

FAILURE ANALYSIS OF THICK COMPOSITE CYLINDERS UNDER EXTERNAL PRESSURE¹

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SUMMARY

Failure of thick section composites due to local compression strength and overall structural instability is treated. Effects of material nonlinearity, imperfect fiber architecture, and structural imperfections upon anticipated failure stresses are determined. Comparisons with experimental data for a series of test cylinders are described.

Predicting the failure strength of composite structures requires consideration of stability and material strength modes of failure using linear and nonlinear analysis techniques. Material strength prediction requires the accurate definition of the local multiaxial stress state in the material. An elasticity solution for the linear static analysis of thick anisotropic cylinders and rings is used herein to predict the axisymmetric stress state in the cylinders. Asymmetric nonlinear behavior due to initial cylinder out of roundness and the effects of end closure structure are treated using finite element methods.

It is assumed that local fiber or ply waviness is an important factor in the initiation of material failure. An analytical model for the prediction of compression failure of fiber composites, which includes the effects of fiber misalignments, matrix inelasticity and multiaxial applied stresses is used for material strength calculations. Analytical results are compared to experimental data for a series of glass and carbon fiber reinforced epoxy cylinders subjected to external pressure. Recommendations for pretest characterization and other experimental issues are presented. Implications for material and structural design are discussed.

INTRODUCTION

The design, analysis and failure prediction of thick fiber composite cylinders is made complex at the materials level by the multiplicity of material characteristics influencing the failure mechanism, and at the structural level by the importance of three

¹ A portion of this work was performed under Subcontract Number 11K-57957C for Martin Marietta Energy Systems at Oak Ridge National Laboratory

dimensional stress states in anisotropic materials. Basic constituent properties such as relative stiffnesses and strength of the fiber and matrix directly affect the mode and stress at material failure. Fabrication related material variables, such as fiber misalignments, ply curvatures, disbonding and resin rich (starved) areas, are also important factors in the compressive failure mechanics of the material. A compression strength model which addresses many of these key material parameters is discussed below. Unlike a semi-empirical phenomenological polynomial failure criterion, this model is physically based on an understanding of the local failure mechanisms. An approach for predicting structural failure of unstiffened hydrostatically loaded composite cylinders, which considers material failure, elastic stability, and nonlinear collapse modes of failure, was developed to evaluate alternative designs. The failure prediction methodology was applied to a series of cylinders fabricated and tested during the DARPA Composite Materials for Future Submarines (CMFS) project. Analysis and experimental failure results for two of the cylinders are discussed below.

COMPRESSIVE STRENGTH OF FIBER COMPOSITES

It has been widely accepted that the axial compressive failure mode of a unidirectional composite is local instability. Microbuckling was first proposed as a failure mechanism by Dow and Gruntfest [1]. This work suggested that small wavelength fiber buckling occurs in a fashion analogous to buckling of a column supported by an elastic foundation. Rosen [2] provided the initial analytical solution for the instability load by treating the reinforcement and matrix as a layered two dimensional medium. Two possible failure modes were considered: one in which adjacent fibers buckle in opposite directions (extensional mode); and one in which adjacent fibers buckle in phase with one another. For composites used for structural applications, the shear mode occurs at a lower applied load and is the governing failure mechanism. For elastic material behavior, the shear mode microbuckling result predicts instability failure at the same stress as the shear kinking mode examined subsequently by Budiansky [3]. Compressive failure for the shear microbuckling and shear kinking modes occurs at a stress numerically equal to the axial shear modulus of the unidirectional composite. This level of stress is not usually achieved in experiments, although the observed failure mode generally agrees with the analytical prediction.

Various investigators have included fiber out-of-straightness or misalignment, inelastic matrix response, weak interfaces and low strain to failure of the fiber to explain the discrepancy between experimental and basic theoretical results. In the model used to predict material failure in the thick walled cylinders, the observed nonlinear shear stress-strain behavior typical of glass and carbon fiber reinforced epoxies has been attributed to nonlinear matrix behavior. If significant shearing stresses are present in the matrix, due to applied loads or generated by local perturbations in fiber straightness, the matrix shear stiffness will be less than the initial

elastic value. For a general three dimensional state of stress, the reduced matrix tangent shear modulus can be computed based upon the second invariant of the deviatoric stress tensor. The reduced matrix shear stiffness results in a reduced composite tangent shear modulus and, hence, lower compressive strengths.

Matrix nonlinearity, imperfect interfaces, and fiber misalignment, while important effects, may not completely account for the discrepancies found between experimental strengths and strengths predicted based upon local instability theories. The failure strength, and failure mode of a fiber composite material is a function of each constituent's stiffness and failure strength. While the primary mode of failure for composites loaded in axial compression appears to be a local instability, it is important to recognize that accurate predictions of composite compressive strength must consider all possible failure modes. A graphical representation of the heterogeneous failure surface of a unidirectional fiber composite can be constructed for up to three components of applied load. Such a failure surface is presented in figure 1. For a uniaxial load (i.e., see also figure 2), the initiating failure mechanism is calculated to be fiber failure. As the applied transverse normal and shear stresses are increased from zero, microbuckling becomes the predominant mode of failure. For very high values of applied transverse normal and shear stresses, matrix failure is predicted to initiate overall ply failure. Hence, determination of the compressive strength of a fiber composite requires definition of the local multi-dimensional stress or strain state in principal material coordinates.

CYLINDER FAILURE ANALYSIS APPROACH

This section outlines a methodology for the failure prediction of hydrostatically loaded composite cylinders. Two levels of variables likely to affect the collapse strength of unstiffened composite cylinders were investigated: local ply (fiber bundle) waviness and global cylinder out of roundness. Material strength prediction is based upon inelastic microbuckling theory. The structural behavior of the cylinders was predicted using a closed form elasticity solution to solve for axisymmetric response and the finite element method to solve for asymmetric response.

A computerized solution for the linear static and linear viscoelastic analysis of thick axisymmetric anisotropic cylinders and rings was used to determine cylinder deflections, nominal fiber bundle (ply) stresses, and strains. This structural model is based upon linear elasticity theory [4, 5] and assumes that the axial strain response of the cylinder is independent of axial location. Discontinuity stresses developed near the end closures are not included. Any linear combination of internal and external pressure, end load, torque, and uniform temperature change may be defined as load inputs. Time dependent linear viscoelastic matrix behavior is permitted by the model but will not be addressed here.

Unidirectional composite (ply) properties were computed using the properties of the fiber and matrix and the composite cylinders assemblage model [6]. Composite material properties were predicted using the three dimensional mini-mechanics theory outlined in reference [7]. To determine a baseline failure pressure for each cylinder design, computed axisymmetric cylinder strains as a function of radius were transformed to principal material coordinates, and input into the nonlinear compressive strength model described above to predict the external pressure at initial material failure assuming that the cylinder response is linearly elastic.

The ABAQUS [8] general purpose finite element code was used to evaluate end closure effects, determine the elastic bifurcation buckling pressure and to evaluate the nonlinear elastic collapse strength of the cylinder. It was assumed that the cylinder is 'long' and, therefore, will buckle with two circumferential lobes. This assumption is supported by closed form energy solution results. Therefore, only a 90° arc segment of the cylinder is necessary to predict the buckling pressure and mode shape. Simple four noded, quadrilateral shell elements which include transverse shear deformation were used in the finite element analyses. A plot of the typical axisymmetric prebuckling displacement pattern and lowest asymmetric buckling mode is shown in figure 3. Although the ABAQUS idealization is relatively simple, the linear axisymmetric displacement results at cylinder midbay compared well with the closed form elasticity solution.

It is well known that linear elastic bifurcation results overpredict the actual collapse load of structures. A large data base of experimental results exists for hydrostatically loaded isotropic cylinders which support this statement. It is generally accepted that small geometric imperfections initiate nonlinear structural behavior, and significantly reduce the cylinder collapse load. This phenomenon can be mathematically modeled in ABAQUS, by imputing a small deviation in the radius as a function of axial and circumferential position and performing a nonlinear incremental loading analysis. As a worst case approach, the initial imperfection pattern was chosen to be the lowest energy mode predicted by the bifurcation buckling solution. Bending strains in the circumferential and axial directions at the inner and outer shell thickness were calculated and input into the nonlinear compressive strength model. The applied bundle (ply) stresses were plotted versus fiber bundle compressive strength to determine the value of pressure at which material failure is initiated.

It should be noted that only initial material failure is predicted. The cylinder may still retain load carrying capacity at a reduced stiffness after initial ply failures. This is analogous to predicting onset of yield in the failure process of a metal structure, while it is known that ultimate failure occurs by forming of a plastic hinge mechanism. A nonlinear material model which includes the inelastic microbuckling strength prediction must be coupled to the structural analysis code to predict the progressive failure of the entire cylinder thickness.

PREDICTED AND MEASURED CYLINDER FAILURES

The physically based compression strength model and structural analyses methods described above were used to predict the collapse of a series of cylinders tested during the CMFS project. These cylinders were fabricated of all graphite-epoxy, all S2 glass epoxy and hybrids of graphite and glass fiber composite. This section describes analysis results, including predicted mode and location of failure, and compares the analyses to experimental data for two of the cylinders.

Cylinder HWB1

The cylinder designated HWB1 is a model scale cylinder of the AUSS hull described in reference [9]. The cylinder was designed and wet filament wound at ORNL using IM6 graphite fibers. Approximate fiber distribution was 69% in the circumferential direction and 31% in the axial direction. The cylinder was tested on rigid end supports, and failed catastrophically at 12,500 psi external hydrostatic pressure.

Stress, Stability and Failure Analysis of HWB1

Calculated strains at 10000 psi external pressure versus the experimental strain gage readings are plotted in figure 4. The elasticity analysis provides a good prediction (within 3%) of the measured circumferential strains at the inner radius. The correlation between the axial strain results is also quite good (within 2%). The strain data correlation suggests that the material properties and structural response of the HWB1 model were characterized to a sufficient degree to predict material failure.

The calculated circumferential, axial, and radial strains at the inner, mid and outer radius were used in the inelastic microbuckling model to determine the pressure at which initial material failure will occur at cylinder midbay. The compressive strength model predicts initial material failure to occur at the inner radius, in the circumferential bundles at an external pressure of 32200 psi. If an inner ply is slightly misaligned with respect to the cylinder tangential direction, initial material failure will occur at a lower value of applied load. Based upon visual observations [10], and the results of recent work on correlation of measured versus experimental data, an initial local fiber waviness of 2° was assumed to be present in some circumferential plies of the cylinder. This reduces the calculated pressure at which microbuckling failure occurs to 20900 psi.

The effects of assumed end conditions on the calculated instability pressure of cylinder HWB1 were evaluated using the ABAQUS finite element code. The effect of neglecting transverse shear deformation (classical plate theory vs. shear deformation theory) in the bending stiffness of the composite shell was also determined. A reduction in

buckling pressure of approximately 15-25% is predicted if the deflection due to shear deformation is included in the plate theory. The effect becomes more pronounced as the fixity of the end conditions is relaxed. The linear finite element analyses predict that the cylinder is elastically stable to 23800 psi if tested on rigid end closures.

A refined elastic collapse strength for the cylinder was predicted by performing a nonlinear incremental loading analysis using large deflection theory. To evaluate the sensitivity of the cylinder to local out of roundness effects, initial imperfection amplitudes of 5 and 50 mils (0.005, 0.050 inches respectively) were input into the ABAQUS finite element model. The fabrication quality of the HWB1 model scale cylinder was reported to be quite good [11]. These amplitudes were used simply to investigate the sensitivity of the predicted failure pressure to slight geometric imperfections.

Results of the nonlinear finite element analyses of the HWB1 cylinder are presented in figure 5. Normal (radial) deflection for two nodes 90 degrees apart on the circumference are plotted versus applied hydrostatic pressure. The elastic collapse strength is defined by the asymptotic increase in normal deflection for a small increase in applied pressure. Also indicated on the figures for comparison is the linear elastic bifurcation buckling pressure. The load deflection curve for the 5 mil initial out of roundness very closely parallels the theoretical Euler type behavior. However, the 50 mil initial out of roundness produces significant nonlinear behavior at much smaller load levels. The elastic nonlinear collapse strength for the 50 mil deviation in radius is predicted to be 17600 psi (approximately a 13% decrease in load).

It has been shown that initial out of roundness patterns inherent to all cylinders produce an asymmetric bending response. Maximum circumferential stresses at the cylinder midbay for the 5 and 50 mil assumed initial imperfections were used in the compressive strength model to predict a nonlinear inelastic type failure (figure 6). This approach predicts that material failure will occur at 19700 psi for the 5 mil imperfection and 14600 psi for the 50 mil imperfection if all plies are perfectly aligned with the cylinder circumference. A 2° circumferential fiber bundle misalignment reduces the predicted pressure at initial microbuckling failure to 17500 psi and 11100 psi, for the assumed out of roundness values of 5 and 50 mils, respectively.

To approximate the rigidity of the end closure structure, strains versus position along the length of the cylinder were computed assuming complete rotational and displacement fixity at the ends. While the circumferential stress near the end closure is reduced, high axial bending and shear stresses will be generated. The maximum calculated axial strain (at the inner radius) is approximately 70% higher than the nominal midbay value. The average thru thickness shear stress in the composite, at the end plate, is calculated to be 0.88 psi per psi of applied pressure. The interlaminar shear strength of the HWB1 material was reported to be 13.0 ksi [9], therefore, shear stresses at the end closures may cause initial interlaminar damage to the shell at

approximately 11000 psi pressure. The compressive strength model predicts initial axial microbuckling failure to occur at 14100 psi external pressure assuming linear behavior to failure. The HWB1 model scale cylinder imploded at 12500 psi external hydrostatic pressure. Strain gage results of the model scale test cylinder showed a significant variation in readings around the circumference [9] indicating some degree of asymmetric behavior. The analyses predict microbuckling failure in the circumferential fibers at the experimental failure pressure, if an initial imperfection amplitude of approximately 35 mils forming two circumferential waves around the cylinder circumference is present. This amount of cylinder out of roundness was not reported.

Based upon the nonlinear collapse analysis results, it is unlikely that structural instability is the initiating failure mechanism for the HWB1 cylinder. Experimental results implied that the graphite epoxy material compressive strength is less than acceptable, since nominal axisymmetric circumferential ply stresses at cylinder failure are calculated to be approximately 90 ksi. It is believed that testing the HWB1 model scale to implosion on rigid end plugs significantly reduced the cylinder strength. The large discontinuity stresses developed due to the radial deflection mismatch at the ends may in fact be the initiating mechanism of failure. Unfortunately, axial strains near the end of the cylinder were not monitored during testing on the rigid end closures.

Cylinder SWT1

The cylinder designated SWT1 is a hybrid concept designed and wet filament wound under the ORNL program [12]. Approximate fiber distribution was 50% circumferential IM6 fibers and 50% axial S2 glass fibers. The cylinder was tested on rigid end supports, and delaminated at the inner radius at 16000 psi external pressure.

Stress, Stability and Failure Analyses of SWT1

The calculated strains at 10000 psi external pressure versus the experimental strain gage readings for SWT1 are plotted in figure 7. The elasticity analysis provides an excellent prediction of the measured circumferential and axial strains at the inner and outer radii. As before, the calculated were input into the inelastic microbuckling model to predict the pressure at which initial material failure occurs at cylinder midbay. The compressive strength model predicts initial material failure to occur at the inner radius in the graphite fiber circumferential plies at an external pressure of 24600 psi. The calculated pressure required to initiate material failure in a region of 2° fiber misalignment is 16000 psi. This quantitatively illustrates the sensitivity of graphite fiber composite cylinder strengths to slight material imperfections. The axial plies in the SWT1 are S2 glass epoxy, and the calculated failure strength due to axial stresses is virtually unaffected (3% reduction) by a 2° bundle misalignment.

The length to diameter ratio for hydrostatic testing of cylinder SWT1 was 1.5, 25% less than the HWB1 cylinder. The S2 glass axial plies produce composite shear moduli which are higher than HWB1. The combination of a lower length to diameter ratio and higher composite shear modulus increases the calculated buckling strength of this cylinder relative to cylinders HWB1 and RGR1. Assuming fully fixed ends, the elastic buckling prediction for SWT1 is 26200 psi.

The imperfection sensitivity of the SWT1 cylinder was studied in the same manner as the HWB1 cylinder. The assumed 5 and 50 mil out of roundness patterns discussed previously were input into the ABAQUS model and nonlinear elastic collapse pressures were determined. Radial deflection is plotted versus load in figure 8. The nonlinear analysis using the 5 mil imperfection predicts a collapse strength within 4 percent of the bifurcation buckling load (as expected). The collapse prediction is reduced by 15%, to 20300 psi for the 50 mil initial cylinder out of roundness. The relatively high elastic buckling predictions, and knowledge that the compressive strength of graphite fiber composites are extremely sensitive to local material imperfections found in cylindrical geometries, suggested that elastic buckling is not likely to be the initiating failure mechanism for the SWT1 cylinder model.

Figure 9 plots the maximum circumferential stresses at midbay of the SWT1 cylinder versus hydrostatic pressure for an assumed initial cylinder out of roundness of 5 and 50 mils. Computed fiber bundle strengths were plotted versus the applied stresses to predict a nonlinear inelastic type failure. This approach predicts that material failure will occur at 20800 psi for the 5 mil imperfection and 15600 psi for the 50 mil imperfection if all plies are perfectly aligned with the cylinder circumference. A 2° fiber misalignment reduces the predicted pressure at initial microbuckling failure to 16000 psi and 10900 psi for the assumed out of roundness values of 5 and 50 mils, respectively.

The zero rotation and radial displacement constraint imposed by the test configuration produces a large axial bending moment and shear stress in the cylinder. The maximum axial stress near the cylinder end (inner radius) is calculated to be 80 percent higher than at midbay. The average shear stress at the cylinder end in the radial direction is calculated to be 0.49 psi per psi of applied pressure. However, for cylinder SWT1, interlaminar failure is not a concern to pressures well above predicted cylinder failure due to the high shear strength of the S2 glass axial plies.

Figure 10 plots experimental and ABAQUS calculated strains versus pressure on the interior surface for two axial distances from the ends of the cylinder. The significant bending moment (and stress gradient) induced by the fixed ends is clearly illustrated by the large difference in calculated strains over an axial distance of only 1.25 inches. Also, the experimental results appear to closely follow the calculated strains at 1.50 inches in from the cylinder end. Reference [11] indicated that the gages were placed approximately 1.00 inches from the end. Based upon correlation of the experimental versus calculated

strains, it appears that the relatively coarse ABAQUS mesh is accurately predicting the cylinder response under hydrostatic loading. If the results are projected back to 0.25 inches from the cylinder end, the compressive axial strain in the S2 glass bundles at 16000 psi pressure exceeds 1.7 percent.

The pressure at which initial compressive microbuckling failure occurs in the SWT1 cylinder model is not a strong function of the assumed end conditions. However, the end conditions do produce high axial ply stresses at the inner radius which may be a contributing mechanism to the failure process. The ABAQUS analysis combined with the material microbuckling model indicates that the axial plies near the ends should fail at approximately 14500 psi pressure if a slight bundle misalignment is present. The pressure at which failure is initiated is increased to approximately 16500 psi if the bundles are perfectly aligned with the axis of the cylinder. Failure of the circumferential bundles at midbay, using an initial cylinder out of roundness of 5 mils or less, is predicted to initiate at 16000 psi external pressure (20000 psi if zero bundle misalignment is assumed). Analysis results showed that the cylinder was structurally stable to well beyond this load. The testing of SWT1 was halted at 16000 psi external hydrostatic pressure due to high acoustic emission. Axial cracks at the inner radius were observed, indicating circumferential ply failure had occurred.

CONCLUDING REMARKS

The initiating mechanism of failure in a unidirectional composite whose primary stress component is compression in the fiber direction is local instability. The nonlinear microbuckling model shows that the local instability compression strength is a function of the shear modulus of the composite. The shear modulus of the composite depends upon the nonlinear shear modulus of the matrix, which can be determined by the effective state of stress in the matrix. Therefore, a key factor in predicting failure of composites in thick walled cylindrical geometries is the accurate determination of the local multidirectional state of stress on the fiber bundle (ply). Stress distributions which may be unimportant to the failure of isotropic materials may significantly reduce the compressive strength of anisotropic composites. This suggests that the compression strength of a fiber composite under multiaxial stress in a thick cylindrical specimen will differ from the strength determined by uniaxially loading a flat coupon. As such, caution must be exercised in the extrapolation of uniaxially loaded flat coupon strength measurements to cylinder strength.

Slight fiber misalignments with respect to the primary load path in a composite leads to a reduction in compression strength with respect to a perfectly oriented material. It is suggested that material failure is initiated in an area of initial ply waviness. The magnitude of strength reduction is dependent upon the applied state of stress and many key material variables. Analytical and experimental

results indicate that composites with high modulus anisotropic fibers in a low modulus resin will be affected most significantly by slight material imperfections. The compression strength of intermediate modulus graphite epoxy materials has been shown to be more sensitive to initial fiber waviness than S2 glass epoxy composites.

An approach for the strength evaluation of unstiffened hydrostatically loaded composite cylinders has been defined which considers both material strength and structural stability modes of failure. The methodology for failure prediction was successfully applied to a series of cylinders tested during the CMFS program. For each of the cylinders studied, small geometric out of roundness was shown to significantly reduce the overall collapse strength. It should be noted that the cylinders were designed based upon nominal stress states, and did not include the discontinuity stresses developed at end closures used for hydrostatic testing. The nonlinear collapse analyses indicate that the testing of cylinders containing graphite epoxy axial plies on flat rigid end closures significantly reduced the overall collapse strength. The rigid end constraints did not significantly reduce the computed and measured collapse strengths of cylinders which contained S2 glass axial reinforcement.

ACKNOWLEDGMENT

This paper describes a portion of the work performed by Materials Sciences Corporation under Subcontract Number 11K-57957C for Martin Marietta Energy Systems at Oak Ridge national Laboratory during the period from July 1, 1989 to June 30, 1990. The program manager for ORNL on the Composite Materials for Future Submarines project was Mr. Ray Garvey.

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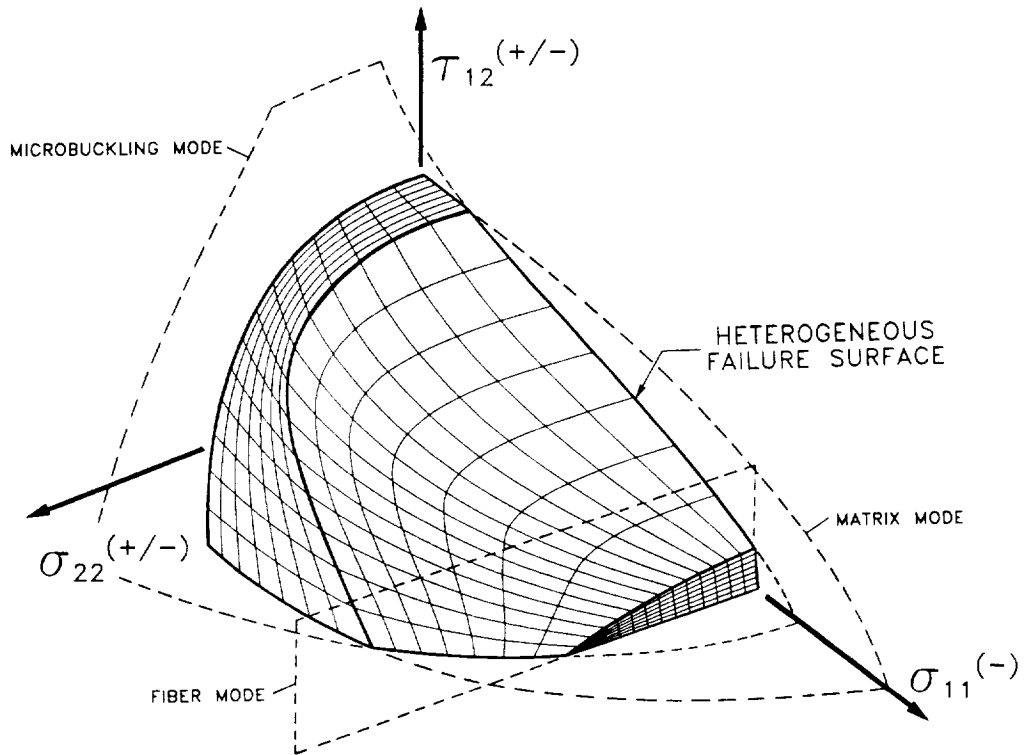


Figure 1. Graphical Representation of Failure Surface Showing Interaction of Modes

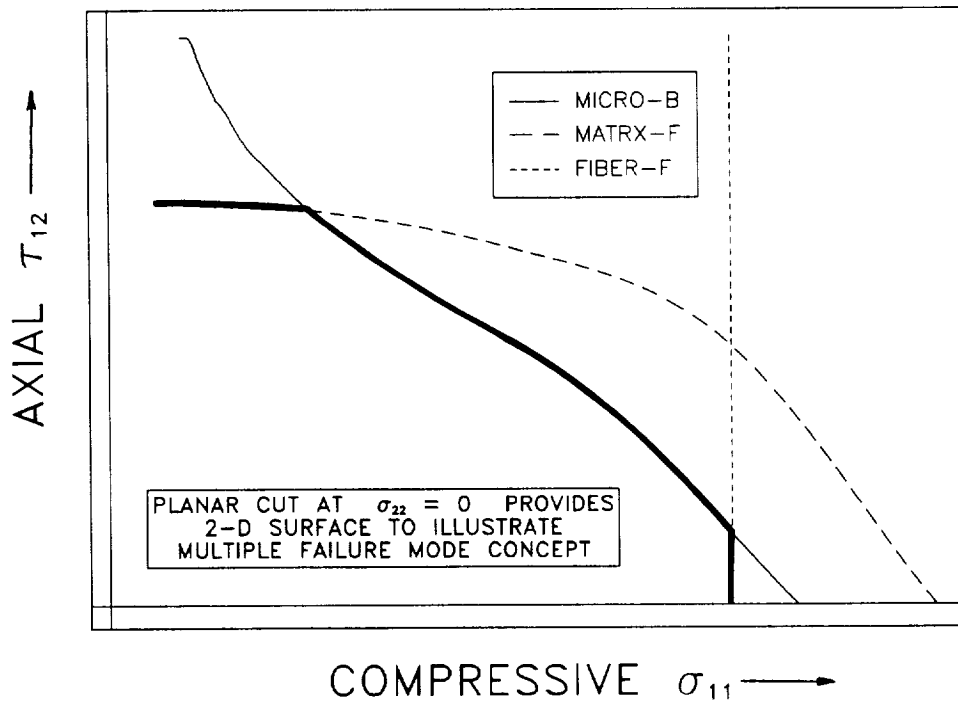


Figure 2. Simplified Failure Surface in Two Dimensional Stress Space

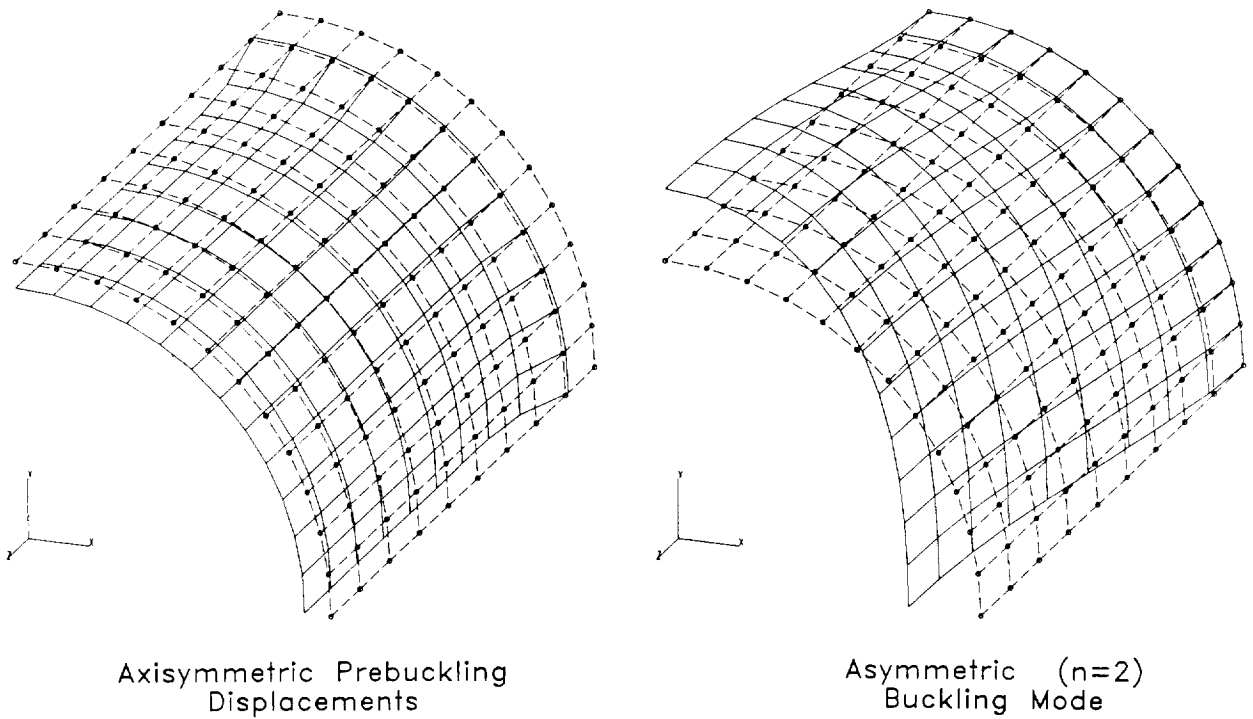


Figure 3. ABAQUS Idealization Used to Predict Cylinder Response to Hydrostatic Pressure

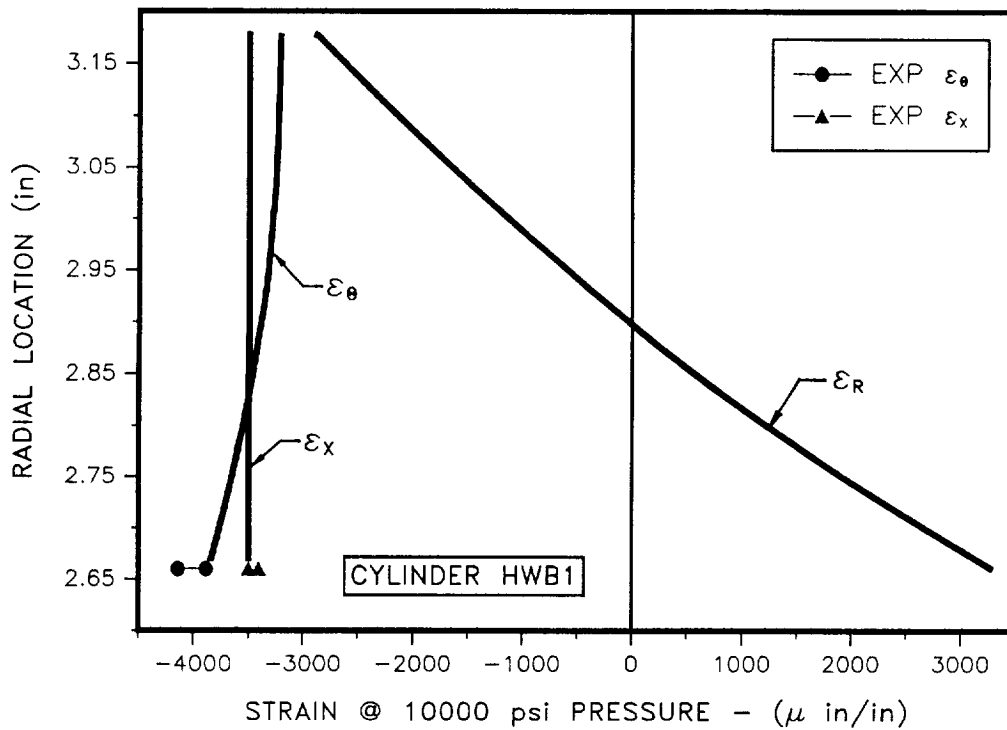


Figure 4. Predicted and Measured Cylinder Strains Versus Radius for HWB1

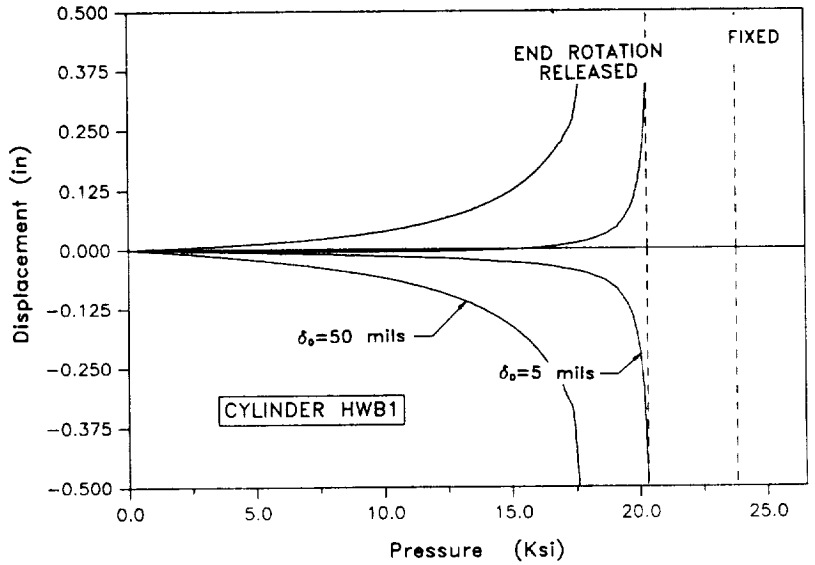


Figure 5. Elastic Nonlinear Collapse Analysis Including Initial Cylinder Out-of-Roundness

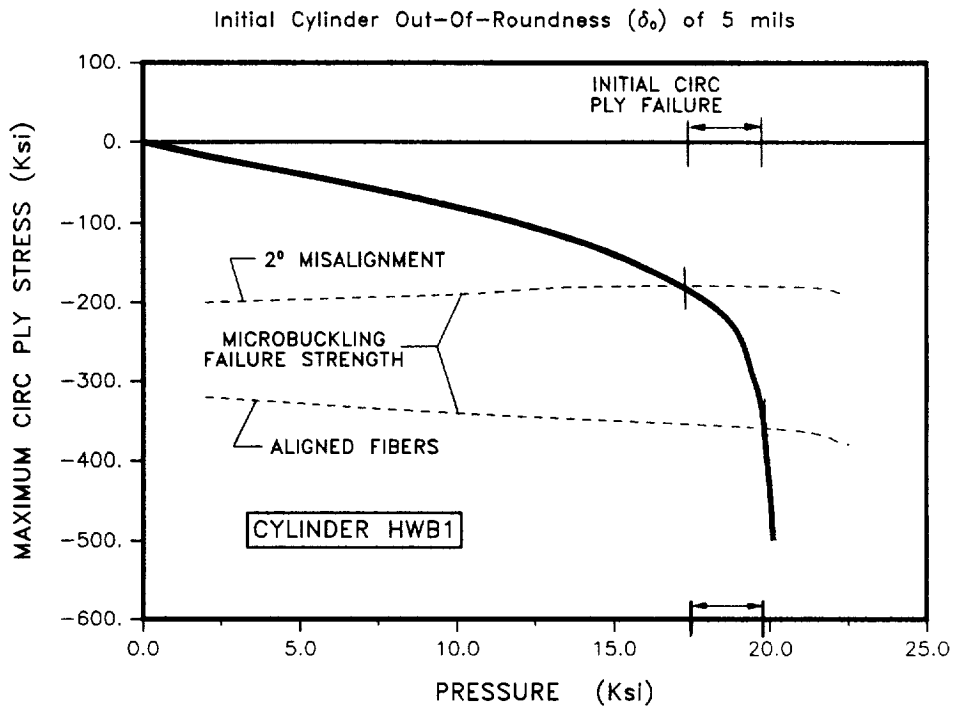


Figure 6. Determination of Initial Material Failure at Midbay of Cylinder HWB1

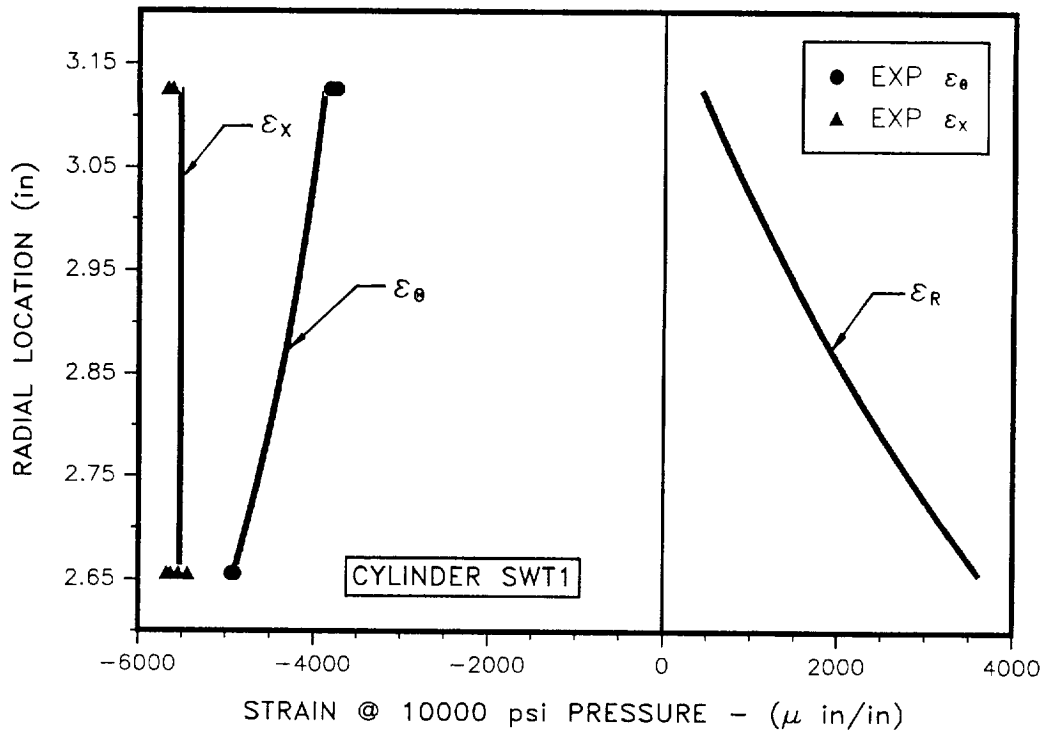


Figure 7. Predicted and Measured Cylinder Strains Versus Radius for SWT1

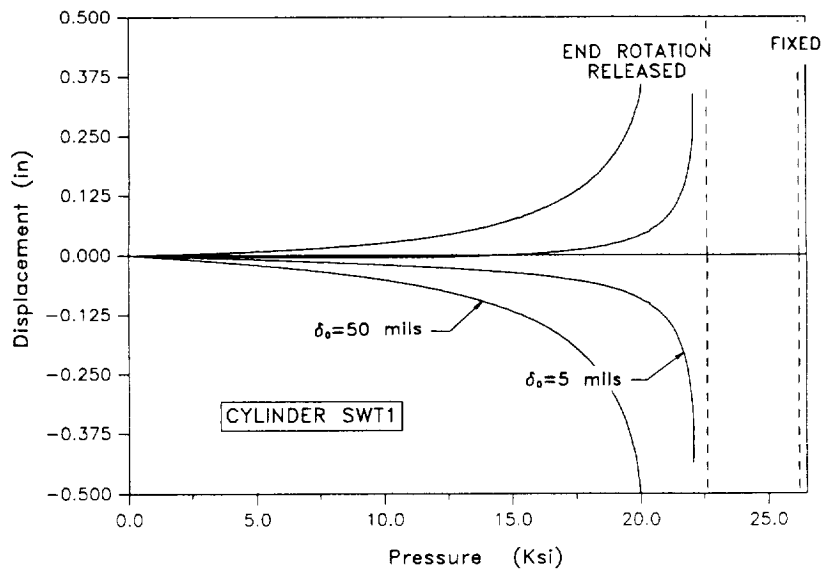


Figure 8. Elastic Nonlinear Collapse Analysis Including Initial Cylinder Out-of-Roundness

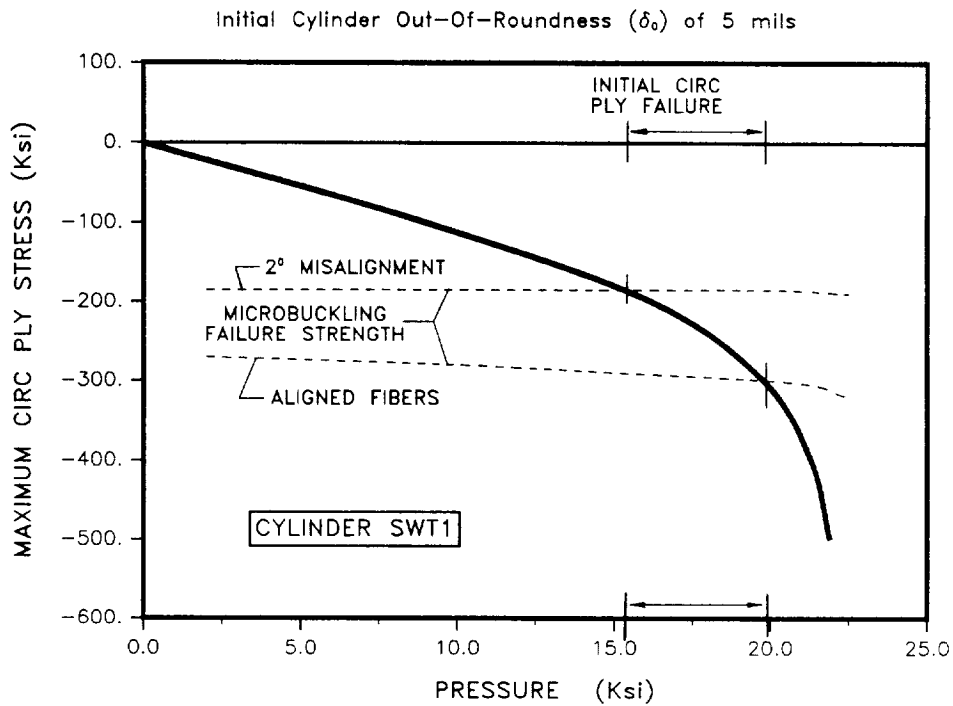


Figure 9. Determination of Initial Material Failure at Midbay of Cylinder SWT1

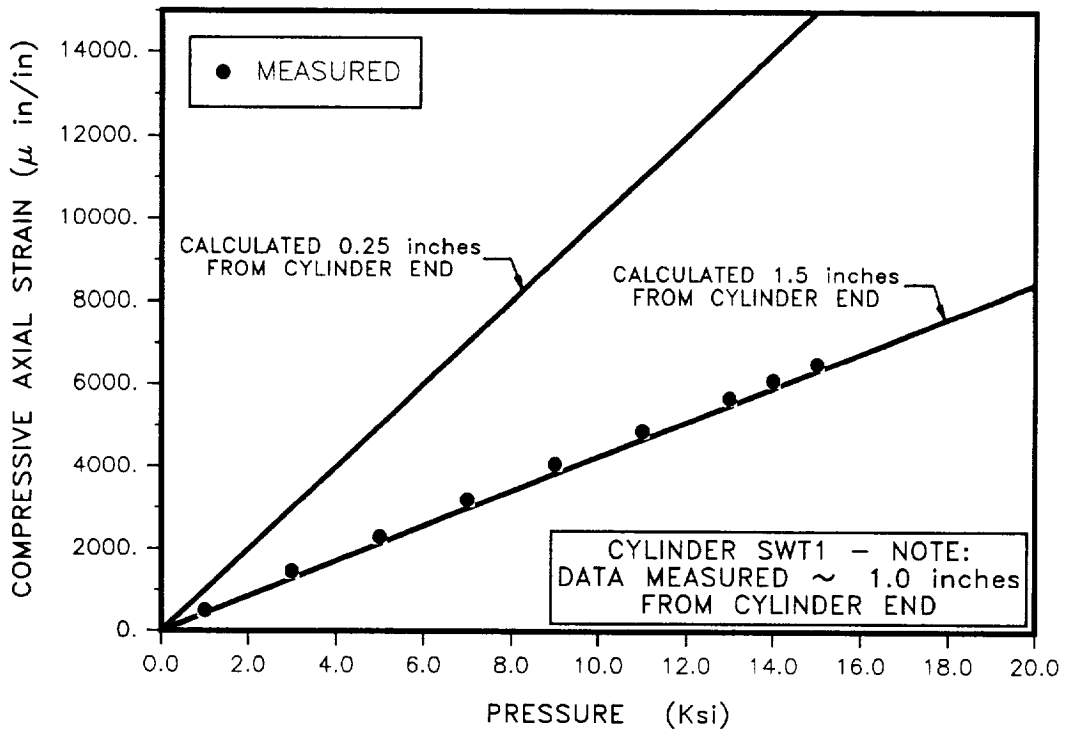


Figure 10. Measured and Predicted Axial Strains at Inside Surface Near End Closure of SWT1