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AMMRC TR 78-38 Supplement

ULTRA-HIGH-MODULUS GRAPHITE/EPOXY CONICAL SHELL DEVELOPMENT

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Convair Division
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<p>The work reported herein represents a preliminary evaluation of support ring concepts for an advanced terminal interceptor (ATT). An ultra-high-modulus graphite/epoxy subscale cone was fabricated and a wedge shaped ring was secondary bonded internally. The cone and ring were successfully tested beyond ultimate load at both RT and 325F. A unique helicoil attachment concept for transferring load into the ring was demonstrated.</p>		

PREFACE

This supplementary report to AMMRC TR78-38 is prepared by General Dynamics Corporation, Convair Division for the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts under contract DAAG46-76-C-0008. This work is part of the program on Development of Hardened ABM Materials, Mr. John F. Dignam, Program Manager. The AMMRC Technical Supervisor is Mr. Lewis R. Aronin.

This report covers work from 1 December 1976 to 30 May 1978. The work was performed by personnel from General Dynamics Convair Division under direction of the Materials and Process Engineering Group. Mr. Julius Hertz is the program manager. Mr. Edward E. Spier, Mr. Hugh McCutchen, and Mr. George W. Smith were responsible for design and analysis functions and Dr. Norman R. Adsit was responsible for specimen testing. Conical shell and ring specimens were fabricated by Mr. Charles M. Ogle.



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SECTION 1

SUMMARY

During Phase I of Contract DAAG46-76-C-0008, General Dynamics Convair Division successfully fabricated subscale ultra-high-modulus graphite/epoxy conical structures for advanced ballistic missile (ABM) structures. The objective of Phase II was to design and analyze an intermediate load introduction ring for an ultra-high-modulus graphite/epoxy frustum constituting a guidance and controls section of an advanced terminal interceptor (ATI).

Preliminary structural analysis was performed to establish the basis for testing such a ring (half-size) in a subscale frustum whose wall thickness was exactly half-size. Existing bulk graphite tooling was utilized to manufacture the shell. The bonded ring joint resisted ultimate design loading at both room temperature and 325F without failure.

After several tests, the ring was loaded to failure at room temperature. Failure occurred at 260% of design ultimate load. The mode of failure was helicoil pullout. The experimental equipment ring was over-designed for the half-scale frustum; however, this was a desirable feature since strengths of small bond joints are difficult to scale to full size hardware. The experimental wedge ring design should certainly be acceptable in its present form for the full scale frustum with the exception that larger fasteners and helicoils would be required. The success of the helicoil inserts (1640 pounds per insert) nearly parallel to the plies offers a simple means of applying tension loads to the ring.

SECTION 2

INTRODUCTION

During Phase I of Contract DAAG46-76-C-0008, General Dynamics Convair Division successfully demonstrated the feasibility of ultra-high-modulus graphite/epoxy structures for advanced ballistic missile (ABM) structures. The guidance and control section of a representative missile was chosen as a representative structural section because it contained design features such as splice joints, support rings, cut-outs, and basic shell, which would need verification in a graphite/epoxy structure. Ten subscale conical frusta representing the basic shell were fabricated, and testing by Martin-Marietta (Reference 1) confirmed their analytically predicted performance. Twelve subscale cones were fabricated to evaluate three types of interleaved titanium foil joint concepts. Four of these latter cones have been tested to date, and they too have been highly successful.

The objective of Phase II of this program was a preliminary evaluation of support ring concepts for an advanced terminal interceptor (ATI). The support ring is located midway in the ATI frustum and holds electronic packaging. As such, it imposes loading onto the joint and into the basic shell. During service, it is anticipated that this equipment ring must withstand imposed loadings both at ambient and elevated temperatures. A maximum operating temperature of 325F was assumed.

SECTION 3

DESIGN AND ANALYSIS

The objective was to design and analyze an intermediate load introduction ring for an ultra-high-modulus graphite/epoxy conical frustum constituting a guidance and controls section of an advanced terminal interceptor (ATI). Preliminary structural analysis was performed to establish the basis for testing such a ring (half-size) in a subscale frustum whose wall thickness was exactly half-size. Existing tooling developed for another program was utilized to manufacture the shell. For this reason, the other dimensions of the shell (radii and length) fell within the range between the full-scale prototype and the half-scale model used in earlier phases of this study. As such, the test article was considered to be very representative of an ATI forward electronics compartment and quite acceptable for testing the half-size ring. Of course, the test loads were properly adjusted to result in ring loads that are consistent with the half-size design.

A survey and evaluation was conducted of candidate ring materials including both metals (aluminum, titanium, Invar, beryllium, and magnesium) and advanced composite systems (graphite/epoxy, Kevlar/epoxy, boron/epoxy, and boron/aluminum). Very early in the study it was apparent that graphite/epoxy offered the most promise of success. All the metals introduced severe bondline thermal stress problems with Invar being the least critical. Among the composite candidates, graphite/epoxy was selected since it offered superior compatibility with the GY70/934 system used for the basic shell wall.

Also early in the design selection process, it was possible to rule out mechanical fastening for two reasons. First, the high stress concentrations due to holes in the shell wall would require a local doubler. This would introduce a weight penalty over and above that for the fasteners themselves. In addition, eccentricity of the ring loads with respect to the shell would be increased due to the presence of the doubler, thereby magnifying the running bending moment (a further weight penalty).

The most attractive design was therefore determined to be an adhesive bonded graphite/epoxy ring. Because of its suitability under the elevated temperature environment (325F), EA934 epoxy adhesive was chosen for this design. A simple, radial-flange type ring was investigated by means of a computerized finite element analysis. The results obtained showed that this type of design introduces severe interlaminar tension stresses at fillet radii. However, prior testing at General Dynamics has demonstrated the feasibility of a wedge-shaped ring for this application. The latter configuration was therefore selected for the test article of the current program.

To establish the area requirement for the ring-to-shell adhesive bond, a series of sub-element joint tests was performed at room and elevated temperatures. Both shear and flatwise tensile specimens were loaded to failure. Thus, the overall design evolved from the combined background of a materials and configuration survey, manual stress analyses, a computerized finite-element analysis, and existing General Dynamics test experience supplemented by test data obtained as part of the current investigation.

Based on the axial distribution of the shell running loads respectively applicable to the room and elevated temperature conditions, together with the total system design features, a discontinuity analysis of the frustum wall was considered to be unnecessary.

RING LOADS

The 325F load condition is critical, and the ultimate loads on the half-scale frustum ring are

$$N_{\text{axial}} = 350 \text{ lb/in (aft)}$$

$$V = 3750 \text{ lb (total transverse shear)}$$

The diameter at the shear surface of the ring to the shell wall is

$$D_s = 5.35 \text{ in.}$$

The maximum ultimate shear flow due to V is

$$q = V/(\pi D/2) = 3750/(\pi \times 5.35/2) = 446 \text{ lb/in}$$

ANALYSIS

The proposed ring design is shown in Figure 3-1, and an equivalent double lap shear test for analysis¹ is shown in Figure 3-2. The dimensions are

$$L = 3 \text{ in.}$$

$$t_2 = 0.45 \text{ in.}$$

¹The ring is not in double shear, of course, but the actual condition is certainly very much better than single shear.

EA934 Adhesive
0.004 in Secondary
Bond

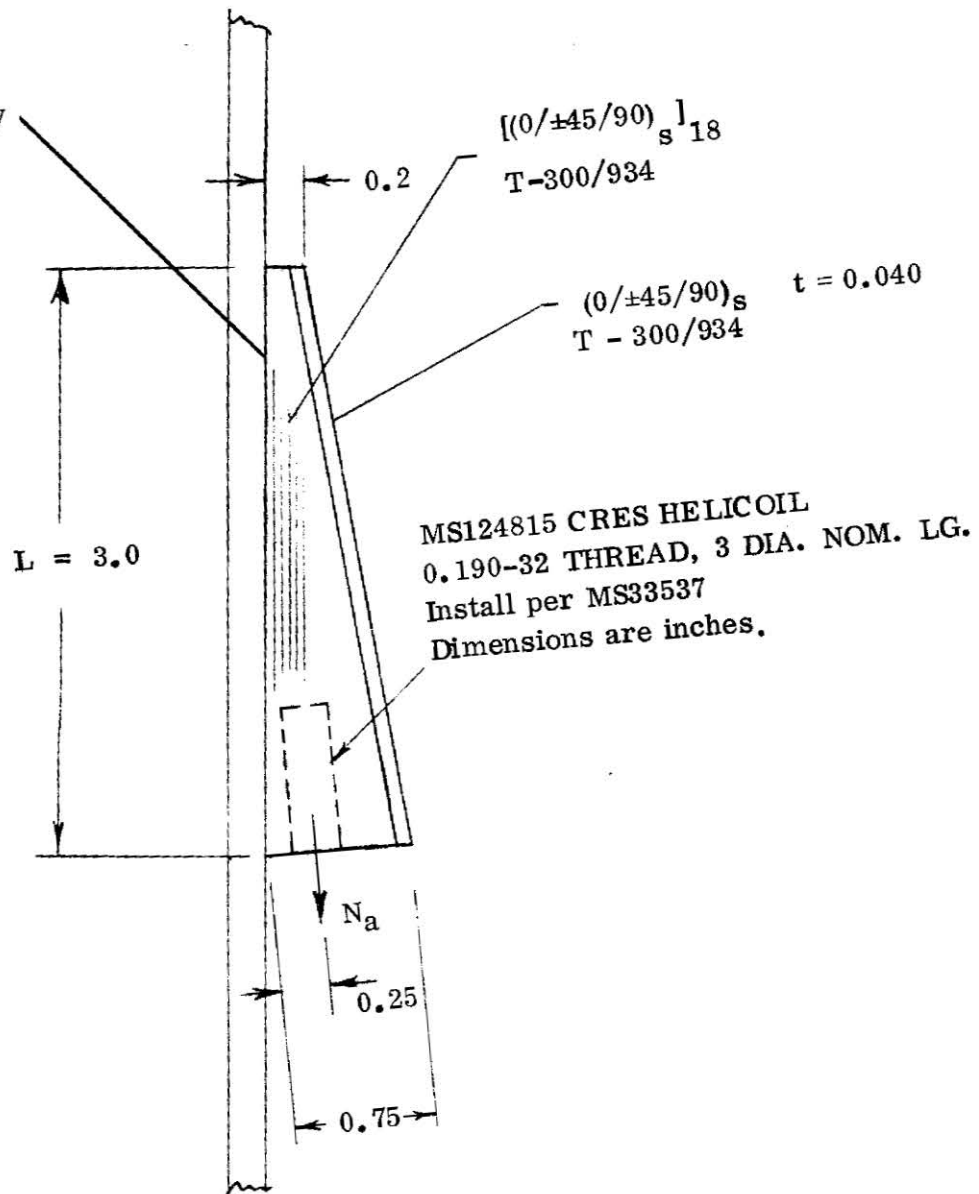


Figure 3-1. Ring for Half-Scale Frustum

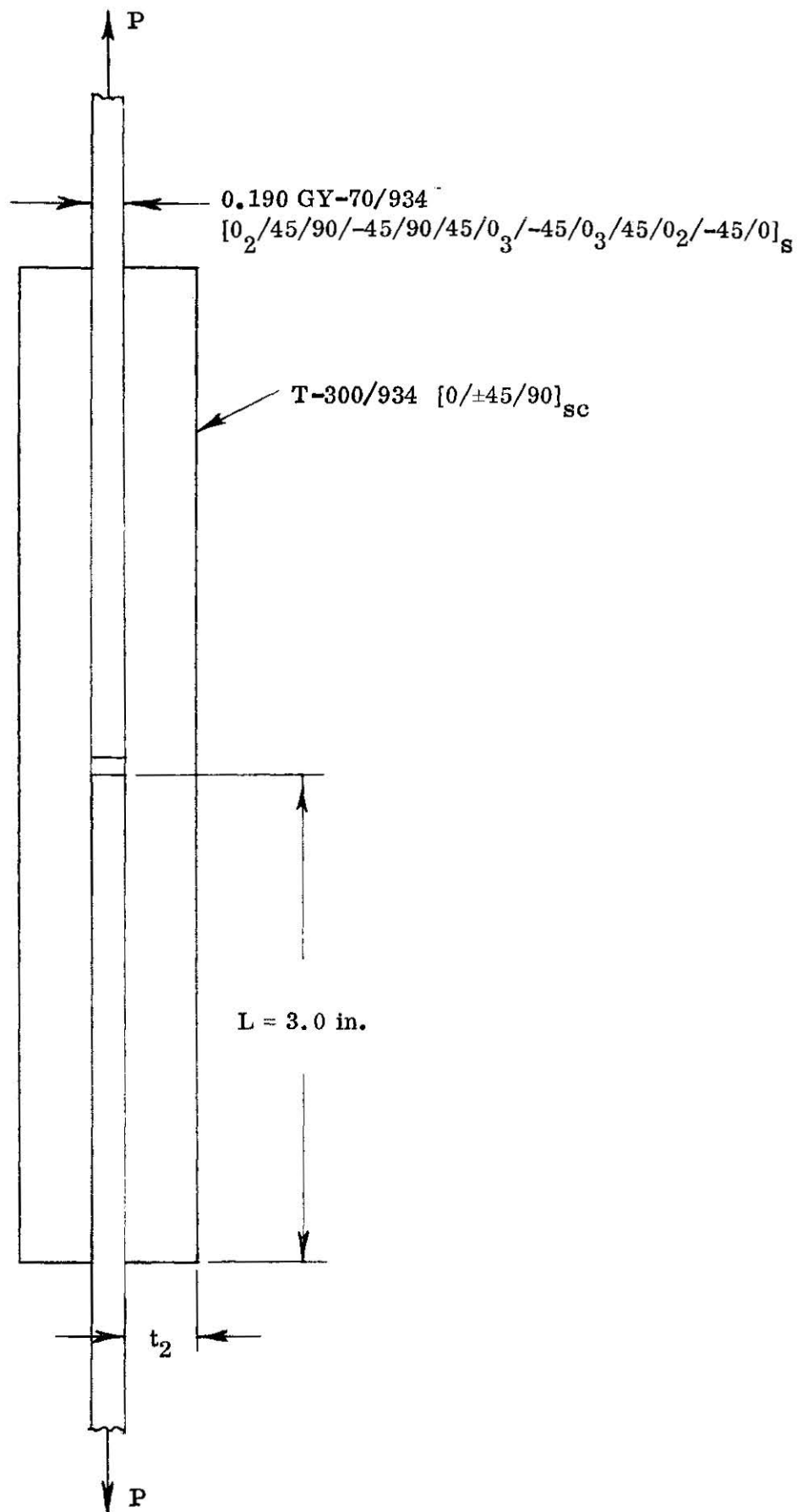


Figure 3-2. Simulated Double Lap Joint for Ring

Element 1

GY-70/934 (325F)

$$E_1 = 24 \times 10^6 \text{ psi}$$

$$G_1 = G_{12} = 0.55 \times 10^6 \text{ psi (interlaminar G)}$$

$$t_1 = 0.19 \text{ in.}$$

[Judgment based on
known corrections
for T-300/934
graphite/epoxy]

Element 2

T-300/934 (325F)

$$E_{11}^t = 21.4 \times 10^6 \text{ psi (Reference 2)}$$

$$E_2 \approx 0.4 E_{11}^t \approx 0.4 \times 21.4 \times 10^6 \approx 8.5 \times 10^6 \text{ psi}$$

$$G_2 = G_{12} = 0.43 \times 10^6 \text{ psi (interlaminar G) (Reference 2)}$$

$$t_2 = 0.45 \text{ in.}$$

Adhesive (325F)

$$G_a = 26,400 \text{ psi (Reference 3)}$$

$$t_a = 0.004 \text{ in.}$$

Load

$$P = 2 N_{\text{axial}} = 2 \times 350 = 700 \text{ lb/in}$$

Maximum Shear Stress (see Section 3.1)

$$\begin{aligned} K^2 &= \frac{\left[\frac{1}{t_2 E_2} + \frac{2}{t_1 E_1} \right]}{\left[\frac{t_1}{4G_1} + \frac{t_a}{G_a} + \frac{t_2}{2G_2} \right]} \\ &= \frac{\left[\frac{1}{0.45 \times 8.5 \times 10^6} + \frac{2}{0.19 \times 24 \times 10^6} \right]}{\left[\frac{0.19}{4 \times 0.55 \times 10^6} + \frac{0.004}{26,400} + \frac{0.45}{2 \times 0.43 \times 10^6} \right]} \\ &= 0.920 \text{ in}^{-2} \\ K &= 0.960 \text{ in}^{-1} \\ N &= \frac{2E_2 t_2}{E_1 t_1} = \frac{2 \times 8.5 \times 10^6 \times 0.45}{24 \times 10^6 \times 0.19} = 1.67 \\ \tau_{\max} &= \frac{K}{N + 1} \left[\frac{1 + N \cosh KL}{\sinh KL} \right] \left(\frac{P}{2w} \right) \\ &= \frac{0.96}{1.67 + 1} \left[\frac{1 + 1.67 \cosh (0.96 \times 3)}{\sinh (0.96 \times 3)} \right] \frac{700}{2 \times 1} \\ &= 226 \text{ psi} \end{aligned}$$

Maximum Shear Stress (VQ/I)

$$\begin{aligned} q_{\max}^V &= 446 \text{ lb/in} \\ \tau_{\max}^V &= q_{\max}^V / L = 446/3 = 149 \text{ psi} \end{aligned}$$

Resultant Maximum Shear

$$\tau_{\max}^R = \sqrt{226^2 + 149^2} = 270 \text{ psi}$$

Maximum Interlaminar Tension

$$M = N_{\text{axial}} \times 0.25 = 350 \times 0.25 = 88 \text{ in-lb}$$

$$\sigma^{\text{it}} = \frac{6M}{L^2} = \frac{6 \times 88}{3^2} = 59 \text{ psi}$$

Average Shear (N_a/L)

$$\tau_{\text{avg}} = N_a/L = 350/3 = 117 \text{ psi}$$

Resultant Average Shear

$$\tau_{\text{avg}}^{\text{R}} = \sqrt{117^2 + 149^2} = 189 \text{ psi}$$

Margin of Safety Based on τ_{max} Plus σ^{it}

The curves of Figure 3-7, Section 3.1 were used for values of τ_{max} . From the meager data available the following procedure is employed:

Find τ_{max} for L equal to two inches and use for the three-inch length of the ring, which is conservative. As shown in Section 3.1, the GY-70/934 is much weaker than the T-300/934 at room temperature. Thus, using the data shown, including the 325F data for T-300/934, estimate τ_{max} for GY-70/934 at 325F.

T-300/934

$$\tau_{\text{max}} (\text{RT}) = 8300 \text{ psi (Section 3.1, Figure 3-7)}$$

$$\tau_{\text{max}} (325\text{F}) = 4300 \text{ psi (Section 3.1, Figure 3-7)}$$

$$R (\text{T-300})_{\text{max}} = \frac{\tau_{\text{max}} (325\text{F})}{\tau_{\text{max}} (\text{RT})}$$

$$= \frac{4300}{8300} = 0.518$$

GY-70/934

$$\tau_{\max} (\text{RT}) = 2950 \text{ psi (Section 3.1, Figure 3-7)}$$

$$\tau_{\max} (325\text{F}) \approx R (\text{T-300})_{\max} \tau_{\max} (\text{RT})$$

$$\approx 0.518 \times 2950 \approx 1528 \text{ psi}$$

$$R_s = \frac{\tau_{\max}^{\text{R}}}{\tau_{\max}} = \frac{270}{1528} = 0.177 \text{ (shear stress ratio)}$$

$$\sigma_{\text{avg}}^{\text{itu}} = 1384 \text{ psi (see Section 3.2)}$$

$$R_t = \frac{\sigma^{\text{it}}}{\sigma_{\text{avg}}^{\text{itu}}} = \frac{59}{1384} = 0.043 \text{ (tension stress ratio)}$$

$$\text{M. S.} = \frac{1}{R_s + R_t} - 1 = \frac{1}{0.177 + 0.043} - 1 = 3.5$$

Margin of Safety Based on τ_{avg} Plus σ^{it}

The procedure followed is similar to that presented above using Figure 3-8 of Section 3.1.

T-300/934

$$\tau_{\text{avg}} (\text{RT}) = 1000 \text{ psi (Section 3.1, Figure 3-8)}$$

$$\tau_{\text{avg}} (325\text{F}) = 600 \text{ psi (Section 3.1, Figure 3-8)}$$

$$R (\text{T-300})_{\text{avg}} = \frac{\tau_{\text{avg}} (325\text{F})}{\tau_{\text{avg}} (\text{RT})}$$

$$= \frac{600}{1000} = 0.6$$

GY-70/934

$$\tau_{avg} (RT) = 1250 \text{ psi (Section 3.1, Figure 3-8)}$$

$$\tau_{avg} (325F) \approx R (T-300)_{avg} \tau_{avg}$$

$$\approx 0.6 \times 1250 = 750 \text{ psi}$$

$$R_s = \frac{\tau_{avg}^R}{\tau_{avg}} = \frac{189}{750} = 0.250$$

$$R_t = 0.043 \text{ (Reference page 3-8)}$$

$$M. S. = \frac{1}{R_s + R_t} - 1 = \frac{1}{0.250 + 0.043} - 1 = 2.38$$

The bonded ring analyzed by the methods presented in Section 3.1, one based on τ_{max} and the other based on τ_{avg} , resulted in margins of safety greater than 2 with both methods. Therefore, it can safely be assumed that the ring as shown in Figure 3-1 will certainly carry the loads, provided the same quality of bond is attained as those in the test specimens.

3.1 ANALYSIS OF ADHESIVELY BONDED GRAPHITE/EPOXY SINGLE AND DOUBLE LAP SHEAR TESTS

The average shear stress obtained from a bonded joint shear test is directly applicable to a design only if the overlap shear lengths are identical. Accordingly, it is desirable to know the maximum shear stress from a test of some overlap length, and then compare the maximum shear stress in the design with the same or some other overlap length. Of course, the adherend thicknesses of the test specimen and the design will most likely be quite different. On the other hand, the adhesive thickness will probably be nearly the same in both instances, probably around 0.004-0.005 inch. Five different series of bonded joint tests were considered, and are designated as A through E tests.

3.1.1 ANALYSIS METHOD. To accomplish the goal expressed previously, it is expedient to use the double lap bonded joint shear equations of Demarkles (Reference 4).

$$\tau_{max} = \frac{K}{N + 1} \left[\frac{1 + N \cosh KL}{\sinh KL} \right] \left(\frac{P}{2w} \right) \quad (1)$$

$$K^2 = \frac{\left[\frac{1}{t_2 E_2} + \frac{2}{t_1 E_1} \right]}{\left[\frac{t_1}{4G_1} + \frac{t_a}{G_a} = \frac{t_2}{2G_2} \right]} \quad (2)$$

$$N = \frac{2E_2 t_2}{E_1 t_1} \quad (3)$$

for the joint shown in Figure 3-3, where

E_1, E_2 = Extensional moduli of elasticity in direction of P

G_1, G_2 = Interlaminar shear moduli of rigidity, approximately equal to G_{UD} (shear modulus of unidirectional laminate)

G_a = Shear modulus of rigidity of adhesive

K = Joint constant

L = Bond length

t_1, t_2 = Thicknesses

t_a = Thickness of adhesive

P = Test Load

w = Width

τ = Shear stress

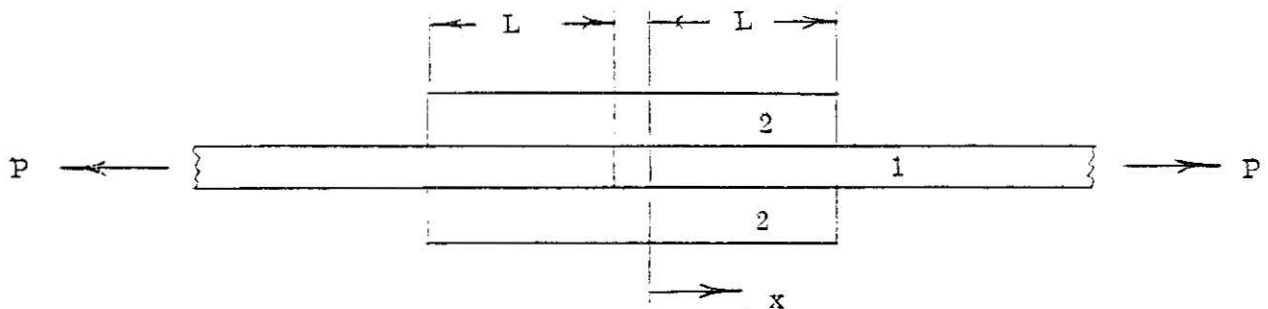


Figure 3-3. Double Lap Bonded Joint Test Specimen

Also shown in Reference 4 is the equation for shear stress at any location in the form

$$\tau = \frac{K}{N+1} \left[\frac{N \cosh Kx + \cosh K(L-x)}{\sinh KL} \right] \left(\frac{P}{2w} \right) \quad (4)$$

and the optimum length of bond should be

$$L_e \geq 4.2/K \quad (\text{Reference 5}) \quad (5)$$

where L_e is called the effective joint length.

It should be noted that Eq 4 results in the maximum shear stress at either $x = 0$, or $x = L$, which is inconsistent with the general belief that the shear stress actually drops to zero at $x = 0$, L and increases rapidly from there to the maximum. Equation 1 was obtained from Eq 4 where $x = L$. It is believed by the author that the presence of this possible error in Demarkles' equations is academic provided both the test results and the design are analyzed by these same equations. Consequently, τ_{\max} as defined here can be considered as merely a parameter that has a real relationship to the actual maximum shear stress and is very close in magnitude.

A TESTS — EA 9309 ADHESIVE

This series of five tests employed 0.004-0.005 inch EA9309 adhesive, 0.22 inch thick GY-70/X-30 graphite/epoxy (element 1), and 0.25 inch thick aluminum alloy plates (elements 2). The length of bond L was 1.5 inches and the width w was 1.0 inch. Failure loads for the five tests were 6130, 6775, 7600, 6750, and 6325 pounds, which gave an average load of

$$P_{\text{avg}} = 6700 \text{ lb}$$

All failures were in the GY-70 laminate, not in the bond.

Material Properties

Aluminum alloy:

$$E = 10^7 \text{ psi}$$

$$G = 3.9 \times 10^6 \text{ psi}$$

GY-70/X-30 Graphite/Epoxy:

$$\left[(0/40/90/140)_2 \right]_{s3}, t = 0.22 \text{ in.}$$

$$\left. \begin{aligned} E_{11} &= 40.7 \times 10^6 \\ G_{12} &= 0.95 \times 10^6 \text{ psi} \end{aligned} \right\} \text{UD}$$

$$E_1 \approx 0.4 E_{11} \approx 0.4 \times 40.7 \times 10^6 \approx 16.3 \times 10^6 \text{ psi}$$

$$G_1 = G_{12} = 0.95 \times 10^6 \text{ psi (interlaminar G)}$$

EA9309 Adhesive (General Dynamics Test Data)

$$E_{\text{initial}} = 447,000 \text{ psi}$$

$$\nu_{\text{initial}} = 0.369$$

$$G_{\text{initial}} = \frac{E}{2(1 + \nu)} = \frac{447,000}{2(1 + 0.369)} = 163,250 \text{ psi}$$

$$\left. \begin{aligned} E_{\text{sec}} &= 341,000 \text{ psi} \\ \nu_{\text{sec}} &= 0.344 \end{aligned} \right\} \text{At failure in Test}$$

$$G_{\text{sec}} = \frac{E}{2(1 + \nu)} = \frac{341,000}{2(1 + 0.344)} = 126,860 \text{ psi}$$

To minimize K and subsequently τ_{max} from test data, the value for G_a should be equivalent to G_{sec} of the adhesive.

Analysis

The values for the terms used in Eq 1, 2, 3 are

$$E_1 = 16.3 \times 10^6 \text{ psi}$$

$$G_1 = 0.95 \times 10^6 \text{ psi}$$

$$t_1 = 0.22 \text{ in.}$$

$$E_2 = 10^7 \text{ psi}$$

$$G_2 = 3.9 \times 10^6 \text{ psi}$$

$$t_2 = 0.25 \text{ in.}$$

$$G_a = 126,860 \text{ psi}$$

$$t_a = 0.0045 \text{ in.}$$

$$L = 1.5 \text{ in.}$$

$$w = 1.0 \text{ in.}$$

$$P = 6700 \text{ lb}$$

By substituting the above values in Eq 2, one obtains

$$K^2 = \frac{\left[\frac{1}{0.25 \times 10^7} + \frac{2}{0.22 \times 16.3 \times 10^6} \right]}{\left[\frac{0.22}{4 \times 0.95 \times 10^6} + \frac{0.0045}{126,860} + \frac{0.25}{2 \times 3.9 \times 10^6} \right]}$$

$$= 7.625 \text{ in}^{-2}$$

$$K = 2.76 \text{ in}^{-1}$$

The value for N from Eq 3 becomes

$$N = \frac{2 \times 10^7 \times 0.25}{16.3 \times 10^6 \times 0.22} = 1.394$$

The maximum shear stress as found by the use of Eq 1 is

$$\tau_{\max} = \left[\frac{276}{1.394 + 1} \right] \left[\frac{1 + 1.394 \cosh (2.76 \times 1.5)}{\sinh (2.76 \times 1.5)} \right] \left(\frac{6700}{2 \times 1} \right)$$

$$= 5509 \text{ psi}$$

The average shear stress is

$$\tau_{\text{avg}} = 6700/2 (1.5 \times 1) = 2230 \text{ psi}$$

B TESTS — EA934 ADHESIVE

This series of three tests employed 0.004 inch EA934 adhesive cured at 150F for two hours and 0.28 inch thick by 0.88 inch wide GY-70/934 graphite/epoxy plates. The tests were actually single overlap shear joints but the composite plates were thick and double thickness was provided in both grips by using aluminum plates as shown in Figure 3-4, thus minimizing peel stresses. The results of these three tests may be conservatively analyzed by the use of Eq 1 to determine the maximum shear stress at failure. A sketch of the test specimen is shown in Figure 3-4, where the phantom lines create a fictitious double lap shear test for use of Eq 1, 2, and 3. The total section can be used for analysis, where the load P becomes twice the test load. The test results are presented in Table 3-1.

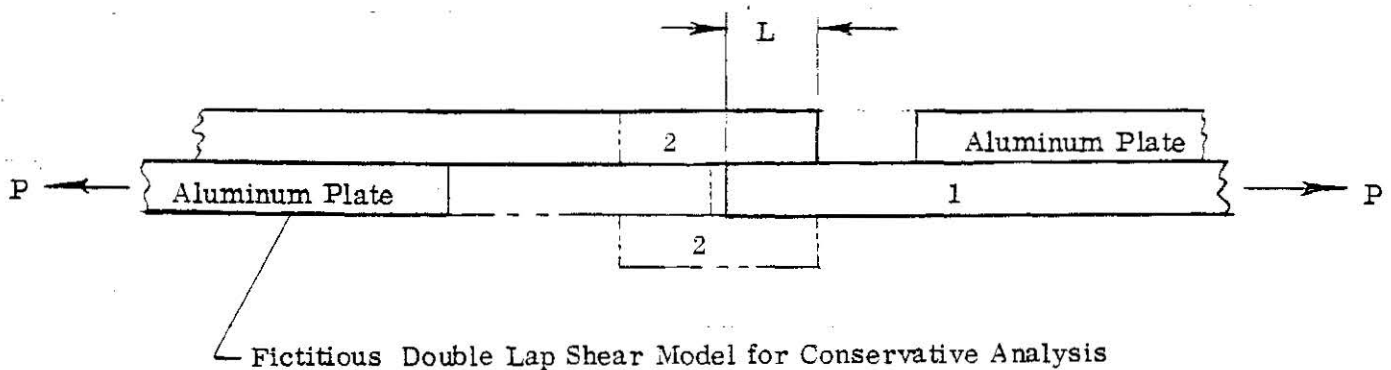


Figure 3-4. Single Lap Shear Test Specimen

Table 3-1. Single Lap Shear Test Results

ID	L (in.)	w (in.)	P (lb)	Failure
B1	0.53	0.88	1500	Interlaminar
B2	0.53	0.88	1440	Interlaminar
B3	2.0	0.92	2275	Interlaminar

Material Properties

GY-70/934 Graphite/Epoxy:

$$\left[0_{14}, 45_{10}, -45_{10}, 90_{10}, 60_4, -60_4 \right]_C$$

$$\left. \begin{aligned} E_{11} &= 40.7 \times 10^6 \text{ psi} \\ G_{12} &= 0.95 \times 10^6 \text{ psi} \end{aligned} \right\} \text{UD}$$

$$E_1 = 14.7 \times 10^6 \text{ psi (lamination theory)}$$

$$G_1 = G_{12} = 0.95 \times 10^6 \text{ psi (interlaminar G)}$$

EA934 Adhesive (General Dynamics Test Data)

$$E_{\text{initial}} = 768,000 \text{ psi}$$

$$\nu_{\text{initial}} = 0.375$$

$$G_{\text{initial}} = \frac{E}{2(1 + \nu)} = \frac{768,000}{2(1 + 0.375)} = 279,000 \text{ psi}$$

$$\left. \begin{aligned} E_{\text{sec}} &= 590,000 \text{ psi} \\ \nu_{\text{sec}} &= 0.343 \end{aligned} \right\} \text{At Failure in Test}$$

$$G_{\text{sec}} = \frac{E}{2(1 + \nu)} = \frac{590,000}{2(1 + 0.343)} = 220,000 \text{ psi}$$

Analysis

The values for the terms used in Eq 1, 2, 3 are

$$E_1 = E_2 = 14.7 \times 10^6 \text{ psi}$$

$$G_1 = G_2 = 0.95 \times 10^6 \text{ psi}$$

$$t_1 = t_2 = 0.28 \text{ in.}$$

$$G_a = 220,000 \text{ psi}$$

$$t_a = 0.004 \text{ in.}$$

$$L = 0.53 \text{ in.}$$

$$w = 0.88 \text{ in.}$$

Test loads for analysis

$$P_{B1} = 2 \times 1500 = 3000 \text{ lb}$$

$$P_{B2} = 2 \times 1440 = 2880 \text{ lb}$$

$$P_{B3} = 2 \times 2275 = 4550 \text{ lb}$$

$$K^2 = \frac{\left[\frac{1}{0.28 \times 14.7 \times 10^6} + \frac{2}{0.28 \times 14.7 \times 10^6} \right]}{\left[\frac{0.28}{4 \times 0.95 \times 10^6} + \frac{0.004}{220,000} + \frac{0.28}{2 \times 0.95 \times 10^6} \right]}$$

$$= 3.035 \text{ in}^{-2}$$

$$K = 1.742 \text{ in}^{-1}$$

The value for N from Eq 3 becomes

$$N = \frac{2 \times 14.7 \times 10^6 \times 0.28}{14.7 \times 10^6 \times 0.28} = 2$$

Maximum and Average Shear in Test B1:

$$\tau_{\max} = \frac{1.742}{2+1} \left[\frac{1 + 2 \cosh (1.742 \times 0.53)}{\sinh (1.742 \times 0.53)} \right] \left(\frac{3000}{2 \times 0.88} \right)$$
$$= 3655 \text{ psi}$$

$$\tau_{\text{avg}} = 1500 / (0.53 \times 0.88) = 3215 \text{ psi}$$

Maximum and Average Shear in Test B2:

$$\tau_{\max} = \frac{1.742}{2+1} \left[\frac{1 + 2 \cosh (1.742 \times 0.53)}{\sinh (1.742 \times 0.53)} \right] \left(\frac{2880}{2 \times 0.88} \right)$$
$$= 3510 \text{ psi}$$

$$\tau_{\text{avg}} = 1440 / (0.53 \times 0.88) = 3085 \text{ psi}$$

Maximum and Average Shear in Test B3:

$$\tau_{\max} = \frac{1.742}{2+1} \left[\frac{1 + 2 \cosh (1.742 \times 2.0)}{\sinh (1.742 \times 2.0)} \right] \left(\frac{4550}{2 \times 0.92} \right)$$
$$= 2970 \text{ psi}$$

$$\tau_{\text{avg}} = 2275 / (2 \times 0.92) = 1235 \text{ psi}$$

C TESTS - EA934 ADHESIVE

Two series of double lap shear tests were performed as shown in Figure 3-5. The results are presented in Table 3-2.

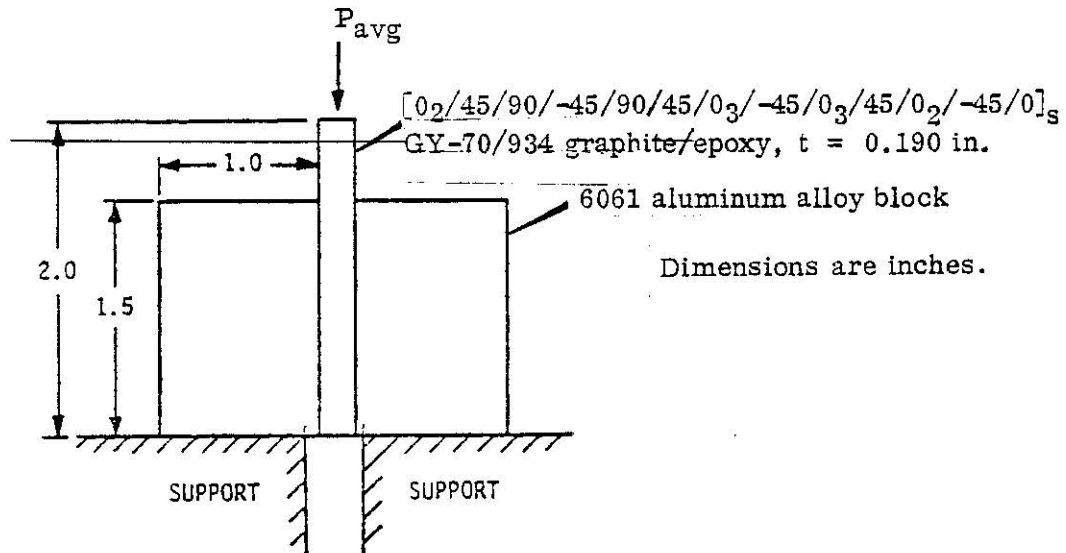


Figure 3-5. Double Lap Shear Bonded Joint Test Specimen

Table 3-2. Double Lap Shear Test Results

ID	Surface Fibers	No. Tests	P _{avg} (lb)	Failure
C1	Parallel to Load	4	6050	Interlaminar
C2	Perpendicular to Load	4	4360	Interlaminar

C1 TESTS

Material Properties

Aluminum alloy:

$$E_2 = 10^7 \text{ psi}$$

$$G_2 = 3.9 \times 10^7 \text{ psi}$$

$$t_2 = 1.0 \text{ in.}$$

GY-70/934 graphite/epoxy:

$$E_1 = 26 \times 10^6 \text{ psi}$$

$$G_1 = G_{12} = 0.95 \times 10^6 \text{ psi (interlaminar G)}$$

$$t_1 = 0.19 \text{ in.}$$

EA934 adhesive:

$$G_a = 220,000 \text{ psi}$$

$$t_a = 0.005 \text{ in. (known)}$$

Analysis

$$L = 1.5 \text{ in.}$$

$$w = 1.0 \text{ in.}$$

$$P = 6050 \text{ lb}$$

$$K^2 = \frac{\left[\frac{1}{1.0 \times 10^7} + \frac{2}{0.19 \times 26 \times 10^6} \right]}{\left[\frac{0.19}{4 \times 0.95 \times 10^6} + \frac{0.005}{220,000} + \frac{1.0}{2 \times 3.9 \times 10^6} \right]}$$

$$= 2.514 \text{ in}^{-2}$$

$$K = 1.585 \text{ in}^{-1}$$

$$N = \frac{2 \times 10^7 \times 1.0}{26 \times 10^6 \times 0.19} = 4.049$$

$$\tau_{\max} = \frac{1.585}{4.049 + 1} \left[\frac{1 + 0.049 \cosh (1.585 \times 1.5)}{\sinh (1.585 \times 1.5)} \right] \left(\frac{6050}{2 \times 1} \right)$$

$$= 4091 \text{ psi}$$

$$\tau_{\text{avg}} = 6050/2(1.5 \times 1) = 2017 \text{ psi}$$

C2 TESTS

Material Properties

Aluminum alloy: same as for C1 tests

GY-70/934 graphite/epoxy:

$$E_1 = 8.1 \times 10^6 \text{ psi}$$

$$G_1 = 0.95 \times 10^6 \text{ psi}$$

$$t_1 = 0.19 \text{ in}$$

EA934 adhesive: same as for C1 tests

Analysis

$$L = 1.5 \text{ in.}$$

$$w = 1.0 \text{ in.}$$

$$P = 4360 \text{ lb}$$

$$K^2 = \frac{\left[\frac{1}{1.0 \times 10^7} + \frac{2}{0.19 \times 8.1 \times 10^6} \right]}{\left[\frac{0.19}{4 \times 0.95 \times 10^6} + \frac{0.005}{220,000} + \frac{1.0}{2 \times 3.9 \times 10^6} \right]}$$

$$= 6.969 \text{ in}^{-2}$$

$$K = 2.640 \text{ in}^{-1}$$

$$N = \frac{2 \times 10^7 \times 1.0}{8.1 \times 10^6 \times 0.19} = 13.0$$

$$\tau_{\max} = \frac{2.640}{13 + 1} \left[\frac{1 + 13 \cosh (2.640 \times 1.5)}{\sinh (2.640 \times 1.5)} \right] \left(\frac{4360}{2 \times 1} \right)$$

$$= 5365 \text{ psi}$$

$$\tau_{\text{avg}} = 4360/2(1.5 \times 1) = 1453 \text{ psi}$$

D TESTS - EA934 ADHESIVE

This series of tests was double lap shear similar to that shown in Figure 3-3. The adhesive used was 0.004 inch EA934 cured at 150F for two hours. Both members (1 and 2) were T-300/934 [0/±45/90]_S, where the ply thickness was 0.010 inch. The measured thickness of these plates was 0.084 inch. The test results are presented in Table 3-3.

Table 3-3. Double Lap Shear Test Results

ID	L (in.)	w (in.)	P (lb)	Failure
D1a	0.99	1.00	2960	Interlaminar
D1b	1.00	1.00	2850	Interlaminar
D2a	2.00	1.00	3840	Interlaminar
D2b	1.98	1.00	4245	Interlaminar

Material Properties

T-300/934 Graphite/Epoxy:

$$\left. \begin{aligned} E_{11}^t &= 22.8 \times 10^6 \text{ psi} \\ G_{12} &= 0.74 \times 10^6 \text{ psi} \end{aligned} \right\} \text{UD}$$

$$E_1 = E_2 \approx 0.4 E_{11} \approx 0.4 \times 22.8 \times 10^6 \text{ psi} \approx 9.1 \times 10^6 \text{ psi}$$

$$G_1 = G_2 = G_{12} = 0.74 \times 10^6 \text{ psi (interlaminar G)}$$

$$t_1 = t_2 = 0.084 \text{ in.}$$

EA934 Adhesive:

$$G_a = 220,000 \text{ psi}$$

$$t_a = 0.004 \text{ in.}$$

Analysis

$$K^2 = \frac{\left[\frac{1}{0.084 \times 9.1 \times 10^6} + \frac{2}{0.084 \times 9.1 \times 10^6} \right]}{\left[\frac{0.084}{4 \times 0.74 \times 10^6} + \frac{0.004}{220,000} + \frac{0.084}{2 \times 0.74 \times 10^6} \right]}$$

$$= 38.0 \text{ in}^{-2}$$

$$K = 6.16 \text{ in}^{-1}$$

$$N = \frac{2 \times 9.1 \times 10^6 \times 0.084}{9.1 \times 10^6 \times 0.084} = 2$$

Maximum and Average Shear in D1 Tests:

$$\tau_{\max} = \frac{6.16}{2+1} \left[\frac{1 + 2 \cosh (6.16 \times 1.0)}{\sinh (6.16 \times 1.0)} \right] \left(\frac{P}{2 \times 1} \right)$$

$$= 2.06 P \text{ in}^{-1}$$

D1a Test

$$\tau_{\max} = 2.06 \times 2960 = 6100 \text{ psi}$$

$$\tau_{\text{avg}} = 2960/2(1 \times 0.99) = 1495 \text{ psi}$$

D1b Test

$$\tau_{\max} = 2.06 \times 2850 = 5870 \text{ psi}$$

$$\tau_{\text{avg}} = 2850/2(1 \times 1) = 1425 \text{ psi}$$

Maximum and Average Shear in D2 Tests:

$$\tau_{\max} = \frac{6.16}{2+1} \left[\frac{1 + 2 \cosh (6.16 \times 2.0)}{\sinh (6.16 \times 2.0)} \right] \left(\frac{P}{2 \times 1} \right)$$

$$= 2.05 P \text{ in}^{-2}$$

D2a Test

$$\tau_{\max} = 2.05 \times 3840 = 7870 \text{ psi}$$

$$\tau_{\text{avg}} = 3840/2(2 \times 1) = 960 \text{ psi}$$

D2b Test

$$\tau_{\max} = 2.05 \times 4245 = 8700 \text{ psi}$$

$$\tau_{\text{avg}} = 4245/2(1.98 \times 1) = 1070 \text{ psi}$$

E TESTS — EA934 ADHESIVE

This series of tests was similar to the D tests, except that the test temperature was raised to 325F within about two minutes of applied heat exposure before the load is applied. The test results are presented in Table 3-4.

Table 3-4. Double Lap Shear Test Results

ID	L _{min} (in.)	w (in.)	P (lb)	Time to Reach 325F (min)	Failure
E1a	0.95	1.00	910	2	Adhesive
E1b	0.98	1.00	915	2	Adhesive
E2a	1.98	1.00	1310	5*	Adhesive
E2b	1.98	1.00	1110	2	Adhesive

*Caused by failure in fixture; test was repeated.

Material Properties at 325F

T-300/934 Graphite/Epoxy:

$$\left. \begin{aligned} E_{11}^t &= 21.4 \times 10^6 \text{ psi} \\ G_{12} &= 0.43 \times 10^6 \text{ psi} \end{aligned} \right\} \text{UD (Reference 2)}$$

$$E_1 = E_2 \approx 0.4 E_{11} \approx 0.4 \times 21.4 \times 10^6 = 8.56 \times 10^6 \text{ psi}$$

$$G_1 = G_2 = G_{12} = 0.43 \times 10^6 \text{ psi (interlaminar G)}$$

$$t_1 = t_2 = 0.084 \text{ in.}$$

EA 934 Adhesive

$$G_a \approx 0.12 G_a \text{ (RT)} = 0.12 \times 220,000 = 26,400 \text{ psi (Reference 3)}$$

$$t_a = 0.004 \text{ in.}$$

Analysis

$$K^2 = \frac{\left[\frac{1}{0.084 \times 8.56 \times 10^6} + \frac{2}{0.084 \times 8.56 \times 10^6} \right]}{\left[\frac{0.084}{4 \times 0.43 \times 10^6} + \frac{0.004}{26,400} + \frac{0.084}{2 \times 0.43 \times 10^6} \right]}$$

$$= 139.93 \text{ in}^{-2}$$

$$K = 11.83 \text{ in}^{-1}$$

$$N = \frac{2 \times 8.56 \times 10^6 \times 0.084}{8.56 \times 10^6 \times 0.084} = 2$$

Maximum and Average Shear in E1 Tests:

$$\begin{aligned} \tau_{\max} &= \frac{11.83}{2+1} \left[\frac{1+2 \cosh(11.83 \times 0.97)}{\sinh(11.83 \times 0.97)} \right] \left(\frac{P}{2 \times 1} \right) \\ &= 3.94 P \text{ in}^{-2} \end{aligned}$$

E1a Test

$$\tau_{\max} = 3.94 \times 910 = 3585 \text{ psi}$$

$$\tau_{\text{avg}} = 910/2(1 \times 0.95) = 479 \text{ psi}$$

E1b Test

$$\tau_{\max} = 3.94 \times 915 = 3605 \text{ psi}$$

$$\tau_{\text{avg}} = 915/2(0.98 \times 1) = 467 \text{ psi}$$

Maximum and Average Shear in E2 Tests:

$$\begin{aligned} \tau_{\max} &= \frac{11.83}{2+1} \left[\frac{1 + 2 \cosh (11.83 \times 1.98)}{\sinh (11.83 \times 1.98)} \right] \left(\frac{P}{2 \times 1} \right) \\ &= 3.94 P \text{ in}^{-2} \end{aligned}$$

E2a Test

$$\tau_{\max} = 3.94 \times 1310 = 5161 \text{ psi}$$

$$\tau_{\text{avg}} = 1310/2 (1.98 \times 1) = 330 \text{ psi}$$

E2b Test

$$\tau_{\max} = 3.94 \times 1110 = 4373 \text{ psi}$$

$$\tau_{\text{avg}} = 1110/2 (1.98 \times 1) = 280 \text{ psi}$$

3.1.2 EVALUATION OF TEST RESULTS. For comparing the test results presented in this report, it is convenient to show the results graphically. Accordingly, the failure load (\bar{N}), the calculated maximum shear stress (τ_{\max}), and the average shear stress (τ_{avg}) are plotted versus the overlap shear length (L) in Figures 3-6, 3-7, and 3-8, respectively. All failures were interlaminar in the graphite/epoxy except for the T-300/934 tests at 325F. Consequently, if sufficient data indicates that the EA934 adhesive is weakest in a graphite/epoxy shear application at 325F, then the curves for \bar{N} or τ_{avg} shown in Figures 3-6 and 3-8, respectively, may be assumed to be approximately indicative of the joint strength. The use of Figure 3-7 for τ_{\max} does not offer such a simplified assumption for reasons unknown to the author. The "C" tests were not included in Figures 3-6 through 3-8 because the test points made no sense relative to the data shown, which may be the result of the manner of testing involved in the "C" tests. The "A" tests, which were conventional and employed the superior EA9309 adhesive, are shown for reference in Figures 3-7 and 3-8.

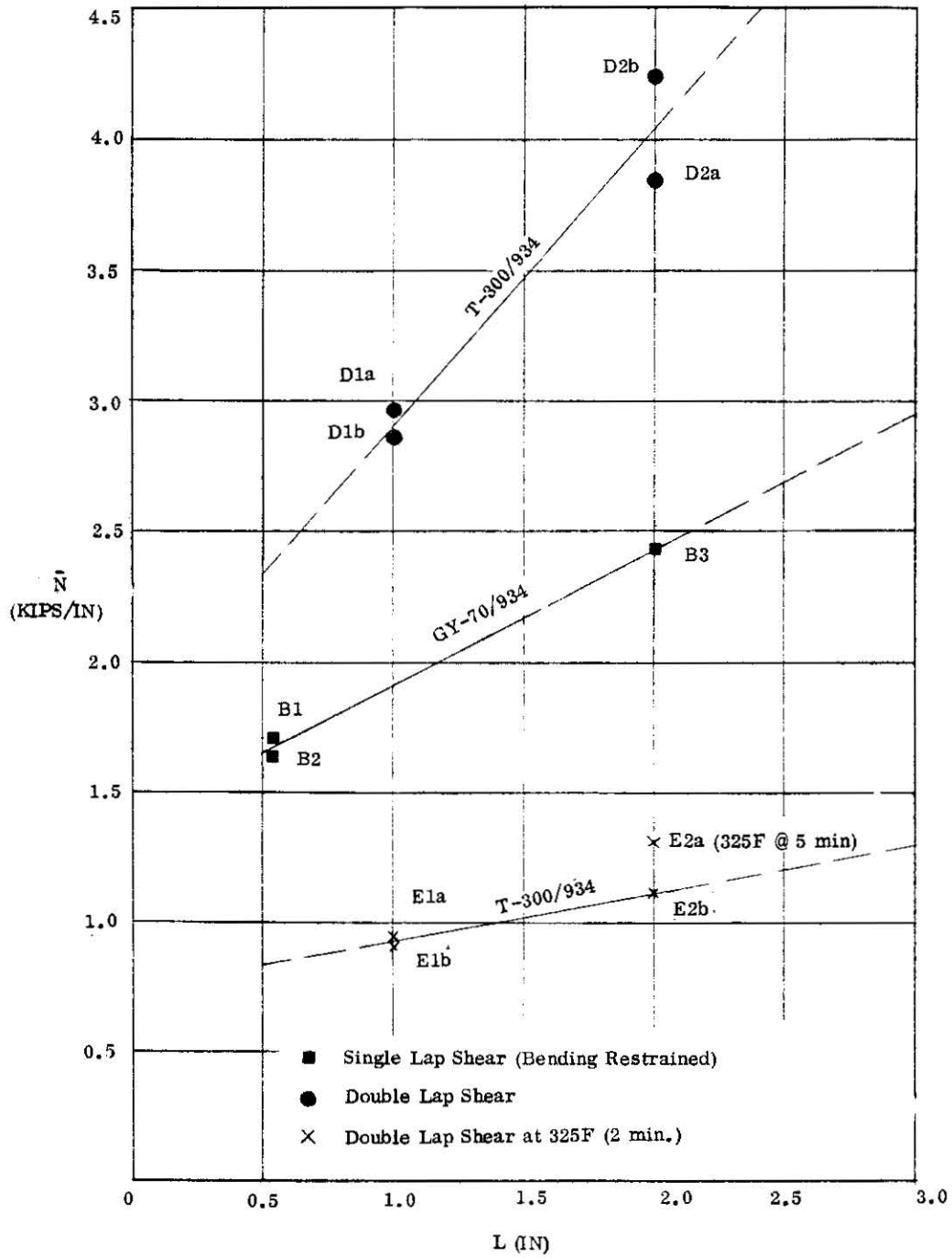


Figure 3-6. Graphite/Epoxy with 0.004 EA934 Adhesive Single and Double Lap Shear Test Loads

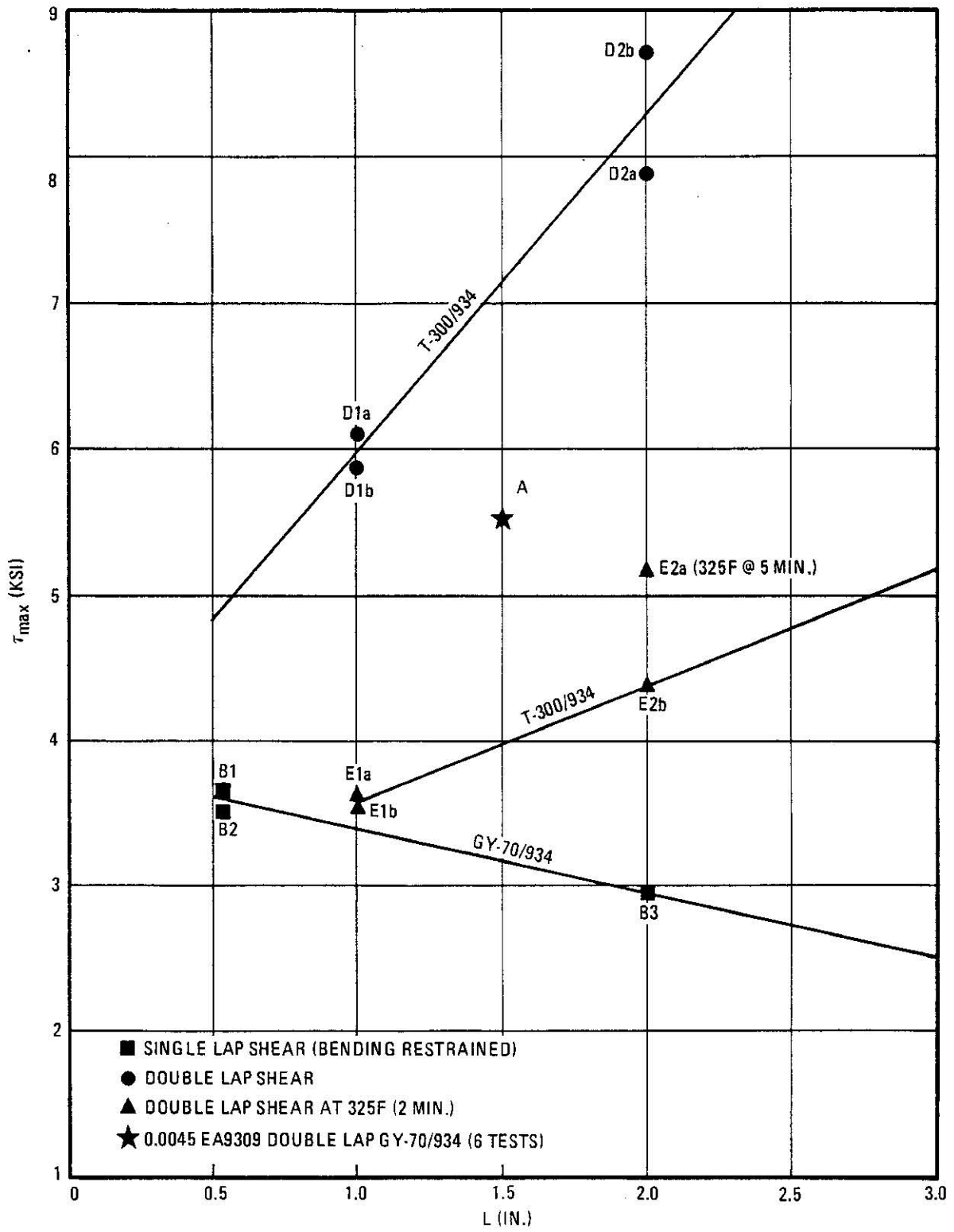


Figure 3-7. Graphite/Epoxy with 0.004 EA934 Adhesive Single and Double Lap Shear Tests, τ_{max}

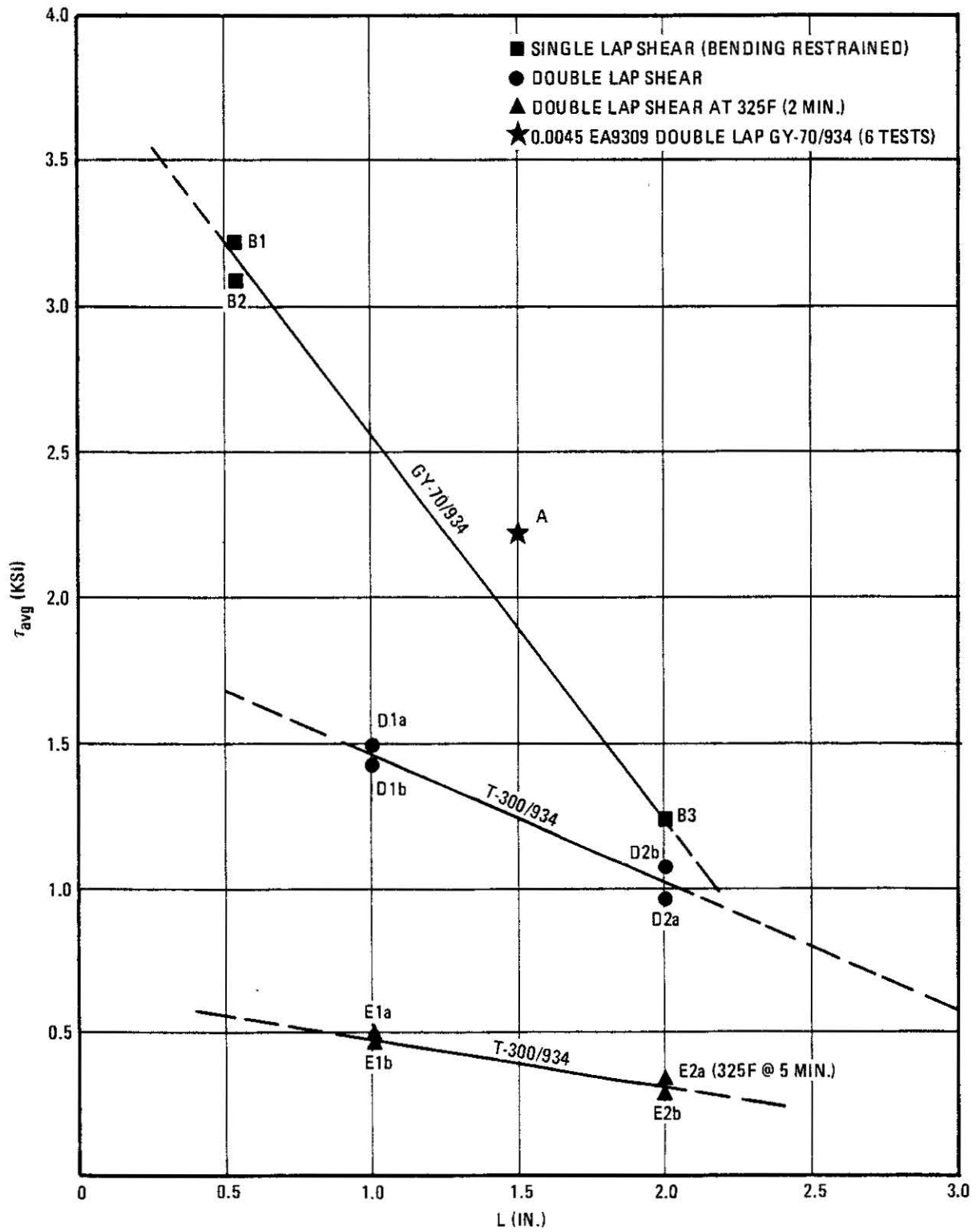


Figure 3-8. Graphite/Epoxy with 0.004 EA934 Adhesive Single and Double Lap Shear Tests, τ_{avg}

The curves shown in Figure 3-7 are not easily explained, for if τ_{\max} was an accurate value, the curves should be horizontal. Thus, it can only be concluded that τ_{\max} by the use of Eq 1 is a parameter that relates failure in a joint relative to the overlap length and the actual maximum shear stress is unknown.

An attempt has been made to correlate a promising theory for lap shear joints with test data, which was found to be an interesting approach but inconclusive in the findings. However, the study does offer some understanding of bonded joint behavior, which may enable the analyst with careful judgment to predict the approximate strength of a bonded joint where EA934 adhesive is employed. Unfortunately, there were too few tests available for the present study. Many more tests are needed to develop an analysis method that can be used with confidence.

3.2 INTERLAMINAR TENSION TESTS (T-300/934 GRAPHITE/EPOXY BONDED WITH EA934)

A series of pi-tension tests was conducted to determine interlaminar tension strength of T-300/934 graphite/epoxy joints where EA934 was used as the adhesive. The test data was used to support the design and analysis of the equipment ring (see Section 3.1). Testing was conducted at room temperature and at 325F. A sketch of a typical test is shown in Figure 3-9, and the test results are presented in Table 3-5. The tensile area, neglecting the threaded hole, is equal to pi (π). The actual net area is equal to:

$$A = \pi - \pi (0.75/2)^2 = 2.70 \text{ in}^2$$

The average interlaminar tensile values are:

Room Temperature

$$\sigma_{\text{avg}}^{\text{itu}} = 1613 \text{ psi}$$

325F

$$\sigma_{\text{avg}}^{\text{itu}} = 1384 \text{ psi}$$

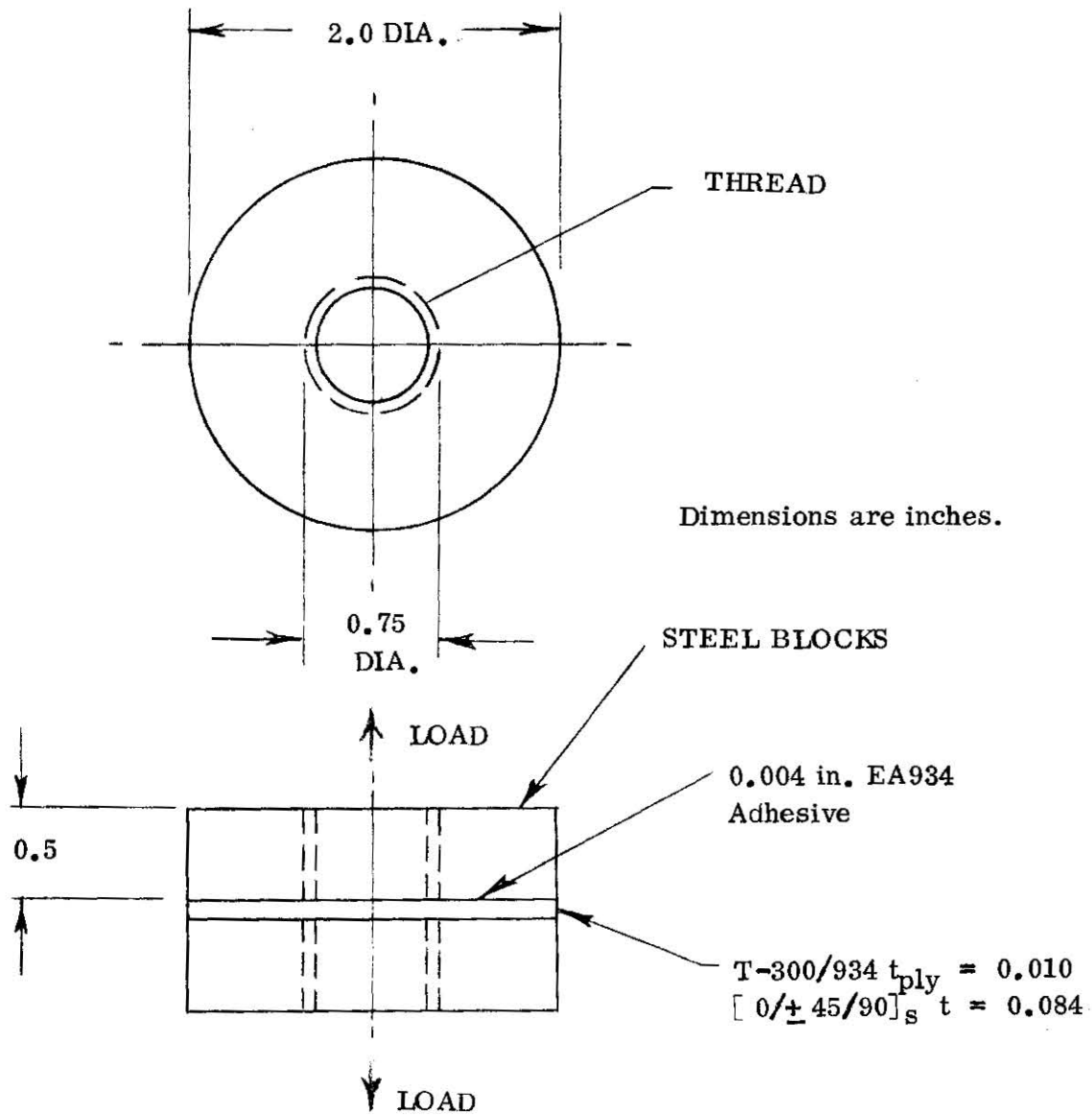


Figure 3-9. Typical Pi-Tension Test Specimen

Table 3-5. Pi-Tension Tests

ID	Temp- erature	Time to Reach 325F (min)	Load (lb)	σ^{it} (psi)	Failure
1	RT		3470	1285	Interlaminar
2	RT		4250	1574	Interlaminar
3	RT		5345	1980	Interlaminar
4	325F	3	3200	1185	Adhesive
5	325F	2	4275	1583	Thread in Steel Part

SECTION 4
SPECIMEN FABRICATION

4.1 CONE FRUSTUM

A 13.4-inch long conical frustum was prepared from HY-E-1534 (GY-70/934) prepreg using batch 4E-31 roll 7 material. The material was prepregged in November 1975, and actual fabrication of the part was the end of August 1977. The age of the material would tend to cause reduced flow and a higher average cured ply thickness. The cone size was selected by the availability of an existing bulk graphite female tool and the need to go to a size larger than the 9.3-inch long cones fabricated earlier (see Reference 6) in order to accommodate the bulkhead ring.

The cone layup was the same as that used in the earlier cones, i. e., $[0_2/45/90/-45/90/45/0_3/-45/0_3/45/0_2/-45/0]_S$. Figure 4-1 shows the bulk graphite tool used for the fabrication of the 13.4-inch long frusta. Only the conical section of the tool was used when laying up the prepreg. The cone angle for the bulk graphite tool is 4.67 degrees, whereas the cone angle for the ATI guidance and control section is 6.27 degrees. This difference in cone angles was not considered significant in evaluating the bulkhead ring and the resulting cone-ring joint.

The layup technique, ply orientations, segment wrap angle, and ply starting point were all identical to those used on the earlier cones (Reference 6). The theoretical segment dimensions were not calculated, and gore dimensions were therefore determined experimentally. Plastic templates were prepared for use in preparing cone gores, and these were then trimmed, as required, for subsequent plies. Layup procedure, debulking, and curing of the 13.4-inch long frustum was identical to that used in the preparation of the first ten 9.3-inch long cones (Reference 6).

Thickness measurements were made on both the top (small diameter) and bottom (large diameter) of the trimmed cone at planes approximately 1.5 inches from each end. Four measurements were made at each end at 90 degree intervals. The range of thickness at the top was 0.210 to 0.215 inch, with an average reading of 0.212 inch. At the bottom, the range of readings was 0.202 to 0.210 inch, with an average reading of 0.206 inch. The approximate cured ply thickness for this cone was 5.5 mils. This compares to an approximate cured ply thickness of 5.2 mils for most of the earlier cones prepared per Drawing 48126 (Reference 6).

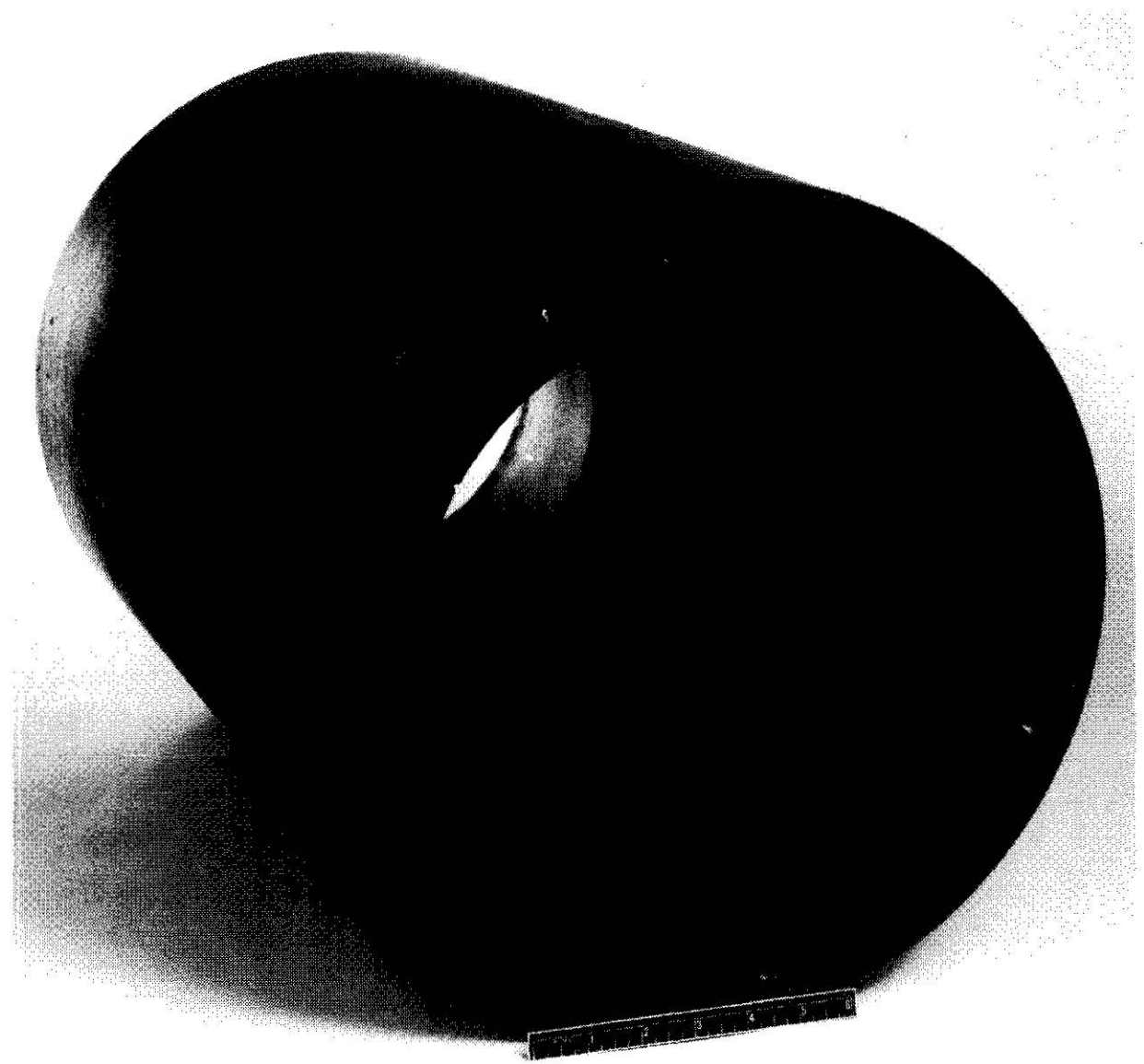


Figure 4-1. Bulk Graphite Tool

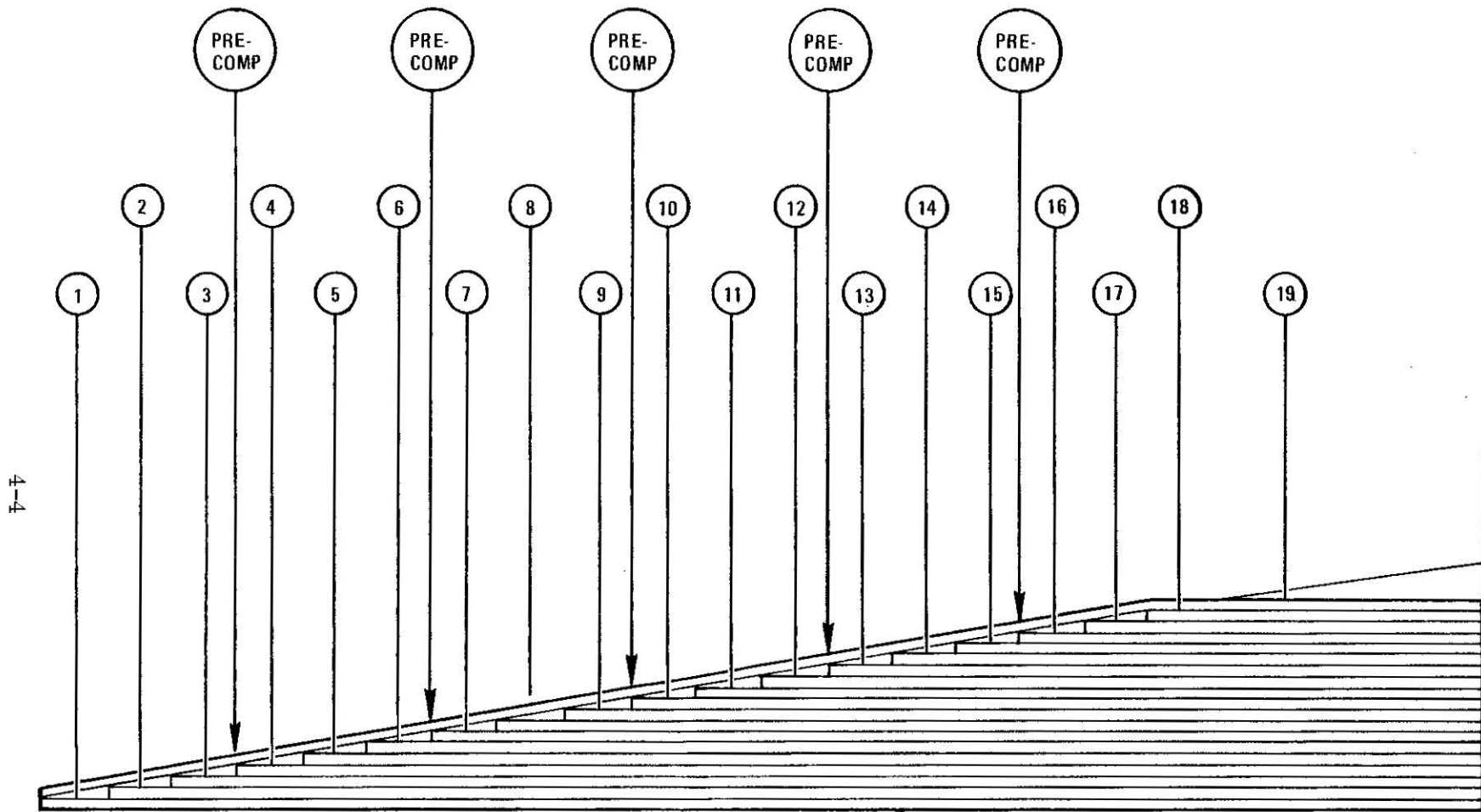
4.2 GRAPHITE/EPOXY RING

The design of the graphite/epoxy ring is shown in Figure 3-1. The material used for the ring fabrication was Fiberite Corporation's HY-E-1034E (T-300/934), batch 5B-64 roll 26. The layup was made using the same female graphite tool shown in Figure 4-1. Modules of $(0/45/-45/90)_S$ material were placed into the tool in a stepwise fashion, using 0.25 inch steps as shown in Figure 4-2, to give a total of $[(0/45/-45/90)_S]_{18}$. An additional overlay of $(0/45/-45/90)_S$ resulted in a total of 152 plies. Each ply consisted of six gore sections. The longitudinal butt joints were offset approximately 1.0 inch for each succeeding module. Five precompactions were conducted during the processing as shown in Figure 4-2. These consisted of vacuum bagging, heating to 150F, applying 50 psig autoclave pressure, and holding 15 minutes at temperature. The bleeder used for each precompaction cycle was one ply of style 181 fabric and two plies of style 1534 glass fabric.

The bleeder for the final cure was three plies of style 7781 glass fabric. The part was vacuum bagged and held in an autoclave under full vacuum at room temperature for a minimum of 30 minutes. The part temperature was raised to $250 \pm 10F$ at 2 to 4F/minute and held at temperature for 45 ± 5 minutes. Autoclave pressure of 100 ± 5 psig was applied, and the part was maintained at $250 \pm 10F$ for an additional 45 ± 5 minutes. The part temperature was raised at 2 to 4F/minute to $350 \pm 10F$ and held for a minimum of two hours at temperature. The part was cooled under vacuum and pressure to below 175F and then debagged.

The ring was trimmed to a 3.0 inch length so that the top face was approximately 0.2 inch wide. The facings of the ring and cone were flat and parallel to 0.002 inch TIR (total indicated reading). The measured dimensions for the ring are shown in Figure 4-3, and Figures 4-4 and 4-5 are photographs of the trimmed ring. Thirty MS124815 CRES helicoils were installed uniformly around the bottom face of the ring as shown in Figure 3-1. The installed helicoils are shown in Figure 4-6. The ring was bonded into the cone using Hysol's EA934 modified epoxy adhesive using a room temperature cure. Wire shims were used to control bondline thickness to approximately 0.004 inch.

The graphite/epoxy cone with bonded ring in place is shown in Figure 4-7. The graphite/epoxy cone was potted with EA934 into slotted, 1.0 inch thick aluminum end rings in preparation for test.

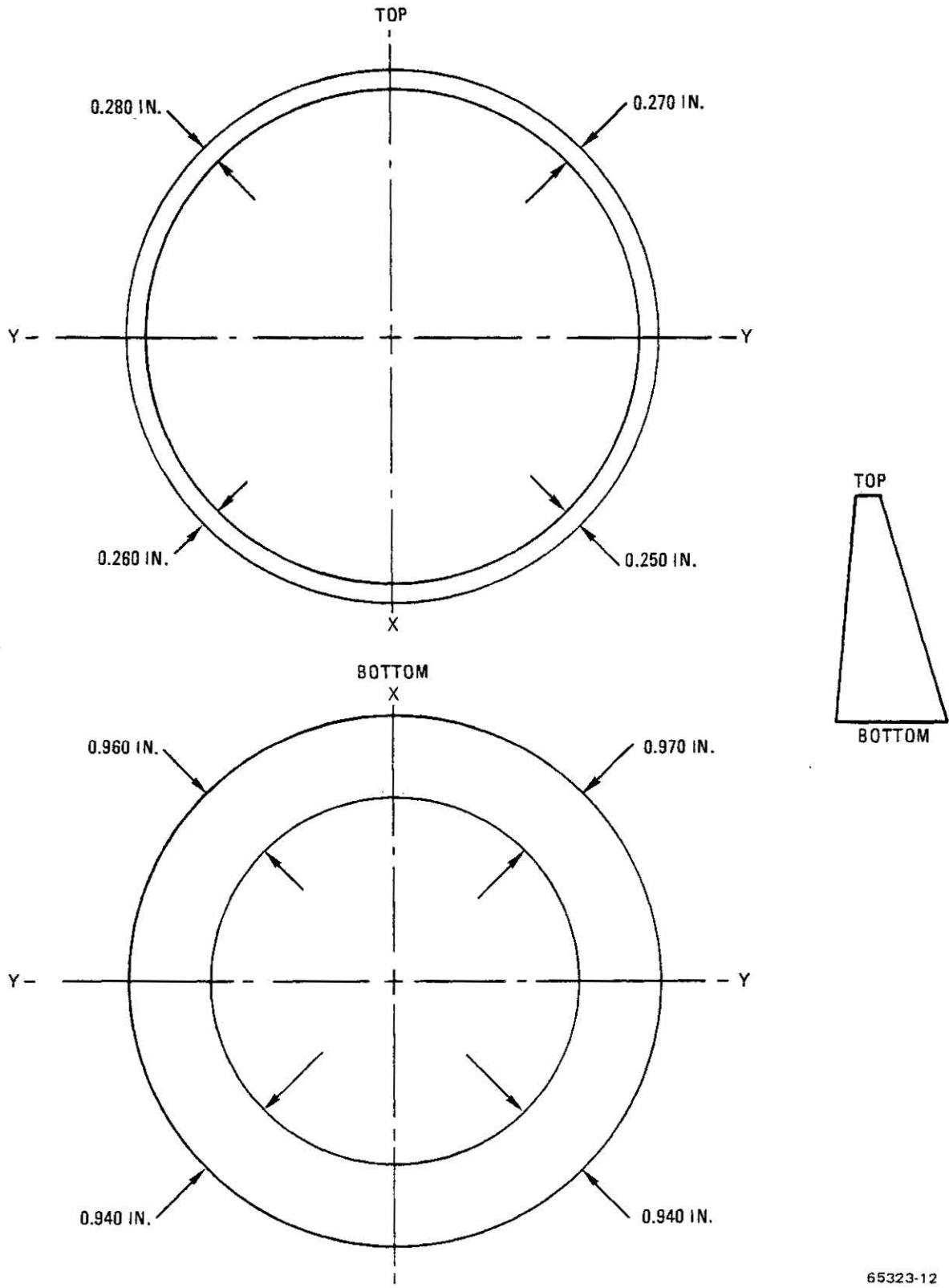


EACH 8-PLY MODULE (0/+45/-45/90/90/-45/+45/0) = 0.040 IN.

8-PLY OVERLAY = 0.040 IN.

65323-11

Figure 4-2. Stepwise Layup of GY-70/934 Modules



65323-12

Figure 4-3. Measured Dimensions for Ring
4-5

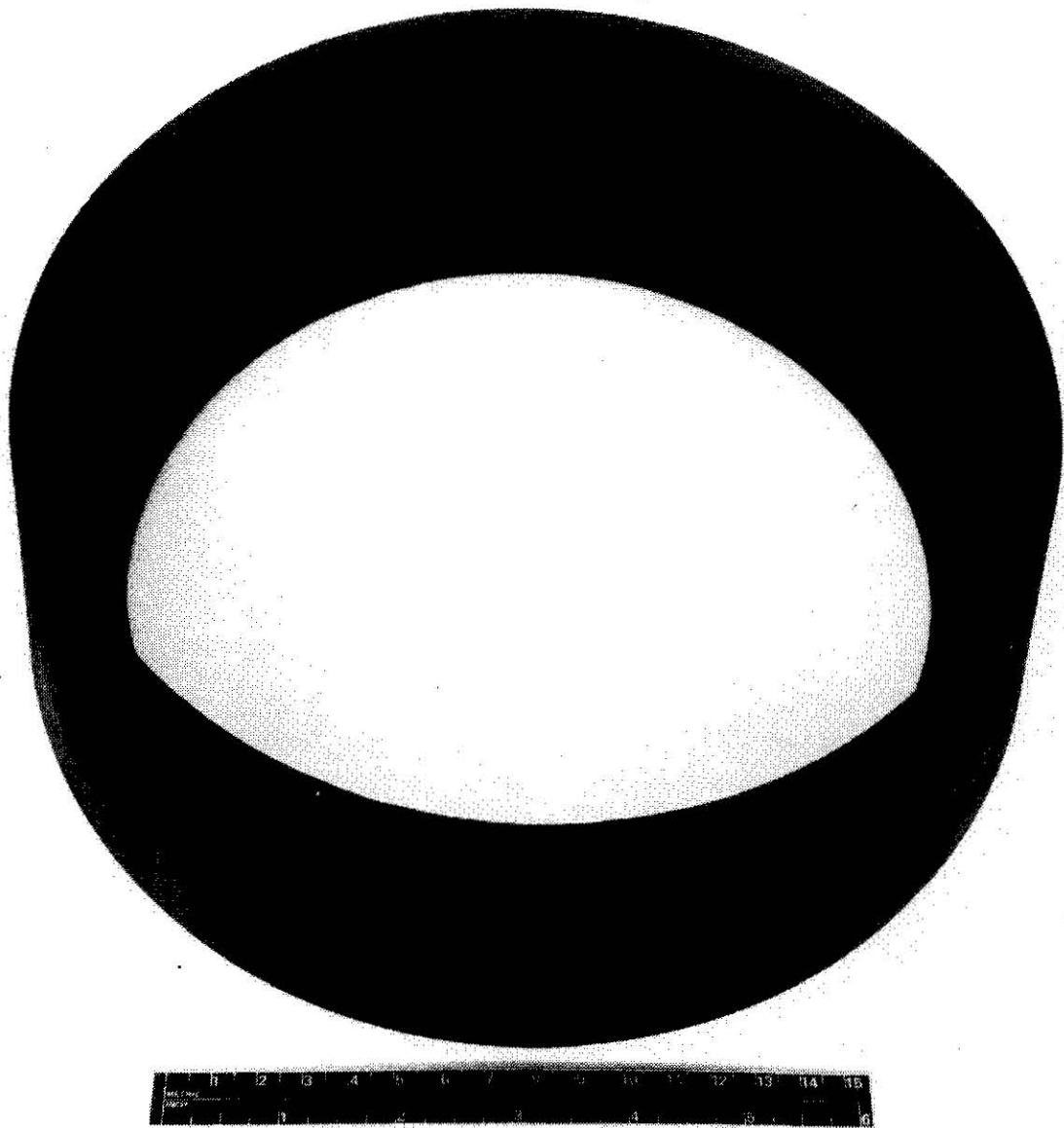


Figure 4-4. Forward View of Trimmed Equipment Ring

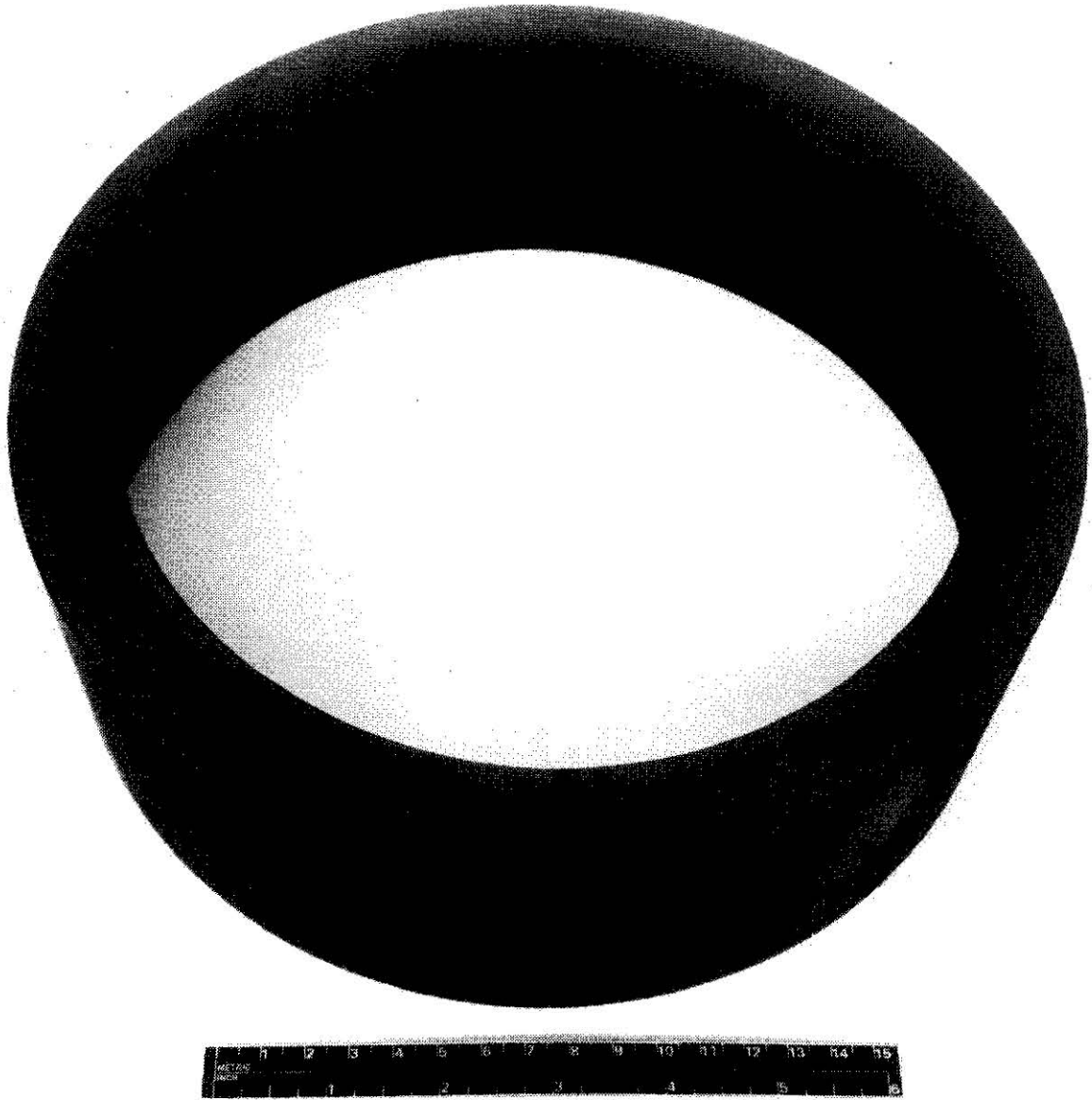


Figure 4-5. Aft View of Trimmed Equipment Ring

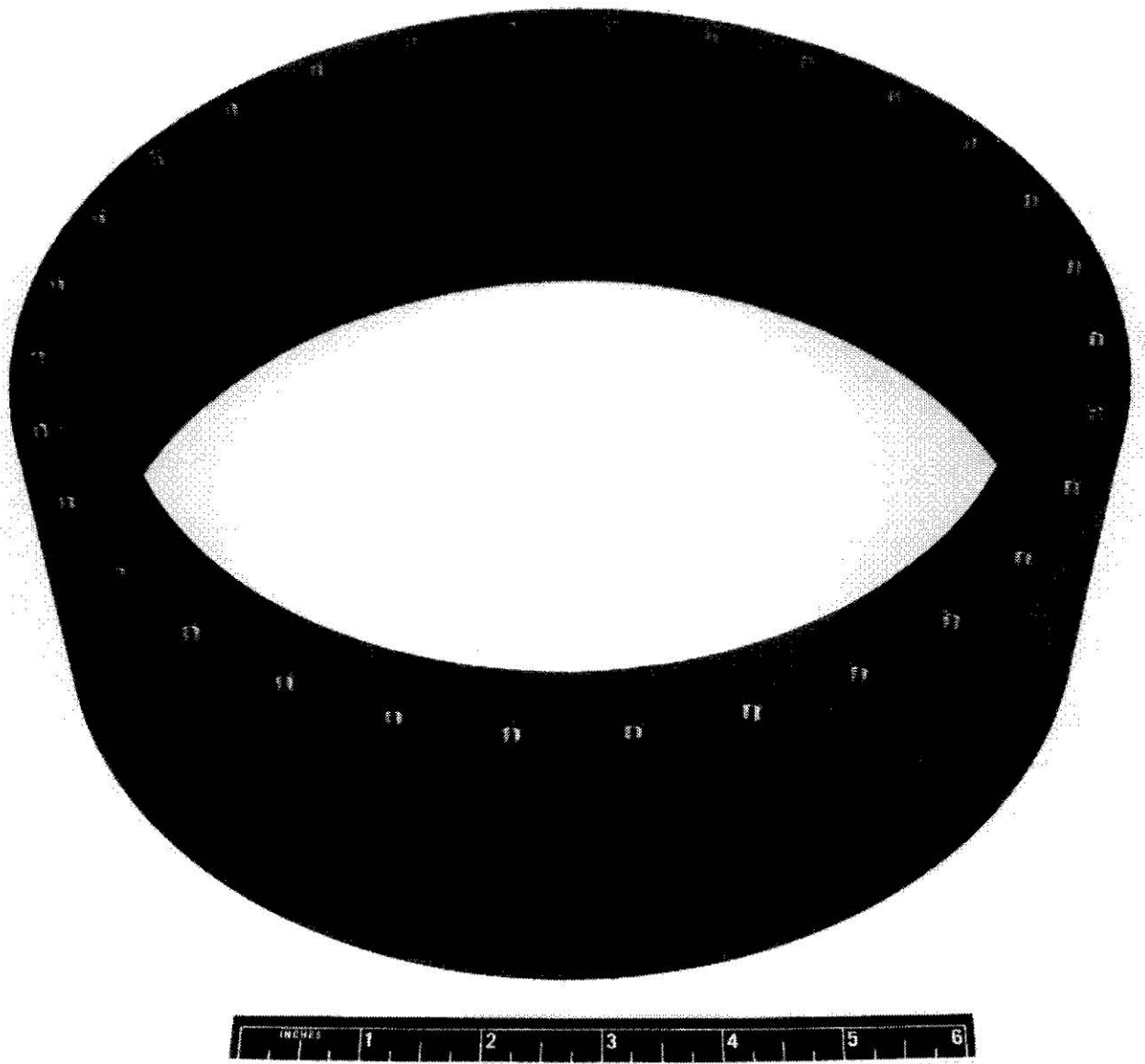


Figure 4-6. Equipment Ring with Helicoils Installed

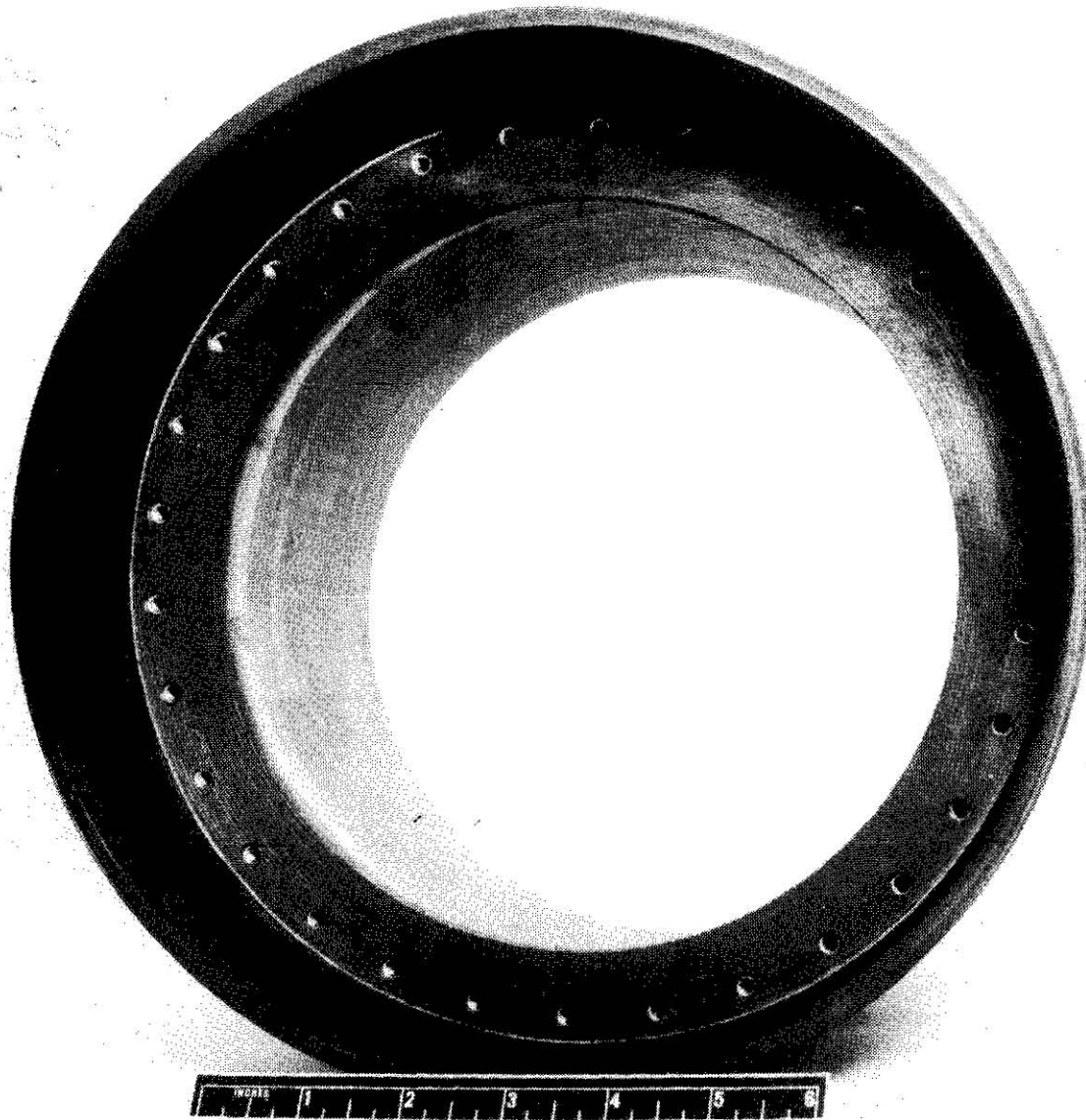


Figure 4-7. Graphite/Epoxy Cone with Equipment Ring Bonded in Place

SECTION 5

TESTING

5.1 TEST PLAN

A test plan was developed early in Phase II. The bonded graphite/epoxy frustum ring was tested in compression only (no shear) to limit load at room temperature and to failure at 325F. The compression is constant and represents the peak compressive stress due to axial compression plus bending loads. The graphite/epoxy ring is shown in Figure 5-1, where threaded helicoil inserts are employed to transmit the tension load, which in the ATI is exerted by a relatively rigid flanged cylinder. The actual dimensions and material of this cylinder are not known. Accordingly, the flanged loading plate shown in Figure 5-2 was selected. Note that the ring is positioned at approximately three inches from the large end instead of at the middle because the larger diameter ring is easier to manufacture on the available female tool. There are 30 3/16 diameter fasteners spaced approximately one inch apart. The test specimen assembly is shown in Figure 5-3. The ends are potted with EA934 adhesive in aluminum alloy blocks as shown. The surfaces are to be parallel within 0.002 TIR. One surface is the ring, which must be machined after bonding.

The testing procedures are presented in Figure 5-4. The room temperature test is shown in Figure 5-4 where both the ring and shell wall limit loads are applied by the procedure shown. The ring load (P_R) is controlled by the load cell, and the frustum load is established by

$$P_F = P_M - P_R$$

where P_M is the machine load.

The test at elevated temperature (325F) is indicated in Figure 5-4b, and a Missimers temperature chamber was selected for controlling temperature. For the temperature condition, the frustum loads are small and are neglected. Thus

$$P_R = P_M$$

and

$$P_F = 0$$

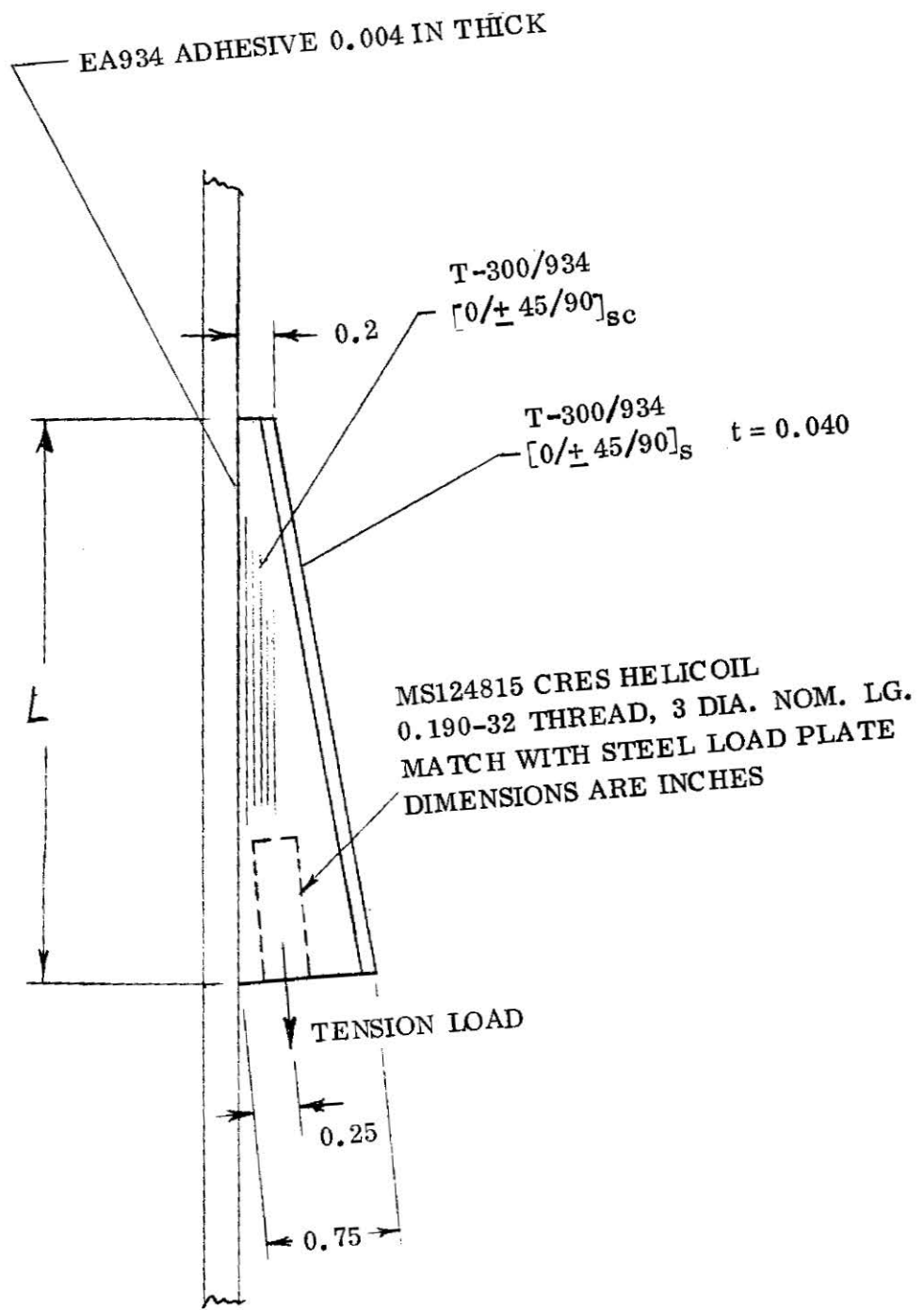


Figure 5-1. Ring for Half-Scale Frustum

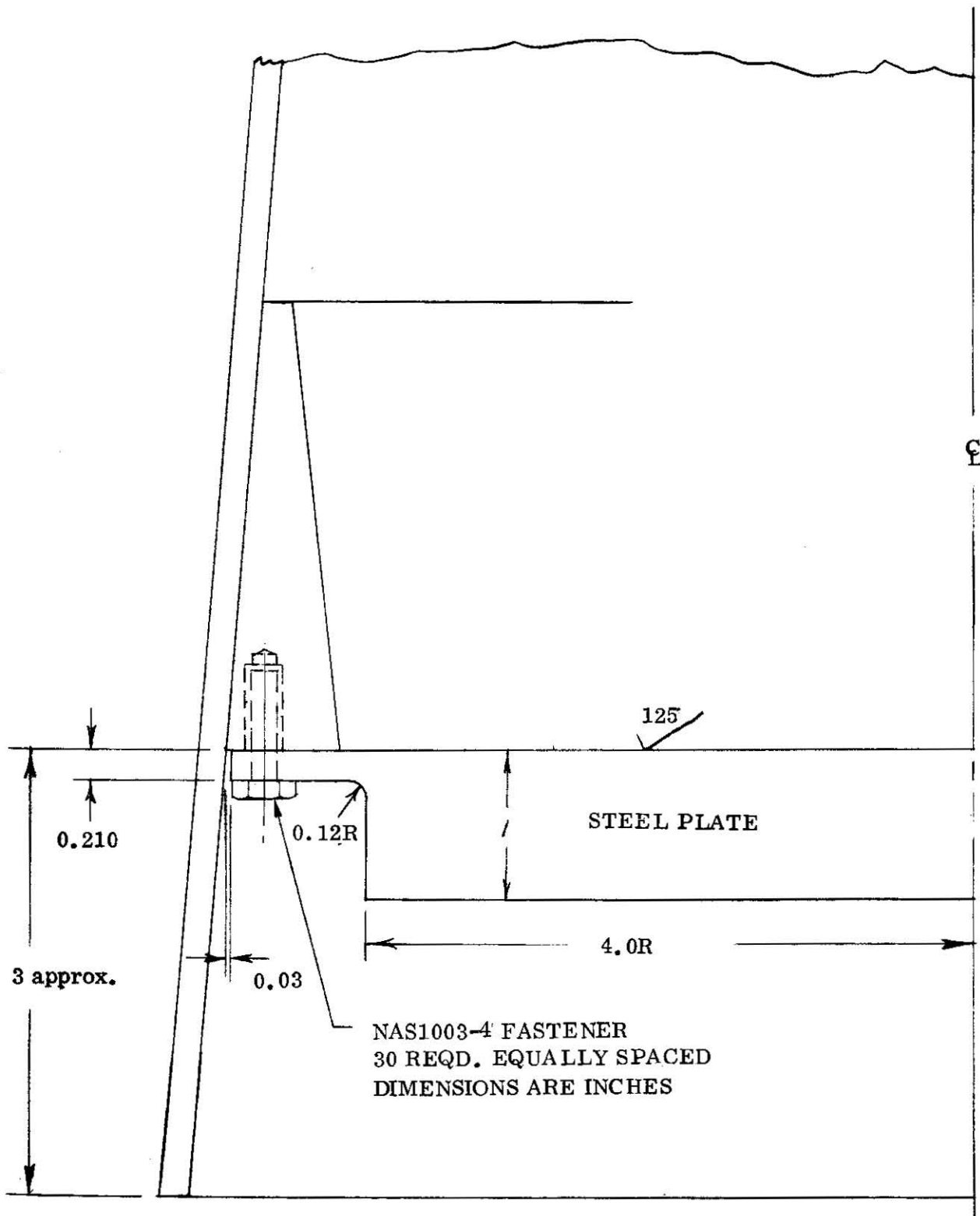


Figure 5-2. Loading Plate for Frustum Ring Test

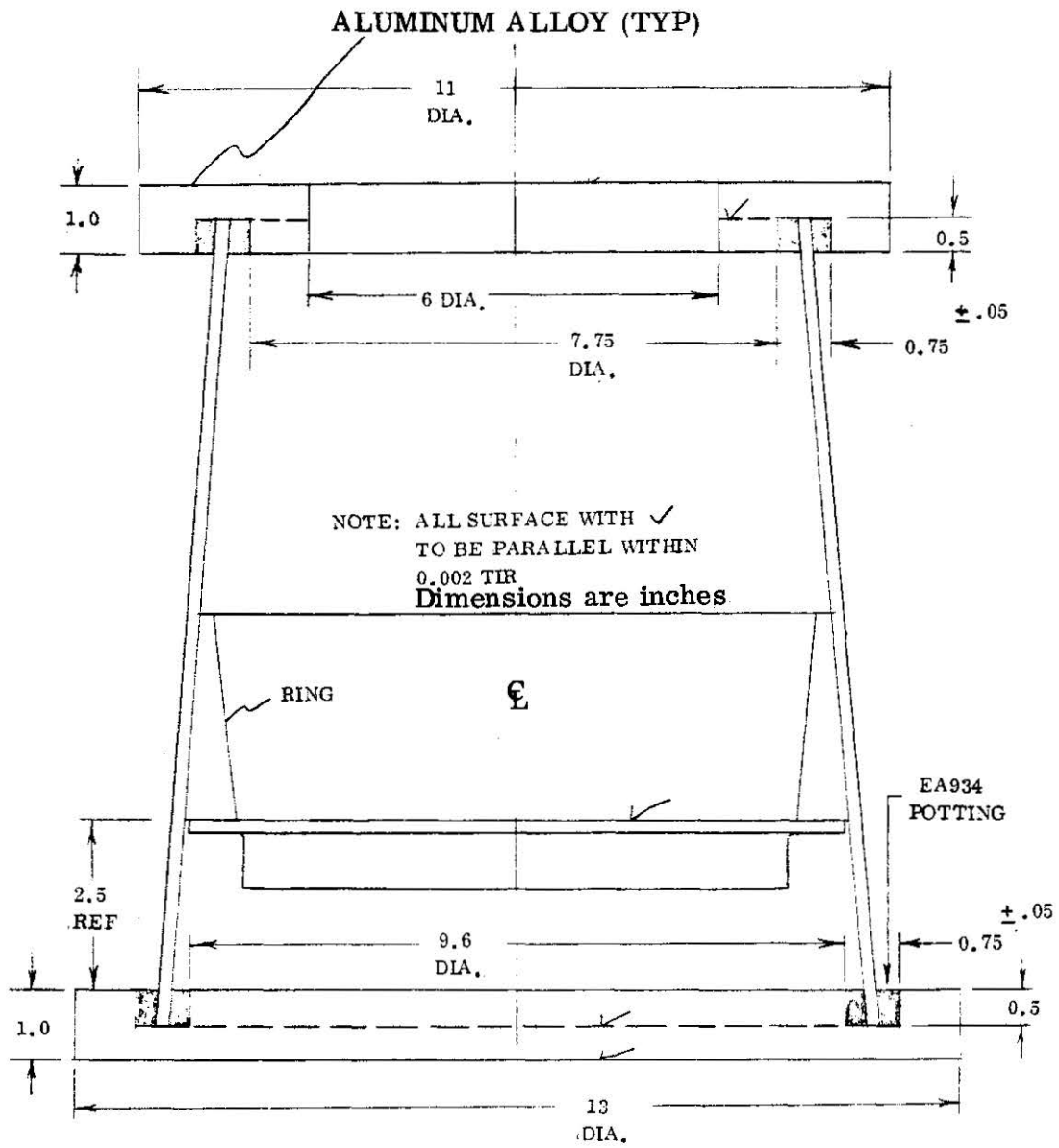


Figure 5-3. Frustum with Ring Test Specimen Assembly

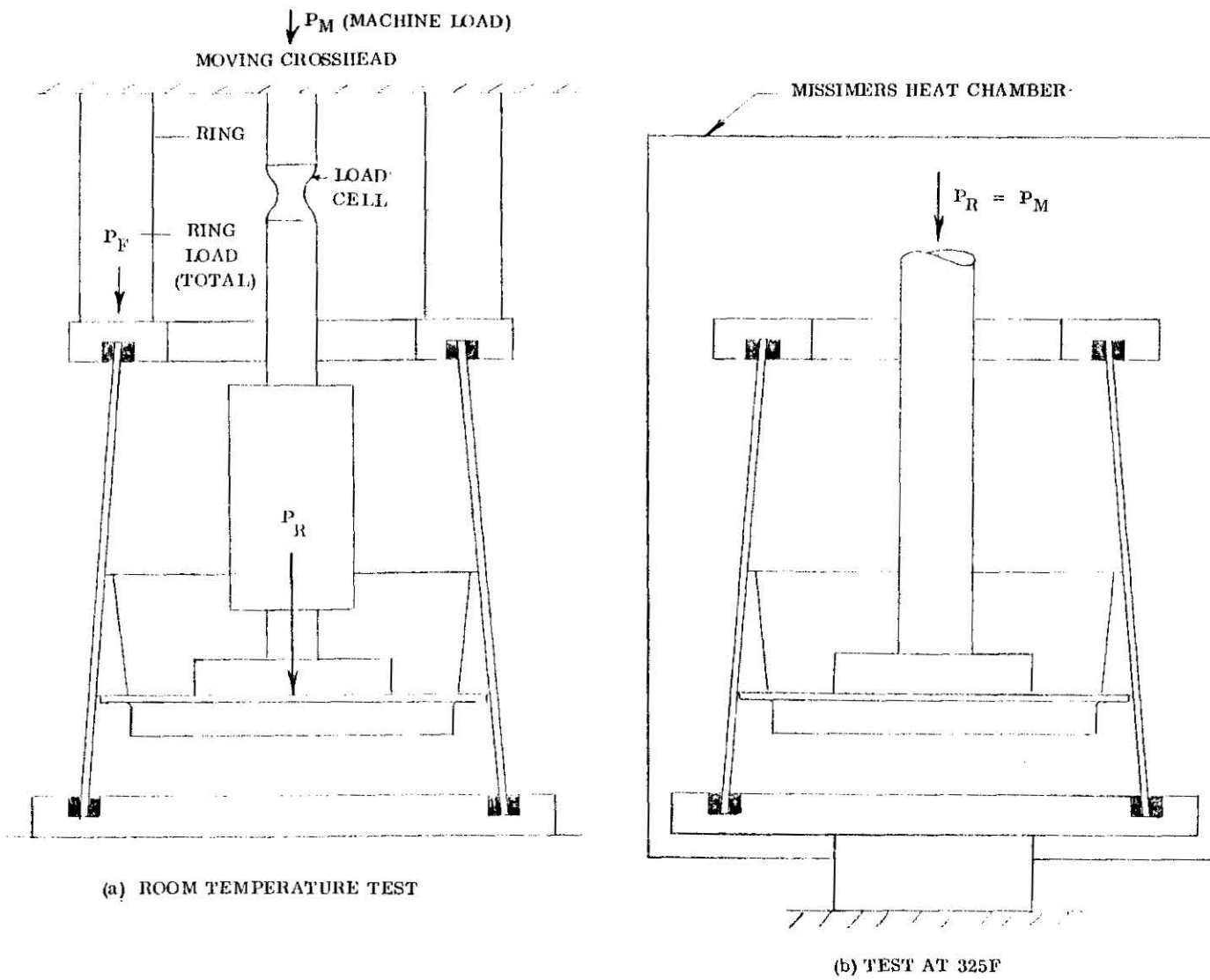


Figure 5-4. Sketch of Frustum Ring Tests

5.2 TEST LOADS

The test loads are determined such that the magnitudes of the running axial loads and maximum shear flow on the ring correspond to those in a half-scale frustum. The diameters of the bond surface at the large end of the ring, half-scale frustum and test specimens, are

$$D_{1/2}^b = 5.35 \text{ in.}$$

$$D_{\text{TEST}}^b = 9.75 \text{ in.}$$

The mean diameters of the small end of half-scale frustum and test specimen are

$$D_{1/2}^{\text{ms}} = 3.82 \text{ in.}$$

$$D_{\text{TEST}}^{\text{ms}} = 8.94 \text{ in.}$$

5.2.1 ROOM TEMPERATURE TEST

Half Scale Frustum Limit Wall Loads:

The loads determined are just forward of the ring load location.

$$N_W^c = 4340 \text{ lb/in (includes compression due to bending)}$$

$$q_{\text{max}}^v = 1049 \text{ lb/in (transverse shear — not included in test)}$$

Half Scale Frustum Limit Ring Load:

$$N_R = 433 \text{ lb/in}$$

$$q_{\text{max}}^v = 555 \text{ lb/in (transverse shear — not included in test)}$$

Test Specimen Limit Loads:

$$P_F = \pi D N_W^c \text{ (Frustum Load)}$$

$$D = D_{\text{TEST}}^b + 0.19 = 9.75 + 0.19 = 9.94 \text{ in.}$$

$$P_F = \pi \times 9.94 \times 4340 = 129,530 \text{ lb}$$

$$P_R = \pi D_R N_R$$

$$D_R \text{ (bolt circle)} = D_{\text{TEST}}^b - 2 \times 0.25$$

$$= 9.75 - 2 \times 0.25 = 9.25 \text{ in.}$$

$$P_R = \pi \times 9.25 \times 433 = 12,580 \text{ lb}$$

$$P_M = P_F + P_R = 129,530 + 12,580 = 142,100 \text{ lb}$$

5.2.2 ELEVATED TEMPERATURE TEST (325F)

Half Scale Frustum Ultimate Ring Loads:

$$N_R = 350 \text{ lb/in}$$

$$q_{\text{max}}^V = 446 \text{ lb/in (transverse shear — not included in test)}$$

Test Specimen Ultimate Loads:

$$P_R = P_M = \pi D_R N_R = \pi \times 9.25 \times 350 = 10,170 \text{ lb}$$

This load provides the ultimate axial ring load without the effects of the transverse shear load. The testing continues until failure occurs. An approximate means of estimating the test load that would result in shear stress from both axial load and transverse shear is:

$$N_R^{\text{EQ}} = \bar{K} N_R$$

$$P_R^{\text{EQ}} = \bar{K} P_R$$

$$\bar{K} = \tau_{\text{max}}^R / \tau_{\text{max}}$$

$$\left. \begin{array}{l} \tau_{\text{max}}^R = 226 \text{ psi} \\ \tau_{\text{max}}^R = 270 \text{ psi} \end{array} \right\} \text{ see Section 3}$$

$$\bar{K} = 270/226 = 1.19$$

$$N_R^{\text{EQ}} = 1.19 \times 350 = 417 \text{ lb/in}$$

$$P_R^{\text{EQ}} = 1.19 \times 10,170 = 12,100 \text{ lb}$$

5.3 TESTING PROCEDURE

Ten strain gages were installed on the graphite/epoxy cone using a room temperature curing cyanoacrylate adhesive, Eastman 910. The positions of the gages are shown in Figure 5-5. Induced thermal stresses in the cone were avoided by use of the room temperature curing adhesive. However, strain readings could only be obtained for the room temperature tests, since the Eastman 910 cannot withstand the 325F in the elevated temperature test.

The sequence of tests is shown in Table 5-1. The general test setup for test 1, the combined cone and equipment ring test, is shown in Figure 5-6. The strain data were read on the digital strain indicator/recorder shown in Figure 5-6. The equipment ring was loaded with the hydraulic cylinder shown in Figures 5-5 and 5-6. The pressure was applied by the hand pump shown in Figure 5-7. The load on the equipment ring was determined by the pressure in the system.

Table 5-1. Test Sequence Summary

Test No.	Date	Temperature	Loading	Maximum Load (lb)
1	4/13	Ambient	Cone & Equipment Ring	129,500 + 12,600 100% DLL
2	4/14	Ambient	Equipment Ring	10,080 80% DLL
3	4/14	+ 325F	Equipment Ring	12,100 100% DLL
4	4/18	Ambient	Cone & Equipment Ring	181,300 + 17,460 140% DLL
5	5/4	Ambient	Equipment Ring	49,300 Failure 390% DLL

The equipment-ring-only tests were run with the specimen in a temperature chamber fitted onto the machine. This setup is shown in Figure 5-8.

In each test the load was applied in increments of 10% of design limit load (DLL). At each point the strain was read. Since a room temperature curing adhesive was used for the strain gages, the data from the gages is only accurate for the first two ambient temperature tests.

5.4 TEST RESULTS

The test sequence is shown in Table 5-1. The part was loaded to 100% DLL for both the cone and equipment ring at ambient temperature. There was no visual damage or indication of damage in the strain reading. The test data of the four axial gages plotted in Figure 5-9 showed that there may have been some initial imbalance in the axial load.

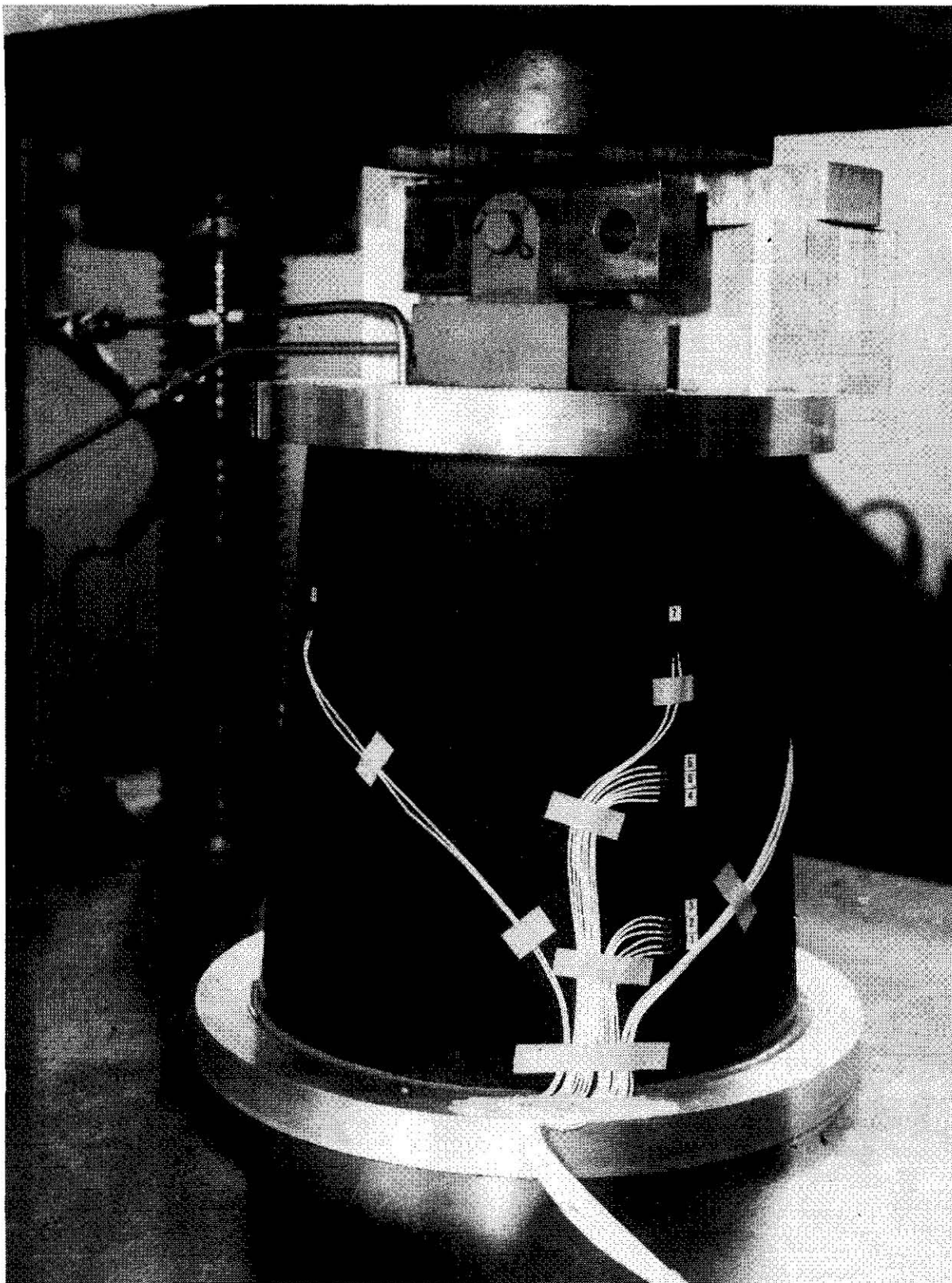


Figure 5-5. Graphite/Epoxy Cone in Test Machine Showing Strain Gages
5-9

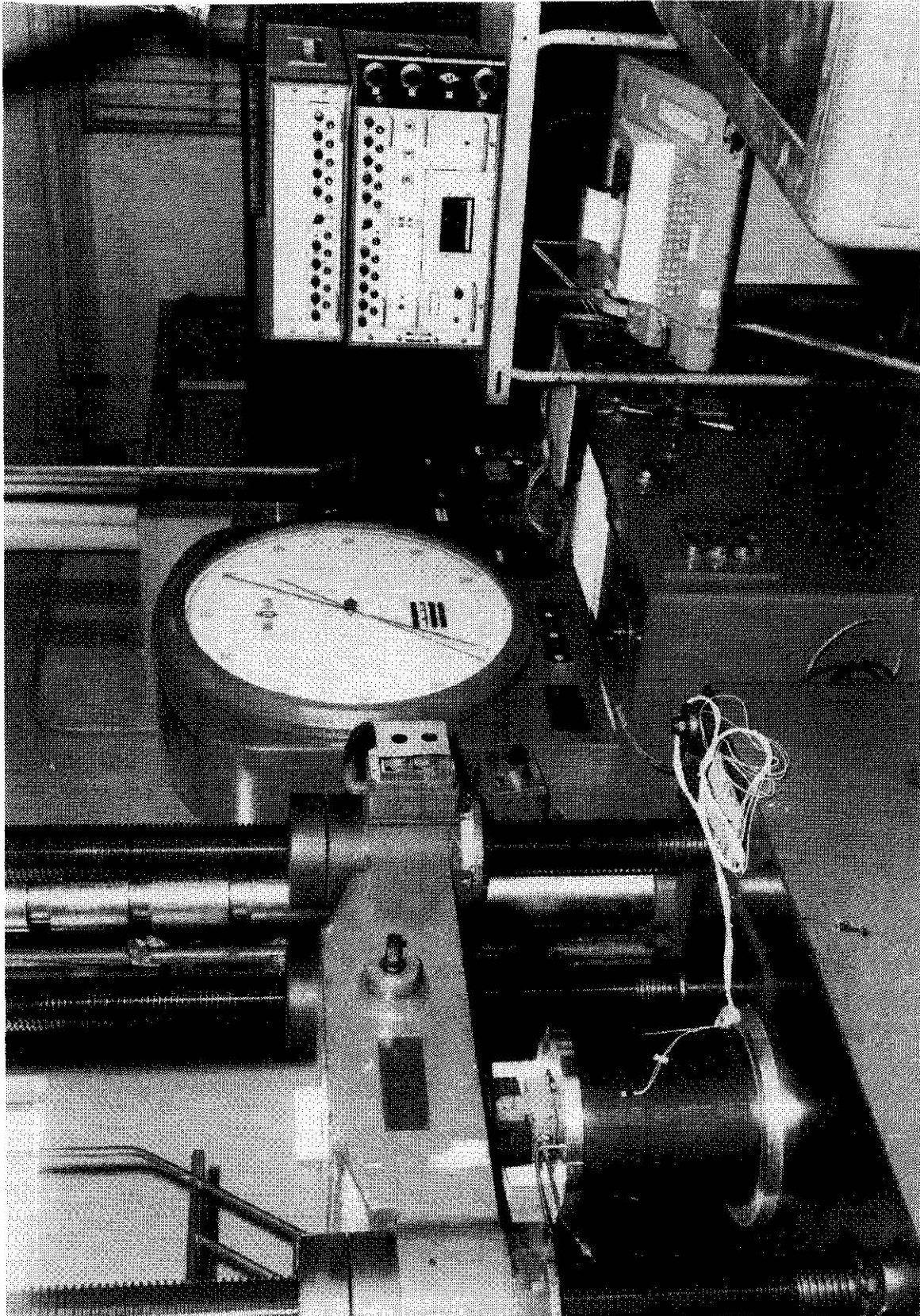


Figure 5-6. General Test Setup for Combined Cone and Equipment Ring Test

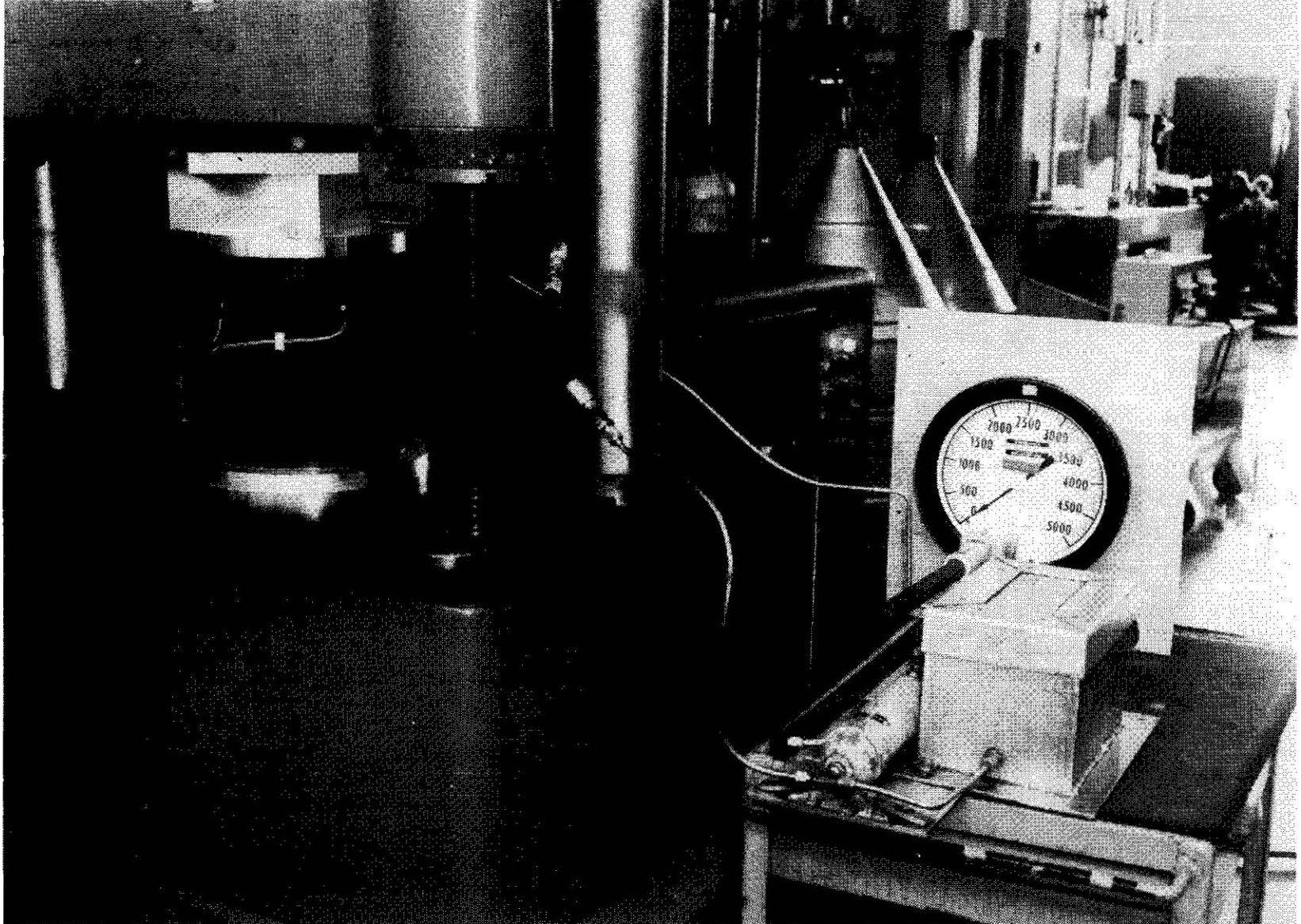


Figure 5-7. Test Setup Showing Pressure Application System

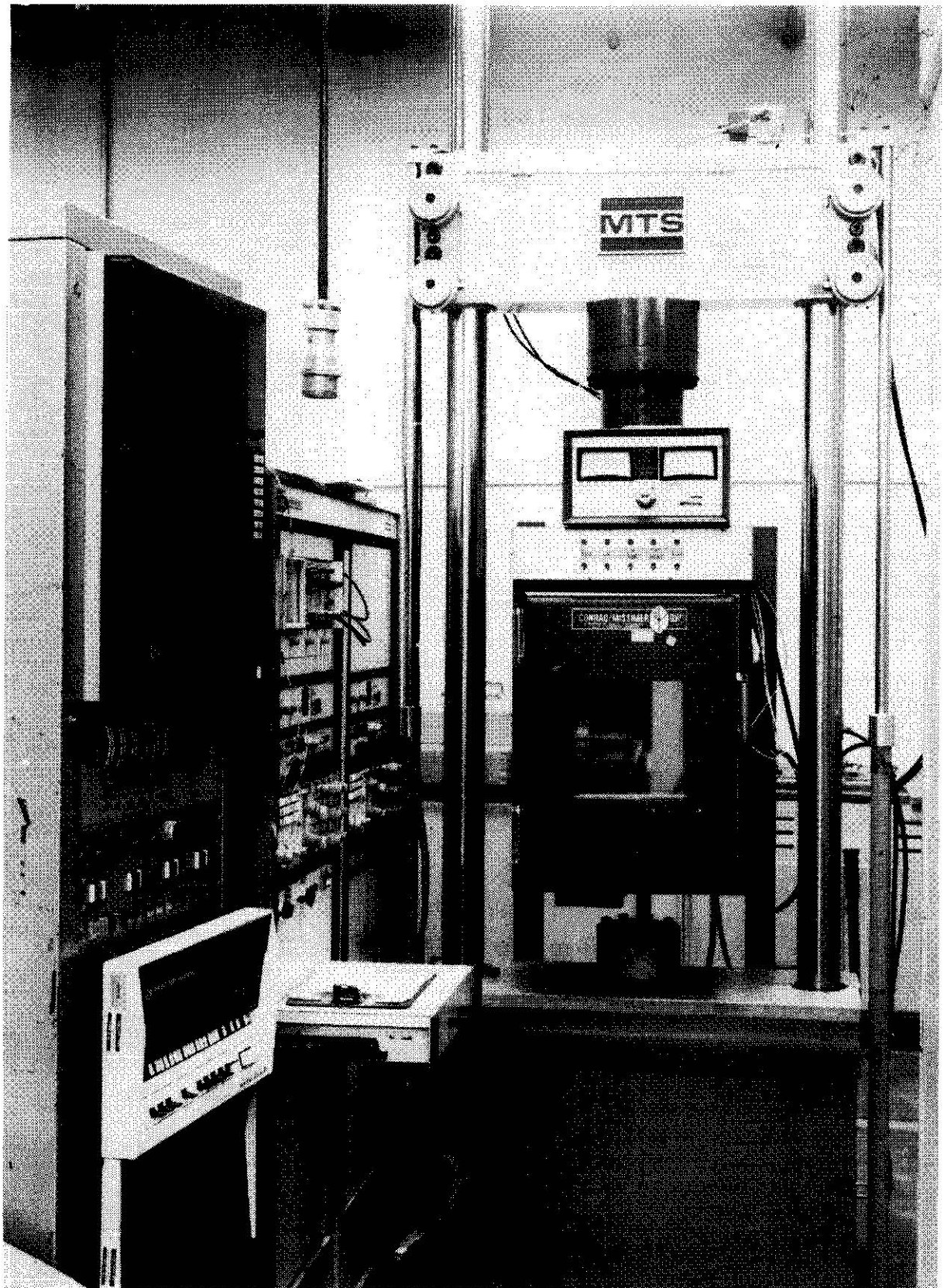


Figure 5-8. High Temperature Test Setup for Testing of Graphite/Epoxy Cone and Equipment Ring

5-13

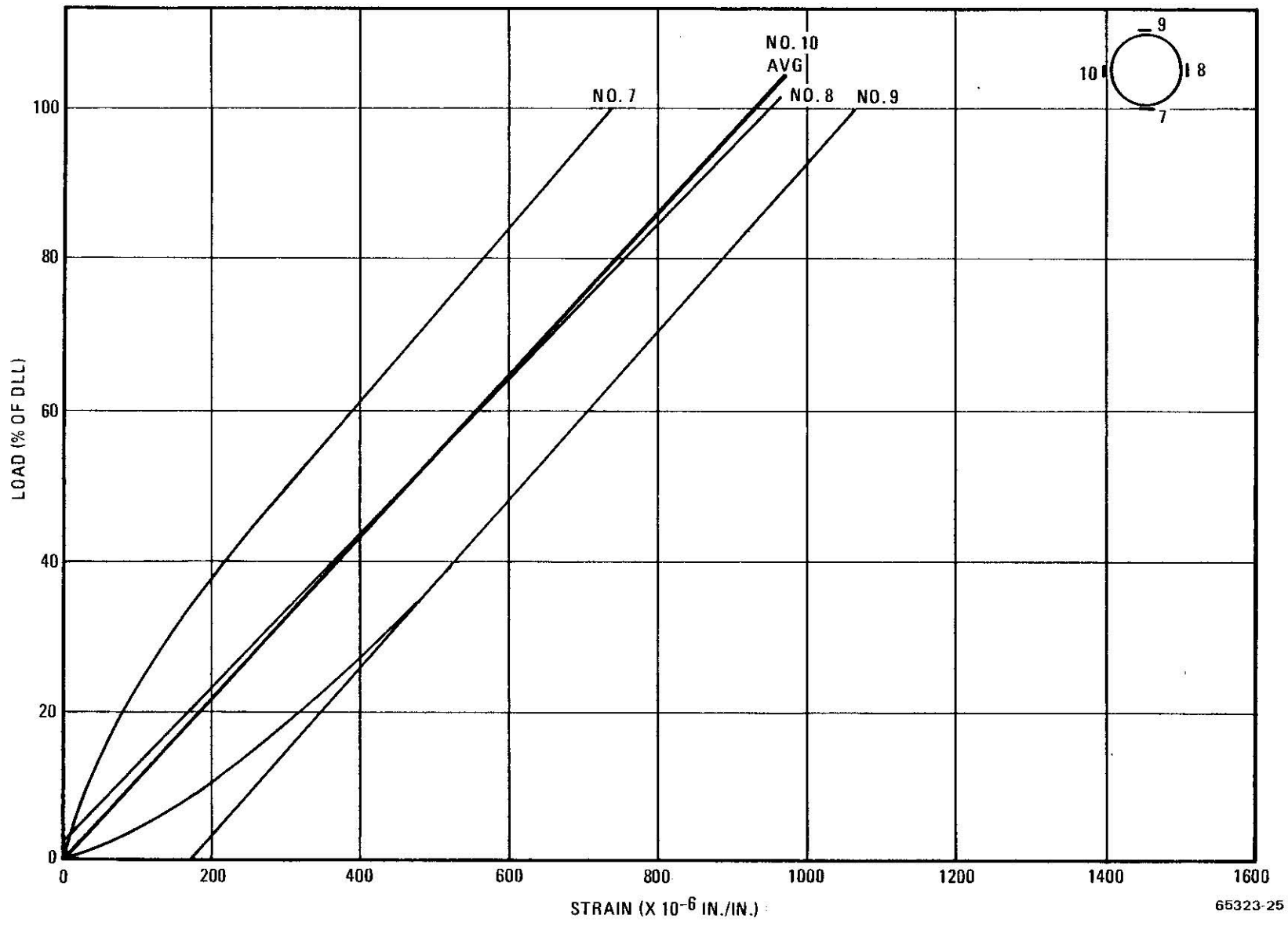


Figure 5-9. Axial Strain Data for the Cone from Test No. 1

The data from the strain gages in the region near the equipment ring are shown in Figures 5-10 and 5-11. These data show that load on the equipment ring caused a bending load in the cone.

The second and third tests (equipment ring only) were uneventful. Test No. 4 was a combined load test. The test was terminated when the capacity of the test machine was reached. The last test was an equipment ring load only test. The ring failed at 390% DLL when the helicoils pulled out of the attachment. This is shown in Figure 5-12.

The increased thickness of the ring provided more edge distance for the helicoil insert. The thickness of the half-scale frustum was to be about 0.190 inch, but the fabricated thickness was about 0.205 inch in the region of the ring. The actual eccentricity of the fasteners was 0.28 inch rather than 0.25 as called out, thus increasing the applied running bending moment. The method of calculating the interlaminar tensile stress due to this bending moment was quite conservative as no benefit from self-equilibrating resisting moments were accounted for in the ring. Since the elevated temperature condition (325F) was critical, only analysis for this case has been presented (see Section 3). Margins of safety for ultimate load at 325F were computed by two different criteria:

- Maximum shear stress plus interlaminar tensile stress

$$\text{M.S.} = 3.5$$

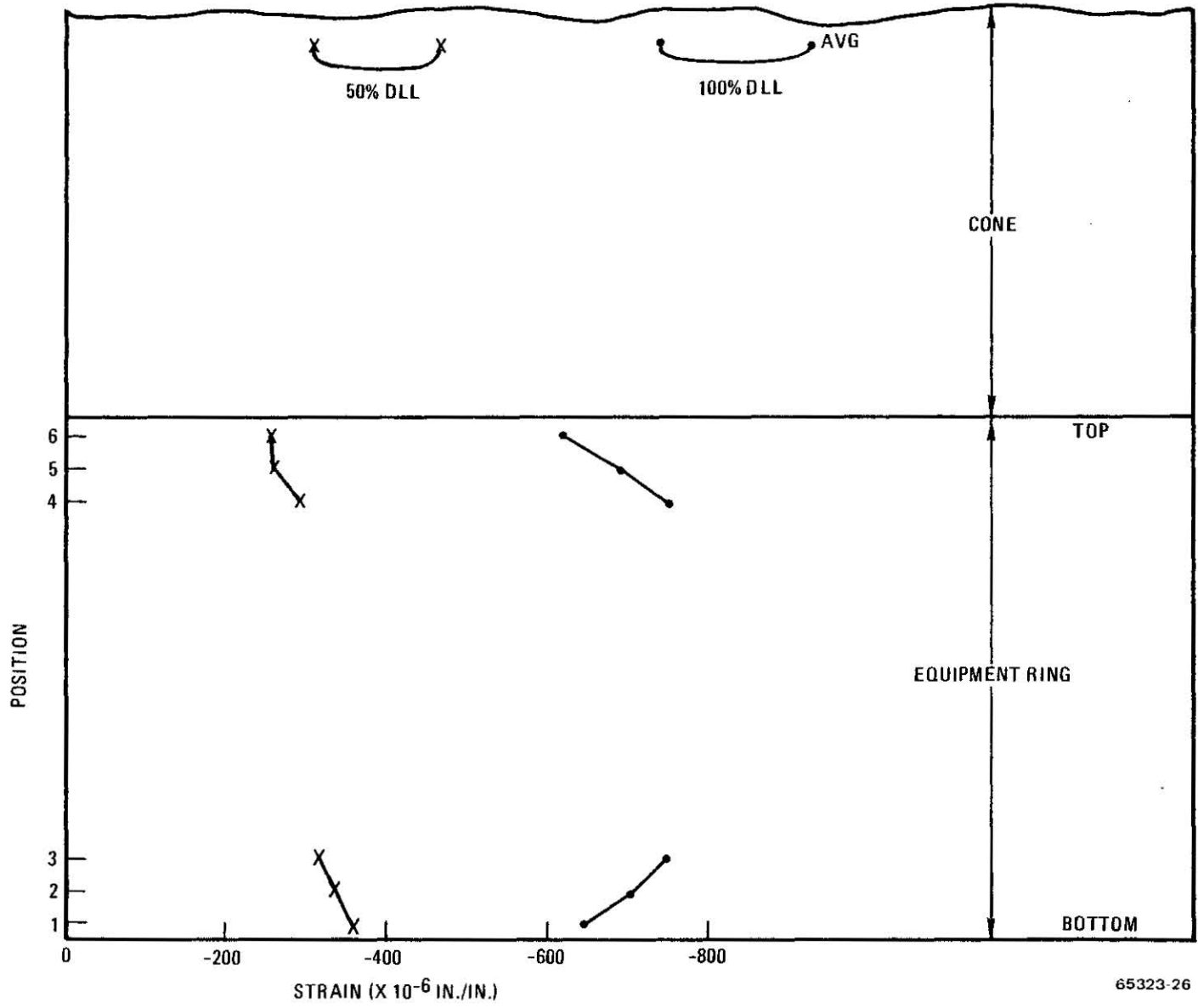
- Average shear stress plus interlaminar tensile stress

$$\text{M.S.} = 2.38$$

Accordingly, it was expected that the capability of the bond was more than 238% above ultimate load. If true, the full size structure should be adequate.

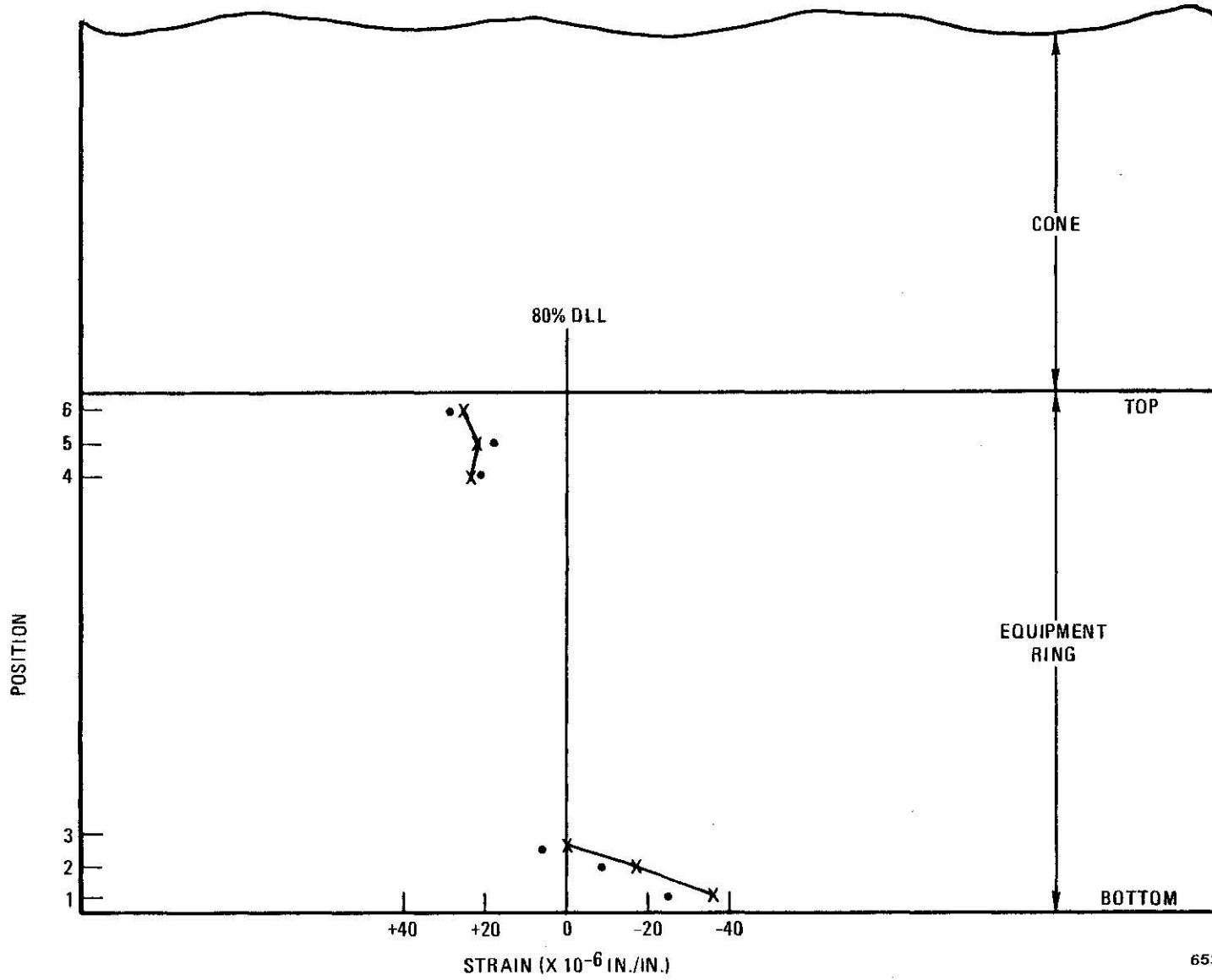
The test results presented in Table 5-1 show that no failure occurred at ultimate load for the 325F case (Test No. 3). Test No. 1 was loaded to the room temperature design limit load, loading both the shell and ring. This loading was repeated up to the capacity of the testing machine, which reached 140% of design limit load. Finally, the ring load only was applied (Test No. 5) until failure at 390% of design limit load (or 260% of design ultimate load) at room temperature. Unfortunately, the helicoil inserts pulled out so that the adhesive bond allowable was not determined. However, a lower bound allowable was determined for room temperature. Since bonded joint allowables cannot be scaled-up from small scale testing, it would be desirable to attain no less than 200% of design loads in the half-scale testing. Thus, it appears that the ring tested would be adequate for the full-size structure.

The fasteners engaged a length of 0.40 inch in the 0.190-32 threads of the helicoil inserts. The failure load per helicoil at room temperature was $49,300 \div 30$ or 1643



65323-26

Figure 5-10. Strain Data from the Gages Near the Equipment Ring, Test No. 1



65323-27

Figure 5-11. Strain Data from Gages Near the Equipment Ring, Test No. 2

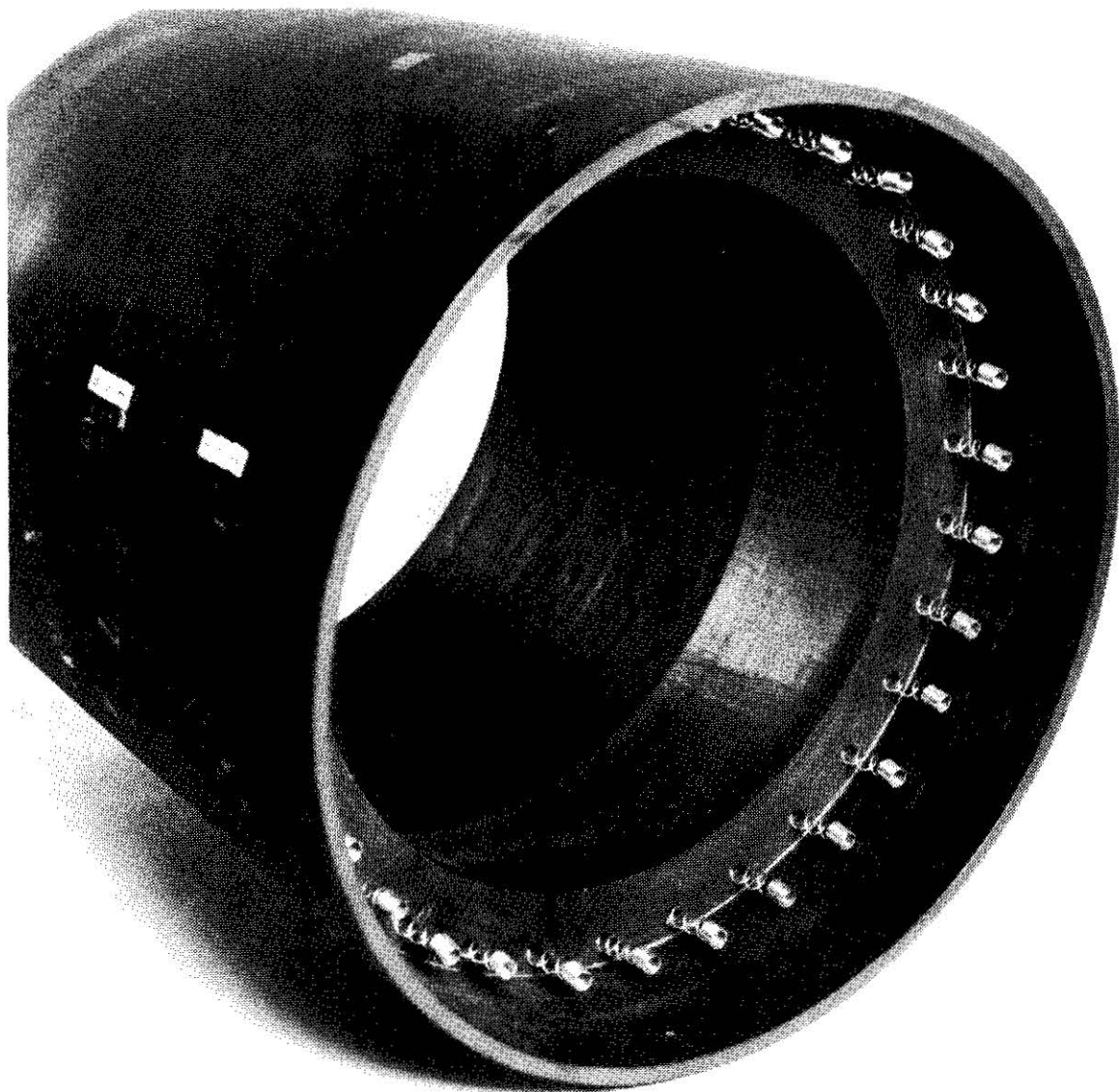


Figure 5-12. Pullout of Helicoils as a Result of Testing to Failure

pounds, which seems remarkable since direction of load in the helicoils was nearly parallel to the plies. A lower bound load at 325F would be $12,000 \div 30$ or 403 pounds per helicoil.

The bondline stress resultant and shear stresses for Test No. 3 at 325F are

$$N = 12,100 / (9.75 \pi) = 395 \text{ lb/in}$$

$$\tau_{\text{avg}} = N/3 = 132 \text{ psi}$$

$$\tau_{\text{max}} = \tau_{\text{max}}^R = 270 \text{ psi (see page 3-6)}$$

The interlaminar tensile stress may be conservatively found by

$$M = 0.28 N = 0.28 \times 395 = 111 \text{ in-lb/in}$$

$$\sigma^{it} = \frac{6M}{L^2} = \frac{6 \times 111}{3^2} = 74 \text{ psi}$$

Apparent expected lower bound margins of safety above the test load may be found as follows:

$$\left. \begin{array}{l} \tau_{avg}^a = 750 \text{ psi} \\ \tau_{max}^a = 1528 \text{ psi} \\ \sigma^{itu} = 1384 \text{ psi} \end{array} \right\} \text{ (see pages 3-8 and 3-9)}$$

$$\left. \begin{array}{l} R^{it} = \frac{74}{1384} = 0.053 \\ R_{avg} = \frac{132}{750} = 0.176 \\ R_{max} = \frac{270}{1528} = 0.177 \end{array} \right\} \text{ Stress ratios}$$

$$M.S._{avg} = \frac{1}{R^{it} + R_{avg}} - 1 = 3.3$$

$$M.S._{max} = \frac{1}{R^{it} + R_{max}} - 1 = 3.3$$

It should be noted that these margins are not comparable with those in Section 3 because transverse shear was included in that analysis.

The bondline average shear stress resultant and interlaminar stresses for the room temperature Test No. 5 are determined as follows:

$$N = 49,300 / (9.75\pi) = 1610 \text{ lb/in}$$

$$\tau_{avg} = N/3 = 537 \text{ psi}$$

$$\left. \begin{array}{l} \tau_{avg}^a = 1250 \text{ psi} \\ \sigma^{itu} = 1384 \text{ psi} \end{array} \right\} \text{ See pages 3-8 and 3-9}$$

$$M = 0.28 N = 0.28 \times 1610 = 450 \text{ in-lb/in}$$

$$\sigma_{it} = \frac{6M}{L^2} = \frac{6 \times 450}{3^2} = 300 \text{ psi}$$

Of course, the margin of safety for this test is zero since the helicoils failed. However, we can predict a margin of safety for the bond as follows:

$$R^{it} = \frac{300}{1384} = 0.217$$

$$R_{avg}^s = \frac{537}{1250} = 0.430$$

$$M.S. = \frac{1}{R^{it} + R_{avg}^s} - 1 = 0.55$$

This represents an expected margin of safety for the bond above the failure load provided the helicoils would not fail first.

The strain gage readings in test Numbers 1 and 4 show that some overall bending was imposed on the conical frustum, while the degree of load uniformity on the ring (helicoils) is unknown. Examination of the strains in Figure 5-10 for test No. 1 reveals that local bending occurred in the shell wall in the region of maximum shear transfer at each end of the ring. The compressive strain in gage 7 located two inches above the ring was about 7300μ -strain. But the first gage in the ring area (No. 6) shows less compressive strain, which can only be the result of relieving tensile strain as a result of the local bending effect. Similar occurrence appears at the opposite end of the ring (gages 1, 2, 3).

SECTION 6
CONCLUSIONS

1. The bonded joint resisted ultimate design loading at both room temperature and 325F without failure.
2. The experimental equipment ring was over-designed for the half-scale frustum; however, this was a desirable feature since strengths of small bond joints are difficult to scale to full size hardware.
3. The experimental wedge ring design should certainly be acceptable in its present form for the full scale frustum with the exception that larger fasteners and heli-coils would be required.
4. The success of the helicoil inserts (1640 pounds per insert) nearly parallel to the plies was a profound discovery and offered a simple means of applying tension loads to the ring.

SECTION 7
RECOMMENDATIONS

1. Complete testing of eight graphite/epoxy frusta remaining from Phase I which have titanium foil interleaved joints.
2. Fabricate two additional graphite/epoxy frusta containing bonded equipment rings similar to the one tested in Phase II and repeat testing at room temperature and 325F to get a statistical base.
3. Conduct a baseline configuration analysis for the full-scale guidance and control section of the ATI.
5. Develop design layouts, manufacturing plans, and full-scale section test plans for a full-scale demonstration test.
6. Fabricate and test a full-scale guidance and control section of the ATI.

SECTION 8

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