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AN EXPERIMENTAL INVESTIGATION OF THE YIELD STRENGTH OF A MACHINED RING-STIFFENED CYLINDRICAL SHELL (MODEL BR-7M) UNDER HYDROSTATIC PRESSURE

by

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ABSTRACT

The effects of initial imperfections and residual welding and rolling stresses on the yield strength of a stiffened cylinder were investigated by tests of a machined and stress-relieved model, Model BR-7M, identical in geometry and of the same material as a previously tested fabricated model, Model BR-7. The experimental collapse pressure of 1502 psi agreed well with collapse pressures computed from theories which account for the plastic reserve strength. The pressure at which yielding began agreed more closely with that calculated by the maximum-shear-stress or the Hencky-Von Mises criterion than with that calculated by the maximum-principal-stress criterion. The data also indicated that the mathematical form of the deflection function of the shell did not change appreciably in the elastic-plastic range. Comparison of the collapse pressures of the machined and welded models indicated that for the geometry tested the residual welding and rolling stresses do not adversely affect the collapse pressure.

INTRODUCTION

To design the shell of a stiffened cylinder for the axisymmetric yield mode adequately it is first necessary to close the gaps in the knowledge regarding yield failures. For this reason a research program was initiated at the David Taylor Model Basin and designated "Project Yield."[1] This project was established with the following general objectives:

1. Experimental validation of theory predicting collapse pressure.
2. Experimental validation of the elastic analyses by measurement of strains and deformations within the elastic range.

In the fabrication of models geometrical imperfections and residual stresses due to rolling and welding inevitably occur. On the other hand, the theories used to predict deformations and collapse pressure assume an initially perfect and stress-free model. In order to evaluate the theory and to determine the effects of imperfections and residual stresses, a machined and stress-free model was manufactured which was a duplicate of the geometry of Model BR-7, one of the welded models tested earlier in the Project Yield program.[2]

The machined model, designated BR-7M, is described in this report together with its instrumentation, test, and test results. The test results are compared with those from tests of the welded model, and the influence of the imperfections and residual stresses on axisymmetric yielding is evaluated. In addition, the behavior of the model in the elastic-plastic state is examined.

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[1] References are listed on page 18.

DESCRIPTION OF MODEL

The geometrical properties of the fabricated and machined models are shown in Table 1. A schematic drawing of Model BR-7M is shown in Figure 1. Essentially the model is a cylinder stiffened externally by rectangular frames forming eight equal bays. At the ends of the model are two heavy frames. The two end bays are 8/10 the length of the other bays. Model BR-7M had 45-deg fillets at the base of the frames of the same size as the welds on the fabricated model, thus the faying width of the frames was closely duplicated.

The model was manufactured from a 2½ -in. flat plate of high tensile steel (HTS). This plate was rolled at the Norfolk Naval Shipyard to 180 deg of arc. Two pieces of the plate were then welded together with two longitudinal seams diametrically opposite one another to form a cylinder. The cylinder was machined at the Model Basin to form the shell and frames of the model.

The cylinder was stress-relieved four times at 1125 deg F for 3 hr: once after rolling and welding to remove the rolling and welding stresses, twice during the rough machining to remove machining stresses, and then after final machining.

The yield strength of the shell was 59,200 psi.

The out-of-roundness of the model was recorded on the recording deflectometer[3] at all the typical frames (except the one nearest the closure bulkhead) and at the center of all the typical bays. In Table 2 are listed the maximum out-of-roundnesses for Model BR-7M and for the welded Model BR-7. These out-of-roundness measurements are the differences between the maximum and minimum radii of the shell contours from the mean circle. The mean circle was taken as that circle which has its center at the centroid of the circularity contour and an area equal to that of the circularity contour. The circularity charts are shown in Figures 2 and 3.

TABLE 1

Dimensions and Yield Strengths of Models BR-7 and BR-7M

Dimension	Model BR-7	Model BR-7M
Thickness of shell, h, in.	0.211	0.211
Mean diameter, D or $2R$, in.	26.899	26.899
h/D	0.00784	0.00784
Frame spacing, center to center, L, in.	2.570	2.570
Effective frame spacing, L_f, in.	2.034	2.044
L/D	0.096	0.096
Effective faying width, b, in.	0.536	0.526
Area of frame, A, sq in.	0.404	0.404
Ratio of frame area to shell area, A/Lh	0.745	0.745
Thinness ratio λ*	0.42	0.46
Compressive yield strength in psi	47,500	59,200

*The thinness ratio is defined as

$$\lambda = \sqrt[4]{\frac{\left(\frac{L_f}{D}\right)^2}{\left(\frac{h}{D}\right)^3}} \cdot \sqrt{\frac{\sigma_y}{E}}$$

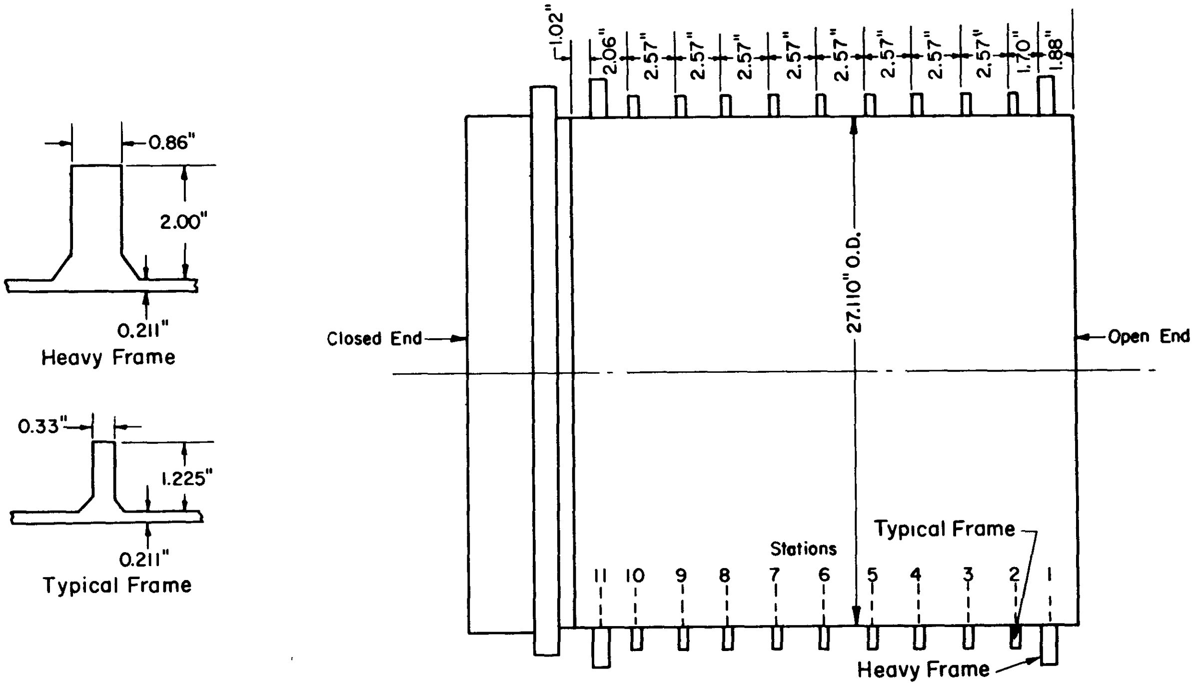


Figure 1 – Schematic Diagram of Model BR-7M

TABLE 2

Out-of-Roundness Measurements of Models BR-7 and BR-7M

Station	Ratio of Out-of-Roundness to Shell Thickness, *e/h*	
	Model BR-7	Model BR-7M
2	0.105	0.057
2½	0.111	0.071**
3	0.088	0.043
3½	0.106	0.047
4	0.080	0.047
4½	0.101	0.043
5	0.100	0.038
5½	0.107	0.047
6	0.087	0.043
6½	0.077	0.047
7	0.121**	0.038
7½	0.093	0.047
8	0.100	0.038
8½	0.090	0.052
9	0.093	0.047
9½	0.089*	0.062*
10	0.102	

*Denotes station in which failure occurred.

**Denotes maximun out-of-roundness measured.

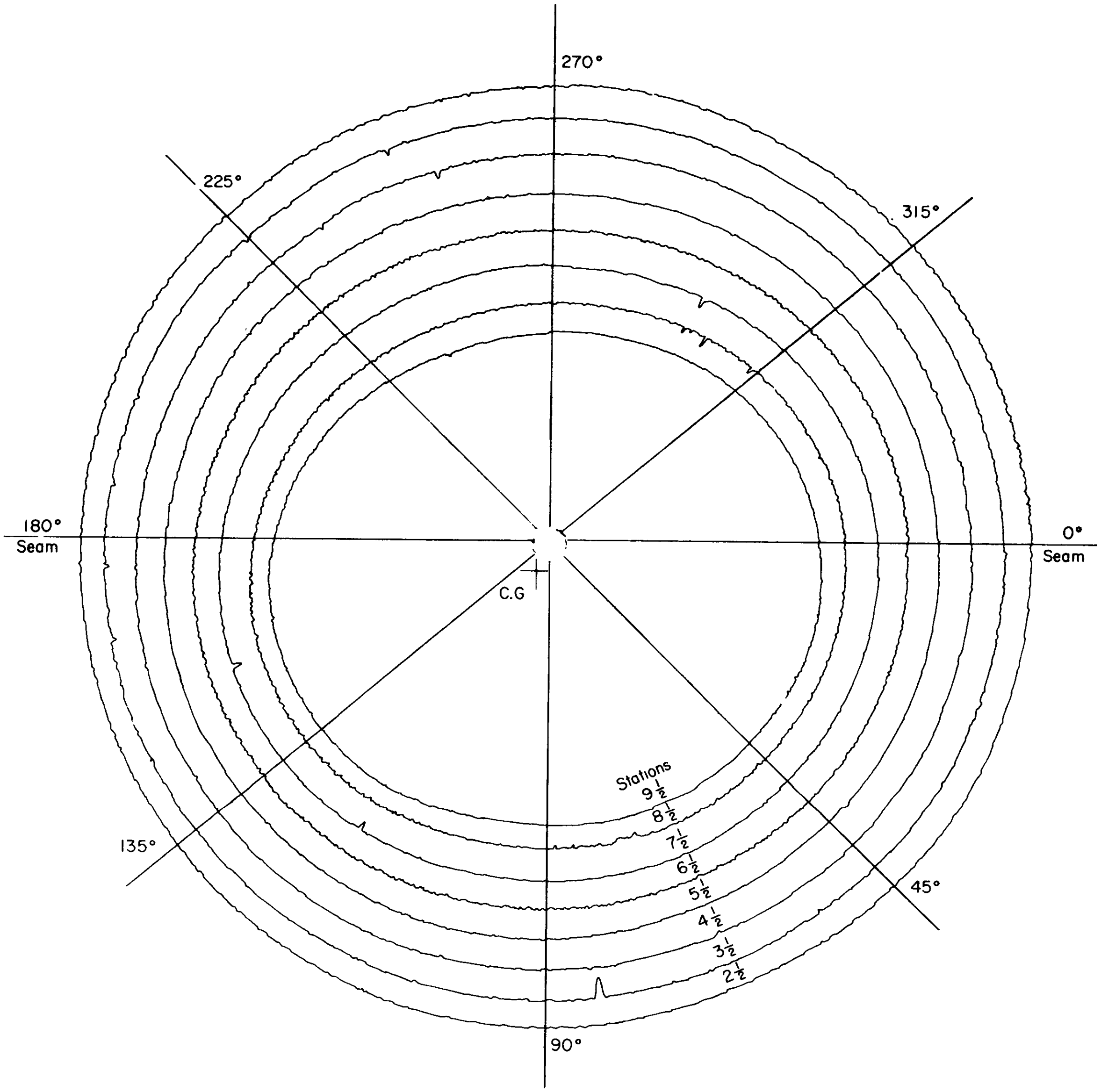


Figure 2 – Initial Shell Contours

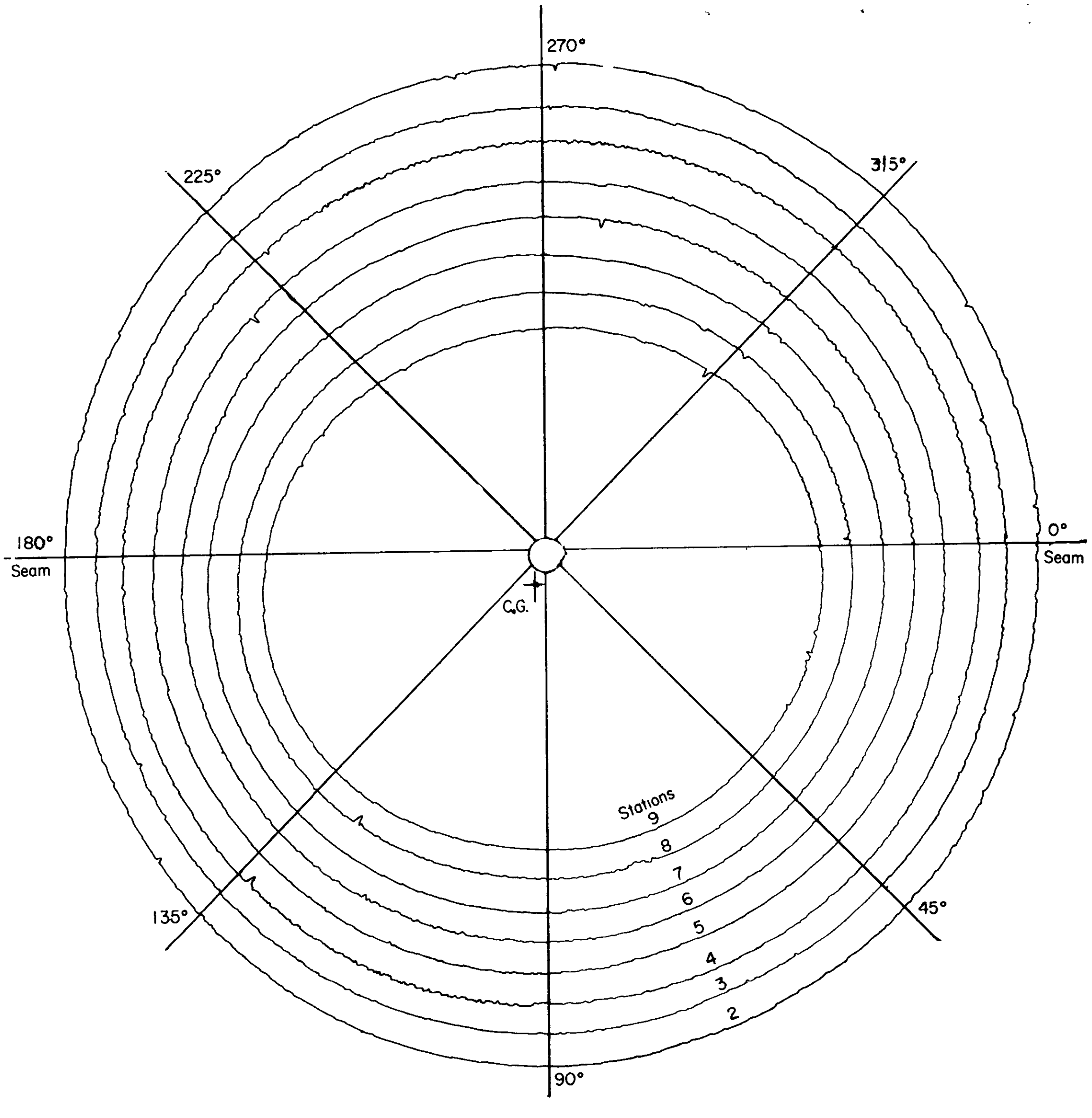
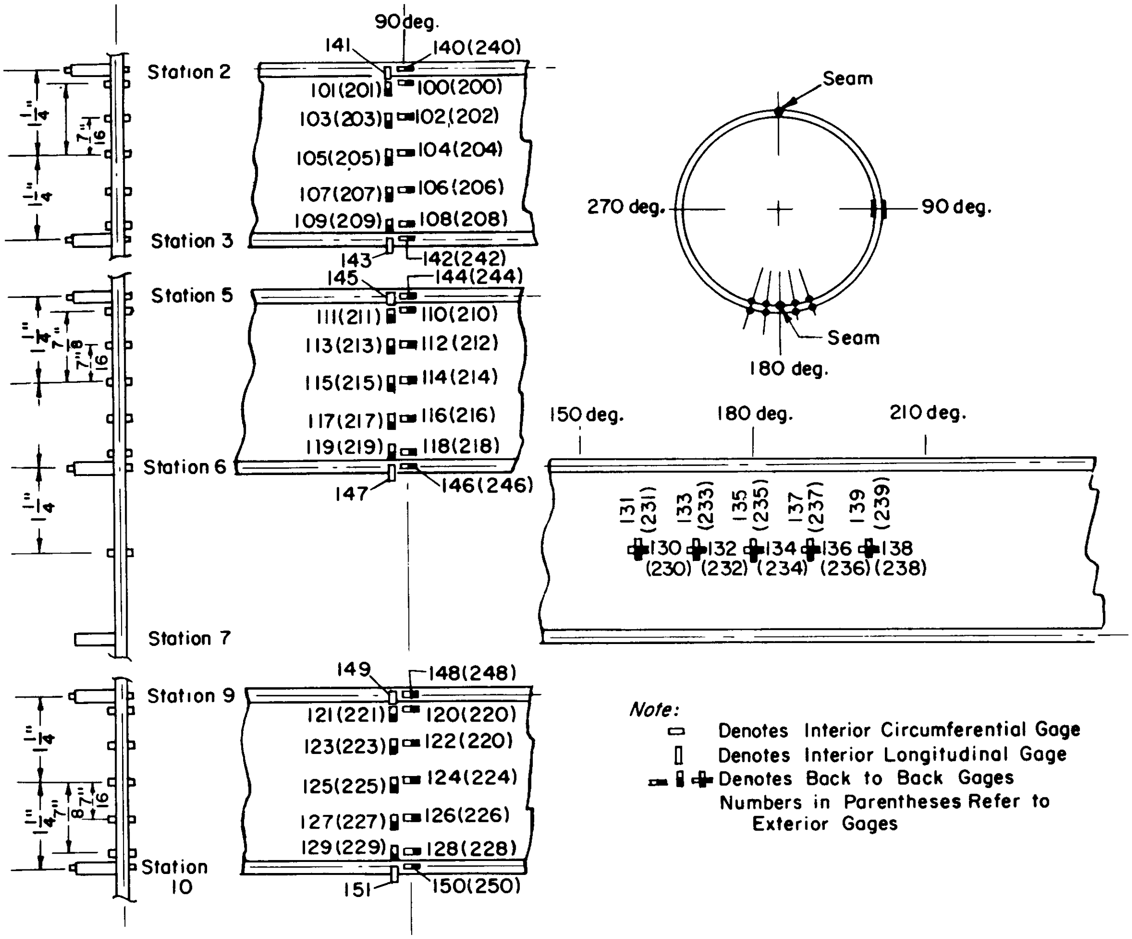


Figure 3 – Initial Frame Contours



Note:

▭ Denotes Interior Circumferential Gage

▯ Denotes Interior Longitudinal Gage

▬ ▮ ✚ Denotes Back to Back Gages

Numbers in Parentheses Refer to Exterior Gages

Figure 4 – Strain Gage Locations

INSTRUMENTATION AND TEST PROCEDURE

In planning the instrumentation two main objectives were kept in mind:

1. The criterion of yielding was to be established.
2. The deformations across a bay were to be obtained in the elastic-plastic range.

To accomplish these objectives strain gages were located as shown in Figure 4.

Since failure of the shell usually occurs in the first typical bay at the end of a model, these bays were instrumented with strain gages; see Figure 4. In addition, a bay in the center of the model was instrumented on the interior and exterior surface at seven locations to obtain an adequate distribution of strains across a bay.

At Station 6½, gages were placed every 10 deg over an arc of 40 deg to detect any formation of buckle lobes in the shell.

Model BR-7M was tested in the 37-in. pressure tank. Pressure was applied in three runs; see Table 3. Strains were recorded at all pressures listed in Table 3.

TABLE 3

Loading Schedule for Model BR-7M

Pressure, psi		
Run 1	Run 2	Run 3
0	0	0
100	200	500
200	400	1000
300	500	1050
400	600	1100
500	700	1130
200	800	1160
0	900	1180
	950	1200
	1000	1220
	1020	1240
	1040	1260
	1060	1280
	1080	1300
	1100	1320
	1120	1340
	1140	1360
	0	1380
		1400
		1420
		1440
		1460
		1480
		1500

TEST RESULTS

Model BR-7M failed at 1502 psi in an axisymmetric yield mode. Damage was visible in the first full-length bays at both ends of the model, Stations 2½ and 9½, although damage at Station 9½ was much greater. Figure 5 shows the model after collapse.

Strain-sensitivity factors were obtained from pressure-strain plots. These factors, defined as strains in microinches per psi of applied pressure, are shown in Figure 6. Plots of strain for gages within a typical bay uninfluenced by the ends of the

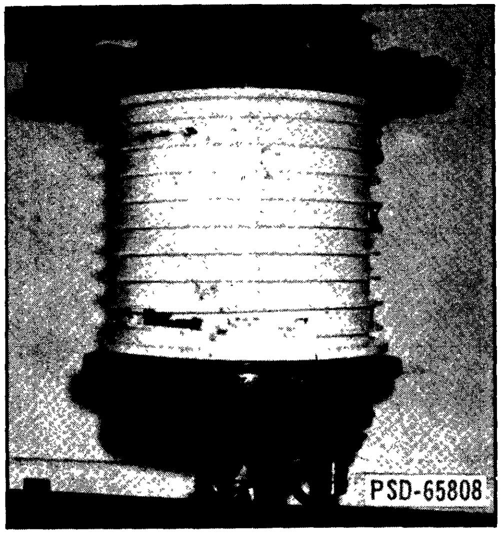
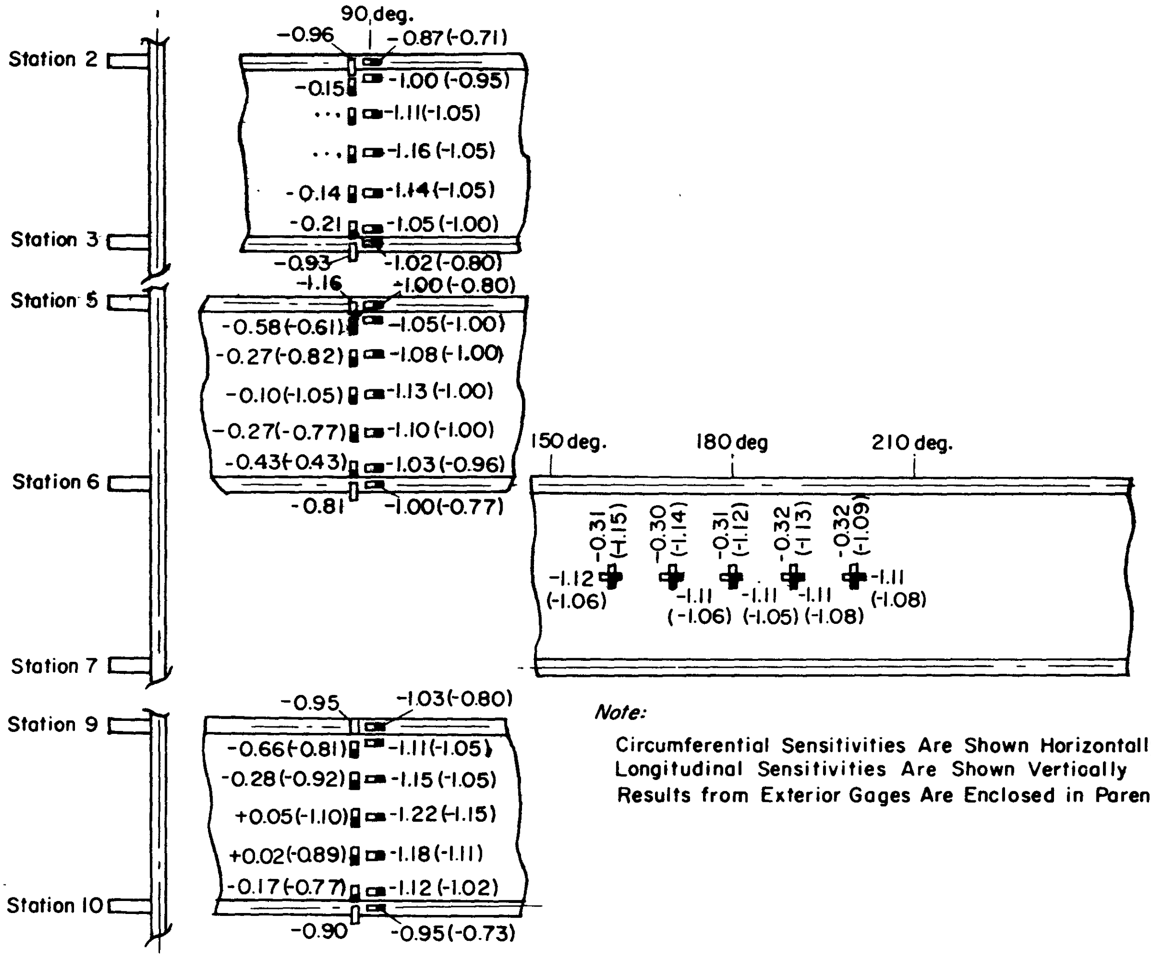


Figure 5 – Model BR-7M After Failure



Note:

Circumferential Sensitivities Are Shown Horizontally
Longitudinal Sensitivities Are Shown Vertically
Results from Exterior Gages Are Enclosed in Parenthesis

Figure 6 – Strain-Sensitivity Factors

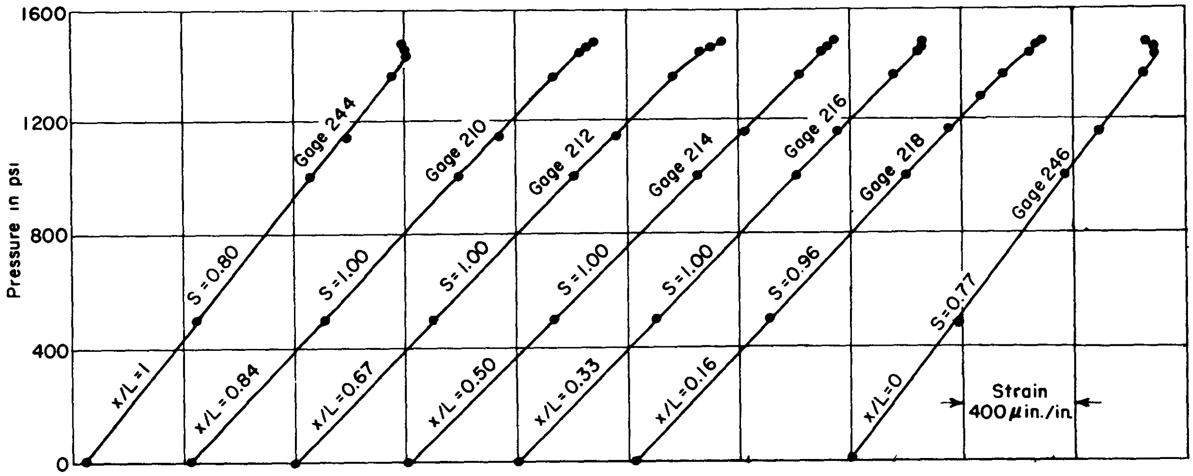


Figure 7a – External Circumferential Gages

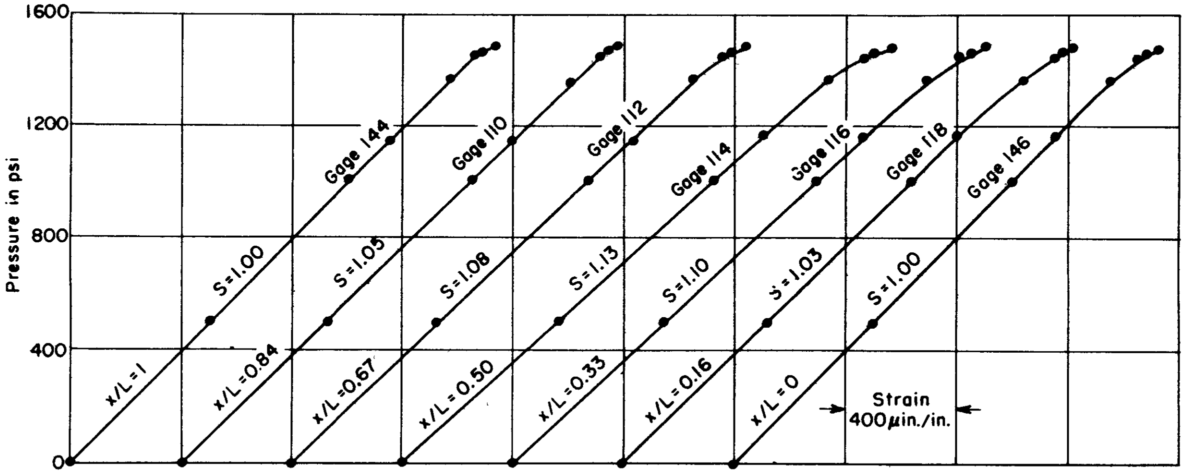


Figure 7b – Internal Circumferential Gages

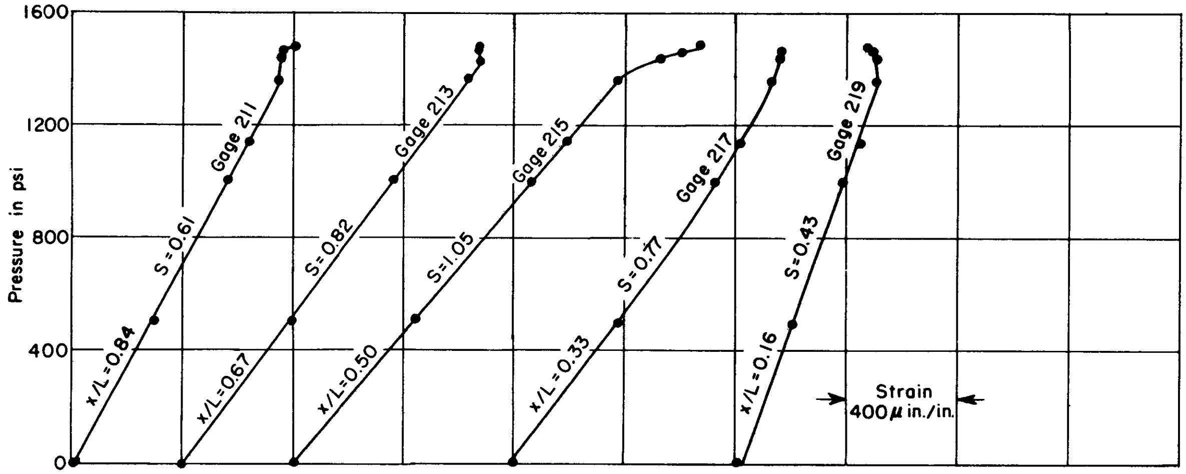


Figure 7c – External Longitudinal Gages

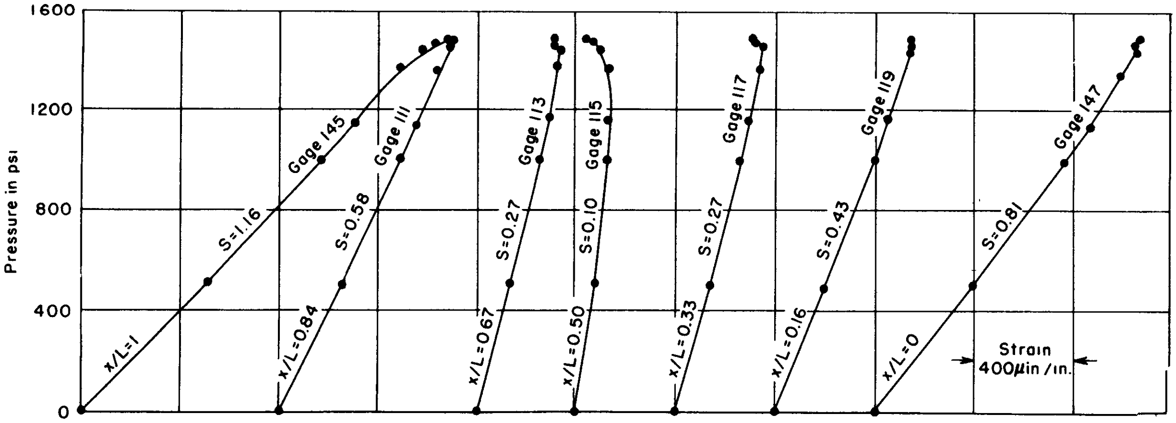


Figure 7d – Internal Longitudinal Gages

Figure 7 – Pressure-Strain Plots in Typical Bay

Sensitivities are denoted by S shown on plots and all are compressive (negative) values.

model are shown in Figure 7. These gages lie between Frames 5 and 6 along the 90-deg orientation. The location of the gage within the bay is indicated by ratios of distance x to frame spacing L shown to the left of the pressure-strain plots. A value of $x/L = 0$ locates the gage at Frame 5, while a value of $x/L = 1.0$ locates a gage at Frame 6.

COMPARISON BETWEEN THEORY AND EXPERIMENT

YIELD PRESSURE

Since Model BR-7M was machined and stress-relieved, the pressure at which yielding began should not be influenced by residual stresses or geometrical imperfections. Thus a comparison between this pressure and those computed by various criteria of yielding can be made with validity and should indicate the most appropriate criterion of yielding for the biaxial state of stress encountered in stiffened cylinders under hydrostatic pressure.

The pressure at which yielding began was determined from strains measured at five points on the exterior of the shell at the center of a typical bay. Longitudinal strains were selected because they are more sensitive to yielding than circumferential strains. The longitudinal strains were examined for that pressure at which pronounced nonlinearity in the pressure-strain plots occurred. Essentially, the average of the longitudinal strains at the five points in microinches per inch was divided by the pressure in psi. The pressure at which these quotients began to change markedly was taken as the yield pressure as indicated in Figure 8. Since the data at five points were used, an average value of the experimental yield pressure could be obtained and is presented in Table 4.

The investigation of the yield pressure considered the following criteria of yielding:[4]

1. Maximum principal stress
2. Maximum shear stress
3. Hencky-Von Mises
4. Maximum strain energy
5. Maximum strain

Yield pressures computed from these criteria and the measured strains are listed in Table 4.

From Table 4 it can be observed that the maximum-shear-stress and the Hencky-Von Mises yield criteria agree best with the experimental yield pressure. The maximum-shear-stress criterion gives a value 4.2 percent lower than the experimental pressure, while the Hencky-Von Mises criterion gives a value 4.6 percent lower. On the other hand, the maximum principal-stress criterion used in Formula [92a][5] of Von Sanden and Gunther is 6.4 percent low, and the maximum-strain and maximum-strain-energy criteria are definitely not valid for predicting yielding in the model tested.

TABLE 4

Experimental and Theoretical Yield Pressures for Model BR-7M

Basis	Yield Pressure, psi
Experimental	1320
Maximum-Principal-Stress Criterion	1236
Maximum-Shear-Stress Criterion	1265
Hencky-Von Mises Criterion	1259
Maximum-Strain-Energy Criterion	1073
Maximum-Strain Criterion	1531

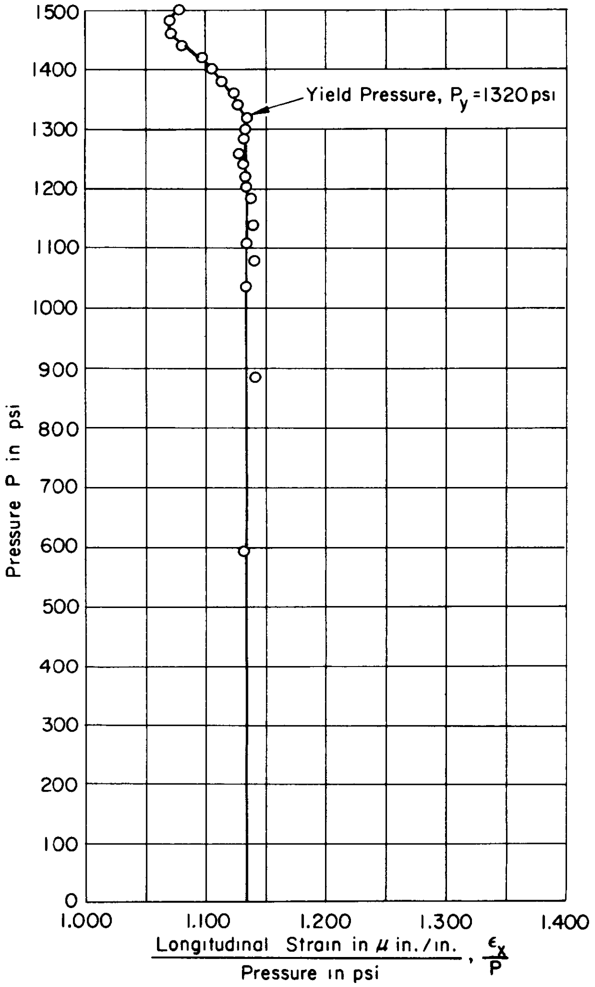


Figure 8 – Plot for Determination of Yield Pressure

TABLE 5

Comparison of Theoretical and Experimental Collapse Pressures

Line			Model BR-7	Model BR-7M
1	Experimental Collapse Pressure, psi		1300	1502
2	Theory of Von Sanden and Gunther,[3] Formula [92]	Theoretical Pressure, psi	997	1243
		Theoretical Pressure / Experimental Pressure	0.767	0.828
3	Theory of Von Sanden and Gunther, Formula [92a]	Theoretical Pressure, psi	1054	1314
		Theoretical Pressure / Experimental Pressure	0.811	0.875
4	Theory of Von Sanden and Gunther, Maximum-Principal-Stress Criterion at Midplane and Midbay	Theoretical Pressure, psi	1112	1386
		Theoretical Pressure / Experimental Pressure	0.855	0.923
5	Theory of Von Sanden and Gunther, [92a], with Hencky-Von Mises Criterion at Exterior Midbay Point	Theoretical Pressure, psi	1114	1388
		Theoretical Pressure / Experimental Pressure	0.857	0.924
6	Theory of Salerno and Pulos[7] with Hencky-Von Mises Criterion at Exterior Midbay Point	Theoretical Pressure, psi	1119	1394
		Theoretical Pressure / Experimental Pressure	0.861	0.928
7	Theory of Von Sanden and Gunther with Hencky-Von Mises Criterion at Midplane and Midbay	Theoretical Pressure, psi	1235	1539
		Theoretical Pressure / Experimental Pressure	0.950	1.025
8	Theory of Lunchick[6] Predicting Fully Plastic Hinge at Midbay	Theoretical Pressure, psi	1210	1510
		Theoretical Pressure / Experimental Pressure	0.931	1.005

COLLAPSE PRESSURE

In Table 5 are listed the pressures calculated by a number of theories which are based on collapse by axisymmetric yielding. In the calculations the yield strengths were taken as 47,500 psi for Model BR-7 and 59,200 psi for BR-7M. The modulus of elasticity used was 30,000,000 psi. Poisson's ratio was assumed to be 0.3. To facilitate comparison of experiment with theory, ratios of theoretical to experimental collapse pressures are given.

The Hencky-Von Mises yield criterion gives pressures closer to the experimental pressures than does the maximum-principal-stress criterion. Von Sanden and Gunther Formulas [92] and [92a] based on a maximum-principal-stress criterion give pressures 12 to 24 percent lower than the experimental collapse pressure. On the other hand the pressures based on the Hencky-Von Mises criterion and Formula [92a] are only 8 to 14 percent lower than the experimental collapse pressure.

The best agreement between experiment and theory is obtained when allowance is made for the plastic reserve strength of the cylinder between the initiation of yielding and final collapse. This allowance can be made simply, but arbitrarily, by neglecting bending stresses and using only membrane stresses to predict yielding; see Lines 4 and 7 of Table 5. Again, the use of the Hencky-Von Mises yield criterion of Line 7 gives better values than the maximum-principal-stress criterion. The use of the Hencky-Von Mises criterion at the midplane and midbay gives pressures within 2 to 5 percent of the experimental pressures. However, a more exact method developed by Lunchick[6] which involves an elastic-plastic analysis of the shell predicts the collapse pressure more closely for machined models.

Since the machined model is closer to the idealized cylinder assumed in the theory than the fabricated model, its collapse pressure would be expected to agree better with that calculated from theory; see Table 5.

COMPARISON OF WELDED AND MACHINED MODELS

YIELD PRESSURE

Yielding in a fabricated model begins at a pressure approximately one-half the pressure at which it begins in a stress-free machined model; see Figure 9. This observation was also made in Reference 2 from the tests of six models. Curves are nondimensional to eliminate any difference in yield strength between the two models. In addition, the curves are for strains at the center of a typical bay, where yielding is considered critical. The differences in pressure at which nonlinearity is pronounced can be attributed to residual stresses induced by rolling and welding. These stresses are known to be high, some exceeding one-half the yield stress,[8] and appreciably reduce the pressure at which yielding begins.

COLLAPSE PRESSURE

Although the residual stresses lower the yield pressure, they did not adversely affect the collapse pressure of Model BR-7. However, previous test results[9] showed that welded models failed at lower pressures than machined models when failure was in the shell-buckling mode.

The strength of the machined and welded models can be compared in Table 5. This table lists nondimensional ratios of theoretical to experimental collapse pressure for the two models, thus eliminating any influence due to differences in yield strength between models.

If the experimental collapse pressure for Model BR-7 is multiplied by the ratio of yield strength of Model BR-7M to that of Model BR-7, the "adjusted collapse pressure" for Model BR-7 becomes 1620 psi, about 8 percent higher than Model BR-7M. This indicates that for the same yield strength the welded model was actually stronger than the machined model. This can be explained on the basis that the welded model had an initial axisymmetric

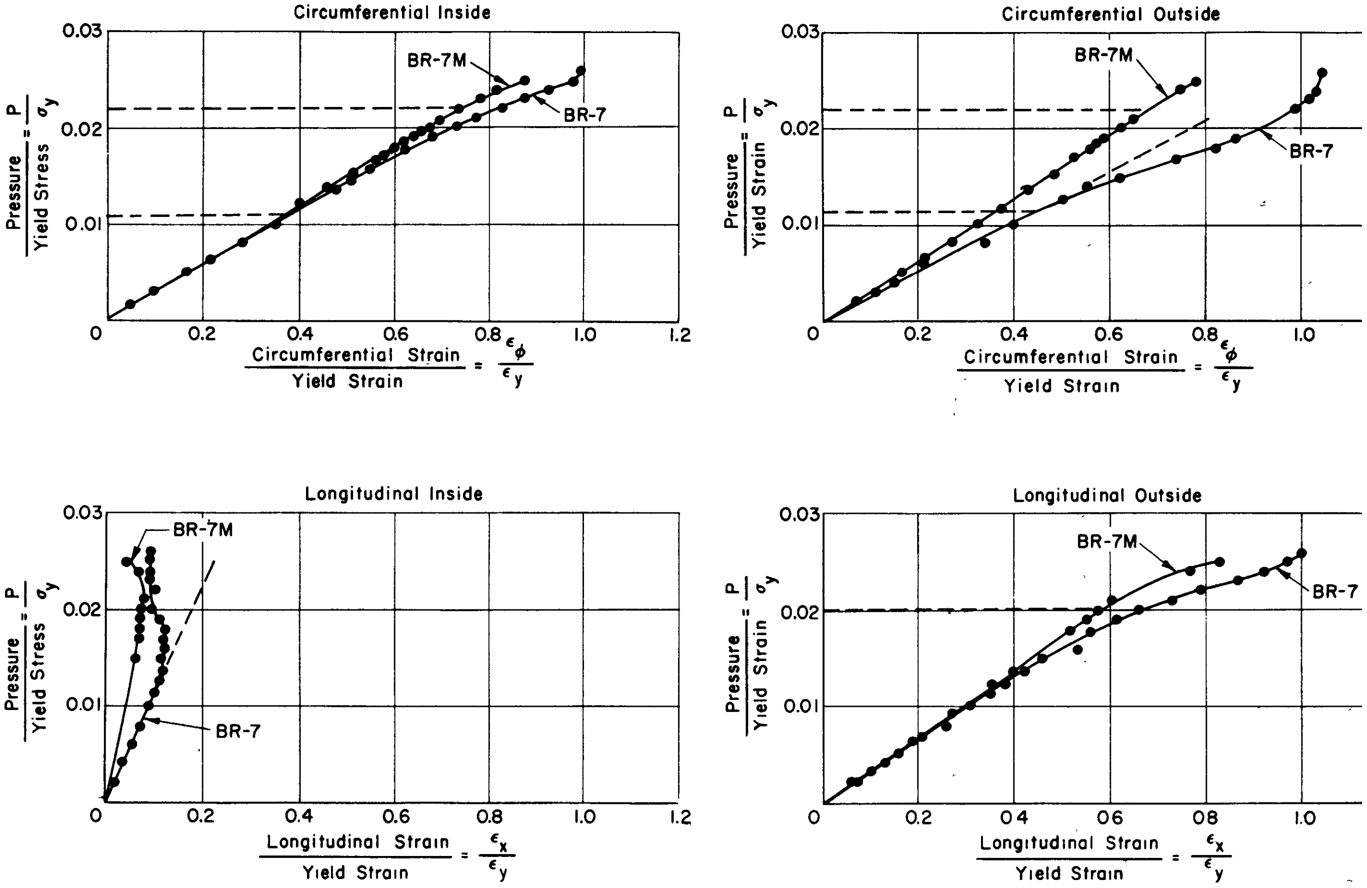


Figure 9 – Comparison of Pressure-Strain Plots between Welded and Machined Models

deflection that was beneficial as it had external frames.[10] Also, the collapse pressure of the fabricated model was probably not influenced by out-of-roundness as it was very small, about 1/10 the shell thickness, and was not in the same mode as the axisymmetric yield failure.

DEFLECTION FUNCTION BEFORE AND AFTER YIELDING

In addition to investigating the strength of a stiffened cylinder, the test of Model BR-7M was designed to provide information on the strains and deflections after yielding begins. This information would prove useful in the development of theoretical expressions for the stresses and strains in the elastic-plastic state.

One assumption which could be made in developing a theory is that the radial deflections are symmetrical with respect to a plane midway between ring stiffeners. To meet this assumption the strains should be studied in a bay at midlength on the cylinder to avoid any influences from the ends. Thus the data presented are for a typical bay between Frames 5 and 6.

The deflection function can be examined from Figure 10 for pressures above and below that at which yielding begins. In Figure 10 the ratio of the average internal and external circumferential strains at a point to that at midbay is plotted against distance across the bay. (Circumferential strain is indicative of deflection which is the product of this strain and the radius to the point.) By plotting the ordinate in Figure 10 as a ratio of strains a single curve would theoretically be obtained if the deflections are elastic and linear with pressure. Figure 10 indicates that this, in general, occurred as the curves for pressures below the yield pressure almost coincide, although they deviate somewhat from one another at one frame ($x/L = 0$). Moreover, Figure 10 indicates that the form of the deflection function does not change appreciably after yielding begins; see curves for pressures higher than the yield pressure

The curvatures of the shell before and after yielding were also examined. The curvature, a function of the second derivative of the deflection for elastic deformations, should be more sensitive to change in shape of the deflected surface than the deflections. The differences in the longitudinal strains on the internal and external surfaces are indicative of curvature, since these differences represent the rotation of a line element through the thickness of the shell. In Figure 11 ratios of the differences of the internal and external longitudinal strains at a point to those at midbay are plotted across the bay. For pressures at which the deformations are elastic and linear, the curves of these ratios should theoretically coincide. As seen in Figure 11, the curves for pressures below the yield pressure were practically coincident. For the pressures above the onset of yielding the curves show a greater departure from the elastic curves than Figure 10. In general, however, curvature plots for the elastic-plastic deformations agree fairly well with those of the elastic deformations.

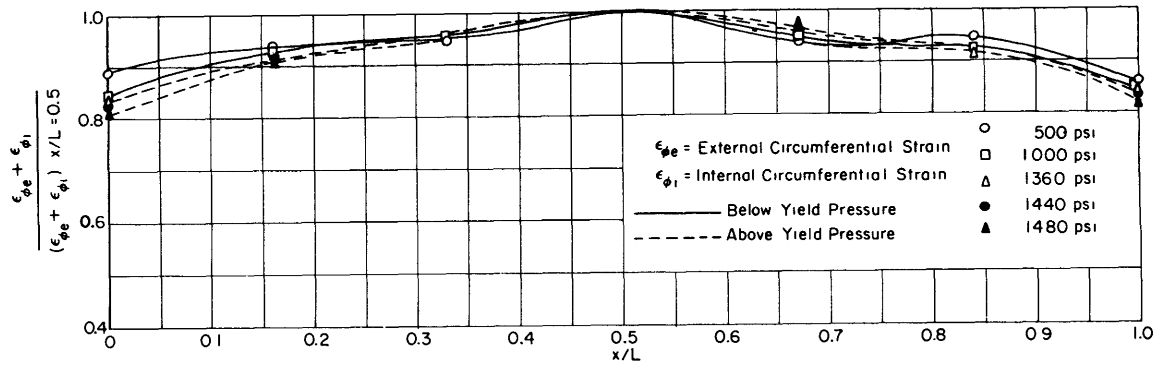


Figure 10 – Deflections of Shell in Elastic and Elastic-Plastic States

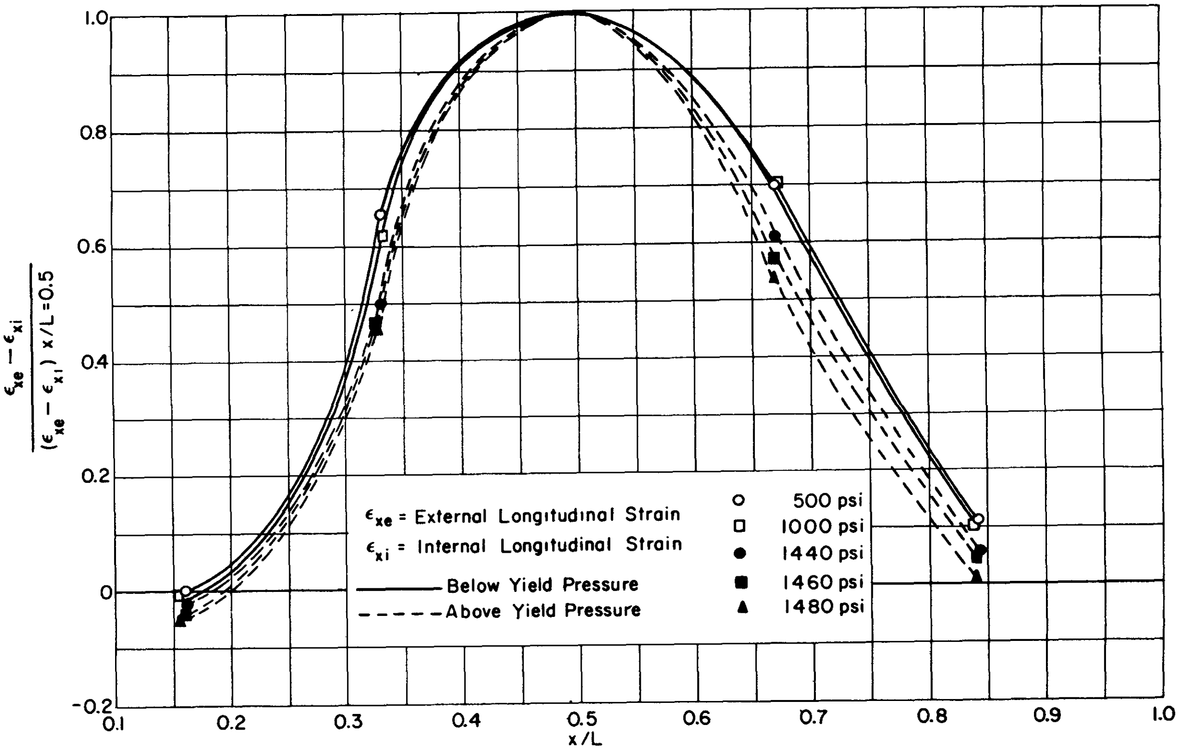


Figure 11 – Curvatures of Shell in Elastic and Elastic-Plastic States

CONCLUSIONS

1. The criterion of yielding for the machined model is either the maximum-shear-stress or the Hencky-Von Mises yield criterion. Further tests would have to be conducted before the proper yield criterion can be definitely established.

2. The residual and rolling stresses induced in a welded, stiffened cylinder reduce the pressure at which yielding begins to approximately one-half that in a stress-free machined cylinder.

3. The collapse pressures for the machined model is most accurately predicted by the elastic-plastic analysis of Lunchick given in Reference 6. The elastic theory of Von Sanden and Gunther coupled with the Hencky-Von Mises yield criterion applied at midplane and at midbay also closely predicts the collapse pressure.

4. The strength of a welded stiffened cylinder failing by yielding can be as great as one formed by machining if the frames are external.

5. For the geometry tested the deflection function after yielding begins remains approximately the same as that prior to yielding at pressure close to the collapse pressure. Hence, if theoretical expressions can be developed either for equilibrium or for the strain energy in the elastic-plastic state, the deflection function can be used together with one of these expressions to determine the relationship between pressure and strains.

RECOMMENDATIONS

1. Similar tests should be conducted on machined models of submarine geometries and yield strengths of steel currently used.

ACKNOWLEDGMENTS

The authors are grateful for the arrangements made by Mr. A.R. Willner of the David Taylor Model Basin for rolling the cylinder, examining the model for defects, and stress-relieving during the various states of manufacture. Mr. M.A. Krenzke assisted in the instrumentation of the model and the conduct of the test.

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