T**3
V2 = VXY*VYX
IF (NDESIGN.EQ.-1) GO TO 470
CY = EY*T/(1.-V2)
DX = EX*T3/(12.*(1.-V2))
IF (NDESIGN.GT.-1) GO TO 480
470 CONTINUE
CY = A11
DX = D22
480 CONTINUE
PSTR = PSAV
B = LF - LS
RR = RO - YR
R = RO - T/2.
R2 = R**2
RATIO = RO/R
INDIC2 = 0

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IF (OKT.EQ.1) GO TO 490
IF (PSAV.LT.0.) RATIO = (RO-T)/R
IF (NDESIGN.LT.1) WRITE (6,60) PSAV
IF (NDESIGN.EQ.1) WRITE (6,61) PSAV
490 CONTINUE
THETA = LS*(CY*(1.-V2)/(4.*DX*R2))**.25
AEFF=AR*(R/RR)**2
IF (AR.LE.0.) AEFF = ARM
BETA = EF*(AEFF + B*T)*(1.-VYX/2.*RATIO**2)/(CY*(1.-V2)) -
1 B*(1.-VXY/2.*RATIO)
600 GAMMA = PSTR*R2*RATIO**2/(4.*SQRT(DX*CY*(1.-V2)))
ITERAT = ITERAT + 1
IF (GAMMA.GE.1.) GAMMA = .999
NETA1 = .5*SQRT(1. - GAMMA)
NETA2 = .5*SQRT(1. + GAMMA)
SIGMAU = -PSTR*R/T
N1 = NETA1*THETA
N2 = NETA2*THETA
DEN = COSH(N1)*SINH(N1)/NETA1 + COS(N2)*SIN(N2)/NETA2
F1 = (COSH(N1)**2 - COS(N2)**2)*4./THETA/DEN
F2 = (COSH(N1)*SIN(N2)/NETA2 + SINH(N1)*COS(N2)/NETA1)/DEN
F4 = (+COSH(N1)*SIN(N2)/NETA2 - SINH(N1)*COS(N2)/NETA1)/DEN
DELTA = EF*(AEFF + B*T) + CY*(1.-V2)*LS*F1
IF (OKT.EQ.1 .OR. INDIC2.EQ.1) GO TO 700
F3 = (-COSH(N1)*SINH(N1)/NETA1 + COS(N2)*SIN(N2)/NETA2)/DEN
F5 = (COSH(N1)*SIN(N2)/NETA1 - SINH(N1)*COS(N2)/NETA2)/DEN
FAC4 = F2*COSH(N1)*COS(N2) + F5*SINH(N1)*SIN(N2)
SIGXBM = 6.*SIGMAU*BETA*F4/(T*DELTA)*SQRT(DX*CY*(1.-V2))
SIGTMF = SIGMAU*BETA/DELTA*CY*(1.-V2)
FAC2 = 6.*SIGTMF*F3*SQRT(DX/(CY*(1.-V2)))/T
SIGXO = .5*SIGMAU*RATIO**2 + SIGXBM
SIGX1 = .5*SIGMAU*RATIO**2 - SIGXBM
SIGTO = SIGMAU - SIGTMF*F2 + VYX*SIGXBM
SIGTI = SIGMAU - SIGTMF*F2 - VYX*SIGXBM
SIGXM = (SIGXO+SIGX1)/2.
SIGTM = (SIGTO+SIGTI)/2.
SXI = ABS(SIGX1/SIGX)
SXO = ABS(SIGXO/SIGX)
STI = ABS(SIGTI/SIGY)
STO = ABS(SIGTO/SIGY)
IF (SIGX1.GT.0.) SX1 = SIGX1/SIGX1
IF (SIGXO.GT.0.) SXO = SIGXO/SIGX1
IF (SIGTI.GT.0.) STI = SIGTI/SIGY1
IF (SIGTO.GT.0.) STO = SIGTO/SIGY1
C KEEP IN MIND THAT FOR ORTHO = 0, SIGX = SIGY = SIGX1 = SIGY1.
IF (ORTHO.EQ.0) SIGVO=SQRT(SIGTO**2+SIGXO**2-SIGTO*SIGXO)/
1SIGX*100.
IF (ORTHO.EQ.0) SIGVI = SQRT(SIGTI**2+SIGX1**2-SIGTI*SIGX1) /
1SIGX*100.
IF(ORTHO.EQ.1) SIGVO = AMAX1(SXO,STO)*100.

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IF(ORTHO.EQ.1) SIGVI = AMAX1(SXI,STI)*100.
SIGXOF = .5*SIGMAU*RATIO**2 + FAC2
SIGXIF = .5*SIGMAU*RATIO**2 - FAC2
SIGTOF = SIGMAU - SIGTMF + VYX*FAC2
SIGTIF = SIGMAU - SIGTMF - VYX*FAC2
SXI = ABS(SIGXIF/SIGX)
SXO = ABS(SIGXOF/SIGX)
STI = ABS(SIGTIF/SIGY)
STO = ABS(SIGTOF/SIGY)
IF (SIGXIF.GT.0.) SXI = SIGXIF/SIGX1
IF (SIGXOF.GT.0.) SXO = SIGXOF/SIGX1
IF (SIGTIF.GT.0.) STI = SIGTIF/SIGY1
IF (SIGTOF.GT.0.) STO = SIGTOF/SIGY1
IF (ORTHO.EQ.0) SIGVOF = SQRT(SIGTOF**2+SIGXOF**2-SIGTOF*SIGXOF) /
1SIGX*100.
IF (ORTHO.EQ.0) SIGVIF = SQRT(SIGTIF**2+SIGXIF**2-SIGTIF*SIGXIF) /
1SIGX*100.
IF(ORTHO.EQ.1) SIGVOF = AMAX1(SXO,STO)*100.
IF(ORTHO.EQ.1) SIGVIF = AMAX1(SXI,STI)*100.
QSTAR = -PSTR*B*(1.-VXY/2.*RATIO) + SIGTMF*T*LS*F1/R
SIGHT = QSTAR*R/(AEFF + B*T)*(R/RR)
SRF = SIGHT
WINF = -PSTR*R2*(1. - VYX/2.*RATIO**2)/(CY*(1.-V2))
WM = WINF + PSTR*R2*BETA*F2/DELTA
WF = WINF + PSTR*R2*BETA*FAC4/DELTA
SXI = ABS(SIGXM/SIGX)
STI = ABS(SIGTM/SIGY)
IF (SIGXM.GT.0.) SXI = SIGXM/SIGX1
IF (SIGTM.GT.0.) STI = SIGTM/SIGY1
IF (ORTHO.EQ.0) STR = SQRT(SIGXM**2+SIGTM**2
1 - SIGXM*SIGTM)/SIGX*100.
IF(ORTHO.EQ.1) STR = AMAX1(SXI,STI)*100.
WRITE(6,100)
WRITE(6,200) SIGXO,SIGX1,SIGTO,SIGTI,SIGVO,SIGVI,WM
WRITE(6,50)STR
WRITE(6,250)
WRITE(6,200) SIGXOF,SIGXIF,SIGTOF,SIGTIF,SIGVOF,SIGVIF,WF
WRITE(6,300)SIGHT
IF (ORTHO.EQ.0) WRITE (6,320)
IF (ORTHO.EQ.1) WRITE (6,322)
WRITE (6,325) SIGY,SIGX,SIGY1,SIGX1
IF (NCURVE.EQ.4) GO TO 80
WRITE (6,310)
DO 70 I=1,NXPNT
70 KSI(I) = STRESX(I)/1000.
WRITE (6,311) (KSI(I),I=1,NXPNT)
WRITE (6,314) (STRINX(I),I=1,NXPNT)
IF (NCURVE.EQ.1) GO TO 80
DO 71 I = 1,NYPNT
71 KSI(I) = STRESY(I)/1000.

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WRITE (6,312) (KSI(I),I=1,NYPNT)
WRITE (6,314) (STRINY(I),I=1,NYPNT)
IF (NCURVE.EQ.2) GO TO 80
DO 72 I = 1,NFPNT
72 KSI(I) = STRESF(I)/1000.
WRITE (6,313) (KSI(I),I=1,NFPNT)
WRITE (6,314) (STRINF(I),I=1,NFPNT)
80 CONTINUE
INDIC2 = 1
IF (PSAV.LE.0.) RETURN
700 A = 6.*BETA*F4/(T*DELTA)*SQRT(DX*CY*(1.-V2))
R5 = -1. + BETA/DELTA*CY*(1.-V2)*F2 - VYX*A
R6 = -0.5*RATIO**2 - A
IF (ORTHO.EQ.0) PC = SIGX*T/R/SQRT(R5**2+R6**2-R5*R6)
IF (ORTHO.EQ.0) GO TO 701
PCX = ABS(SIGX*T/R/R6)
PCY = ABS(SIGY*T/R/R5)
PC = AMIN1(PCX,PCY)
701 CONTINUE
ER = (PSTR-PC)/AMAX1(PSTR,PC)
PSTR=PC/(1.-ER/2.)
IF (ABS(ER).GT..001) GO TO 600
IF (OKT.EQ.1) RETURN
WRITE (6,350) PC
RETURN
50 FORMAT( /5X,'CALCULATED MIDBAY MEMBRANE STRESS LEVEL IS ',F10.4,'
1PERCENT YIELD.')
60 FORMAT ( /5X,'ANALYSIS PRESSURE IS ',F7.0,' PSI')
61 FORMAT ( /5X,'DESIGN PRESSURE IS ',F6.0,' PSI')
100 FORMAT( /5X,'SHELL STRESSES AT MIDBAY')
200 FORMAT( /35X,'OUTSIDE',I2X,'INSIDE',/,10X,'LONGITUDINAL (PSI)',4X,
1F10.0,8X,F10.0/,10X,'CIRCUMFERENTIAL (PSI)',1X, F10.0,8X,F10.0/,
210X,'PERCENT YIELD ',6X,F10.4,8X,F10.4, /,10X,
3'RADIAL DEFLECTION (IN.)',6X,F7.4)
250 FORMAT( /5X,'SHELL STRESSES AT THE FRAME')
300 FORMAT(10X,'HOOP STRESS IN FRAME (PSI)',F10.0)
310 FORMAT ( 5X,'STRESS-STRAIN DATA ECHIO ... (STRESS IS IN KSI FOR EC
1HO ONLY.)')
311 FORMAT ( 5X,'X',10(1X,F6.2))
312 FORMAT ( 5X,'Y',10(1X,F6.2))
313 FORMAT ( 5X,'F',10(1X,F6.2))
314 FORMAT ( 6X,10(1X,F6.5))
320 FORMAT (/5X,'* YIELD STRESSES (USED WITH VON MISES YIELD CRITERI
1ON) ')
322 FORMAT (/5X,'* YIELD STRESSES (USED WITH MAXIMUM STRESS YIELD CR
1ITERION) ')
325 FORMAT ( 24X,'HOOP (C) = ',F7.0,' PSI',8X,'AXIAL (C) = ',F7.0,
1 ' PSI '/24X,'HOOP (T) = ',F7.0,' PSI',8X,'AXIAL (T) = ',F7.0,
2 ' PSI ')
350 FORMAT( /5X,'AXISYMMETRIC COLLAPSE PRESSURE = ',F6.0, ' PSI, BASED

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1 ON OUTER FIBER ',6X,'STRESSES AT MID-BAY.')
```

END

SUBROUTINE RENVON(PINELB)

C THIS SUBROUTINE DIRECTLY CALLS LOCAL TO CALCULATE THE ELASTIC

C INTERBAY OR MONOCOQUE SHELL INSTABILITY PRESSURE WHEN INDIC5 = 0

.

C WHEN NCURVE .NE. 4, REDUCE IS CALLED WHICH CALLS LOCAL TO CALCU-

C LATE THE INELASTIC VALUE BY USING TANGENT MODULI.

COMMON DUM(10),EX,EY,EF,VXY,VYX

COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,

1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,

2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7

COMMON /STRESS/ STRX,STRY,PIB,NSAVEI,PGEN,NSAVEG

IF (INDIC5.EQ.0) CALL LOCAL(EX,EY,VXY,VYX,PIB,NSAVEI)

IF (NCURVE.EQ.4) RETURN

J = 1

C PRINT *, " CALL REDUCE FROM RENVON"

CALL REDUCE(PINEL,NSAVEI,J)

PINELB = PINEL

RETURN

END

SUBROUTINE RIBAR(DASP)

C THIS SUBROUTINE MODIFIES EXISTING RIB DIMENSIONS TO GIVE A

C DESIRED ASPECT RATIO WITHOUT AFFECTING SHELL INERTIA.

C H = RIB HEIGHT, W = RIB WIDTH, DASP = DESIRED ASPECT RATIO.

COMMON DUM(23),H,W

COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,

1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,

2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7

REAL IE,IE1

CALL IECAL(IE)

C PRINT *," RIBARI ",DUM(8),DUM(9),DUM(1),DUM(3),H,W,DUM(5)

DO 50 I = 1,300

ITERAT = ITERAT + 1

W = H/DASP

CALL IECAL(IE1)

Q = (IE-IE1)/AMAX1(IE,IE1)

IF (ABS(Q).LT..0001) RETURN

H = H/(1.-Q/2.)

50 CONTINUE

CALL IECAL(IE)

RETURN

END

SUBROUTINE RIBBIT(RINGS,SECDEP,DW,DASP)

C THIS SUBROUTINE WHIPS UP A GOOD INITIAL DESIGN OF A MONOCOQUE

C OR RING STIFFENED SHELL FROM WHICH THE MANY REFINEMENTS ARE MADE

C THROUGHOUT THE PROGRAM IN THE DESIGN OPTION.

COMMON AREA,IR,YR,LF,LS,ARM,L,RO,T,GXY,EX,EY,EF,VXY,VYX,VPLAS,R,

1 P,STR,SIGX,SIGY,DUM1(2),H,W,OD

COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,

```

1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
INTEGER ORTHO
REAL IR,K,L,LF,LS
C PRINT *, " RIBBITT",RO,T,AREA,YR,H,W,LS
SIGMAY = SQRT(SIGX**2 + SIGY**2 - SIGX*SIGY)
ETX = EX
ETY = EY
ETF = EF
VLT = VXY
VTL = VYX
IF (NCURVE.EQ.4) GO TO 10
C ASSUME 80 PERCENT YIELD AND A STRESS RATIO OF 2.
S = .8
K = .5
SF = S*SIGMAY
SY = SF
SX = K*SY
IF (ORTHO.EQ.0) THEN
SX = SQRT(SX**2 + SY**2 - SX*SY)
SY = SX
END IF
C PRINT *, " CALL MODULI FROM RIBBIT"
CALL MODULI(SX,SY,SF,ETX,ETY,ETF,VLT,VTL,NCURVE)
10 CONTINUE
RO = OD/2.
NRINGS = RINGS
LS = L/(RINGS + 1.)
LF = LS
T = P*RO/(2./SQRT(3.)*SIGMAY + P/2.)
DO 100 ITERAL = 1,100
C PRINT *, " RIBBIT1 ",RO,R,T,LF,VLT,VTL
CALL LOCAL(ETX,ETY,VLT,VTL,PCRTL,NCRTL)
C PRINT *, " RIBBIT2 ",RO,R,T, LF,PCRTL,NCRTL,ETX,ETY
IF(ITERAL.EQ.1.AND.PCRTL.GE.P) GO TO 115
F = (P-PCRTL)/AMAX1(P,PCRTL)
IF (ABS(F).LT..001) GO TO 115
T = T/(1. - F/3.)
100 CONTINUE
115 IF (NRINGS.GT.0) GO TO 116
W= 0.
H= 0.
AREA= 0.
IR= 0.
YR= 0.
DW= 0.
DASP= 0.
SECDEP=0.
RETURN
116 CONTINUE

```

```

H = ABS(SECDEP - T)
IF (H.LT.T) H = T
W = H/2.
NCRITL = -100
YR = T + H/2.
ITERAG = 0
200 ITERAT = ITERAT + 1
AREA = W*H
IR = AREA*H**2/12.
LS = LF - W
ITERAG = ITERAG + 1
IF (ITERAG.EQ.150) GO TO 207
IF (W.LE.LS) GO TO 205
LS = LF/2.
CALL RIBDW(LS)
205 NCRITL = -100
CALL GENERL(ETX,ETY,ETF,VLT,VTL,PCRTIG,NCRITL)
G= (P-PCRTIG)/AMAX1(P,PCRTIG)
IF (ABS(G).LT..01) GO TO 207
W = W/(1.-G)
GO TO 200
207 CONTINUE
IF (DW.GT.0..AND.W.GT.DW) CALL RIBDW(DW)
IF (ISEC.EQ.1) CALL RIBH(SECDEP)
AR = H/W
IF (AR.LT.DASP) CALL RIBAR(DASP)
AR = H/W
IF (AR.GT.4..AND.W.LT..125) CALL RIBDW(0.125)
AREA = W*H
IR = AREA/12.*H**2
YR = T + H/2.
LS = LF - W
C PRINT *, " RIBBITA",RO,T,AREA,YR,H,W,LS
IF (W.LE.LS) RETURN
LS = LF/2.
CALL RIBDW(LS)
LS = LF - W
C PRINT *, " RIBBITB",RO,T,AREA,YR,H,W,LS
RETURN
END
SUBROUTINE RIBDW(DW)
C THIS SUBROUTINE MODIFIES EXISTING RIB DIMENSIONS TO GIVE A DESIRED
C RIB WIDTH WITHOUT AFFECTING SHELL INERTIA.
C H = RIB HEIGHT, W = RIB WIDTH, DW = DESIRED WIDTH.
COMMON DUM(23),H,W
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
REAL IE,IE1
CALL IECAL(IE)

```

```

C  PRINT *," RIBDWI ",DUM(8),DUM(9),DUM(1),DUM(3),H,W,DUM(5),DW
W = DW
DO 50 I = 1,300
ITERAT = ITERAT + 1
CALL IECAL(IE1)
Q = (IE-IE1)/AMAX1(IE,IE1)
IF (ABS(Q).LT..0001) RETURN
H = H/(1.-Q/2.)
50 CONTINUE
CALL IECAL(IE)
RETURN
END
SUBROUTINE RIBH(SECDEP)
C  THIS SUBROUTINE MODIFIES EXISTING RIB DIMENSIONS TO GIVE A
C  DESIRED SHELL SECTION DEPTH WITHOUT AFFECTING SHELL INERTIA.
C  T = SHELL THICKNESS, H = RIB HEIGHT, W = RIB WIDTH.
C  SECDEP = H + T = SECTION DEPTH.
COMMON DUM1(3),LF,LS,DUM2(3),T,DUM3(14),H,W
COMMON /COUNT/ ITERAT,INDIC,INDIC2,INDIC3,
1 INDIC5,NDESIGN,ORTHO,NOKG,NCURVE,OK,ITERAM,OKM,ITERAG,OKG,ISEC,
2 NPLOT,NOKM,NRINGS,NEGLAM,INDIC7
REAL IE,IE1,LF,LS
WW = W
HH = H
C  IF (T.LE.0.) PRINT *," RIBH ",H,W,LF,LS,T,ITERAT
CALL IECAL(IE)
C  PRINT *," RIBH I ",DUM2(3),T,DUM1(1),DUM1(3),H,W,LS
H = ABS(SECDEP - T)
DO 50 I = 1,300
ITERAT = ITERAT + 1
CALL IECAL(IE1)
Q = (IE-IE1)/AMAX1(IE,IE1)
C  IF(H.LT.0.) PRINT *," RIBHIE ",H,W,LS,LF,IE,IE1,Q,I
IF (ABS(Q).LT..0001) RETURN
W = W/(1.-Q/2.)
LS = LF - W
IF (LS.LT.W) GO TO 70
50 CONTINUE
CALL IECAL(IE)
RETURN
70 CONTINUE
H = HH
W = WW
CALL IECAL(IE)
LS = LF/2.
CALL RIBDW(LS)
LS = LF - W
C  PRINT *," RIBH B ",DUM2(3),T,DUM1(1),DUM1(3),H,W,LS
RETURN
END

```

APPENDIX B: THESIS CODE INPUT FILE

The program input file allows the user to generally describe fixed shell geometry variables (such as L and OD), properties of the shell and ring material(s), and the applied load: external hydrostatic pressure (PSTR). This appendix shows the input file to be read by the THESIS code. The input file is named DAPS3 INP. This is the same input file read by the DAPS3 code when used as a "stand alone" shell design program (in both "design" and "analysis" modes). Adherence to the character spacing is mandatory to insure that the input parameters are read properly.

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80

- (1) N1⁹ N2¹⁰ N3¹¹ N4¹²
 (2) TITLE
 (3) HHH
 (4) A11 A22 D11 D22
 (5) EX VYX VPLAS SIGX GXY EY EF
 (6) PSTR SIGY SIGX1 SIGY1 PEL STRX STRY NSAVE
 (7) L OD T RHO RHOF
 (8) AR IR YR LF LS ARM
 (9) RINGS SECDEP DW DASP RINGSI RINGSF DRINGS ISEC
 (10) SIGXNOM SIGYNOM NX¹³ NY¹⁴ NF¹⁵
 (11) STRESX(I), I = 1,NXPNT
 (12) STRINX(I), I = 1,NXPNT
 (13) STRESY(I), I = 1,NYPNT
 (14) STRINY(I), I = 1,NYPNT
 (15) STRESF(I), I = 1,NFPNT
 (16) STRINF(I), I = 1,NFPNT

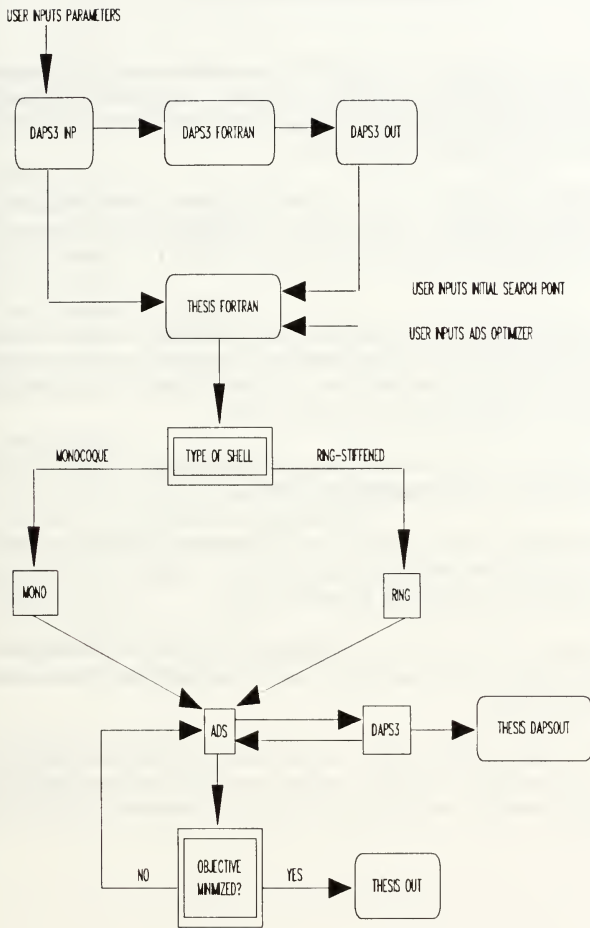
 INPUT LINE FORMATS: (1): 4I5
 (2): 7A10
 (3): 7A10
 (4): 8F10.3
 (5): 8F10.3
 (6): 7F10.3, I5
 (7): 8F10.3
 (8): 8F10.3
 (9): 7F10.3, I5
 (10): 2F10.3, 3I5
 (11) THRU (16): 10F8.0

NOTE: (1) BLANK ENTRIES ARE READ AS ZERO
 (2) NOT ALL INPUT LINES REQUIRED, DEPENDING ON VALUES OF NPLOT, NCURVE,
 NDESIGN, AND ORTHO

-
- ⁹ "N1" = NPLOT
¹⁰ "N2" = NCURVE
¹¹ "N3" = NDESIGN
¹² "N4" = ORTHO
¹³ "NX" = NXPNT
¹⁴ "NY" = NYPNT
¹⁵ "NF" = NFPNT

APPENDIX C: THESIS CODE FLOW CHART LOGIC

This appendix shows the flow chart logic of the interaction between the THESIS and DAPS3 codes.



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1. Naval Surface Weapons Center Technical Report 80-269, *Axisymmetric Stresses and Deflections, Interbay Buckling, and General Instability of Orthotropic Hybrid, Ring-Stiffened Cylindrical Shells Under External Hydrostatic Pressure*, by J.R. Renzi, 19 April 1981.
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7. Shin, P.Y., and Castillo, H.A., "A Homotopy Method for Optimal Design Using an Envelope Function," paper presented at the 33rd Structures, Structural Dynamics, and Materials (SDM) Conference, Dallas, Texas, 13 April 1992.

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Monterey, CA 93940

Thesis

C315 Castillo

c.1 Optimum design of isotropic monocoque and ring-stiffened circular cylindrical shells subject to external hydrostatic pressure.

Thesis

C315 Castillo

c.1 Optimum design of isotropic monocoque and ring-stiffened circular cylindrical shells subject to external hydrostatic pressure.

