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HYDROSTATIC TESTS OF CONICAL REDUCERS BETWEEN CYLINDERS WITH AND WITHOUT STIFFENERS AT THE CONE-CYLINDER JUNCTURES

by

Martin A. Krenzke

STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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Report 1187

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Subj: NS731-038; Strength of conical reducer sections; forwarding of report on

Encl: (1) DTMB Report 1187 entitled "Hydrostatic Tests of Conical Reducers between Cylinders with and without Stiffeners at the Cone-Cylinder Junctures" 15 copies

1. In enclosure (1) is reported a limited series of experiments carried out to determine the effect on mode of collapse and collapse pressure of stiffeners at the junctures of a conical reducer section between cylinders of different diameters. Tests of six 45-deg conical sections indicated that the collapse pressure is increased by placing stiffeners at the junctures and that excessive rotation of the stiffener at the juncture decreases the collapse pressure.

E. E. Johnson

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HYDROSTATIC TESTS OF CONICAL REDUCERS BETWEEN CYLINDERS WITH AND WITHOUT STIFFENERS AT THE CONE-CYLINDER JUNCTURES

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February 1959

Report 1187
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ABSTRACT

Six 45-deg unstiffened conical sections between cylinders of different diameters were subjected to external hydrostatic pressure to study the effect on collapse pressure of placing stiffeners at the junctures. These tests indicate that the collapse pressure depends on the deflection and rotation at the cone-cylinder junctures as well as on the geometry of the cone itself.

For this series of reducer sections with stiffeners at the junctures, the collapse pressure appears to be associated with that pressure at which yielding first occurs at points other than at the juncture. No definite relation between initial yielding and collapse pressure for reducer sections without stiffeners at the junctures could be derived from the results of these tests.

INTRODUCTION

At the time this investigation was begun, very little was known about the collapse strength of steep conical reducer sections bounded by cylinders of different diameters under hydrostatic pressure. Such structures are frequently encountered in pressure vessels; and available pressure-vessel codes, which were based neither on theoretical considerations nor on systematic experiments, left much to be desired, particularly for steep cones. With the incorporation of conical reducer sections in submarines, the need for a better understanding of the structural behavior of such configurations was increased. Of particular interest was the effectiveness of stiffeners at the cone-cylinder junctures in increasing collapse strength. The stresses at cone-cylinder junctures under uniform pressure had been adequately studied,[1,2] but it had been observed that high local stresses at these junctures could be developed without causing collapse under hydrostatic pressure. Therefore this series of limited experiments was carried out with the following objectives:

1. To determine the actual collapse pressures of conical reducer sections without stiffeners at the junctures, and

2. To determine the effect of stiffeners at the junctures of the conical reducer with the adjoining cylinders on the mode of collapse and collapse pressure.

This report describes tests of six models subjected to external hydrostatic pressure. The geometries, measured strains, and collapse pressures are presented. Suggestions for improvements in structural cone-cylinder junctures are given in the Appendix.

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[1]References are listed on page 20.

DESCRIPTION OF MODELS

Six 45-deg reducer sections (three with stiffeners at the junctures and three without) were constructed. The following parameters were the same for all models:

α, one-half the apex angle, 45 deg.

h_1, the thickness of the large cylinder, 1/2 in.

h_2, the thickness of the small cylinder, 3/8 in.

R_1, the inside radius of the large cylinder, 28 in.

R_2, the inside radius of the small cylinder, 18 in.

L, the slant height of the cone, 14.14 in.

The ratios of thickness of cone h to $2R_1$, selected to avoid a shell-buckle type of failure of of the conical section, were 0.0067, 0.0086, and 0.0112; i.e., h = 3/8, 1/2, and 5/8 in. respectively. Figure 1 is a schematic drawing of a typical model.

Models 1, 3, and 5 had no stiffeners at the junctures, whereas models 2, 4, and 6 had 1-in. by 4-in. rectangular external stiffeners at both junctures. Photographs of each type of model are shown in Figure 2.

The models were fabricated by rolling and welding together steel plates which were considered to have a Young's modulus E and a Poisson's ratio v of 30,000,000 psi and 0.3, respectively. All cylinders had one longitudinal seam, and all cones had two longitudinal seams. These seams were staggered along the axis of the model so that the longitudinal seam of the cylinder was 90 deg away from that of the cone. No butt welds on the frames were located less than 45 deg from a longitudinal seam of either the cone or the cylinder.

Specimens were cut from the plate before the models were fabricated, to determine the yield points of the material; see Table 1.

The models were fabricated so that the difference between maximum and minimum diameters in any plane normal to the axis of the model was less than one-half the shell thickness.

TEST APPARATUS AND PROCEDURE

Wire-resistance strain gages were used to measure strains in the longitudinal and circumferential directions. They were located so as to indicate the strain distribution at the junctures as well as over the total length of the cone. Gages were mounted on both the interior and the exterior surfaces, being placed back to back whenever possible; exceptions to this procedure were governed by the geometry of the junctures. Figure 3 is a typical gage-location diagram.

The models were tested in the 8-ft-diameter pressure tank.[3] Hydrostatic pressure applied to the models was measured by means of an elastic-tube pressure gage and checked by a Bourdon gage. Pressure was applied in increments to each model in several runs.

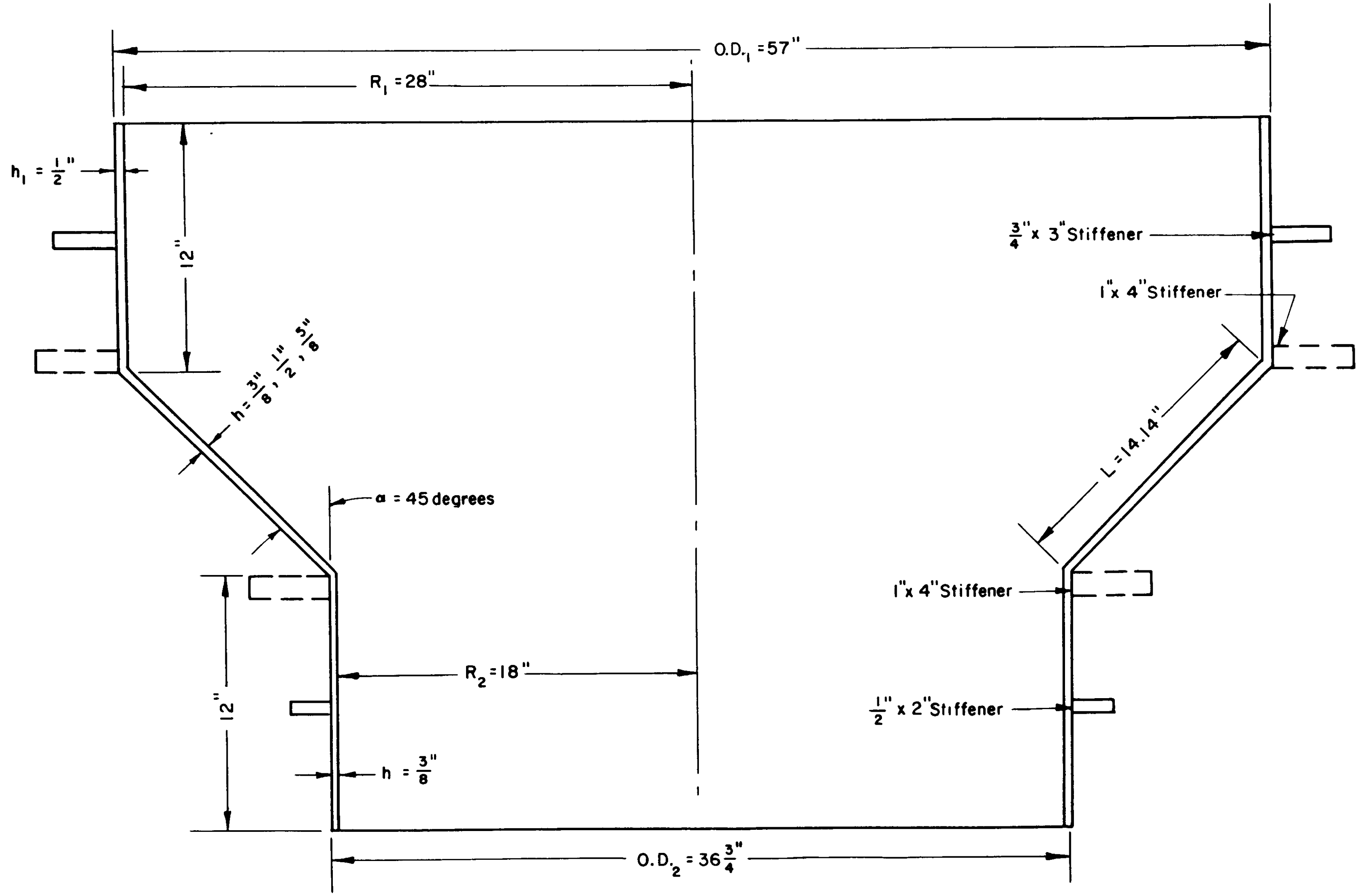


Figure 1 – Schematic Drawing of Typical Model

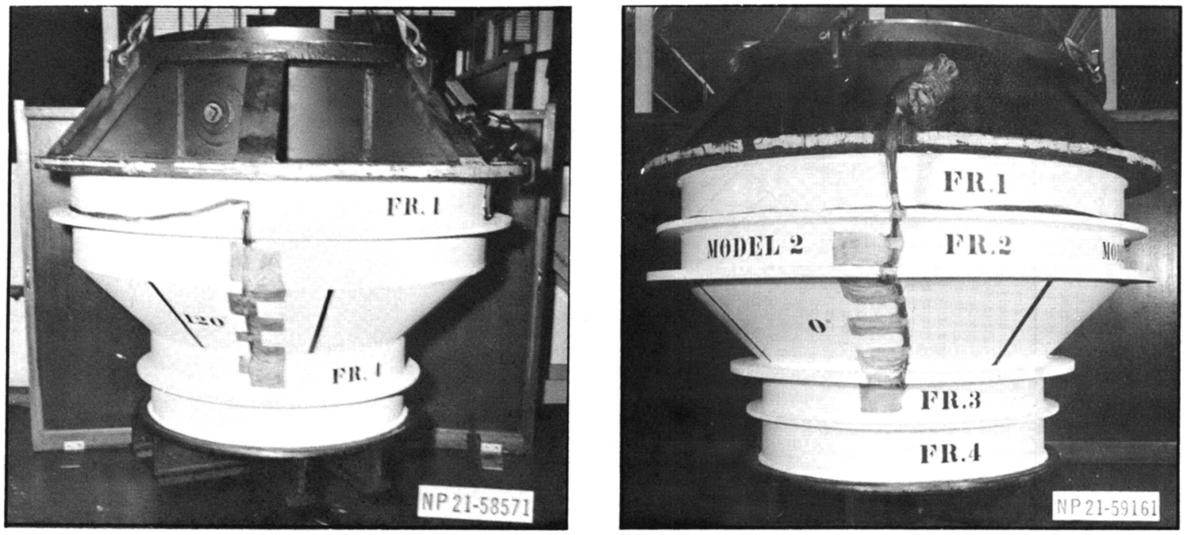


Figure 2a – Model Without Stiffeners at Junctures

Figure 2b – Model With Stiffeners at Junctures

Figure 2 – Photographs of Models before Testing

TABLE 1

Yield Points of Material Used in Models

Section of Model	Yield Point, psi					
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Large Cylinder	40,400	40,400	40,400	37,200	42,600	42,600
Cone	41,300	41,300	40,400	37,200	39,000	39,000
Small Cylinder	38,900	38,900	38,900	37,400	40,200	40,200
1/2-in. by 2-in. Stiffener	38,600	38,600	38,600	39,500	47,100	47,800
3/4-in. by 3-in. Stiffener	39,100	39,100	39,100	34,000	40,100	38,800
1-in. by 4-in. Stiffeners	*	*	*	50,400		51,900

*The yield point of this stiffener is not available.

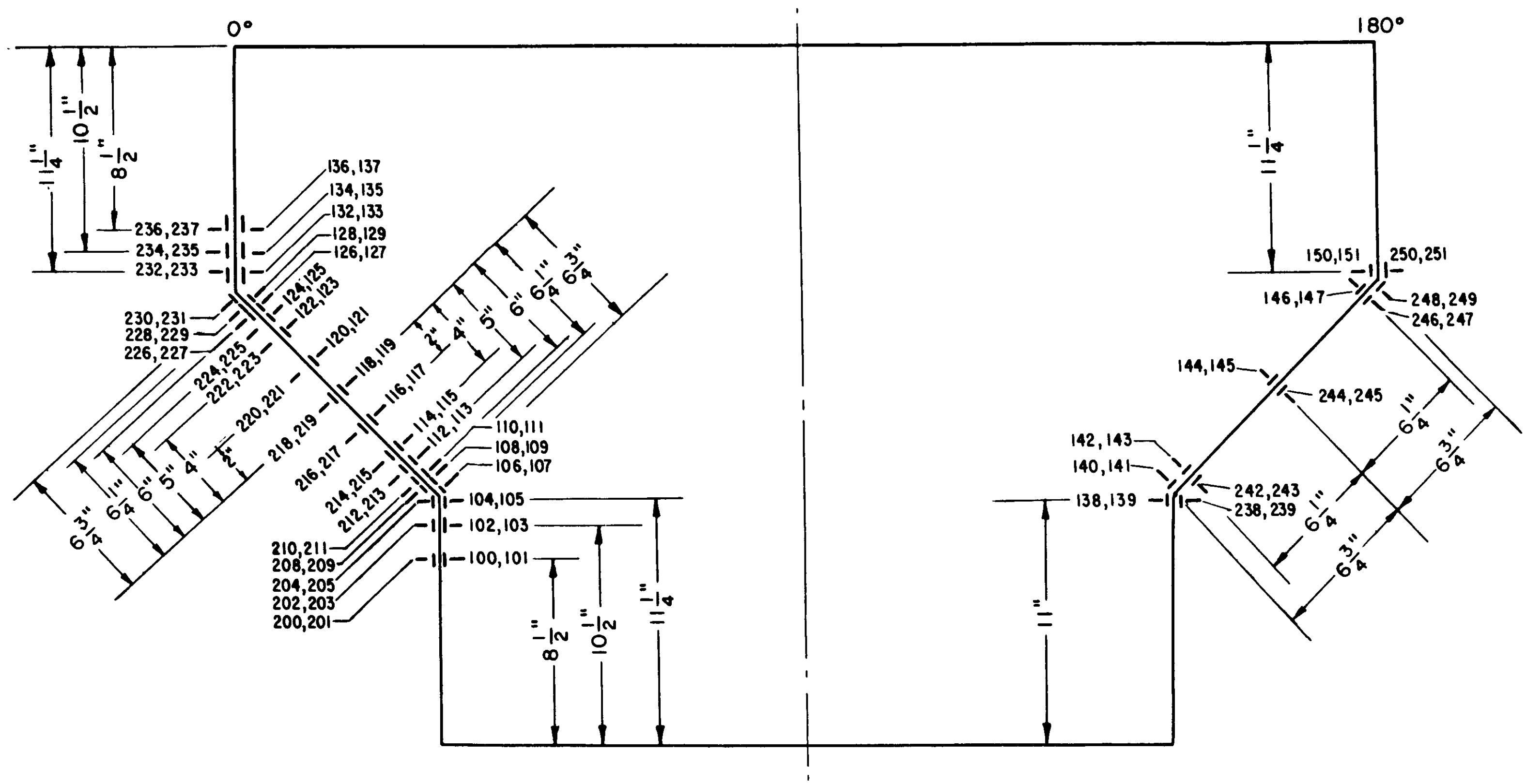


Figure 3 – Gage Location Diagram for Model 5

All even numbered gages measure circumferential strain. All interior gages have numbers beginning with 100; exterior gages, 200.

EXPERIMENTAL RESULTS

Models 1, 3, and 5, *without* stiffeners at the junctures, failed at pressures of 325 psi, 468 psi, 535 psi, respectively. In each model the small juncture was severely deformed inward; in Model 5, there was also permanent outward deflection of the large juncture. In Models 1 and 3, additional distortion occurred in the form of lobes within the conical portion. Photographs of these failures are shown in Figure 4.

Models 2, 4, and 6, *with* stiffeners at the junctures, failed at pressures of 410 psi, 640 psi, and 890 psi, respectively. Failure of these models, as shown in Figure 5, was confined to the shell of the cone.

Typical plots of pressure against strain are presented in Figure 6. The distribution of experimental strain-sensitivity factors (the slopes of the linear portions of these plots) is shown in Figures 7 and 8.

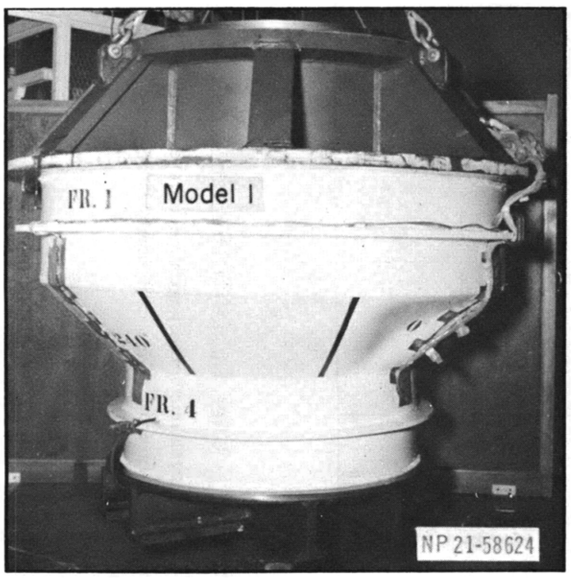


Figure 4a – Model 1

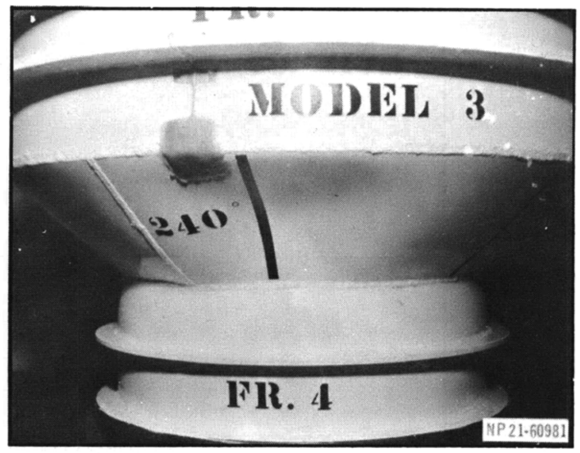


Figure 4b – Model 3

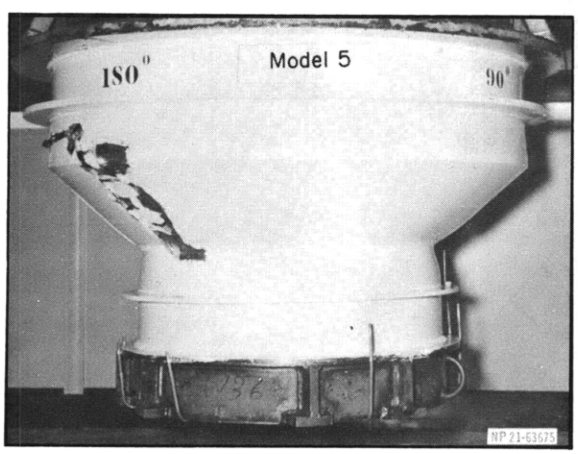


Figure 4c – Model 5

Figure 4 – Photographs of Models without Stiffeners at Junctures after Failure

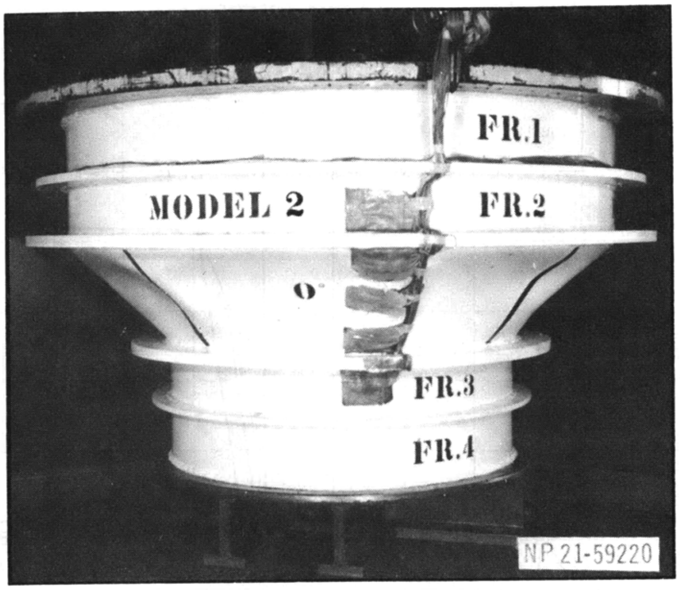


Figure 5a – Model 2

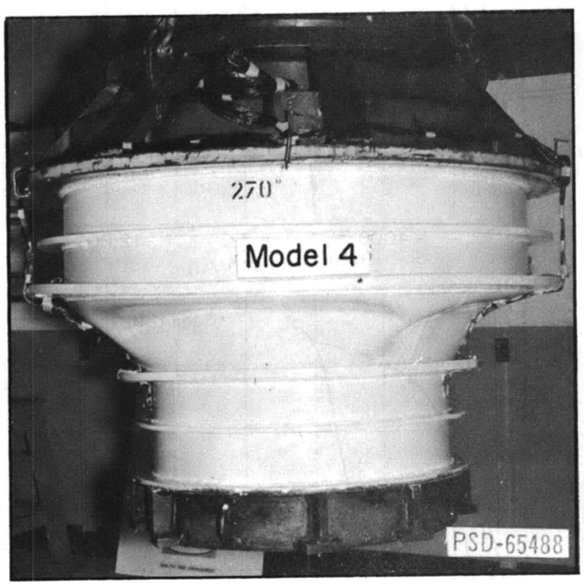


Figure 5b – Model 4

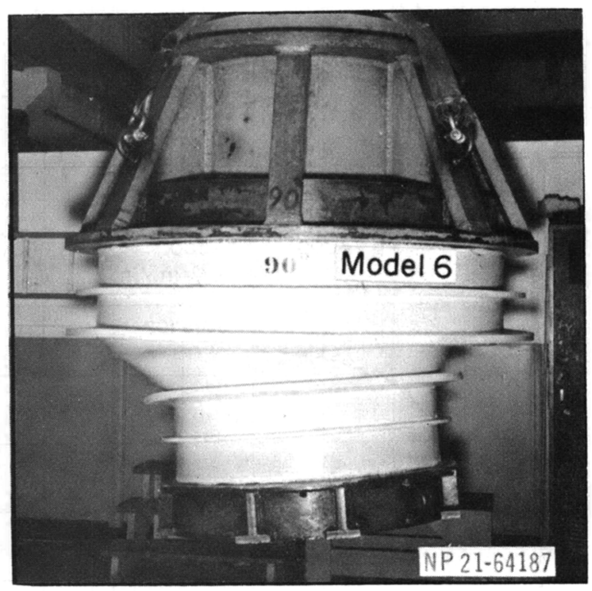


Figure 5c – Model 6

Figure 5 – Photographs of Models with Stiffeners at Junctures after Failure

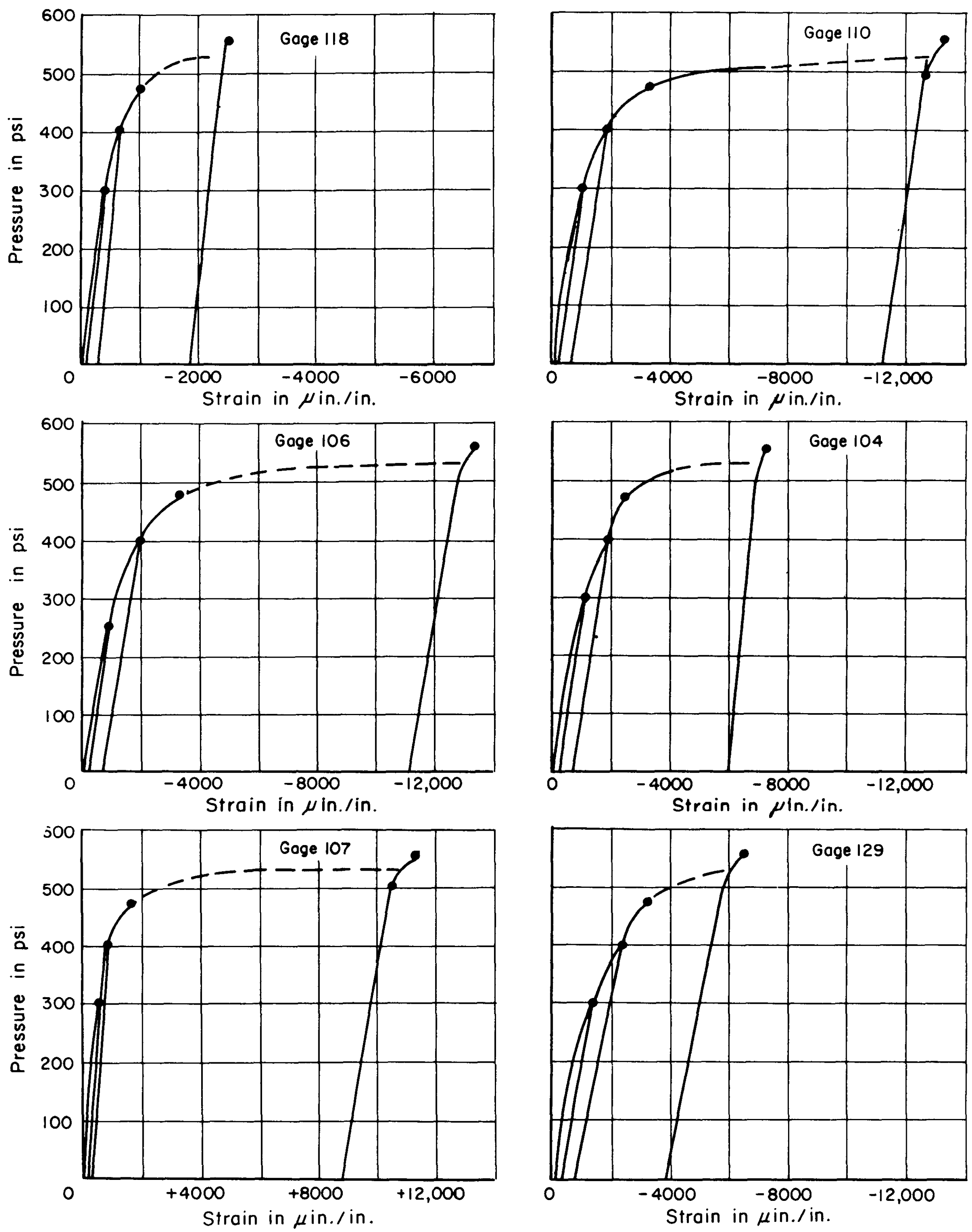


Figure 6 – Typical Curves of Pressure against Strain for Model 5

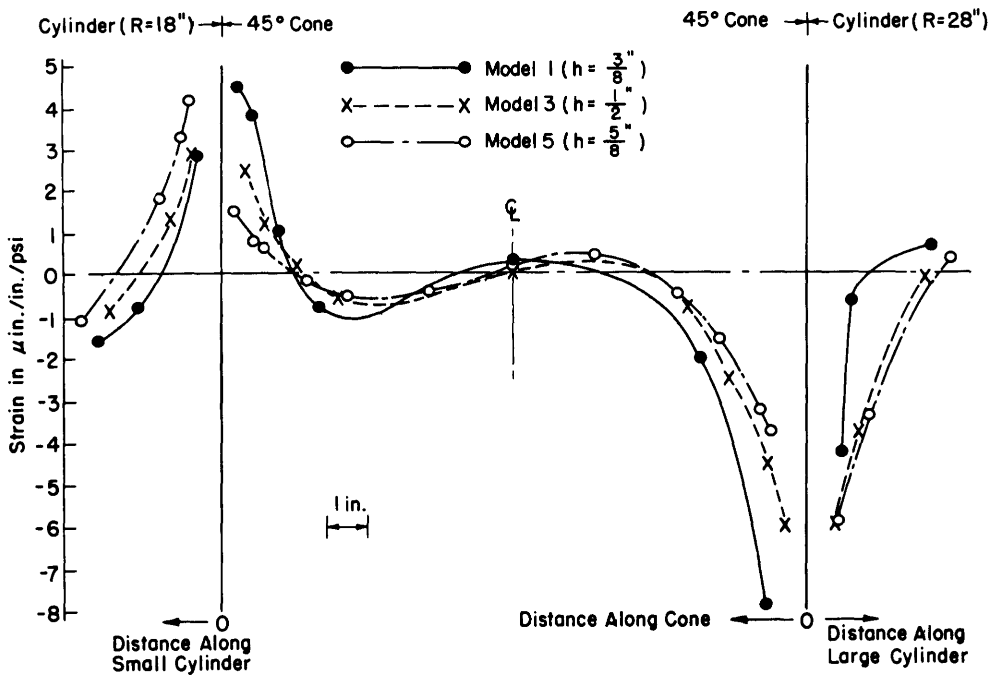


Figure 7a – Longitudinal Strains, Interior Surface

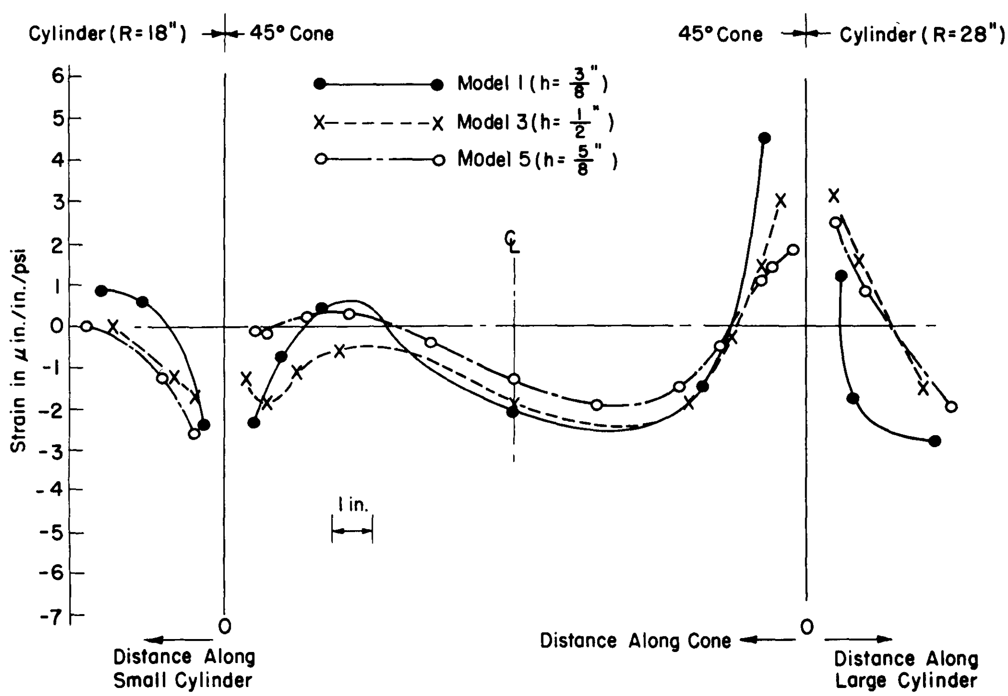


Figure 7b – Longitudinal Strains, Exterior Surface

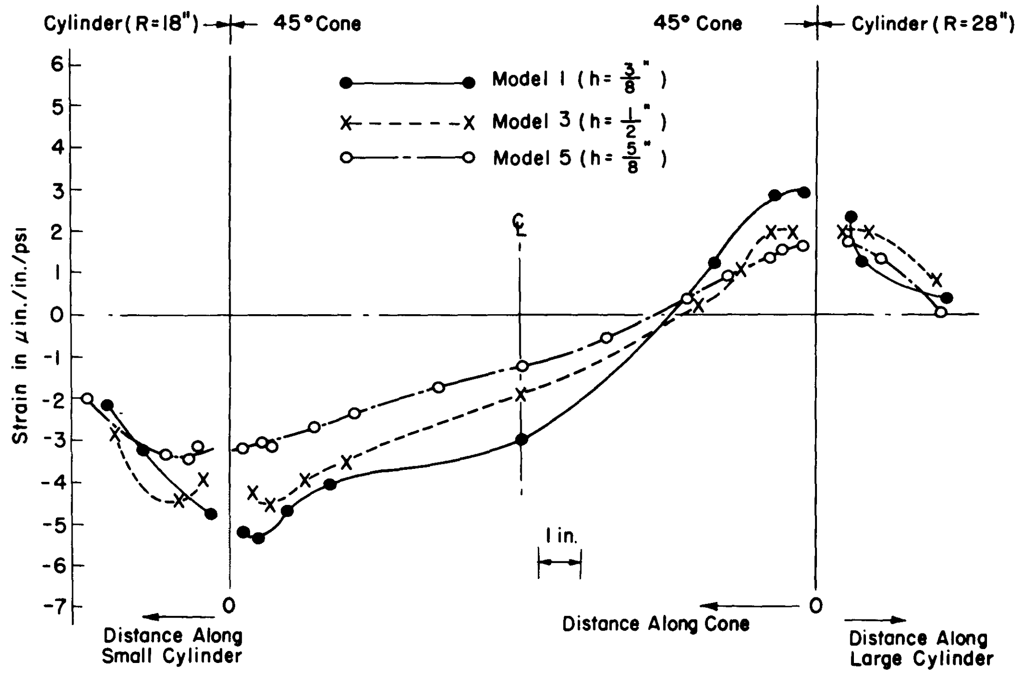


Figure 7c – Average Circumferential Strain

Figure 7 – Longitudinal and Circumferential Strains in Models without Stiffeners at Junctures

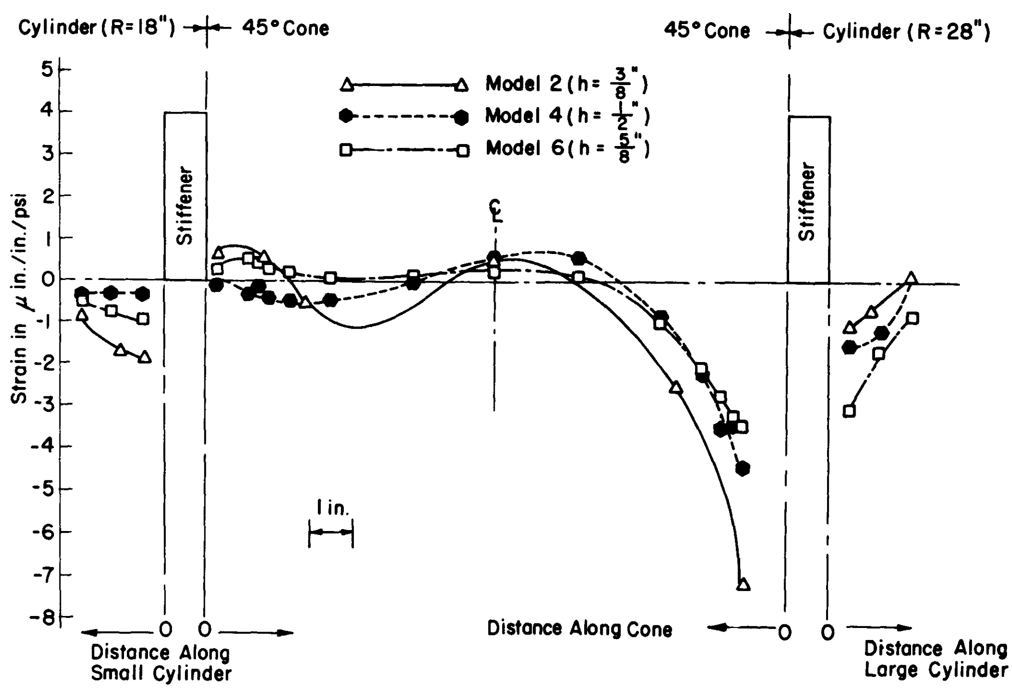


Figure 8a – Longitudinal Strain, Interior Surface

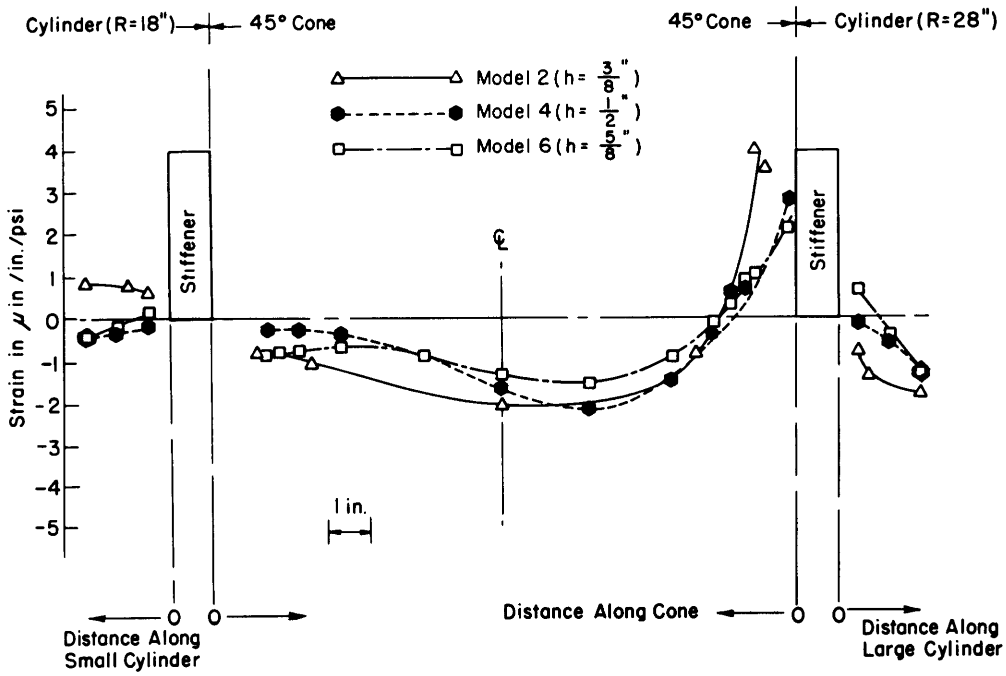


Figure 8b – Longitudinal Strain, Exterior Surface

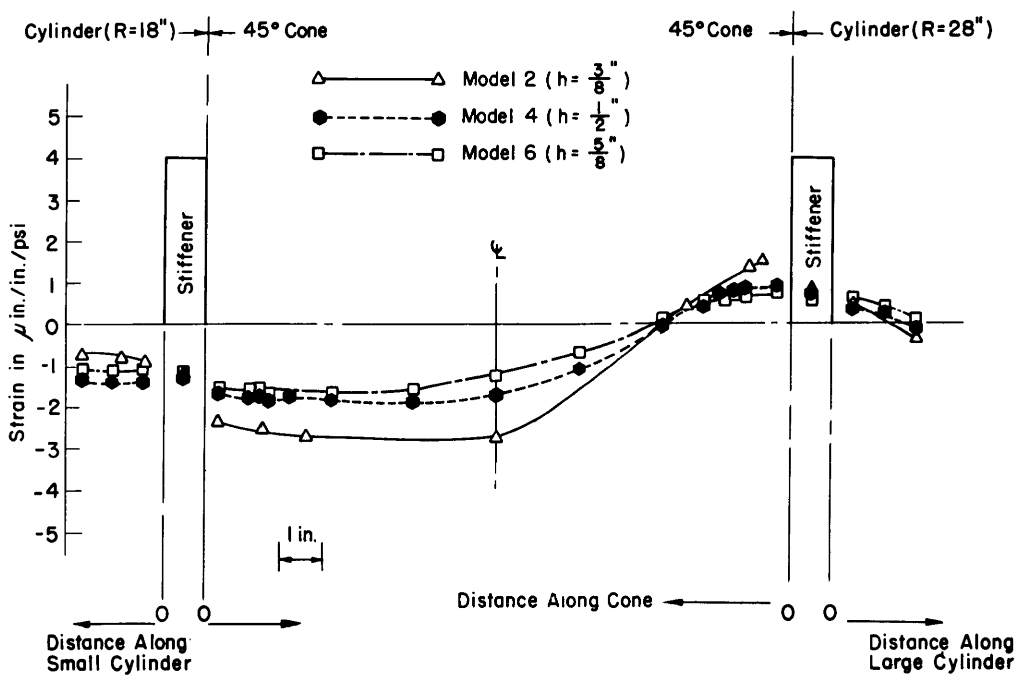


Figure 8c – Average Circumferential Strain

Figure 8 – Longitudinal and Circumferential Strains in Models with Stiffeners at Junctures

DISCUSSION OF RESULTS

From Figure 8c it is seen that there was appreciable rotation of the stiffeners at both junctures. At the small end the rotation was toward the cone, thus increasing the stress in the cone. At the large end rotation was toward the cylinder. Any rotation of the stiffener at the juncture must have a weakening effect on a well-designed reducer section. If the external frame at the small end rotates toward the cone, it increases the circumferential strains in the cone as well as the longitudinal strains on the exterior surface of the cone. If the external frame at the small juncture rotates toward the cylinder, it decreases the circumferential strains in the cone but increases them in the cylinder, thus weakening the cylinder.

Increasing the moment of inertia of the stiffener has a relatively small effect on reducing the rotation. This is illustrated by Model 2, which had a relatively rigid stiffener but nevertheless had excessive rotation at the junctures. A more economical method of limiting rotation is to set the net moment applied to the stiffener equal to zero and thus eliminate the problem; see the Appendix.

There can be considerable deflection at the juncture before failure occurs; see Figure 7. However, these large deflections are undesirable in design. For a hull reinforced by stiffeners, an outward movement at the large end of the cone would weaken the first typical bay from the juncture in both the cylinder and the cone.[4] Also, just how much deflection may be permitted at the juncture before failure occurs has not as yet been determined. There appears, however, to be a point after which adding area to the frame will have little effect on the collapse pressure of the reducer section; see Figure 4 of Reference 5. If the critical stress condition is at a distance of more than $\pi/2\beta$ from the stiffener, where

$$\beta = \sqrt[4]{\frac{3(1-\nu^2)\cos^2\alpha}{R^2 h^2}}$$

the collapse pressure will be increased *very little* by adding more material at the intersection. A greater increase in strength is obtained by adding the material nearer the point of critical stress.

Experimental strains for a model with stiffeners at the junctures are compared in Figure 9 with strains predicted by a Geckeler-type analysis.[2] It will be noted that the agreement is good near the junctures but becomes poorer with increasing distance from a juncture. This discrepancy results because the theory does not account for the influence of stiffeners in the cylinder or the influence of another juncture on the deformations of the cylindrical and conical shells.

The relationship between the thickness of the cone and the collapse pressure, after adjustment for slight differences in yield point, is shown in Figure 10. A proportionally greater increase in strength resulting from stiffening the junctures occurred for the thicker cones. Since the thickness of the smaller cylinder was kept constant, the restraint offered by this

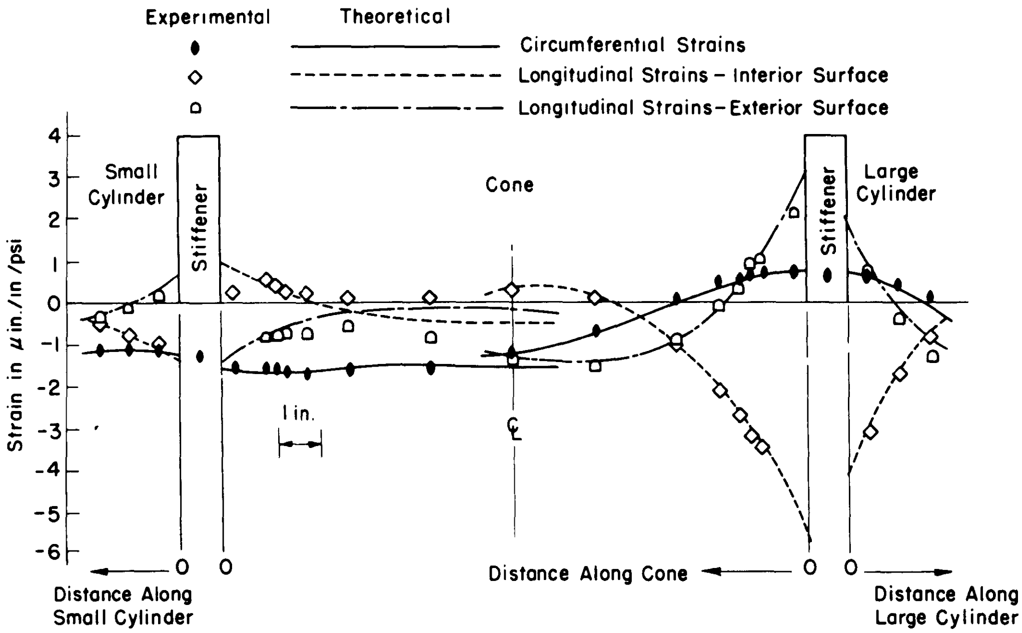


Figure 9 – Comparison of Experimental and Theoretical Strains for Model 6

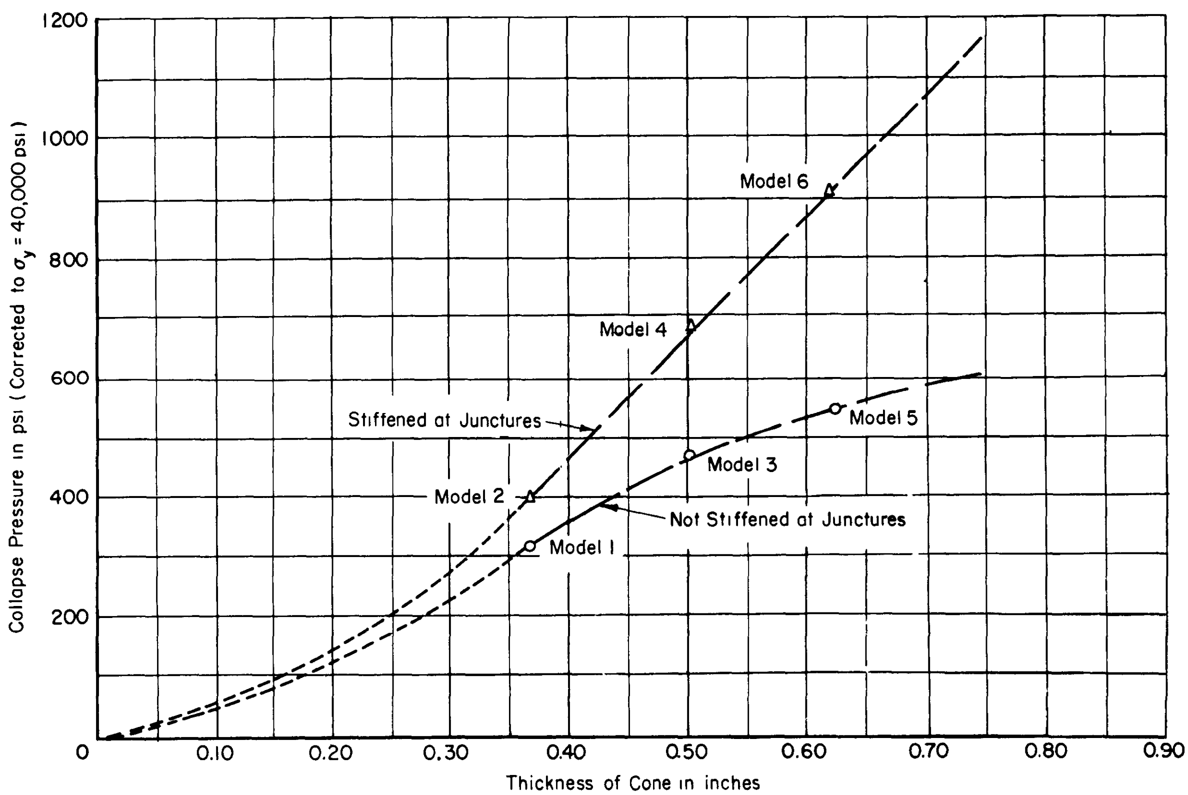


Figure 10 – Collapse Pressure Plotted against Thickness of Cone

TABLE 2

Comparison of Efficiency Factors for Models with and without Stiffeners at the Junctures

Model	1	2	3	4	5	6
Cone Thickness (h) in.	0.375	0.375	0.500	0.500	0.625	0.625
Frame Volume cu in.	None	1,297	None	1,297	None	1,297
Cone Volume cu in.	777	777	1,038	1,038	1,303	1,303
Cylinder Volume cu in.	746	746	746	746	746	746
Total Volume cu in.	1,523	2,820	1,784	3,081	2,049	3,346
Collapse Pressure (P_c) psi	325	410	468	640	535	890
Yield Point (σ_y) psi	41,300	41,300	40,400	37,200	39,000	39,000
Interior Volume (V_1) cu in.	36,583	36,583	36,583	36,583	36,583	36,583
Total Weight (W_m) lb	431.9	799.8	505.9	873.8	581.1	948.9
Efficiency Factor (η_G)	0.667	0.454	0.837	0.751	0.865	0.880

cylinder against deflection at the smaller juncture became less effective as the cone became thicker.

One formula [6] which shows the relative efficiency of a model is expressed by an efficiency factor

$$\eta_g = \frac{P_c V}{\sigma_y W_m}$$

where P_c is the collapse pressure,

V is the volume of the model,

σ_y is the yield point of the material, and

W_m is the weight of the material.

These efficiency factors are listed in Table 2. The portion of the model used was that between the intermediate stiffeners of the cylinders. The models with stiffeners at the junctures were not as efficient as the models without stiffeners at the junctures for both the 3/8-in. cone and the 1/2-in. cone. This suggests that the cylinders were offering appreciable support to the conical sections and reduced the effectiveness of the stiffeners. With the 5/8-in. cone the efficiency factors were about equal, and extrapolating the data shows that a 3/4-in. cone with stiffeners at the junctures would be 20 percent more efficient than one with no stiffeners at the junctures. This series of tests clearly shows that a theory must take into consideration the boundary conditions in order to predict accurately the collapse pressure of cones or conical frustums.

By applying the Hencky-Von Mises yield criterion[7] to the elastic strain measurements shown in Figures 7 and 8, the following general observations can be made:

1. For all models, yielding occurred at the large juncture at pressures appreciably below the collapse pressure.

2. For models without stiffeners at the junctures, yielding next took place at the small juncture; for models with stiffeners, yielding next took place away from the small juncture at about one-third to one-half of the distance to the large end.

3. The yield stress was reached throughout the thickness in Model 6 over about one-half the slant height at a pressure of approximately 85 percent of the collapse pressure. It is believed that in rolling this thick plate to the relatively small diameter the yield point was raised. However, this should not affect the comparison of the structural performance of models with and without stiffeners at the junctures.

It should be noted that because these observations are based on elastic strain measurements they are not entirely realistic. Once a plastic hinge is formed at a given location, the strains at other locations become nonlinear whether the material has reached its yield point or not. However, they do clarify the differences in structural behavior of the two types of models.

CONCLUSIONS

1. Collapse pressure can be increased appreciably by placing stiffeners at junctures of cones and cylinders.

2. Failure does not occur at a pressure associated with initial yielding at the juncture.

3. Excessive rotation of the stiffener at the juncture decreases the collapse pressure of a reducer section or adjoining cylinder.

4. Adding area to the stiffener is effective only as long as the stress condition of that portion of the shell influenced by the stiffener is worse than that of the remainder of the shell.

5. The Geckeler approximation adequately predicts elastic strains near the juncture.

RECOMMENDATIONS

1. Further analytical work should be conducted to establish procedures for designing stiffeners at junctures for least weight.

2. Tests should be conducted to confirm the analysis presented in the Appendix.

3. A similar program on *stiffened* cones should be considered.

ACKNOWLEDGMENTS

The author wishes to express his appreciation for the critical review and the helpful advice provided by Dr. M.E. Lunchick, Mr. R.D. Short, and Mr. E.E. Johnson. The computations and experimental tests were performed with the able assistance of Messrs. J.A. Nott, J.A. Overby, H.P. Rietman, and C.I. York.

APPENDIX

A PROCEDURE FOR DESIGN OF CONE-CYLINDER JUNCTURES

The following procedure may be used to design a juncture of a cone and a cylinder. The procedure is based on the assumption that the optimum design should allow no rotation of the stiffener at the juncture.

The edge rotations and displacements for a shell at a juncture may be expressed in terms of edge coefficients as follows:

$$\theta_i = a_i M_i + b_i H_i + c_i p \qquad [1a]$$

$$\overline{w}_i = d_i M_i + g_i H_i + f_i p \qquad [1b]$$

where a_i, b_i, c_i, d_i, g_i, and f_i are edge coefficients defined and discussed in Reference 5,

θ_i is the angle of rotation of the tangent to the meridian due to deformation,

w_i is the displacement normal to the axis of symmetry at an edge,

M_i is the moment in the meridional plane, at an edge,

H_i is the force normal to the axis of symmetry, at an edge, and

p is the pressure acting on the outer surface.

Equations [1a] and [1b] do not consider secondary forces or moments. Therefore p may be assigned a value of unity when uniform pressure is the only externally applied load.

The well-known expressions for the rotation and deflection of a ring are

$$\theta_{fr} = \frac{R^2 M}{EI} \qquad [2]$$

and

$$\Delta_{fr} = \frac{R^2 F}{EA} \qquad [3]$$

where R is the radius to the centroid of the ring,

I is the moment of inertia of the cross section of the ring,

M is the total moment applied to the ring,

F is the sum of the radial forces applied to the ring, and

A is the cross-sectional area of the ring.

Equations [1a] and [1b] may be solved for the moment and shear force acting on each shell at an edge by assigning a deflection and assuming zero rotation at the juncture.

The assumption that the juncture does not rotate may be satisfied by applying the shears and moments obtained from Equations [1] with $\theta_i = 0$ and $w_i = \Delta$ to the following expression of compatibility:

$$\theta_{fr} = 0 = \frac{R_{fr}^2}{EI}\left[\left(\frac{R_{\text{cone}}}{R_{fr}} \cdot H_{\text{cone}} - \frac{R_{\text{cyl}}}{R_{fr}} H_{\text{cyl}}\right)\frac{b}{2} + \frac{R_{\text{cone}}}{R_{fr}} \cdot M_{\text{cone}} - \frac{R_{\text{cyl}}}{R_{fr}} \cdot M_{\text{cyl}} - p\,\frac{(R^2_{\text{cone}} + R^2_{\text{cyl}})}{4\,R_{fr}} \cdot x\right] \qquad [4]$$

where b is the width of the stiffener,

R is the radius to the centroid of the cross section in question, and

x is the distance between the intersections of the centerline of the two shells with the stiffener, normal to the axis of symmetry.

The sign convention used in Equation [3] is shown in Figure 11.

Equation [4] may thus be solved for the built-in eccentricity x required to eliminate rotation of the juncture

$$x = 4\,\frac{\left[(R_{\text{cone}}\,H_{\text{cone}} - R_{\text{cyl}}\,H_{\text{cyl}})\,\frac{b}{2} + R_{\text{cone}}\,M_{\text{cone}} - R_{\text{cyl}}\,M_{\text{cyl}}\right]}{p\left[R^2_{\text{cone}} + R^2_{\text{cyl}}\right]} \qquad [5]$$

The area of the ring stiffener required to restrict the deflection to the previously assigned value may simply be found by setting the force F in Equation [3] equal to the sum of the shear forces H_i applied to the ring and the force produced by the radial pressure being applied to the surface of the ring.

$$A = \frac{R^2}{E\Delta}\left[H_{\text{cone}} + H_{\text{cyl}} + pb\right] \qquad [6]$$

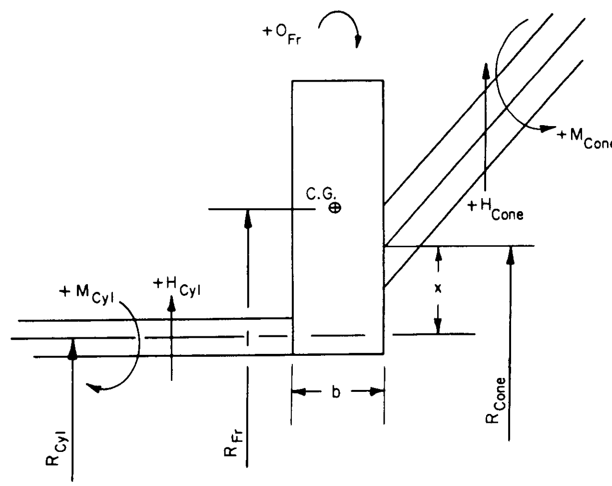
It should be noted that the moments and shears applied to the shells at the juncture may be determined by the preceding method without solving for the eccentricity x or the area of the frame.

The stresses in the outer fiber of a shell at an edge due to a moment and shear may be determined by the procedure presented in Reference 2.

Therefore, by assigning several values to the deflection in Equation [1b] and solving for the corresponding moments and shears, the designer may readily find the area of stiffener required to limit the maximum stress at the intersection to a predetermined allowable value. The allowable stress may be governed by considerations of fatigue of the metal.

A special case for the small diameter juncture is worthy of mention. If the thickness h of the cylinder is equal to $h \cos \alpha$ of the cone and it is desired to have the juncture deflect a value of hoop deflection which is the same for both the cone and the cylinder, the following formula will predict the area required to produce such an effect:

Figure 11 – Sign Convention Used For Cone-Cylinder Junctures



$$R^2 \frac{\left[\frac{PR}{2}\tan\alpha\right]}{EA} = \text{Hoop deflection of cylinder or cone} = \frac{PR^2}{Eh}\left[1 - \frac{\nu}{2}\right] \text{or } A = \frac{Rh\tan\alpha}{2\left[1-\frac{\nu}{2}\right]} \qquad [5a]$$

where h is the thickness of the cylinder,

α is one-half the apex angle of the cone,

R is the radius of the cylinder, and

A is the area of the stiffener.

Another special case for the small juncture would be applicable to a cylinder and cone with intermediate stiffeners. Assume that the juncture will be designed for zero rotation. Then, if the deflection of the stiffener at the juncture is set equal to the midbay deflection or the frame deflection of a typical bay in the cylinder, and if the length of the first bay of the cylinder is set accordingly, the stress condition in the first bay of the cylinder will be equal to that in a typical bay. This deflection pattern will also eliminate the weakening effect that is usually present in the first typical bay.[4]

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Six 45-deg unstiffened conical sections between cylinders of different diameters were subjected to external hydrostatic pressure to study the effect on collapse pressure of placing stiffeners at the junctures. These tests indicate that the collapse pressure depends on the deflection and rotation at the cone-cylinder junctures as well as on the geometry of the cone itself.

For this series of reducer sections with stiffeners at the junctures, the collapse pressure appears to be associated with that pressure at which yielding first occurs at points other than at the juncture. No definite relation between initial yielding and

1. Conical shells – stresses – Measurement
2. Conical shells – Collapse
3. Conical shells (Stiffened) – Stresses – Measurement
4. Conical shells (Stiffened) – Collapse

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collapse pressure for reducer sections without stiffeners at the junctures could be derived from the results of these tests.

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