(3)

BOSOR4

STRUCTURAL ANALYSIS SYSTEMS - Vol. 2

Software — Hardware
Capability — Compatibility — Applications

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1986

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BOSOR4—PROGRAM FOR STRESS, STABILITY AND VIBRATION OF COMPLEX, BRANCHED SHELLS OF REVOLUTION

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ABSTRACT

BOSOR4 performs stress, stability, and modal vibration analysis of complex, segmented, branched shells of revolution made of elastic material. It can be used to analyze prismatic shells and panels. It performs moderately large deflection axisymmetric stress analysis, small deflection nonsymmetric stress analysis, modal vibration with axisymmetric nonlinear prestress included, and buckling analysis with axisymmetric or nonsymmetric prestress. Symmetric and nonsymmetric buckling modes can be found. There is provision for realistic engineering details such as eccentric load paths, internal supports, arbitrary branching conditions, and a library of wall constructions, including layered orthotropic with temperature-dependent material properties. BOSOR4 is divided into three processors. The user provides input data in an interactive mode. Extensive "HELP" prompts and definitions are available, so that looking up variable definitions in a user's manual is seldom necessary. CALCOMP-type plotting routines are called from a processor that produces plot files. Prebuckling state and buckling or vibration modes are plotted. BOSOR4 runs extremely fast.

THEORETICAL BACKGROUND AND PROGRAM OVERVIEW

The BOSOR4 computer program was developed in response to the need for a tool which would help the engineer to design *practical shell structures*. An important class of such shell structures includes segmented, branched, ring-stiffened shells of revolution. Even if the actual structure is not a shell of revolution, it is usually beneficial to use BOSOR4 in the preliminary design and analysis phases of a project because one can easily and very rapidly obtain good estimates of the behavior. The engineer is thereby guided to make appropriate models for use with general purpose programs, for which the investment in labor and computer time are usually far greater than those required to generate models for and obtain results with BOSOR4.

The complex segmented and branched shells of revolution may have various meridional geometry, wall construction, boundary conditions, ring reinforcements, stringer reinforcements, and types of loading, including nonuniform distributed and line loads and nonuniform temperature distributions.

Table 1 lists the characteristics and status of BOSOR4 as of November 1, 1984.

The program is currently in widespread use and is maintained by the developer. Notices of bugs found are distributed to all known users. BOSOR4 has been thoroughly checked out by comparisons with other known solutions, tests, and by extensive use at many different institutions the world over for more than 10 years.

TABLE 1 BOSOR4 at a Glance

KEYWORDS: shells, stress, buckling, vibration, nonlinear, elastic, shells of revolution, rings, branched, composites, discrete

PURPOSE: To perform stress, buckling, and modal vibration analyses of ring-stiffened, branched shells of revolution loaded either axisymmetrically or nonsymmetrically. Complex elastic wall construction permitted. Buckling and/or stress response to harmonic or random base excitation.

DATE: 1972; most recent update 1985

DEVELOPER: Dr. David Bushnell, 93-30/255, Lockheed Applied Mechanics, 3251 Hanover St., Palo Alto, California 94304, (415)858-4037

METHOD: Finite difference energy minimization; Fourier superposition in circumferential variable; Newton method for solution of nonlinear axisymmetric problem; inverse power iteration with spectral shifts for eigenvalue extraction; Lagrange multipliers for constraint conditions; thin shell theory.

RESTRICTIONS: 3000 degrees of freedom (dof) in nonaxisymmetric problems; 2000 dof in axisymmetric prebuckling stress analysis; maximum of 80 Fourier harmonics per case; knockdown factors for imperfections not included; radius/thickness should be greater than about 10. Up to 80 shell segments permitted, each with its own meridional geometry, wall construction, loading, and constraint conditions; linear elastic material.

Language: FORTRAN 77.

DOCUMENTATION: BOSOR4 User's Manual (Ref. 1) and 11 journal articles and a book with numerous examples (References 2 through 13); Interactive input with on-line HELP. Hierarchical interactive "HELP" file is also available. A file called BOSOR4ST.ORY is included with the program system. This file describes how to use BOSOR4 on the VAX and contains information about how to get the plotting capability "up" at the user's facility. BOSOR4ST.ORY also identifies improvements in the VAX-BOSOR4 capability beyond those of earlier versions of BOSOR4.

INPUT: interactive input. Required for input are shell segment geometries, ring geometries, number of mesh points, ranges and increments of circumferential wave numbers, load and temperature distributions, shell wall construction details, and constraint conditions.

OUTPUT: Displacements and stress resultants or extreme fiber stresses, buckling loads, vibration frequencies; list and plots.

HARDWARE: VAX11/750, 11/780, VMS operating system; CALCOMP-type plot subroutine calls. IBM, PRIME versions also available (see below).

SIZE: 1400 blocks required for storage of BOSOR4 absolute elements; 1600 blocks required for source files; 1200 blocks required for relocatables; from 1000-5000 blocks required for I/O for a typical case.

USAGE: About 200 institutions are using BOSOR4. It is currently being used on a daily basis by many of them. (See Table 3 for partial list.)

RUN TIME: Typically 1 to 15 minutes on VAX11/780, VMS operating system.

AVAILABILITY: VAX version available from developer (address above); Price: $1000.00 includes all documentation, magnetic tape with source, relocatables, absolutes, test cases, further documentation. IBM and VAX versions available from Professor Victor I. Weingarten, Structural Research and Analysis Corporation, 1661 Lincoln Blvd., Suite 100, Santa Monica, California, 90404, Tel.(213)452-2158; Prime Version available from Howard Jaeger, Code 244.5, MS 060, Mare Island Naval Shipyard, Vallejo, California 94592, Tel.(707)646-2444 or -3273. VAX version also available from Professor G. D. Galletly, Mechanical Engineering Department, The University of Liverpool, P.O. Box 147, Liverpool L69 3BX, United Kingdom. Prices of BOSOR4 available from others than the developer not known. One time purchase price.

MAINTENANCE: Developer sends out notices of bugs and other news from time to time.

FIELD OF APPLICATION

The BOSOR4 capability is summarized in Table 2.

TABLE 2 BOSOR4 Capability Summary

TYPE OF ANALYSIS:

1. Nonlinear axisymmetric stress analysis (by itself or for generating prebuckling or prestress states for bifurcation buckling or modal vibration analyses)

2. Linear symmetric or nonsymmetric stress analysis (by itself or for generating prebuckling states for bifurcation buckling analysis)

3. Bifurcation buckling with linear symmetric or nonsymmetric prestress analysis, or with nonlinear symmetric prestress analysis

4. Modal vibration with nonlinear axisymmetric prestress analysis

5. Response to harmonic loading (excitation via applied loads)

6. Response to harmonic or random base excitation

SHELL GEOMETRY AND CONSTRAINT CONDITIONS:

1. Multiple-segment, branched shells, each segment with its own wall construction, geometry, loading, constraint conditions, nodal point spacing and distribution (constant nodal point spacing recommended).

2. Especially simple input for cylinders, cones, plates, spherical, ogival, toroidal, ellipsoidal shell segments

3. General meridional shape: point-by-point input (not recommended unless absolutely necessary)

4. Axisymmetric sinusoidal or random imperfections (small amplitude only!)

5. Axial and radial discontinuities in shell meridian (keep them small!)

6. Arbitrary choice of reference surface location relative to the material in the

shell segment wall (near the material, though!)

7. Branched shells

8. Prismatic shells and composite built-up panels[10]

9. juncture full or partial compatibility; sliding

10. constraints to ground at segment ends or within segments

11. Winkler elastic foundation

WALL CONSTRUCTION:

1. Linear elastic material

2. Monocoque constant or variable thickness

3. Layered orthotropic; composite laminate

4. Layered orthotropic with temperature-dependent material

5. Corrugated semisandwich

6. Any of the above wall types reinforced by stringers and/or rings treated in the model as "smeared out"

7. Any of the above wall types further reinforced by rings treated as discrete beam-type structures with torsional-flexural stiffness

8. Arbitrary wall construction supplied via 6 x 6 integrated constitutive law ($C(i,j)$ matrix)

9. Wall properties varying along the shell meridian

LOADING:

1. Axisymmetric or nonsymmetric temperature distributions

2. Axisymmetric or nonsymmetric pressure, traction components

3. Axisymmetric or nonsymmetric line loads at discrete rings

4. Axisymmetric or nonsymmetric imposed displacements at discrete rings

5. Load sets A (eigenvalue parameter) and B (constant)

6. Harmonic (time-varying) applied loads

7. Harmonic or random base excitation

BOSOR4 performs the following analyses:

1. a nonlinear stress analysis for axisymmetric behavior of axisymmetric shell systems (moderately large deflections, linear elastic material);

2. a linear stress analysis for axisymmetric and nonaxisymmetric behavior of axisymmetric shell systems subjected to axisymmetric and nonaxisymmetric loads;

3. an eigenvalue analysis in which the eigenvalues represent buckling loads or vibration frequencies of axisymmetric shell systems subjected to axisymmetric

loads. Eigenvectors correspond to axisymmetric and to nonaxisymmetric buckling or vibration modes.

4. BOSOR4 has additional branches corresponding to buckling of nonaxisymmetrically loaded shells of revolution and corresponding to stress and buckling of shells subjected to harmonic or random base excitation. These capabilities represent combinations of the first three analysis types.

Figure 1 shows some examples of branched structures which can be handled by BOSOR4. Figure 1(a) represents part of a multiple-stage rocket treated as a shell of seven segments; Figure 1(b) represents part of a ring-stiffened cylindrical shell in which the ring is treated as two shell segments branching from the cylinder; Figure 1(c) shows the same ring-stiffened cylindrical shell with the ring treated as "discrete", that is the ring cross section can rotate and translate but not deform, as it can in the branched shell model shown in Fig. 1(b). Figures 1(d,e,f) represent branched prismatic shell structures, which can be treated as shells of revolution with very large average circumferential radii of curvature, as described in reference 10.

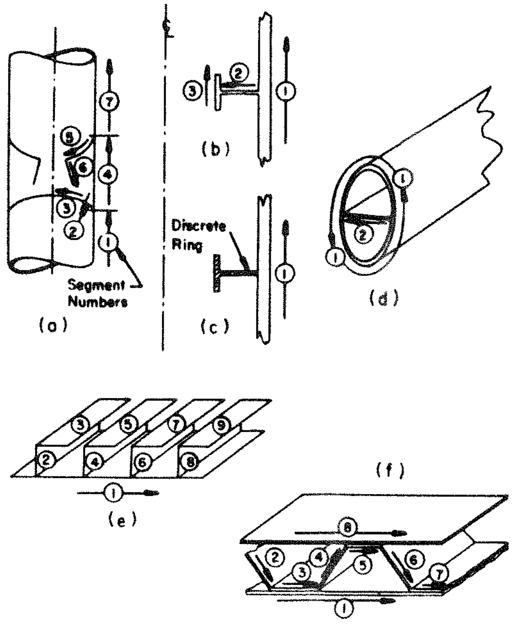


Fig. 1. Examples of branched structures which can be analyzed with BOSOR4

GOVERNING ASSUMPTIONS IN THE BOSOR4 THEORY

The assumptions upon which BOSOR4 is based are:

1. The wall material is linear elastic.

2. Thin shell theory holds: normals to the undeformed surface remain normal.

3. The structure is axisymmetric, and in modal vibration analysis and nonlinear

stress analysis the loads and prebuckling or prestress deformations are axisymmetric.

4. The axisymmetric prebuckling deflections in the nonlinear theory, while considered finite, are moderate. That is, the square of the meridional rotation can be neglected compared to unity.

5. In the calculation of displacement and stresses in nonsymmetrically loaded shells, linear theory is used. This branch of the program is based on standard small-deflection analysis.

6. A typical cross sectional dimension of a discrete ring stiffener is small compared with the radius of the ring.

7. The cross sections of the discrete rings remain undeformed as the structure deforms, and the rotation about the ring centroid is equal to the rotation of the shell meridian at the attachment point of the ring. (except, of course, if the ring is modelled as a flexible shell branch or branches!).

8. The discrete ring centroids coincide with their shear centers.

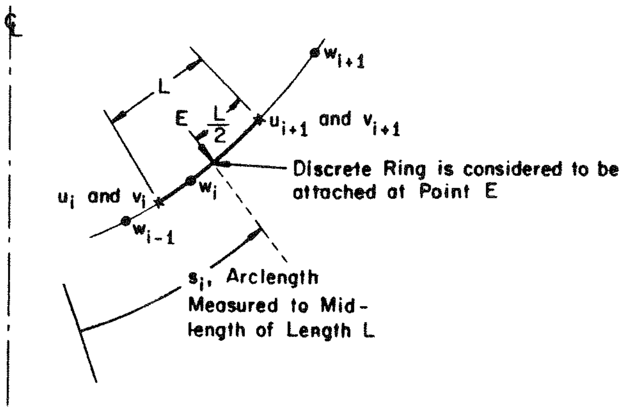
9. If meridional stiffeners are present, they are numerous enough to include in the analysis by an averaging or "smearing" of their properties over any parallel circle of the shell structure. Meridional stiffeners can be treated as discrete for prismatic structures, as illustrated in Figs. 1 (d,e,f).

10. In bifurcation buckling analyses of nonaxisymmetrically loaded shells the analysis is carried out in two phases: 1. a linear nonsymmetric stress analysis is first performed; 2. for a user-selected meridian, bifurcation buckling analyses are then conducted. The assumption in this second phase of the analysis is that the prebuckling state of the shell along the user-chosen meridian is the same for all other meridians: it is axisymmetric.

METHOD AND DISCRETIZATION

The BOSOR4 analysis is based on energy minimization with constraint conditions. The total energy of the system includes strain energy of the shell segments and discrete rings, potential energy of the applied line loads and pressures, and kinetic energy of the shell segments and discrete rings. Thermal strains are included. The constraint conditions arise from displacement conditions at the boundaries of the structure, displacement conditions that may be prescribed anywhere within the structure, and compatibility conditions at junctions between shell segments. These constraint conditions are introduced into the energy function by means of Lagrange multipliers.

The components of energy, work, and constraints are initially integro- differential forms. The circumferential dependence is eliminated by separation of variables and the assumption that variation with respect to the circumferential coordinate θ is trigonometric ($\sin n\theta$, $\cos n\theta$). Displacements and meridional derivatives of displacements are then written in terms of the shell wall reference surface meridional, circumferential, and normal displacement components, u_i, v_i, w_i, respectively, at the finite-difference nodal points. Integration is performed by multiplication of the energy-per-unit-meridional-length by the length L of the "finite-difference element". This unusual kind of finite element is depicted in Fig. 2. It is described more fully in reference 4. The unknowns in the discretized problem are the nodal point degrees of freedom, u_i, v_i, w_i, and Lagrange multipliers, λ_i. Solution of the equation systems corresponding to the various nonlinear and linear simultaneous algebraic equations goes extremely fast on the computer because the average bandwidth of the equations is very small, discretization being only in one coordinate direction. This is the reason that BOSOR4 runs very fast, even on minicomputers.



$$\lfloor q_i \rfloor = \lfloor w_{i-1}, u_i, v_i, w_i, u_{i+1}, v_{i+1}, w_{i+1} \rfloor$$

Fig. 2. Finite difference discretization: the "finite difference element". The meridional length of the element is L; the single integration point is at the element midlength E; the nodal degrees of freedom involved in the local stiffness, mass, and load-geometric matrices for the ith finite element are identified in the vector q_i.

In the nonlinear axisymmetric stress analysis the energy expression has terms that are linear, quadratic, cubic, and quartic in the dependent variables, u_i and w_i. The cubic and quartic energy terms arise from the rotation-squared terms that appear in the expression for reference surface meridional strain and in the constraint conditions. Energy minimization leads to a set of nonlinear algebraic equations that are solved by the Newton-Raphson method. Stress and moment resultants are calculated in a straightforward manner from the meshpoint displacement components through the constitutive equations and the kinematic relations.

The results from the nonlinear axisymmetric or linear nonsymmetric stress analysis are used in the eigenvalue analyses for buckling and vibration. The "prebuckling" or "prestress" meridional and circumferential stress resultants and the meridional rotation appear as known variable coefficients in the energy expressions that govern bifurcation buckling and modal vibration. These expressions are homogeneous quadratic forms. The values (eigenvalues) of a parameter (load or frequency) that render the quadratic forms stationary with respect to infinitesimal variations of the dependent variables represent buckling loads or natural frequencies. These eigenvalues are calculated from a set of linear homogeneous equations.

Details of the analysis are presented in references 3, 7, 11, 12. The user's manual

USER-FRIENDLY FEATURES OF BOSOR4

The following features make the latest version of BOSOR4 very easy to use:

1. *HIERARCHICAL INTERACTIVE "HELP" UTILITY:* New users of BOSOR4 can learn about what BOSOR4 does, how to use it, how to modify cases, what the various commands do, what is contained in various files generated by BOSOR4 runstreams, etc.

Examples of the use of *HELP* are listed in Appendix 1 at the end of this paper. This appendix contains useful information about BOSOR4, so please read it for information as well as an example of the *HELP* utility.

2. *INTERACTIVE INPUT WITH ON-LINE HELP:* The user provides input data interactively. If the user wants help in connection with any input datum, he or she simply types *H*(ELP) instead of the datum called for by the interactive prompt. BOSOR4 responds with a paragraph or paragraphs of explanation. Appendix 2 lists a typical BOSOR4 runstream for providing input data for a nonlinear buckling analysis of an externally pressurized spherical cap resting on a frictionless plane. In several instances the user called for *H*(ELP).

3. *ANNOTATED FILE OF INPUT DATA PRODUCED:* Upon successful completion of the case (actually, successful completion of the preprocessor phase of the case), BOSOR4 produces a file, such as that listed in Appendix 3, that can be modified and used for future similar cases, thereby rendering it unnecessary for the user to answer all the questions interactively again. This file (which in the example of Appendix 3 corresponds to the case of the spherical cap just mentioned) also serves to document the problem.

4. *EDITING UTILITY "MODIFY" FOR MODIFYING CASES:* Page 3 of Appendix 1 describes this feature. Modification is carried out automatically by the BOSOR4 system through use of "key phrases", such as "DISCRETE RING INPUT FOLLOWS" or "LINE LOAD INPUT FOLLOWS" that appear in the annotated file of which Appendix 3 is an example. Small files, such as RINGS.QUE and LINELOADS.QUE, generated interactively when the user gives the command *MODIFY*, are inserted in the annotated input file,

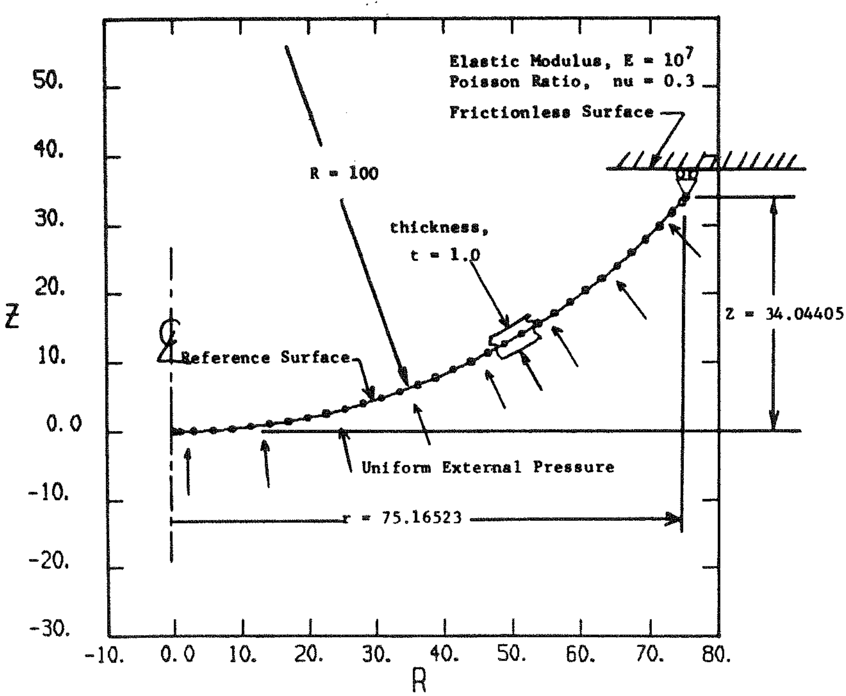


Fig. 3. Sample problem geometry: shallow spherical cap on frictionless plane with uniform external pressure. The nodal points are the locations of the midlengths of the finite difference elements.

replacing earlier entries at these locations. This feature renders it unnecessary to generate new cases from the beginning when there are only a few modifications wanted by the user.

5. *PLOTS:* Plots of the discretized model, prebuckling deflections, and buckling modes are produced via CALCOMP-type subroutine calls. Examples are shown in Figs. 3, 4, and 5, which represent output from the sample case treated as in Appendices 2 and 3. BOSOR4 will also produce "x,y" plots of displacements, stress components and stress and moment resultants, in which "x" is the arc length along the meridian of the shell of revolution.

EXAMPLES OF APPLICATION

DETAILED EXAMPLE CASE: Appendix 2 contains a sample runstream for interactive input of data for a nonlinear buckling analysis of an externally pressurized spherical cap lying on a frictionless plane. Appendix 3 lists the annotated input file produce by BOSOR4 for documentation of the case and for use in future similar cases. The specifics of the case and discretization are shown in Fig. 3. Some results are plotted and listed in Figs. 4 and 5. In order to save space, listed output from this example are not reproduced here. This output is self-explanatory.

In this example boundary conditions and nonlinear geometric effects are very important. A linear bifurcation buckling analysis of the same cap on the same frictionless plane yields a critical pressure p_{cr} = 851 with n_{cr} = 10 circumferential waves. Compare with the nonlinear model, which yields p_{cr} = 248

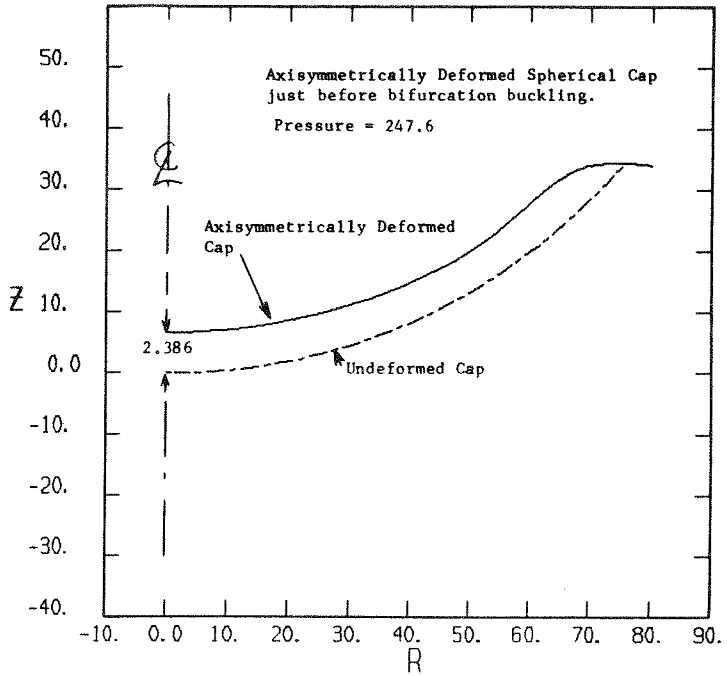


Fig. 4. Axisymmetric prebuckling deformation at an external pressure, p_{cr} = 247.6psi. The normal displacement at the crown is w = 2.386in.

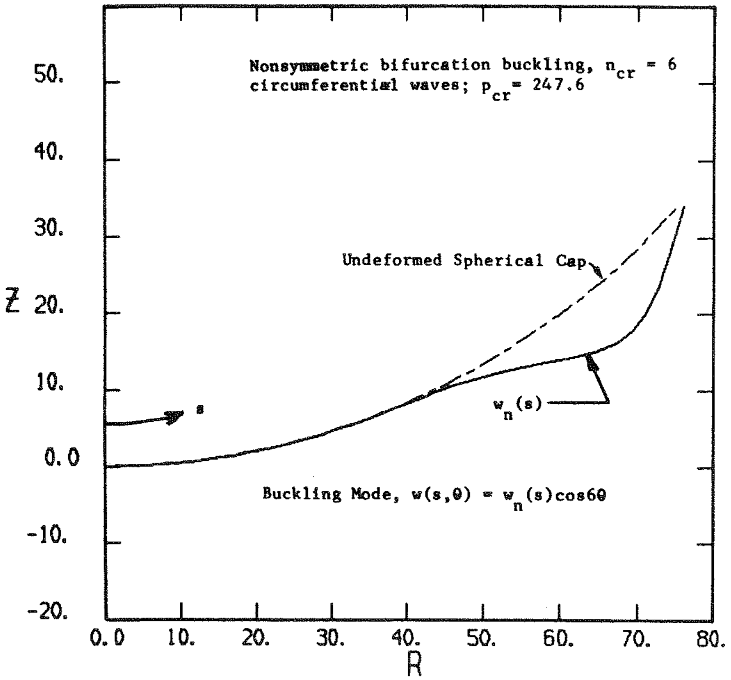


Fig. 5. Bifurcation buckling mode predicted by BOSOR4 for the test problem shown in Fig. 3. Nonlinear geometric prebuckling effects are accounted for in this prediction.

with n_{cr} = 6 circumferential waves. The classical buckling pressure of a complete spherical shell with the same radius R, thickness t, and material is p_{cl} = 1210.

NONLINEAR STRESS ANALYSIS: Figure 6 shows part of an internally pressurized elliptical tank which has been thickened locally near the equator for welding. The engineering drawings called for an elliptically shaped inner surface with the thickness varying as shown. The maximum stress occurs at the outer fiber at point C because there is considerable local bending there due to the rather sudden change in direction or eccentricity of the load path in the short segment ACB. The nonlinear theory gives lower stresses than does the linear theory because the meridional tension causes the tank to change shape in such a way as to decrease the local excursion of the load path, thereby decreasing the effective bending moment acting at point C. The tank had been built and a linear analysis had been performed. The user of the tank wanted to know if it would withstand a somewhat higher internal pressure than that for which it had originally been designed. The lower stress predicted with nonlinear theory gave this user enough margin of safety to avoid the necessity of redesign.

BUCKLING DUE TO QUASI-STATIC BASE EXCITATION: The United States Nuclear Regulatory Commission is interested in the development of methods for the calculation of buckling loads of large steel reactor containment vessels under various dynamic loads, including those from an earthquake. Figure 7 illustrates the predicted behavior of one such shell in which body forces from 1g vertical and 1g horizontal ground acceleration components are applied to the structure as if they were static. The buckling load factor λ_{cr} = 21.4 and critical number of circumferential waves, n_{cr} = 10, are computed by BOSOR4 from a model that

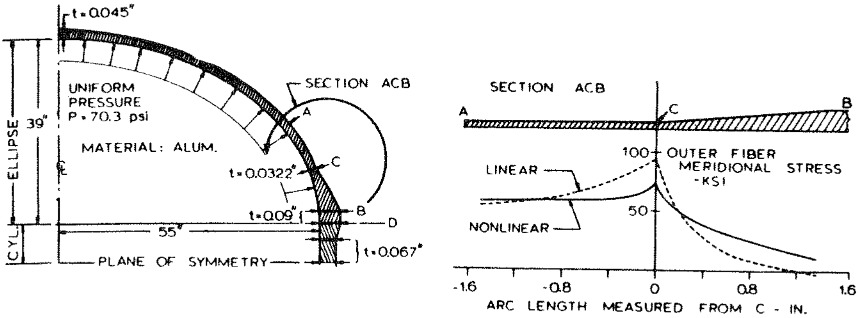


Fig. 6. Linear and nonlinear axisymmetric analyses of an internally pressurized ellipsoidal tank with variable thickness. The stress concentration at Point C is due to load path eccentricity, and the predicted stresses decrease if nonlinear geometric effects are accounted for.

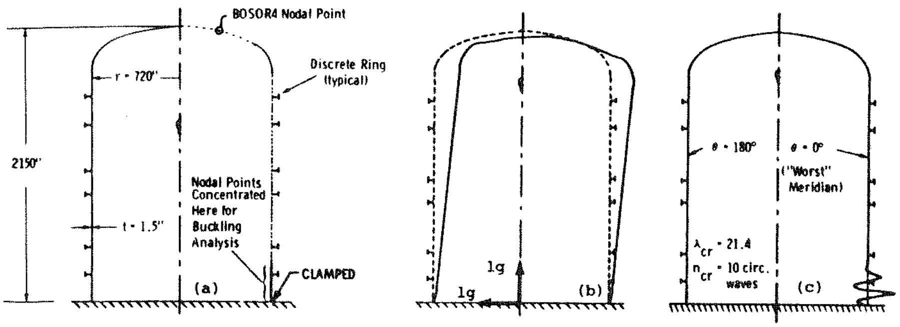


Fig. 7. Buckling of nuclear reactor steel containment vessel due to ground accelerations: (a) BOSOR4 discretized model; (b) prebuckling deformation due to 1*g* vertical and 1*g* horizontal ground acceleration components; (c) predicted buckling mode, critical load factor, λ_{cr} = 21.4, and number of circumferential waves, n_{cr} = 10.

accounts for the nonaxisymmetry of loading in the prebuckling phase of the analysis, but treats the membrane stress distribution along the "worst" (most axially compressed) meridian as if it were axisymmetric in the stability phase of the analysis. (The user selects the "worst" meridian. If it is hard to tell which the "worst" meridian is, the user may, through as many "restarts" as he or she wants, find buckling load factors and mode shapes for several meridians.)

UNEXPECTED LOCAL BUCKLING: In Fig. 8 is illustrated a local buckling failure of a large, expensive, semisandwich, corrugated, ring-stiffened payload shroud (a and b) that was subjected to axial compression and bending. The shroud failed unexpectedly during proof testing because of local buckling near a field joint (c and d). In short regions on either side of the field joint, where the external corrugations are cut away as shown in Fig. 8(d), the axial load path is deflected inward from the neutral axis of the cross section of the combined corrugations and skin to the middle surface of the skin and doubler. This local inward excursion of the axial load path creates under axial compression the localized hoop compression that causes local nonsymmetric bifurcation buckling in a mode displayed in Fig. 8(c). Because of the short axial length of the circumferentially compressed region, the critical buckling mode has a rather large number of

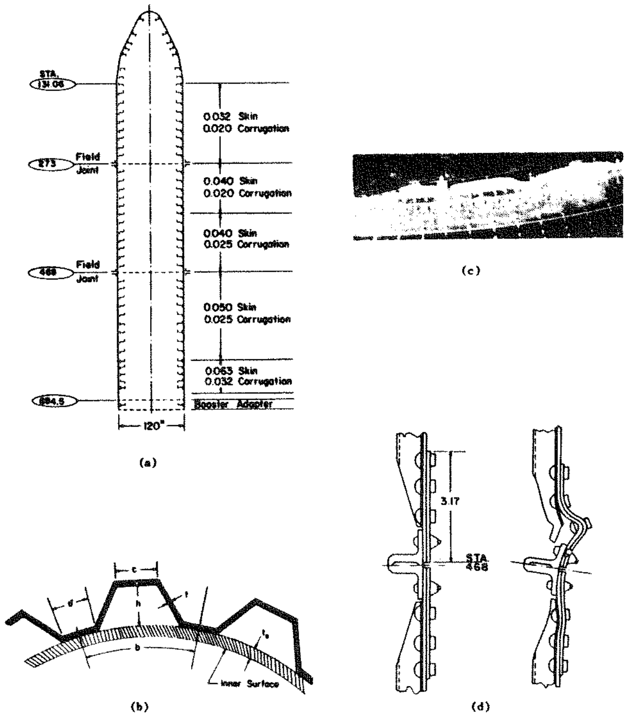
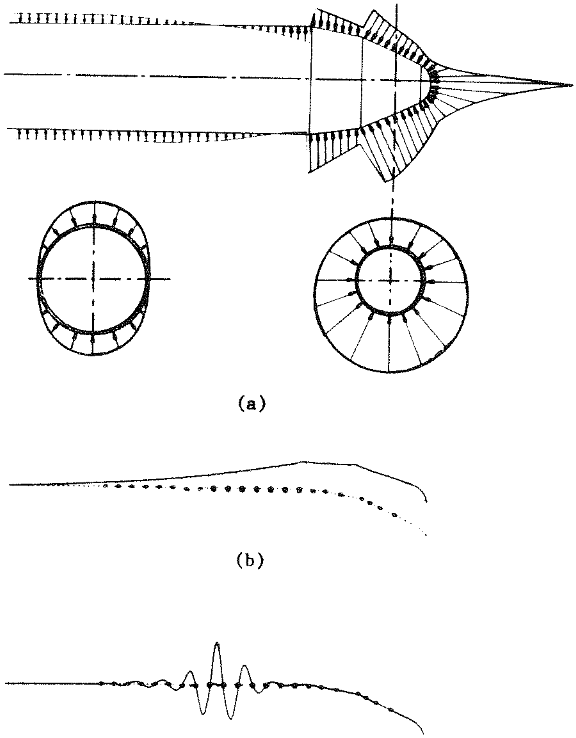


Fig. 8. Local failure of a large payload shroud under axial compression and bending: (a) Typical ring-stiffened rocket payload shroud configuration; (b) Corrugated, semi-sandwich wall; (c) Interior view of portion of complete shroud buckled locally next to field joint at Station 468; (Three waves are visible.) (d) Field joint geometry and buckle configuration. Buckling is caused by the narrow band of circumferential compression arising from the inward excursion of the axial load path near the field joint.

circumferential waves. This mode was obtained by BOSOR4, after the test unfortunately, because those responsible for the test were not aware that this type of local buckling was possible.

BUCKLING UNDER NONSYMMETRIC AERODYNAMIC PRESSURE: Figure 9 shows nonsymmetric pressure loading on the corrugated, ring-stiffened rocket payload shroud displayed in Fig. 9(a,b). The pressure distribution, measured in a wind tunnel, corresponds to a small angle of attack. The payload shroud, attached to a heavy rocket motor stage at its aft end, bends as a beam, as shown in Fig. 9(b). The side under maximum axial compression, the leeward side, buckles between ring stiffeners as shown in Fig. 9(c). Buckling does not occur at the root of the beam because the shell wall is made of thicker gauge material there, as indicated in Fig. 8(a).



(a)

(b)

(c)

Fig. 9. Buckling mode of nonsymmetrically loaded rocket payload shroud shown in Fig. 9(a): (a) Pressure distribution measured in a wind tunnel test; (b) Prebuckling beam-type deflection; (c) Nonsymmetric buckling mode. Buckling is between the discrete rings and occurs with 13 circumferential waves.

NONLINEAR BEHAVIOR OF INTERNALLY PRESSURIZED FUEL TANK: Figures 10 and 11 pertain to this section. The geometry of the problem is shown in Fig. 10. The tank wall and skirt are divided into segments as indicated. Under small internal pressure the portion of the rocket fuel tank enclosed in the rectangle in Fig. 10 is drawn radially inward, resulting in the development of a narrow band of hoop compression that might lead to bifurcation buckling. At the top of Fig. 11 is shown a bifurcation buckling mode predicted by BOSOR4 with use of linear theory. The modal normal displacement component $w_b(s,\theta)$ varies around the circumference as $\cos 90\theta$.

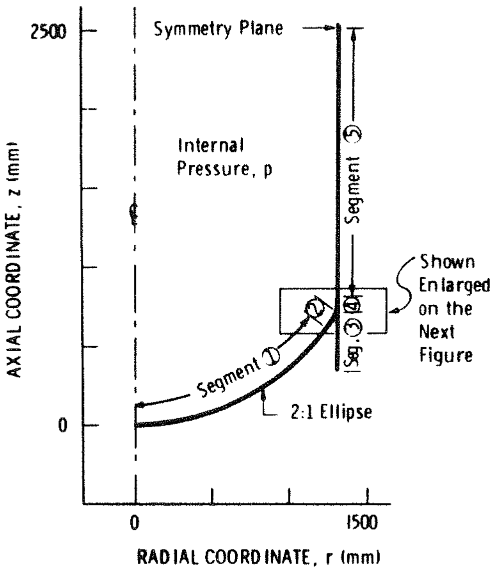


Fig. 10. Bottom part of rocket fuel tank as modelled for input to the BOSOR4 program. Loading is uniform internal pressure. Problem is to determine if the shell buckles in the region enclosed in the small rectangle.

This is a problem for which the use of linear theory in the prebuckling phase of the analysis is inadequate. As the internal pressure is increased the ellipsoidal dome changes shape. The hoop stresses are redistributed and grow more slowly than linearly with pressure, as indicated in the bottom of Fig. 11. As the internal pressure p is increased, the hoop resultant becomes tensile in the region where linear theory predicts bifurcation buckling to occur, and the peak hoop compression initially increases more slowly than predicted by linear theory, eventually reaching a maximum value of about -800 N/mm at a pressure of 1.4 Pa, after which it decreases with further increase in internal pressure. Thus, the prediction by BOSOR4 with nonlinear prebuckling effects included is that bifurcation buckling will not occur at all.

MODAL VIBRATION OF A CRYOGENIC COOLER: BOSOR4 has been in use at Lockheed and elsewhere since 1972. During that time it has been used in several projects, some of them involving rather complex segmented and branched shells of revolution. An example is shown in Fig. 12, which depicts a somewhat idealized model of cryogenic cooler. The axisymmetric structure consists of a series of fiberglass tubes from which are suspended two axisymmetric cryogenic tanks. The object of this study was to determine the natural frequencies of the cooler corresponding to beam-type modes (n = 1 circumferential wave). The segmented and discretized model is shown in Fig. 13 and the first four vibration modes are displayed in Fig. 14. The first two vibration modes and frequencies found by BOSOR4 agreed well with those from tests. The higher two modes were not sought in the test.

WORLDWIDE USE OF BOSOR4

Various versions of BOSOR4 have been in use worldwide since 1972. Table 3 lists many organisations that over the years have used BOSOR4 (and the plastic

TABLE 3 Applications of BOSOR4 and BOSOR5

AEROSPACE STRUCTURES: BOSOR4 has been used extensively by Jet Propulsion Laboratory, Bell Aerospace, California Institute of Technology, Centre Spatial de Toulouse, France (Ariane booster design), DFVLR in West Germany, Fokker Aircraft Space Division in The Netherlands, Ford Aerospace (antennas), Harris Corp. (antennas), Hughes Aircraft (Venus Pioneer Capsules), Martin Marietta (Space Shuttle Fuel Tanks), SPAR Aerospace in Canada, Technion in Israel, TRW Systems, NASA. Lockheed Missiles and Space Co: Satellite Systems Division has used BOSOR4 extensively over more than 12 years for the design of ring and stringer stiffened shrouds and for the design of frangible joints; Lockheed Missiles Systems Division has used BOSOR4 for buckling predictions of rocket booster equipment sections, nose fairings, ring reinforced composite shells; Lockheed Advanced Systems has used BOSOR4 extensively for the analysis of mirrors for optical systems and for the analysis and design of cryogenic coolers.

AIRCRAFT ENGINES: General electric, Motor-Columbus (Switzerland), Pratt and Whitney, SAAB-SCANIA, Volvo Flygmotor (Sweden).

ROCKET MOTORS: BOSOR4 has been used extensively by Aerojet Liquid Rocket Co., Thiokol, Hercules, UTC, Societe Europeene de Propulsion (France)

AUTOMOBILE WHEEL RIMS: Simpson, Gunpertz and Heger Co.

SUBMARINE PRESSURE HULLS: BOSOR4 and BOSOR5 have been extensively used by U.S. Navy research labs (David W. Taylor NSRDC, NUSC, NOSC); by the French Navy (Service Technique des Constructions et Armes Navales); by the English Navy (Naval Construction Research Establishment); Weidlinger Associates, General Dynamics Electric Boat Division.

CONTAINERS: Continental Can, Alcoa, U.S. Steel (beverage cans); Monsanto, Dow Chemical

CIVIL ENGINEERING STRUCTURES: Aeronautical Research Institute of Sweden (large vessels for storing beer!); Burns and Roe, Chicago Bridge and Iron (large oil tanks); Oxford University (liquid natural gas tanks); Illinois Institute of Technology (corrugated grain storage bins); Envirotech Information Systems, Monsanto, Dow (chemical storage tanks); Princeton University (cooling towers); Universite de Liege, Belgium and Gent University (large water tanks); University of Liverpool (buckling of internally pressurized ellipsoidal and torispherical heads)

NUCLEAR INDUSTRY: Battelle Pacific Northwest Labs, CERN-European Organization for Nuclear Research (Switzerland), Chicago Bridge and Iron (containment vessels), Franklin Institute Research Lab, General Electric, Pittsburgh Des Moines Steel, Stone and Webster Engineering, Union Carbide Corporation Nuclear Division, Westinghouse Electric, Kraftwerk Union (West Germany), U.K. Atomic Energy Authority, U.S. Nuclear Regulatory Commission

OFFSHORE ENGINEERING, SHIPPING: General Dynamics Shipbuilding (spherical LNG tanks); Lloyd's of London, Det Norske Veritas (Norway), Shell KSEPL (The Netherlands)

buckling program BOSOR5). Types of problems solved with the BOSOR programs are indicated.

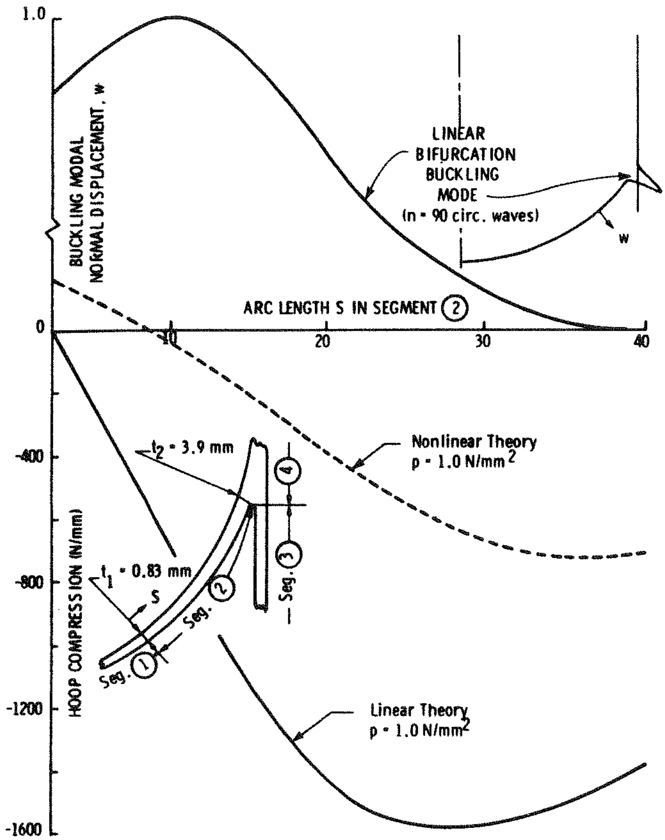


Fig. 11. Nonsymmetric buckling mode (top) and hoop resultants from linear and nonlinear theory (bottom) for the part of the internally pressurized rocket motor enclosed in the small rectangle in the previous figure. Use of linear theory leads to a prediction of buckling, but use of nonlinear theory leads to a prediction that buckling will never occur.

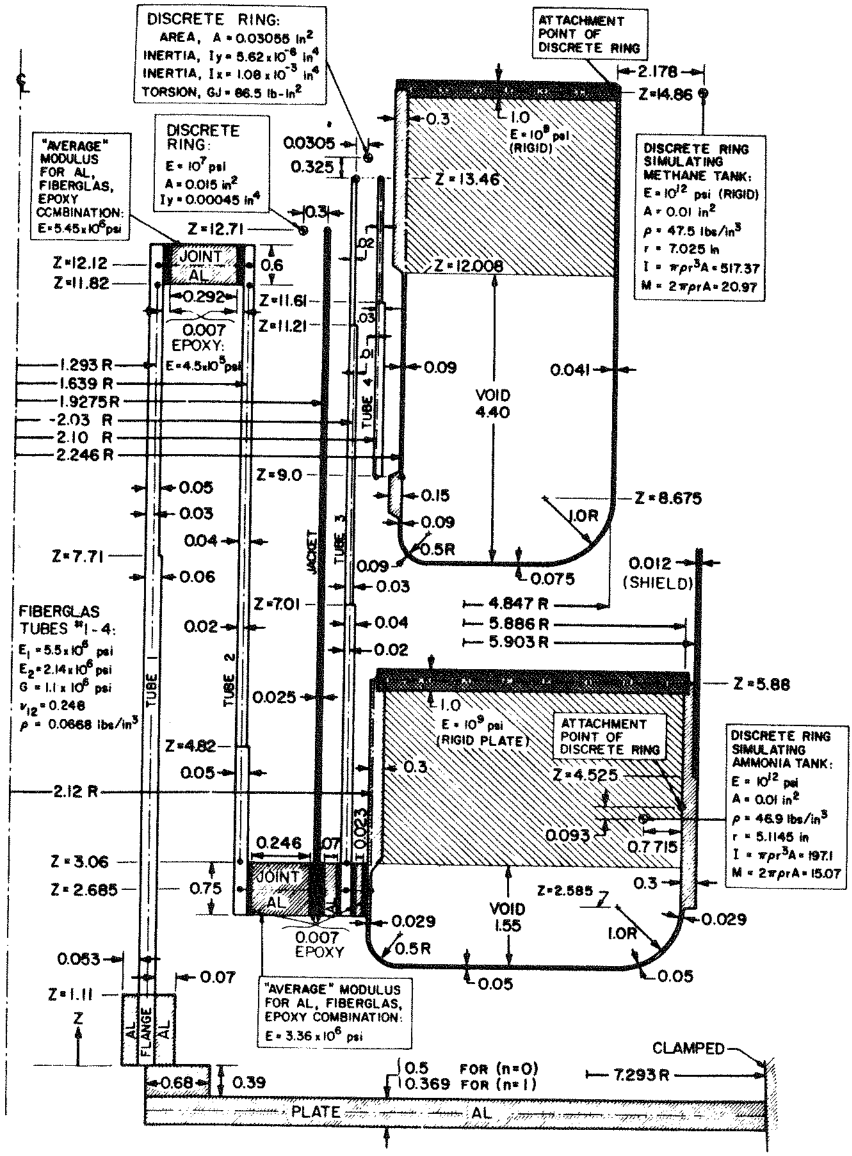


Fig. 12. Cryogenic cooler modelled as a complex, branched shell for analysis by BOSOR4

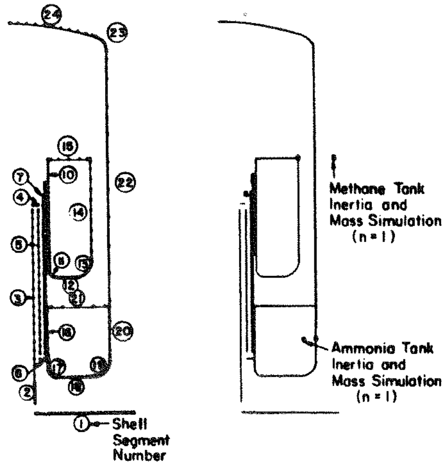


Fig. 13. BOSOR4 segmented, branched, and discretized model. The mass properties of the Methane Tank and Ammonia Tank are simulated by introduction of two discrete rings, as indicated on the right. Half of the cooler is shown.

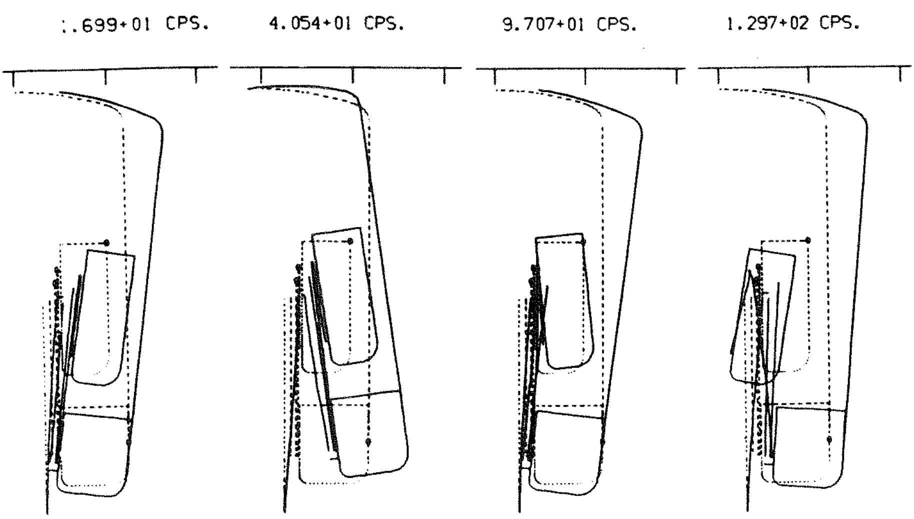


Fig. 14. First four lateral vibration modes predicted with the BOSOR4 model. Lateral vibration corresponds to $n = 1$ circumferential wave. Half of the cooler is shown.

REFERENCES BY D. BUSHNELL PERTANENT TO BOSOR4

1. BOSOR4 - Program for Stress, Buckling and Vibration of Complex Shells of Revolution. Structural Mechanics Software Series, edited by N. Perrone and W. Pilkey, University Press of Virginia, Charlottesville, Va., pp. 11-143, 1977.

2. Buckling of Shells - Pitfall for Designers. *AIAA Journal*, *19*, No. 9, pp. 1183-1226, 1981.

3. Computerized Analysis of Shells - Governing Equations. *Computers and Structures*, *18*, No. 3, pp. 471-536, 1984.

4. Finite Difference Energy Models Versus Finite Element Models: Two Variational Approaches in One Computer Program. *Numerical and Computer Methods in Structural Mechanics*, (edited by Fenves, Perrone, and Schnobrich), Academic Press, New York, pp. 291-336, 1973.

5. Evaluation of Various Analytical Models for Buckling and Vibration of Stiffened Shells. *AIAA Journal*, *11*, No. 9, pp. 1283-1291, 1973.

6. Nonsymmetric Buckling of Cylinders with Axisymmetric Thermal Discontinuities. *AIAA Journal*, *11*, No. 9, pp. 1292-1295, 1973.

7. Stress, Stability, and Vibration of Complex, Branched Shells of Revolution. *Computers and Structures*, *4*, pp. 399-435, 1974.

8. Local and General Buckling of Axially Compressed, Semi-Sandwich, Corrugated, Ring-Stiffened Cylinder. *Journal of Spacecraft and Rockets*, *9*, No. 5, pp. 357-363, May 1972.

9. Stress and Buckling of Nonuniformly Heated Cylindrical and Conical Shells. (with S. Smith), *AIAA Journal*, *9*, No. 12, pp. 2314-2321, 1971.

10. Stress
2004-2013, 1971.

11. Analysis of Ring-Stiffened Shells of Revolution Under Combined Thermal and Mechanical Loading. *AIAA Journal*, *9*, pp. 401-410, 1971.

12. Analysis of Buckling and Vibration of Ring-Stiffened, Segmented Shells of Revolution, *International Journal of Solids and Structures*, *6*, pp. 157-181, Feb. 1970.

13. *Computerized Buckling Analysis of Shells*, Nijhoff, The Netherlands (1985).

APPENDIX 1. EXAMPLE OF USE OF THE HIERARCHICAL INTERACTIVE HELP UTILITY

```
$ HELP4
<BOSOR4>
   Help on various BOSOR4 features can be obtained by typing

          HELP4 TOPIC SUBTOPIC

   in which TOPIC stands for a key word such as COMMAND, DEBUG,
   FILES, OVERVIEW, or PROGRAMS; and SUBTOPIC stands for another
   key word belonging as a subtopic under either COMMAND, DEBUG,
   FILES, OVERVIEW, or PROGRAMS. For example,

          HELP4 COMMAND INPUT

   will give you information about providing input data for BOSOR.

   Information is available on the following topics:

 COMMAND        DEBUG         FILES
 OVERVIEW       PROGRAMS
```

```
 Next, please type HELP4 TOPIC, in which TOPIC stands for one of the
 topics listed above.

$ HELP4 OVERVIEW
<BOSOR4>
   OVERVIEW

   Information is available on:

 ANALYSES      HOWTORUN      SAMPLERUN      SUMMARY
 EXPERT        DOCUMENTS     LOGIN

 Next, please type HELP4 OVERVIEW SUBTOPIC, in which SUBTOPIC stands
 for one of the subtopics listed above.

$ HELP4 OVERVIEW SUMMARY
<BOSOR4>
   SUMMARY of purpose of BOSOR4...

In BOSOR4 a complex, branched, stiffened shell of revolution is
treated as an assemblage of shell segments or branches, each with its
own geometry (flat, cylindrical, spherical, etc), loading, wall
construction, and material properties.  In this version of BOSOR4 you
provide the input data in a "conversationally" interactive mode on a
segment-by-segment basis.

Before beginning an interactive session you should already have
decided how to divide the structure that you are analyzing into
segments and branches, and you should have available to you all
dimensions and material properties and loading.  You should also
have decided what kind of analysis to perform.

You provide input data interactively.  The prompting
information contains references to page numbers and figures and
tables that are contained in:

"BOSOR4--Program for stress, buckling, and vibration of complex shells
of revolution", STRUCTURAL MECHANICS SOFTWARE SERIES,Vol. I, edited by
N. Perrone and W. Pilkey, Univ. Press of Virginia,Charlottesville,
pp. 11-143 (1977).  This is the user's manual for earlier BOSOR4's.

$ HELP4 OVERVIEW HOWTORUN
<BOSOR4>
   HOW TO RUN BOSOR...

      You first activate BOSOR4 commands via the command BOSOR4LOG.
      This command must be given before you do any BOSOR4 work.
      Input data are then prepared interactively via the INPUT
      command or a series of INPUT commands. Files with the name
      'NAME'.SEG;n ,  n = 1, 2, 3, . . .(NSEG+1), in which 'NAME' is
      a name you assign to the case and NSEG is the number of
      structural segments in the model, are then concatenated into
      a single file, 'NAME'.ALL, via  ASSEMBLE.  Then a batch run
      is initiated via the command  BOSORALL.  Plots are obtained
      via the command  BOSORPLOT.

      SAMPLE RUNSTREAM:

              BOSOR4LOG       (You activate the BOSOR4 commands.)
              INPUT           (You supply data interactively. It is
                               automatically stored on 'NAME'.SEG;n)
```

```
          ASSEMBLE        ('NAME'.SEG;n files are concatenated into
                           a single file, 'NAME'.ALL)
          BOSORALL        (A batch run through the BOSOR4 pre- ,
                           main-, and post-processors is initiated)
          BOSORPLOT       (Plot files *.PLV are generated)

$ HELP4 COMMANDS
<BOSOR4>
   COMMANDS

   Information is available on:

  ASSEMBLE    BOSORALL    BOSORPLOT    CHECKFILE    CLEANUP
  GETLIB      GETSEGS     INPUT        MODIFY
  ORDERSEG    RESETUP     RESTART      BOSOR4LOG    PLOT

  Next, please type HELP4 COMMAND SUBTOPIC, in which SUBTOPIC stands
  for one of the subtopics listed above.

$ HELP4 COMMANDS MODIFY
<BOSOR4>
   MODIFY

      This command allows you to edit files with the names 'NAME'.SEG.
      You first answer questions pertaining to a particular category of
      structural information. This short interactive session produces
      a file with a name such as GEOM.QUE (for meridional geometry),
      RINGS.QUE (for discrete rings), LINELOADS.QUE (for line loads),
      CONSTRAIN.QUE (for constraint conditions), etc.  Following the
      short interactive session, (which you can bypass if a suitable
      *.QUE file already exists), MODIFY automatically inserts this
      *.QUE file into the proper position in the 'NAME'.SEG file and,
      if you wish, tests the new 'NAME'.SEG file using the utility
      CHECKFILE.

MODIFY works because of certain key phrases embedded in the 'NAME'.SEG
files.  These key phrases tell MODIFY where the new data should
be inserted.  Because of this, MODIFY should only be used with NAME.SEG
files that have been generated from a good NAME.DOC file via the
utility GETSEGS. (GETSEGS disassembles the NAME.DOC file into NAME.SEG
files.) MODIFY may not work when you apply it to NAME.SEG files that
have been generated in some shortcut manner, such as by means copying
from other segments or otherwise using the VAX editor to generate
NAME.SEG files.
```

APPENDIX 2. BOSOR4 SAMPLE CASE EXTERNALLY PRESSURIZED SPHERICAL CAP ON FRICTIONLESS PLANE

Appendix 2 contains the interactive session for input data.

```
$ BOSOR4LOG
Previous logical name assignment replaced

 BOSOR4 COMMANDS HAVE BEEN ACTIVATED.

The BOSOR4 commands, in the general order in which
you would probably use them, are:

  HELP4       (get information on BOSOR4.)
  INPUT       (you provide segment-by-seg. input)
  ASSEMBLE    (concatenates segment data files)
```

```
  BOSORALL     (batch run of pre, main, post proc.)
  BOSORPLOT    (batch run for generating plot files)
  RESETUP      (input for restart run, same model)
  RESTART      (batch run of main and postprocessors)
  CLEANUP      (delete all except for .DOC file)
  GETSEGS      (generate segment files from .DOC)
  MODIFY       (modify a segment file)
  CHECKFILE    (check  a segment file)

Please consult the following sources for more
information about BOSOR4:

  1. HELP4 file     (type HELP4)
  2. BOSOR4ST.ORY  (good idea to print this file)
  3. Documents listed under HELP4 OVERVIEW DOC


 $ INPUT

PROMPT FILES HAVE NOW BEEN ASSIGNED.

ENTER BOSOR4 CASE NAME: CAP

Do you want to provide data for a new structural
segment, or add data to that for an existing
structural segment (Y or N) ? : Y

AGAIN, ENTER THE BOSOR4 CASE NAME
CAP
Which segment is this?=1
Are you correcting, adding to, or checking an existing file?=N

Please provide a title (42 characters or less)...

EXT. PRESSURE ON CAP ON FRICTIONLESS PLANE
INDIC = analysis type indicator=H

 0= nonlinear axisymmetric stress (and collapse) analysis,
-2= stability determinant calculated for increasing load,
-1= bifurcation buckling with nonlinear prebuckling analysis,
 1= bifurcation buckling with linear    prebuckling analysis;
   (Actually the prebuckling analysis is the same as for
    INDIC = -1.  However, the applied load is never changed
    during a case.  Linear behavior is exhibited as long as
    the user applies a load that is very small compared to
    the design load.)

 2= modal vibration with axisymmetric nonlinear prestress.
 3= linear nonsymmetric stress analysis;
 4= bifurcation buckling with linear nonsymmetric prebuckling.

INDIC = analysis type indicator=-2
NPRT = output options (1=minimum, 2=medium, 3=maximum)=1
ISTRES= output control (0=resultants, 1=sigma, 2=epsilon)=0
NSEG  = number of shell segments (less than 95)=1

The following input must be provided by you for each
shell segment.  See p. 61 for a list of the types of
input data required.  (Page numbers refer to the BOSOR4 user's
manual, "BOSOR4--Program for Stress, Buckling, and Vibration of
Complex Shells of Revolution", STRUCTURAL MECHANICS SOFTWARE SERIES-
Vol. 1, edited by N. Perrone and W. Pilkey, University Press of
Virginia, Charlottesville, VA, 1977, pp 11-143)
```

```
NMESH = number of node points (5 = min.; 98 = max.)=31
NTYPEH= control integer (1 or 2 or 3) for nodal point spacing=3

Geometry of the current segment...
NSHAPE= indicator (1,2 or 4) for geometry of meridian=2
R1     = radius at beginning of segment (see p. 66)=0
Z1     = axial coordinate at beginning of segment=0
R2     = radius at end of segment=75.16523
Z2     = axial coordinate at end of segment=34.04405
RC     = radius from axis of rev. to center of curvature=0
ZC     = axial coordinate of center of curvature=100
SROT=indicator for direction of increasing arc (-1. or +1.)=H

See Figures on p. 66
-1 means anticlockwise;  +1 means clockwise.

SROT=indicator for direction of increasing arc (-1. or +1.)=-1.

Imperfection geometry....
IMP   = indicator for imperfection (0=none, 1=some)=0
NTYPEZ= control (1 or 3) for reference surface location=H

NTYPEZ = 1 means that the distance from the shell wall
leftmost surface to the reference surface varies along
the meridian. By "leftmost" we mean as we face in the
direction of increasing meridional arc length, s.  See
the figure at the bottom of p. 66.

NTYPEZ = 3 means that the distance from  the  leftmost
surface of the wall to the reference surface is const-
ant as we proceed along the meridian, s.

NTYPEZ= control (1 or 3) for reference surface location=3
ZVAL  = distance from leftmost surf. to reference surf.=.5
Do you want to print out r(s), r'(s), etc. for this segment?=Y
NRINGS= number (max=20) of discrete rings in this segment=0
K=elastic foundation modulus (e.g. lb/in**3)in this seg.=0

The following input is related to loading of this
segment.  Please see pp. 73-77 for discussion and
definitions. Also, you may wish to review pp. 58-60.
There is more discussion in the "pitfalls" section
on pp. 120-123.

There are four classes of loads:
a. mechanical line loads and/or imposed displacement
   components, applied at centroids of discrete rings;
b. thermal line loads at discrete rings;
c. pressure and tractions distributed over the surface;
d. temperature distribution through thickness and over
   surface.

In connection with mechanical line loads and/or imposed
displacement components, the word "load" is used to mean
either an imposed load or an imposed displacement.

LINTYP= indicator (0, 1, 2 or 3) for type of line loads=H

0 means none
1 means mechanical line loads and/or imposed displacements;
2 means thermal line loads only;
3 means both mechanical and thermal line loads.
```

```
Note that if LINTYP is greater than 0 there must be
discrete rings on which to "hang" the line loads and/or
imposed displacement components.
Line loads are assumed to act at the centroids of discrete
rings. They are positive as shown on page 74, bottom.
Imposed displacement components also "act" at ring centroids.
They are positive as shown on page 51, bottom (USTAR,WSTAR,CHI).

In the following input for line loads or imposed displacements...
 V(K) can mean axial load or imposed axial displacement;
      [note: positive V (load) is in opposite direction from
             positive V (imposed axial displacement USTAR)]
 S(K) can mean circ. load or imposed circ. displacement;
HF(K) can mean radial load or imposed radial displacement;
FM(K) can mean meridional moment or imposed rotation CHI (p.51).

LINTYP= indicator (0, 1, 2 or 3) for type of line loads=0
IDISAB= indicator (0, 1, 2 or 3) for load set A and B=H

0 means no distributed loads  (no pressure or thermal loading)
1 means only distributed load set A is present
2 means only distributed load set B is present
3 means both distributed load set A and distributed load set B
  are present

Load set A is considered to be multiplied by the eigenvalue,
whereas load set B is not. Load set B is a fixed preload.

IDISAB= indicator (0, 1, 2 or 3) for load set A and B=1

Next, provide input for distributed loads in load set A.
(loads that are to be multiplied by the eigenvalue)...


SURFACE LOADS FOR LOAD SYSTEM "A"...
NLTYPE=control (0,1,2,3) for type of surface loading=H

NLTYPE= 0 means no pressure, surface traction, or
          temperature distribution on this shell segment.
NLTYPE= 1 means pressure and/or surface traction, but
          no temperature distribution on this segment.
NLTYPE= 2 means temperature distribution, but no pressure
          or surface traction.
NLTYPE= 3 means both pressure and temperature.

NLTYPE=control (0,1,2,3) for type of surface loading=1
NPSTAT= number of meridional callouts for surface loading=H

Minimum value is NPSTAT = 2, corresponding to callout points
at the beginning and at the end of the segment. Maximum
value is NPSTAT = 20

NOTE  The first at last points along the meridian must be
      included as callouts.

NPSTAT= number of meridional callouts for surface loading=2
NLOAD(1)=indicator for meridional traction (0=none, 1=some)=0
NLOAD(2)=indicator for circumferential traction=0
NLOAD(3)=indicator for normal pressure     (0=none, 1=some)=1
PN(i)   = normal pressure (p.74) at ith callout, PN( 1)=H

Sign convention is shown in the fig. on p. 74. Also, see
```

Table A4 and p. 85. The total pressure is PN(i)*g(theta), where g(theta) is a Fourier series defined below. In the figure on p. 74 the loads PT, PC, and PN are called p1, p2, p3, respectively.

```
PN(i)   = normal pressure (p.74) at ith callout, PN( 1)=-1.
PN(i)   = normal pressure (p.74) at ith callout, PN( 2)=-1.

NTYPE = control for meaning of loading callout (2=z, 3=r)=H

See pp. 69 for further discussion and examples.
NTYPE = 2 means callouts for meridional variation of
          surface traction and pressure will be axial
          coordinates;
NTYPE = 3 means callouts will be radial coordinates.

NTYPE = control for meaning of loading callout (2=z, 3=r)=3
R(I)  = radial coordinate of Ith loading callout, r( 1)=0
R(I)  = radial coordinate of Ith loading callout, r( 2)=75.16523

Wall construction input follows...

NWALL=index (1, 2, 4, 5, 6, 7, 8) for wall construction=H

NWALL = 1 means general C(i,j)  (see p.90)
NWALL = 2 means monocoque isotropic
NWALL = 4 means fiberwound, layered, constant thickness
NWALL = 5 means layered orthotropic, variable thickness
NWALL = 6 means corrugated (corrugations run axially)
NWALL = 7 means semi-sandwich axially corrugated, that is
          a smooth sheet is fastened to a corrugated sheet
NWALL = 8 means layered orthotropic with temperature-
          dependent material properties, variable thickness

Smeared stiffeners may be added to any of these types.
The smeared stiffeners may be either or both rings and
stringers.

NWALL=index (1, 2, 4, 5, 6, 7, 8) for wall construction=2

Input for monocoque, isotropic wall construction...

E     = Young's modulus for skin=10000000.
U     = Poisson's ratio for skin=.3
SM =mass density of skin (e.g. alum.=.00025 lb-sec**2/in**4)=0
ALPHA = coefficient of thermal expansion=0
NRS  = control (0 or 1) for addition of smeared stiffeners=0
NSUR  = control for thickness input (0 or 1 or -1)=H

NSUR  = 0 means reference surface is middle surface
        (We will not need to provide thickness, since
         we have already provided ZVAL, the distance
         from the leftmost surface to the ref. surf.)

NSUR  = 1 means the reference surface is the outer or
        rather the rightmost surface. Again, we do
        not need to provide input for the thickness,
        since ZVAL is the same as the thickness in
        this case.

NSUR  =-1 means that the reference surface is arbitrarily
```

```
          located with respect to the leftmost surface (It
          might be the leftmost surface itself). Therefore,
          you will have to provide additional input data
          to establish the wall thickness.

NSUR   = control for thickness input (0 or 1 or -1)=0
Do you want to print out ref. surf. location and thickness?=N
Do you want to print out the C(i,j) at meridional stations?=N
Do you want to print out distributed loads along meridian?=N

Directory DRC1:[BUSHNELL]

CAP.SEG;1               8/8      22-OCT-1984 17:30

Total of 1 file, 8/8 blocks.
Want to add more structural segments now (Y or N) ? : N
Have you supplied data for all structural segments? : Y

Next, give global input and input for constraint
conditions....

Do you want to supply these data now (Y or N) ? : Y
Previous logical name assignment replaced

AGAIN, ENTER THE BOSOR4 CASE NAME
CAP
How many segments in the structure?=1
INDIC = analysis type indicator=-2
Are you correcting, adding to, or checking an existing file?=N
NLAST = plot options  (-1=none, 0=geometry, 1=u,v,w)=0

Your structure may contain segments that are very short
compared to the whole model being analyzed here. This detail
will not show up well in plots of the entire undeformed and
deformed structure. Therefore you may wish to get expanded
plots of these regions. Please identify these regions by
segment number and give a magnification factor for each region.
Note that the magnification factor must be an integer.
The center of the expanded plot will be at the first point of
the segment so identified. The extent of structure plotted
will of course depend on the magnification factor you choose.

Are there any regions for which you want expanded plots?=N
NOB   = starting number of circ. waves (buckling analysis)=6
NMINB = minimum number of circ. waves  (buckling analysis)=2
NMAXB = maximum number of circ. waves  (buckling analysis)=15
INCRB = increment in number of circ. waves (buckling)=1
NVEC  = number of eigenvalues for each wave number=1

Next, please provide factors P and DP, TEMP and DTEMP, which
are multipliers for the pressure, surface traction, and
temperature distributions in load system "A". Note that these
multipliers are applied only to load system "A". They are not
applied to load system "B". (Load system "A" represents the
"eigenvalue" load system. Load system "B" is constant
throughout the case.)

P      = pressure or surface traction multiplier=H

The factor P is applied only to the distributed mechanical
loads in load system "A". For example, if INDIC is less than
three (axisymmetric loading), the normal pressure along Segment
```

No. i for load system "A" is given in the first load step by:

```
pressure = P*PN(j)          j = 1, 2, ....NMESH(i)
```

in which PN(j) is the meridional pressure distribution.

See pp. 58-60 for further discussion of loading parameters.

```
P       = pressure or surface traction multiplier=200
DP      = pressure or surface traction multiplier increment=100
TEMP    = temperature rise multiplier=0
DTEMP   = temperature rise multiplier increment=0
Number of load steps=20
OMEGA   = angular vel. about axis of revolution (rad/sec)=0
DOMEGA = angular velocity increment (rad/sec)=0
How many segments in the structure?=1
```

Four kinds of constraint conditions exist in BOSOR4:

1. constraints to ground (e.g. boundary condtions)
2. juncture compatibility conditions
3. regularity conditions at poles (where radius r = 0)
4. constraints to prevent rigid body displacements

See the fig. on p. 54, for example. There is a constraint to ground (boundary condition) at Segment 8, Point 8; there are several juncture conditions (e.g. Seg. 2, Pt. 1 is connected to Seg. 1, Pt. 9); there are several poles (e.g. Seg. 1, Pt. 1). Note that if a shell is not anywhere attached to ground, such as is the case for the example shown on p. 57, the user must choose a node at which to prevent rigid body motion. This node is to be chosen in the section below where the user is asked about constraints to ground. In a section following the "constraints-to-ground" section, the user will be asked to provide specific data for preventing rigid body motion. Types of rigid body motion are shown on p. 56. An example of appropriate input data is listed on p. 57, bottom.

```
 CONSTRAINT CONDITIONS FOR SEGMENT NO. ISEG =           1
Number of poles (places where r=0) in SEGMENT=1
IPOLE = nodal point number of pole, IPOLE( 1)=1
At how many stations is this segment constrained to ground?=1
INODE = nodal point number of constraint to ground, INODE( 1)=31
IUSTAR=axial displacement constraint (0 or 1 or 2)=1
IVSTAR=circumferential displacement(0=free,1=0,2=imposed)=0
IWSTAR=radial displacement(0=free,1=constrained,2=imposed)=0
ICHI=meridional rotation (0=free,1=constrained,2=imposed)=0
D1    = radial component of offset of ground support=0
D2    = axial component of offset of ground support=0
Is this constraint the same for both prebuckling and buckling?=Y
Is this segment joined to any lower-numbered segments?=N
```

It may be necessary to provide additional constraint to ground in order to prevent rigid body motion. All possible types of rigid body motion are shown on p. 56. Rigid body motion corresponds to n = 0 or n = 1 circumferential waves. There is no rigid body component for any harmonic with n greater than or equal to 2. For modal vibration problems rigid body motion need be prevented only if the structure is loaded.

```
Given existing constraints, are rigid body modes possible?=N
Do you want to list output for segment( 1)=Y
```

```
Do you want to list forces in the discrete rings, if any?=N

Directory DRC1:[BUSHNELL]

CAP.SEG;2                 6/8      22-OCT-1984 17:40
CAP.SEG;1                 8/8      22-OCT-1984 17:30

Total of 2 files, 14/16 blocks.

If you have completed input for all structural
segments and for the constraint conditions, next
give the command  ASSEMBLE

 $ ASSEMBLE
Enter BOSOR case name: CAP
Enter number of segments in the structure: 1
 DELETE-W-FILNOTDEL, error deleting DRC1:[BUSHNELL]FORO*.*;*
-RMS-E-FNF, file not found
 DELETE-W-FILNOTDEL, error deleting DRC1:[BUSHNELL]CAP.BLK;*
-RMS-E-FNF, file not found

Don't worry about above error messages, if any.

You have the following files with the name
CAP.ALL :
  No files found.

Any old CAP.ALL files that you want to save (Y or N)?: N
 DELETE-W-FILNOTDEL, error deleting DRC1:[BUSHNELL]CAP.ALL;*
-RMS-E-FNF, file not found

You have the following files with the name
CAP.SEG :

Directory DRC1:[BUSHNELL]

CAP.SEG;2                 6/8      22-OCT-1984 17:40
CAP.SEG;1                 8/8      22-OCT-1984 17:30

Total of 2 files, 14/16 blocks.

Do you have exactly  2 CAP.SEG files (Y or N)? : Y
Are the CAP.SEG files in the correct order (Y or N)?: Y
Do you want to delete the CAP.SEG files? (Y or N): N
 CAP.SEG;n files are now
             assembled into the file CAP.ALL
You now have the following files with the name
CAP.* :
Directory DRC1:[BUSHNELL]
CAP.ALL;2                13/16     22-OCT-1984 17:45
CAP.SEG;2                 6/8      22-OCT-1984 17:40
CAP.SEG;1                 8/8      22-OCT-1984 17:30
Total of 3 files, 27/32 blocks.
Now you can give the command  BOSORALL

 $ BOSORALL
ENTER BOSOR4 CASE NAME: CAP
WHAT DISK:[DIRECTORY.SUBDIR] FOR YOUR I/O?: DRC1:[BUSHNELL.MESH]
WHAT DISK:[DIRECTORY.SUBDIR] CONTAINS BOSOR4?: DRC1:[BUSHNELL.BOSOR4]
F(AST),S(YS$BATCH),T(EST),N(ORMAL),ORH(UGE) QUEUE?: F
```

```
Give time, in the format 04-JUL-1984:16:00, after
which you want the batch run started. If you want
the batch run started as soon as possible, simply
hit RETURN.

RUN BATCH JOB AFTER (RETURN or DAY-MONTH-YEAR:HOUR:00):
  Job 8320 entered on queue FAST
```

APPENDIX 3. ANNOTATED FILE, CAP.DOC, CREATED BY BOSOR4 PREPROCESSOR

```
EXT. PRESSURE ON CAP ON FRICTIONLESS PLANE
      -2       $ INDIC = analysis type indicator
       1       $ NPRT = output options (1=minimum, 2=medium, 3=maximum)
       0       $ ISTRES= output control (0=resultants, 1=sigma, 2=epsilon)
       1       $ NSEG  = number of shell segments (less than 95)
    H          $
    H          $ SEGMENT NUMBER    1    1    1    1    1    1    1    1
    H          $ NODAL POINT DISTRIBUTION FOLLOWS...
      31       $ NMESH = number of node points (5 = min.; 98 = max.)( 1)
       3       $ NTYPEH= control integer (1 or 2 or 3) for nodal point spacing
    H          $ REFERENCE SURFACE GEOMETRY FOLLOWS...
       2       $ NSHAPE= indicator (1,2 or 4) for geometry of meridian
       0       $ R1      = radius at beginning of segment (see p. 66)
       0       $ Z1      = axial coordinate at beginning of segment
  75.16523     $ R2      = radius at end of segment
  34.04405     $ Z2      = axial coordinate at end of segment
       0       $ RC      = radius from axis of rev. to center of curvature
     100       $ ZC      = axial coordinate of center of curvature
 -1.000000     $ SROT=indicator for direction of increasing arc (-1. or +1.)
    H          $ IMPERFECTION SHAPE FOLLOWS...
       0       $ IMP    = indicator for imperfection (0=none, 1=some)
    H          $ REFERENCE SURFACE LOCATION RELATIVE TO WALL
       3       $ NTYPEZ= control (1 or 3) for reference surface location
0.5000000      $ ZVAL  = distance from leftmost surf. to reference surf.
    Y          $ Do you want to print out r(s), r'(s), etc. for this segment?
    H          $ DISCRETE RING INPUT FOLLOWS...
       0       $ NRINGS= number (max=20) of discrete rings in this segment
       0       $ K=elastic foundation modulus (e.g. lb/in**3)in this seg.
    H          $ LINE LOAD INPUT FOLLOWS...
       0       $ LINTYP= indicator (0, 1, 2 or 3) for type of line loads
    H          $ DISTRIBUTED LOAD INPUT FOLLOWS .
       1       $ IDISAB= indicator (0, 1, 2 or 3) for load set A and B
    H          $ SURFACE LOAD INPUT FOR LOAD SET "A" FOLLOWS
       1       $ NLTYPE=control (0,1,2,3) for type of surface loading
       2       $ NPSTAT= number of meridional callouts for surface loading
       0       $ NLOAD(1)=indicator for meridional traction (0=none, 1=some)
       0       $ NLOAD(2)=indicator for circumferential traction
       1       $ NLOAD(3)=indicator for normal pressure     (0=none, 1=some)
-1.000000      $ PN(i)   = normal pressure (p.74) at ith callout, PN( 1)
-1.000000      $ PN(i)   = normal pressure (p.74) at ith callout, PN( 2)
       3       $ NTYPE = control for meaning of loading callout (2=z, 3=r)
       0       $ R(I)  = radial coordinate of Ith loading callout, r( 1)
 75.16523      $ R(I)  = radial coordinate of Ith loading callout, r( 2)
    H          $ SHELL WALL CONSTRUCTION FOLLOWS...
       2       $ NWALL=index (1, 2, 4, 5, 6, 7, 8) for wall construction
0.1000000E+08  $ E      = Young's modulus for skin
0.3000000      $ U      = Poisson's ratio for skin
       0       $ SM =mass density of skin (e.g. alum.=.00025 lb-sec**2/in**4)
       0       $ ALPHA = coefficient of thermal expansion
       0       $ NRS  = control (0 or 1) for addition of smeared stiffeners
```

```
    0     $ NSUR   = control for thickness input (0 or 1 or -1)
N         $ Do you want to print out ref. surf. location and thickness?
N         $ Do you want to print out the C(i,j) at meridional stations?
N         $ Do you want to print out distributed loads along meridian?
H         $
H         $ GLOBAL DATA BEGINS...
    0     $ NLAST = plot options  (-1=none, 0=geometry, 1=u,v,w)
N         $ Are there any regions for which you want expanded plots?
    6     $ NOB   = starting number of circ. waves (buckling analysis)
    2     $ NMINB = minimum number of circ. waves  (buckling analysis)
   15     $ NMAXB = maximum number of circ. waves  (buckling analysis)
    1     $ INCRB = increment in number of circ. waves (buckling)
    1     $ NVEC  = number of eigenvalues for each wave number
  200     $ P       = pressure or surface traction multiplier
  100     $ DP      = pressure or surface traction multiplier increment
    0     $ TEMP    = temperature rise multiplier
    0     $ DTEMP   = temperature rise multiplier increment
   20     $ Number of load steps
    0     $ OMEGA   = angular vel. about axis of revolution (rad/sec)
    0     $ DOMEGA = angular velocity increment (rad/sec)
H         $ CONSTRAINT CONDITIONS FOLLOW....
    1     $ How many segments in the structure?
H         $
H         $ CONSTRAINT CONDITIONS FOR SEGMENT NO.    1     1     1     1
H         $ POLES INPUT FOLLOWS...
    1     $ Number of poles (places where r=0) in SEGMENT( 1)
    1     $ IPOLE = nodal point number of pole, IPOLE( 1)
H         $ INPUT FOR CONSTRAINTS TO GROUND FOLLOWS...
    1     $ At how many stations is this segment constrained to ground?
   31     $ INODE = nodal point number of constraint to ground, INODE( 1)
    1     $ IUSTAR=axial displacement constraint (0 or 1 or 2)
    0     $ IVSTAR=circumferential displacement(0=free,1=0,2=imposed)
    0     $ IWSTAR=radial displacement(0=free,1=constrained,2=imposed)
    0     $ ICHI=meridional rotation (0=free,1=constrained,2=imposed)
    0     $ D1     = radial component of offset of ground support
    0     $ D2     = axial component of offset of ground support
Y         $ Is this constraint the same for both prebuckling and buckling?
H         $ JUNCTION CONDITION INPUT FOLLOWS...
N         $ Is this segment joined to any lower-numbered segments?
H         $ RIGID BODY CONSTRAINT INPUT FOLLOWS...
N         $ Given existing constraints, are rigid body modes possible?
H         $ "GLOBAL3" QUESTIONS (AT END OF CASE)...
Y         $ Do you want to list output for segment( 1)
N         $ Do you want to list forces in the discrete rings, if any?
```