NAS8 26675

FABRICATION OF 1/3 SCALE BORON/EPOXY BOOSTER THRUST STRUCTURE

Phase I Final Report

CR-119958

January to September 1971

September 1971

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Prepared Under Contract No. NAS8-26675

By

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For

Marshall Space Flight Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GRUMMAN AEROSPACE

FOREWORD

The work reported herein was performed under the sponsorship of the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama, 35812. Mr. J.H. Ehl is the Contracting Officers Representative.

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ABSTRACT

This report describes the analytical methods, design techniques, materials, tooling, various manufacturing processes, quality control, test procedures and results associated with the fabrication and test of 1/3 scale boron/epoxy, tubular, booster thrust structure members. Five specimens were fabricated and tested under the Phase I program - 2 subelements, which served to confirm the adequacy of the integrally bonded boron/epoxy to titanium splice and 3 full tubes with boron/epoxy center regions and titanium ends. The test results verified the adequacy of the design and confirmed the forecast weight saving of 32 percent for the full tubes.

An important aspect of the program; the quality control non-destructive test techniques and results are also presented. The techniques used provided a high degree of confidence in the ability to detect imperfections in the completed specimens.

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1.0 INTRODUCTION AND SUMMARY

A one-third scale booster thrust structure for the space shuttle was designed using both boron/epoxy and titanium by Grumman under an in-house program. The boron/epoxy design showed a 22 percent overall weight saving. This study resulted in the program for fabrication and test of the boron/epoxy tubular members which is described in detail in this report.

This program was undertaken to confirm the design procedures, analytical methods, projected weight saving and manufacturing feasibility and to substantiate, by test, the structural integrity of the boron/epoxy tubular members of the thrust structure.

The scope of Phase I of the program provided for the fabrication and test of the center member of a one-third scale shuttle truss. Five test specimens were provided in all, comprising two identical subelements and three identical full tubes. In phase II of the program, a complete two dimensional truss will be fabricated and tested.

The subelement specimens which were .3801 m (15 in.) in length, with an inside diameter of 89.10 mm (3.508 in.), are representative of the boron-epoxy to titanium adhesive bonded joint used on the full tube. These specimens were tested under uniaxial compression loads representing the maximum axial load which would be experienced by the center member in the one-third scale three-dimensional truss.

The full tube specimens were .857 m (33.75 in.) in length with the same inside diameter as the subelements. These specimens were tested under an axial compression load with required end moments. The combined loading is representative of the maximum loads which are experienced by the center member in the three-dimensional one-third scale truss structure. Each of these specimens were instrumented with strain gages and deflectometers. All tests were conducted at room temperature.

Of the five specimens tested (2 subelements and 3 full tubes) 3 specimens (1 subelement and 2 full tubes) exceeded design ultimate load (D.U.L.). Subelement number 1 and tube number 1, both of which showed ultrasonic discontinuities, exceeded limit load but did not reach ultimate. The failure of these specimens to reach ultimate was predicted and attests to the high degree of confidence afforded by the non-destructive test techniques employed for Quality Control. It should be noted that the program provided sufficient flexibility to analyze product deficiencies as they occurred and to incorporate the necessary processing changes prior to the fabrication of subsequent parts. This is apparent when it is noted that the processing for subelement number 2 was modified from that used on subelement number 1 and processing for tube numbers 2 and 3 were modifications of that used in tube number 1. The modifications, which proved to be completely successful, are discussed in detail in this report.

An overall weight savings of 22 percent with an associated weight savings of 32 percent for a single tubular member were confirmed by the results of the program.

2.0 DESIGN

2.1 Thrust Structure Geometry

The geometry of the baseline one-third scale booster thrust structure is shown in Figure 2-1. The structure is 1.01 m (40 inches) high inscribed within 3.04 m (120 inches) maximum envelope ring diameter. There are nine engine support points, one located centrally within a 2.03 m x 2.03 m (80 inch x 80 inch) square with the remaining eight located at each corner and mid-point of each side of the square. Section A-A of Figure 2-1 shows the two dimensional center beam and the nine members of which it is composed. The center member of this beam is the member which has been fabricated and tested under the Phase I program.

2.2 Tube Design

A comparative study of the efficiency of square and circular section boron/epoxy tubes showed that use of square section tubes would result in a tube weight penalty ranging from 30 to 50 percent. Circular section tubes were therefore chosen for the truss members.

It was also apparent that there would be a considerable problem if the loads, approximately 890×10^3N (200 kips), were introduced directly into the boron/epoxy tubes by bolting or bonding these directly to corner fittings for final assembly. In the former case, the relatively low bearing strength of boron/epoxy would result in an unacceptable build-up of end thickness and an associated significant weight penalty. In the latter case, it was found that the adhesive stresses would be unacceptably high, that this technique would probably not be relatable to final assembly of a full scale structure and that reliable inspection and non-destructive testing of these bonded joints would be difficult if not impossible.

It was therefore decided to use semi-circular stepped titanium splice fittings, bonded into each end of the boron/epoxy tubes, which would be drilled and bolted to the corner fittings for final assembly. Figure 2-2 shows a schematic of the tube splice.

The boron/epoxy tubes were first sized using a graphical technique which was developed to obtain optimum tube geometry and disposition of the

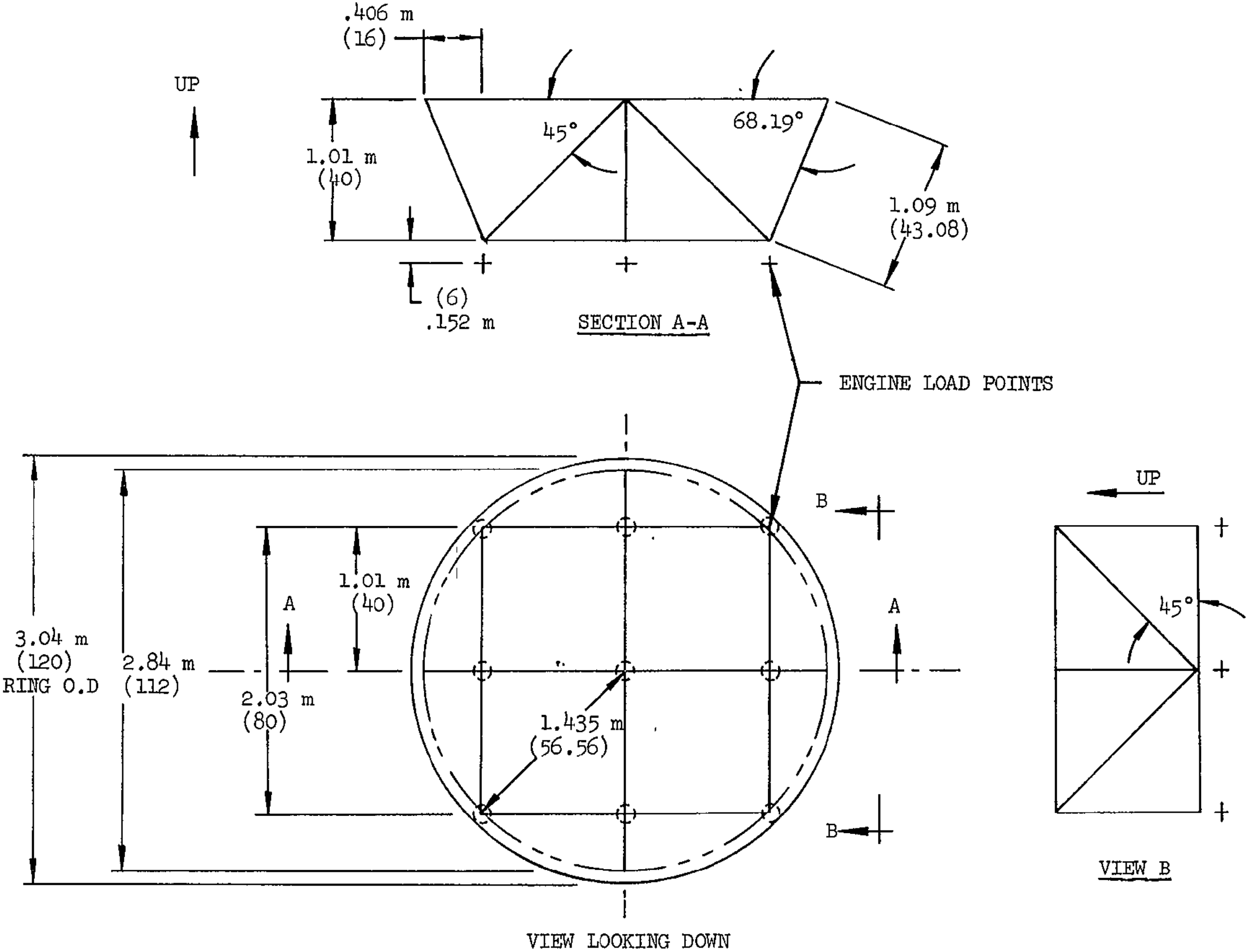

Figure 2-1 Geometry - One-Third Scale Booster Thrust Structure

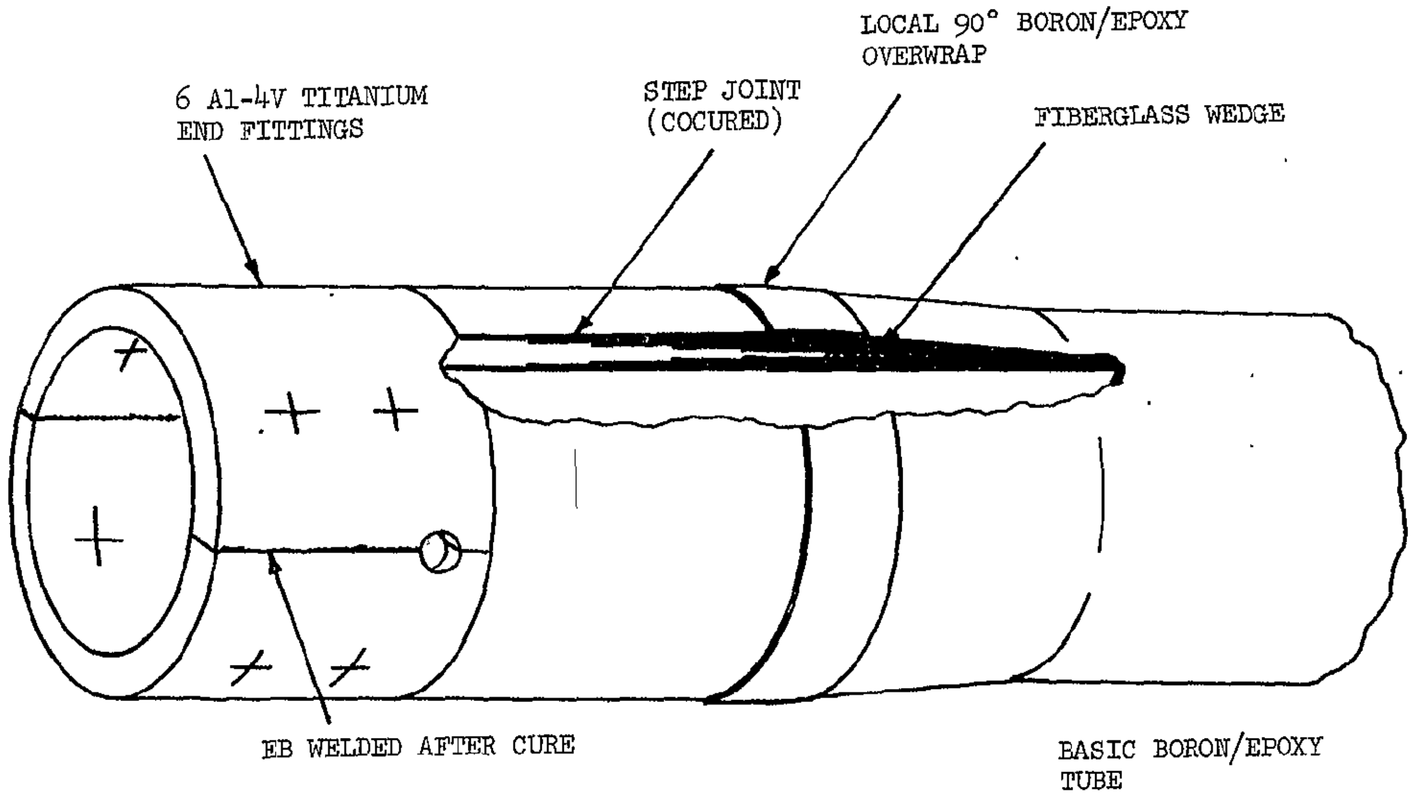

Figure 2-2 Tube Splice Schematic

plies using a 0/90/$\pm$45 layup. This was achieved by first equating the tube local instability stress to the ultimate compression strength of the laminate. The resulting value of allowable stress was then equated to the maximum applied stress in the tube wall. The effects of the transverse shear stiffness of the tube were included in the beam-column analysis which was used to determine the magnitude of maximum applied stress. Both axisymmetric and antisymmetric instability modes of local instability were examined using the equations developed in References 1 and 2. The theoretical buckling stress coefficients were reduced for design purposes to account for geometrical and material property variations. The resulting equations used for design were:

$$F_{cr} = 0.30 \frac{t}{r} \left[E_x \, E_\theta\right]^{\frac{1}{2}} \tag{1}$$

for axisymmetric local instability and for antisymmetric local stability:

$$F_{cr} = 0.71 \frac{t}{r} \left[(E_x \, E_\theta)^{\frac{1}{2}} \, G_{x\theta}/(1 - (\nu_{x\theta} \, \nu_{\theta x})^{\frac{1}{2}}\right]^{\frac{1}{2}} \tag{2}$$

The tube length is L, mean radius is r and thickness is t. E_x and E_θ are the axial and circumferential moduli of elasticity of the composite material, $G_{x\theta}$ is the in-plane shear modulus and $\nu_{x\theta}$ and $\nu_{\theta x}$ are respectively the major and minor Poisson's ratios. The longitudinal, transverse and shear moduli of the boron/epoxy material used for this study are shown in Figure 2-3 and Figure 2-4 shows the variation of local buckling stress with layup. Further studies showed that a layup with approximately 80 percent 0-degree layers, 15 percent $\pm$ 45-degree layers and 5 percent 90-degree layers was close to optimum for the loads and geometries of the majority of tubes in the truss structure.

A relatively simple equation, which slightly over estimates the maximum stresses in the tube wall, was derived to account for the beam-column effects:

$$f_{MAX} = f \left(1 + \frac{2(M_1 + M_2)}{Pr} \Big/ \sin \pi(f/F_{col})^{\frac{1}{2}}\right) \tag{3}$$

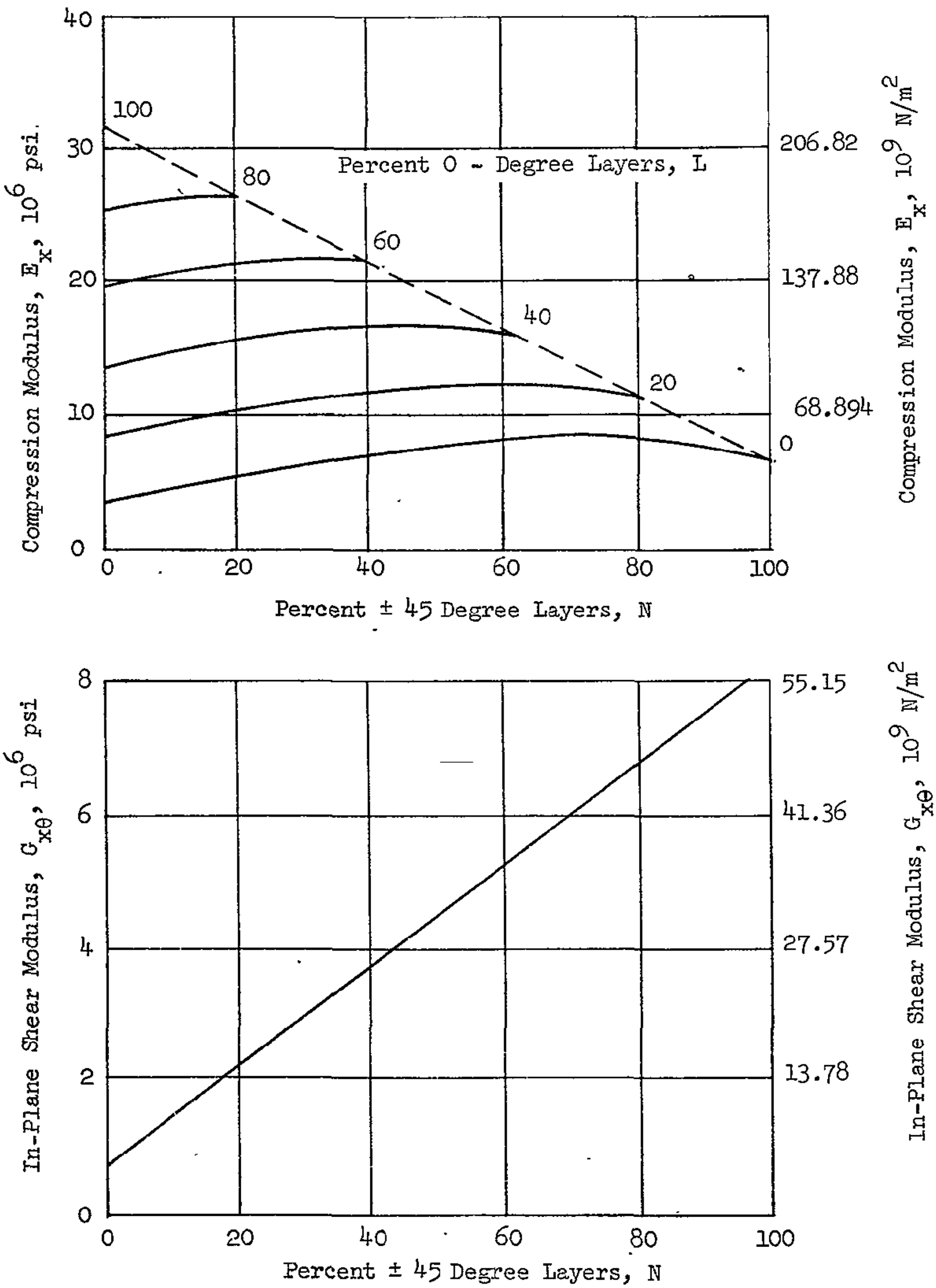

Figure 2-3 Compression and In-Plane Shear Moduli of Elasticity of Boron-Epoxy at Room Temperature

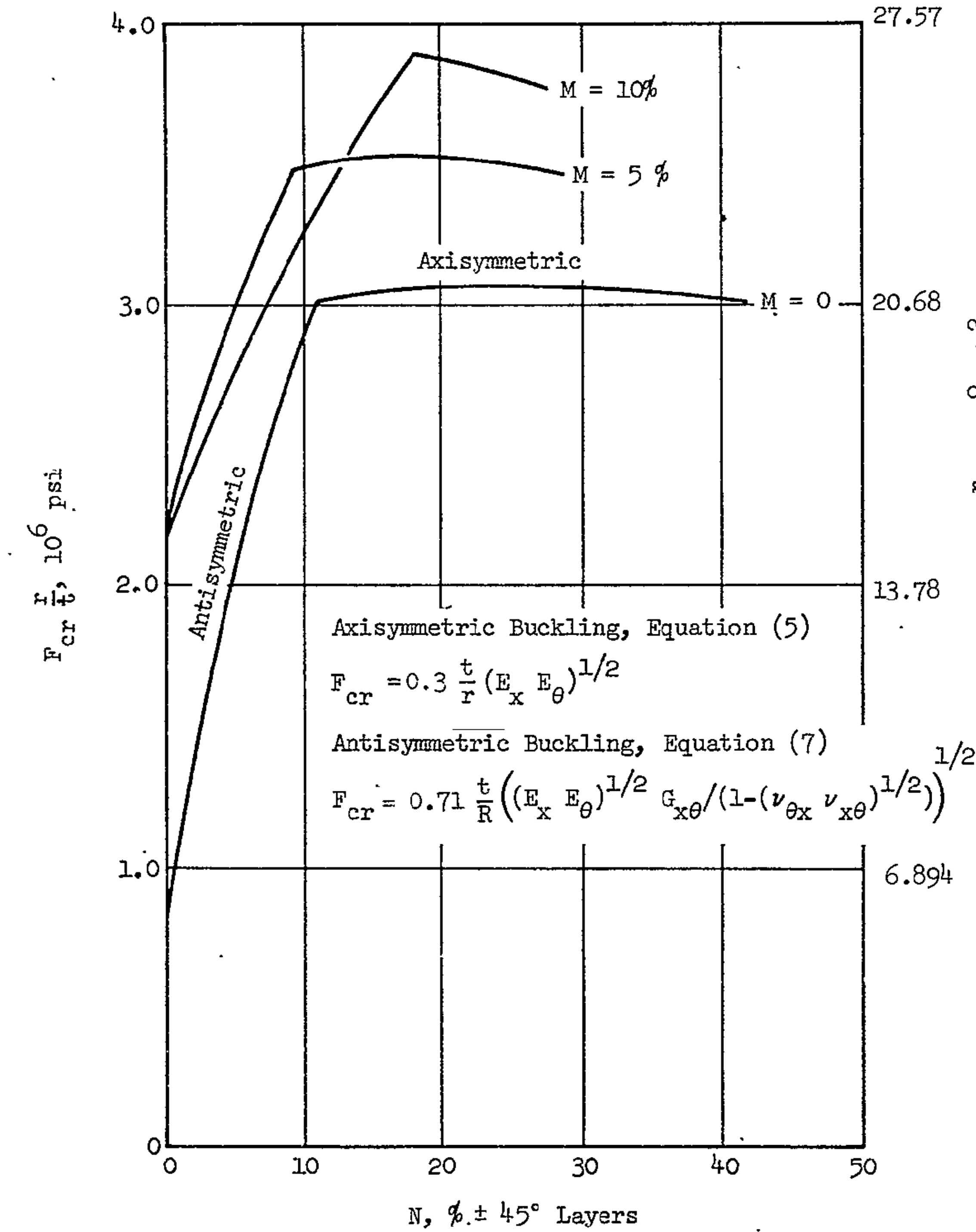

Figure 2-4 Local Instability of Boron-Epoxy Tubes

where f is the average applied stress (P/A). F_{col} is the overall instability stress given by:

$$F_{col} = \tfrac{1}{2} \Big/ \left(\frac{L^2}{\pi^2 E_x r^2} + \frac{1}{G_{x\theta}} \right) \tag{4}$$

With approximately 80 percent 0-degree layers, the ultimate compression strength, F_{cu}, of the boron/epoxy laminate was limited by the interlaminar shear modulus G_z of the laminate (Reference 3). Hence, using an average shear modulus of 2.205 x 10^9 N/m^2 (320 ksi) with a reduction factor of .78 for design:

$$F_{cu} = .78\ G_z = 1.723 \times 10^9\ N/m^2\ (250\ ksi) \tag{5}$$

To determine the optimum tube average stress and geometry, the lower value of local buckling stress obtained from either equation (1) or (2) was equated to the maximum applied stress, equation (3), and the ultimate strength, equation (5). The resulting equation, in terms of structural index, (P/L^2), applied end moment ratio, $(M_1 + M_2)/PL$ and average stress was solved using graphical techniques and resulted in the curves for optimum stress and geometry shown in Figure 2-5.

The tube geometries were then iteratively adjusted for the effects of the titanium end fitting splices and also for the results of a more refined computerized beam-column analysis which accounted for the variation in stiffness along the length of the tube.

Detail design of the bonded splices was also accomplished iteratively with the aid of a computer program. The splices were designed by first considering the basic tube laminate and loading intensity. Additional plies were added to the laminate and a number of steps was chosen. Using the results of an initial computer run, the number and location of plies, drop off rate, number of steps, step length and titanium thicknesses were all varied until a splice of desired strength was achieved. Two or three additional computer runs were normally required to complete the stepped joint design. The five step splice of both these members has a design strength of 3.93 x 10^6 N/M (22,436 lb./in.). The initial configuration of the subelement and tube specimens fabricated and tested under the Phase I program are shown in Figures 2-6 and 2-7.

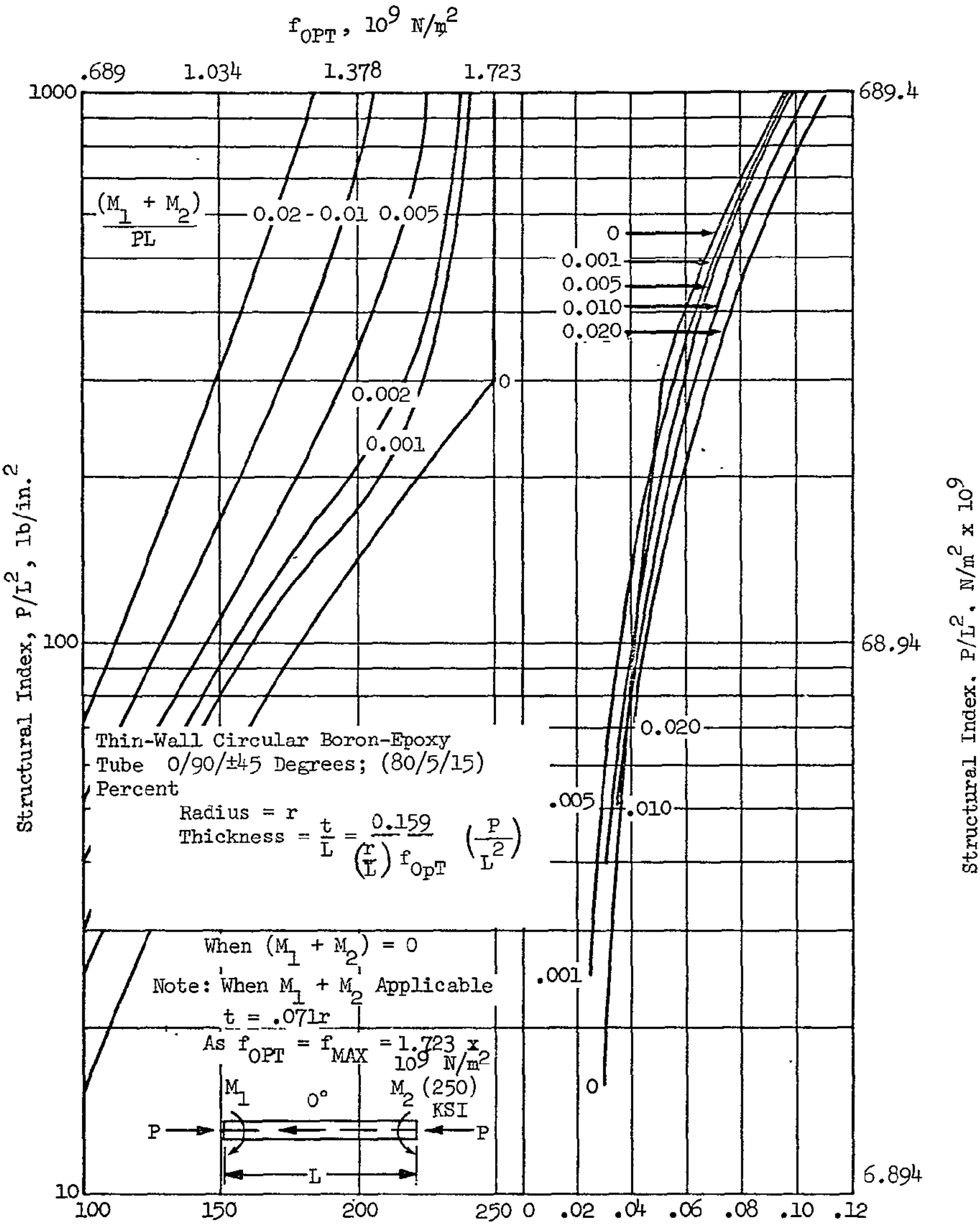

Figure 2-5 Optimum Geometry of Boron/Epoxy Tubes

Final assembly of the truss is made by bolting the ends of each of the tubes to the apex fittings. In order to maintain minimum length joints and minimum diameter tubes, 1.518×10^9 N/m^2 (220 ksi) steel bolts are used.

3.0 MATERIALS AND MANUFACTURING

3.1 Material Procurement

The material required for fabrication of the tubular members were:

- o Boron/epoxy preimpregnated tape
- o 6Al-4V annealed titanium plate
- o Metlbond 329 Type IA adhesive
- o 1.518×10^9 N/m^2 (220,000 psi) heat treat steel bolts
- o Steel nuts and nut retainers

The boron/epoxy tape was purchased to GAC specification GM3004A, Type IIIF and contained AVCO, North Wilmington, boron filament and the Narmco 5505 resin system. This material is now known commercially as AVCO Rigidite 5505. The titanium was purchased to MIL-T-9046, Comp. C and the adhesive to GAC specification GM4355. All hardware was in accordance with SPS standards.

3.2 Tool Design

Tool requirements for the program were as follows:

Subelement Mold Form (MOF)
Subelement Layup Mandrel (TFT)
Subelement Layup Template (LT)
Tube Specimen Mold Form (MOF)
Tube Specimen Layup Mandrel (TFT)
Tube Specimen Layup Template (LT)
Tube Wrapping Machine (MCA)
Splice Plate Weld Fixture (WF)

3.2.1 Mold Forms

The mold forms for the subelement tubes and the component tubes were similar in design. These were female molds split axially along the center line, the inside surface being the molding surface (Figures 3-1 and 3-2). The molds were rough machined from steel bar stock, with finish grinding of the mating surfaces. Both halves were then assembled with locating pins and cap screws. A flat pattern contour template was made

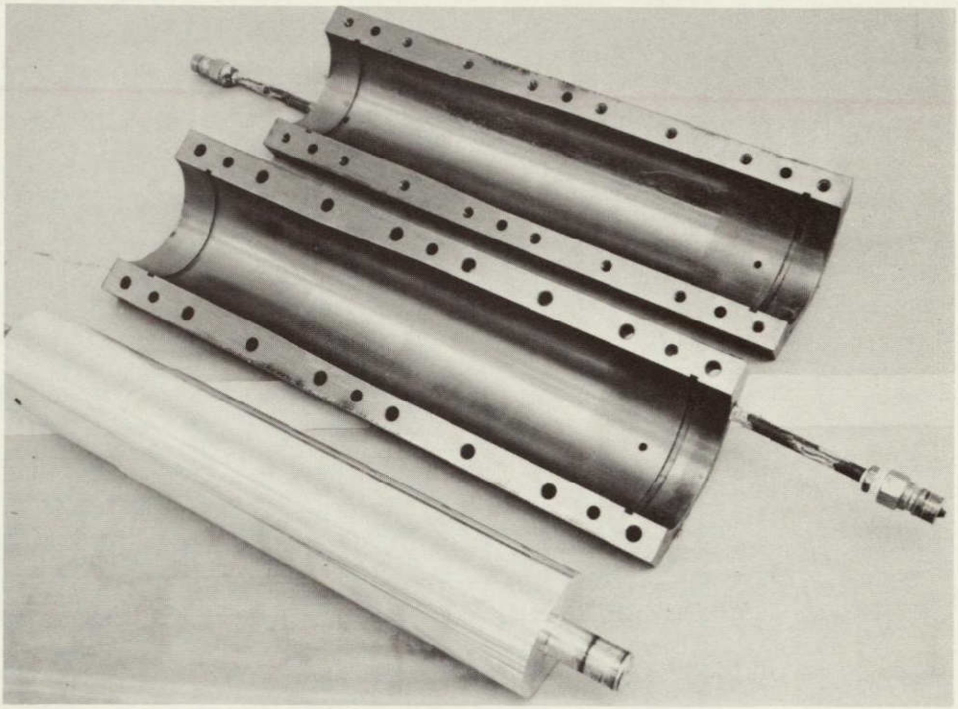

Figure 3-1 Subelement Mold Form and Layup Mandrel

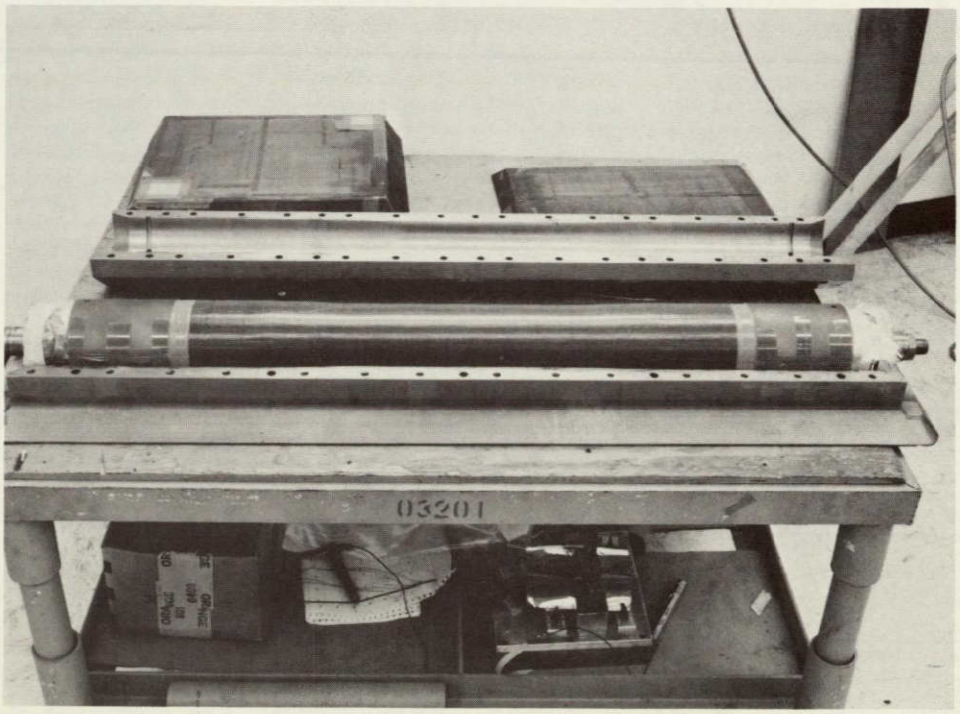

Figure 3-2 Tube Mold Form with Uncured Tube in Place

of the molding surface and checked for accuracy. The molding surfaces were then machined to finish dimensions using a tracing lathe. The split feature of the molds facilitated in-process inspection during final machining. Index holes, vacuum grooves, and vacuum fittings were then added.

3.2.2 Layup Mandrels

The subelement tube incorporated a splice plate at one end only, allowing the use of a solid layup mandrel. The mandrel was machined from aluminum bar stock (Figure 3-1). Indexing holes, provided for location of the splice plate halves, were coordinated with the subelement mold form. Removal of the mandrel from the laid-up subelement was accomplished by pulling it through the larger end of the tube.

The full tube incorporated splice plates at both ends. The inside diameter of the plates was smaller than the inside diameter at the center of the tube, causing the layup mandrel to be locked in. This necessitated the design of a breakaway type mandrel to allow removal prior to cure. This mandrel consisted of an arbor, two tapered plugs and a silicone rubber sleeve cast to the mandrel configuration. To remove this mandrel from the layup, the part was positioned in the mold, the mold closed and a vacuum was applied to the envelope bag. The arbor was then removed from one end, the tapered plugs were removed from each end, and the silicone sleeve was collapsed and pulled out. This type of mandrel design was selected over that of an all metal type because it could be easily adapted to different outside configurations and dimensional changes. Figure 3-3 shows the mandrel.

3.2.3 Tube Wrapping Machine

The tube wrapping machine is a hand operated tool that laid-up and compacted the boron tape on the tube layup mandrel. This tool consists of a wind-up roller, pressure roller, vacuum table and tube layup mandrel. Figure 3-4 shows the tube wrapping machine.

The tube fabrication procedure utilized with the wrapping machine was:

- o Apply boron tape to the mylar layup template
- o Position the template on the wrapping machine and attach to the wind-up roller
- o Apply vacuum to the template

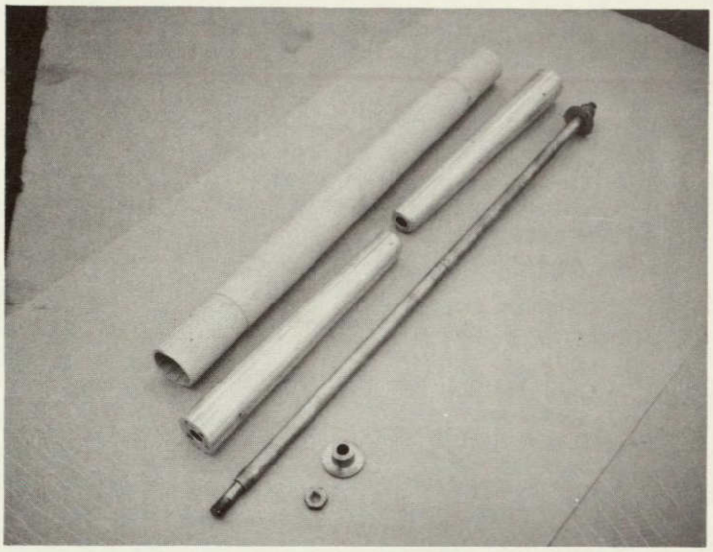

Figure 3-3 Tube Layup Mandrel

Figure 3-4 Tube Wrapping Machine

- o Wind template 2 turns on the wind-up roller
- o Position layup mandrel and adjust pressure roller
- o Turn wind-up roller until boron tape is fed between the layup mandrel and the pressure roller, transferring the tape to the mandrel

As the boron plies were transferred to the layup mandrel the circumferential length of each ply was checked by the use of witness lines on the layup template and the layup mandrel. When the layup was completed the wrapped mandrel was removed and transferred to the mold form, see Figure 3-2. This approach for wrapping the boron/epoxy plies was originally conceived for wrapping of straight wall tubes. The concept was modified for wrapping tapered tubes by the addition of tapered metal shims between the compaction roller and the boron/epoxy layup. A gauge was provided to check the longitudinal position of the plies during layup. Each wrapped ply was also checked in diameter for proper compaction during layup.

The machine was also employed to wrap the subelement tubes using additional pillars to support the shorter layup mandrel.

3.2.4 Layup Templates

A typical boron/epoxy tape layup template, for the subelements and the full tubes is shown in Figure 3-5. Information on the template includes ply number, ply trim, ply orientation, ply position, ply slit locations and template feed direction. To minimize handling problems, each template was made to include no more than five plies. Slitting of the boron/epoxy to accommodate the tapers presented no problem when wrapping the full plies although some repositioning of the slit portions was required before final compaction of the ply. Short plies did not wrap properly with the machine and had to be positioned by hand (Figure 3-4) before compaction.

3.2.5 End Fitting Weld Fixture

The electron beam welding fixture was a simple holding device that securely held the tube on the splice plate outside diameter. Splash bars were positioned inside the tube opening to prevent the electron beam from passing through to the opposite side of the splice plate.

Figure 3-5 Mylar Layup Template

3.3 Parts Fabrication

3.3.1 Titanium End Fitting Machining

The split, stepped, titanium end fittings for the subelements and full tube assemblies were fabricated as matched pairs from two blocks of surfaced titanium plate. Stock size was sufficient to allow bolting the plates together with an .715 mm (.030 inch) shim between the two plates. The assembly was 50.8 mm (2 inches) longer than the completed part, with the bolts being located in the 25.4 mm (1 inch) of excess material at either end. The bolts served to hold the parts together during the ensuing machining. After bolting the stock together, one end of the assembly was faced off to provide a reference plane from which all the steps for the internally bored diameters were located. After completion of the internal boring operation, the external diameters were turned on a lathe to drawing requirements. When completed, the excess material at each end of the part was cut away. The end fittings are shown in Figures 3-6 and 3-7. It should be noted that when the excess end material was parted from the end fittings the thinnest step of the fittings, at the seam, had a tendency to spring outward approximately 1 mm (.040 inch). The condition, which was local, resulted from material stress relief after machining and was not serious. An attempt was made to correct this condition on the first two sets of end fittings by discriminant use of the dry honing process. This proved ineffective and the remaining six sets of end fittings were utilized without any rework once it was determined that only slight finger pressure was required to overcome the sprung condition.

In addition to the titanium end fittings used for the actual tubes, three pairs of constant wall thickness fittings were fabricated for electron beam welding studies. Fabrication procedures for these fittings were similar to those previously described.

3.3.2 Electron Beam Welding Studies

Parametric studies were conducted to establish optimum machine settings for electron beam welding the titanium end fittings with the included shims and filler wire. The shims and filler wire are required to fill the gap between the titanium end fittings to minimize distortion and porosity. Full thickness titanium split rings were mounted in the welding fixture and

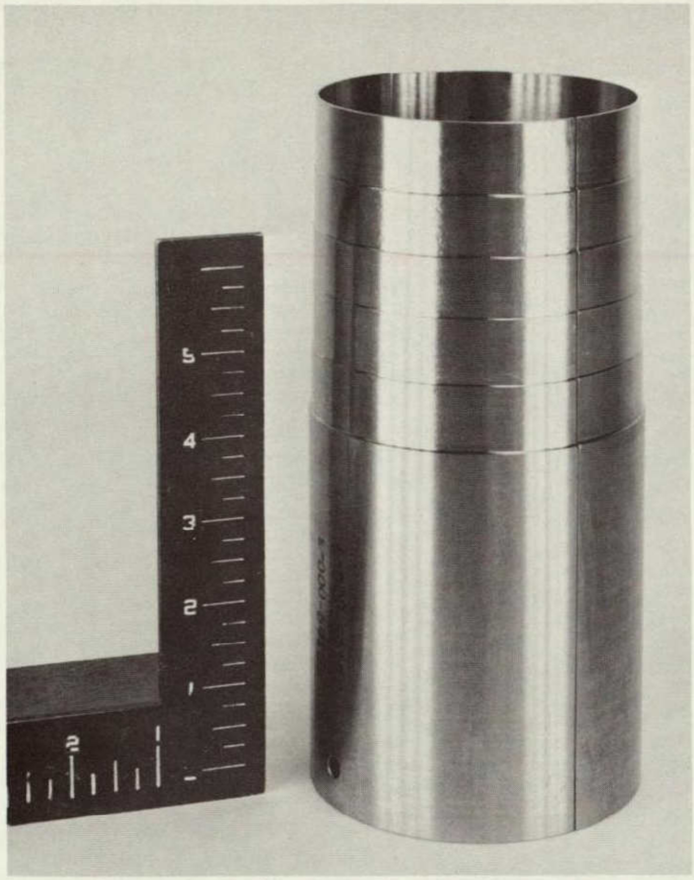

Figure 3-6 Titanium End Fittings

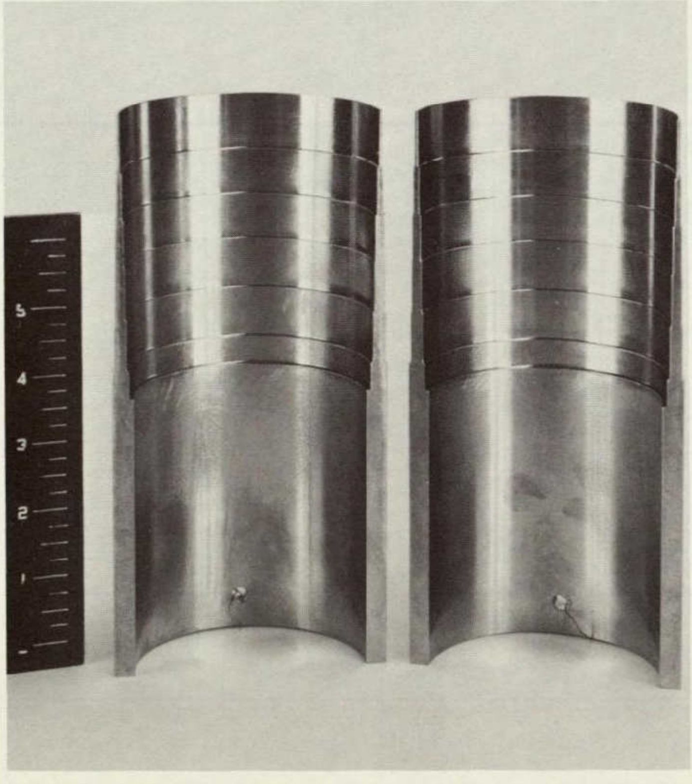

Figure 3-7 Titanium End Fittings

fitted with copper chill bars to serve as a heat sink. The sample welds were made and visually examined. When the optimized parameters had been established the trial welds were examined using production quality control techniques before any production parts were welded. This study showed that the process yielded high quality welds, which were consistently repeated on all subsequent subelements and full tube specimens.

3.3.3 Subelement Fabrication

Prior to fabrication of any actual boron/epoxy, a fiberglass replica of the subelement specimen was made using the same techniques that were to be used in manufacturing the actual parts. These techniques included slitting of the various plies necessary to compensate for the taper in the outside diameter, laying the plies on mylar, rolling the plies into a tubular configuration, inserting the split, stepped titanium end fitting and placing the completed assembly into the split female mold form. This producibility study was designed to highlight any potential fabrication problems which might be encountered on the actual parts.

Following successful fabrication of the fiberglass replica, laminating and bonding of subelement number 1 was initiated. This process was initiated by tightly wrapping a tubular nylon film bag on the layup mandrel. The bag was sized to extend 10 cm (4 inches) beyond each end of the mandrel and the excess material was rolled up. The various components of the bleeder system were cut to size, sewn into a continuous strip, and tightly wrapped onto the mandrel using the tube wrapping machine. This device had a spring loaded silicone rubber roller mounted beneath the wrap mandrel to exert pressure as the tube was being wrapped. A vacuum chuck was used to tension the mylar prior to wrap to assist in compacting the laminate. A takeup roll was provided to roll up the bare mylar after the boron/epoxy (B/Ep) had been wrapped. A locating gauge was mounted above the wrap mandrel to assure accurate positioning of the individual B/Ep plies relative to the steps in the titanium end fittings.

After the bleeders had been wrapped on the mandrel, the B/Ep tape was laid up on the mylar and inspected. Those plies which tapered were slit at half inch intervals so that they could open up in the splice plate area to accommodate the changes in part diameter. Each mylar contained several B/Ep plies, with nine mylars used for the thirty-six individual plies of B/Ep required. Each mylar in turn was placed on the vacuum chuck, and coordinated to the wrap mandrel by means of the locating gauge. The thickness of the part was measured at various stages to verify adequate wrap compaction necessary to insure insertion of the layup in the split mold with the required clearance. When all the B/Ep plies faying to the internal diameter face of the titanium end fittings had been wrapped, the end fittings, which had been pretreated by dry honing, immersion in Pasa Jel 107M and an application of EC2333 primer were coated with Metlbond 329, Type IA film adhesive, and positioned on the wrap mandrel. The fiberglass epoxy (Narmco 7743/2054 prepreg) shim plies were cut to size and wrapped onto the mandrel, followed by the remaining B/Ep plies needed to complete the layup operation. A nylon peel ply was added to the outside diameter of the element extending 3.25 cm (1.25 inch) from the B/Ep end before the assembly was placed in the split mold.

The split mold was overwrapped with fiberglass bleeder and the assembly was placed in a second nylon film sleeve. The excess bagging material was unrolled from the mandrel and sealed to the outer film sleeve with sealant tape. A vacuum was applied to expand the part sufficiently to permit removal of the mandrel. The bag was checked and a vacuum of 508 mm of Hg (20 inches of mercury) minimum was applied. Concurrently with the subelement, a solid B/Ep laminate and a B/Ep/titanium molded lap shear panel were laid up and bagged to serve as Process Verification Panels. The subelement and test panels were placed in an autoclave and cured using a carbon dioxide atmosphere as follows:

- Maintain 508 mm of Hg (20 inches of mercury) and heat assembly to 339°K (150°F)
- Apply 345×10^3 N/m^2 (50 psi) and reduce vacuum to 50.8 mm (2 inches of mercury)
- Heat assembly to 408°K ± 8.3°K (275 ± 15°F) in 30 ± 5 minutes and hold for 60 ± 10 minutes
- Increase assembly temperature to 449°K ± 5.5°K (350 ± 10°F) in 20 ± 10 minutes and hold for 90 ± 5 minutes
- Cool to 356°K (180°F) in not less than 40 minutes before releasing pressure
- Apply 508 mm of Hg (20 inches of mercury) and remove from autoclave
- Oven post cure at 463.7 °K $^{+5.5}_{-0}$ °K (375 $^{+10}_{-0}$ °F) for 4 hours ± 10 minutes

Visual examination of the completed subelement number 1 revealed the following:

- o The fibers in the exterior 90° ply were distorted in several localized areas
- o The presence of some small local voids, that appeared to be only in the surface 90° ply
- o Local discontinuities in surface resin layer
- o A resin rich wrinkle was present on the inside diameter near the plain B/Ep end indicating a possible disarray of the inner 90° ply
- o The per ply thickness was at the upper range of the specified limit

Subsequent ultrasonic inspection revealed an additional void in the area of the integrally molded B/Ep to titanium splice.

Materials and Process Engineering analysis of the defects resulted in several minor modifications to the manufacturing process. These modifications were:

- o The wrap mandrel diameter was reduced by .5 mm (.020 inch). This modification reduced the compaction required to permit placing the wrapped part in the mold and eliminated the resin rich wrinkle on the inside diameter caused by disarray of the bleeder system when the mandrel was removed.
- o The cure cycle was modified. The presence of the small local voids in the B/Ep, the single splice void and the relatively high per ply thickness regions were symptomatic effects of insufficient autoclave pressure necessary to expand the laminate against the mold form. This resulted in inadequate compaction. The 345×10^3 N/m^2 (50 psi) curing pressure used had been successfully used to mold over a hundred solid B/Ep tubes. The subelement however, with its titanium splice plates and increased gage, required use of higher pressure. Therefore, future parts were subjected to a 2 hour hold at 325°K (125°F) and 863×10^3 N/m^2 (125 psi) to insure proper seating of the part against the mold prior to beginning the resin cure cycle, which used 518×10^3 N/m^2 (75 psi).

- o Nylon peel ply was applied to the full length of the B/Ep outside diameter to eliminate apparent surface porosity.

The above noted modifications were used for fabrication of subelement number 2, see Figures 3-8 and 3-9, and proved to be effective. Subsequent inspection revealed a high quality part, without any of the defects noted on subelement number 1.

Following laminating and bonding the various operations necessary for the completion of the subelements were performed. The initial operation, which involved electron beam welding of the two halves of the titanium end fittings was typical for both subelements. Titanium surface preparation prior to welding was:

- o Mechanically cleaning the gaps between the two semicircular end fittings to remove excess adhesive and resin flow from the laminate cure process
- o Immersion in an alkaline cleaner at 338.7°K (150°F) followed by rinsing and drying
- o Immersion in an acid etch pickeling bath (HNO_3 followed by rinsing and drying

The tube was then set up in the electron beam welding chamber and a vacuum applied. Welding of the end fittings was initiated 12.7 mm (.50 inch) from the boron epoxy/titanium interface, extending approximately .1016 m (4.0 inches) to the end of the part. Welding parameters were determined earlier in the program using replicas of the actual parts. The welds were found to be void free upon X-ray examination.

The remaining operations involved finish machining of the subelements and potting of the B/Ep ends to prevent end brooming under test. Finish machining included net trimming of both the boron and titanium ends, as well as drilling two 6.35 mm diameter (.25 inch diameter) weld stop holes. B/Ep trimming was accomplished by placing the potted subelements on an expandable silicone rubber mandrel equipped with steel end plates. The assembly was set-up in a Cincinnati number 2 cutter-grinder fitted with

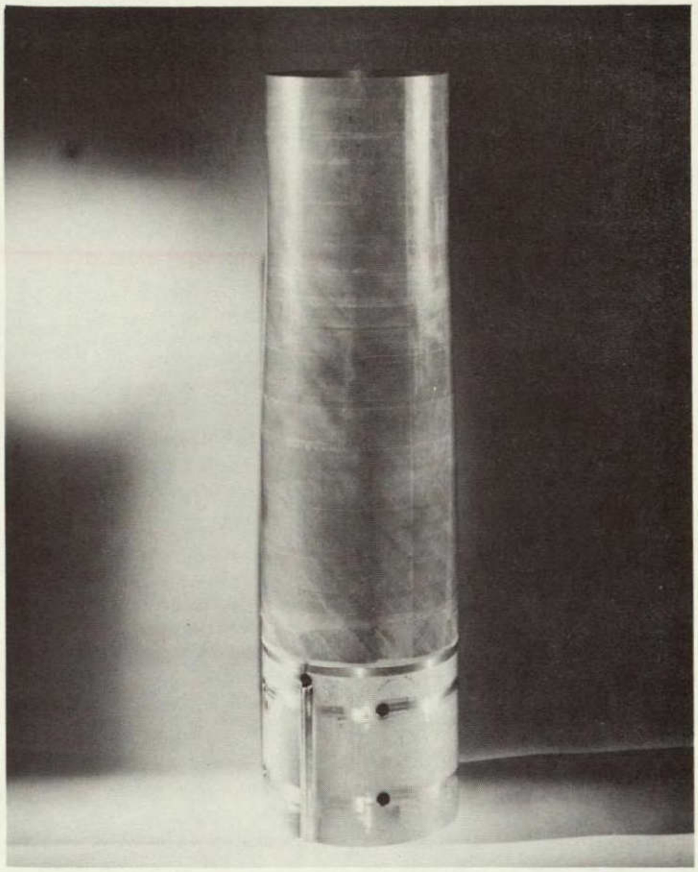

Figure 3-8 Subelement Number 2

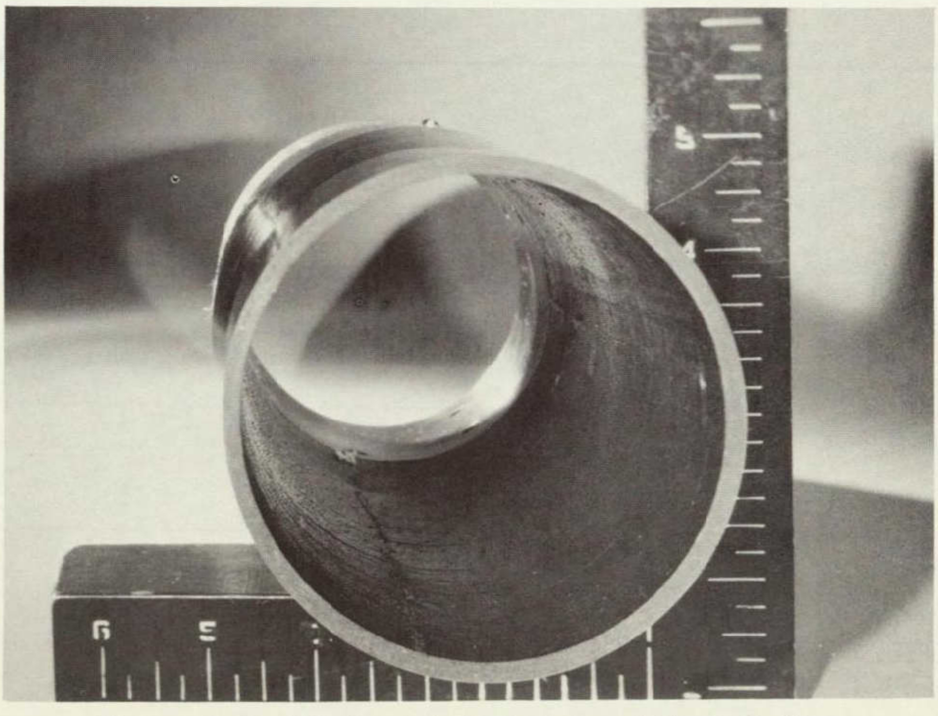

Figure 3-9 Subelement Number 2 - Internal View

an .2032 m diameter (8 inch diameter) 60 grit diamond wheel. The head was rotated 90 degrees to the axis of the mandrel and the B/Ep was cut to length. The excess 25.4 mm (1.0 inch) of titanium was removed by a conventional turning operation. Tolerances maintained on flatness and parallelism for the B/Ep end cut was .0254 mm (.001 inch).

Due to the different manner in which the tests were conducted, there were some differences in the final machining of subelement numbers 1 and 2. The inside diameter of the titanium end fitting of subelement number 2 was finish turned to remove the weld flash and to true-up the mating surface to accept the test fitting. After finish turning the eight bolt holes, which attached the subelement to the test fixture, were laid out and drilled. The holes were pilot drilled undersize, 6.35 mm (.25 inch) in diameter and opened up on assembly. These two operations were not performed on subelement number 1.

A total of three anti-brooming configurations were used for the two subelements. A description of each is as follows:

- Configuration Number 1 - The outside diameter of the B/Ep end was potted with stepped, continuous, circumferential wraps of 7743/2054 fiberglass epoxy for the initial test of subelement number 1. This operation was initiated by removal of the local layer of peel ply from the tube and application of one layer of Metlbond 329 adhesive. The fiberglass overwrap was laid up over the adhesive and vacuum bag cured. The inside diameter was potted with TC94351/TH2-3520, room temperature curing potting compound, per GAC specification GM4006 and an aluminum ring. Aluminum pretreatment, prior to assembly, consisted of immersion in non-etch alkalai and dichromate baths. The part was subsequently tested, and a premature brooming failure occurred.
- Configuration Number 2 - Subelement number 1 was mounted on a mandrel, set up in a cutter grinder and the damaged B/Ep end removed with a diamond grit circular blade. Subsequent

to the trimming operation, the composite end of the subelement was ground flat and parallel to the titanium end, within .0254 mm (.001 inch). Concurrent with this rework a steel anti-brooming end fixture was fabricated. The steel fixture was machined with a circular groove 9.53 mm (.375 inch) in depth and a diameter equal to that of the subelement, plus .254 mm (.010 inch). After machining, the end fixture was heat treated to R_c 55 hardness and the base of the groove checked for flatness (within .0254 mm (.001 inch)) and parallelism (within .0254 mm (.001 inch)) to the base of the end fixture. The two parts were assembled by potting the subelement into the groove in the end fixture with Epon 934 epoxy adhesive and cured under ambient conditions at a load of 22,200 N (5000 pounds) in a hydraulic press. Silicone rubber pads were used to take up any irregularities in the platen surfaces. The part was again tested with good results (failure occurred in tube section without any evidence of brooming).

- Configuration Number 3 - The anti-brooming device utilized for subelement number 2 was a combination of the two configurations used for the test of subelement number 1. The 90° fiberglass overwrap was retained and was located immediately adjacent to the grooved steel end fixture. Processing of the assembly of this combination anti-brooming device was as previously described, except that the potting material was changed to the more fluid and castable Epocast 8052/9226 system in lieu of Epon 934.

It should be noted that one additional difference existed between subelement numbers 1 and 2. A local 25.4 mm (1.0 inch) wide, 3 ply, 90° B/Ep overwrap was added to subelement number 2 at the laminate transition point. Incorporation of the overwrap was dictated by test results of subelement number 1. A secondary bond and cure cycle using vacuum bag pressure only was employed to install the overwrap.

3.3.4 Tube Fabrication

Tube number 1 was laid-up and cured using the same two step molding cycle successfully used on subelement number 2. Visual inspection of this part revealed some surface voids and subsequent N.D.T. inspection indicated the presence of some discontinuities in the bonded splice at one end of the tube only. Materials and Process Engineering evaluation of the discrepancies attributed the cause to insufficient prepreg expansion in conjunction with the larger part size, resulting from:

- Use of a continuous wrap bleeder system
- Deficient pressure/temperature relationship
- Continuous wrap of the external 90° B/Ep ply

As a result of this analysis, process changes for fabrication of tube numbers 2 and 3 were recommended and incorporated. These changes were:

- Replacement of the fiberglass bleeder systems with overlapping strips of 6.34 mm (1/4 inch) wool felt
- An increase in the temperature during the expansion step of the molding cycle from 324.8°K (125°F) for two hours to 366.4°K (200°F) for one hour, while maintaining the 863×10^3 N/m^2 (125 psi) pressure.
- Splitting the external 90° ply longitudinally, such that the ply is laid up in two halves with each half lapping itself by 12.68 mm (.50 inch).

Tube numbers 2 and 3 were subsequently laminated and cured using these process modifications. The process modifications were effective, visual inspection revealing high quality parts and ultrasonic non-destructive test showing that the parts were free of discontinuities. Figure 3-10 shows tube number 2.

Processing for the tubes in the areas of wrapping, electron beam welding, finish machining of the titanium end fittings and assembly of the 90° B/Ep overwrap were all similar to methods previously described for the subelements.

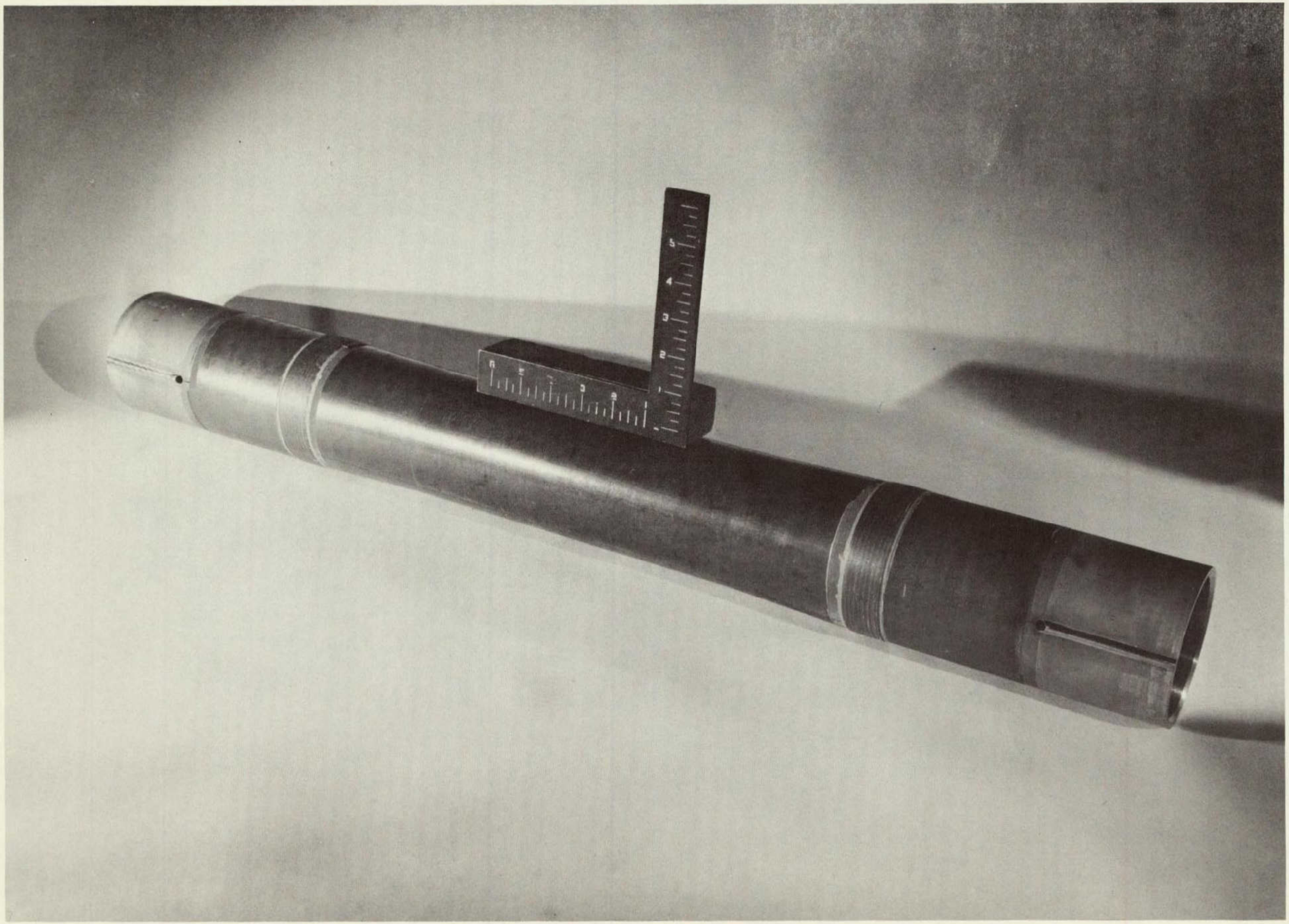

Figure 3-10   Tube Number 2

4.0 QUALITY CONTROL

4.1 Destructive Testing

4.1.1 Receiving Inspection

All incoming materials were inspected in accordance with procedures described in the applicable Grumman Material Specifications (GM). The boron reinforced preimpregnated materials were inspected per GM3004, Type IIIF. The testing required for this inspection included physical and mechanical property determinations. The mechanical properties checked were longitudinal and transverse flexural strength and modulus at 297°K (75°F) and at 463°K (375°F). Horizontal shear strength tests were performed at 297°K (75°F) only. The physical properties tested were resin content, volatile content and flow. The properties measured on the material utilized are recorded in Table 4-1.

Eleven thousand and seventy four feet of Rigidite 5505 boron preimpreganted tape was received and tested. One transverse flexure specimen tested at room temperature failed lower than the minimum requirements. Engineering was presented the test data and accepted the material after an evaluation of the vendor test results and the results of tests performed at Grumman.

4.1.2 Process Control

Process verification test tabs were processed with each autoclave cycle to verify that the adhesives and organic matricies were adequately cured. Testing was conducted at room temperature on coupons from:

- A unidirectional 15 ply test panel fabricated from the same batch of tape and undergoing the same cure cycle as the part. Coupons from this panel were tested for longitudinal flexural strength, modulus and horizontal shear strength.
- A B/Ep to titanium lap shear panel, utilizing the same adhesive and cure cycle as the part. These coupon tests verify the adhesive cure for the integrally molded B/Ep to titanium splice.

All tests were satisfactory, except for one longitudinal flexure specimen for subelement number 2 which was 4% below the minimum required strength. The results were presented to engineering for disposition and the part was accepted. Test results are shown in Table 4-2.

Batch No.	Roll No.	Panel No.	Long. Flex.				Trans. Flex.				Horiz. Shear Stren.	Resin Cont. %	Resin Flow %	V'tle Cont. %
			Strength $N/m^2 \times 10^9$		Modulus $N/m^2 \times 10^9$		Strength $N/m^2 \times 10^9$		Modulus $N/m^2 \times 10^9$					
			297°K (75°F)	463°K (375°F)	297°K (75°F)	463°K (375°F)	297°K (75°F)	463°K (375°F)	297°K (75°F)	463°K (375°F)	297°K (75°F)			
42	5	B-550	1.6295 (246)	1.433 (208)	195 (28.4)	168 (24.5)	.0903 (13.1)	.0799 (11.6)	18.68 (2.71)	8.61 (1.25)	.1165 (16.9)	32.2	9.4	1.50
			1.682 (244)	1.433 (208)	191 (27.8)	165 (24.0)	.0854 (12.4)	.0744 (10.8)	17.99 (2.61)	8.54 (1.24)	.1178 (17.1)			
			1.723 (250)	1.468 (213)	198 (28.8)	172 (25.0)	.0916 (13.3)	.0744 (10.8)	18.47 (2.68)	9.30 (1.35)	.1151 (16.7)			
Min. Req'd Per GM3004			1.654 (240)	1.103 (160)	186 (27)	137 (20)	.0896 (13)	.0551 (8)	13.78 (2)	5.51 (.8)	.0896 (13)	32±2	12±3	.3-1.7

NOTE: Values in parenthesis are ksi for strength and psi x 10^6 for modulus.

Table 4-1 AVCO Rigidite 5505 Receiving Inspection Data

Table 4-2 Process Control Test Data

Batch/ Roll No.	Part No.	B/Ep to Ti Shear $N/m^2 \times 10^6$ (psi)	Longitudinal Flex. Strength $N/m^2 \times 10^9$ (psi $\times 10^3$)	Longitudinal Flex. Modulus $N/m^2 \times 10^9$ (psi $\times 10^6$)	Horiz. Shear Strength $N/m^2 \times 10^6$ (psi $\times 10^3$)
375/5	SE No. 1	16.68 (2420) 15.58 (2260) 19.30 (2800) 19.44 (2820) 19.17 (2780)			
42/4			1.758 (255) 1.696 (246) 1.703 (247) 1.668 (242) 1.675 (243)	187.5 (27.2) 186.1 (27.0) 189.6 (27.5) 186.1 (27.0) 187.5 (27.2)	102.7 (14.9) 102.7 (14.9) 95.1 (13.8) 102.0 (14.8) 105.5 (15.3)
375/4	SE No. 2	17.51 (2540) 17.79 (2580) 17.30 (2510) 16.27 (2360) 19.44 (2820)			
42/4			1.716 (249) 1.786 (259) 1.744 (253) 1.593 (231) 1.675 (243)	194.4 (28.2) 193.7 (28.1) 188.9 (27.4) 188.9 (27.4) 198.5 (28.8)	112.4 (16.3) 108.2 (15.7) 107.5 (15.6) 106.2 (15.4) 106.2 (15.4)
387/20	Tube No. 1	20.61 (2990) 19.37 (2810) 20.54 (2980) 20.82 (3020) 20.06 (2910)			
42/22			1.744 (253) 1.661 (241) 1.675 (243) 1.682 (244) 1.724 (250)	192.3 (27.9) 192.3 (27.9) 186.1 (27.0) 189.6 (27.5) 190.3 (27.6)	110.3 (16.0) 110.3 (16.0) 108.2 (15.7) 112.4 (16.3) 113.8 (16.5)
387/21	Tube No. 2	22.20 (3220) 23.30 (3380) 25.58 (3710) 24.06 (3490) 22.82 (3310)			
42/7			1.744 (253) 1.799 (261) 1.820 (264) 1.848 (268) 1.730 (251)	203.4 (29.5) 197.2 (28.6) 199.2 (28.9) 206.1 (29.9) 196.5 (28.5)	109.6 (15.9) 108.2 (15.7) 106.2 (15.4) 106.2 (15.4) 98.6 (14.3)

Table 4-2 Process Control Test Data (Continued)

Batch/ Roll No.	Part No.	B/Ep to Ti Shear $N/m^2 \times 10^6$ (psi)	Longitudinal Flex. Strength $N/m^2 \times 10^9$ (psi x 10^3)	Longitudinal Flex. Modulus $N/m^2 \times 10^9$ (psi x 10^6)	Horiz. Shear Strength $N/m^2 \times 10^6$ (psi x 10^3)
387/27	Tube No. 3	19.30 (2800)			
		22.40 (3250)			
		22.00 (3190)			
		22.40 (3250)			
		22.13 (3210)			
42/7			1.668 (242)	198.5 (28.8)	109.6 (15.9)
			1.675 (243)	191.0 (27.7)	109.6 (15.9)
			1.682 (244)	195.1 (28.3)	109.6 (15.9)
			1.655 (240)	187.5 (27.2)	108.2 (15.7)
			1.710 (248)	195.1 (28.3)	116.5 (16.9)
Minimum Required Per SPG-011		15.17 (2200)	1.655 (240)	186.1 (27.0)	89.6 (13.0)

4.2 In-Process Inspection

The fabrication of all test specimens, beginning with the storage and distribution of materials, and continuing through the manufacturing cycles of layup, cure and machining was under continuous quality control surveillance. All prepreg and adhesive materials were stored at 0°F and distributed only by the Quality Control Group. This insured that only materials known to be acceptable were used. The layup of all panels was monitored, each individual ply being examined for proper fiber orientation. Operation sheets assured the sequence of manufacture. Permanent records of time, temperature, pressure, and vacuum were maintained during all cure cycles to make sure that each run complied to the prescribed cycle. The dimensions of all machined specimens were measured to assure conformance with the governing engineering drawings.

4.3 Non-Destructive Testing

The required non-destructive testing (N.D.T.) performed on each tube was accomplished using through-transmission reflection ultrasonics. The criteria employed were:

- Laminates - The maximum permitted void or delamination shall not exceed 12.70 mm (0.50 inch)
- Adhesive Bonded Joints - The maximum permitted void or delamination shall not exceed 6.35 mm (0.25 inch)

The through-transmission reflection technique involves the use of a transducer located on one side of the laminate and a reflector plate on the other side. Sound energy is transmitted from the transducer, reflected off the reflector back through the laminate and collected by the same transducer. Low frequency focused transducers (2.25 MHz) were employed. If a defect is present, it presents an interface which blocks a proportional amount of the acoustic energy from reaching the reflector. This results in a loss of sound energy reflected back to the transducer, which in turn produces an attenuated signal on the cathode ray tube. The Quality Control standard used for evaluation of the parts in conjunction with the through-transmission reflection technique, is shown in Figure 4-1. The standard simulates the parts and contains designed in defects. In addition x-radiography was employed to assess the integrity of the electron beam welded joints.

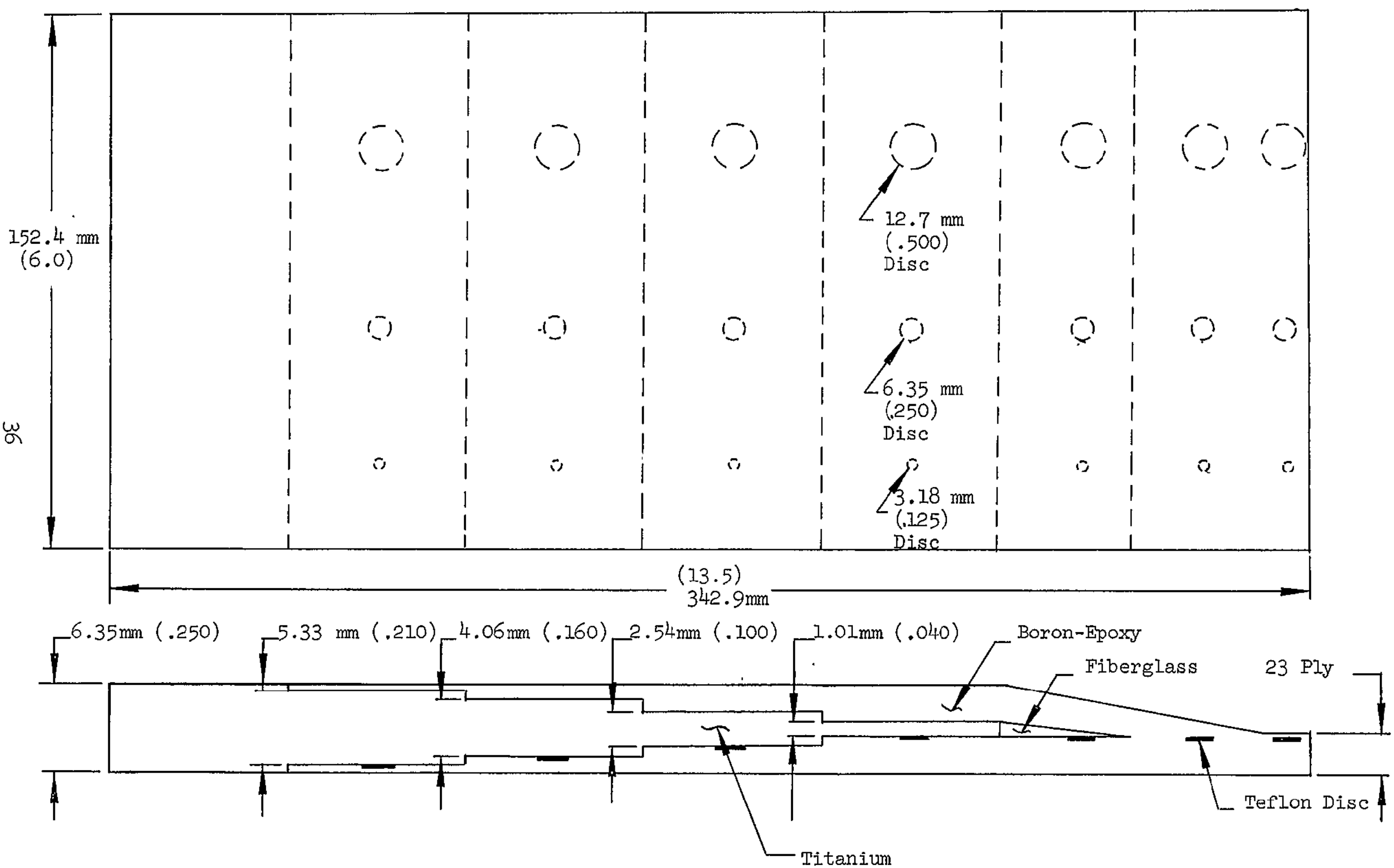

Figure 4-1 Ultrasonic Test Standard

4.3.1 Subelement and Tube N.D.T.

Subelement number 1 was found to contain one large void (approximately 5.08 cm (2 inches) x 12.70 cm (5 inches) in the area of the integrally molded titanium splice plate. Subelement number 2 was scanned and found to be free of any ultrasonic discontinuities. Tube number 1 was found to contain numerous surface voids by visual examination. In addition an area approximately 5.08 cm (2 inches) x 10.16 cm (4 inches) in the splice plate region showed ultrasonic discontinuities. Tube numbers two and three were found to be free of any ultrasonic discontinuities.

5.0 TEST AND FAILURE ANALYSIS

5.1 Subelement Testing

The results of static testing the subelement specimens, along with failure descriptions are presented in Table 5-1.

5.1.1 Test Procedure

Two subelement specimens, each representative of the B/Ep to titanium joints at the tube ends, were statically tested under uniaxial compression loading. The specimens were individually installed in a universal testing machine and subjected to test loading at a rate of $.4448 \times 10^6$ N/minute (100,000 lb/minute). Loading continued until major failure occurred.

Original plans were to attach a steel end fitting to the titanium end of each specimen in a manner representing the attachments in the three-dimensional one-third scale thrust structure. Figure 5-1 details the fitting installation. However, due to the reported irregularities in the first subelement and since no problem was anticipated at the bolted joint, it was decided to test the specimen without the steel fixture at the titanium end. In addition, an early test would indicate any load introduction problems at the potted end of the tube. The second-subelement specimen, which was a high quality part, was tested with the associated fixturing attached.

5.1.2 Subelement Tests and Failure Analysis

The first subelement specimen attained a load of $.7232 \times 10^6$ N (162,600 pounds, or 70 percent design ultimate load (DUL)) at which time a brooming type failure occurred at, and was contained in, the immediate vicinity of the potted end of the specimen. Figure 5-2 shows the specimen set up in the testing machine, prior to testing. After test the failed section of the B/Ep was removed and the specimen re-potted into a grooved steel end fixture. Figure 5-3 shows the specimen after rework and prior to retest. At an applied compressive load of $.7561 \times 10^6$ N (170,000 pounds, 74 percent DUL) failure occurred. Figure 5-4 shows the failed specimen. The primary failure was located in the B/Ep approximately 25.4 mm (1 inch) from the potted end, and extended circumferentially around the specimen.

Table 5-1 Summary of Test Results, Subelement and Tube Specimens

Specimen		Design Ultimate Loads		Failure Loads		MS	Remarks
		Axial	Bending Moment	Axial	Bending Moment		
Subelements	AD169-1000, No. 1	1.023×10^6N (230,000 lb.)	None	0.7561×10^6N (170,000 lb.)	None	-.26	Compressive Failure in Laminate
Subelements	AD169-1000, No. 2	1.023×10^6N (230,000 lb.)	None	1.254×10^6N (282,000 lb.)	None	.23	Splice Failure
Tubes	AD169-1001, No. 1	$.9118 \times 10^6$N (205,000 lb.)	2.626×10^3N-M (23,197 in.-lb.)	0.6703×10^6N (150,700 lb.)	1.932×10^3N-M (17,104 in.-lb.)	-.26	Compressive Failure at Center of Tube
Tubes	AD169-1001, No. 2	$.9118 \times 10^6$N (205,000 lb.)	2.626×10^3N-M (23,197 in.-lb.)	1.1053×10^6N (248,500 lb.)	3.187×10^3N-M (28,205 in.-lb.)	.21	Splice Failure at Upper Fitting
Tubes	AD169-1001, No. 3	$.9118 \times 10^6$N (205,000 lb.)	2.626×10^3N-M (23,197 in.-lb.) (Note 1)	1.084×10^6N (243,750 lb.)	3.126×10^3N-M (27,666 in.-lb.) (Note 1)	.19	Splice Failure at Upper Fitting

NOTE: 1 - Moments shown are for upper fitting only. Lower fitting moment at design ultimate load is 1.056×10^3 N-M (9,027 in.-lb.) and at failure 1.214×10^3 N-M (10,742 in.-lb.).

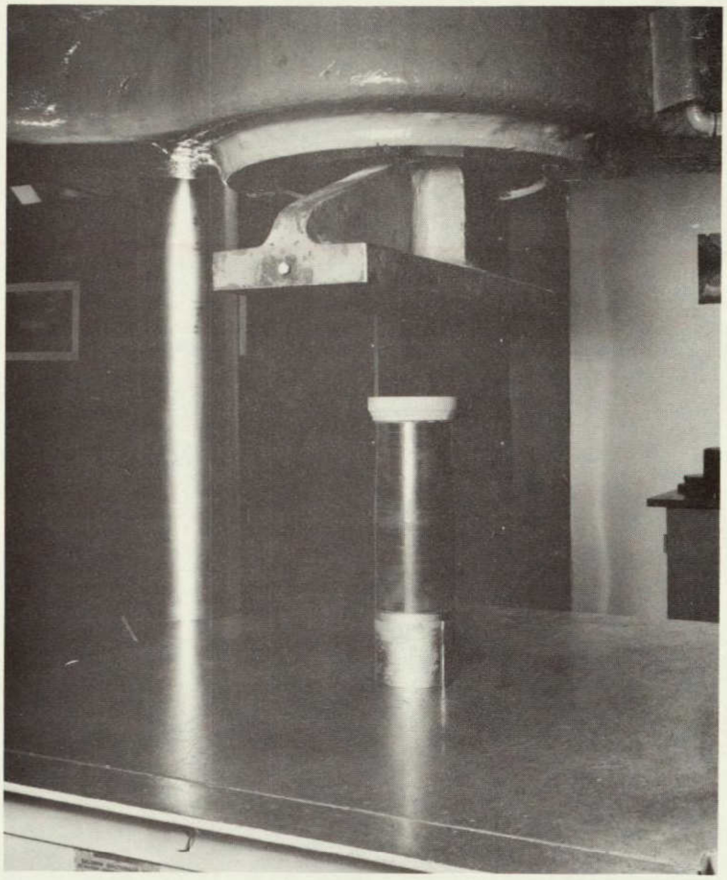

Figure 5-2 Subelement Number 1 Prior to Test

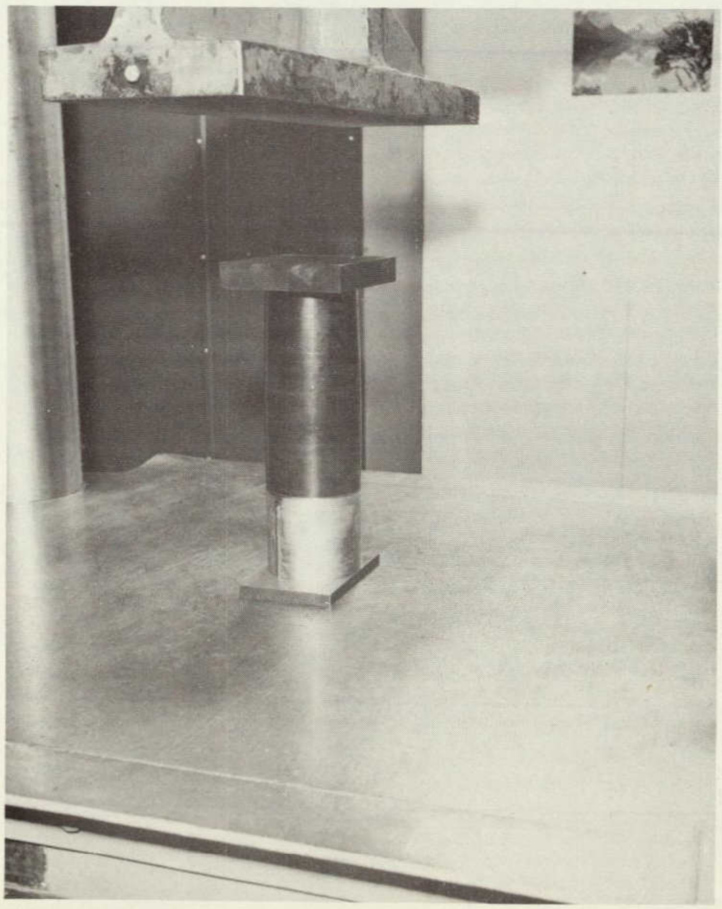

Figure 5-3 Subelement Number 1 After Rework

Figure 5-4 Side View of Failed Subelement Number 1

Internal inspection of the specimen indicated that failure of the boron laminate did not extend through the entire thickness. There are two possible explanations for this failure:

- The steel end fixture provided sufficient restraint to radial growth to induce bending stresses in the tube wall, which would relieve the compressive stress on the inner surface and increase the stress on the outer surface. In an effort to minimize the induced bending stress, the boron end of subelement number 2 was reinforced by a 90° fiberglass overwrap (identical to that used for the first test of this subelement).

- The presence of some local circumferential delaminations, noted when the part was trimmed, approximately 4-6 plies in depth could reduce the effective thickness of the tube wall and thus the instability stress.

A second failure, extending over the B/Ep to titanium bonded joint at the juncture of the titanium fitting halves, was also noted. This failure originated at the initial splice transition point (load kick point) and progressed approximately 102 mm (4 inches) toward the titanium end. Again, internal inspection of the specimen revealed that the failure did not progress through the entire laminate thickness. The failure appeared to be tensile in nature, which prompted an investigation of induced hoop tension stresses at the load kick point. Results of the analysis showed that hoop stresses could have been developed which were sufficiently large to cause failure of the outer 90 degree ply. The following assumptions were made for this analysis:

- Only the exterior 90° ply was assumed effective in resisting the hoop tension load resulting from the splice transition
- The length over which the load was reacted was no greater than 6.35 mm (.25 inch).

As a result of this investigation, all remaining test specimens were reinforced locally at the transition point by a 3 ply 90° wrap, 25.4 mm (1 inch) wide. The overwrap was installed using secondary bond and cure cycles.

A third observed failure, which was the disbonding of the boron from the internal last step of the splice, was noted after the specimen was removed from the test rig. This was probably a secondary failure resulting from the outer ply failures at the boron end.

In conclusion, it was felt that the cause of premature primary failure was not typical, and could be attributed to the presence of delaminations at the boron end of the tube, resulting from the previous test and the quality of the boron laminate.

The second subelement/test fixture assembly, installed in the universal testing machine, is shown in Figure 5-5. For this test a electromechanical deflection measuring device was mounted on the test platform and set-up to record axial deflection. At an applied compressive load of 1.254×10^6 N (282,000 pounds, 122 percent DUL) failure occurred. The failure was located and contained in the immediate vicinity of the upper boron-titanium stepped bonded splice. The failed specimen is shown in Figure 5-6. A plot of specimen axial deflection versus applied load is presented in Figure 5-7.

The failing load predicted using the "STEP*" computer program is 1.209×10^6 N (271,933 pounds) for compression yield in the titanium at the end of step 4. The failure load was within 4% of this predicted load. A possible sequence of events leading to the failure is, at 1.209×10^6 N (271,933 pounds) the titanium at step 4 yielded and a redistribution of load took place, increasing the load in the boron on the adjacent steps. The specimen continued to take load until the load in the boron exceeded its capability and the ultimate failure was compression in the boron. Had there not been any redistribution of load the predicted failing load of the boron would be 1.298×10^6 N (292,000 pounds) or 4% greater than the actual failing load.

Upon disassembly of the test fixture, permanent shear deformation was found in each of the eight bolts connecting the tube to the steel fixture. The bolt holes in both the titanium and steel fittings also showed signs of yielding. This yielding, of both end fittings and bolts, is seen in the load versus deflection plot (Figure 5-7).

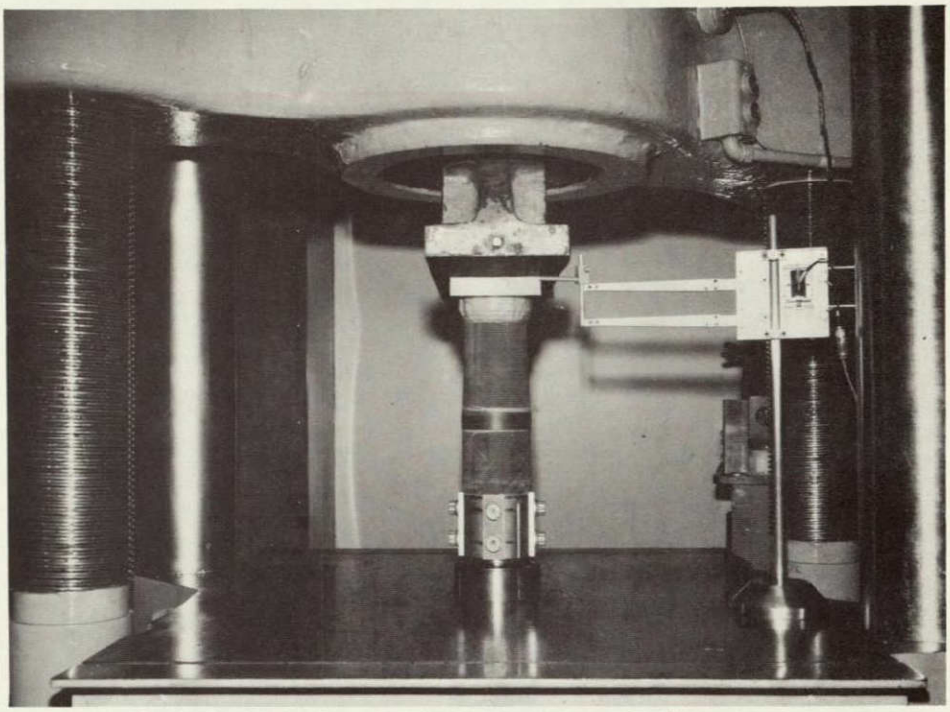

Figure 5-5 Subelement Number 2 Prior to Test

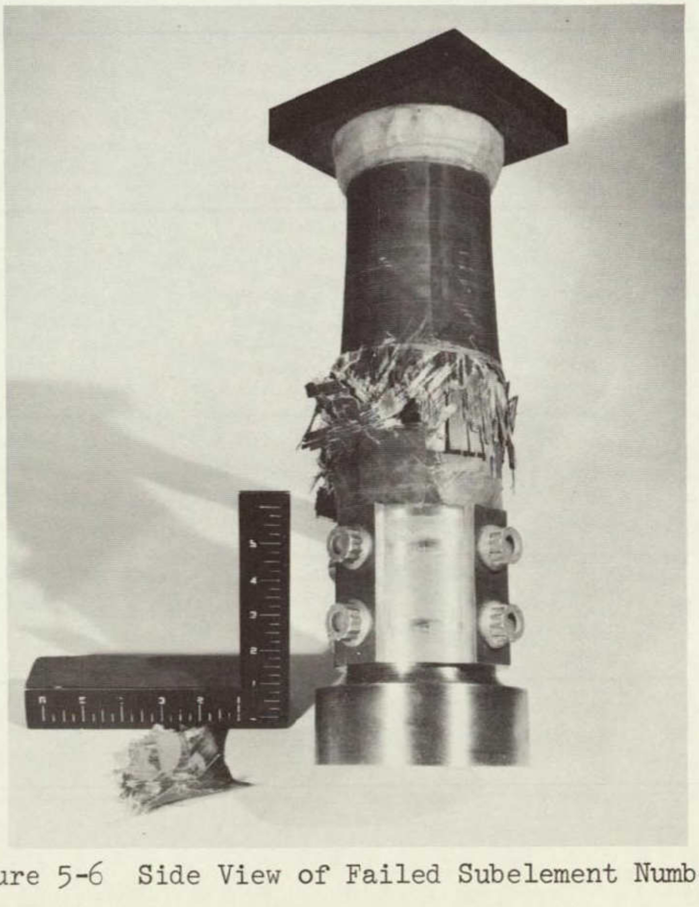

Figure 5-6 Side View of Failed Subelement Number 2

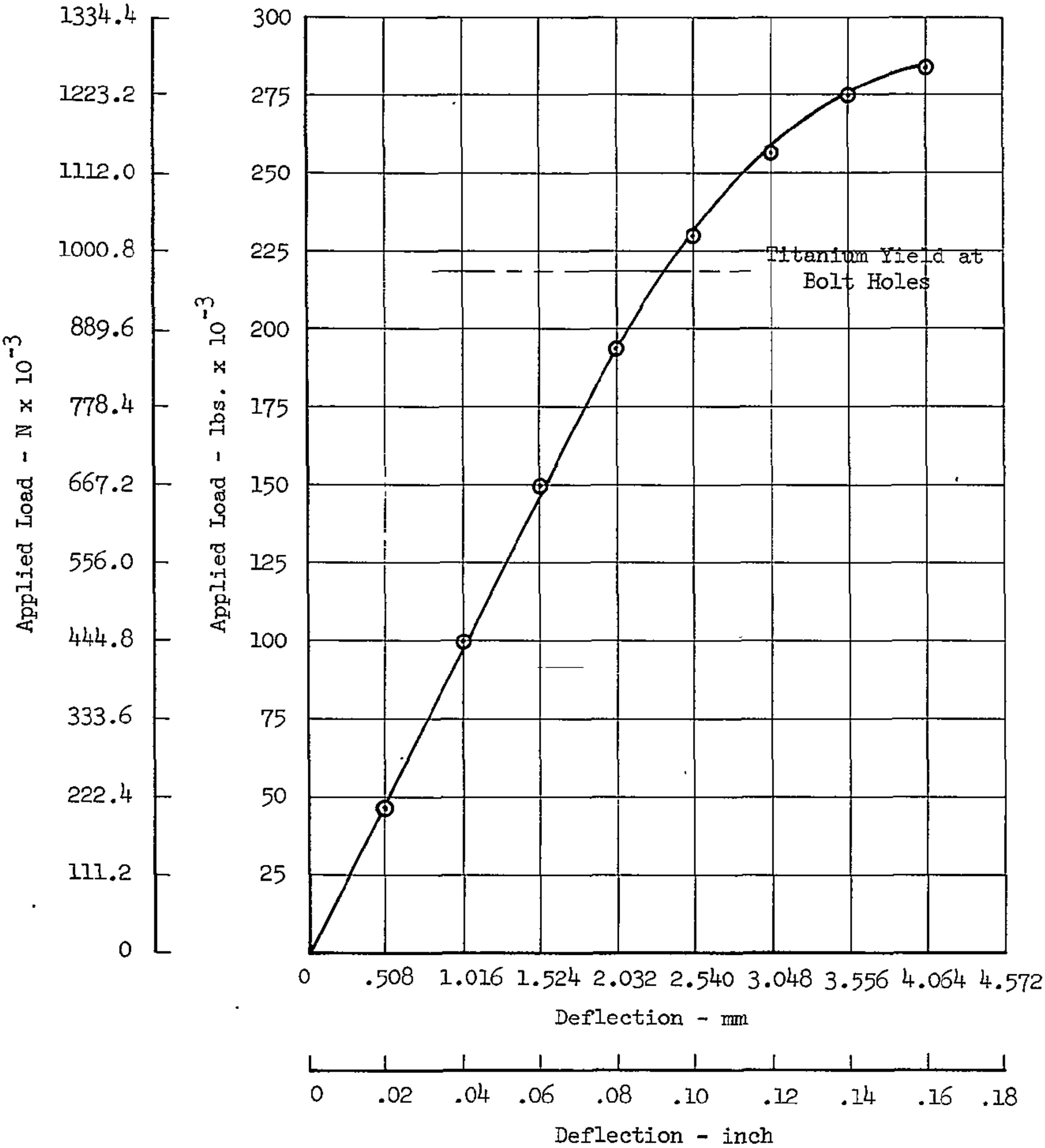

Figure 5-7 Axial Deflections, Subelement Number 2

It should be noted that removal of the steel anti-brooming plate failed to reveal any failure present in the B/Ep potted end. The stress level in the B/Ep at this section was calculated to be 1461×10^6 N/m^2 (212,000 psi).

5.2 Tube Testing

The results of static testing the tube specimens along with failure descriptions are presented in Table 5-1.

5.2.1 Instrumentation

Each tube specimen was instrumented with 12 three circuit rosette strain gages and three calibrated linear motion deflectometers in the locations shown in Figures 5-8 and 5-9, respectively. Figure 5-10 shows tube specimen number 3 with strain gages installed.

5.2.2 Test Procedure

Three tube specimens, each representative of the center member of a three-dimensional one-third scale shuttle thrust structure, were statically tested under combined loadings. Prior to test, steel end fittings were bolted to the titanium ends of the specimens in a manner representative of the actual attachments in the thrust structure. Tube numbers 1 and 2 were tested with the load introduced 2.88 mm (0.1135 inch) off tube centerline at the upper test fitting in conjunction with a flat bearing surface on the lower fitting. Figure 5-11 details the fitting installation while Figure 5-12 shows tube number 1 set up prior to test. This configuration did not provide for the proper beam column moment distribution over the length of the tubes. Subsequently, and prior to testing tube specimen number 3, the lower fitting was reworked to include a semi-circular slot 1.123 mm (0.0442 inch) off its centerline. This offset provided an ultimate lower end moment of 1.056×10^3 N-M (9,027 inches-pounds), matching that required for the center member of the three dimensional truss. The upper fitting remained unchanged for this test. Figure 5-13 shows the specimen set up in the testing machine. In addition, Figure 5-14 schematically presents a comparison of the test set up including ultimate applied loads and moments for tubes 1, 2 and 3.

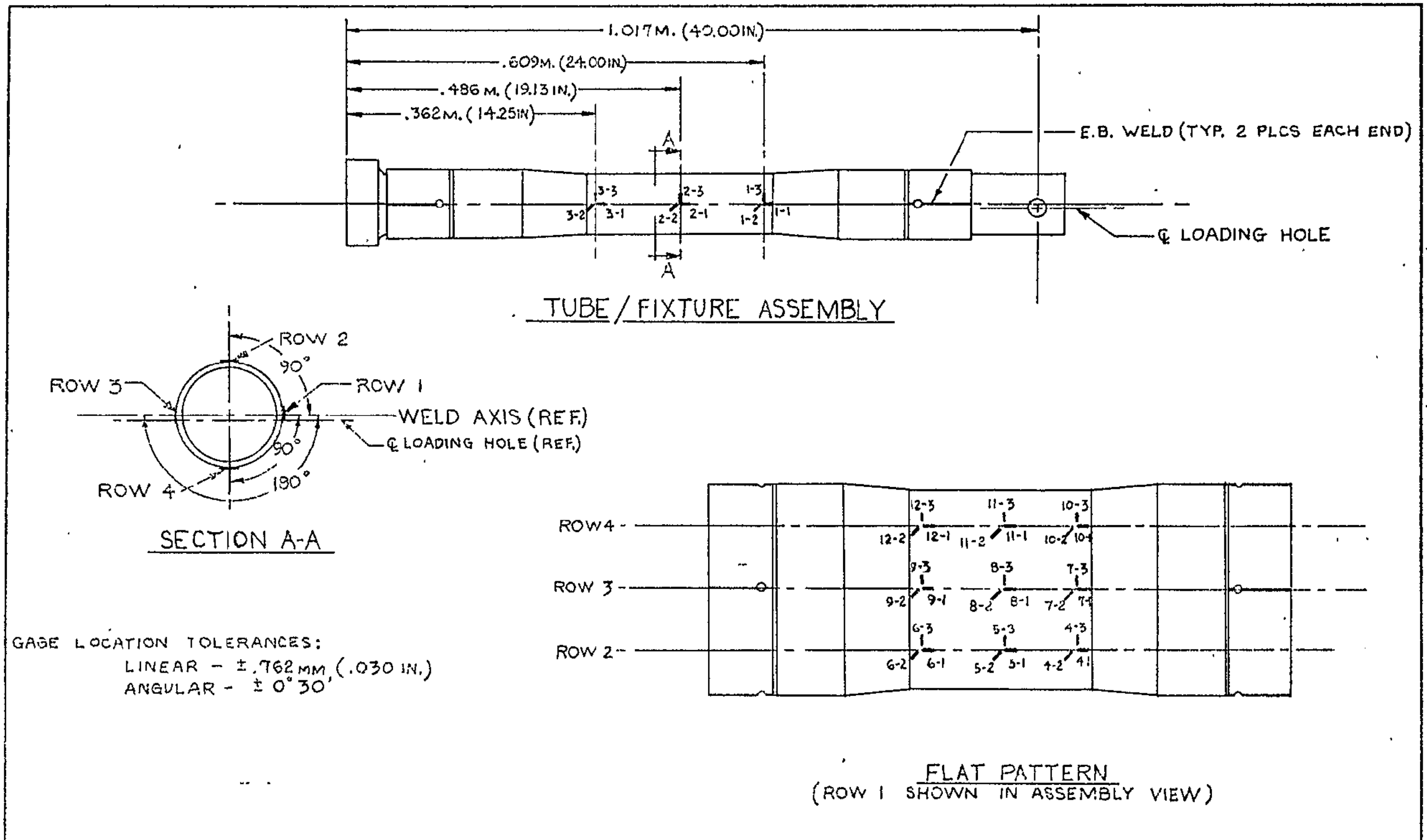

FIGURE 5-8 STRAIN GAGE LOCATIONS — NASA ONE-THIRD SCALE BORON-EPOXY BOOSTER THRUST STRUCTURE

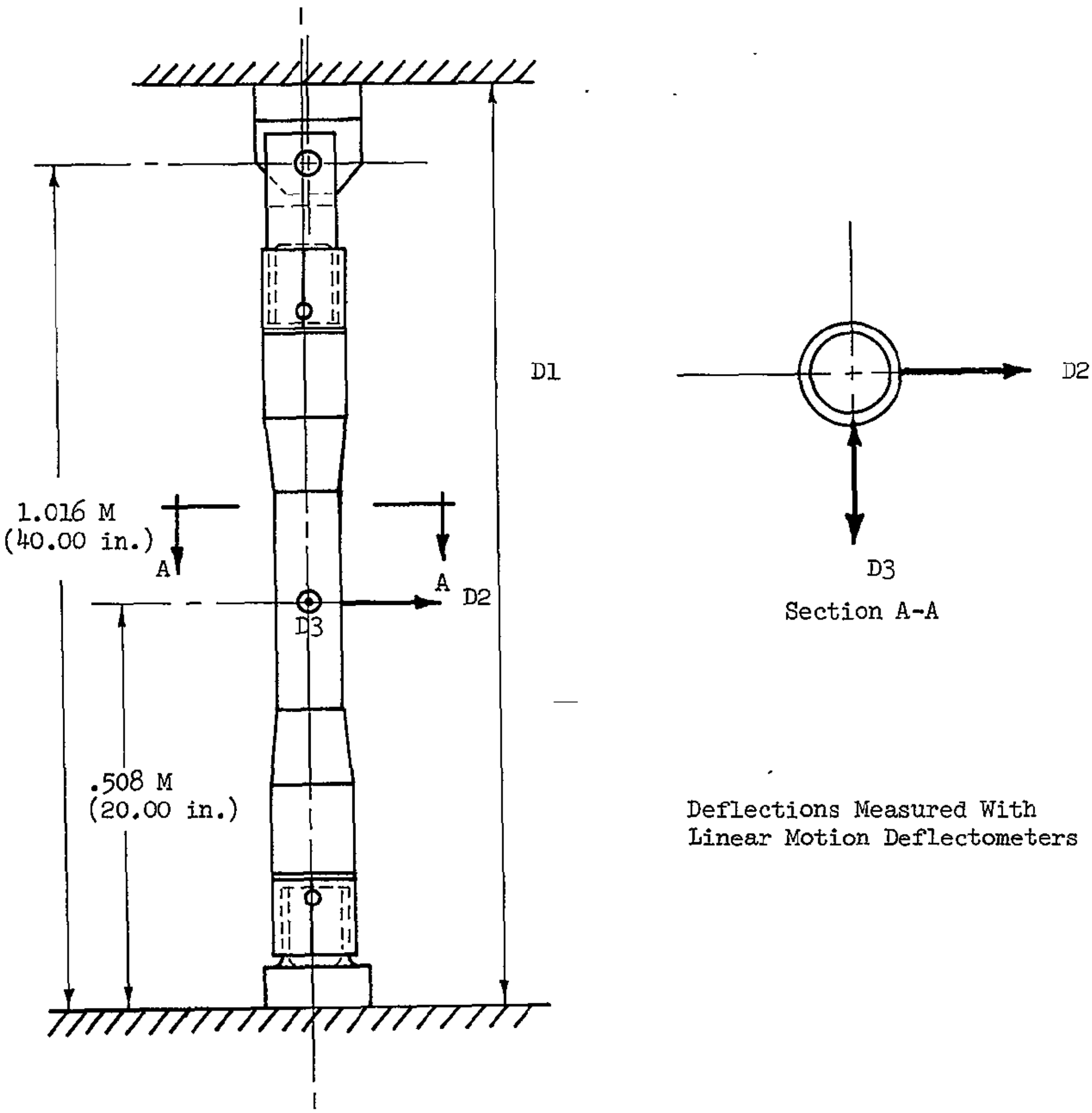

Figure 5-9 Deflection Measurement Locations for Tube Specimens

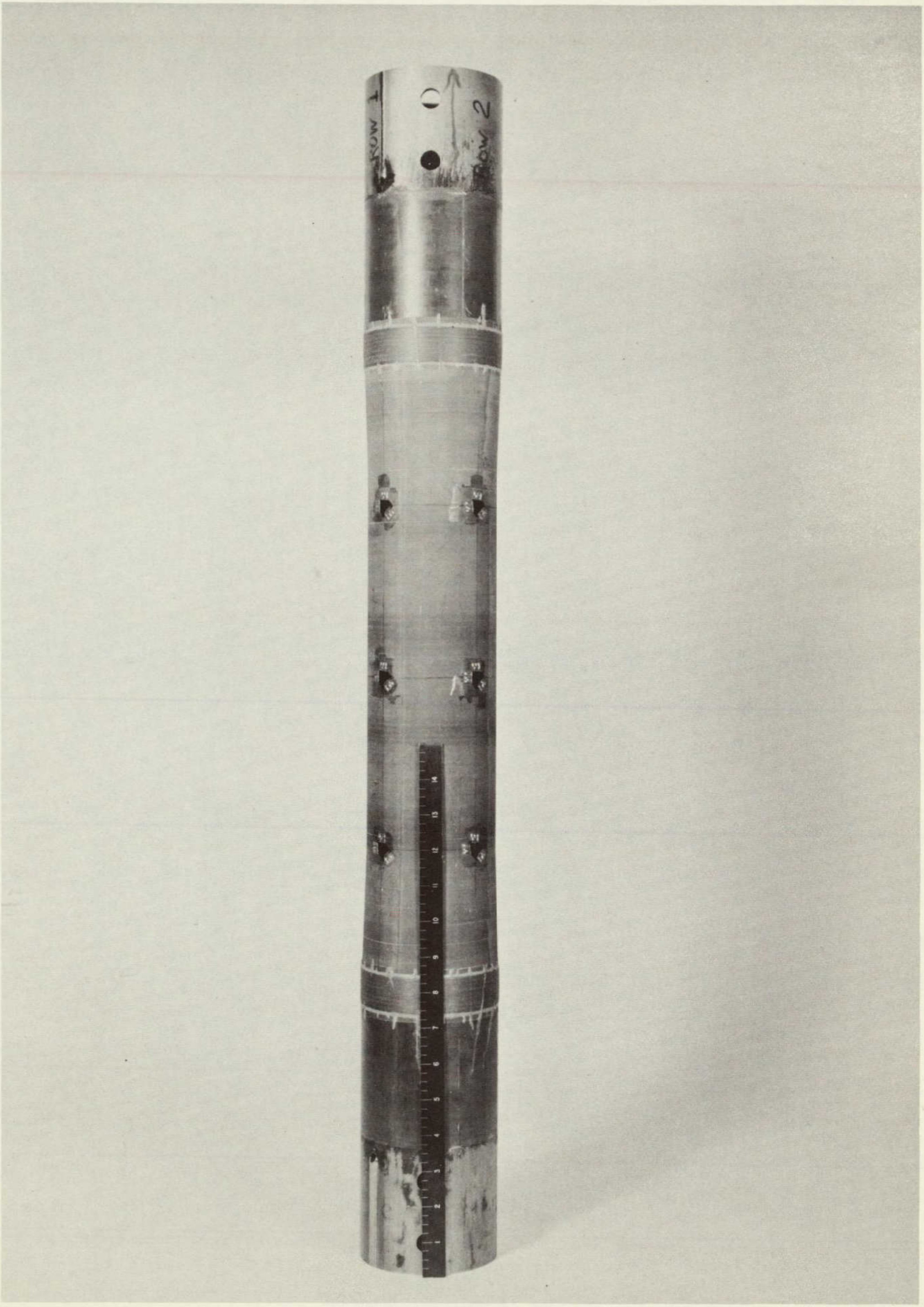

Figure 5-10 Tube Specimen Number 3 With Strain Gages Installed

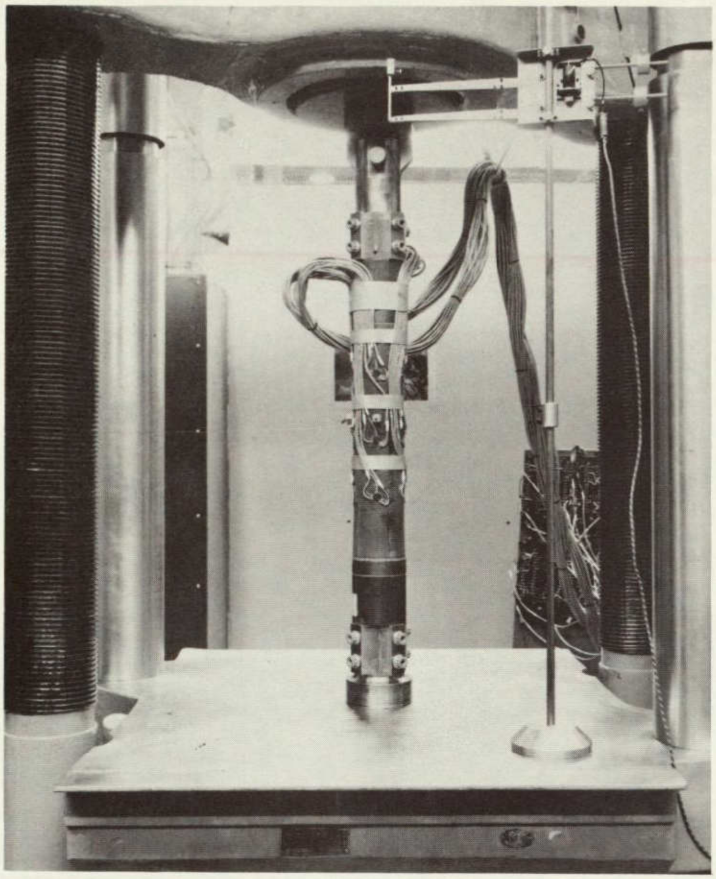

Figure 5-12 Tube Specimen Number 1 Set Up in Testing Machine

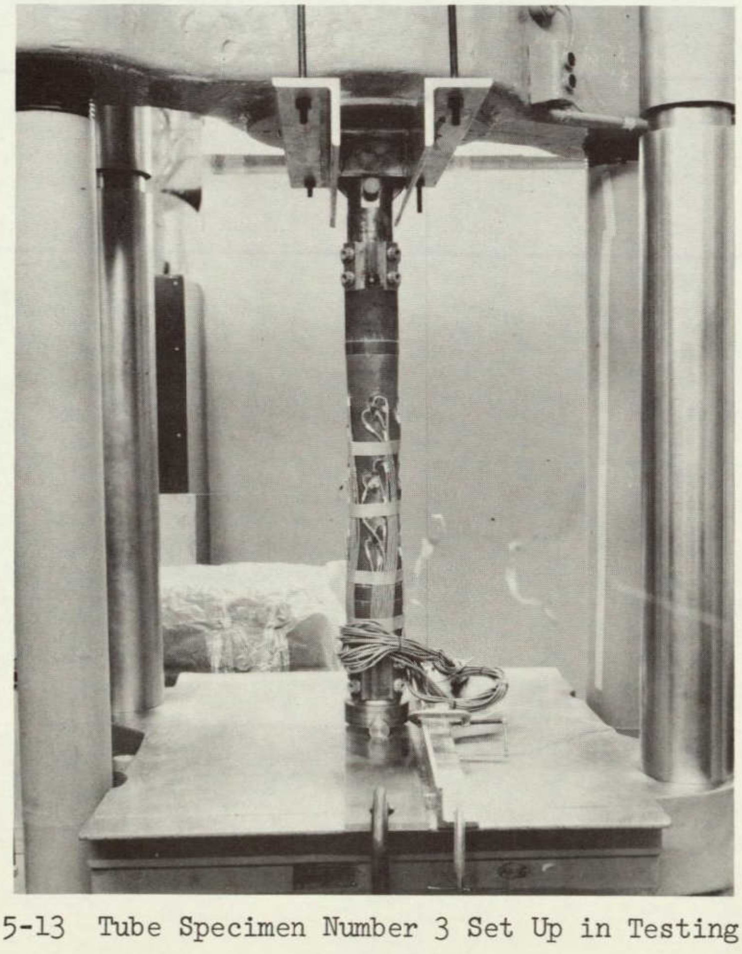

Figure 5-13 Tube Specimen Number 3 Set Up in Testing Machine

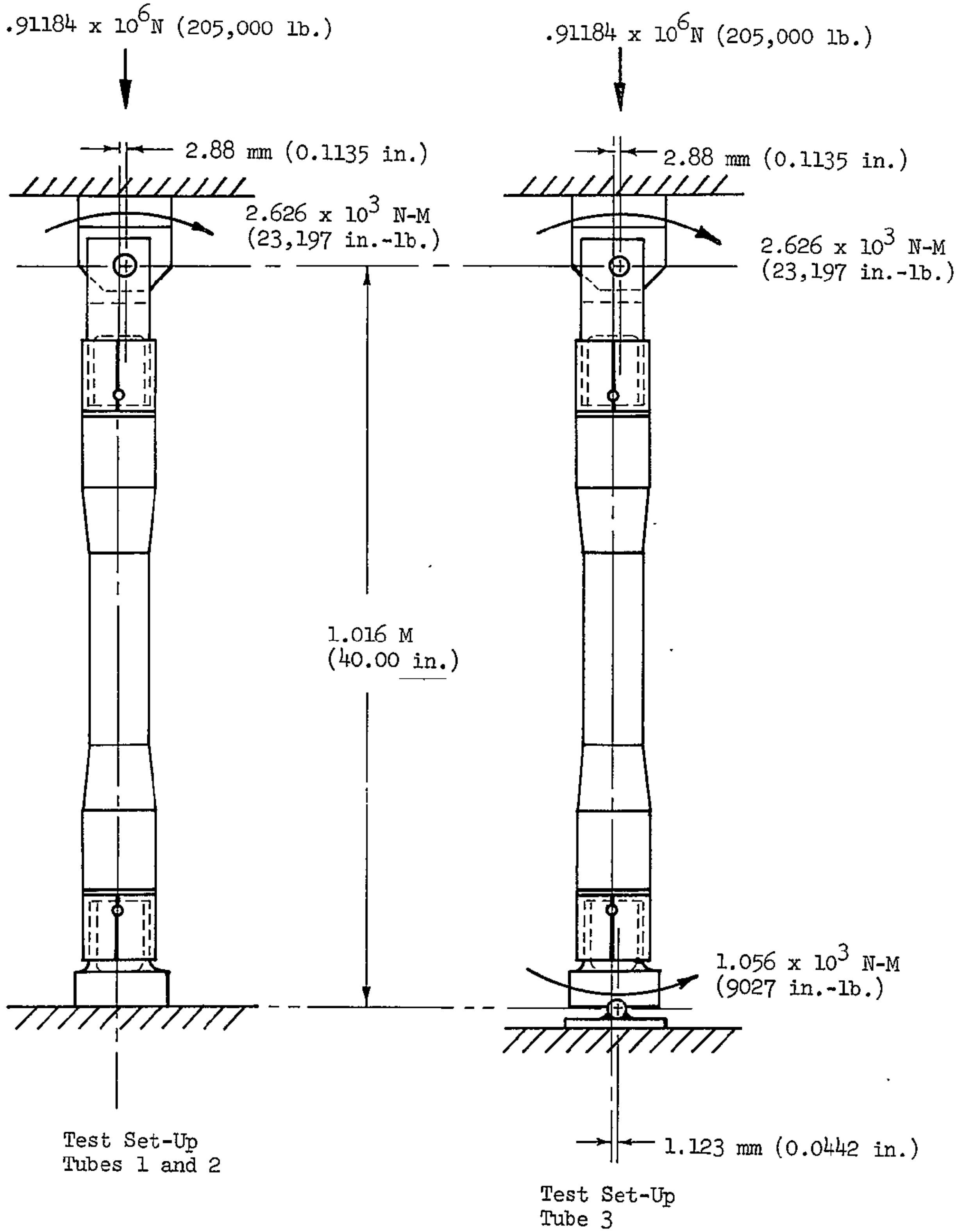

Figure 5-14 Comparison of Test Set-Up for Tubes 1 and 2 and Tube 3

The test specimen/fixture assemblies were individually installed in a universal testing machine and incrementally loaded to failure with specimen strains and deflections recorded at each increment. The log of test is presented in Figure 5-15.

5.2.3 Tube Test and Failure Analysis

The test results for the tube specimens, including failure loads and bending moments are reported in Table 5-1. A plot of specimen axial deflections versus applied load is presented in Figure 5-16. The strains associated with the last loading increment are presented in Table 5-2 and the failed specimens are shown in Figures 5-17 through 5-20. The failure analysis for each of the three tubes is as follows:

- The first tube to undergo test was tube number 2. The specimen failed at a load of 1.1503×10^6 N (248,500 pounds) and moment of 3.186×10^3 N-M (28,205 in.-lb.)(122% D.U.L.). The failure occurred in the boron-titanium splice. The predicted failure at $.9118 \times 10^6$ N (205,000 pounds) and applied moment of 2.626×10^3 N-M (23,197 in.-lb.) is for yielding in the titanium at the end of step 5. Assuming that yielding does not constitute failure , the next critical area is the boron at step 4 at a splice loading of 4.327×10^6 N/m (24,710 lb./in.). Considering the specimen as a beam column with equal end moments, this loading would occur at an axial load of $.9296 \times 10^6$ N (209,000 pounds) and end moment of 2.677×10^3 N-M (23,633 in.-lb.). However, investigation of strain data from gages 10 and 4, 11 and 5, 12 and 6 indicate that the specimen did not behave as was predicted, the gages showing that the moment was decreasing towards the lower fitting. Gages 10 and 4 show a moment of 3.801×10^3 N-M (33,646 in.-lb.) and gages 11 and 5 show a moment of 2.445×10^3 N-M (21,641 in.-lb.), gage 6 was inoperable during the test and no moment could be derived from the pair 12 and 6. The predicted moments at these gage locations are 9.545×10^3 N-M (84,495 in.-lb.) and 9.9109×10^3 N-M (87,723 in.-lb.) respectively.

LOG OF TEST

TITLE: NASA ONE-THIRD SCALE BOOSTER THRUST STRUCTURE

TEST CONDITION: STATIC TEST DATE: JULY/AUGUST 1971

CONDUCTED BY: R.J. CHALUS TUBE NUMBERS 1, 2 AND 3

RUN NO.	TEST LOAD N x 10^6	TEST LOAD LBS.	PERCENT DUL	REMARKS	PHOTO NUMBER
1	0	0	0	BASE LOAD	
2	.0912	20,500	10		
3	.1824	41,000	20		
4	.2736	61,500	30		
5	0	0	0	BASE LOAD	
6	.0912	20,500	10		
7	.1824	41,000	20		
8	.2736	61,500	30		
9	.3648	82,000	40		
10	.4559	102,500	50		
11	.5471	123,000	60		
12	.5927	133,250	65		
13	.6512	146,400	71.4	LIMIT	
14	.6839	153,750	75	BEGIN 15 SECOND RUNS	
15	.7295	164,000	80		
16	.7751	174,250	85		
17	.8207	184,500	90		
18	.8663	194,750	95		
19	.9119	205,000	100	DESIGN ULTIMATE	
20	.9575	215,250	105		
21	1.0031	225,500	110		
22	1.0487	235,750	115		
23	1.0943	246,000	120		
24	1.1399	256,250	125		

ENG 524.1A 3-66

Figure 5-15

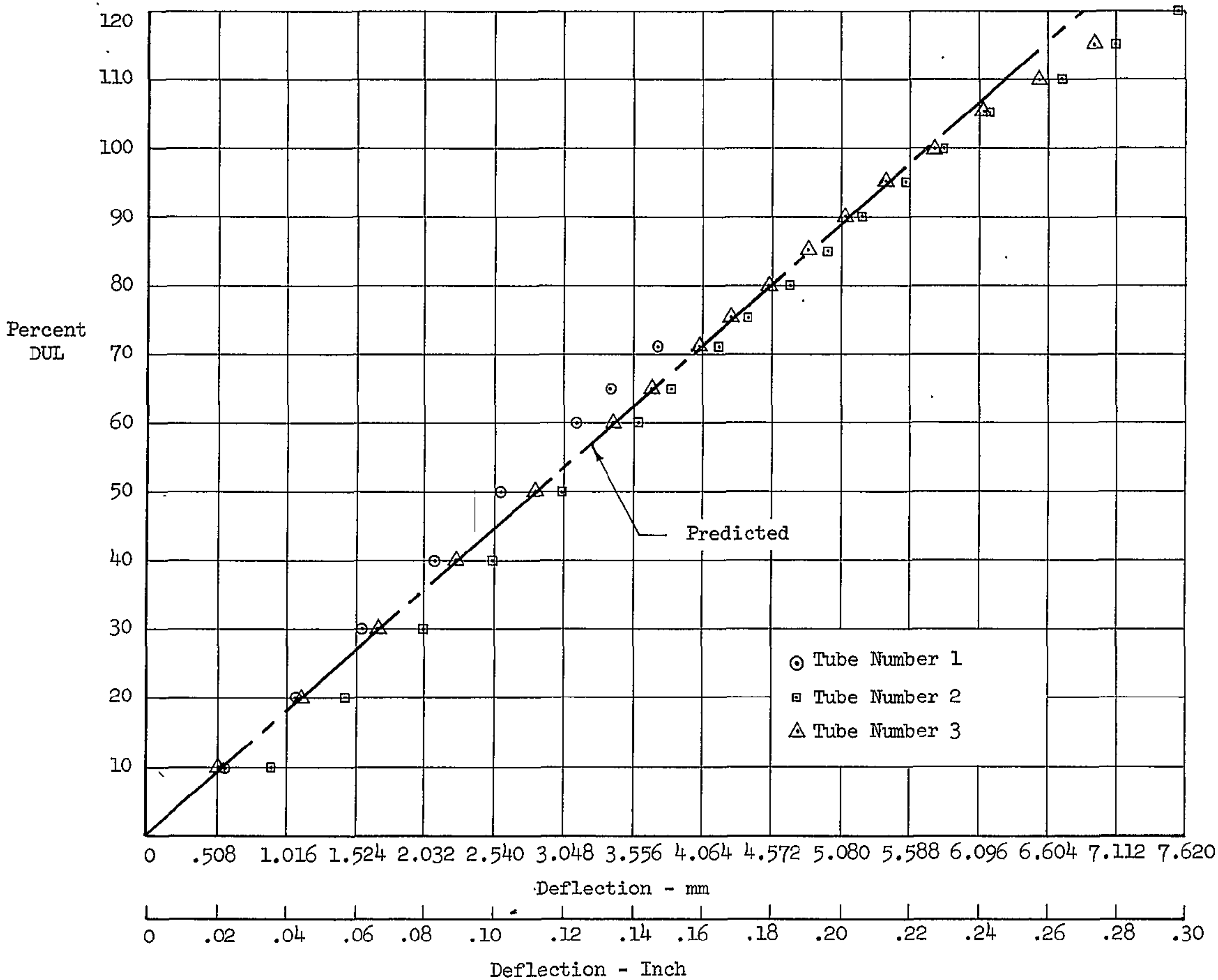

Figure 5-16 Axial Deflections, Tube Specimens 1, 2 and 3

Table 5-2 Strain Gage and Deflection Readings - Tube Specimens

Specimen No.	AD169-1001, No. 1	AD169-1001, No. 2		AD169-1001, No. 3	
Applied Load, N	.65118x10^{6}N (1)	.65118x10^{6}N (1)	1.0942x10^{6}N (2)	.65118x10^{6}N (1)	1.0486x10^{6}N (3)
Measurement	Strain μ mm/mm				
1-1 Strain	-4513	-5426	-9120	-4280	-6792
1-2	-2355	-839	-1410	-1454	-2265
1-3	1386	461	775	1272	2139
2-1	-5230(4)	-4504	-7570	-4222	-6682
2-2	-6036(4)	-895	-1505	-1805	-2903
2-3	1348(4)	1380	2320	1411	2416
3-1	-4426	-4617	-7760	-4691	-7714
3-2	-2589	-1785	-3000	-2398	-4434
3-3	1066	1095	1840	425	430
7-1	-4926	-5087	-8550	-4318	-6829
7-2	-2958	-1696	-2850	-1054	-1484
7-3	689	702	1180	1346	2306
8-1	-5410	-4677	-7860	-4463	-7020
8-2	-4594	-2005	-3370	-1628	-2409
8-3	1612	1142	1920	1312	2192
9-1	-3999	-4076	-6850	-4885	-8000
9-2	-1812	-2166	-3640	-2130	-3649
9-3	1541	1523	2560	295	-34
4-1	-3637	-4492	-7550	-3643	-5516
4-2	-1841	-1303	-2190	-1496	-2219
4-3	1756	637	1070	1287	2129
5-1	-5451	-4141	-6960	-4175	-6698
5-2	-4884	-1339	-2250	-1811	-2844
5-3	1540	1250	2100	1089	1656
6-1	-4341	OUT	OUT	-4099	-6467
6-2	-2332	OUT	OUT	-2033	-3333
6-3	1160	1339	2250	479	608
10-1	-5204	-5801	-9750	-4600	-7562
10-2	-2390	-2118	-3560	-1894	-3176
10-3	1121	756	1270	743	1155
11-1	-4675	-4879	-8200	-5061	-8548
11-2	-3469	-1654	-2780	-2036	-3402
11-3	2563	OUT	OUT	1238	1942
12-1	-4481	-4356	-7320	-5128	-8944
12-2	-2019	-1815	-3050	-2937	-5821
12-3 Strain	1393	1333	2240	41	-910
D1 Head Deflection	3.759 mm (.148 In.)	4.504 mm (.177 In.)	7.569 mm (.298 In.)	4.038 mm (.159 In.)	6.959 mm (.274 In.)
D2 Mid-Span Deflection	.2540 mm (.010 In.)	.4534 mm (.018 In.)	.7620 mm (.030 In.)	.5588 mm (.022 In.)	1.2446 mm (.049 In.)
D3 Mid-Span Deflection	.2032 mm (.008 In.)	.0756 mm (.003 In.)	.1270 mm (.005 In.)	.0254 mm (.001 In.)	.1524 mm (.006 In.)

NOTES: (1) Limit load (146,400 lbs.), 71.4 percent design ultimate.

(2) 120 percent design ultimate (246,000 lbs.).

(3) 115 percent design ultimate (235,750 lbs.).

(4) Data recorded at .5927 x 10^{6}N (133,250 lbs.), 65 percent design Ultimate.

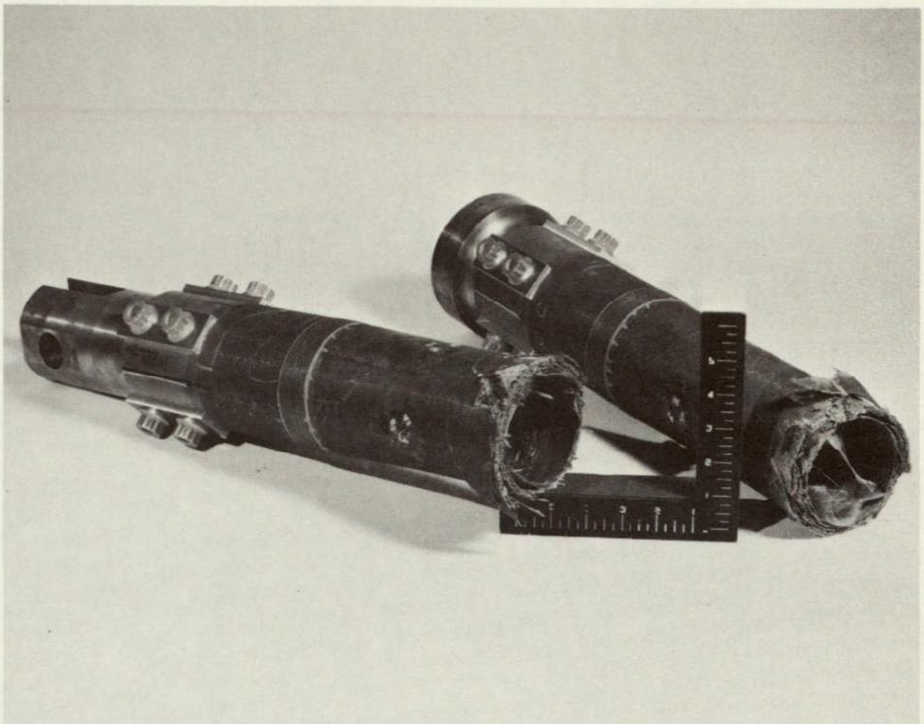

Figure 5-17 Failure of Tube Number 1

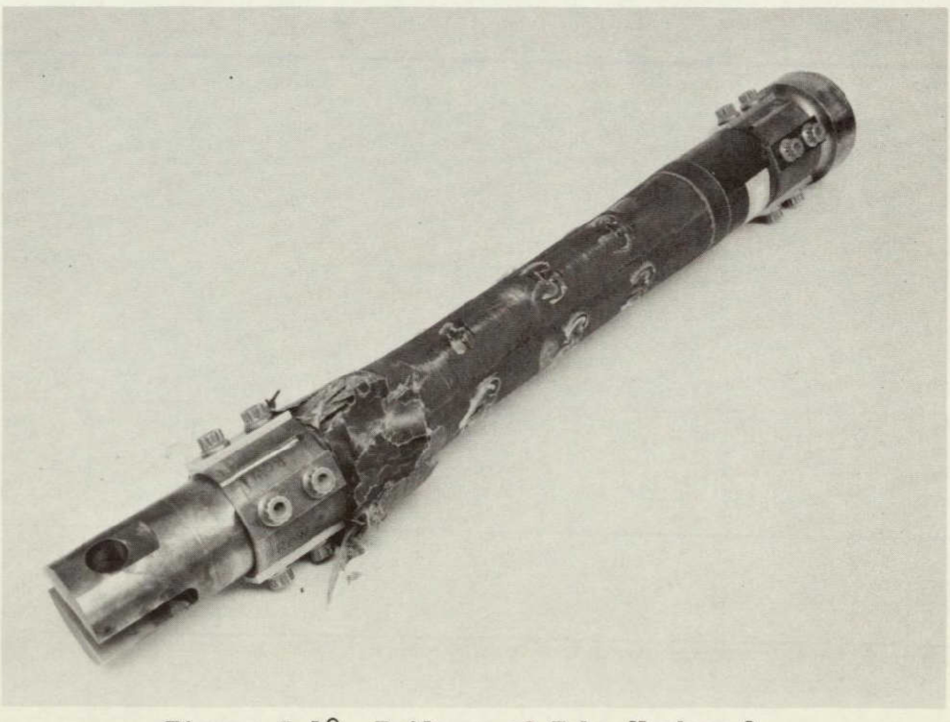

Figure 5-18 Failure of Tube Number 2

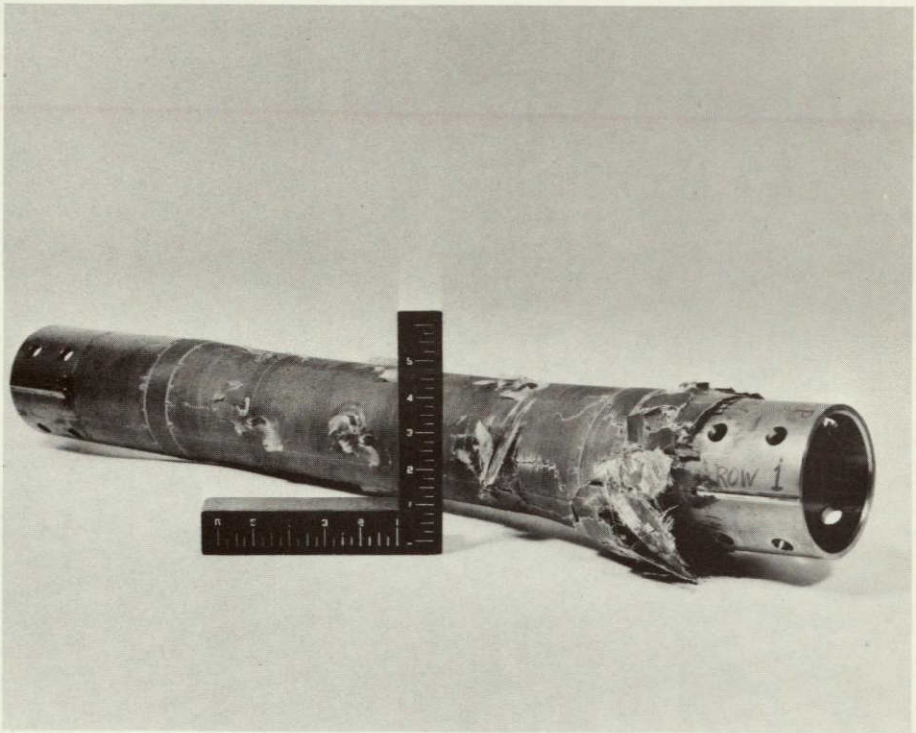

Figure 5-19 Failure of Tube Number 3

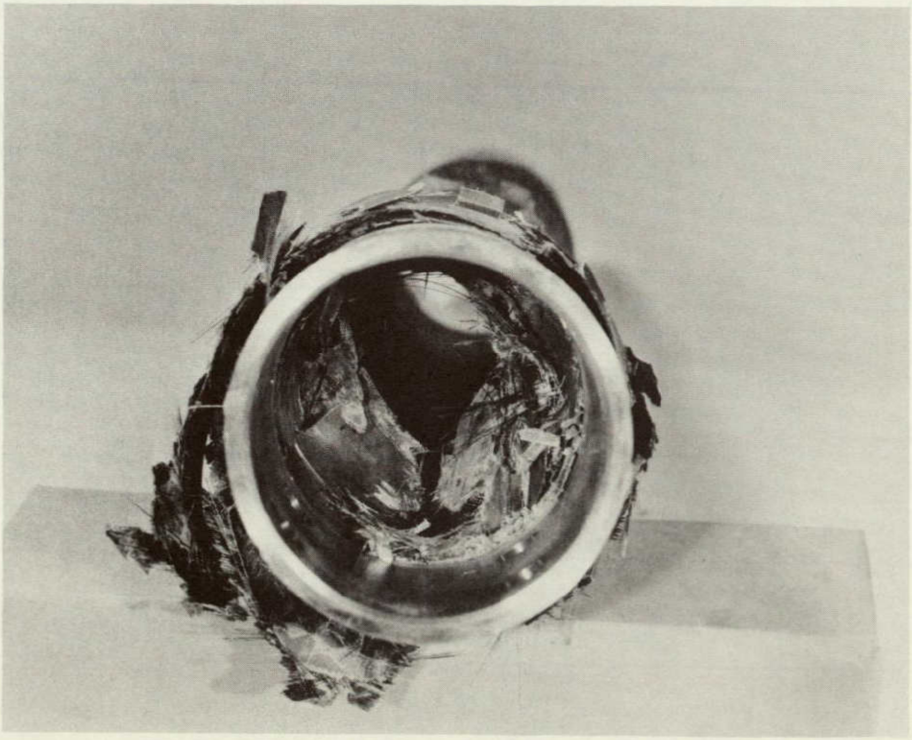

Figure 5-20 Close-Up of Tube Number 3 Internal Failure

Assuming a linear variation of moment between x = 0 (loading pin) and x = .4064 M (x = 16.0 inches, location of gages 10 and 4), the moment at the end of step 4 is 3.415×10^3 N-M (30,229 in.-lb.) and the maximum splice loading at failure is 4.344×10^6 N/m (24,800 lb./in.) which is within 0.3% of the predicted strength of the splice. It should be noted that tube number 2 was a void free part, as measured by NDT (ultrasonics).

- Tube number 1, the second specimen tested, failed in compression at the center of the tube at a load of $.6703 \times 10^6$ N (150,700 pounds) and applied end moment of 1.932×10^3 N-M (17,104 in.-lb.)(74% D.U.L.). Plots of strain in the 0°, 90° and 45° directions of gage number 2 indicated a failure in the laminate between 65 and 71% D.U.L., this was verified by observers who reported hearing clicks eminating from the specimen at this load level. The maximum stress level in the laminate at failure, obtained from strain data, was 911×10^6 N/M^2 (132,100 lb./in.^{2}) at gage number 2, the laminate stability stress is 1716×10^6 N/M^2 (248,860 lb./in.^{2}). Non-destructive (ultrasonics) analysis of the specimen had shown numerous voids in the boron/titanium splices and in the all boron laminate in the region of failure. It is felt that the premature failure was caused by the poor quality of the laminate. As was the case with the test of tube number 2, the strain gages indicated the moments decreasing toward the lower fitting. The probable cause for this behavior is the flat surface of the lower test fitting restraining the rotation of the lower end of the tube and thus reducing the beam-column interaction. To remedy this the lower test fitting was reworked (for tube number 3 test) to incorporate an eccentric pin support. An offset of 1.123 mm (.0442 inch) was used so that the moments would be representative of the center member in the three dimensional truss.

- Tube number 3 failed at 119% DUL under an applied axial load of 1.084×10^6 N (243,750 pounds) and applied end moments of 3.126×10^3 N-M (27,666 in.-lbs.) and 1.214 N-M (10,742 in.-lbs.) at the upper and lower fittings respectively. The failure was contained in the boron-titanium bonded splice identical to the failure of tube number 2. Instrumentation consisted of 12-3 gage rosette strain gages arranged in four rows of three gages each, located with a 90° pitch. Two opposite rows were used to monitor the bending moment in the tube by measuring the difference in strain between opposing gages. The moment distribution found from these strain gages differed from the predicted distribution, but was in close agreement with the results of tube number 2. Gages 10 and 4 showed a moment of 3.817×10^3 N-M (33,791 in.-lbs.), gages 11 and 5 showed a moment of 3.272×10^3 N-M (28,962 in.-lbs.) and gages 12 and 6 showed a moment of 4.67×10^3 N-M (41,339 in.-lbs.). Proceeding as with tube number 2 and interpolating the splice loading at the end of step 4, yielded a loading at failure of 4.267×10^6 N/M (24,368 lbs./in.). This loading was 99% of the failure load predicted by the "STEP*" splice program.

The analysis used to preduct the beam column deflections was developed for a beam composed of three uniform segments, the differential equation was integrated for each segment, and a set of simultaneous equations linear in the unknown coefficients found by equating deflection, slope and shear at the segment interfaces. By solving these equations the deflection and hence the bending moment is known along the length of the beam. For this tube the end segments were assumed to have a length equal to the distance from the adjacent node to the beginning of the stepped splice, and stiffness equal to that of the bolted portion of the titanium end fittings. As a result of this assumption the length of the titanium within the stepped splice, as well as the stiffness of the steel test fixtures was neglected. A parametric study of the above method has revealed that the beam column deflection is highly sensitive to small variations in end segment length and stiffness. Another probable cause of error is the end restraint. Although pins were used there is the probability of substantial rotational restraint being present in the form of pin friction.

Based upon the test results and a parametric study of the method of analysis it was judged that the conservative predictions were the result of an inability to accurately idealize the tube end properties and to determine the tube end conditions.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based upon the results of this program, the following conclusions and recommendations are presented:

Conclusions

- o The methods and techniques utilized for the design and analysis result in B/Ep tubular thrust structure members, which are capable of consistently satisfying structural requirements (test results for 3 members averages 120% design ultimate load).
- o The 32% weight savings of the B/Ep tubular member over a comparable titanium member has been substantiated.
- o The B/Ep exhibited approximately 9% greater axial stiffness than a comparable titanium tube.
- o The materials (B/Ep) and manufacturing processes developed are applicable to full scale tubular members.
- o The in-process and non-destructive test techniques and analysis applied throughout the program have conclusively demonstrated the ability to pre-determine the quality of the parts.
- o The adequacy of the integrally bonded, co-cured B/Ep to titanium joints was thoroughly verified.

Recommendations

- o Evaluate suitability of B/Ep for full scale members at minimum costs.
- o Determine the suitability of the Quality Assurance techniques for full scale structures.
- o Optimize manufacturing methods and tooling for production of full scale structures.

7.0 REFERENCES

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