NAS8 26675-1

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

Phase II Final Report

June 1971 to June 1972

September 1974

Prepared Under Contract No. NAS8-26675

By

Advanced Composite Group
GRUMMAN AEROSPACE CORPORATION
Bethpage, New York 11714

For

Marshall Space Flight Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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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. O. Meredith is the Contracting Officers Representative.

The work was performed by the Advanced Composites Group of Grumman Aerospace Corporation, Bethpage, New York 11714. The Project Supervisor at Grumman is Mr. R.N. Hadcock and the Assistant Project Supervisor is Mr. J. Sicari.

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ABSTRACT

This report describes the design, materials, tooling, various manufacturing processes, quality control, test procedures and results associated with the fabrication and test of a 1/3 scale boron/epoxy, booster thrust structure.

A complete two-dimensional truss type thrust structure, comprised of nine boron/epoxy tubular members and six apex fittings, was fabricated under the Phase II program. The program was an extension of the Phase I effort, under which single tubular components of the same structure were fabricated and tested. The Phase II effort resulted in structurally representative flight hardware, and although not tested to date, verified the manufacturing feasibility and projected weight savings (30%) for this type of structure.

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

1.0 INTRODUCTION AND SUMMARY

A one-third scale, two-dimensional booster thrust structure segment applicable to early Space Shuttle booster configurations was designed using both boron/epoxy and titanium. The boron/epoxy design showed a 22 percent overall weight saving. When projected to a full size structure a 30% weight saving can be expected.

This program was undertaken as an extension to the Phase I program, which resulted in the successful testing of single boron/epoxy tubular members. The intent was to confirm the design procedures, analytical methods, projected weight savings and manufacturing feasibility and to substantiate, by test, the structural integrity of the boron/epoxy tubular members as part of a representative structure.

The scope of the Phase II program provided for the fabrication and test of a nine member truss type beam 2.84 m (112 inches) in length and 1.01 m (40 inches) deep. The nine boron/epoxy tubular members fabricated ranged in length from .831 m (32.72 inches) to 1.122m (44.18 inches) and in diameter from .0762 m (3.00 inches) to .0982 m (3.87 inches). Six titanium apex fittings and two lug fittings were also fabricated, completing the details required for truss assembly. The structure was completely instrumented and shipped to the NASA, MSFC for test in June of 1972. Due to a reorientation of funding priorities the structure has not been tested to date, and therefore no results are available.

2.0 DESIGN

2.1 Thrust Structure Geometry

The geometry of the one-third scale, three-dimensional booster thrust structure is shown in Figure 2-1. The structure is 1.01m (40 inches) high inscribed within a 3.04m (120 inches) maximum envelope ring diameter. There are nine engine support points, one located centrally within a 2.03m x 2.03m (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 truss beam which has been fabricated and delivered under the Phase II program. The beam is composed of nine members and is 1.01m (40 inches) high and 2.84m (112 inches) in length.

2.2 Design Loads

The applied loads used for the design of the two-dimensional thrust structure were taken from the three-dimensional design conditions. The applied loads were then adjusted to account for the removal of members in the third dimension and the different boundary conditions associated with the test structure as compared to the actual vehicle structure. The resultant member loading, however, is fully representative in both magnitude and type. Two loading conditions were used for design:

- Condition 1 - zero engine gimbal, applied loads in the XY plane aligned with the X axis
- Condition 2 - +Y engine gimbal, applied loads in the XY plane at an angle of .122 rad. (7°) to the X axis for two load points and in the XY plane aligned with the X axis for the two remaining load points.

Applied loads for the two design conditions are given in Table 2-1.

Internal member loads for the two-dimensional thrust structure were generated with the use of an "ASTRAL" stiffness method Finite Element Analysis (F.E.A.) of Reference 1. The idealization for the F.E.A. is shown in Figure 2-2 and is composed of 8 nodes and 11 members. All members are beam elements with moment capability at both ends, except those which connect nodes 7 or 8 which have no moment capability in the

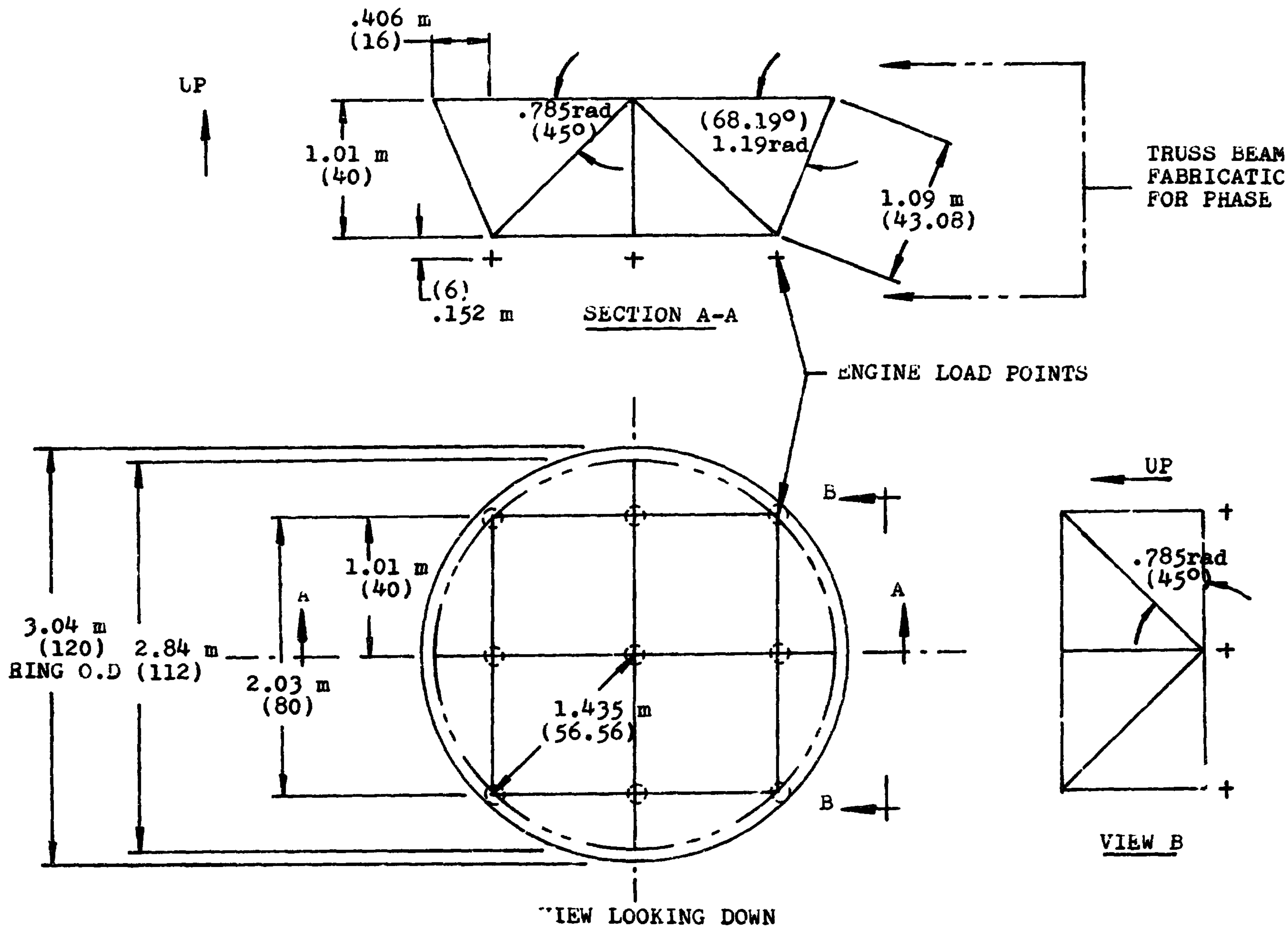


FIGURE 2-1 GEOMETRY - ONE-... SCALE BOOSTER THRUST STRUCTURE

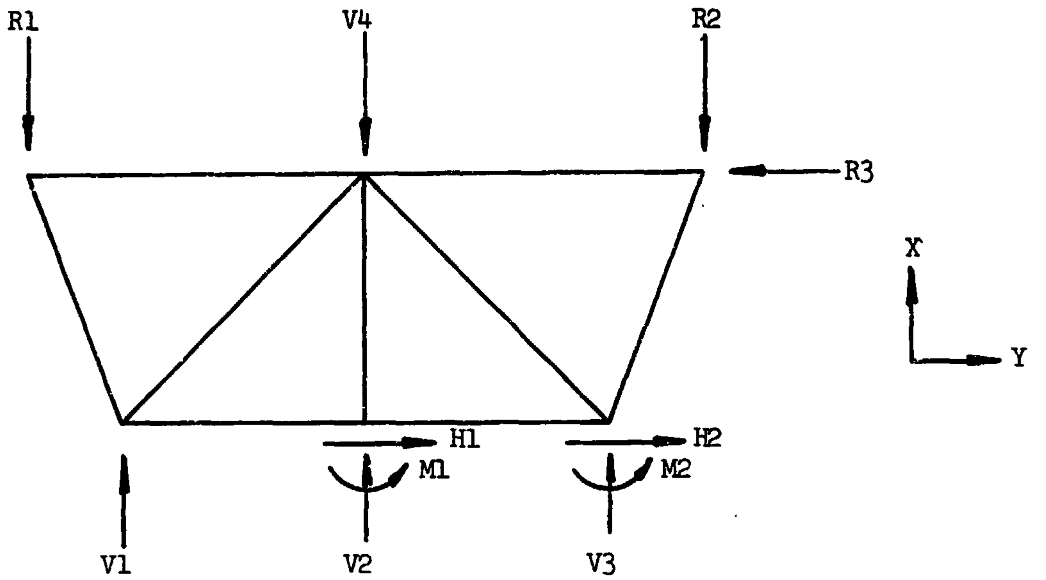


TABLE 2-1 2D THRUST STRUCTURE APPLIED LOADS - ULTIMATE

LOAD	CONDITION 1 0 rad (0°) ENGINE GIMBAL		CONDITION 2 .122 rad (7°) ENGINE GIMBAL	
	METRIC-N	CUSTOMARY-LB	METRIC-N	CUSTOMARY-LB
V1	487278	109550	487278	109550
V2	1339147	301067	1339147	301067
V3	487278	109550	487278	109550
V4	669573	150533	669573	150533
H1	0	0	82210	18482
H2	0	0	164421	46965
M1	0	0	493281	110899
M2	0	0	986563	221799

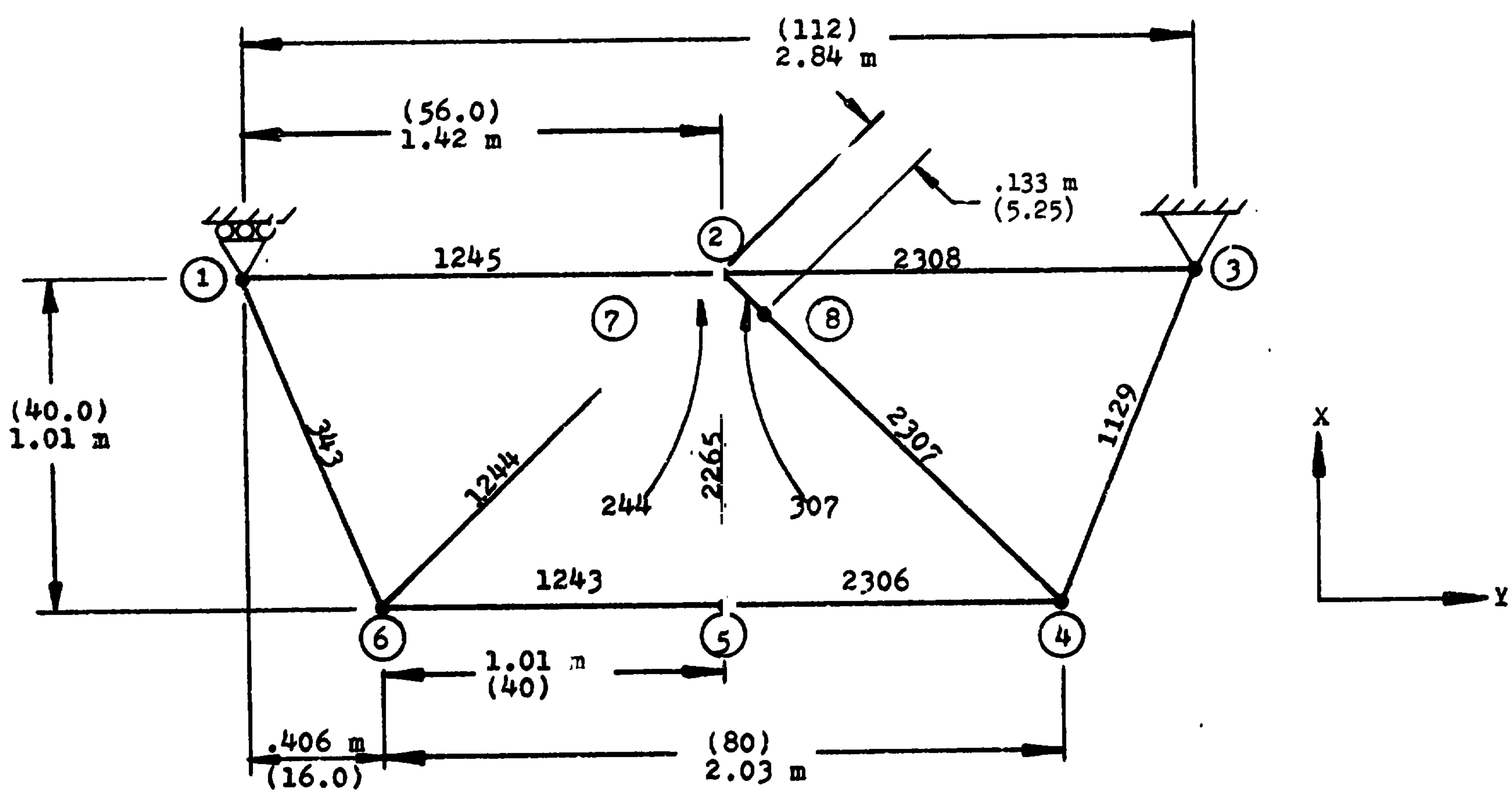


FIGURE 2-2 FEA IDFALIZATION 2D THRUST STRUCTURE

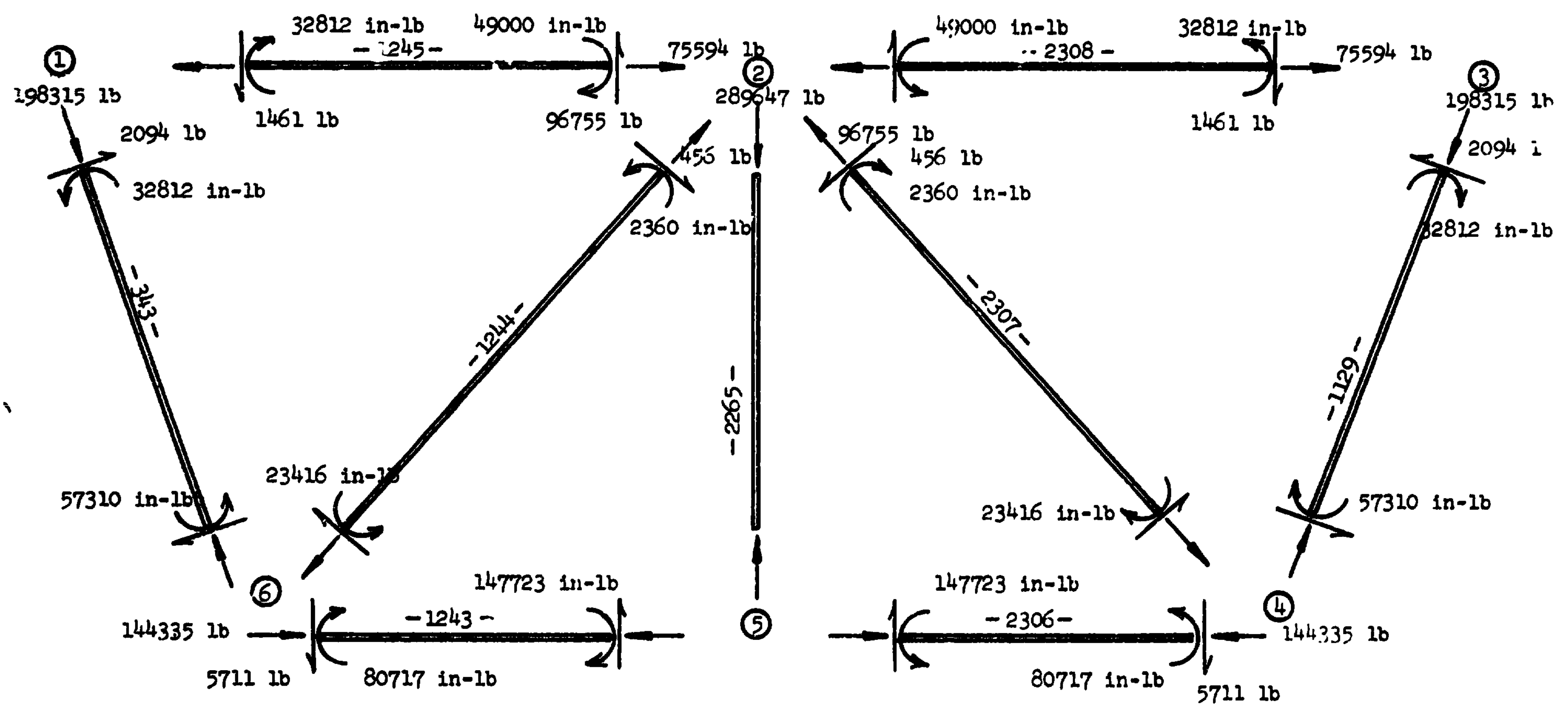


FIGURE 2-3 INTERNAL LOADS 2D TRUSS - CONDITION I ULTIMATE (CUSTOMARY UNITS)

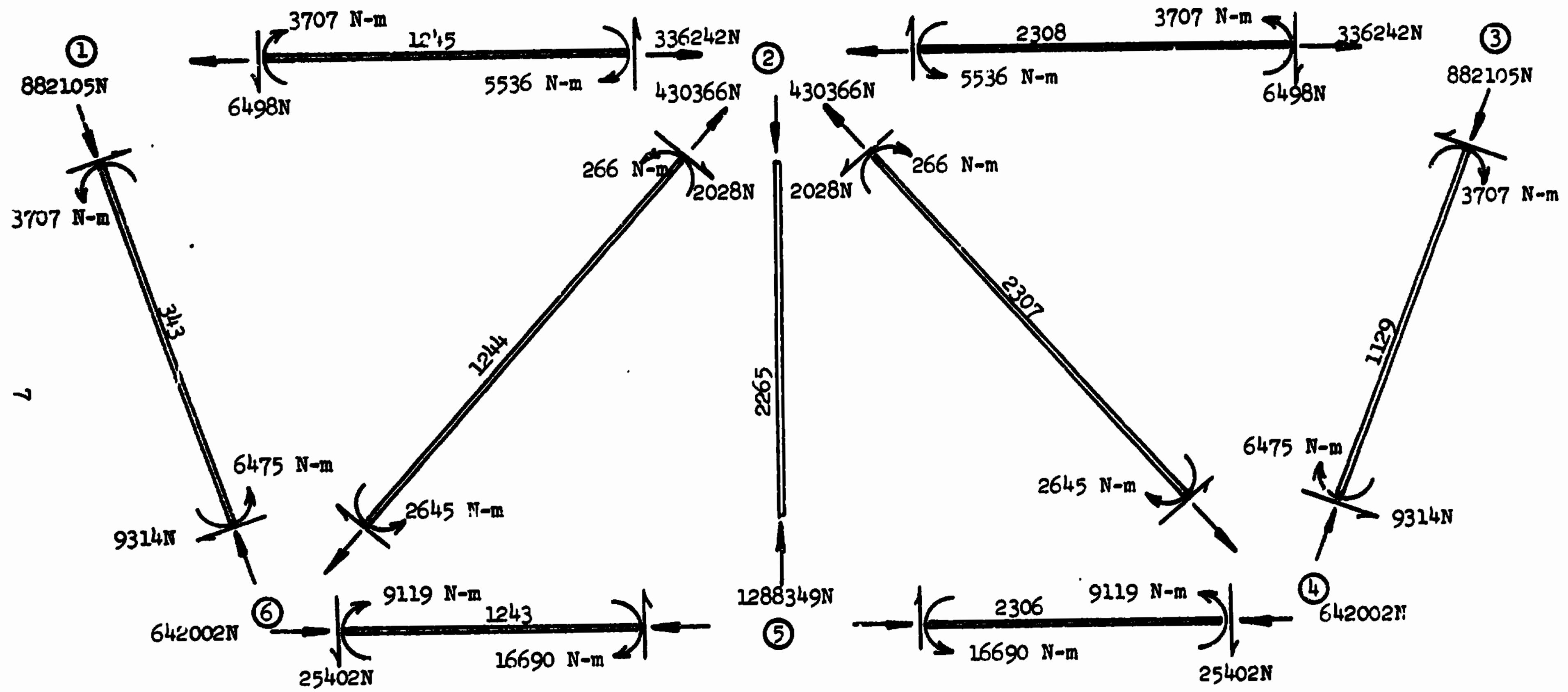


FIGURE 2-3A INTERNAL LOADS 2D TRUSS - CONDITION I ULTIMATE (METRIC UNITS)

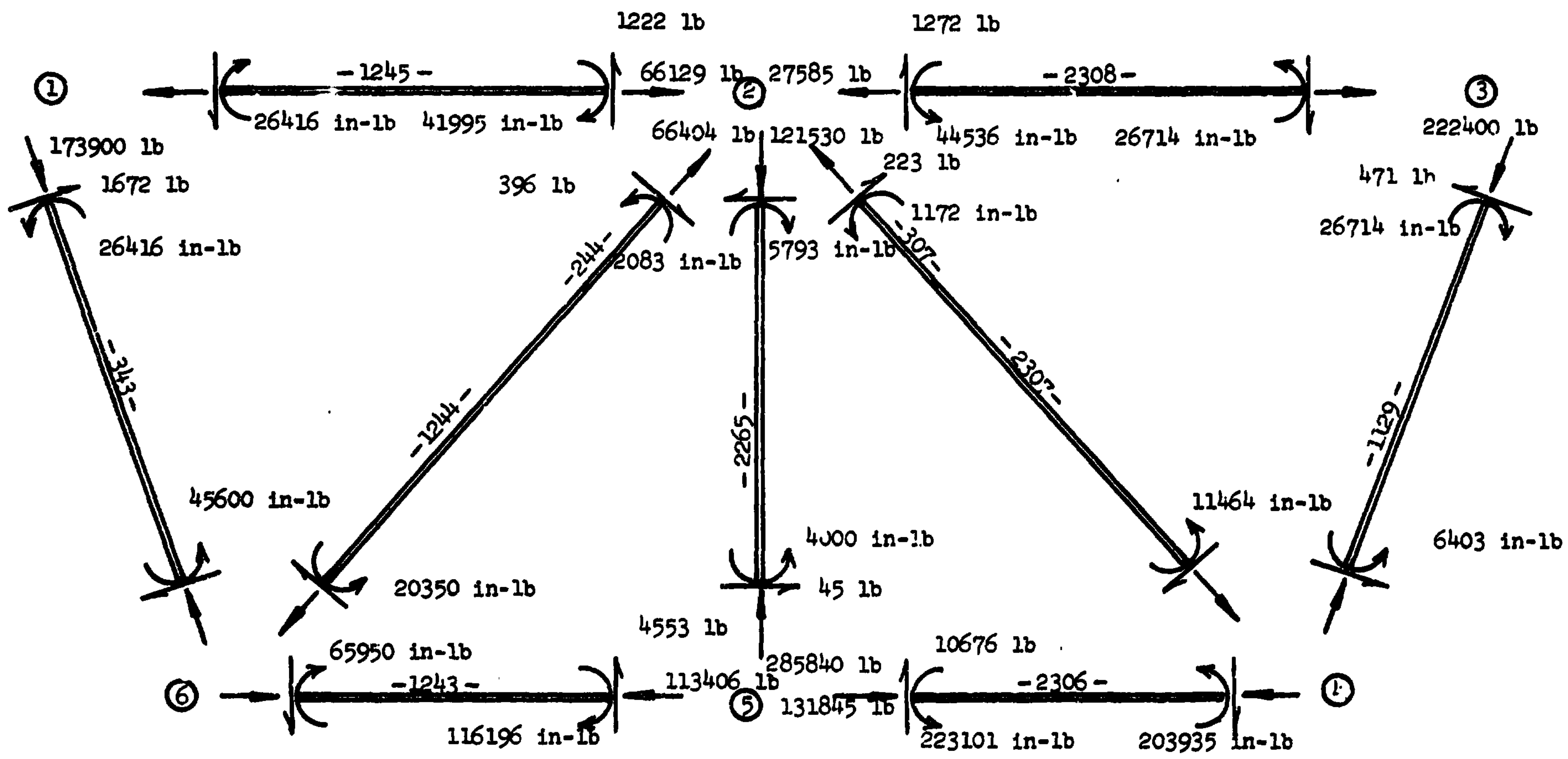


FIGURE 2-4 INTERNAL LOADS 2D TRUSS - CONDITION II ULTIMATE (CUSTOMARY UNITS)

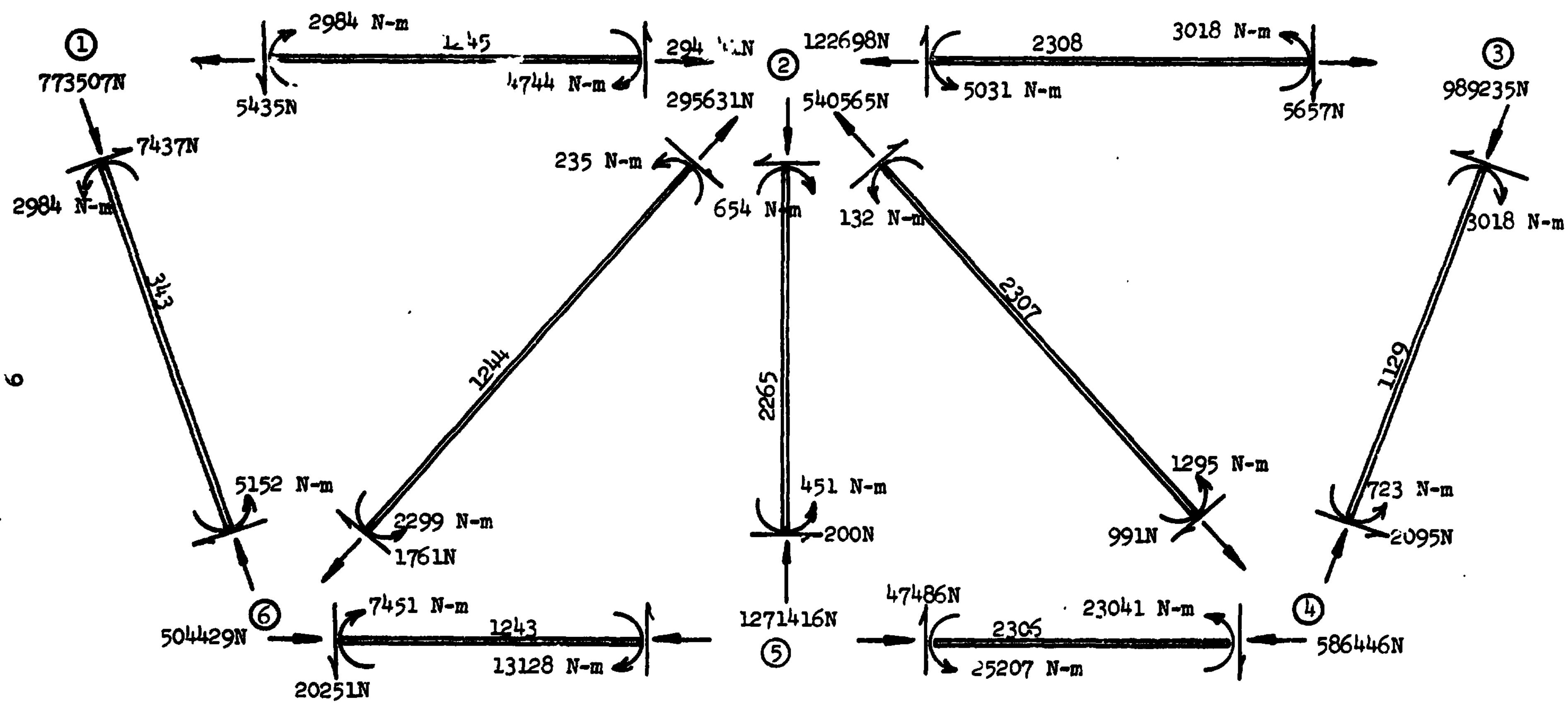
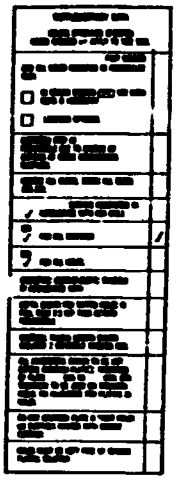
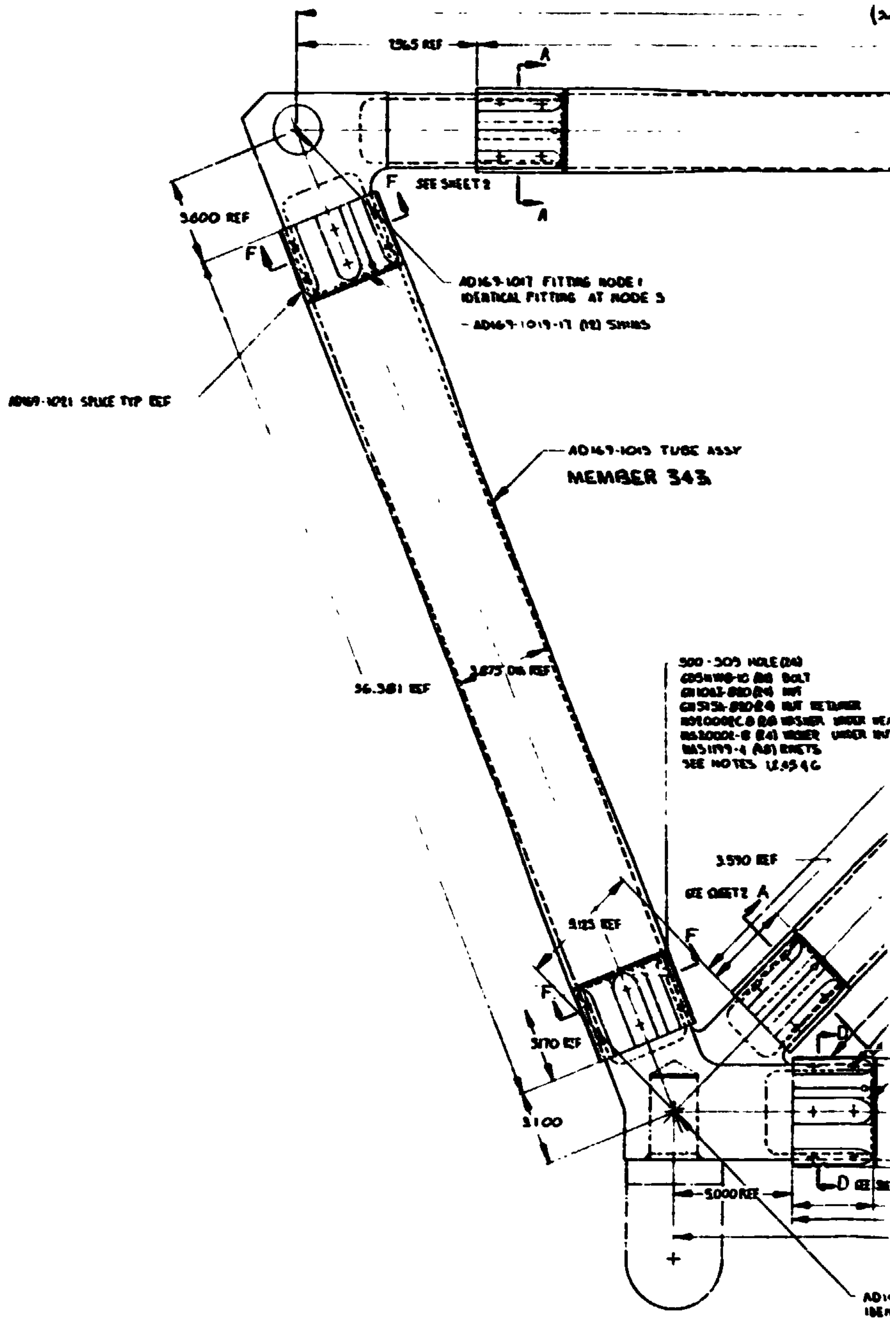


FIGURE 2-4A INTERNAL LOADS 2D TRUSS - CONDITION II ULTIMATE (METRIC UNITS)





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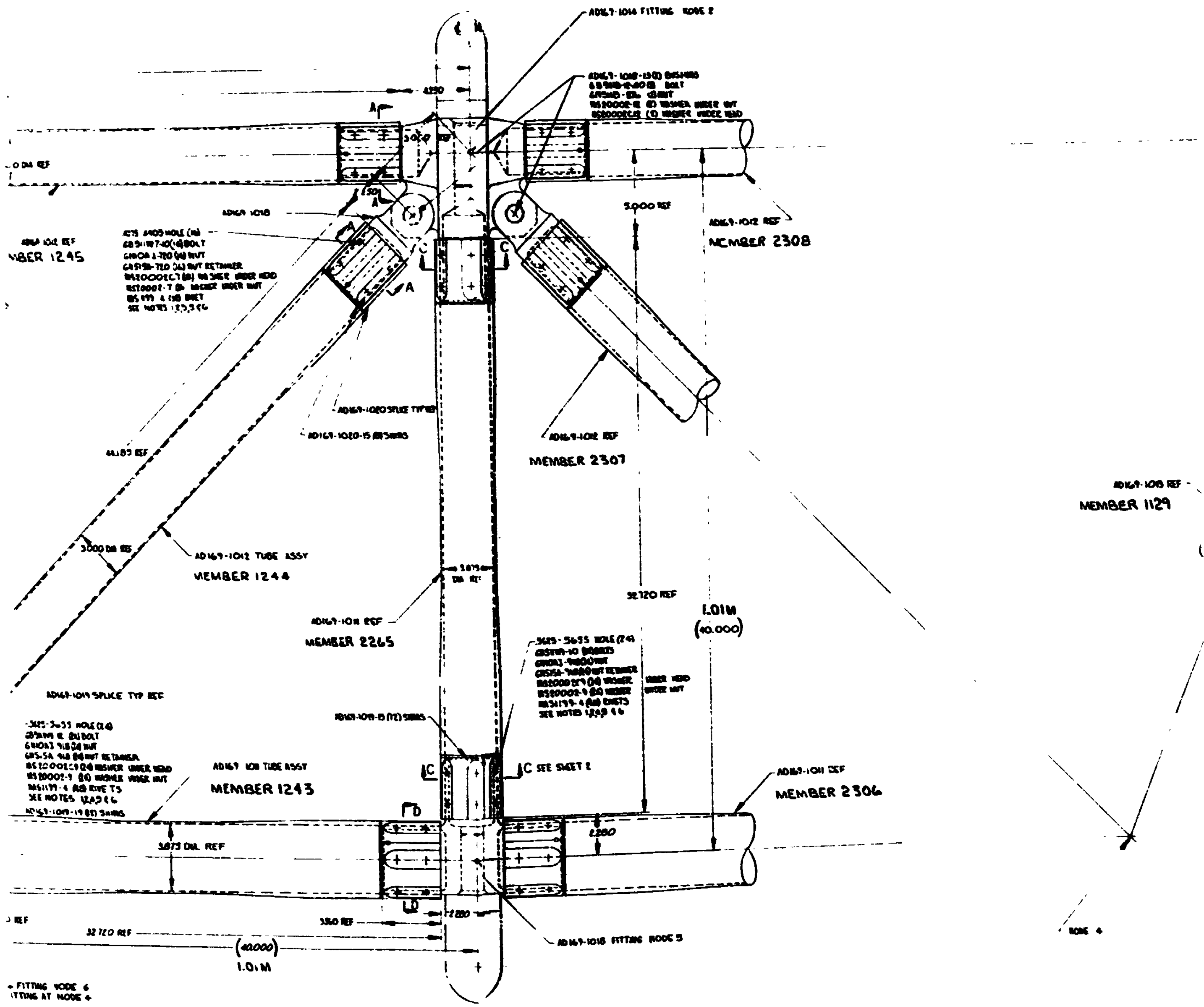

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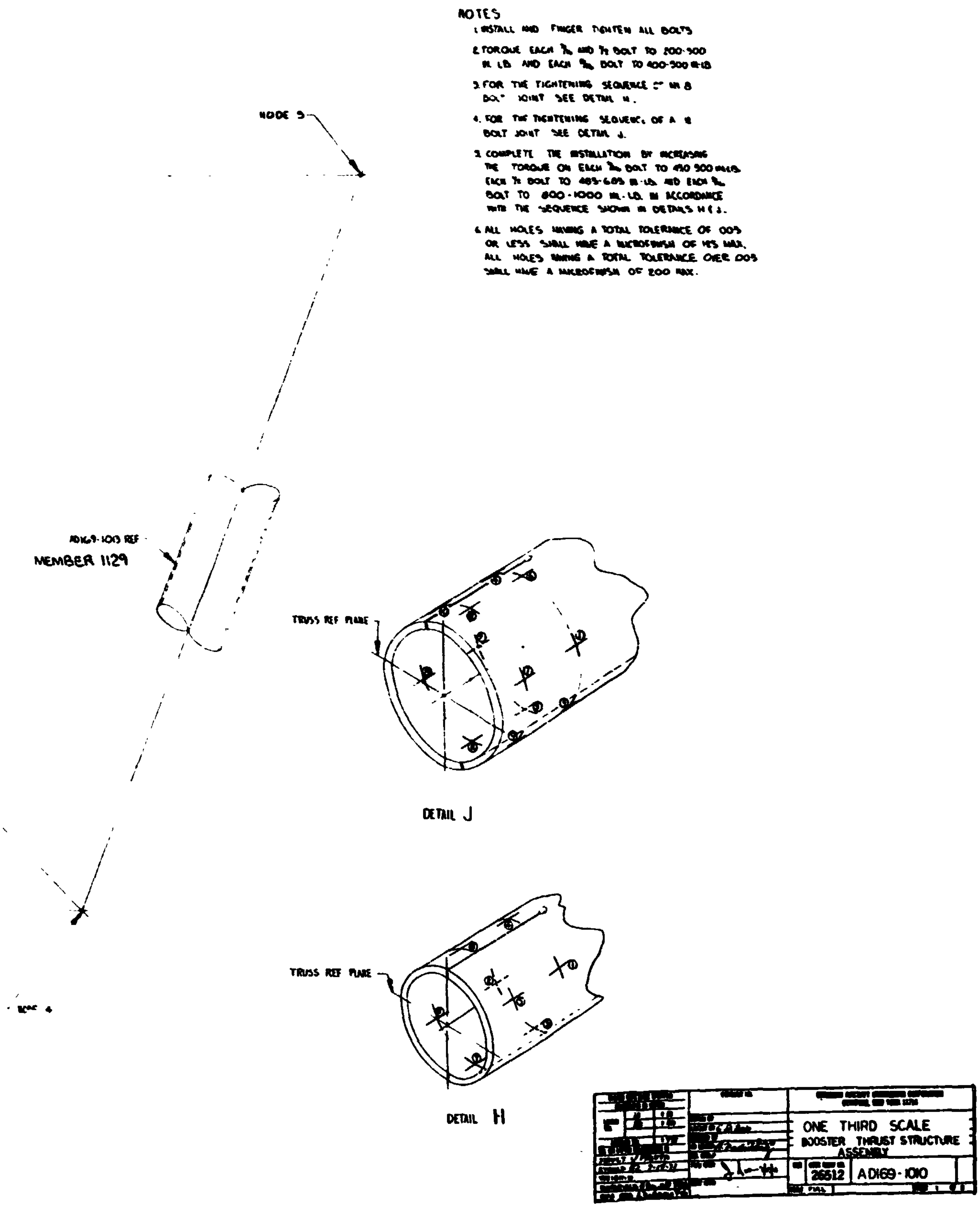

Figure 2-6 Two-Dimensional Thrust Structure Assy

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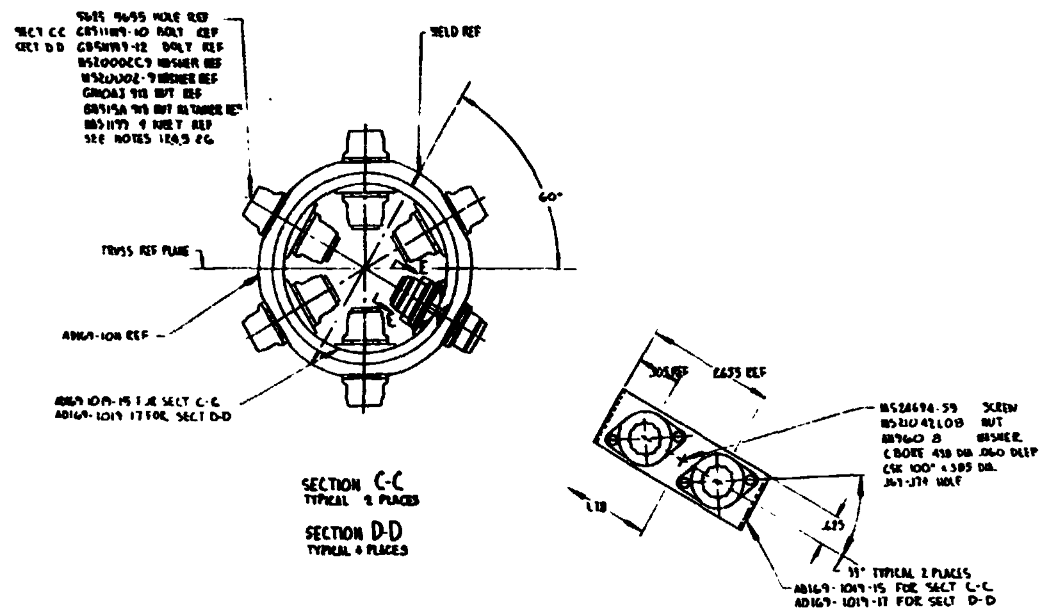
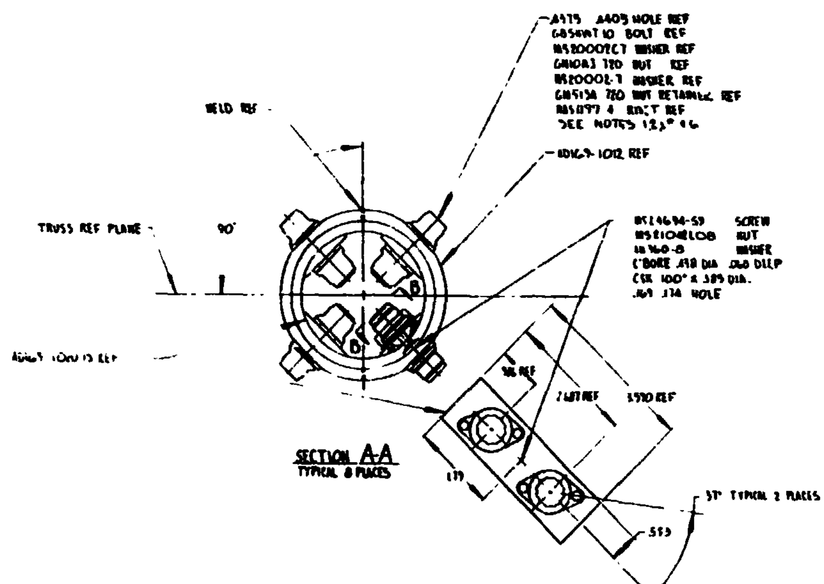


SECTION C-C
TYPICAL 2 PLACES

SECTION D-D
TYPICAL 4 PLACES

SECTION E-E
TYPICAL 4 PLACES



SECTION A-A
TYPICAL 8 PLACES

SECTION B-B
TYPICAL 4 PLACES

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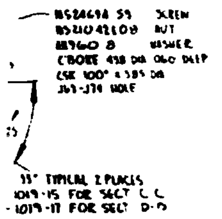
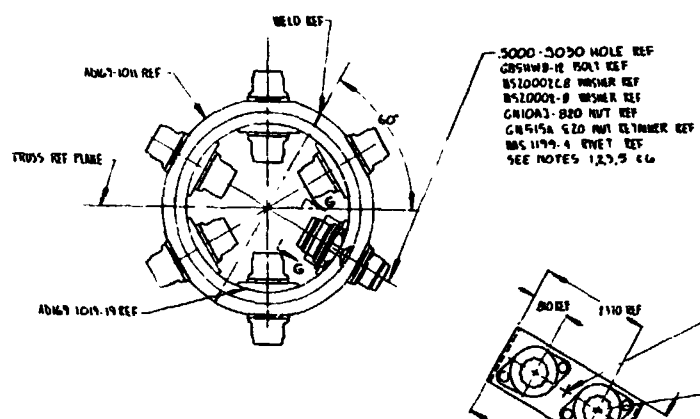
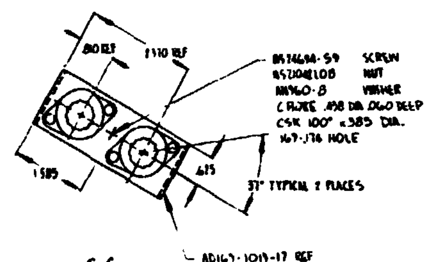




SECTION F-F
TYPICAL 4 PLACES



SECTION G-G
TYPICAL 4 PLACES

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Figure 2-5

FOLDOUT FRAME 2

plane of the truss. The truss is restrained against X translation at nodes 1 and 3 and against Y translation at node 3. Internal member loads for Conditions 1 and 2 are shown in Figures 2-3 and 2-4.

2.3 Thrust Structure Assembly and Structural Arrangement

The complete two-dimensional thr structure assembly is shown in Figure 2-5. It is comprised of nine boron/epoxy tubes, six titanium apex fittings and two titanium lug fittings. Due to symmetry, there are only five different tubes and four different apex fittings required for the entire truss assembly. Only three different detail configurations were used for the five tubes. This was possible since the resultant critical loading for the chosen identical members were so similar. This approach resulted in a structure that was less costly to fabricate than the structure with five different tubes and incurred only a small weight penalty. Common tubes are utilized for members 2265, 1243, and 2306-1244, 1245, 2307 and 2308-1129 and 343. Common apex fittings are used at nodes 1 and 3 as well as 4 and 6, with the fittings at nodes 2 and 5 being used in only one location each.

Design of the thrust structure was influenced by assembly requirements which necessitated the use of pin ended (lug type) joints at the end of members 1244 and 2307 contiguous to the apex fitting at node 2. This type of joint, while necessary to achieve a simple yet effective assembly procedure, also resulted in an apex fitting design which was significantly lighter and less complex than a fitting which would have been required to provide bending restraint to these members.

The actual assembly of the structure was accomplished from three subassemblies; the center subassembly and the left and right side subassemblies. Composition of each subassembly is as follows:

- Center Subassembly - Apex fittings at nodes 2 and 5, to which members 2265, 1245, 2308, 1243 and 2306 were assembled.
- Left Side Subassembly - Apex fittings at nodes 1 and 6 to which members 343 and 1244 were assembled.
- Right Side Subassembly - Apex fittings at nodes 3 and 4 to which members 1129 and 2307 were assembled.

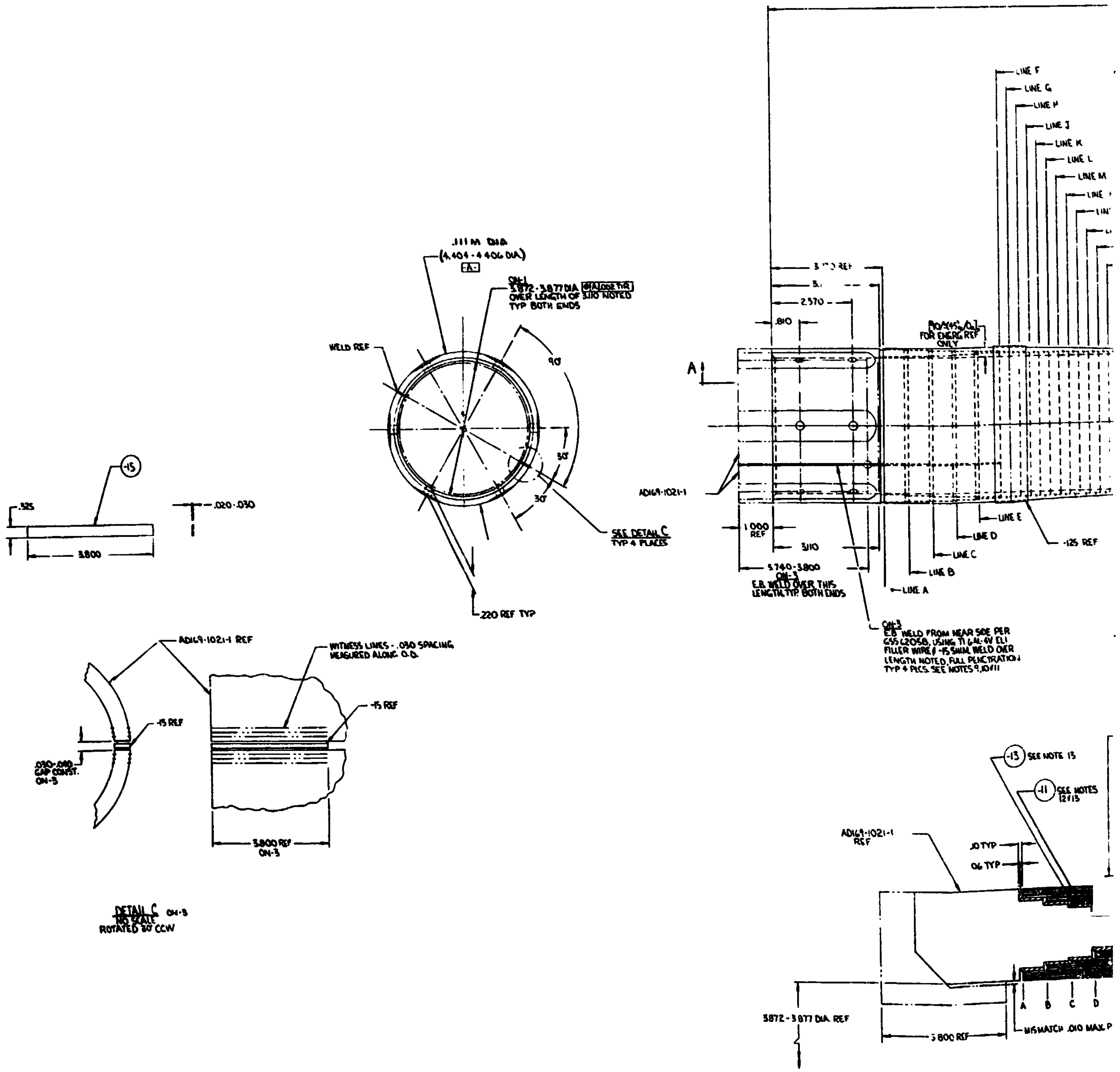
The subassemblies were each prefitted and, upon completion, aligned in a common plane. The left and right side subassemblies were then moved laterally toward the center subassembly, effecting final assembly.

The attachment of all members and fittings (except the node 2 lug attachments) was accomplished with 1.515×10^9 N/m^2 (220 ksi) bolts in conjunction with nut plate assemblies attached to the inside diameter of each tubular portion of the apex fittings. The lug attachments were made by insertion of a clampup bushing through the common hole of the parts to be joined, followed by bolt and nut installation. Subsequent to the installation of all required hardware all bolts were torqued to prescribed levels indicated on the engineering drawing.

2.4 Tube Design

The basic members of the truss are designed as circular boron/epoxy tubes, capped at both ends by split-circular, stepped, titanium splice fittings, bonded within the laminate. The design of a typical tube (member 343) is shown in Figures 2-6 and 2-7. The titanium splice fittings are initially split to facilitate fabrication of the boron/epoxy tubes, which are layed-up under size, and subsequently "expanded" in a female mold form. After laminate cure, the split-end fittings are joined by electron beam welding. Subsequent to welding of the end fittings the internal diameter of the tube (over the titanium fitting length) is finish machined. This machining removes the weld flash and sizes the mating surface for assembly into the two-dimensional truss structure.

Optimum tube sizes for the boron/epoxy beam-column members were obtained from the curves of Reference 2, and then adjusted for a refined moment distribution by utilizing a computerized stepped beam-column analysis. The analysis includes the effect of shear deformation as well as the increased stiffness of the titanium end fittings. Further adjustments to member size were incorporated to accommodate limiting splice loads - both bonded and bolted. Limits for the splice loadings were established as a result of studying numerous parameters, such as basic tube laminate requirements, bonded splice laminate requirements, bonded and bolted splice lengths, laminate transitions, bolt size, and influence of the tube internal diameter on the configuration of the titanium apex fittings. The tubular tension members



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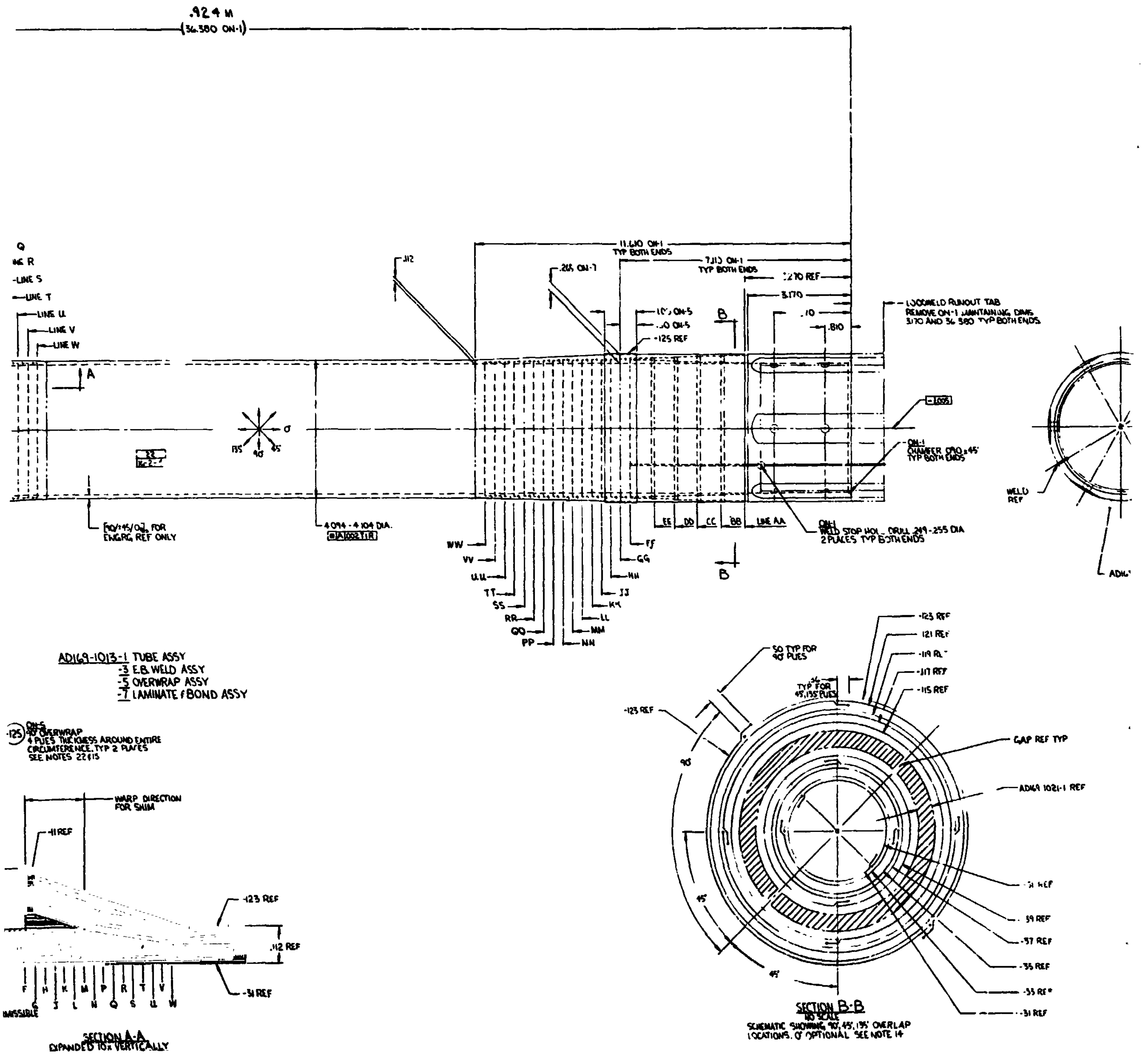

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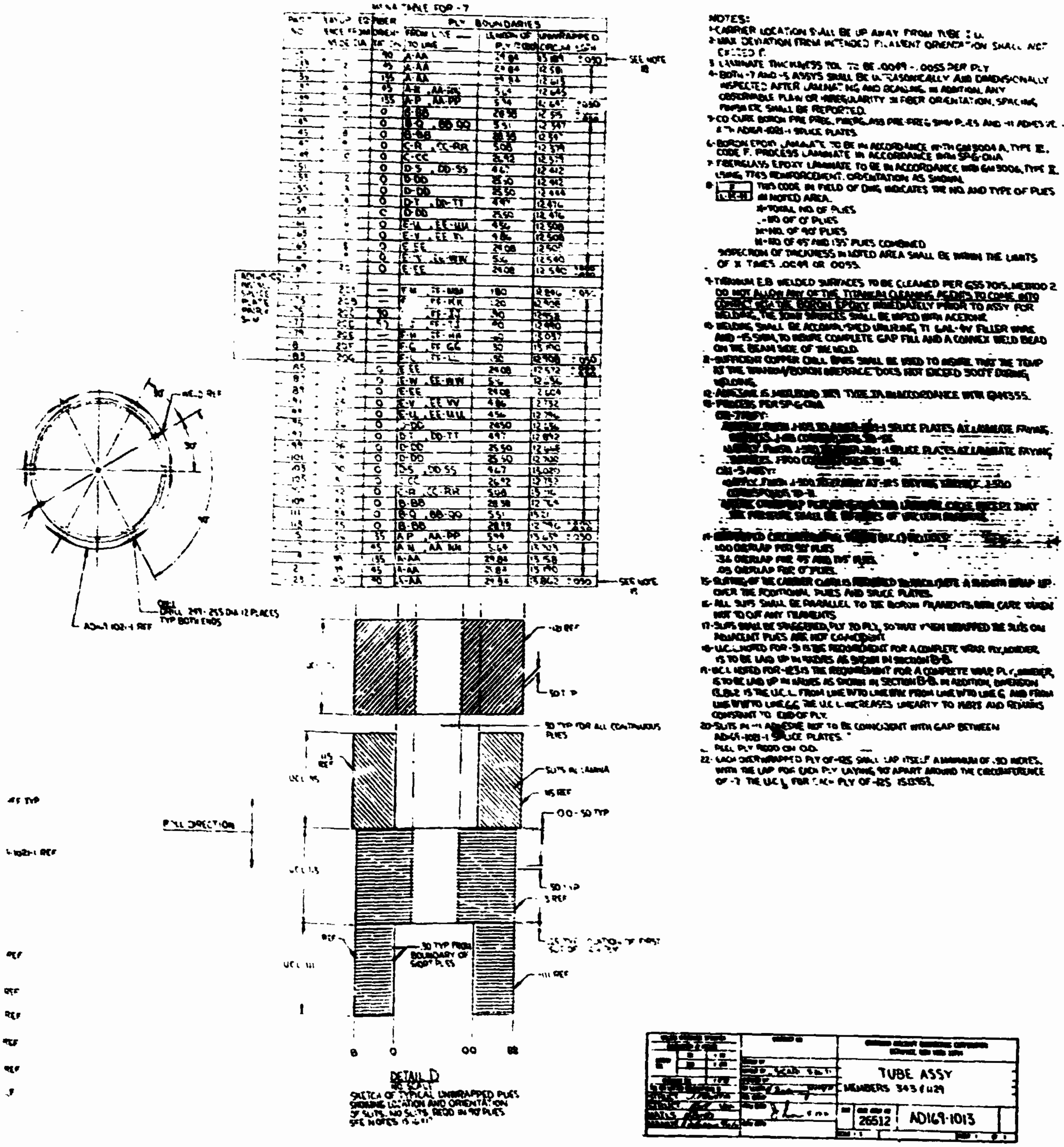
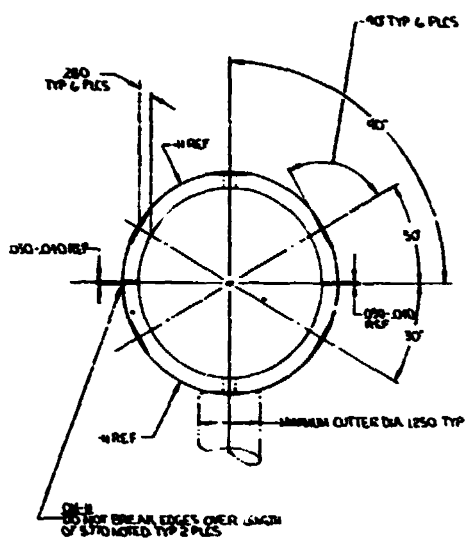


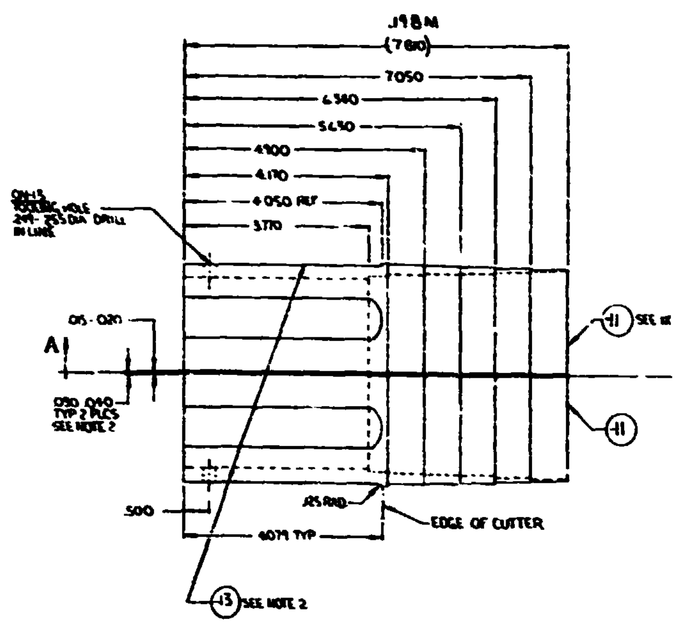
Figure 2-6 Tube Assy Members 343 and 1129

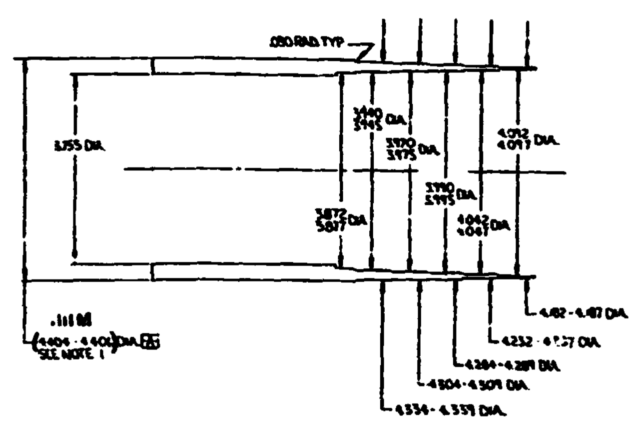
FOLDOUT FRAME 5

AMD 2

NOTES:
1 ALL DIAMETERS TO BE CONCENTRIC TO [B] WITHIN .002 TIR.
2 -13 BECOMES -11 (2) UPON COMPLETION OF .030-.040 CUT SHN.







SECTION A-A

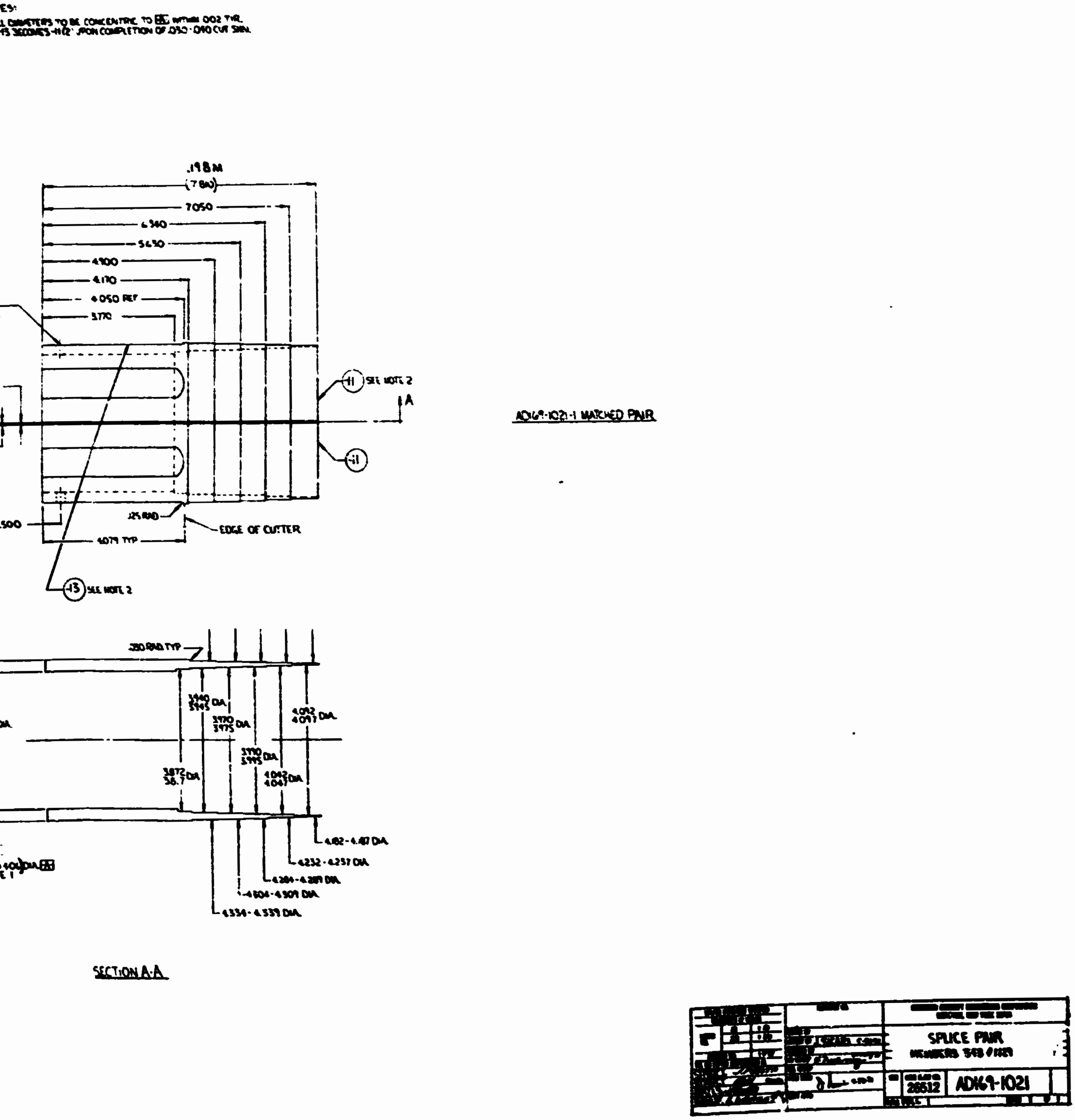


Figure 2-7

Titanium Splice Fitting Members 343 and 1129

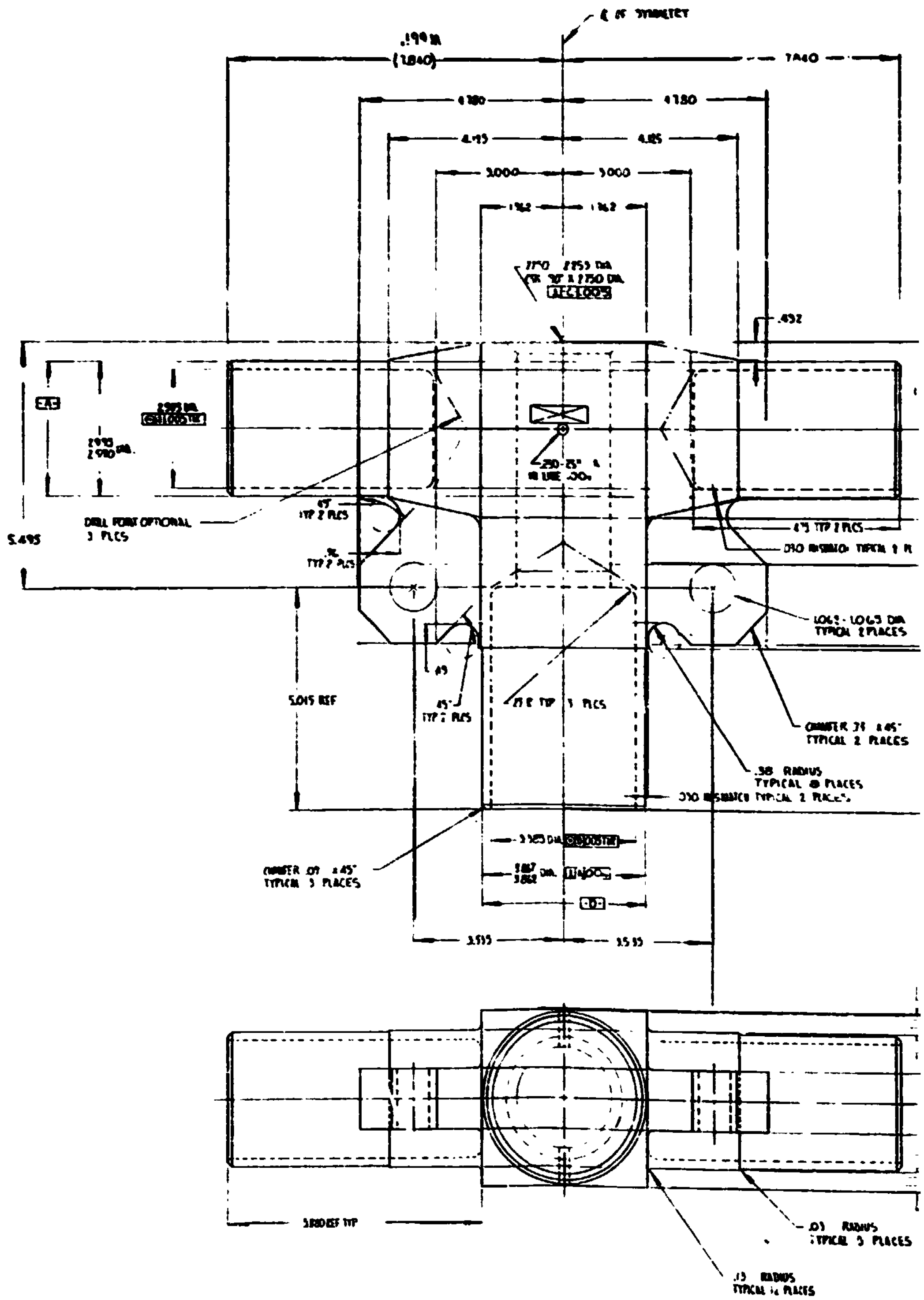
for the truss were designed using standard techniques, with the same consideration given to the splices as previously described.

The bonded splices at either end of each boron/epoxy tubular member were designed by the Grumman developed STEP* computer program of Reference 3. The program performs a close-form elastic analysis, including plasticity corrections due to the non-linear behavior of the adhesive, for symmetric stepped bonded joints. In the design, the basic unspliced tube laminate and its ply stacking sequence are first considered. Additional plies of boron/epoxy are added to this laminate, and the total laminate is distributed over an assumed number of steps in the titanium splice fitting. A computer run is then made. Based on the results of the initial run, number of plies, drop off rate, number of steps, step length, and titanium gage are varied until a splice of the desired strength is achieved. The procedure is iterative and usually requires two or three runs to obtain an effective splice. The additional plies are added to the basic laminate at a rate of two per increment, each increment is 7.62 mm (0.30 inch), with the longest additive ply nearest the center of the splice. A fiberglass boron/epoxy shim is also added to compensate for the initial titanium thickness, and to provide a smooth fiber transition into the splice.

Bolted joints, through the titanium end fittings, are used at both ends of each tube for final assembly of the truss structure. The titanium fittings have flats machined on the outside diameter in the vicinity of the bolted joint, to provide a mating surface for the bolt head thus eliminating separate external radius blocks. The bolted joint itself is accomplished with the use of 1.515×10^9 N/m^2 (220 ksi) bolts. The use of these high strength bolts results in minimum length joints in conjunction with minimum diameter tubes.

2.5 Apex Fitting Design

There are six apex fittings of four different configurations required for assembly of the two-dimensional thrust structure. Due to symmetry of the structure the fittings at nodes 1 and 3 are identical as are the fittings at nodes 4 and 6. The fittings at nodes 2 and 5 are centrally located and therefore are utilized in only one location each. The fittings were designed to be structurally representative of a flight structure, but were simplified in design to minimize fabrication cost. A typical apex fitting is shown in Figure 2-8. The fittings, fabricated from 6Al-4V annealed



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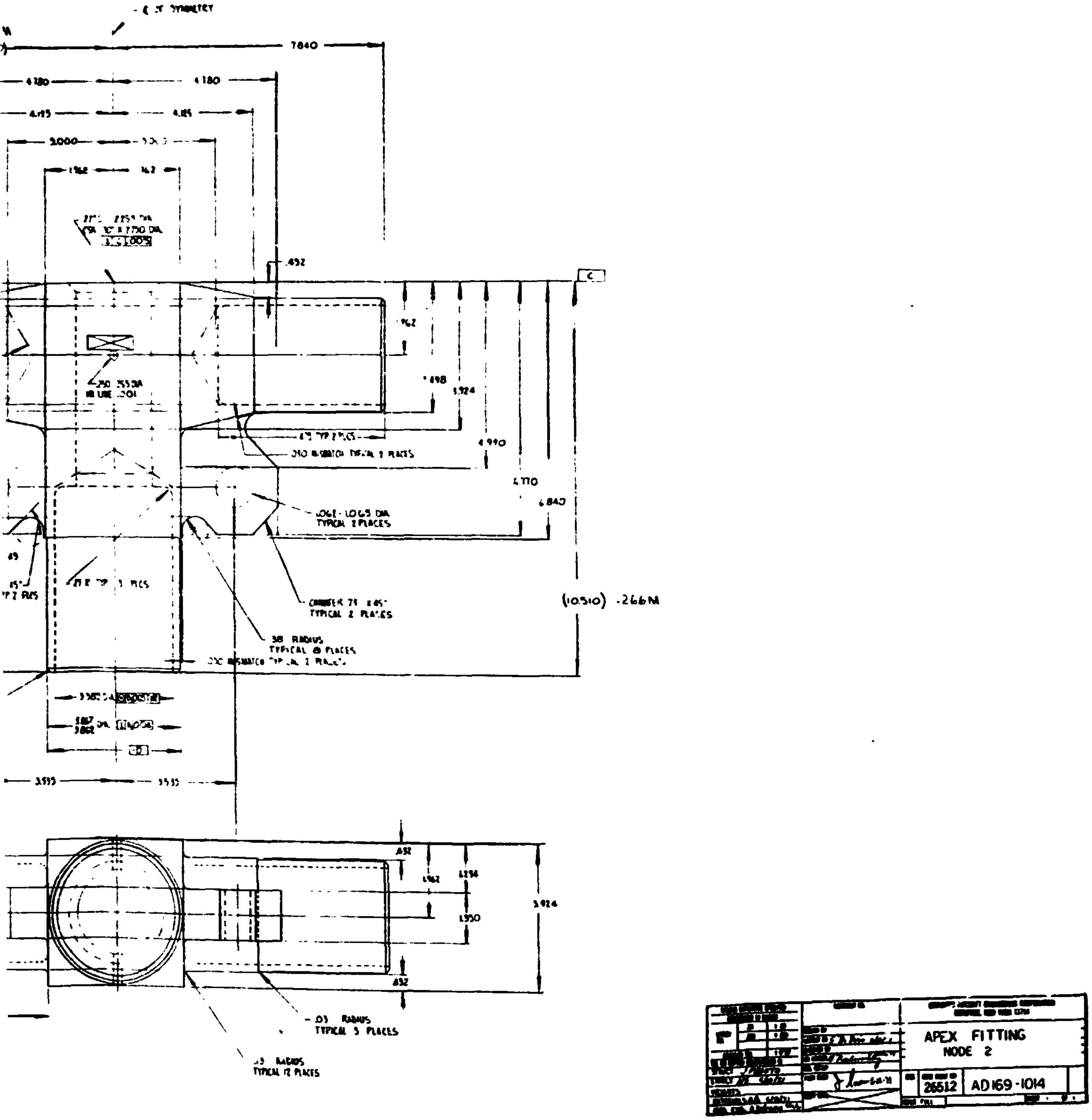


Figure 2-8 Titanium Apex Fitting Node 2

FOLDOUT FRAME 2

titanium bar stock, consist basically of a central hub area off of which cylindrical, and in one case lug type appendages, have been machined. The cylindrical sections mate with the inside diameter of the tube and contain the nut plate assemblies which serve to attach the boron/epoxy tubes to the fittings. The lug sections, which are used on the fitting at node 2, are male type and mate to female type fittings incorporated at one end of members 1244 and 2307. The lug type connection of these members at node 2 is necessary for truss assembly but also allows a low weight, uncomplicated machined part to be used for the fitting at node 2.

In addition to the design of the fittings for the resultant internal member loads, consideration was given to provide a test interface with suitable load introduction. As a result a 57.15 mm (2.25 in.) diameter socket was incorporated in the fittings at nodes 2, 4, 5 and 6 into which a steel test fitting was inserted to establish the load introduction interface. At nodes 1 and 3 the load reaction points, similar holes were provided in the fittings, only in a plane perpendicular to the truss plane. Upon assembly to the test fixture these holes receive pins providing the desired end supports.

2.6 Weight Comparison

Tubular member weights resulting from the design of the two-dimensional truss are presented in Table 2-2. The boron/epoxy weights were calculated from actual detail design; the titanium weights were computed from an optimum or near optimum weight study. A working stress level of 792.8×10^{6}N (115,000 psi) was used for the titanium members in compression, this was due to the non-linearity of the modulus at values approaching the compression yield stress. In order to arrive at an equitable weight comparison, identical titanium tubes were used in the same positions in the truss assembly, where identical boron/epoxy tubes were utilized.

Table 2-2 Comparative Tubular Member Weights - Two Dimensional Truss

Member	Boron/Epoxy Design Member Weight - N (lbs)	Titanium Design Member Weight - N (lbs)
343	41.76 (9.39)	62.67 (14.09)
1243	45.68 (10.27)	68.32 (15.36)
1244	29.89 (6.72)	40.38 (9.08)
1245	29.89 (6.72)	40.38 (9.08)
2205	45.68 (10.27)	68.32 (15.36)

3.0 MATERIALS AND MANUFACTURING

3.1 Material Procurement

The materials required for the fabrication of the two-dimensional thrust structure were:

- o Boron/epoxy three inch wide continuous preimpregnated tape
- o 6Al-4V annealed titanium rod and bar stock
- 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 Grumman Aerospace Specification GM3004A, Type III and contained United Aircraft filament impregnated with the 3M SP290 resin system. The titanium and adhesive were purchased to Grumman Aerospace Corporation specifications GM3112A and GM4355, respectively. All hardware was in accordance with Standard Pressed Steel specifications.

3.2 Tool Design

Tool requirements for the program were as follows:

- o Mold Form (MOF) - 3 Required
- o Layup Mandrel (TFT) - Combination Tool
- o Layup Template (LT) - 3 Required
- o Tube Wrapping Machine (MCA) - 1 Required
- o Weld Fixture (WF) - 2 Required
- o Inspection Fixture (ICF) - 1 Required

3.2.1 Mold Forms

The mold forms used to fabricate the Phase I and Phase II tubes were similar in basic design. The three tools were female molds split along the longitudinal centerline, with the inside surface being the molding surface. 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 of the molding surface and checked for accuracy. The molding surfaces were then machined to finish dimensions using a tracing lathe. Index holes, vacuum grooves and vacuum fittings were then added.

Several modifications were incorporated into the Phase II mold forms to enhance performance. These modifications included: the addition of slotted vacuum bleed rings and vacuum ports at both ends of the tool, additional bleeder ports and incorporation of cast silicone rubber seals at the tool ends, with a matched faying surface to the titanium splice fittings. The latter modification was utilized to minimize lateral resin bleed out during cure. A typical mold form is shown in Figure 3-1.

3.2.2 Layup Mandrels

The layup mandrel was designed to accommodate all three tube configurations with one combination tool. The mandrel was an all metal breakaway type consisting of one steel arbor, common to all tube configurations, two circular aluminum end plugs and a five section aluminum main plug, which differed for each tube size. The end plugs were provided with locators to accurately position the titanium splice fittings longitudinally and radially. The use of a breakaway type of mandrel was dictated by the tube configuration which caused the mandrel to become locked in upon completion of the tube wrapping operation, and the desire to remove the mandrel prior to further processing. Mandrel removal was a relatively simple operation with the resultant design. To remove the mandrel from the layup the part was positioned in the female mold, the mold closed and a vacuum applied to the envelope bag. The arbor was then removed from one end, followed by end plug removal from each end. This exposed the split center section which was collapsed and pulled out. A typical mandrel is shown in Figure 3-2.

3.2.3 Tube Wrapping Machine

The tube wrapping machine was a hand operated tool that layed-up and compacted the boron tape on the tube layup mandrel. This tool consisted of a wind-up roller, pressure roller, vacuum table and tube layup mandrel.

The wrapping machine used for Phase II was a redesigned version of the Phase I machine. Modifications were made to accommodate the three tube designs, provide for more positive location of splice plates and to allow for more flexibility of layup procedures during tube fabrication. Position of the takeup roller was made movable rather than fixed. This permitted the angle at which the layup template was pulled through the pinch rollers to be adjusted during layup to best accommodate the ply buildup. The compaction

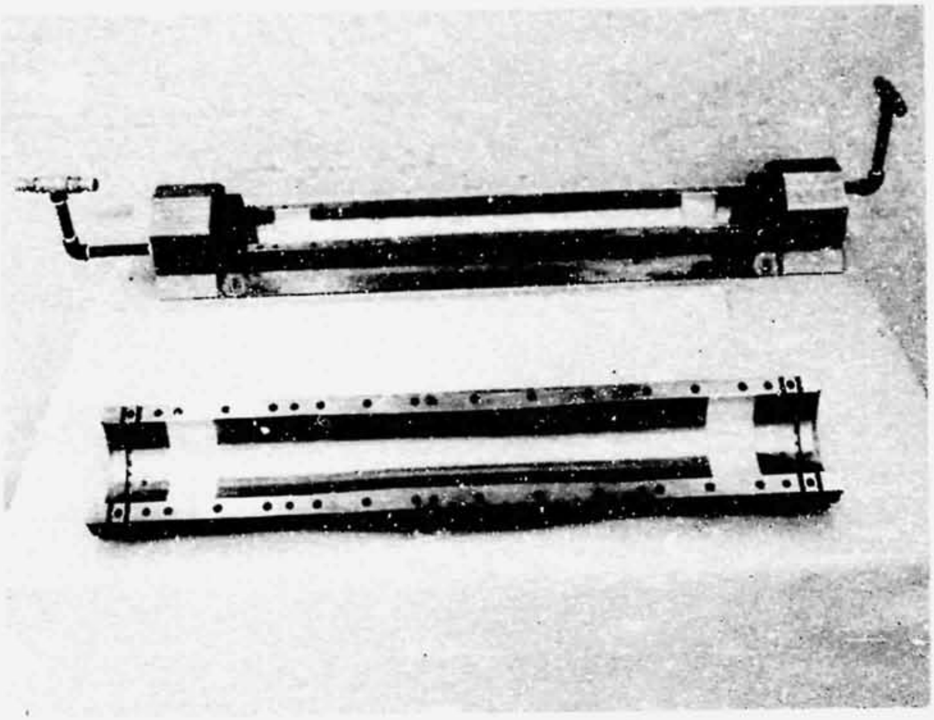


Figure 3-1 Tube Mold Form

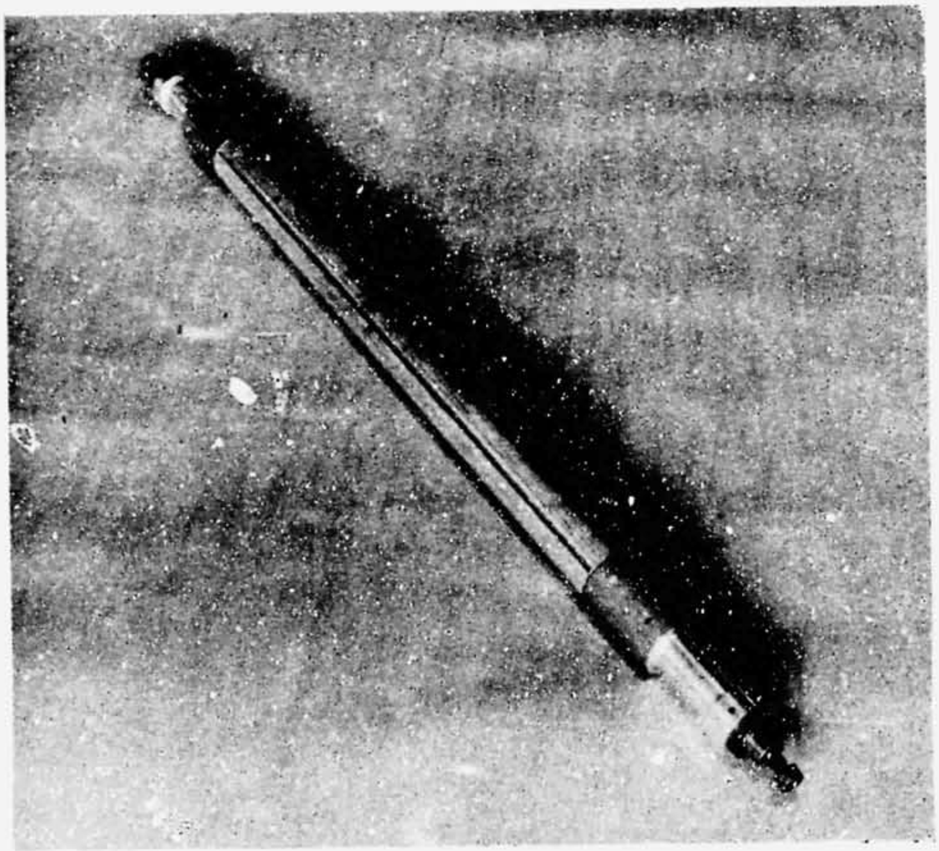


Figure 3-2 Tube Layup Mandrel

roller setup was changed from one straight roller to one straight and one contoured roller for each tube configuration. During Phase I it was determined that using a straight roller for the complete layup did not permit the proper compaction once the splice plates were introduced into the layup. The new concept used the straight roller for compaction prior to positioning the splice plates and the contoured roller with the plates in position. The vacuum table was also modified to allow for a more gentle introduction of boron into the compaction rollers. Figure 3-3 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 straight compaction roller
- o Position the template on the wrapping machine and attach to the wind-up roller
- o Apply vacuum to the template
- o Wind template two 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
- o Continue layup to insertion of splice plates
- o Replace straight compaction roller with proper contoured roller
- o Position splice plate locators on layup mandrel and insert splice plates
- o Adjust compaction pressure and complete layup

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. A gauge attached to the layup machine was used to check the longitudinal position of the plies during layup. In addition, part diameter was continuously checked during wrapping to insure proper compaction. When the layup was completed the wrapped mandrel was removed and transferred to the mold form.

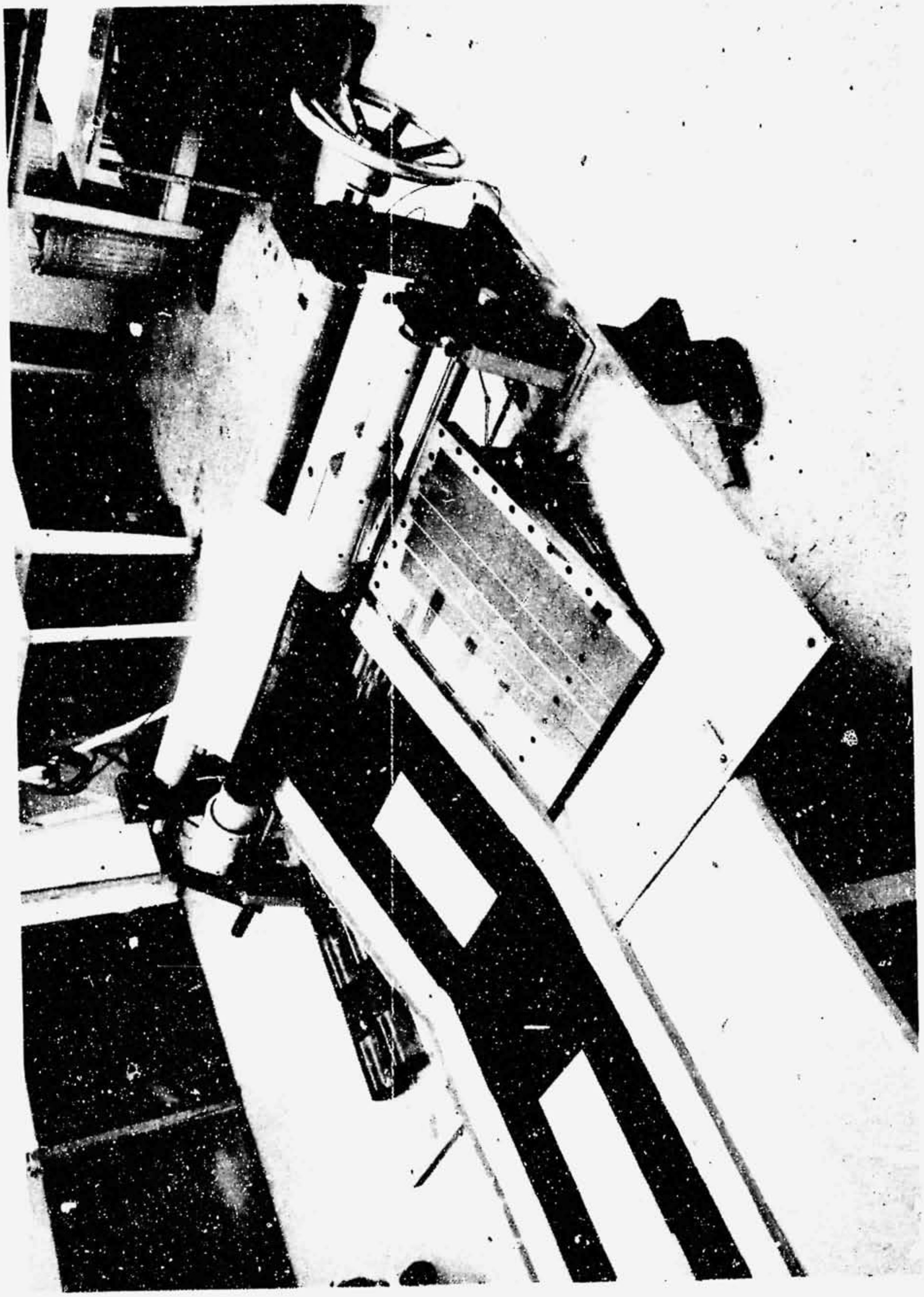


Figure 3-3 Tube Wrapping Machine

3.2.4 Layup Templates

Layup templates used for the Phase II tubes were of the same type as Phase I; .0127 mm (0.005 inch) thick mylar film.

A typical boron/epoxy tape layup template is shown in Figure 3-4. 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 length plies although some repositioning of the slit portions was required before final compaction of the ply. Again, as in Phase I operation, the short plies did not machine wrap properly and had to be positioned by hand before compaction. Although positioning the short plies by hand is more time consuming than by machine it is quite accurate and represents the best existing method.

3.2.5 Titanium Splice Fitting Weld Fixture

The titanium splice fitting weld fixture was similar in design to the tool used for the Phase I program. It was a simple V-block type holding fixture which securely held the splice fitting during the welding operation. Used in conjunction with the holding fixture were splash bars (to prevent the electron beam from passing through to the opposite side of the part) and a run-on fixture. The latter was necessary to prevent damage to the tube since the weld was initiated from the boron/epoxy side rather than the tube end.

3.2.6 Q.C. Inspection Fixture

The Quality Control inspection fixture was a holding tool used to mount the tubes for ultrasonic inspection. It was placed in the test tank and positioned relative to the scanning motion of the test probe. As the probe completed a pass an indexing device was activated causing the tube to rotate through a fixed angle. A single fixture was fabricated which was adaptable to the three tube configurations. The fixture is shown in Figure 3-5.

3.2.7 Assembly Tooling

Assembly tooling consisted of an assembly fixture and removable drill jigs. The assembly fixture, shown in Figure 3-6, positioned the apex fittings in the proper spacial relationship to each other, with the fittings

Figure 3-4 Mylar Layup Template

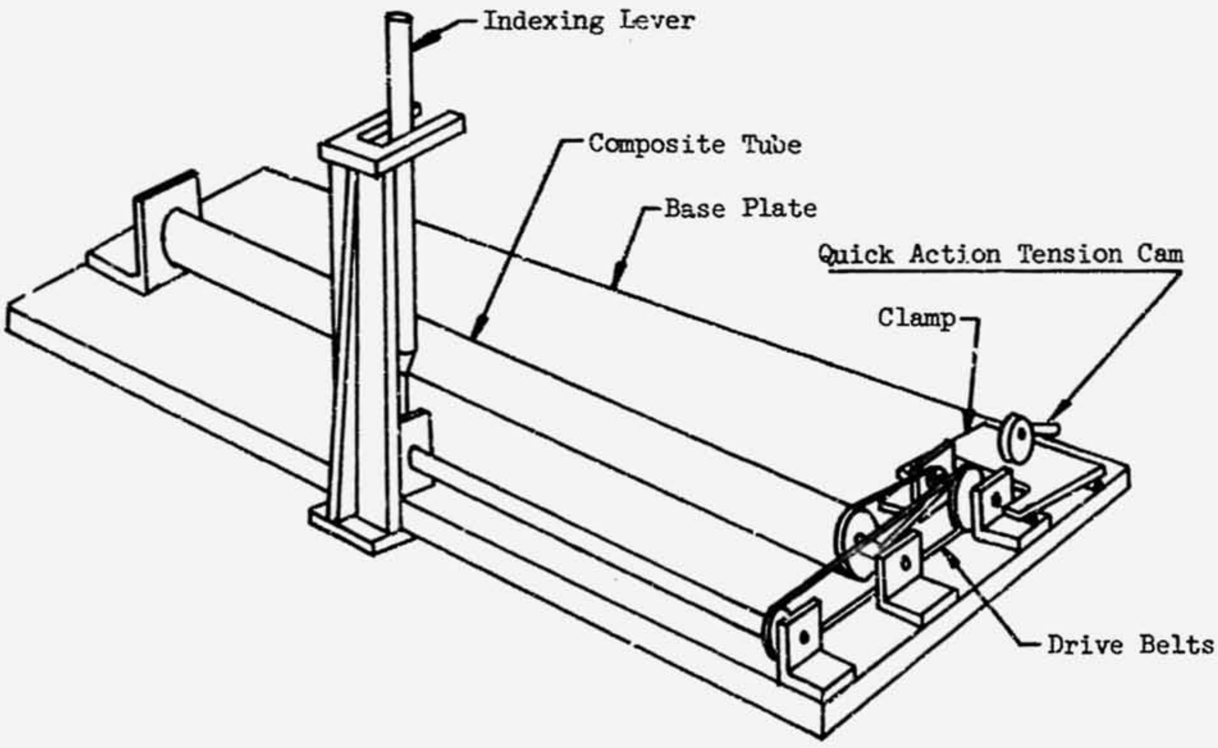


Figure 3-5 Q.C. Tube Holding Fixture

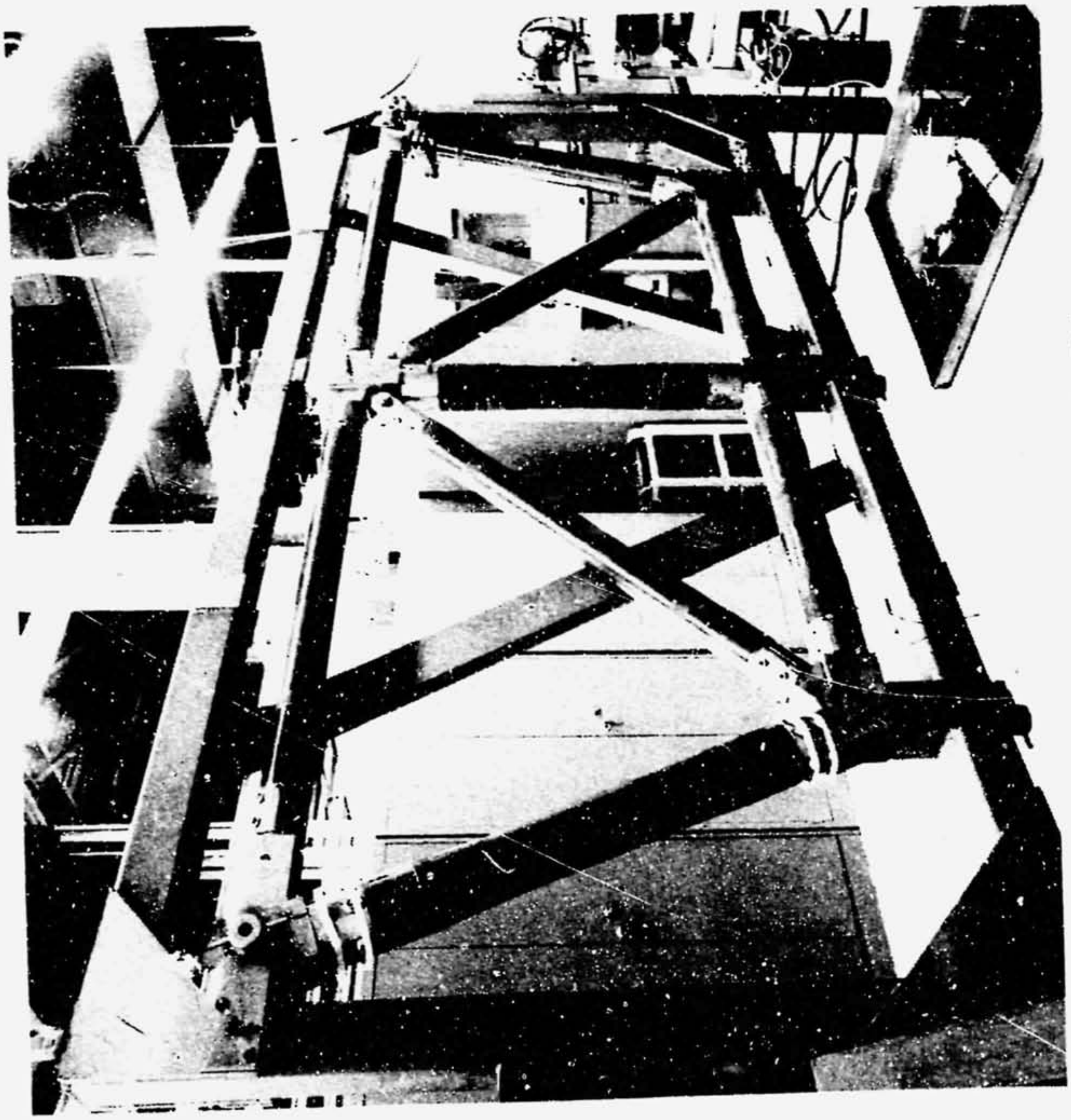


Figure 3-6 Truss Assembly Fixture

in turn locating the boron/epoxy tubes. Lateral fitting location at nodes 2, 4, 5 and 6 was provided by vertically sliding pins engaging holes bored in the apex fittings. Vertical location was provided with banking surfaces machined on the fixture. At nodes 1 and 3 both lateral and vertical fitting location was provided by pins. At these nodes, however, the pins engaged the apex fittings in a line normal to the plane of the thrust structure. Close dimensional control was provided between the pins at nodes 1 and 3 and the banking surfaces at nodes 4, 5 and 6. The fitting location at node 2 was made adjustable to account for any tolerance accumulation.

The drill jigs were simple V-block type holding clamps that were positioned to the pre-drilled holes in the tube splice fittings. The drill jig in turn held and positioned the portable automatic drilling head. The drill jig and automatic drilling head are shown in Figure 3-7.

3.3 Parts Fabrication

The two-dimensional thrust structure assembly required fabrication of titanium splice fittings, titanium apex and lug fittings and boron/epoxy tubes. A detailed describtion of the manufacturing operations required to fabricate these parts, as well as those necessary for final thrust structure assembly follows.

3.3.1 Titanium Splice Fitting Machining

The titanium splice fittings were machined from 6Al-4V annealed titanium rod stock. Fabrication was initiated by rough cutting the rod to lengths of approximately .304m (12 in.) and boring the inside diameter to 2.54 mm (.10 in.) undersize. The stock was then mounted in a lathe where the outside diameter was turned to 2.54 mm (.10 in.) oversize. Following the initial turning operation the part was put through a stress relief cycle per Grumman Standard Specification (GSS) 6205, which called for a temperature exposure of 922.03°K (1200°F) for four hours followed by a slow cool down in the oven to 644.26°K (700°F). The cycle was used to minimize if not eliminate any final part distortion caused by residual machining stress. After completion of the stress relief operation the parts were remounted on a lathe and turned to the finished configuration. This was followed by milling of flats on the fitting outside diameters and the drilling of 6.35 mm (.25 in.) diameter pilot holes. The final operation involved the parting of the fitting along its longitudinal

Figure 3-7 Automatic Drilling Head and Drill Jig

centerline, yielding two semi-circular halves. The parting was accomplished with a 1.016 mm (.040 in.) circular saw attached to a milling head. Typical splice fittings (part number AD169-1019) are shown in Figures 3-8 and 3-9.

3.3.2 Apex Fitting Machining

A single large billet of annealed 6Al-4V titanium was purchased to provide stock for all the apex fittings. The billet was sawed into blocks of suitable size for the individual apex fittings, squared and deburred. Following the preliminary sizing operations the planform outline of each fitting was laid out on its repsective block and the excess material was removed by sawing. The shaped and deburred blocks were mounted in a lathe and the cylindrical ends machined to final dimension. Close tolerances were maintained on the angular relationship of one cylindrical end to the other as this was essential to insure proper truss assembly. Subsequent to turning, the set back surfaces and lugs were milled to the drawing configuration and any holes required were jig bored. The fittings were then deburred, inspected dimensionally and cleaned by immersion in a non-etch alkali. After cleaning the parts were dye-penetrant inspected (per MIL-I-6866), recleaned and packaged. All fittings fabricated for the two-dimensional thrust structure are shown in Figures 3-10 through 3-14.

3.3.3 Tube Fabrication

The manufacturing processes used for the boron/epoxy (B/Ep) tube fabrication under the Phase II program were similar, but not identical, to those previously used for the tubes fabricated under Phase I. The changes made were due primarily to usage of the 3M SP290 resin system in lieu of AVCO 5505. The 3M system exhibited considerably more tack which, while simplifying the tube wrapping operation, also resulted in significantly higher resin flow. This necessitated modification of the bleeder system and cure cycle to compensate for the increased flow. The basic processes and techniques used for the fabrication of the Phase II tubes follows as well as a detailed description of the process modifications made. The overall tube fabrication sequence is shown in Figure 3-15.

The basic tube fabrication process was initiated by wrapping a tubular nylon film bag on the layup mandrel. The bag was sized to extend beyond each end of the mandrel with the excess material tightly packaged at the ends. The various components of the bleeder system were cut to size, including a full nylon peel ply, segmented plies of 116 glass and a layer

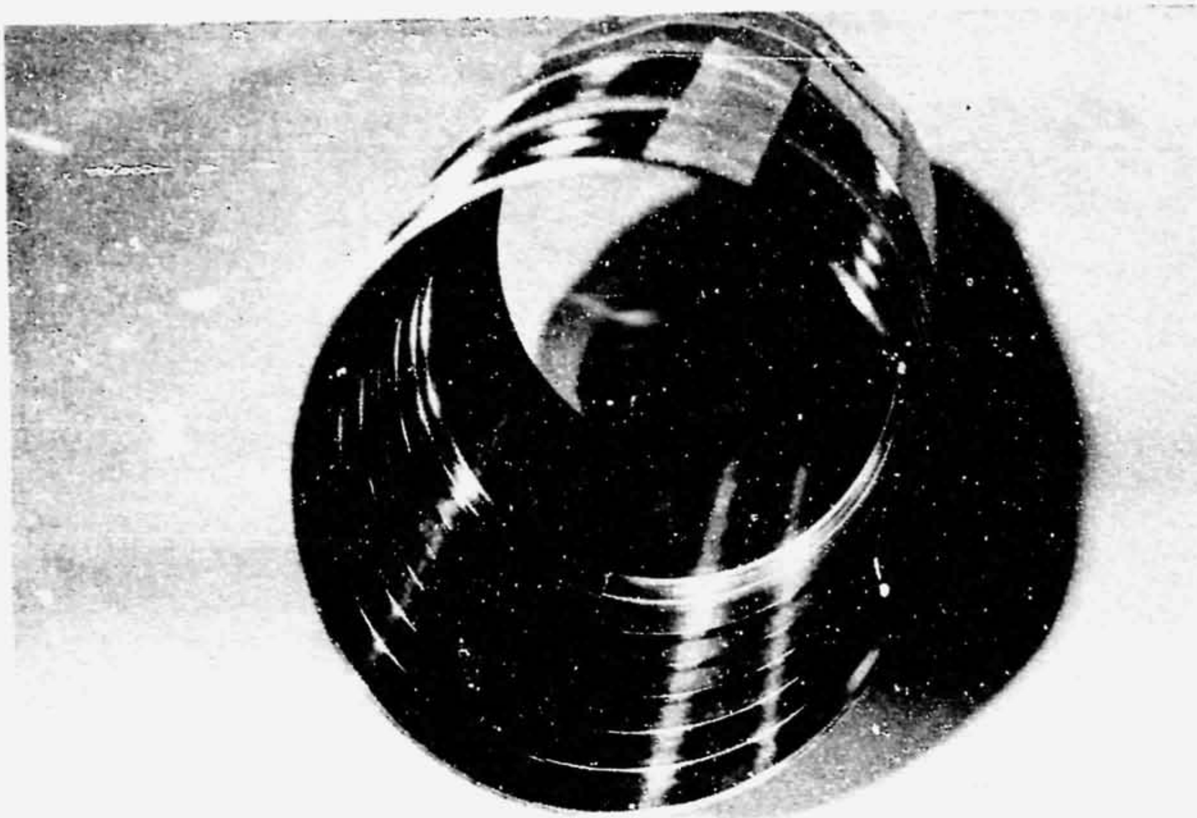


Figure 3-8 Titanium Splice Fitting (AD169-1019)

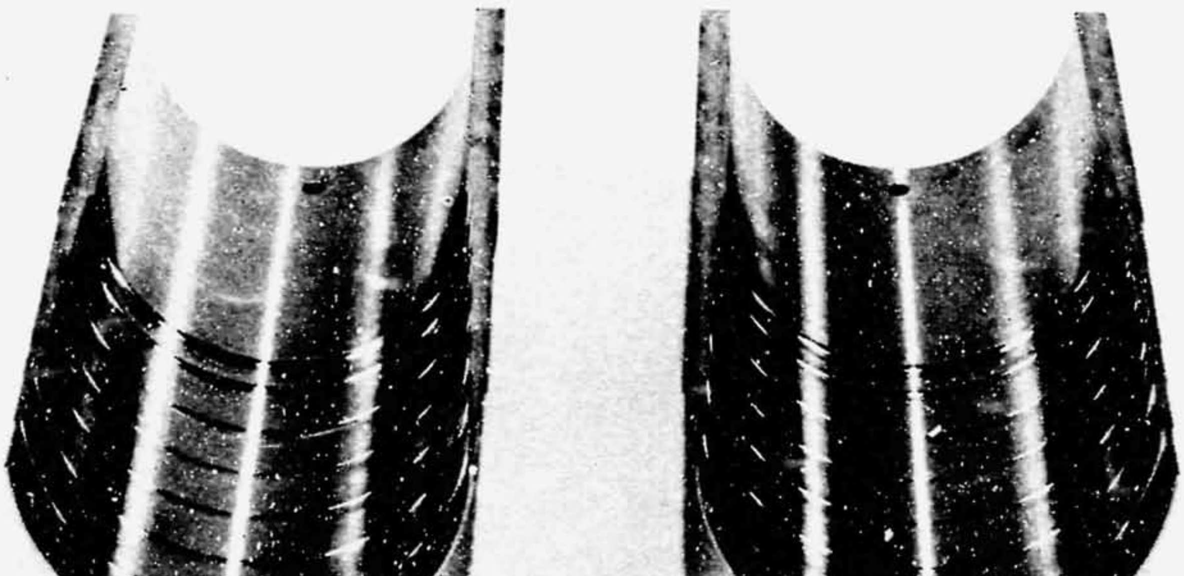


Figure 3-9 Titanium Splice Fitting (AD169-1019)

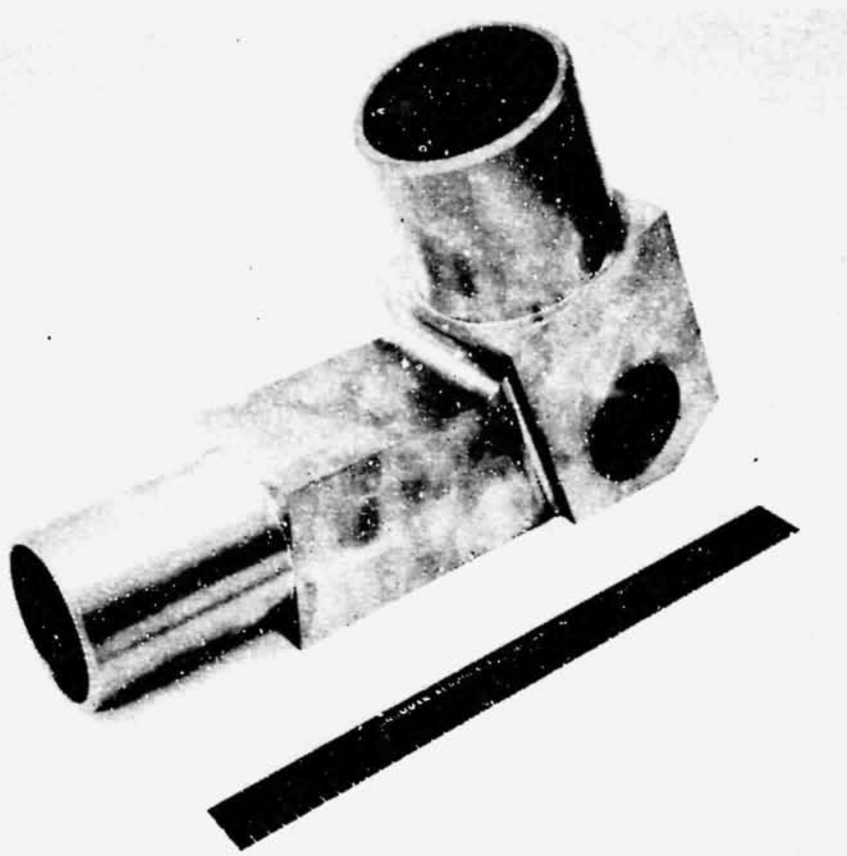


Figure 3-10 Apex Fitting - Nodes 1 and 3 (AD169-1017)

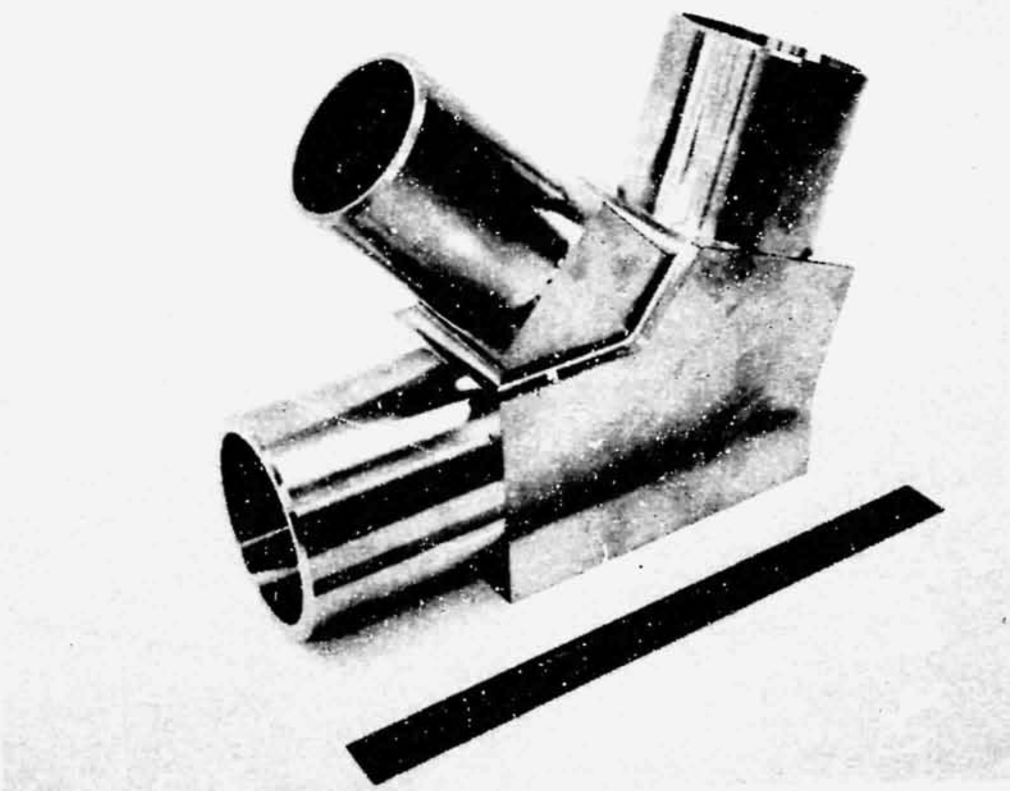


Figure 3-11 Apex Fitting - Nodes 4 and 6 (AD169-1016)

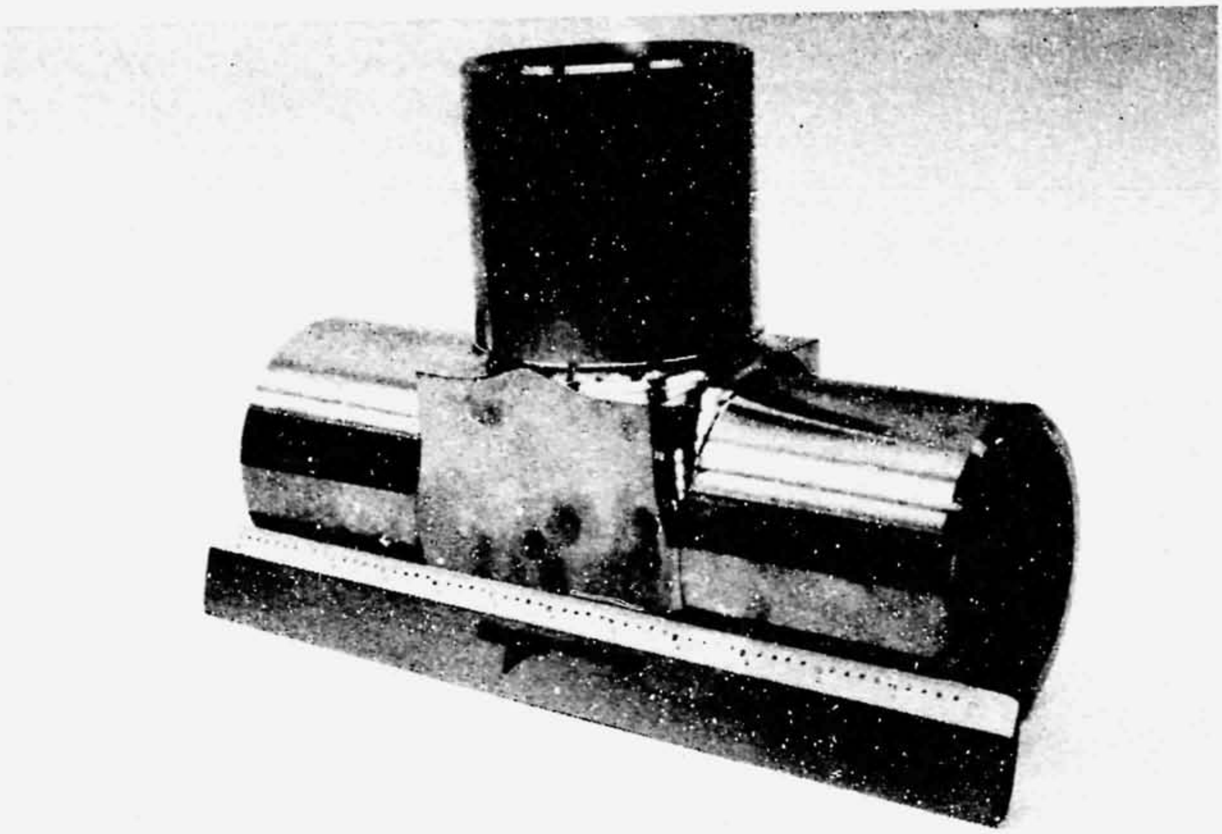


Figure 3-12 Apex Fitting - Node 5 (AD169-1015)

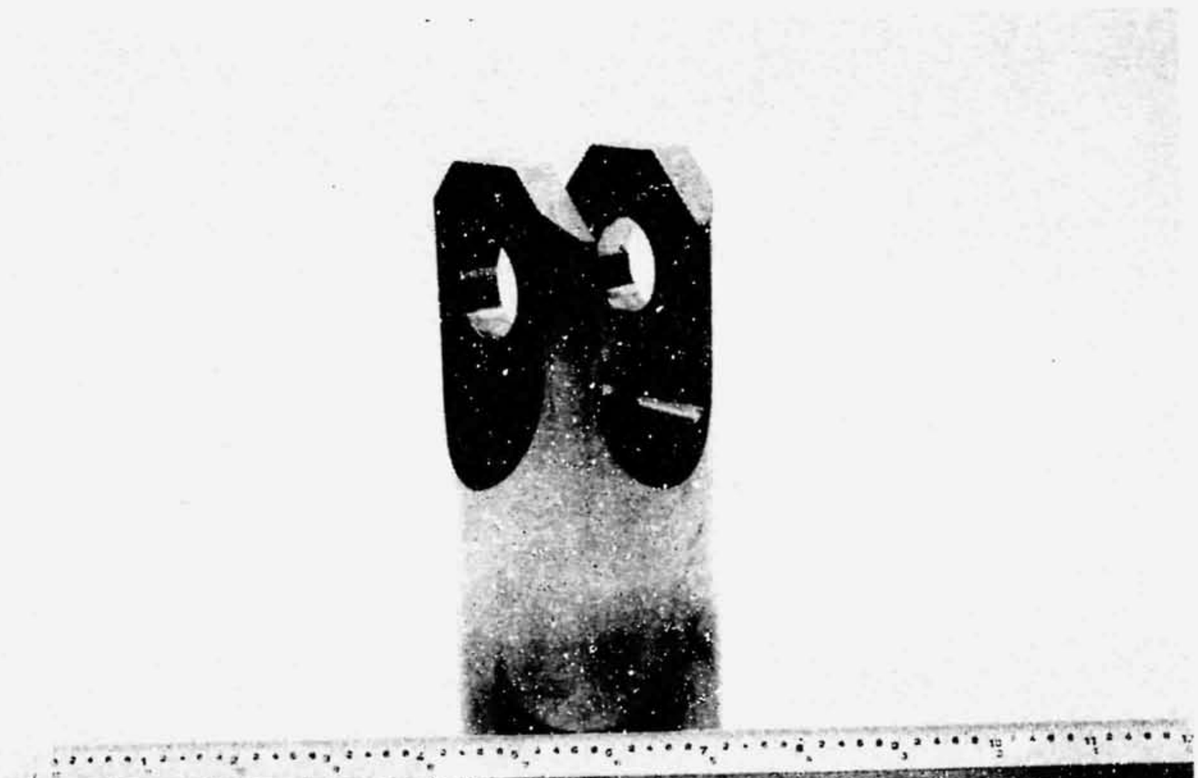


Figure 3-13 Lug Fitting (AD169-1018)

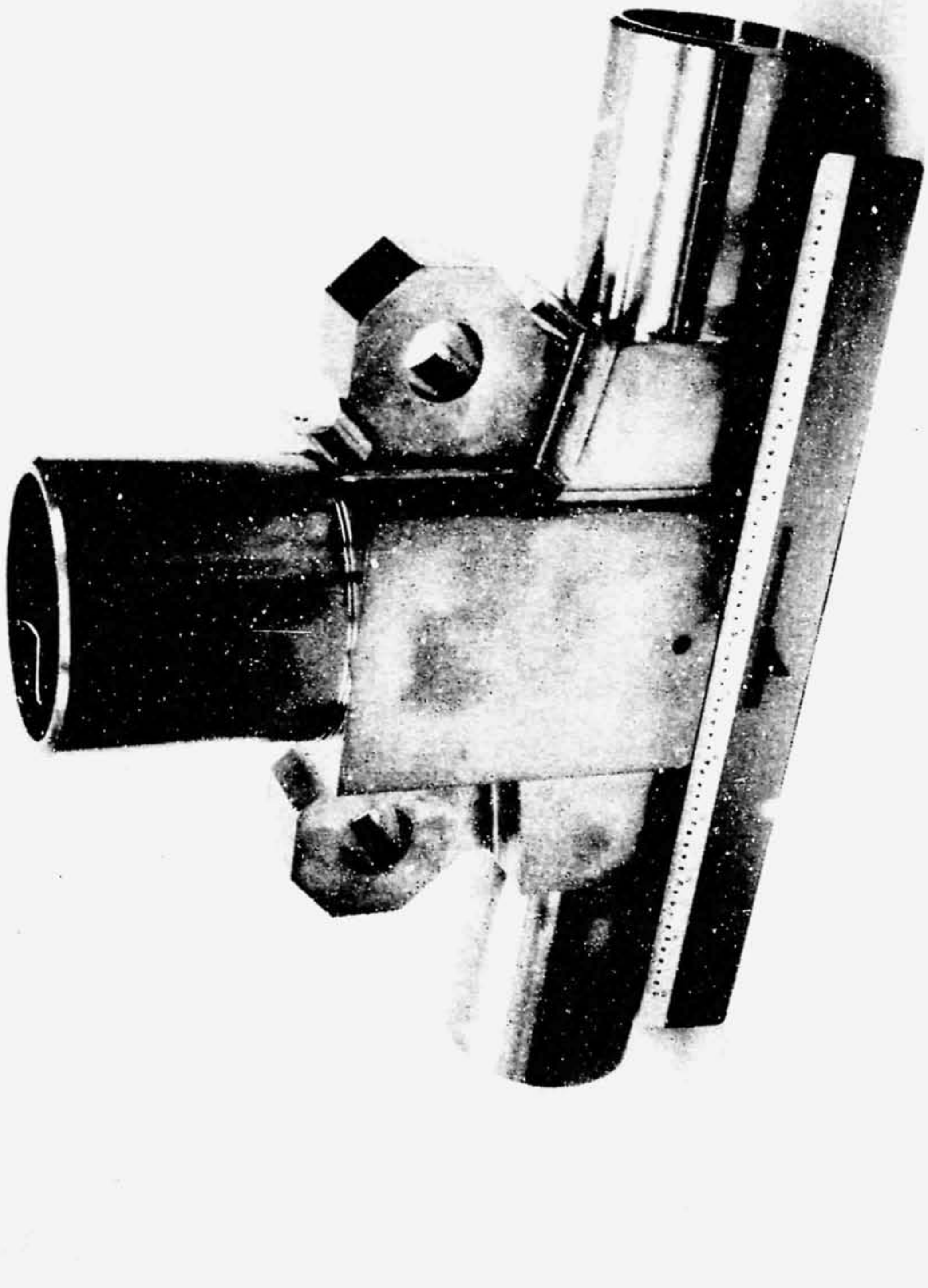


Figure 3-14 Apex Fitting - Node 2 (AD169-1014)

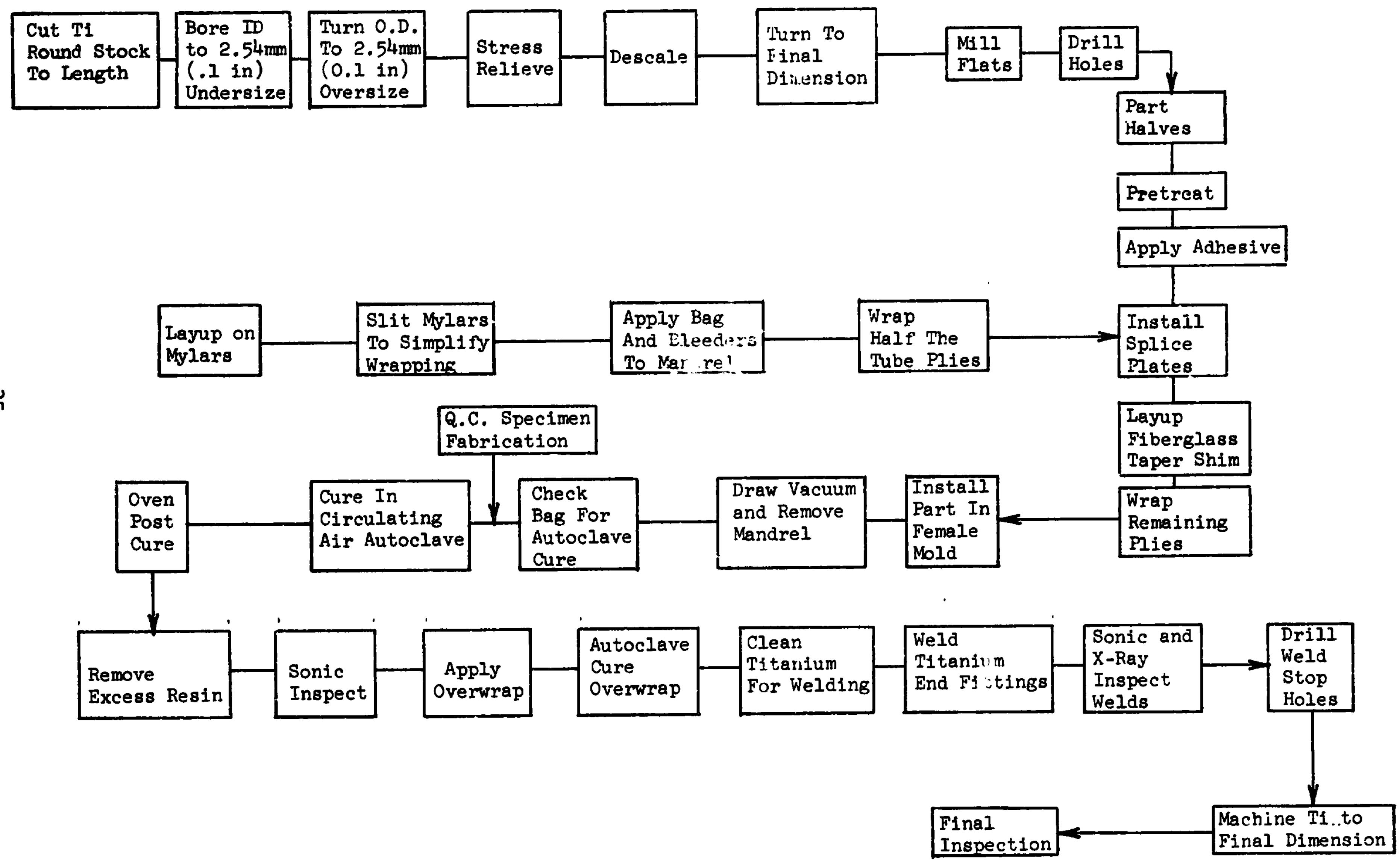


Figure 3-15 Tube Fabrication Sequence

of slit mylar film, 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 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 splice fittings.

After the bleeders had been wrapped on the mandrel, the B/Ep tape was layed up on the mylars and inspected. Those plies which tapered were pre-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 approximately nine mylars used for the numerous 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. Part diameter was measured at various stages to verify adequate wrap compaction necessary to insure insertion of the layup in the split female mold with the requ... clearance. When all the B/Ep plies faying to the internal diameter face of the titanium splice fittings had been wrapped, the splice fittings (which had been pretreated by dry honing, immersion in Pasa Jell 107M and an application of EC2333 primer) were coated with Metlbond 329, Type IA film adhesive, and positioned on the wrap mandrel. 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 tube extending 3.25 cm (1.25 in.) from the B/Ep end before the assembly was placed in the female split mold.

The split mold was overwrapped with fiberglass bleeder and the assembly was placed in a second vacuum bag (nylon film sleeve). Excess bagging material was unpackaged from the mandrel and sealed to the outer film sleeve with sealant tape. A vacuum was applied to expand the layup sufficiently to permit removal of the mandrel. The bag was checked and a vacuum of 508 mm of Hg (20 in. of mercury) minimum was applied. Concurrently with the tube a solid B/Ep laminate and a B/Ep/titanium molded lap shear panel were layed-up and bagged to serve as Process Verification Panels. The tube and test panels were placed in an autoclave and cured.

Prior to beginning the fabrication of the production B/Ep tubes one full size tube (AD169-1011) was built as a tool proveout using fiberglass/epoxy prepreg in place of the B/Ep except for the outer three plies. Since the average per ply thickness of the fiberglass/epoxy is .254 mm (10 mil) vs. .127 mm (5 mil) for the B/Ep, only half the total number of plies were used for layup. A new laminate table was prepared indicating which plies were to be removed in order to achieve the proper tube configuration through the taper area. Fabrication techniques used for the fiberglass tube were identical to those to be used for the B/Ep tubes except that the stepped titanium end fittings were coated with teflon tape and a spray release agent to permit removal after tool proveout was complete. These plates were later used on the production B/Ep tubes.

Items checked during tool proveout included:

- Proper tracking of layup templates
- Amount of vacuum required for proper tension of layup templates
- Position of wind-up roller to aid in proper compaction of the tube
- Ease of removal of split layup mandrel
- Positioning of splice plates and tube dimensions after cure

The resultant part, shown in Figure 3-16, confirmed that all tooling worked as anticipated. In addition, part quality was exceptional.

Following successful molding of the fiberglass/boron/epoxy replica, the first tube, AD169-1011, No. 1 was wrapped and cured. The part was visually and dimensionally inspected with both inspections inferring that the tube was sound, however that there seemed to be excessive resin flow, even though a modified bleeder had been used to compensate for the higher resin flow of the SP290 (3M) system. Also noted at this time was a lateral flow of resin out the tube ends and a 33.4°K (60°F) temperature spread on the tool. Based on the good visual inspection and nominal per ply thickness, it was decided to wrap and cure AD169-1011, No. 2. A modification was made to the cure cycle to reduce the excess flow. Steps were also taken to reduce the temperature spread. The changes incorporated were:

Figure 3-16 Tool Proveout Tube

- o Reduction of the temperature and pressure used for the initial holding step to insure seating of the tube against the mold form, without removing excess resin
- o Insulation of the bottom of the tool to minimize the temperature variation from top to bottom. (Tube numbers 1 and 2 were cured in a conduction type autoclave.)

After the second tube, AD169-1011, No. 2, was cured it was found that these modifications were not totally effective since the tube had some surface irregularities and the excessive lateral resin flow was still present. In addition, the temperature spread was reduced but was still higher than desired. Both tubes were sent to Quality Control for N.D.T. inspection. Both were found to contain ultrasonic discontinuities, all of which were located at the top of the tube (the surface away from the autoclave heated platen).

Rather than immediately dispositioning both tubes as rejects it was decided to have the tubes undergo a proof test. The intent of the test was to verify NDT relationship to structural integrity of the parts. Loading for both tests were the ultimate axial loads experienced by the members as part of the thrust structure assembly. Details of the testing are given in Section 5. Part number AD169-1011, No. 1 passed the proof test, was sent back to Quality Control for ultrasonic inspection (to insure no additional discontinuity growth) and was used in the assembly. The No. 2 tube failed the proof test. As a result the splice fittings were reclaimed (there was no damage to these parts) and were used on the replacement tube.

Before tube AD169-1011, No. 3 was fabricated the following process changes were made to accommodate the SP290 resin system:

- o Installation of silicone rubber seals in the molds at the ends of the titanium splice plates to prevent lateral resin flow
- o Curing in a convection autoclave (hot air circulating) to minimize temperature variations across the tool
- o Modification of the cure cycle

Tube AD169-1011, No. 3 was cured using this revised process which proved to be most effective. Subsequent ultrasonic inspection revealed a high quality part without any of the defects noted on numbers 1 and 2. The revised process then became the standard method of fabrication and was used to manufacture all remaining tubes - AD169-1012, Nos. 1 and 4, AD169-1013, Nos. 1 and 2 and the replacement for AD169-1011, No. 2. The modified cure cycle used in conjunction with the above noted changes was:

- Apply full vacuum, 68.6 cm Hg (27 in. Hg) minimum
- Place part on blocks near the door of a circulating air autoclave with open ends facing the side walls
- Raise temperature to 338°K (150°F) maximum as recorded by the hottest thermocouple in 8-12 minutes
- Apply 731 x 10^3 N/m^2 (95 psi) positive pressure and hold for 2 minutes with the vacuum system turned off. If the vacuum falls below 25.4 cm Hg (10 in. Hg), abort the run and rebag part
- If the part passes the vacuum check maintain the part at 338°K (150°F) and full vacuum plus 731 x 10^3 N/m^2 (95 psi) for 30-45 minutes. The maximum thermocouple reading permitted during this cycle is 352.59°K (175°F)
- Raise temperature to 388.7°K (240°F), reduce pressure to 654 x 10^3 N/m^2 (85 psi) and reduce vacuum to 5.08 cm Hg (2 in. Hg) maximum
- Raise part temperature to 438.7°K (330°F) in not more than 40 minutes as measured by hottest thermocouple
- Hold the part at 438.7°K (330°F) under 654 x 10^3 N/m^2 (85 psi) and 5.08 cm Hg (2 in. Hg) vacuum for 90 ± 10 min. The permitted range of all thermocouples (part or tool) shall be 438.7-455.3°K (330-360°F)
- Cool part to 422°K (300°F) and apply full vacuum while maintaining 654 x 10^3 N/m^2 (85 psi)
- Cool to 338°K (150°F) and remove from autoclave under full vacuum.

Following ultrasonic and visual inspection, all tubes were overwrapped with local, 25.4 mm (1.0 in.) wide, 90° B/Ep plies in the splice transition region. This procedure was accomplished by removal of the external peel ply and applying one layer of Metlbond 329, Type 1A adhesive and the required number of 90° plies to the outside diameter of the tube. This was followed by application of the bleeder system consisting of one ply TX1040, one ply 116 glass cloth, one ply perforated mylar and two plies of 181 glass. The overwrap was envelope bagged and cured 60-90 minutes at 450 ± 5°K (350 ± 10°F) at 310×10^3-517×10^3 N/m^2 (45-75 psi).

Following the laminating of the overwrap the various operations necessary for the completion of the tubes were performed. The initial operation was electron beam welding of the two halves of the titanium splice fittings. Titanium surface preparation prior to welding was:

- o Mechanically cleaning the gaps between the two semicircular splice fittings to remove excess adhesive and resin flow deposited 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 pickling bath (HNO_3) followed by rinsing and drying

Titanium 6Al-4V shims, typically 1.52 mm (.060 in.) thick, were fitted in the gaps between titanium splice fittings. Next, copper chill bars were installed on the inside diameter of the tube near the boron/titanium interface. The tube was then mounted in the weld fixture and positioned relative to the motion of the gun. After a vacuum was drawn the welding of the splice fittings was initiated 12.7 mm (.50 in.) from the boron/epoxy/titanium interface, extending approximately .1016 m (4.0 in.) to the end of the part. Titanium filler wire (6Al-4V) was used in conjunction with the shims to fill the gap between the titanium fittings to minimize distortion and porosity. The welding parameters used had been determined previously using replicas of the splice plates. All welds were examined radiographically using production procedures. Only one weld of the forty made in this phase required rework due to an under fill on the inside diameter which might not have been removed in subsequent machining operations.

The fabrication of the tubes was completed by conventional machining operations including:

- o Turning the inside diameter to the final dimension
- o Parting excess titanium at both ends
- o Chamfering the inside diameter
- o Jig boring stop holes at the termination of the welds and pilot holes for fasteners

All the tubes were dimensionally inspected prior to acceptance. Completed tubes, one of each configuration fabricated, are shown in Figure 3-17.

3.3.4 Truss Assembly

The assembly of the truss was a conventional drilling/fastening operation performed using an assembly fixture, drill jigs and Quackenbush drills.

Details of the truss structure final assembly operation and the sequence of performance are as follows:

- o Prefit entire structure and check dimensionally
- o From pilot holes on tubes, line drill and ream tubes and apex fittings full size. This consisted of drilling 184 holes of 3 different sizes
- o Inspect holes
- o Mark tubes and apex fittings to insure proper reassembly
- o Disassemble entire structure
- o Deburr and clean both tubes and fittings
- o Drill retention hole in radius blocks from drill tool
- o Drill retention hole in apex fittings from drill tool (counter bore and countersink required) and deburr
- o Insert radius blocks in apex fitting inside diameter and secure with fastener
- o Line drill and ream radius blocks through fitting
- o Remove radius blocks from fitting and deburr
- o Using an actual bolt as a tool, locate nut and nut retainer on flat portion of radius block
- o Using nut retainer as a drill tool drill two nut retainer retention holes through radius block. Countersink far side and deburr

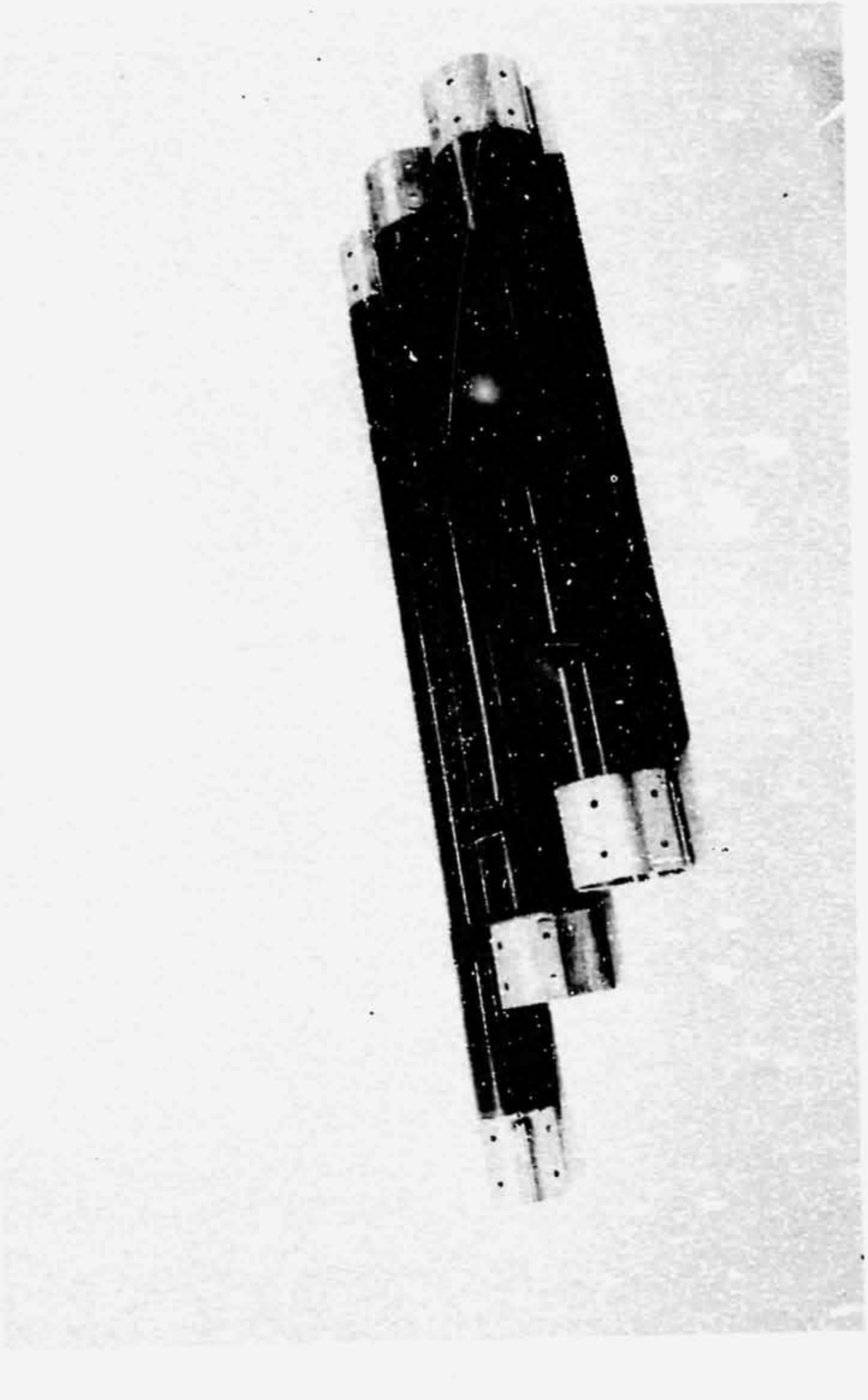


Figure 3-17 Boron/Epoxy Tubes (AD169-1011, 1012 and 1013)

- Install rivets in nut retainer retention holes and squeeze rivet
- Inspect assembly
- Remove bolt and install radius block assembly in apex fitting
- Fasten with screw and nut
- Complete steps 1 through 16 for all tubes
- Reassemble truss
- Install bolts and torque
- Inspect assembly

Figures 3-18 and 3-19 depict the completed two-dimensional truss assembly. Subsequent to assembly the peel ply was removed from the B/Ep and strain gages were bonded to the tubes. This was followed by application of a seal coat of Epon 956 to all areas of the tube not covered by strain gages. After sealing had been accomplished the strain gages were wired and the truss assembly was removed from the assembly fixture for attachment of the test load introduction fittings. The structure was shipped to MSFC in June of 1972 for static testing.

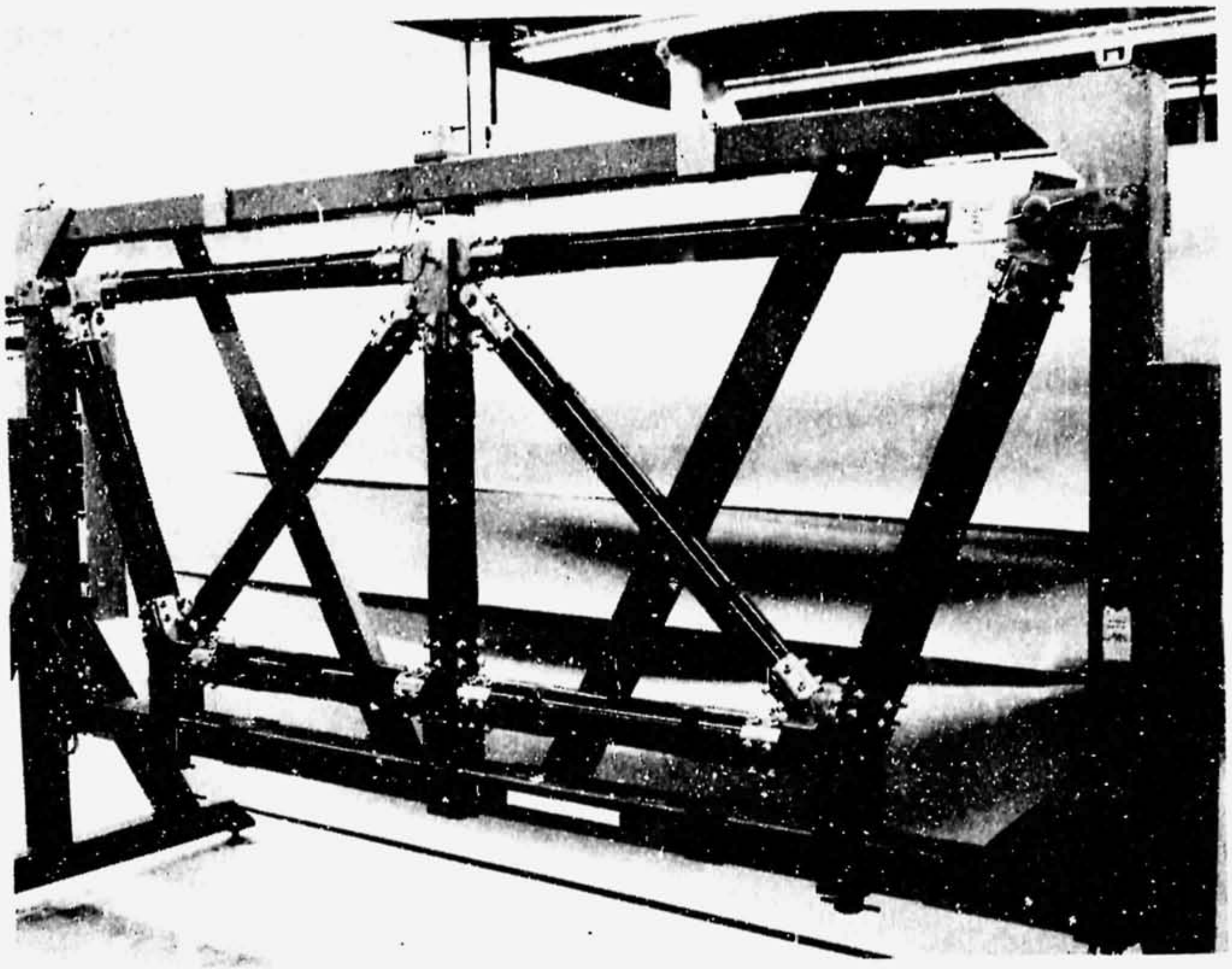


Figure 3-18 Completed Assembly, 1/3 Scale Thrust Structure

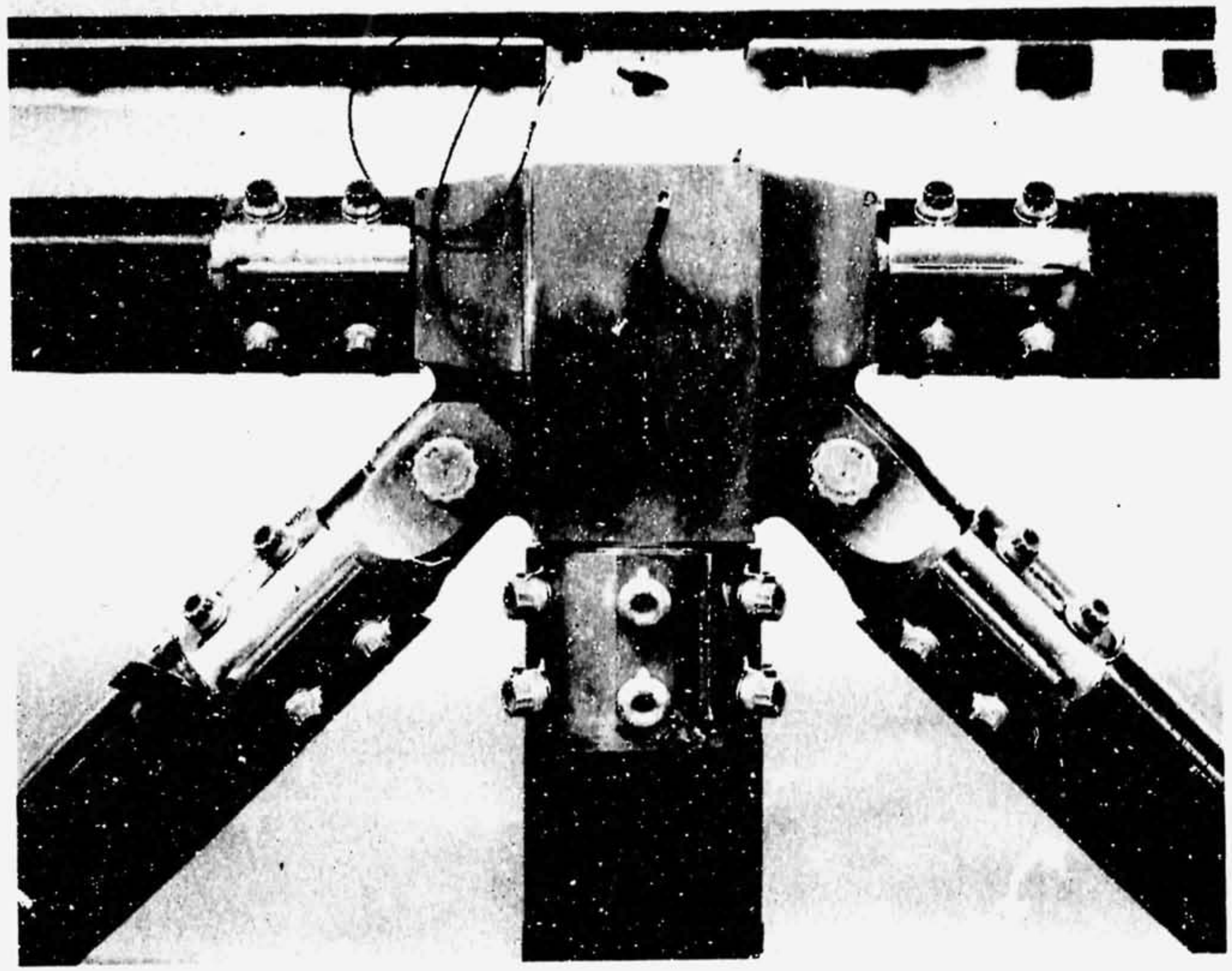


Figure 3-19 Close-Up of Node 2 - 1/3 Scale Thrust Structure

4.0 QUALITY CONTROL

The Quality Control tasks performed for this program included:

- o Destructive Testing
- o In-Process 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 [illegible]°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.

The boron/epoxy preimpregnated tape utilized for this program was received in two shipments. The resin flow for batch 206 exceeded (by 1%) the maximum required by specification and the volatile content for batch 220 was below (by 0.1%) the minimum required by specification. Engineering was presented the test data and after careful evaluation accepted the material since the out-of specification physical properties could be corrected by modifications in processing without effecting part performance.

Three shipments of 6Al-4V titanium were also received and accepted in accordance with Grumman Specification GM3112A, Amendment No. 1. The shipments consisted of .104m x .304 x .457m (4 1/8 in. x 12 in. x 18 in.) multiples of forged annealed and cleaned billet, and .117m x .304m (4 5/8 in. dia. x 12 in.) multiples and .092m x .304m (3 5/8 in. dia. x 12 in.) multiples of forged annealed and turned billet. The chemical composition verification included an analysis for the major constituents of the alloy. All of the elements were found to be in accordance with the specified range as required in GM3112A. The mechanical property verification tests consisted of ultimate tensile strength and yield and the percent elongation. All test results were satisfactory. The results are presented in Table 4-2.

Table 4-1 SP290 Receiving Inspection Data

Batch	Roll	Tensile Strength $N/m^2 \times 10^9$ (psi x 10^3) R.T.	Tensile Strength $N/m^2 \times 10^9$ (psi x 10^3) 375°F	Horizontal Shear $N/m^2 \times 10^6$ (psi x 10^3) R.T.	Horizontal Shear $N/m^2 \times 10^6$ (psi x 10^3) 375°F	Resin Content %	Resin Flow %	Volatile Content %
206	2	1.627 (236)	1.449 (209)	113.1 (16.4)	39.8 (5.78)	34	19	0.5
		1.462 (212)	1.434 (208)	111.0 (16.1)	52.4 (7.60)			
		1.620 (235)	1.449 (209)	111.7 (16.2)	53.2 (7.71)			
220	4	1.537 (223)	1.303 (189)	103.4 (15.0)	56.5 (8.2)	33	16.5	0.2
		1.661 (241)	1.490 (216)	115.1 (16.7)	60.0 (8.7)			
		1.530 (222)	1.262 (183)	99.3 (14.4)	59.3 (8.6)			
		1.468 (213)	1.303 (189)	97.9 (14.2)	59.3 (8.6)			
		1.510 (219)	1.241 (180)					
M'nimum Required Per GM3004A		1.379 (200)	1.034 (150)	89.6 (13)	34.5 (5)	32 ± 2	9-18	0.3-1.7

Table 4-2

Mechanical Properties Verification of 6Al-4V Annealed Titanium

Size cm (in.)	Ultimate Tensile Strength $N/m^2 \times 10^6$(ksi)	Tensile Yield Strength $N/m^2 \times 10^6$(ksi)	Elong. %
10.478 (4.125)			
L	930.7 (135.0)	841.1 (122.0)	10.0
	925.2 (134.2)	865.2 (125.5)	14.0
LT	969.3 (140.6)	882.4 (128.0)	12.0
ST	981.0 (142.3)	918.3 (133.2)	12.0
9.208 (3.625)			
L	1010.7 (146.6)	941.7 (136.6)	16.0
	976.9 (141.7)	882.4 (128.0)	13.0
T	982.4 (142.5)	915.5 (132.8)	11.0
11.748 (4.625			
L	965.2 (140.0)	889.3 (129.0)	12.0
	958.3 (139.0)	890.0 (129.1)	12.0
T	962.4 (139.6)	890.7 (129.2)	15.0
Min. Req'd Per GM3112	896.2 (130.0)	827.3 (120.0)	10.0

4.1.2 <u>Process Control</u>

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:

- o 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.

- o 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.

The coupon test results relating to tube cumulative numbers 1 through 7 were satisfactory. The horizontal shear strength relating to tube cumulative numbers 8 and 9 (AD169-1012-7, No. 4 and AD169-1013-7, No. 2) was below minimum as was the flexural strength and modulus relating to tube number 10 (AD169-1011-7). The results were presented to engineering for disposition. Though the test results were below minimum, the tubes made from this material were accepted (after N.D.T. inspection) based on the following:

- o The process control test specimens yielding low horizontal shear strengths exhibited per ply thicknesses of .1193 mm (.0047 in.) which was below the minimum specification value of .1245 mm (.0049 in.). Inspection of the tubes, however, yielded per ply thicknesses within the specified range of .1245-.1398 mm (.0049-.0055 in.).

- o The process control test specimens yielding low flexural strengths and moduli were observed to have an irregular surface and thus the resultant data was suspect. Tube surfaces during the identical run were satisfactory.

The complete test tab results for all tubes are presented in Table 4-3.

Table 4-3 Process Control Test Data MB329 and 3M SP290 Boron/Epoxy

Batch/ Roll No.	Part No.	B/Ep to Ti Shear $N/m^2 \times 10^6$ (psi)	Longitudinal Flexure		Horizontal Shear Strength $N/m^2 \times 10^6$ (psi $\times 10^3$)
			Strength $N/m^2 \times 10^9$ (psi $\times 10^3$)	Modulus $N/m^2 \times 10^9$ (psi $\times 10^6$)	
381/30	AD169-1011-7 No. 1 Cum. No. 1	20.82 (3020) 19.17 (2780) 20.96 (3040) 20.27 (2940) 20.89 (3030)			
206/4			1.806 (262) 1.854 (269) 1.786 (259) 1.806 (262)	205.4 (29.8) 201.3 (29.2) 194.4 (28.2) 200.6 (29.1)	108.9 (15.8) 108.9 (15.8) 110.3 (16.0) 111.7 (16.2)
381/30	AD169-1011-7 No. 2 Cum. No. 2	18.61 (2700) 17.65 (2560) 22.06 (3200) 19.03 (2760) 20.41 (2960)			
206/1			1.696 (246) 1.786 (259) 1.737 (252) 1.786 (259)	191.0 (27.7) 193.7 (28.1) 193.7 (28.1) 184.8 (26.8)	99.3 (14.4) 106.2 (15.4) 107.5 (15.6) 98.6 (14.3)
381/30	AD169-1011-7 No. 3 Cum. No. 3	21.51 (3120) 27.71 (4020) 27.58 (4000) 28.95 (4200) 25.51 (3700)			
206/1			1.930 (280) 1.930 (280) 2.082 (302) 2.082 (302)	214.4 (31.1) 206.1 (29.9) 219.2 (31.8) 219.2 (31.8)	101.3 (14.7) 111.0 (16.1) 105.5 (15.3) 105.5 (15.3)
381/30	AD169-1012-7 No. 1 Cum. No. 4	28.13 (4080) 27.58 (4000) 27.02 (3920) 28.27 (4100) 28.20 (4090)			

Table 4-3 Process Control Test Data MB329 and 3M SP290 Boron/Epoxy (Continued)

Batch/ Roll No.	Part No.	B/Ep to Ti Shear $N/m^2 \times 10^6$ (psi)	Longitudinal Flexure Strength $N/m^2 \times 10^9$ (psi $\times 10^3$)	Longitudinal Flexure Modulus $N/m^2 \times 10^9$ (psi $\times 10^6$)	Horizontal Shear Strength $N/m^2 \times 10^6$ (psi $\times 10^3$)
206/1			1.875 (272) 1.937 (281) 1.917 (278) 1.875 (272)	202.7 (29.4) 202.7 (29.4) 206.8 (30.0) 203.4 (29.5)	106.9 (15.5) 105.5 (15.3) 105.5 (15.3) 109.6 (15.9)
381/30	AD169-1012-7 No. 2 Cum. No. 5	20.27 (2940) 23.85 (3460) 24.54 (3560) 22.75 (3300) 23.16 (3360)			
206/1			2.020 (293) 2.116 (307) 1.917 (278) 2.068 (300)	198.5 (28.8) 208.2 (30.2) 199.2 (28.9) 212.3 (30.8)	120.0 (17.4) 114.4 (16.6) 114.4 (16.6) 109.6 (15.9)
366/1	AD169-1012-7 No. 3 Cum. No. 7	25.37 (3680) 27.58 (4000) 24.68 (3580) 27.71 (4020) 26.96 (3910)			
206/3			1.889 (274) 1.827 (265) 1.882 (273) 1.910 (277)	200.6 (29.1) 188.2 (27.3) 193.7 (28.1) 198.5 (28.8)	113.1 (16.4) 103.4 (15.0) 102.7 (14.9) 110.3 (16.0)
366/1	AD169-1013-7 No. 1 Cum. No. 6	24.26 (3520) 22.82 (3310) 24.89 (3610) 24.27 (3520) 22.61 (3280)			
206/2			2.013 (292) 1.896 (275) 1.937 (281) 1.896 (275)	199.9 (29.0) 193.0 (28.0) 194.4 (28.2) 191.0 (27.7)	102.7 (14.9) 101.3 (14.7) 103.4 (15.0) 103.4 (15.0)

Table 4-3 Process Control Test Data MB329 and 3M SP290 Boron/Epoxy (Continued)

Batch/ Roll No.	Part No.	B/Ep to Ti Shear $N/m^2 \times 10^6$ (psi)	Longitudinal Flexure Strength $N/m^2 \times 10^9$ (psi $\times 10^3$)	Longitudinal Flexure Modulus $N/m^2 \times 10^9$ (psi $\times 10^6$)	Horizontal Shear Strength $N/m^2 \times 10^6$ (psi $\times 10^3$)
366/1	AD169-1012-7 No. 4 Cum. No. 8	25.09 (3640) 24.68 (3580) 23.58 (3420) 19.99 (2900) 23.30 (3380)			
220/4			1.786 (259) 1.786 (259) 1.786 (259) 1.682 (244)	219.2 (31.8) 204.1 (29.6) 193.7 (28.1) 197.2 (28.6)	66.2 (9.6) 65.5 (9.5) 82.7 (12.0) 65.5 (9.5)
366/1	AD169-1013-7 No. 2 Cum. No. 9	24.82 (3600) 27.02 (3920) 26.61 (3860) 26.89 (3900) 28.40 (4120)			
220/4			1.730 (251) 1.848 (268) 1.730 (251) 1.730 (251)	199.2 (28.9) 199.9 (29.0) 208.9 (30.3) 201.3 (29.2)	78.6 (11.4) 88.9 (12.9) 66.9 (9.7) 66.9 (9.7)
366/1	AD169-1011-7 No. 2A Cum. No. 10	31.02 (4500) 25.65 (3720) 26.47 (3840) 26.89 (3900) 27.71 (4020)			
220			1.544 (224) 1.537 (223) 1.593 (231) 1.593 (231)	184.1 (26.7) 173.7 (25.2) 180.6 (26.2) 184.8 (26.8)	106.9 (15.5) 98.6 (14.3) 98.6 (14.3) 104.1 (15.1)
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 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. Permanent records of time, temperature, pressure and vacuum were maintained during all cure cycles to insure that each run complied to the prescribed cycle. The dimensions of all machined specimens were measured to assure conformance with the governing engineering drawings. Surveillance continued during the various subassembly fabrication sequences. Inspection points included dimensional checks on drilled holes and hole locations as well as the use of proper hardware and the satisfactory installation of same.

4.3 Nondestructive 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 in.)
- Adhesive Bonded Joints - The maximum permitted void or delamination shall not exceed 6.35 mm (0.25 in.)

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. This standard was used to evaluate the bonded splices, transition areas and basic laminate of the tubes. A splice plate from one of the Phase I tubes was used to fabricate the standard.

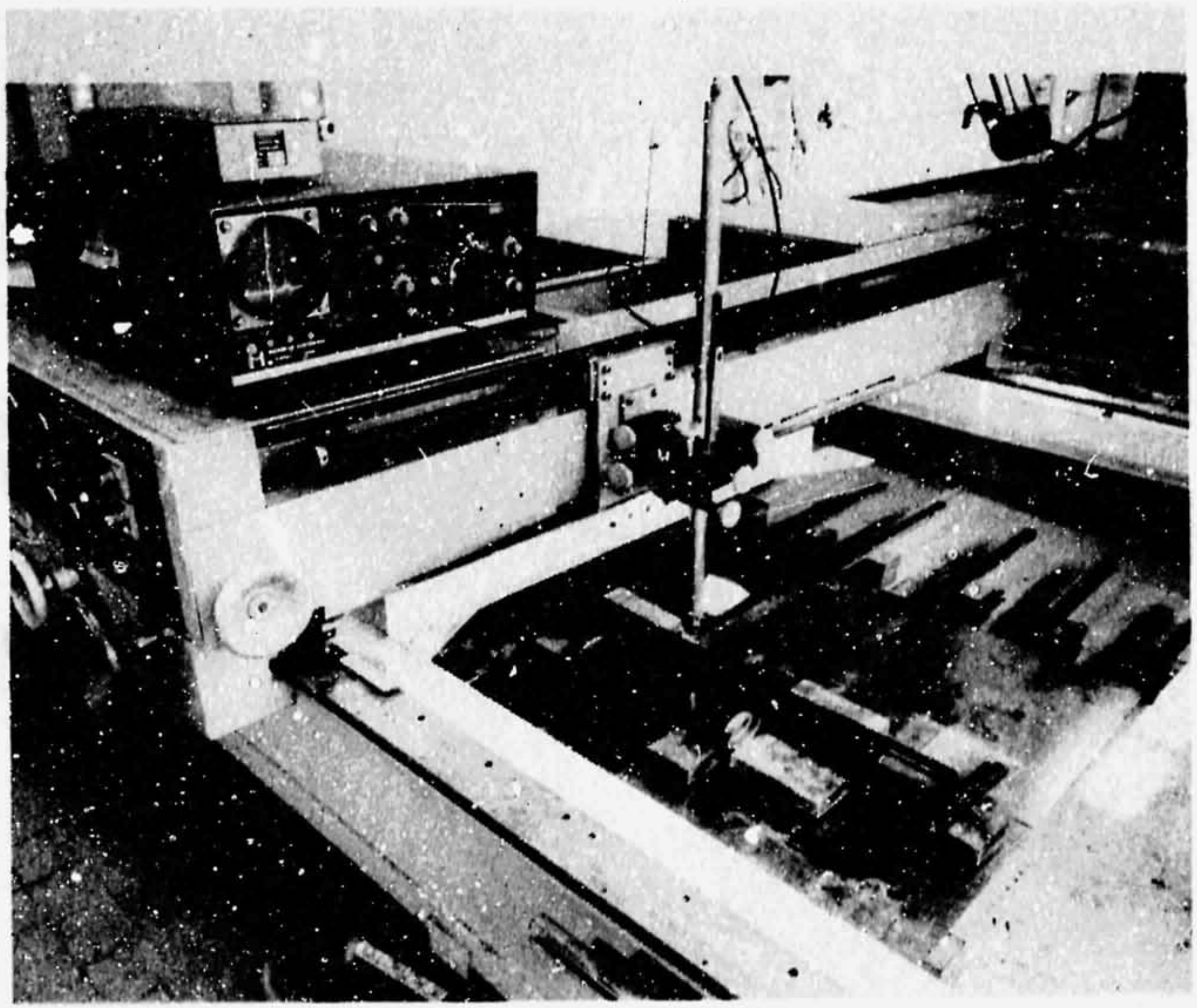


Figure 4-1 Quality Control Standard and Through Transmission Equipment

In addition, X-radiography was employed to assess the integrity of the electron beam welded joints.

4.3.1 Tube N.D.T.

Three of the ten tubes evaluated yielded ultrasonic discontinuities. Subsequent destructive examination of one of the tubes confirmed the indications, which were attributed to voids and porosity. Part number AD169-1011, No. 1 contained two discontinuities at either end in the region of the integrally molded splice plates. The discontinuities measured 10.16 cm x 11.43 cm (4 in. x 4.5 in.) and 15.24 cm x 11.43 cm (6 in. x 4.5 in.). Two additional discontinuities were also detected in the laminate area. They measured approximately 1.27 cm x 1.91 cm (.50 in. x .75 in.) each. The second tube (P/N AD169-1011, No. 2), after ultrasonic evaluation revealed three areas which caused a loss in the ultrasonic signal. One of these discontinuities was later shown to be a surface void. The next area indicated a discontinuity located in the splice region. This measured 5.08 cm x 7.62 cm (2 in. x 3 in.). The remaining questionable area yielded a weak return signal. This was attributed to laminate porosity. Part number AD169-1012, No. 3, contained two void areas. Both void areas were near the top center line of the tube above the titanium splice plate and one to three plies in depth. The size of the voids were 6.35 mm x 57.15 mm (.25 in. x 2.25 in.) with the long dimension along the length of the tube and 6.35 mm x 25.4 mm (.25 in. x 1.00 in.) again with the long dimension along the length of the tube.

All three parts were placed on MRR for engineering disposition. Action taken on tube number AD169-1011, Nos. 1 and 2 involved proof loading, the results of which are discussed in Section 5 of this report. Tube number AD169-1012, No. 3 was judged acceptable based upon the following:

- The void depth was located between the first and third plies
- The cross sectional area affected represented only 2.5% of the total even if the void extended throughout the entire thickness
- There was a 15% margin of safety in the splice area where the void was present

Additional precautions taken involved the addition of secondary bonded 90° overwrap, covering the entire splice area and locating the member between nodes 2 and 3 in the truss where the load experienced was only 62% of design ultimate.

5.0 TEST AND FAILURE ANALYSIS

5.1 Tube Proof Load Testing

The proof test program was initiated to demonstrate the structural integrity of two tubes (AD169-1011 cumulative numbers 1 and 2) which were shown by ultrasonic inspection to contain discontinuities in and adjacent to the splice region. The intention was to test each tube to a predetermined load which would impose upon the splice, the highest running load (ultimate) that the member would experience during normal service in the two-dimensional thrust structure. A proof test would be considered successful if, after sustaining the required load, subsequent ultrasonic inspection showed no discontinuity growth in previously identified areas and no new discontinuity indications. In addition to proof testing the two flawed tubes discussed above, it was decided to test an identical member (AD169-1011 cumulative number 3) which had passed ultrasonic inspection. Testing of this member was not necessary but was conducted for Quality Control N.D.T. verification.

5.1.1 Instrumentation

For the purposes of load introduction verification the tubes were instrumented with axial strain gages located as shown in Figures 5-1 and 5-2. Strain data was measured and recorded at each increment of load application.

5.1.2 Test Procedure

The test specimens were individually installed in a Baldwin model universal testing machine (UTM) and statically tested under axial compression with the loads applied in 10 percent increments. No special test fixturing was used to introduce the UTM loads to the tubes. However, to insure the application of uniform axial loads the titanium ends of each tube were machined flat and parallel within .0256 mm (.001 in.) prior to test. The test logs used for the proof loads are presented in Figures 5-3 through 5-5.

5.1.3 Tube Test Results

The test results for the three tubes that were proof tested are presented in Table 5-1. Strains associated with the last loading incre-

NOTE: Strain gage numbers 1 and 2 located over areas of indicated discontinuity (approximately 25.4 mm (1.0 in.) from over-wraps).

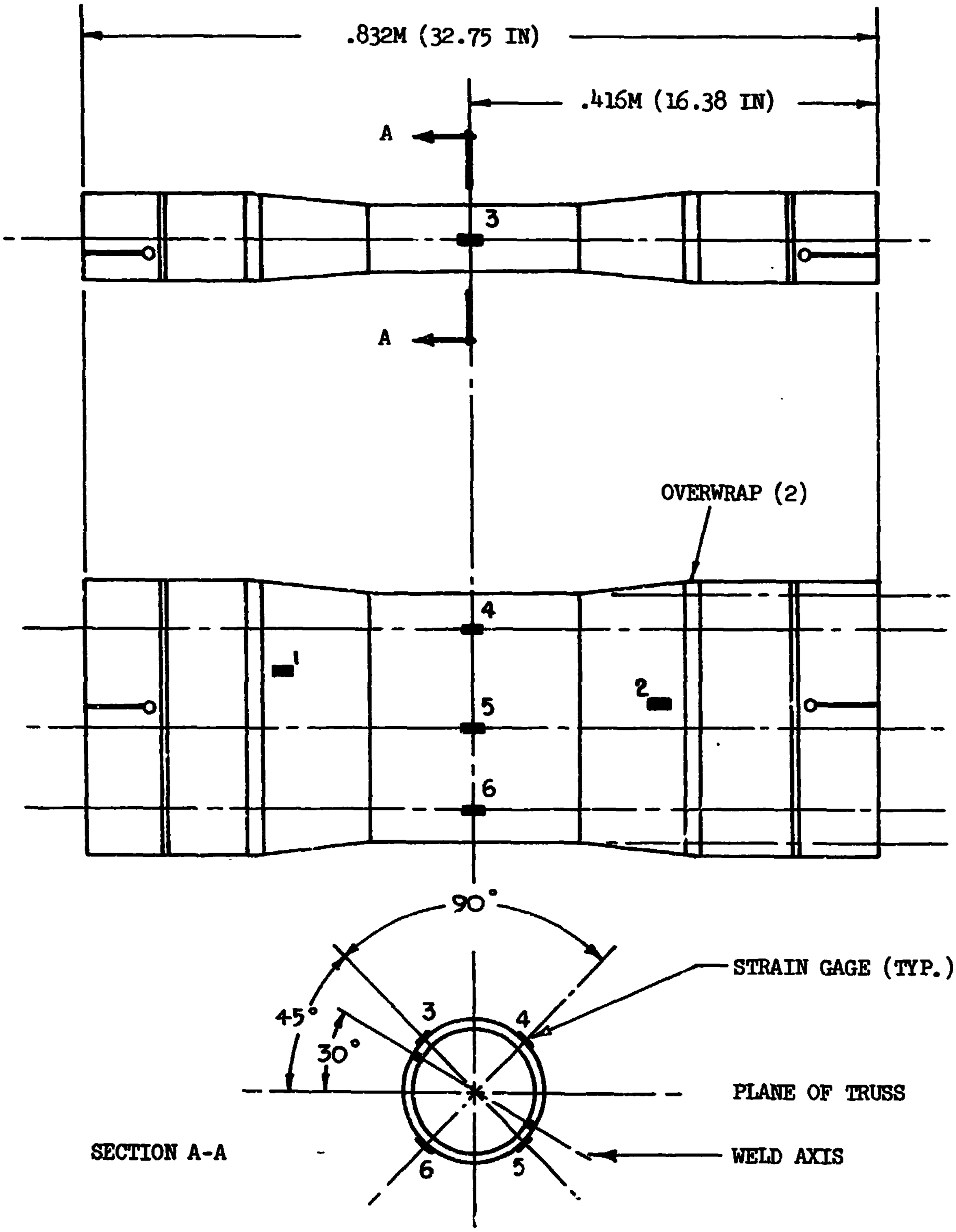


Figure 5-1 Strain Gage Locations, Tube AD169-1011, Nos. 1 and 2

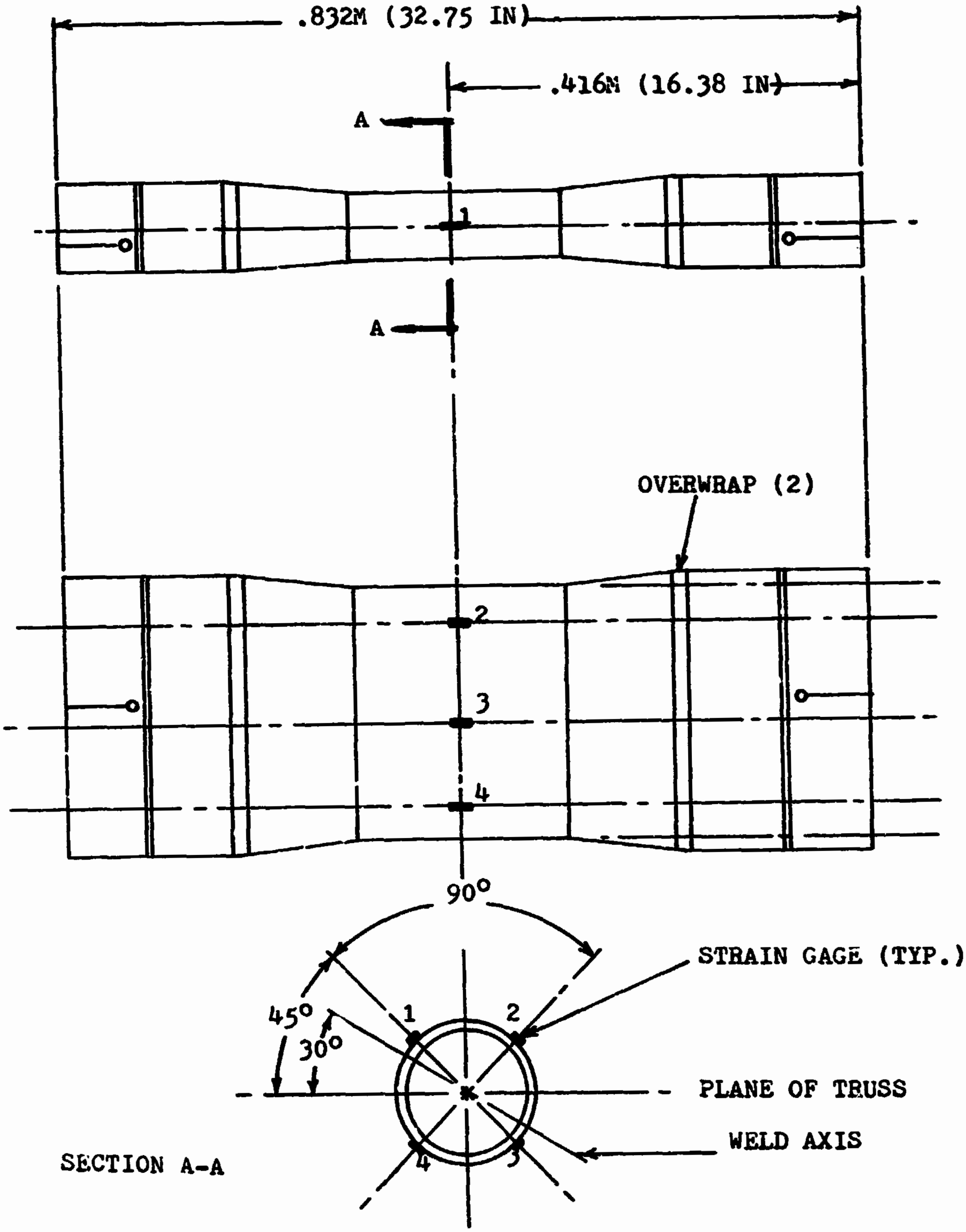


FIGURE 5-2 STRAIN GAGE LOCATIONS, TUBE AD169-1011 NO. 3

LOG OF TEST

TITLE: BOOSTER THRUST STRUCTURE, TUBE AD169-1011, NO. 1 PROOF LOAD

TEST CONDITION: STATIC TEST DATE:

CONDUCTED BY: R. CHALUS

RUN NO.	UTM TEST LOAD N x 10^6	LBS.	PERCENT LIMIT SPLICE LOADING	REMARKS	PHOTO NUMBER
1	0	0	0	BASE LOAD	
2	.0890	20,000	14		
3	.1779	40,000	28		
4	.2669	60,000	42		
5	.3558	80,000	56		
6	.4448	100,000	70		
7	.5338	120,000	84		
8	.6227	140,000	98		
9	.7117	160,000	112		
10	.8006	180,000	126		
11	.8451	190,000	133		
12	.8896	200,000	140	MAXIMUM PROOF LOAD	
13	.7117	160,000	112		
14	.4448	100,000	7C		
15	C	0	0	BASE LOAD	

ENG 524.1A 3-66

LOG OF TEST

TITLE: BOOSTER THRUST STRUCTURE, TUBE AD169-10011, NO. 2 PROOF LOAD

TEST CONDITION: STATIC TEST DATE:

CONDUCTED BY: R. CHALUS

RUN NO.	UTM TEST LOAD N x 10^6	TEST LOAD LBS.	PERCENT LIMIT SPLICE LOADING	REMARKS	PHOTO NUMBER
1	0	0	0	BASE LOAD	
2	.1112	25,000	12		
3	.2224	50,000	24		
4	.3336	75,000	36		
5	.4448	100,000	49		
6	.5560	125,000	61		
7	.6672	150,000	73		
8	.7784	175,000	85		
9	.8896	200,000	98		
10	1.0008	225,000	109		
11	1.1120	250,000	121		
12	1.2232	275,000	133		
13	1.2855	289,000	140	MAXIMUM PROOF LOAD	
14	1.1120	250,000	121		
15	.8896	200,000	98		
16	.6672	150,000	73		
17	.4448	100,000	49		
18	.2224	50,000	24		
19	0	0	0	BASE LOAD	

ENG 524.1A 3-66

Figure 5-4

LOG OF TEST

TITLE: BOOSTER THRUST STRUCTURE, TUBE AD169-1011, NO. 3 PROOF LOAD

TEST CONDITION: STATIC TEST DATE:

CONDUCTED BY: R. CHALUS

RUN NO.	UTM TEST LOAD N x 10^6	UTM TEST LOAD LBS.	PERCENT LIMIT SPLICE LOADING	REMARKS	PHOTO NUMBER
1	0	0	0	BASE LOAD	
2	.0890	20,000	10		
3	.1779	40,000	20		
4	.2669	60,000	30		
5	.3558	80,000	40		
6	.4448	100,000	50		
7	.5338	120,000	60		
8	.6227	140,000	70		
9	.7117	160,000	80		
10	.8006	180,000	90		
11	.9203	206,900	100	DESIGN LIMIT LOAD	
12	1.0124	227,600	110	MAXIMUM PROOF LOAD	
13	.7117	160,000	80		
14	.5338	120,000	60		
15	.3558	80,000	40		
16	.1779	40,000	20		
17	0	0	0	BASE LOAD	

ENG 524.1 3-66

CONTRACT
MODEL

REPORT
DATE

F ure 5-5

Table 5-1 Summary of Proof Load Tests

Specimen	Proof Load	Maximum Test Load	% Proof Load	Remarks
AD169-1011, No. 1	$.889 \times 10^6$N (200,000 lbs.)	0.8896×10^6N (200,000 lbs.)	100	Specimen sustained proof load with no signs of failure.
AD169-1011, No. 2	1.285×10^6N (289,000 lbs.)	0.8451×10^6N (190,000 lbs.)	66	Specimen failed through void area.
AD169-1011, No. 3	1.012×10^6N (227,600 lbs.)	1.0124×10^6N (227,600 lbs.)	100	Specimen sustained proof load with no signs of failure.

ment are presented in Table 5-2. A brief description of the test and results for each of the three tubes is as follows:

- AD169-1011, No. 1 Proof Test - This member was subjected to a pure axial compressive load of 889,000N (200,000 lbs.) without any sign of failure. The load represented the ultimate splice loading this member would experience when loaded as part of the two-dimensional truss structure. Figure 5-6 shows the test load vs. strain plot, along with predicted strain plots. The strain readings were linear up to and down from proof load. Readings taken at zero load after holding proof load for 25 seconds showed no residual strain. Subsequently, through-transmission reflection inspection indicated that the boundaries of the discontinuities had not changed nor had any additional damage been imposed. It was judged from the test result and subsequent NDT inspection that the tube was adequate for use in the two-dimensional truss in the location specified, which was between nodes 5 and 6 (member number 1243).

- AD169-1011, No. 2 Proof Test - Again, as in the proof test of No. 1, the member was subjected to an axial compressive load. The tube failed at an applied load of 845,120N (190,000 lbs.) at the laminate transition point. Strain readings to failure were linear and somewhat less than predicted. Figure 5-7 presentes the test load vs. strain diagram, as well as the predicted strains. Location of the failure was in one of the areas previously determined to contain a discontinuity. Figures 5-8 and 5-9 show two views of the failed tube, the areas outlined in white denote the discontinuities. The load sustained represented 65.7 percent of the ultimate splice loading this member would have experienced as part of the truss structure.

Table 5-2 Strain Gage Readings - Proof Load Tests

Specimen Number	AD169-1011 No. 1	AD169-1011 No. 2	AD169-1011 No. 3
Applied Load	0.8896×10^6 N(1) (200,000 lbs.)	0.7784×10^6 N(2) (174,900 lbs.)	1.0124×10^6 N(1) (227,600 lbs.)
Strain Measurement	Strain, μ mm/mm (μ in/in)		
1	2975	2250	6721
2	2690	2150	6378
3	6860	5497	6870
4	6725	5611	6625
5	6750	5289	----
6	6900	5435	----

NOTES: (1) 100% proof load

(2) 61 percent proof load (specimen failure at 66 percent)

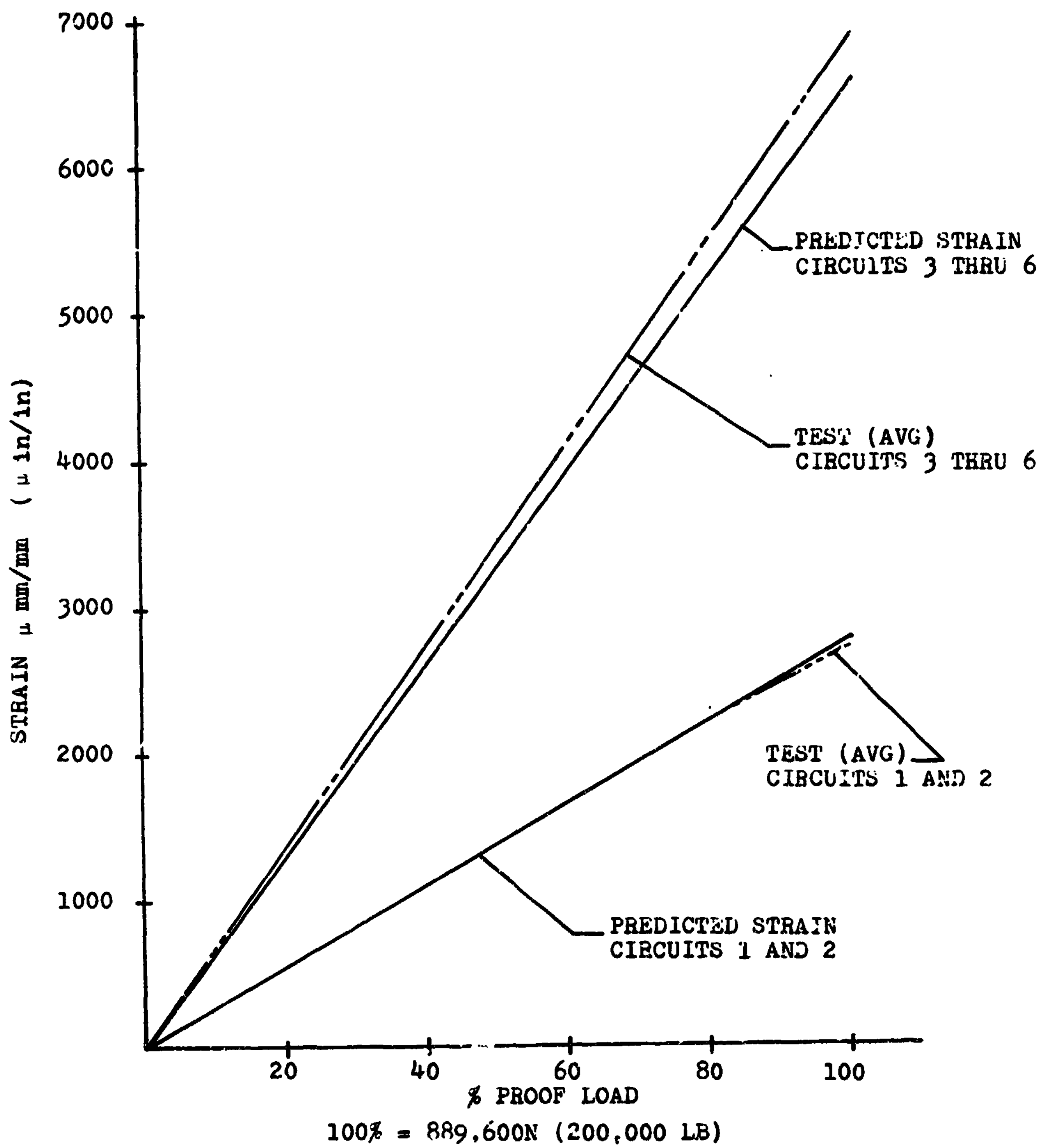


FIGURE 5-6 LOAD VS. STRAIN DIAGRAM FOR AD169-1011 NO. 1 PROOF TEST

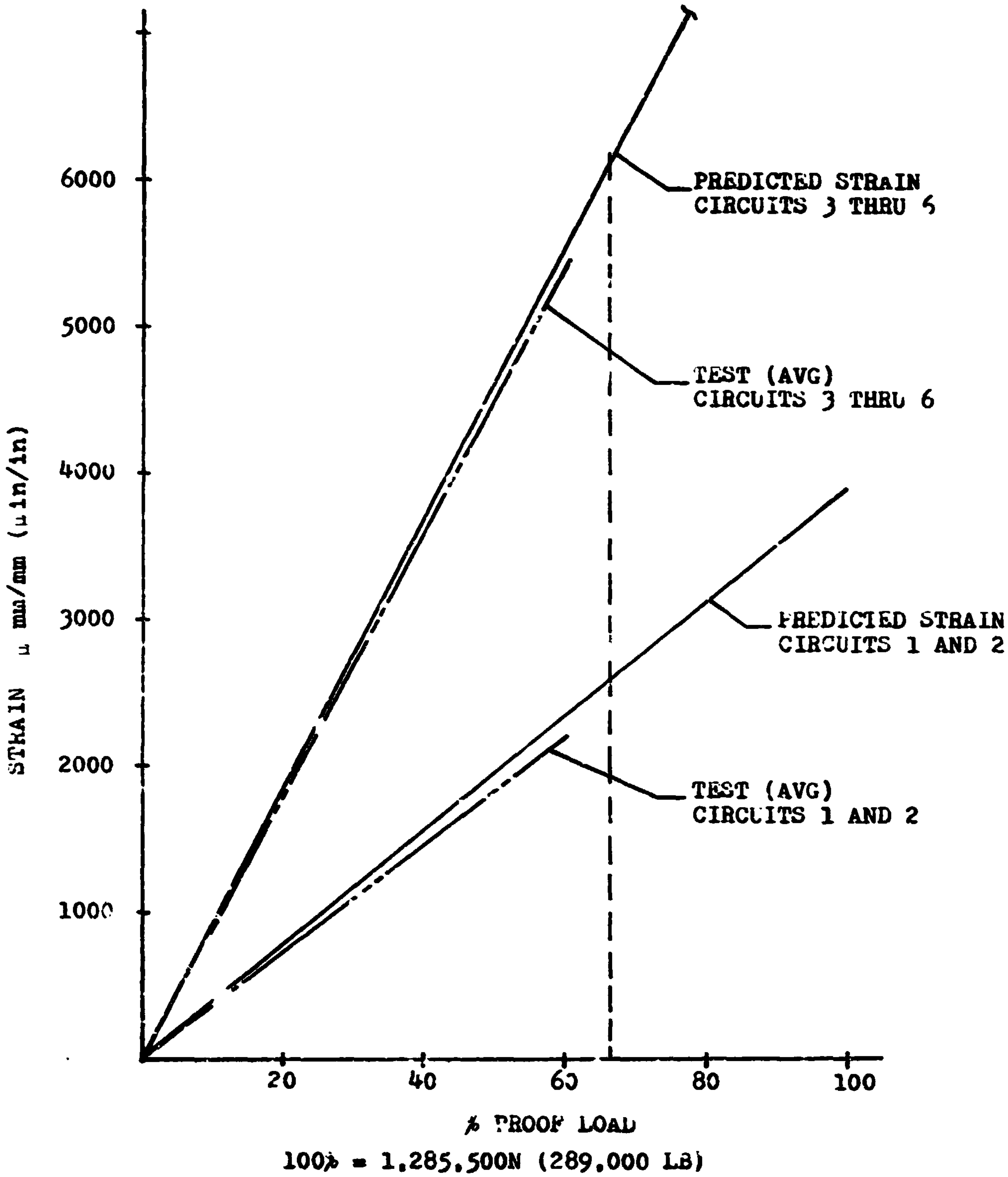


FIGURE 5-7 LOAD VS. STRAIN DIAGRAM FOR AD169-1011 NO. 2 PROOF TEST

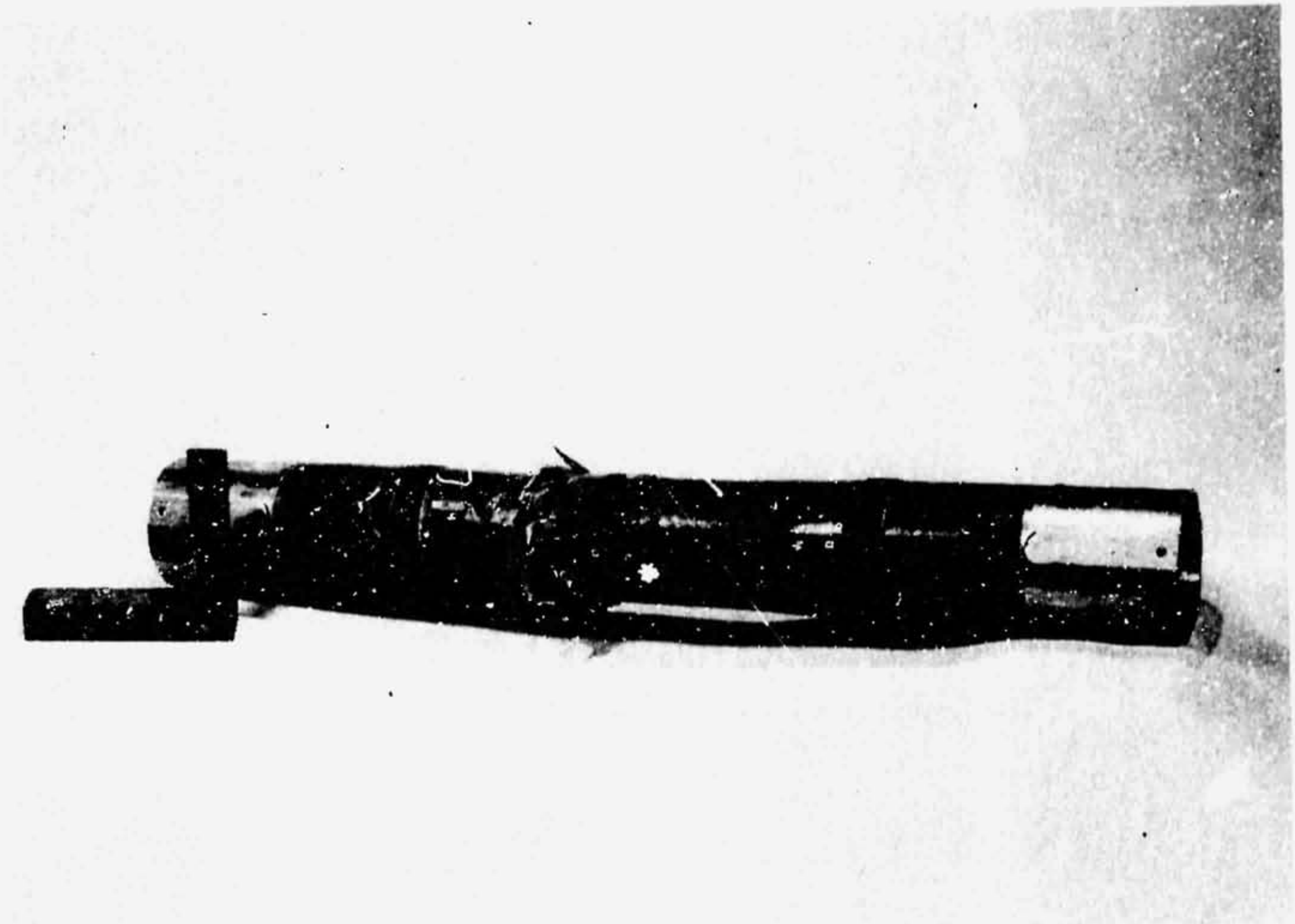


Figure 5-8 Failed Tube - AD169-1011, No. 2 - Proof Test

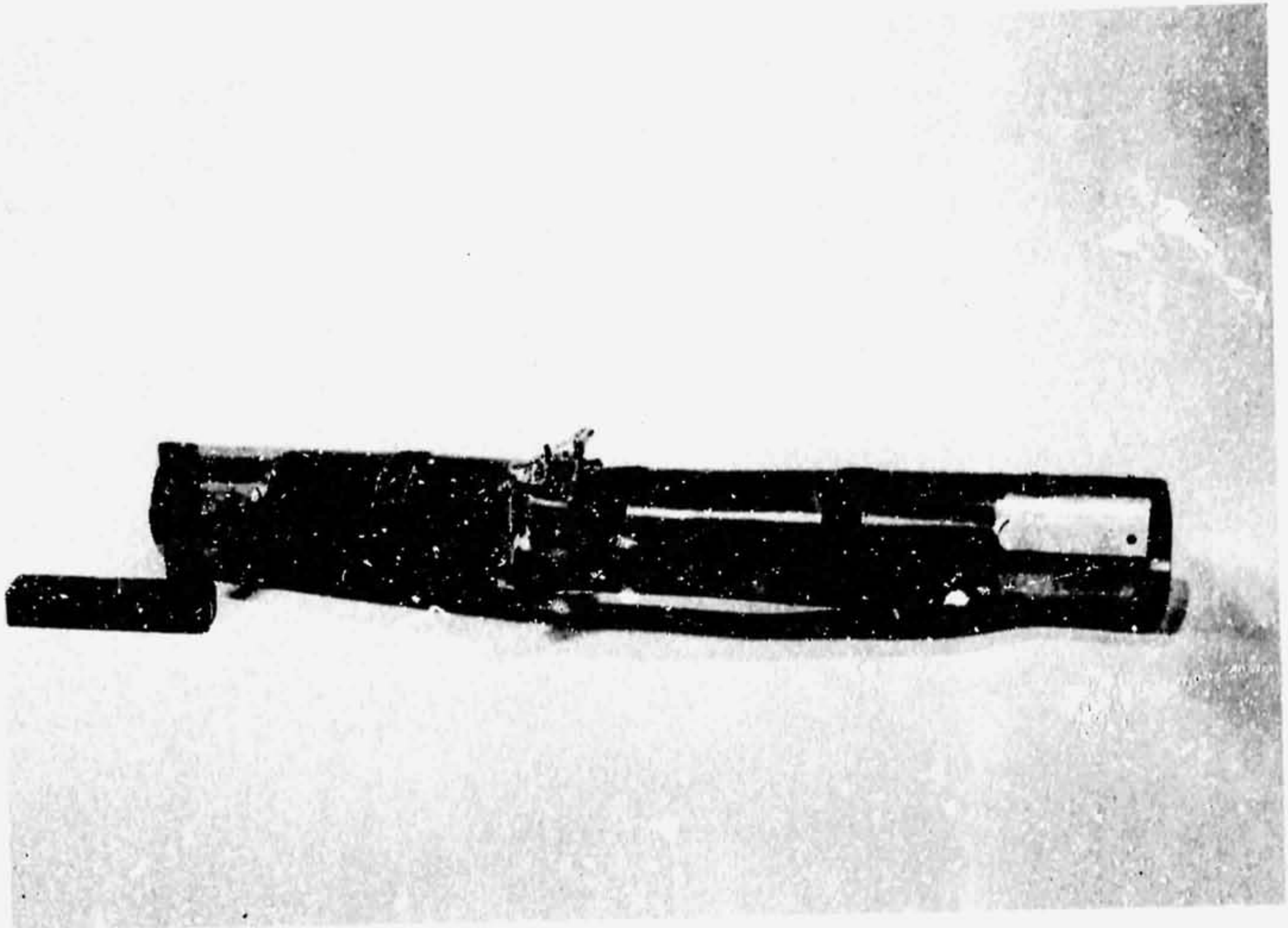


Figure 5-9 Failed Tube - AD169-1011, No. 2 - Proof Test

- AD169-1011, No. 3 Proof Test - The final member to be proof tested was AD169-1011, No. 3. This tube, which had passed NDT, was tested for Quality Control verification. The member was tested in a manner identical to the two other tubes. A compressive load of 1,012,000N (227,600 lbs.) representing 110 percent of design limit load (D.L.L.) was applied and successfully carried. Measured strains up to and down from 110 percent D.L.L. were linear. Figure 5-10 shows the load vs. strain diagram as well as the predicted strain. This particular tube was used between nodes 2 and 5 (member 2265) in the truss structure.

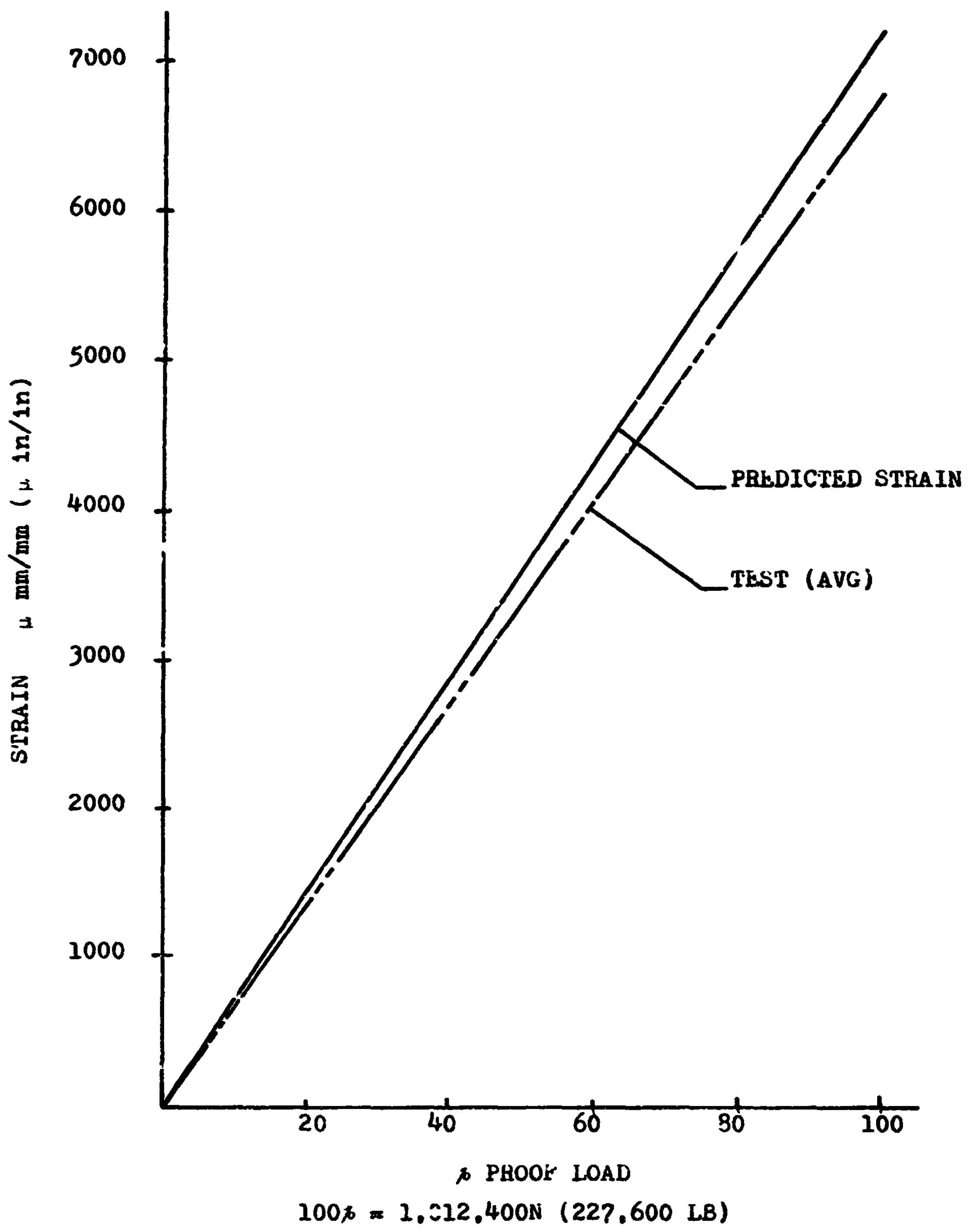


FIGURE 5-10 LOAD VS. STRAIN DIAGRAM FOR AD169-1011 NO. 3 PROOF TEST

5.2 Two Dimensional Thrust Structure Testing

A nine member Two-Dimensional One Third Scale Boron/Epoxy Booster Thrust Structure was fabricated under this program (see Figure 5-11). The specimen was delivered to the Test Division of the Astronautics Laboratory, George C. Marshall Space Flight Center for structural testing. A test plan (Reference 4) was also provided to support this effort.

5.2.1 Test Procedure

The test specimen is initially loaded in two design conditions. In condition number 1, the least critical, all engines are directed in the longitudinal (+X) direction. Applied and reacted loads associated with this condition are shown in Figure 5-12. In the second load condition all engines are gimbaled from the longitudinal direction and directed in the +X and +Y directions. Figure 5-13 shows the applied loads and moments required to satisfy load condition number 2. All testing is performed at room temperature.

The Booster Thrust Structure specimen is tested as a simply supported beam supported at nodes 1 and 3 (see Figure 5-11). Movement of the truss at node 3 shall be restricted in all three directions while at node 1 restraints shall be provided in the X and Z direction only. In addition, restraints shall be provided at nodes 2, 4, 5 and 6 to eliminate motion in the Z direction. The specimen must be free to deflect in the X and Y direction at these locations.

All loads are applied at the required hardpoints using hydraulic cylinders monitored by calibrated load links.

The test program consists of loading to 50 percent of limit load in condition 1 and 2 followed by limit loading in both conditions. The specimen is then loaded to ultimate load (140 percent limit) in condition number 1, followed by loading to failure in condition 2. Test loads are applied in 10 percent increments of limit load to limit and then in 5 percent increments to ultimate and to failure. Specimen strain and deflection measurements are recorded at each increment.

5.2.2 Instrumentation

The specimen is instrumented with 108 three circuit rosette strain gages (type FAER-25R-12S13-ET) and 20 axial gages (type FAB-25-12S13), in conjunction with a three wire unshielded cable system. Deflection measurements are required at 15 locations noted in the test plan (Reference [4]).

The completely instrumented thrust structure is shown in Figure 5-14.

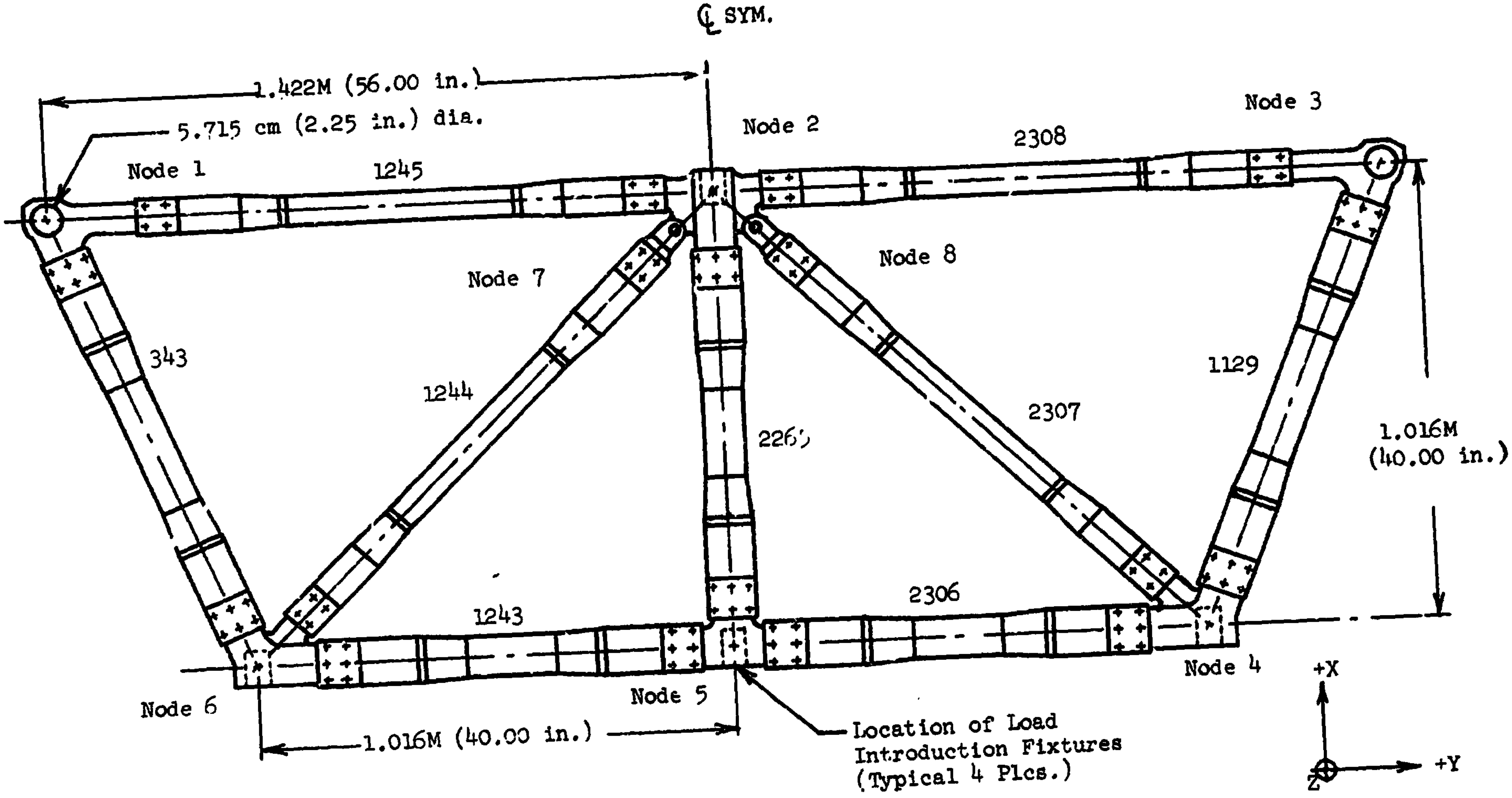
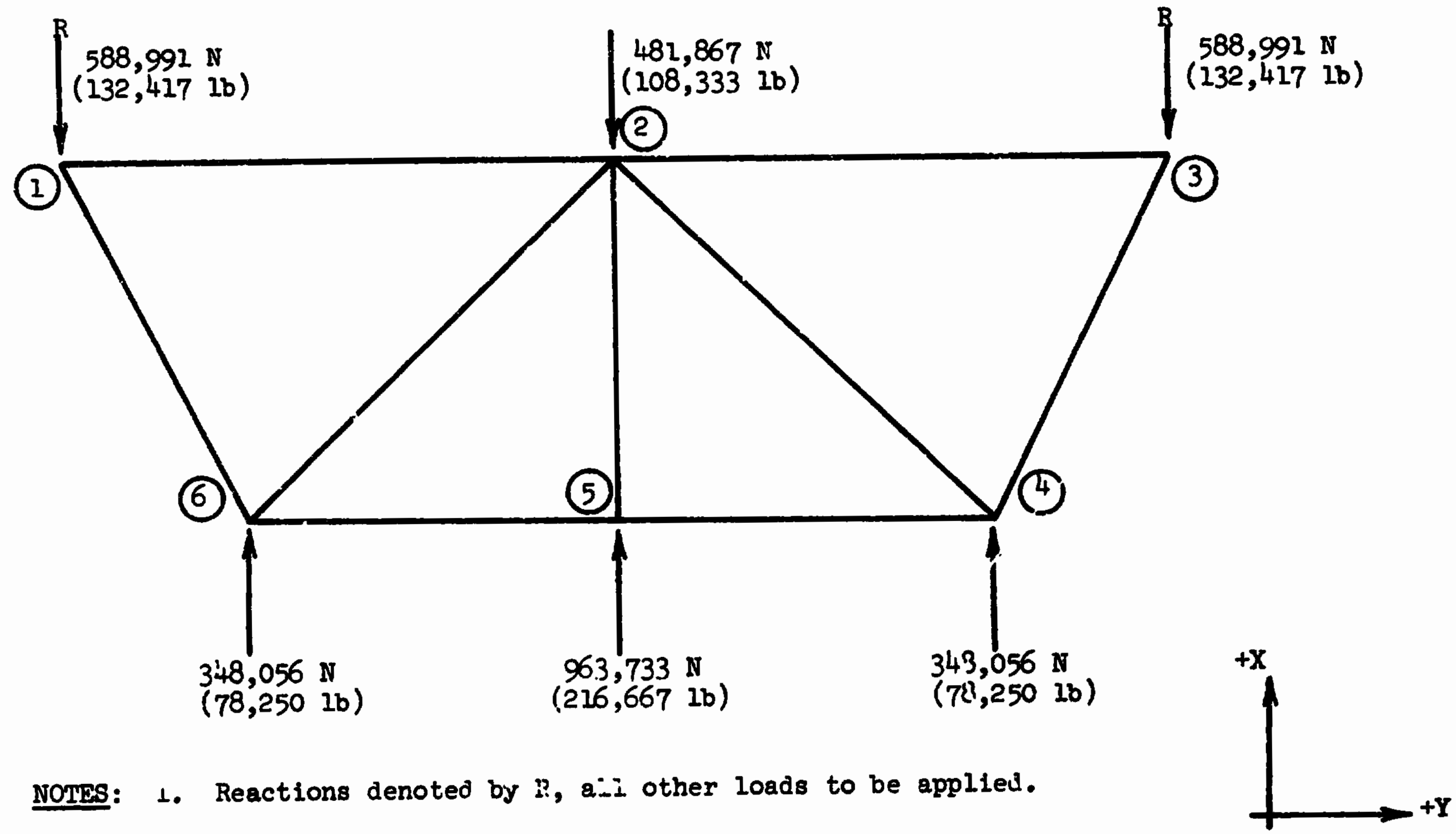
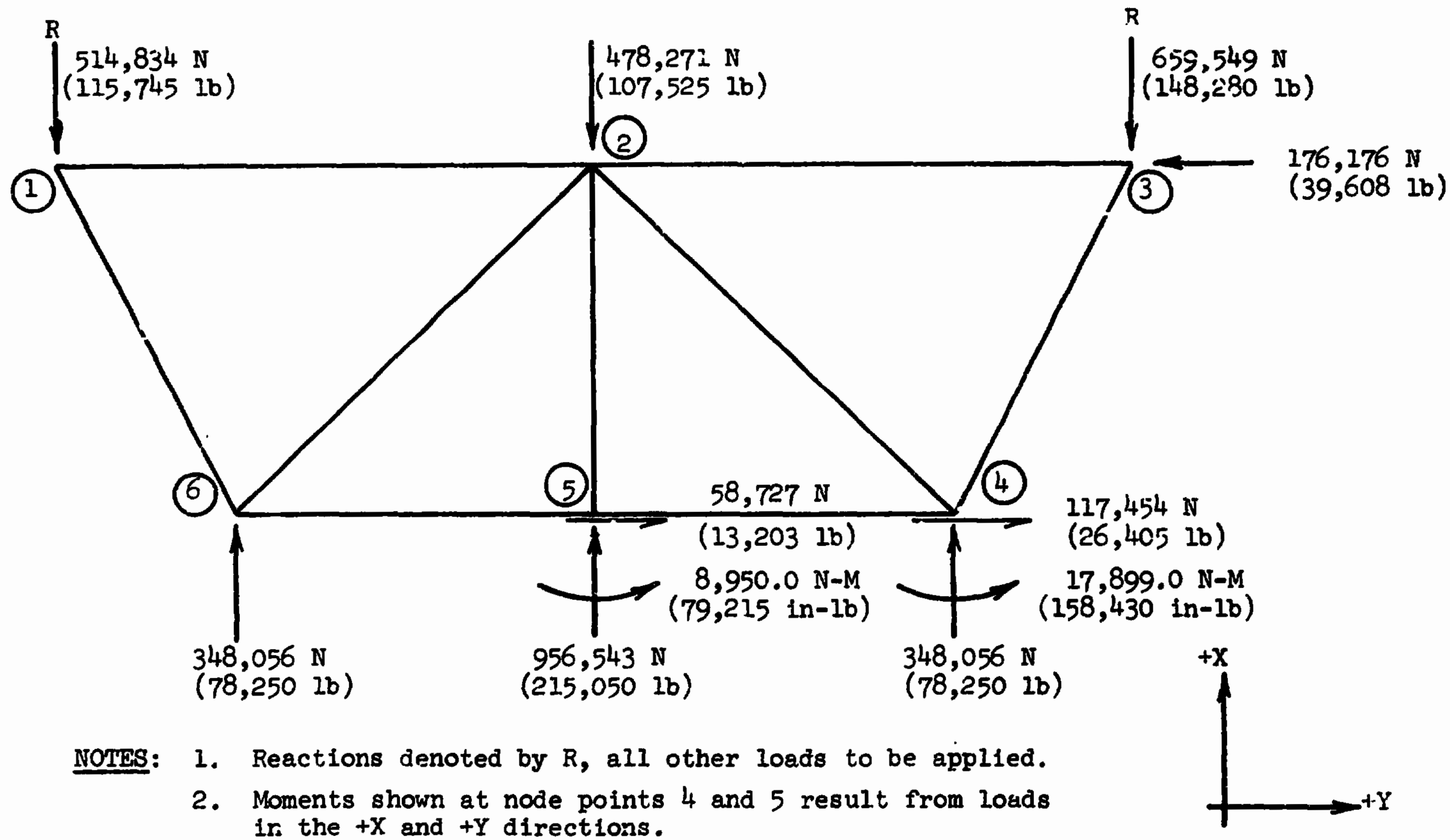


Figure 5-11 Booster Thrust Structure Test Specimen



NOTES: 1. Reactions denoted by R, all other loads to be applied.

Figure 5-12 Limit Static Loads - Condition Number 1



NOTES: 1. Reactions denoted by R, all other loads to be applied.

2. Moments shown at node points 4 and 5 result from loads in the +X and +Y directions.

Figure 5-13 Limit Static Loads - Condition Number 2

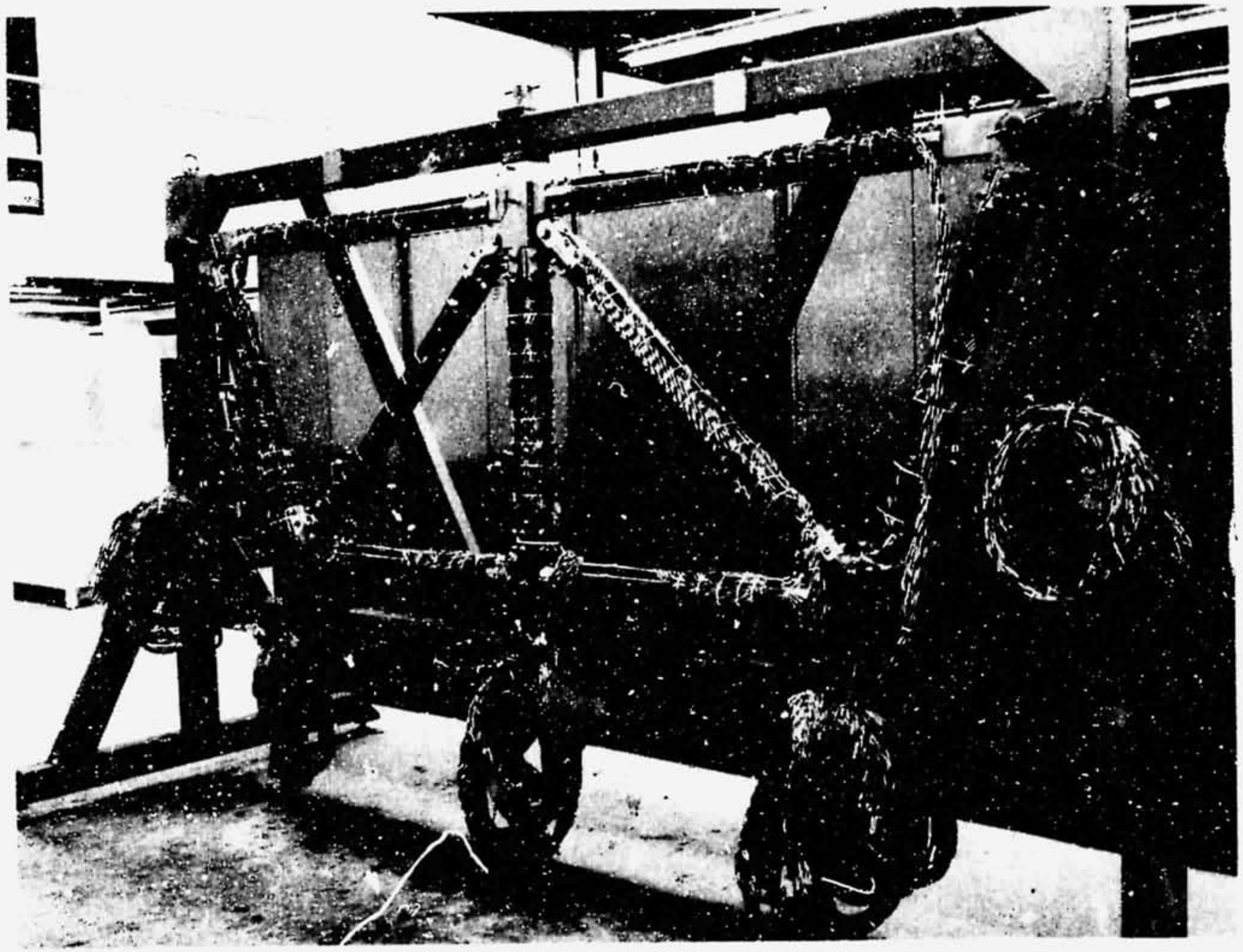


Figure 5-14 1/3 Scale Thrust Structure - Instrumented

6.0 CONCLUSIONS AND RECOMMENDATIONS

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

<u>Conclusions</u>

- The average weight savings of 30% for the B/Ep tubular members over comparable titanium tubes has been substantiated.
- The materials and manufacturing processes developed are suitable for productic
- 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 parts.
- The N.D.T. techniques have been further verified by proof testing.
- The truss assembly technique has been fully verified.

<u>Recommendations</u>

- A program extension for the fabrication and test of flight size (full scale) hardware would be desireable.
- Optimize the manufacturing methods and tooling for production of full scale structures.

7.0 REFERENCES

1. "ASTRAL-IDEAS PROGRAM S3" Grumman Ideas Manual, Volume IIA, Grumman Aerospace Corporation, Bethpage, N.Y., September 1968.
2. Hadcock, R.N., "Optimum Geometry of Advanced Composite Tubular Columns", Grumman Advanced Development Note ADN 02-01-71.3, June 1971
3. Corvelli, N. and Saleme, E., "Analysis of Bonded Joints", Grumman Advanced Development Report ADR 02-01-70.1, July 1970
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APPENDIX A

Conversion of S.I. Units to U.S. Customary Units

Physical Quantity	U.S. Customary Unit (×)	Conversion Factor (=)	SI Unit
Length	in.	2.54×10^{-2}	Meters - m
Angle	Degrees	1.745×10^{-2}	Radians - rad
Force	lbs	4.448	Newtons - N
Stress	lbs/in^2	6.894×10^{3}	Newtons Per Square Meter - N/m^2
Bending Moment	in.-lbs	1.129848×10^{-1}	Newton Meters - N-m
Temperature	°F	$\frac{5}{9}[t_{°F}-32]$	Degrees Centigrade - °C