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CYCLIC PRESSURE-LOADING TESTS OF A RING-STIFFENED CYLINDER FABRICATED OF GLASS-FILAMENT REINFORCED PLASTIC

by

William P. Couch and Kenneth Hom

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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ABSTRACT

A cyclic test with a 1-minute hold at maximum pressure was conducted on a ring-stiffened, glass-reinforced plastic cylinder. The model was subjected to a pressure variation from 200 to 6700 psi, which corresponds to one-half the collapse pressure of a model with similar geometry tested under short-term hydrostatic loading. At the conclusion of 8626 cycles, no apparent loss in structural integrity was noted. The model was then loaded to a hydrostatic pressure of 14,000 psi without catastrophic failure; however, inspection of the model revealed crazing on the inside surface of the shell in regions corresponding to maximum longitudinal and circumferential stresses.

INTRODUCTION

Under the sponsorship of the Bureau of Ships,[1] the David Taylor Model Basin has a research program to determine the feasibility of using glass-reinforced plastics (GRP) as a structural material for pressure hulls of deep-diving submersibles. The fatigue characteristics of filament-wound, glass-reinforced plastics were of primary concern at the onset of this program. Investigations by IIT Research Institute under Bureau of Ships Contract NObs 86461 indicated that reasonable fatigue life might be expected from filament-wound GRP at composite stress levels on the order of 50,000 psi. These results were obtained from uniaxial compression specimens and thick-walled, unstiffened cylinders subjected to external uniform pressures.

Although the IIT fatigue studies have served as a guide to the structural research engineer in the design of GRP pressure hull components, there existed little experimental data of cyclic tests conducted with external pressure vessels incorporating design features similar to what might be expected in actual deep-depth vehicles. In fact, Reference 2 presents the only data on cyclic tests of actual hull structures under external pressures published prior to 1963 and known to the authors. The results of these tests were extremely discouraging. Two ring-stiffened cylinders were cyclic-tested to two-thirds of the collapse pressure of similar models collapsed under hydrostatic pressure. The cylinders were cycled at a rate of approximately 10 cycles per hour and failed after 86 and 442 cycles. These cylinders represented an early "state-of-the-art" in both material and fabrication of external pressure vessels.

Recent fatigue tests with structural models have been much more successful. H.I. Thompson Fiber Glass Company (HITCO), under Bureau of Ships Contract NObs 88351 to study problems in the design of closure heads, large openings, and joints in filament-wound pressure hulls for a collapse depth of 30,000 ft, has consistently obtained with structural

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[1] References are listed on page 11.

models 10,000 cycles without failure.[3,4,5] These models were pressure-cycled to a depth of 15,000 ft, which generated maximum stresses in the structure on the order of 50,000 psi. The models were fabricated from prepreg E-HTS/E787 and S-HTS/E787, 20-end rovings with a resin content of 20 ± 2 percent. The cycling rate was 9 cycles per minute, over 50 times as fast as that imposed on the cylinders tested in Reference 2.

The high cycling rate used by HITCO coupled with their excellent results opened a question as to whether similar results could be obtained at lower cycling rates. Also, it was felt that more meaningful fatigue data could be obtained if pressure cycles incorporated a dwell time at maximum pressure. A model, designated as RV-1F, was chosen to obtain a preliminary answer to these questions. The model was subjected to a cyclic-loading schedule as shown in Figure 1; the result obtained is the subject of this report. The outer surfaces of the model were coated with a rubber sealing compound to prevent contact of the pressure medium with the model; this was done in order to eliminate any possible effects due to absorption of the pressure medium into the laminate and to study only the influence of cyclic loading on the structure.

Model RV-1F represents the hull geometry in the region of the large-diameter opening of a pressure hull now under study by both HITCO[3,4,5] and the Model Basin. The investigation is part of a feasibility study into using GRP for the pressure hull of deep-submergence vehicles. Details of the entire pressure hull are shown in Figure 2. The test results of Model RV-1F, although they represent only a part of the study, were significant enough to warrant a separate report for rapid dissemination. Static strength and other fatigue studies (now underway) will be documented in future Model Basin reports.

The strain-time measurements obtained from an unstiffened GRP cylinder subjected to a cyclic load similar to that shown in Figure 1 are presented in the Appendix.

DESCRIPTION OF MODELS

Model RV-1F represents the cylinder geometry in way of the large opening of the pressure hull shown in Figure 2. The model is three frame spaces long. The entire model was machined from a single thick-walled cylinder fabricated of prepreg E-HTS/E787, 20-end rovings with a resin content of 20 ± 2 percent. The fiber distribution is shown in Figure 3 along with other model details and the test setup. Fillets with 1/2-in. radius at the toe of the frames were machined into the structure; this feature was not incorporated in other models tested under hydrostatic pressure.

Another model, designated RV-1, was used for hydrostatic-strength studies. This model is five frame spaces long and has the same hull geometry as Model RV-1F. Test results of this model afford a datum for the fatigue tests of Model RV-1F. Details of Model RV-1 are shown in Figure 4; the model was fabricated with slightly oversized frames shrunk onto the inside of the shell. The material was the same as that used for Model RV-1F.

TEST PROCEDURE

The ends of Model RV-1F were sealed by two closure heads machined from 17-4 PH steel. They were heat-treated and ground to provide smooth, hard surfaces so that the ends of the model would deflect under load with the least resistance to friction. In one of the flat plates, a threaded hole was provided for attaching a pipeline leading to the outside of the pressure tank. This pipeline was added to assist in detecting a possible failure of the model during the cyclic test.

The entire model was coated with a rubber sealing compound, with a large bead of the compound placed at both ends along the intersection of the closure head and the model. The primary purpose of using a sealing compound was to protect the cut-fiber surfaces near the ends of the model. Recent tests[6] have shown appreciable strength reduction in cylindrical structural models subjected to high pressures for a relatively short duration where cut fibers of the laminate were exposed to the pressure medium. When the cut-fiber surfaces were protected, no apparent strength reduction was noted.

The cyclic tests of Model RV-1F were conducted in pressure facilities at IIT Research Institute. External pressure with a variation of 200 to 6700 psi at a rate of one cycle every 3 minutes was imposed on the model. The approximate time intervals during each cycle were 1 1/2 minutes from minimum to maximum pressure, 1 minute at maximum pressure, and 1/2 minute from maximum to minimum pressure. The pressure cycle is shown graphically in Figure 1. Oil was used as the pressurizing medium.

After the cyclic tests, the model was tested hydrostatically at the Model Basin.

TEST RESULTS AND DISCUSSION

Inspection of Model RV-1F by IIT personnel after 8626 cycles revealed that the rubber compound around the intersection of the closure head and model had broken loose. Removal of the closure head indicated no sign of oil leakage into the model. The test was discontinued, short of the original goal of 10,000 cycles, since the method of sealing the ends of the model seemed to be unreliable, and continued use of this sealing technique would only jeopardize the model.* It was feared that the cut-fiber ends of the model would become unprotected to the pressure medium, thus leading to premature failure. The model was shipped back to the Model Basin where it was subjected to a hydrostatic pressure of 14,000 psi without failure; however, inspection of the model after it was tested hydrostatically revealed crazing on the inside surface of the shell.

Model RV-1, used for static-strength studies,[6] failed at a pressure of 13,700 psi; failure occurred in the shell near the frames. Since Model RV-1F is of the same geometry as the static

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*An improved seal technique is being used on fatigue tests now underway; results will be reported in Reference 6.

model but incorporates large fillets at the base of the frames where failure is prone to occur, its overall strength should be somewhat higher than Model RV-1. With this consideration, it would be difficult to accurately assess what strength reduction, if any, occurred due to cyclic loading of Model RV-1F. The results, however, were very favorable.

Figure 5 gives the measured stresses in Model RV-1 at a pressure of 6700 psi. The stresses were determined from strain measurements in conjunction with the following elastic material constants; see Reference 7:

Fiber Distribution	E_ϕ, psi	E_x, psi	$\nu_{\phi x}$	$\nu_{x\phi}$
4C:2L	6.40×10^6	4.45×10^6	0.188	0.130
9C:1L	7.20×10^6	3.50×10^6	0.242	0.118

Figure 5 shows that at a pressure of 6700 psi, corresponding to the maximum cyclic pressure on Model RV-1F, the highest measured stress on Model RV-1 was 54,300 psi. In this region of the structure, it is reasonable to assume that the stresses were of the same magnitude in Model RV-1F.

CONCLUSIONS

Although the cyclic-fatigue studies that have been and are being conducted on realistic hull structures by HITCO and the Model Basin are promising, potential shortcomings such as the deleterious effects of long-term exposures to a deep-submergence environment on the load-carrying capacity of filament-wound structures have not been determined. These can only be established after extensive investigations. Studies with structural models cycled at stresses higher than 50,000 psi should be carried out in an effort to determine the design limitation of filament-wound structures.

Means must be provided to protect the laminate, particularly the cut-fiber surfaces, from the environment. Possibilities toward alleviating this apparent shortcoming may exist in protective coatings or metallic jackets. Studies have been initiated along these lines by the Bureau of Ships and the Model Basin.

ACKNOWLEDGMENT

The authors are indebted to Mr. A.R. Willner for his guidance in the operation of the cyclic facilities necessary for the conduct of the test to determine the strain response of an unstiffened cylinder. The results of this test are given in the Appendix.

APPENDIX

STRAIN RESPONSE OF A GRP CYLINDER UNDER CYCLIC LOADING

The test results of Model RV-1F would not be meaningful if a delayed strain response of significant magnitude existed during the loading cycle. A limited study was conducted to determine the strain response of an unstiffened cylinder cycled under the same maximum stress-time conditions as Model RV-1F.

An unstiffened cylinder (shown in Figure 6), fabricated of the same material and with the same fiber distribution as the shell of Model RV-1F, was subjected to a pressure variation of 200 to 10,000 psi at time intervals very similar to those imposed on the stiffened structure. The actual pressure cycle used on the unstiffened cylinders is shown graphically in Figure 7.

The cylinder was instrumented with electrical resistance strain gages at two midlength locations, 180 degrees apart, on both the inside and outside surfaces of the cylinder. Measurements were taken with a dynamic strain recorder. Figure 6 gives the average values of the strains measured from the two locations.

A maximum stress of 50,700 psi at the maximum cyclic pressure of 10,000 psi was computed using the strains shown in Figure 6 in conjunction with elastic material constants given on page 4. This stress is of the same order of magnitude as that determined for Model RV-1F (54,300 psi at a maximum cyclic pressure of 6700 psi). Thus, it can be said that the maximum stress-time cycle of the unstiffened cylinder is similar to that of Model RV-1F.

Figure 8 is a typical strain-time plot determined from one of the strain gages. The particular plot shown in Figure 8 was obtained from a circumferential gage located on the inside surface of the cylinder. An inspection of Figures 7 and 8 indicates that the pressure trace and the strain trace are of the same character; i.e., every crook of one curve is duplicated on the other and occurs at the same time. Therefore, the fatigue cycle used in this study exhibited no appreciable delay in the strain response to loading.

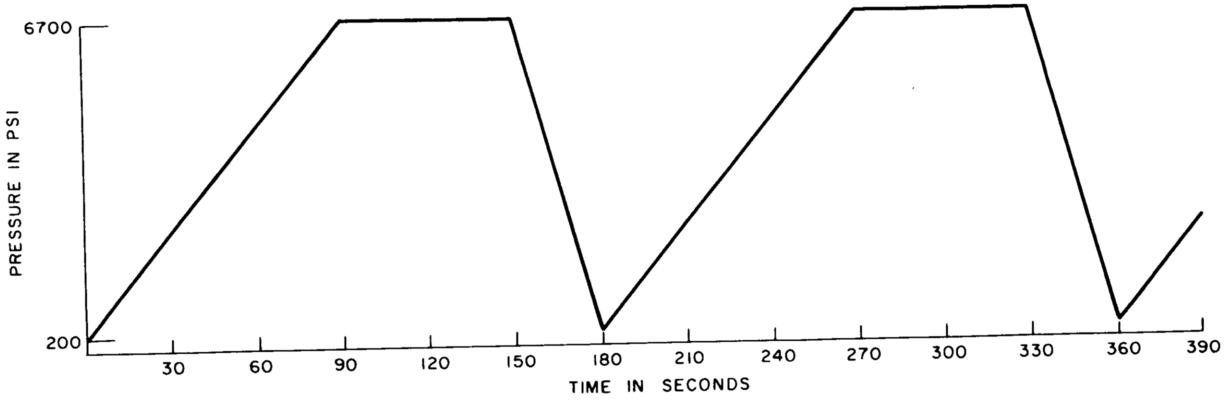

Figure 1 – Pressure Cycle Used on Model RV-1F

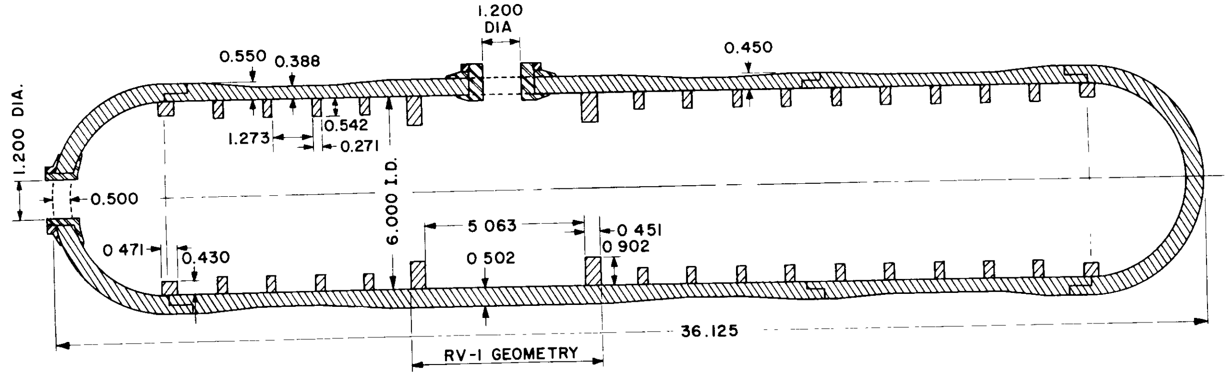

Figure 2 – Small-Scale Pressure Hull Designed for Collapse Depth of 30,000 Feet

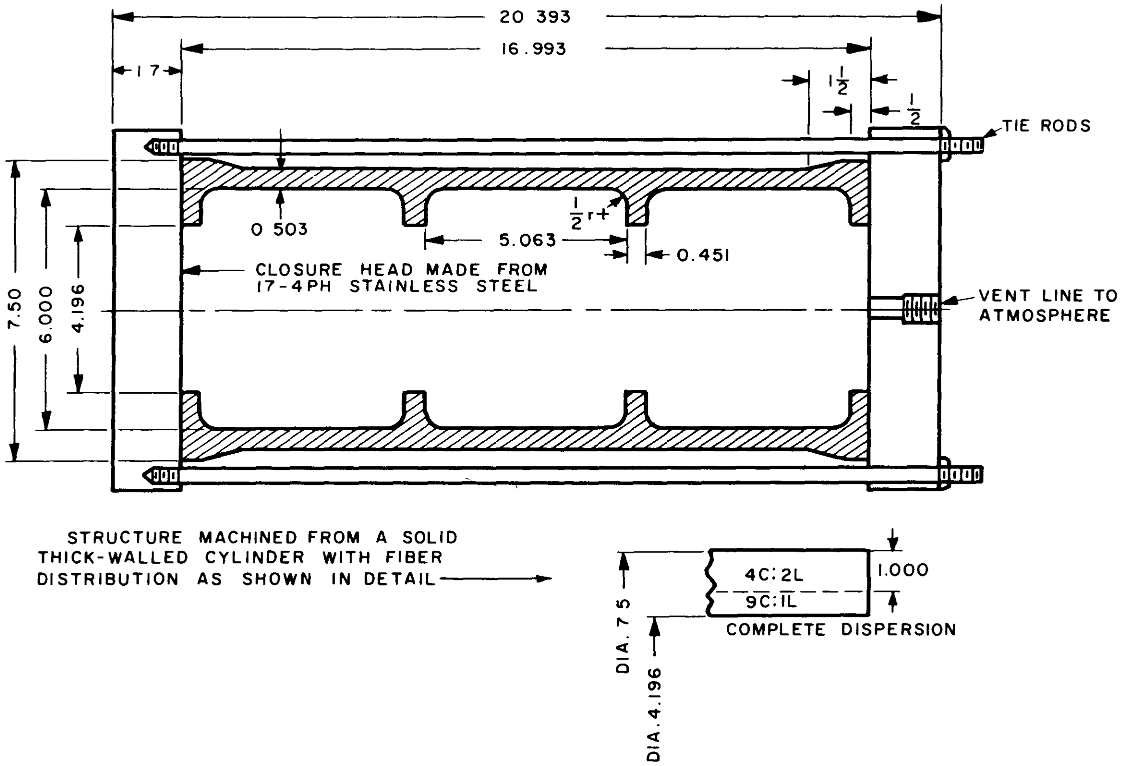

Figure 3 – Details of Model RV-1F

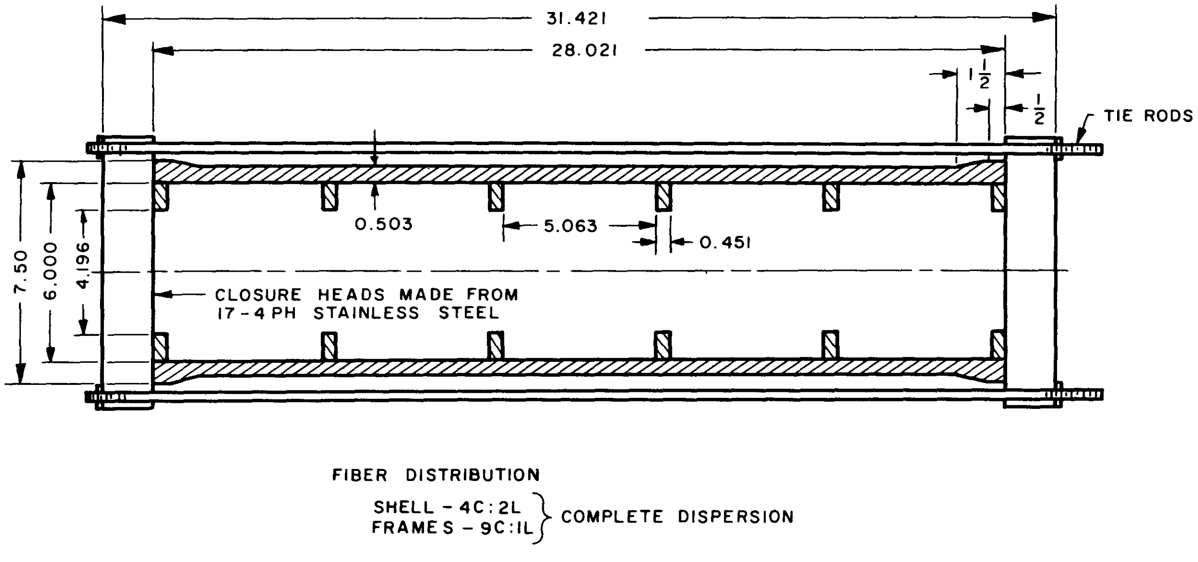

Figure 4 – Details of Model RV-1

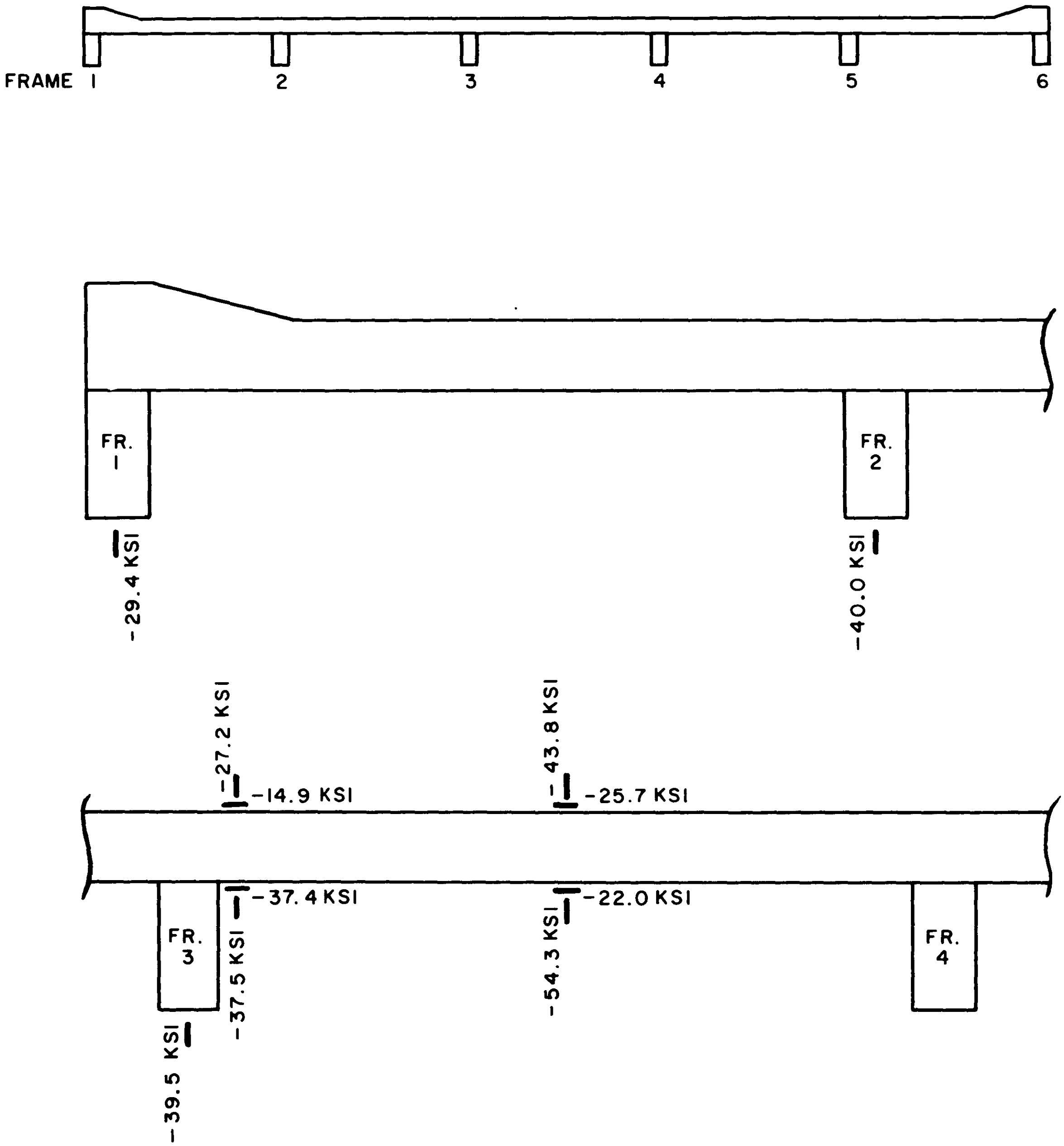

Figure 5 – Measured Stresses in Model RV-1 at a Pressure of 6700 PSI

The values shown represent the circumferential and longitudinal stresses and are written vertically and horizontally, respectively.

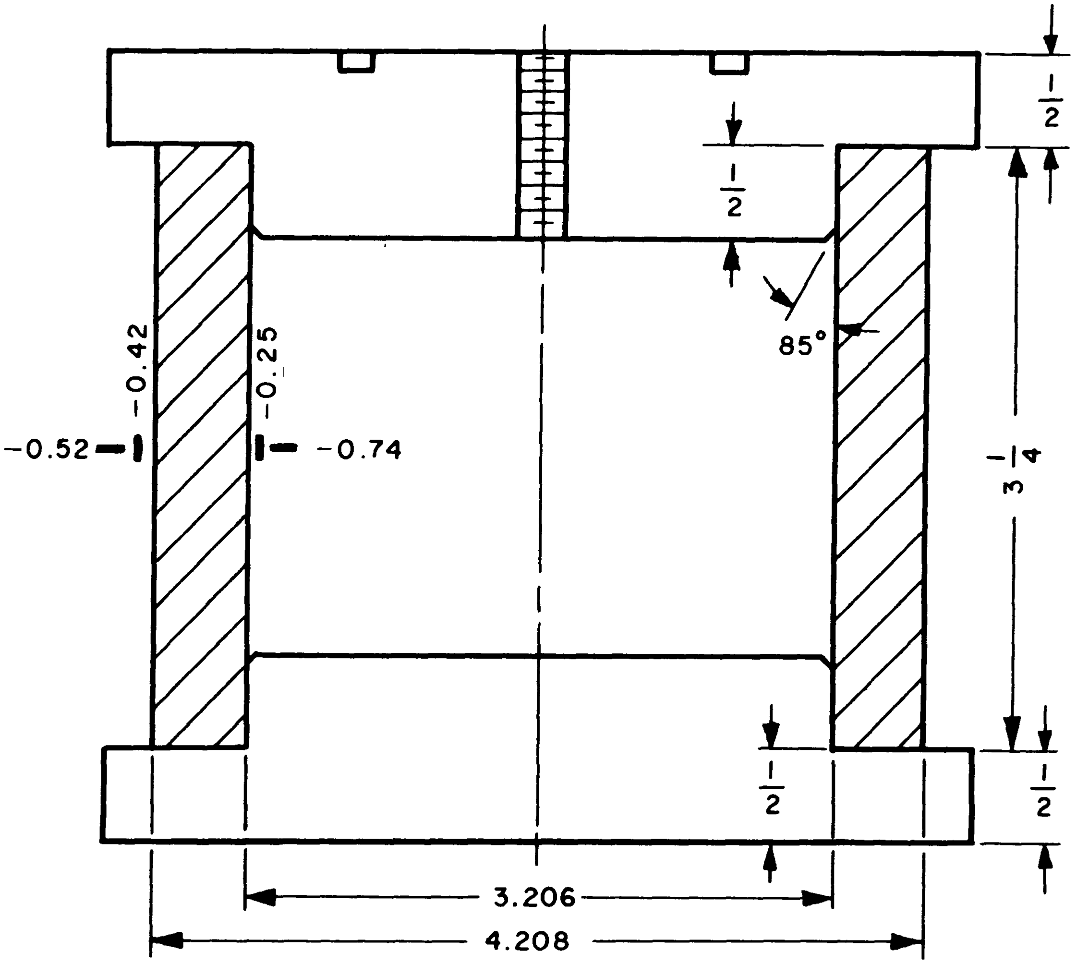

Figure 6 – Details and Strain Measurements of an Unstiffened GRP Cylinder

The values shown represent the circumferential and longitudinal strain measurements (μin/in/psi) and are written horizontally and vertically, respectively.

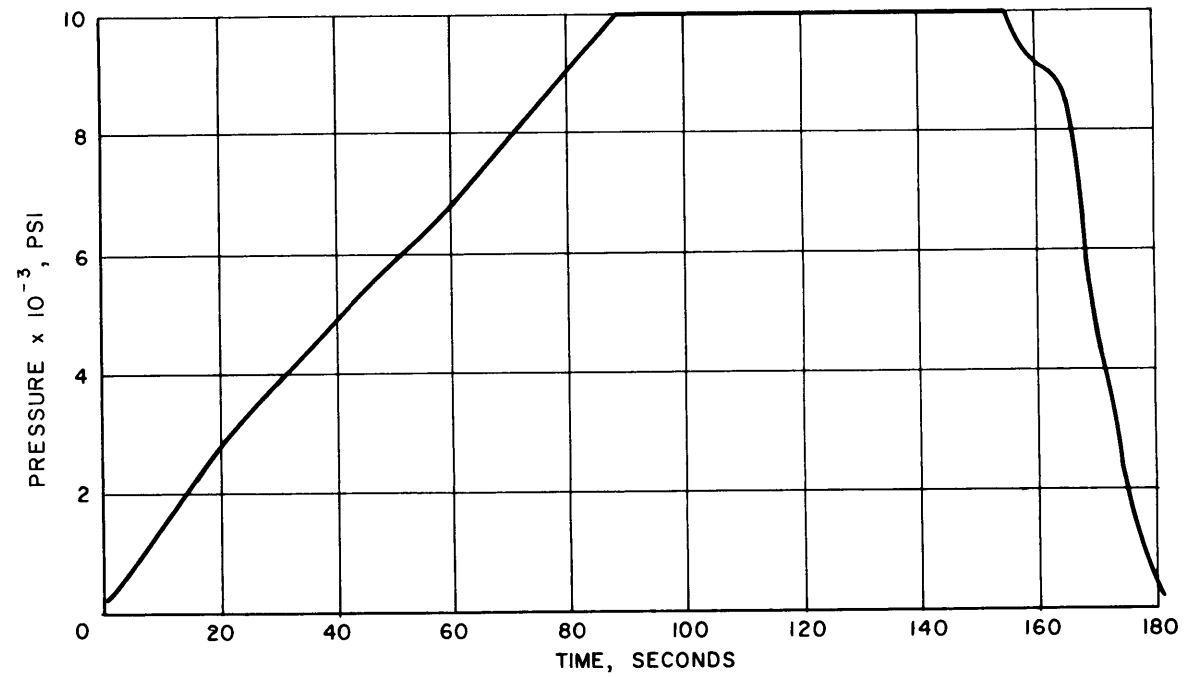

Figure 7 – A Typical Pressure Cycle for the Unstiffened GRP Cylinder Tested

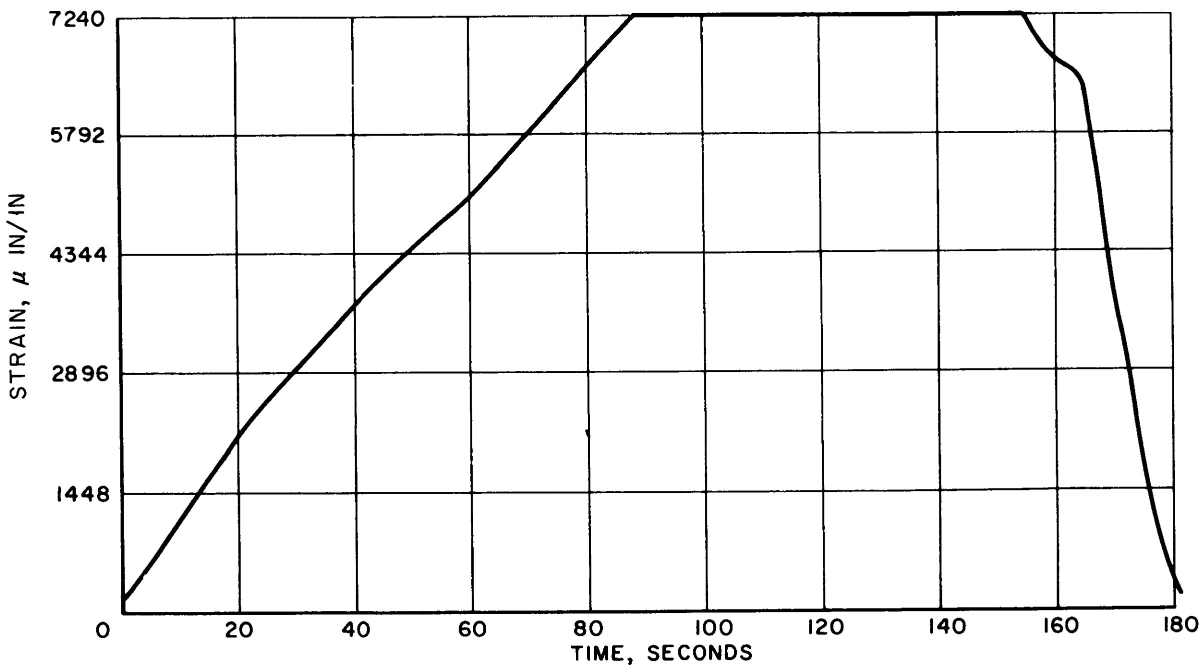

Figure 8 – Typical Strain-Response Measured on the Unstiffened GRP Cylinder Tested

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