Report 2132

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WASHINGTON, D.C.

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HYDROSTATIC PRESSURE TESTS OF CYLINDERS FABRICATED FROM HOLLOW-FILAMENT, GLASS-REINFORCED PLASTIC

by

John L. Proffitt

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STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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TABLE OF CONTENTS

Page

ABSTRACT 1

ADMINISTRATIVE INFORMATION 1

INTRODUCTION 1

DESCRIPTION OF MODELS 2

TEST PROCEDURE AND RESULTS 2

DISCUSSION AND CONCLUSIONS 3

ACKNOWLEDGMENTS 5

REFERENCES 13

LIST OF FIGURES

Figure 1 – Models HP-1 through HP-4L 6

Figure 2 – Density versus Filament Hollowness 7

Figure 3 – Strain-Gage Locations and Measured Strain Sensitivities for HP Cylinders 8

Figure 4 – HP Cylinders after Collapse 9

Figure 5 – Failure Curves for HP Cylinders 10

Figure 6 – Measured Moduli versus Hollowness for HP Series 11

LIST OF TABLES

Table 1 – Measured Material and Physical Characteristics of the Models 12

Table 2 – Experimental Moduli, Buckling Pressures, Stresses, and Collapse Pressures for HP Series 12

ABSTRACT

Four pairs of unstiffened cylinders composed of filament-wound, glass-reinforced plastic were subjected to hydrostatic loading to determine the possible benefits to be gained through the use of hollow filaments. Three pairs had hollow-filaments with different ratios of inner diameter to outer diameter, (0.55, 0.57, and 0.62) and the remaining pair employed solid fibers. The results indicate that this hollow-filament material has excellent static strength-weight characteristics for deep-submergence applications. Before its feasibility can be fully established, however, further tests are needed, particular cyclic loading studies and tests involving models with structural details.

ADMINISTRATIVE INFORMATION

This investigation was conducted under the sponsorship of the Bureau of Ships, Code 634C, Project Number S-F013 05 03, Task 1025.

INTRODUCTION

The Taylor Model Basin is currently investigating the feasibility of glass-reinforced plastic (GRP) cylinders for deep-submergence applications. The strength-weight characteristics of GRP pressure hulls are comparable to if not better than those of metallic hulls, as demonstrated by tests reported in Reference 1.*

The fairly successful test results obtained thus far have spurred interest in developing ways to further increase the structural performance of GRP pressure hulls. Until very recently, the major effort in this area was concentrated on materials composed of solid-glass fibers, preimpregnated in a resin matrix, which were wound on a mandrel to produce the pressure-hull cylinder. The introduction of hollow-glass filaments, however, raised the question of whether their use might give more efficient hull structures. For this reason, the Model Basin conducted preliminary tests to determine the response under hydrostatic loading of three pairs of hollow-filament-wound GRP cylinders with different ratios of inner to outer diameter and to obtain empirical data on their material properties in order to establish reliable design criteria for subsequent pressure-hull models. The results of these tests are reported herein and compared to those obtained on a pair of unstiffened cylinders with solid fibers.

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*References are listed on page 13.

DESCRIPTION OF MODELS

At the onset of this program, it was desired to investigate hollow-filament GRP structures with a collapse pressure of 17,778 psi (40,000 ft). Because the state of information concerning the physical and material properties of hollow-filament laminates was rather nebulous at the beginning of this investigation, several fairly broad assumptions were made to aid in the design of the models. It is obvious that as the hollowness of the glass filament increases, the modulus and strength of the glass-resin matrix decreases. The deleterious effect of increasing hollowness, however, is offset by the decrease in density of the laminate. The density can be calculated if the ratio of inner diameter to outer diameter (K) of the glass filament and the percent of resin in the laminate are known. Therefore it was decided to test six unstiffened cylinders, two each with K ratios of 0.50, 0.60, and 0.65, and two unstiffened cylinders with solid fibers. The three hollowness factors were arbitrarily selected, and the solid-fiber laminate was fabricated to act as a control on the tests. Each pair of cylinders was composed of a short (11.4 in.) and a long (24 in.) cylinder. The short cylinders were used to determine realistic stress levels which could be expected, and the long cylinders were used to determine buckling strength.

The eight models were to have a constant weight-displacement ratio based on the assumption that the percent of resin volume in each was the same. The value chosen for the weight-to-displacement ratio was an estimate based on expected moduli and densities which would give rise to a collapse pressure in the range of 18,000 psi for the long cylinders of higher K ratios.

Because the resin volume in the laminate varied from model to model and the K values were not those exactly specified, the resultant weight-to-displacement ratios also varied. The measured physical properties of the eight cylinders are compared in Table 1. Figure 1 gives dimensions of the eight models, and Figure 2 presents the measured densities of the cylinders after fabrication as a function of the hollowness of the glass filaments.

Both the hollow and the solid filaments used to fabricate these models were of E-type glass supplied by the Pittsburgh Plate Glass Company. After preimpregnation into 20 end rovings with an E787 resin system at the U.S. Polymeric Corporation of Santa Ana, California, the material was supplied to H.I. Thompson Fiber Glass Company of Gardena, California, where the models were fabricated in exactly the same manner as many previous solid-glass filament models.[1] The fibers were oriented in a 2 circumferential to 1 longitudinal pattern throughout the shell thickness.

TEST PROCEDURE AND RESULTS

The test procedure for each of the four pairs of cylinders was identical. The models were instrumented with foil resistance gages as shown in Figure 3. The flat steel plates used to close the four short models had internal shoulders which provided an unsupported length of 10.6 in. The shoulders ensured that the cylinders behaved as finite length cylinder with known end conditions. The flat plates used on the four long cylinders had no shoulders in order to more closely approach semi-infinite length conditions.

All eight models were hydrostatically tested in the 13-in. tank at the Model Basin, using oil as the pressurizing medium. Two pressure runs were conducted to a maximum pressure of 5000* psi in 250-psi increments. Strain data were recorded at each pressure increment. The models were collapsed in the 17 1/2-in. high-pressure tank, using water as the pressurizing medium. All models were sealed with a rubber-based waterproofing compound after they were filled with oil and vented to the atmosphere to absorb the energy released at collapse. No strain data were recorded on this final pressure run. Figure 3 gives the average measured strain sensitivities, and Figure 4 shows the models after collapse. Note the lighter color of the six hollow-filament cylinders in the photograph.

Table 2 presents the experimental moduli, elastic buckling pressures, and actual collapse pressures for the eight cylinders. From the strain data taken, the circumferential and longitudinal moduli were calculated by using the Lamé stresses for a thick-walled cylinder and assuming a Poisson's ratio** of 0.15 for the solid glass cylinders[2] and 0.24 for the hollow filament cylinders.[3] The buckling pressure for each cylinder was determined by using the equations of Reference 4 based on the calculated circumferential moduli. Because these equations are applicable to thin-walled cylinders as presented, they were modified as shown in Table 2.

DISCUSSION AND CONCLUSIONS

Figure 5 presents strength-weight curves for the eight cylinders of the series. Two plots are presented, one for the short cylinders and one for the long cylinders. The buckling portion of each curve was determined from the equations of Reference 4 (modified to account for the thick cylinder walls), the densities of Figure 2, and the circumferential moduli of Table 2. The stress level (straight line) portion is based on a compressive Lamé stress of 100,000 psi on the inside surface of the cylinder wall. This value was chosen since three of the four short cylinders failed close to this stress level.

The low observed collapse pressure of Model HP-4 might have been due to adverse end conditions or to water penetration into the surface of the cylinder, causing premature collapse. Therefore it is probably not reasonable to consider the stress of 76,030 psi at collapse as the ultimate in this range of hollowness, particularly in view of the higher stress obtained when

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*Models HP-1 and HP-1L were subjected to only 3000 psi as insurance against possible damage to the models during the recording of strain data.

**The assumption that Poisson's ratios ν_ϕ and ν_x are equal violates Maxwell's reciprocal theorem, but it may be of no great importance as far as determing the buckling pressure is concerned because ν always appears in the form $(1 - \nu^2)$ in the more important terms of the stability determinant.

Model HP-4L was tested. Indeed, from the appearance of the four short models after collapse (Figure 4), one would hesitate to conclude that HP-1, HP-2, and HP-3 had failed because the wall stresses at the center of the model had reached the ultimate strength of the material. Certainly the presence of circumferential cracks at the cylinder ends might suggest stress failure in this region, but whether this effect was primary or secondary cannot be determined. As was mentioned previously, the 100,000-psi value for the ultimate stress was only an estimate and was used throughout the plot in order to show more clearly the weight advantage gained as filament hollowness increases.

The ratio of wall thickness to mean diameter for Model HP-1 (solid filaments) is in the buckling range of previously tested GRP cylinders fabricated from similar materials. It is more reasonable to assume in this case, however, that collapse was due to stress failure since the resin content of HP-1 was 24 percent by weight as compared to 19 percent for the previously reported cylinders.[2] Such an increase in resin content would almost surely lower the strength level of the laminate to the point where this would be the critical mode of failure.

This same circumstance is probably responsible for lowering the value of the moduli of Models HP-1 and HP-1L below that of previously tested unstiffened cylinders constructed of E glass and an E787 resin system[2] although the disparity is within the realm of experimental error. The decrease in moduli of the eight models is plotted in Figure 6 as a function of the hollowness of the glass filaments. It is seen that within rather broad limits, the calculated moduli are inversely proportional to the relative decrease in area of the glass fiber (K^2).

All four of the long cylinders failed in the buckling region. The increased buckling pressures obtained from the hollow-filament cylinders at comparable weight-to-displacement ratios was evident. The discrepancy between the experimental points of Figure 5b and the calculated curves, which are based on a semi-infinite length, is to be expected. Reference to Table 2, however, reveals that three of the cylinders failed above the pressure predicted by Von Mises.[4] Normally, less than simple support end conditions would place the collapse pressures somewhere between those presented in Table 2. There is no tenable explanation for the behavior of these cylinders. However, unpublished Model Basin tests indicate that a heavy-walled unstiffened aluminum cylinder five diameters in length also collapsed at a pressure about 30 percent above the predicted semi-infinite collapse pressure.

The strength-weight characteristics of a hollow-filament laminate in a pressure-hull structure offer a definite advantage over solid-filament GRP. The efficiency gained by using a hollow-filament laminate in an unstiffened cylinder is sufficient to make such a structure competitive with a ring-stiffened solid fiber GRP cylinder. From the experimental results in Figure 5b, it is seen that for a collapse pressure of 13,333 psi (30,000 ft), the ratio of weight of material to weight of sea water displaced for a cylinder using hollow fibers ($K = 0.62$) would be about 0.57, which compares very favorably with that of previously tested solid-fiber GRP cylinders.[1] Furthermore, it should be realized that an unstiffened configuration is far from the optimum geometry, from the standpoint of the most expeditious use of a material. With the introduction of stiffening systems, the *static* strength efficiency of hollow-filament structures should be increased further.* How the addition of stiffeners will affect the fatigue strength of such a structure is not known, however.

There appears, then, to be cause for optimism concerning the use of hollow-filament GRP. It must be remembered, however, that these tests were preliminary and, at best, limited in scope since they included only short-term static strength. At the present time, nothing is known about the structural response of hollow-filament GRP under cyclic loading, about the effect of realistic penetrations and closures on the collapse strength, and whether larger scale (and hence more massive) sections will behave in the same manner as these small-scale models. These areas must be thoroughly investigated before the feasibility of hollow-filament GRP as a deep-submergence material can be documented. It is planned to construct two models consisting of an unstiffened cylinder of hollow-filament GRP fitted with a titanium end closure designed to be compatible with the cylinder.[5] One model will be subjected to hydrostatic pressure, and the other will be tested under cyclic loading.

The problem areas mentioned above are areas where all glass-reinforced plastics have been notably lackluster in performance and where much intensive investigation is now being concentrated. Probably, then, the same type of program will be necessary for hollow-filament GRP as more is learned about its structural characteristics.

ACKNOWLEDGMENTS

The author wishes to thank Mr. Gerald D. Ward who was responsible for obtaining all data relating to the physical properties of the cylinders and who also supervised the pressure tests. The assistance of Mr. Kenneth Hom in the analysis of the test results is also acknowledged.

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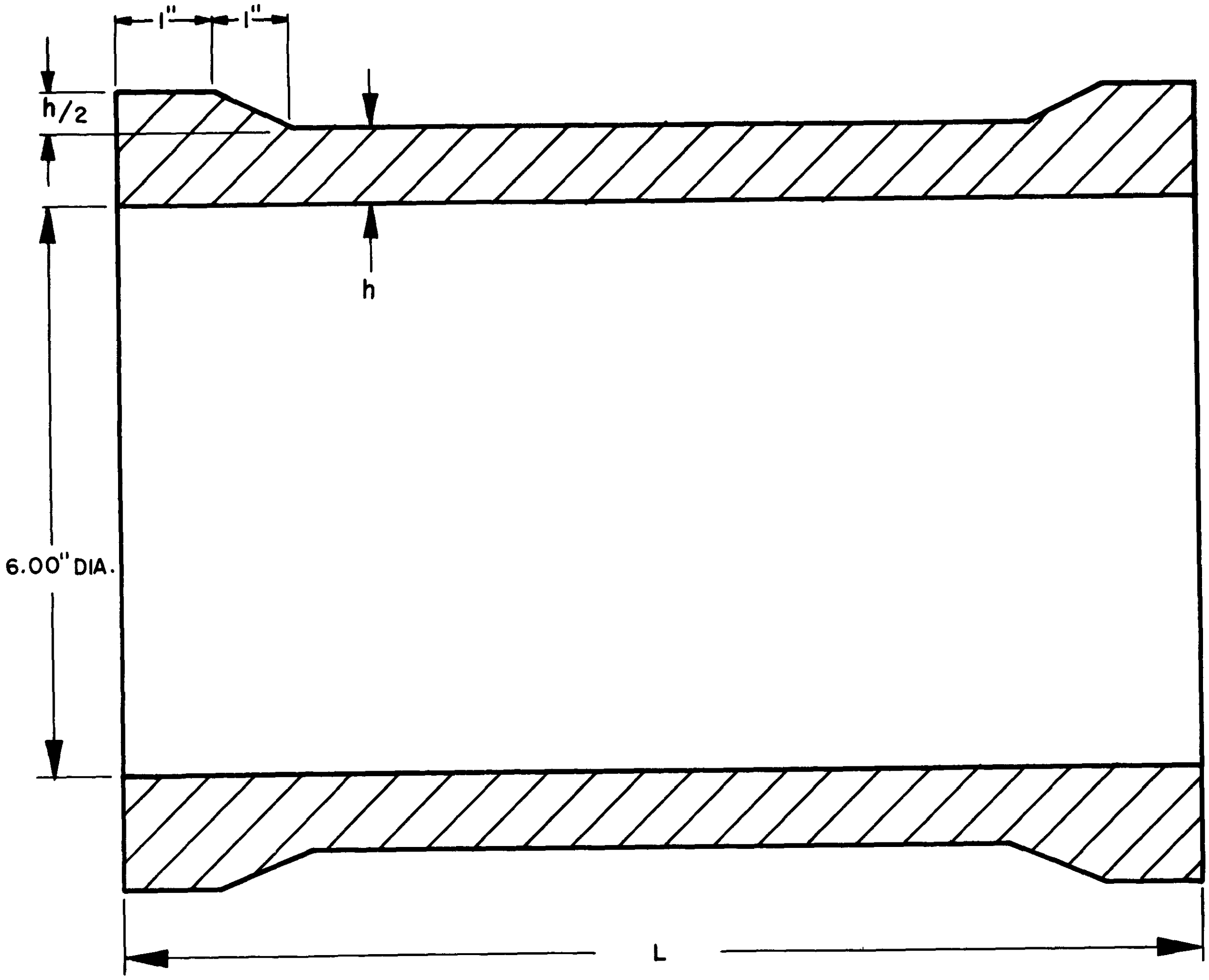
*A greater advantage exists at lesser depths since the strength of these shells are even more critically dependent on elastic stability.



Model	*h*	*L*
HP-1	0.561	11.40
HP-1L	0.561	24.00
HP-2	0.789	11.40
HP-2L	0.789	24.00
HP-3	0.924	11.40
HP-3L	0.924	24.00
HP-4	1.035	11.40
HP-4L	1.035	24.00

Figure 1 – Models HP-1 through HP-4L

All dimensions in inches.

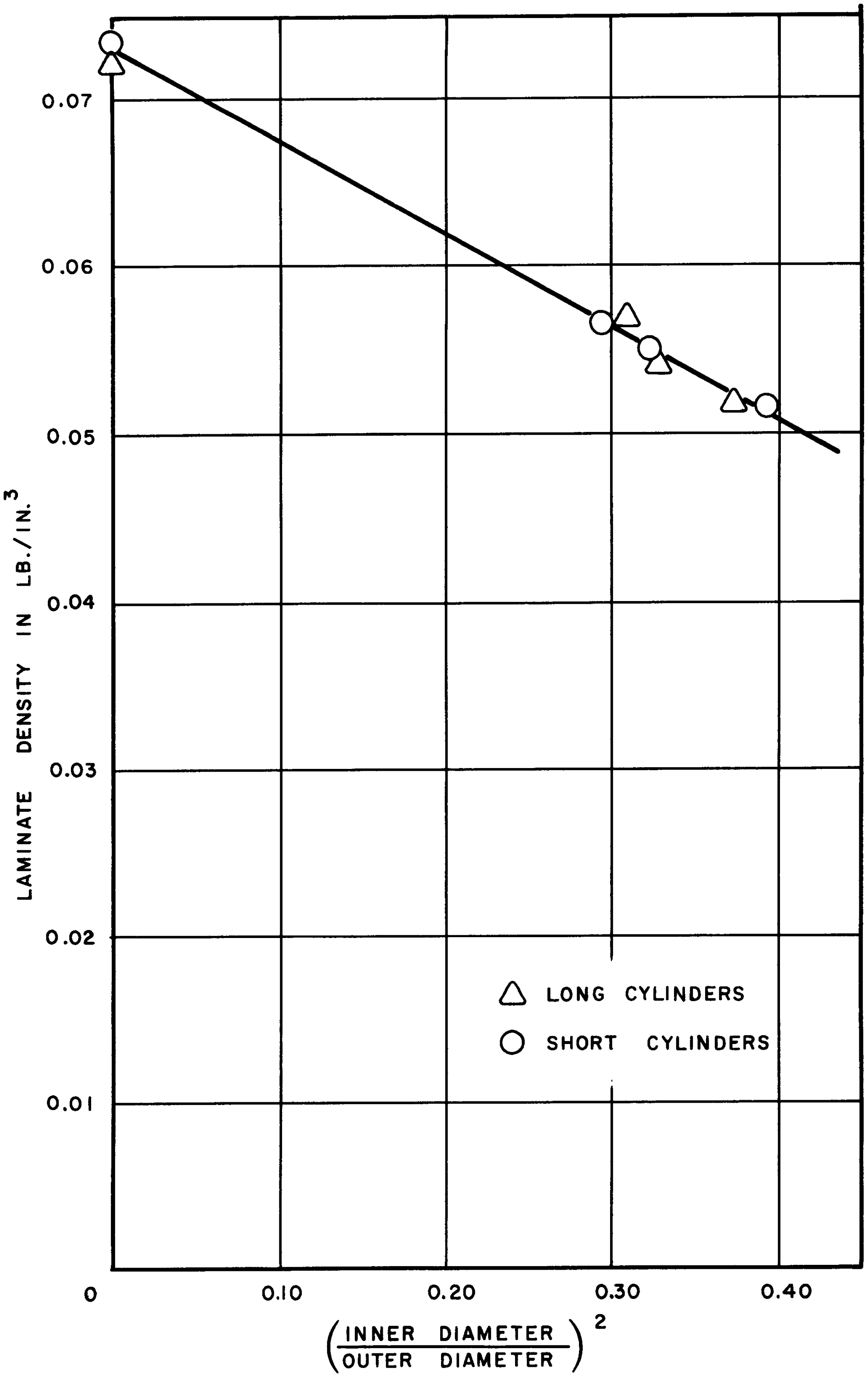
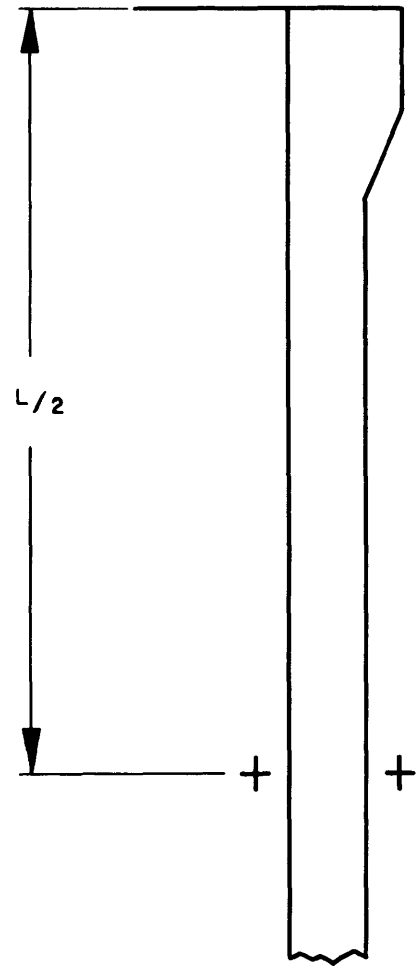


Figure 2 – Density versus Filament Hollowness



Average Sensitivities								
Gage	HP-1	HP-1L	HP-2	HP-2L	HP-3	HP-3L	HP-4	HP-4L
1	0.70	0.62	0.73	0.73	0.80	0.75	0.70	0.73
2	1.16	1.21	1.42	1.33	1.35	1.36	1.36	1.30
3	0.69	0.64	0.77	0.72	0.80	0.74	0.70	0.74
4	1.18	1.20	1.40	1.34	1.35	1.36	1.35	1.33
5	0.72	0.67	0.74	0.74	0.79	0.75	0.70	0.74
6	1.15	1.19	1.38	1.35	1.35	1.38	1.35	1.38
7	0.71	0.65	0.74	0.71	0.79	0.74	0.68	–
8	1.17	1.17	1.40	1.34	1.35	1.35	1.36	1.36
9	0.69	0.60	0.74	0.68	0.72	0.73	0.68	–
10	0.88	0.90	0.96	0.90	0.88	0.93	0.85	0.85
11	0.68	0.62	0.72	0.70	0.73	0.71	0.68	0.67
12	0.88	0.92	0.96	0.89	0.87	0.90	0.85	0.85
13	0.67	0.69	0.73	–	0.73	0.74	–	0.66
14	0.88	0.91	0.96	0.89	0.88	0.90	0.86	0.87
15	0.65	0.65	0.72	0.70	0.72	0.73	0.68	0.66
16	0.88	0.92	0.97	0.87	0.88	0.90	0.85	0.85

Gage Numbers				
	0 deg	90 deg	180 deg	270 deg
Inside	1, 2	3, 4	5, 6	7, 8
Outside	9, 10	11, 12	13, 14	15, 16

Figure 3 – Strain-Gage Locations and Measured Strain Sensitivities for HP Cylinders

Odd numbers indicate longitudinal gages and even numbers indicate circumferential gages.

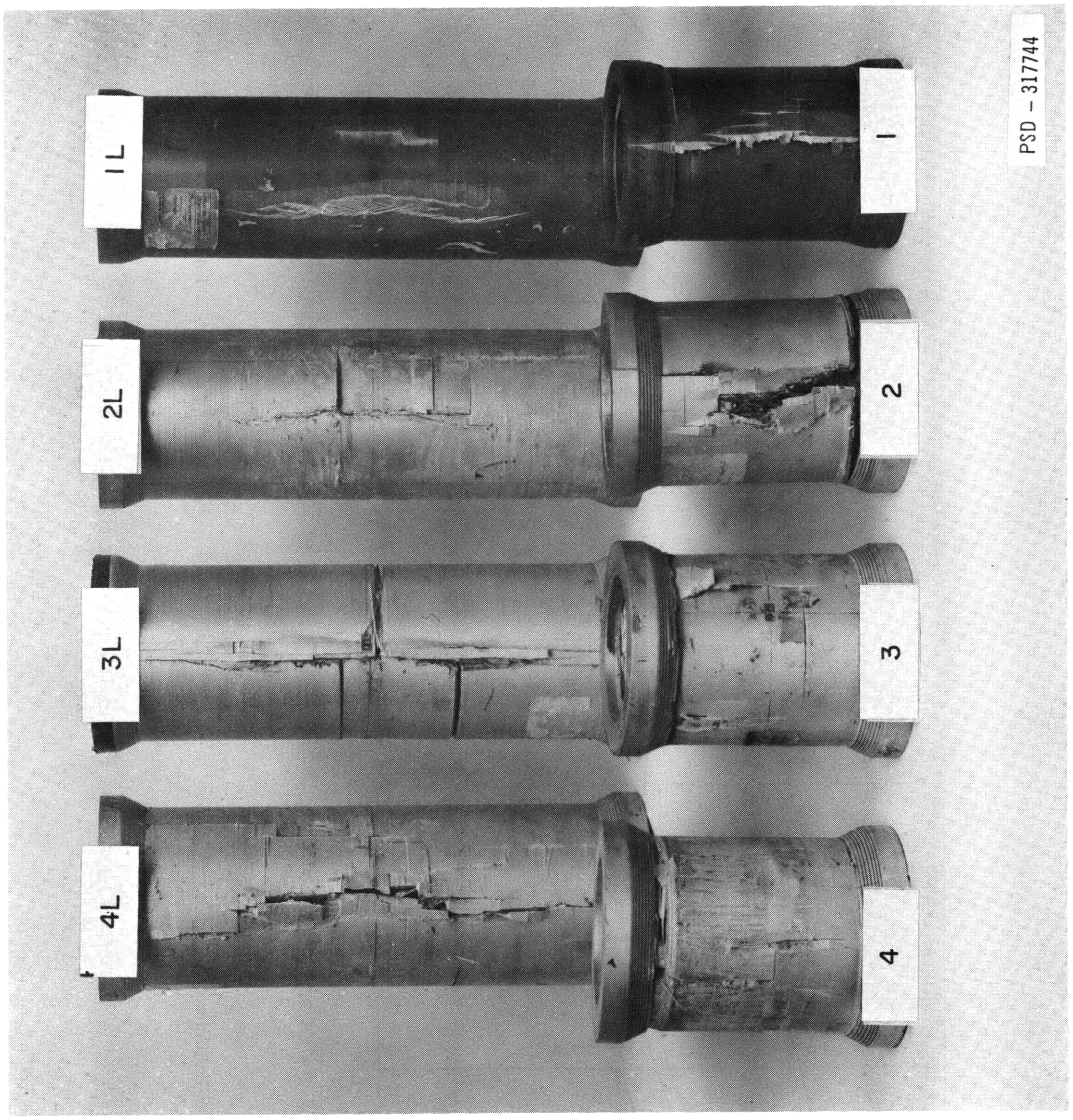


Figure 4 – HP Cylinders after Collapse

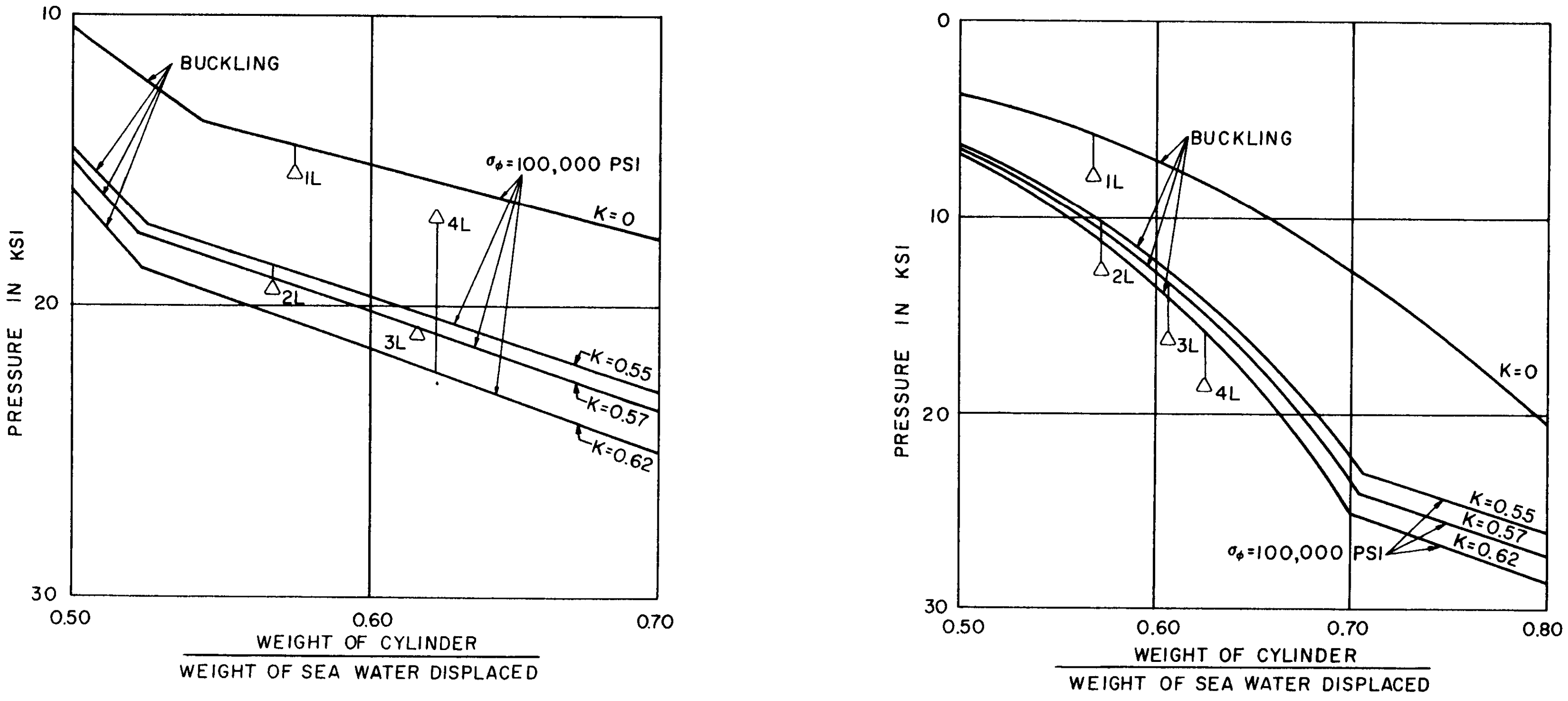


Figure 5a – Short Cylinders ($L = 10.6$)

Figure 5b – Long Cylinders ($L = 24$)

Figure 5 – Failure Curves for HP Cylinders

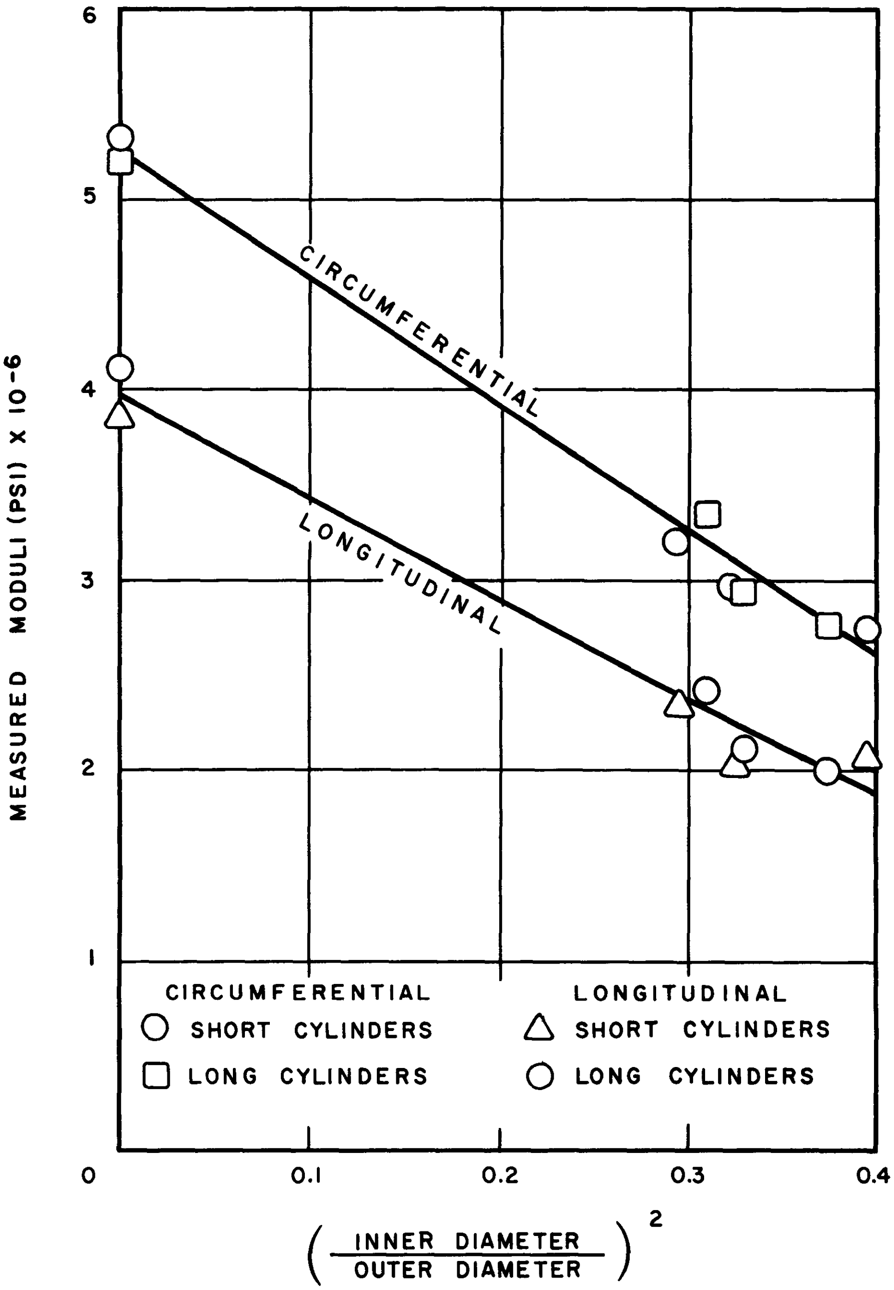


Figure 6 – Measured Moduli versus Hollowness for HP Series

TABLE 1

Measured Material and Physical Characteristics of the Models

Model	Laminate			Cylinder
	Fiber $\frac{ID}{OD}$ (K)*	Percent Resin by weight*	Density (lb/in.^{3})	$\frac{\text{Weight}}{\text{Displacement}}$
HP-1	0	24.3	0.0734	0.575
HP-1L	0	25.0	0.0725	0.568
HP-2	0.543	30.7	0.0564	0.568
HP-2L	0.556	31.1	0.0567	0.572
HP-3	0.569	35.8	0.0550	0.617
HP-3L	0.573	37.8	0.0540	0.606
HP-4	0.627	35.1	0.0516	0.623
HP-4L	0.610	36.4	0.0518	0.625

*Data furnished by H.I. Thompson Fiber Glass Company.

TABLE 2

Experimental Moduli, Buckling Pressures, Stresses, and Collapse Pressures for HP Series

Model	E_ϕ	E_x	Buckling Pressures (psi)*		P_{exp} (psi)	$\sigma_{\phi i}$ (psi)**
	(10^6 psi)		Equation [6][4]	Equation [A][4]		
HP-1	5.30	3.83	16,500		15,600	107,500
HP-1L	5.22	4.09	7,190	6,150	7,900	54,430
HP-2	3.20	2.33	22,790		19,450	104,270
HP-2L	3.34	2.41	11,780	9,960	12,700	68,070
HP-3	2.94	2.03	28,900		20,900	100,600
HP-3L	2.94	2.12	14,810	13,070	16,220	78,090
HP-4	2.77	2.07	35,330		17,000	76,030
HP-4L	2.77	1.99	19,090	16,310	18,600	83,180

*The equations of Reference 4 were modified by substituting the term $\left[\left(\frac{t}{D}\right)^2\left(\frac{t}{D_0}\right)\right]$ wherever the expression $\left(\frac{h}{D}\right)^3$ appeared in the original equations. Equation [6] is the von Mises equation for cylinders of finite length; Equation [A] is the Bresse-Bryan equation for cylinders of infinite length.

**Calculated circumferential inside (Lame) stress.

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13. ABSTRACT

Four pairs of unstiffened cylinders composed of filament wound, glass-reinforced plastic were subjected to hydrostatic loading to determine the possible benefits to be gained through the use of hollow filaments. Three pairs had hollow-filaments with different ratios of inner diameter to outer diameter, (0.55, 0.57, and 0.62) and the remaining pair employed solid fibers. The results indicate that this hollow-filament material has excellent static strength-weight characteristics for deep-submergence applications. Before its feasibility can be fully established, however, further tests are needed, particular cyclic loading studies and tests involving models with structural details.

14. KEY WORDS	LINK A		LINK B		LINK C	
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Deep-Submergence Pressure Hulls						
Material Density						
Hydrostatic Pressure Tests						
Buckling Pressure						
Stress Level						

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5. Submarine hulls--Materials
I. Proffitt, John L.
II. S-F013 05 03; Task 1025
III. T:Hollow-filament, glass-reinforced plastic

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