NASA CR-132519

(NASA-CR-132519) EVALUATION OF A METAL FUSELAGE FRAME SELECTIVELY REINFORCED WITH FILAMENTARY COMPOSITES FOR SPACE SHUTTLE APPLICATION Final Report (Boeing Aerospace Co., Seattle, Wash.) 124 p HC $5.25 G3/18

N75-14819

Unclas 08051

EVALUATION OF A METAL FUSELAGE FRAME SELECTIVELY REINFORCED WITH FILAMENTARY COMPOSITES FOR SPACE SHUTTLE APPLICATION

FINAL REPORT

By

S. Oken, D. E. Skoumal and J. W. Straayer

Prepared by the
Research and Engineering Division
Boeing Aerospace Company
Seattle, Washington

For

Langley Research Center
National Aeronautics and Space Administration

Page intentionally left blank

Page intentionally left blank

FOREWORD

This report was prepared by the Boeing Aerospace Company, Seattle, Washington, in compliance with Contract NAS 1-10797. It is the final report on this program and covers all four phases of the work that was completed during the period between May 1971 and February 1974. This program was sponsored by the National Aeronautics and Space Administration's Langley Research Center, Hampton, Virginia. Dr. John Davis, Jr. was the Contracting Officer's Representative.

The performance of this contract was under the management of J. W. Straayer, Supervisor, Structures Research and Development Group; Sam Oken was the Technical Leader.

The authors wish to acknowledge the contributions of the following principal contributors to the program:

J. E. Bell	Stress
D. K. Stome	Stress
R. N. Karnes	Optimization Studies
E. W. Brogren	Thermal Analysis
C. R. Speelman	Manufacturing
D. R. Gieseking	Manufacturing
M. M. House	Testing

All numerical values used in this report are expressed in the International (SI) System of Units. Equivalent U. S. Customary Units are given in parentheses following the SI Values.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 SUMMARY

This is the final report on a program performed for the NASA Langley Research Center by the Boeing Aerospace Company (BAC) under Contract NAS 1-10797. It summarizes the development work accomplished and the results obtained to evaluate the reinforcement of metal frames with advanced composites for space shuttle applications.

Both theoretical and experimental investigations were performed in this program. Full-scale frame designs were developed to establish theoretical weight savings made available by the use of composite reinforced metal concepts. Experimental investigations were performed to evaluate the critical details used in the designs. In general, the results of this program clearly established that the reinforced metal concept provides a 25% weight savings when compared to equivalent all-metal construction.

To establish the weight savings made available by using composite reinforced metal concepts, full scale reinforced designs and competing all-metal designs were developed. These designs included all-aluminum, all-titanium, boron/epoxy reinforced aluminum, boron/epoxy reinforced titanium and boron/polyimide reinforced titanium. A typical space shuttle orbiter frame was first selected as a base for establishing frame geometry, loads and criteria. This information was incorporated in a computerized optimization program which was used to develop the structural materials distribution for the full scale designs. These results were then incorporated into detail designs of the full-scale frames. Weight and cost data was then developed using these detail designs. The results showed that the reinforced designs were 25% lighter than the all-metal designs, and that these weight savings could be made at a cost of approximately \$441/kg (\$200/lb).

Structural elements were tested to evaluate the critical details and verify the allowables used in the full-scale frame designs. These included, tension tests of composite-metal transitions, compression tests of chord crippling and column specimens and 1.22m (4 ft.)

curved beam tests. Tests were performed at both room and maximum service temperatures. All specimens incorporating boron/epoxy aluminum and boron/epoxy titanium that were tested, verified the concepts and allowables used in design. Some of the elements incorporating boron/polyimide reinforcements failed prematurely.

Curved beam components that were representative of full-scale hardware were fabricated and tested. The beams were 2.44 m (8 ft.) long and incorporated the same curvature, depths and critical details used in the basic elements of the full-scale frame design. Beams were made from each of the material systems described earlier. One beam made with each of the material systems was first cycled to limit load 400 times and then loaded to failure. All of these beams failed above their design ultimate, except the boron/polyimide titanium beam. This test was then repeated with a second beam and it met these design conditions. A second beam incorporating boron/epoxy aluminum was tested to failure at 394°K (250°F) and a second beam incorporating boron/epoxy titanium was tested at 464°K (375°F). Both beams failed at loads above those required to meet design conditions at these temperatures.

A model frame approximately 1/3 size was fabricated and tested. It incorporated the boron/epoxy-titanium material system and included the same critical details used in the full-scale designs. The frame was instrumented and then installed in a fixture for testing. The frame was then loaded in a manner which simulated the limit levels of the two critical design conditions. The frame was then loaded in the orbiter ignition condition to failure. The frame failed at 8% above its design ultimate.

The results of the experimental investigation verified the allowables used in the full-scale designs. Component and the model frame tests established that the concepts used in the designs were feasible and the weight savings developed were realistic.

2.0 INTRODUCTION

Previous studies on the Space Shuttle have indicated that its payload weight fraction is extremely small. Also, space systems with a reusable capability, such as the Shuttle, place a relatively high cost value on weight savings. Therefore, the use of advanced technology to save weight becomes attractive because of both cost and performance.

A very promising concept that appears to have a high potential for saving weight in a cost effective manner is the selective reinforcement of metal structure with filamentary composites. Previous programs investigating this concept for various applications have shown that workable weight saving designs are available and can be produced at reasonable cost. The objective of this program was to develop the technology and demonstrate the use of the reinforced metal concept for Space Shuttle frame designs. A frame was selected for study that was representative of the type of construction used in the bulk of the frames in the orbiter vehicle. The results obtained in this program would therefore be highly repetitive and represent a significant impact on the structural weight of the overall vehicle.

The work performed in this program included both theoretical and experimental investigations. Full-scale design studies were performed to establish theoretical weight savings. Component tests were performed to evaluate the critical details used in the designs and provide credibility to the weight saving results. Finally, a model frame was fabricated and tested to provide a final evaluation of highly representative construction under realistic load conditions.

3.0 FRAME DESIGN STUDIES

Design studies were performed to establish the weights and costs of competing all-metal and filamentary composite reinforced metal orbiter frames. The geometry, criteria and loads were based on a frame selected from a high cross-range Space Shuttle orbiter configuration having external LH_2 tankage. An automated design optimization program was used to develop the structural material distribution around the frames. These results were then incorporated into detail designs. The detail frame designs were used to establish frame weights and costs.

Frame Selection

The frame that was selected to establish geometry, loads and criteria in this study was located at the aft end of the payload section (Sta 1502) in a high cross-range orbiter configuration (see Figure 3.0-1). This frame (Figure 3.0-2) was representative of the geometry and construction of approximately 80 other frames in the orbiter. It provided support for the fuselage shell, T.P.S. panels, payload deck and payload hinge loads. It was shaped to provide room for the installation of a 4.57 m (15 ft.) diameter payload. It was 8.93 m (29.3 ft.) wide at the base and 3.99 m (13.1 ft.) high. The cross-section of its basic elements consisted of built-up "I" members.

Material Selection

The selection of materials to be used in the design studies was based on their potential for realistically impacting the shuttle orbiter design. Basic criteria included: 1) suitability for full-scale production, 2) demonstrated large part production capability, and 3) initial availability of 75% of the required program design data. The materials selected were 7075-T6 aluminum, 6Al-4V titanium, Rigidite 5505/4 boron/epoxy composite and boron/Skybond 703 polyimide. All but the polyimide composite met the above criteria. It was included because of its potential elevated temperature service capabilities. Table 3.0-1 lists the materials used in the various designs along with the adhesives and surface preparation used for assembly and the associated maximum design temperatures.

Loads

An ASTRA (Reference 1) computerized loads analysis was performed on the frame. Sixteen load conditions were studied. The results obtained showed that five were critical for the design of the frame. Table 3.0-2 lists these five load conditions along with the maximum design temperatures associated with the frame material systems.

Full-Scale Frame Design

The full-scale design studies were performed based on the requirements of a frame located in the aft payload section of a high cross-range orbiter with external LH_2 tankage. Initially, preliminary designs were developed for both all-metal (aluminum and titanium) and composite reinforced metal frames. These designs were used to identify critical interface requirements, and as base for initiating structural optimization and detail design refinements.

The initial interface and design requirements identified included: 1) providing a capability for mechanically attaching thermal protection and fuselage shell panels at the frame station, 2) providing continuity across the frame station for fuselage longerons, and 3) attachment provisions between frame elements. Both the all-metal and the composite reinforced metal designs used similar approaches for meeting the above requirements. Extensions stabilized with high density honeycomb core were incorporated in the outer chords to provide a means for attaching the fuselage shell and TPS structure. This technique had been effectively used in the past in metal bonded structure to provide stability and prevent crushing in mechanical attachment areas. The longeron continuity was attained by machining off-sets in the longerons to joggle over the frame chords. The longerons passed through clearance holes in the webs which were locally reinforced with doublers. Kick loads resulting from the longeron off-sets were transferred into the frame webs with shear clips.

In the reinforced designs all the composites terminated with stepped titanium transition fittings. Basic members in all the designs terminated as all-metal sections and were therefore connected in a similar manner using mechanical attachments.

Initial preliminary designs were prepared. The overall geometry used is shown in Figure 3.0-3. The basic cross-section of the members were built-up "I's", (Fig. 3.0-4). The all-metal members incorporated machined "Tees" in the chords attached to shear resistant webs. In the reinforced designs, the "Tees" were machined to a minimum gage and then reinforced with unidirectional boron composites.

Both the all-metal and the reinforced preliminary frame designs were then refined using an automated computerized design program to establish the material distribution for producing least weight designs. This approach was based upon two existing Boeing computer programs. The first, TES-222 (Reference 1) consists of a high-speed finite element stress analysis program combined with a directed search (non-linear programming) technique. The second, the BUCLASP (Reference 1) buckling program, was used to generate tables of critical buckling strains for chord element geometries. The TES-222 ingested these tables and performed a least-squares best-fit solution for each flange cross-section configuration to determine their margins of safety. The frames were therefore optimized taking into account the variability of compression allowable strains. The program also used a tension allowable of 6000 for the reinforced designs and the ultimate tension strain of the metal in the all-metal designs to determine margins of safety in the tension critical areas. The webs of both the all-metal and reinforced designs were the same (all metal) and were designed to be shear resistant.

The preliminary frame designs were used as a starting point for developing the least weight designs. Initial inputs to TES-222 included the material distribution based on these designs, frame geometry, a set of loads, criteria and material properties. The program then produced a sequence of designs. Each design in the sequence was either lighter or less over-stressed than the previous design. The program eventually produced a design whose weight or overstress was a relative minimum.

To produce the minimum weight designs the frame was first modeled, as shown in Figure 3.0-5, for use with the TES-222 program. This program produced a sequence of designs by directly optimizing several flange sections, as shown in Figures 3.0-6 and -7. All other sections varied linearly between the optimized areas. This procedure was repeated until the structural material distribution for the least weight designs was arrived at. A typical example of weight reductions produced during the design cycling is shown for the boron/epoxy reinforced titanium design in Figure 3.0-8. Typical material distribution developed using this technique is shown in Figures 3.0-9, -10 and -11 for this same design. A summary of the optimization problem data for the reinforced titanium design and the competing all-titanium design is shown in Table 3.0-3..

The results of automated minimum weight design studies were then incorporated in the final detail designs of both the all-metal frames and the composite reinforced metal frames shown in Figures 3.0-12 and -13. These designs incorporated tapered metal and composite flange areas as indicated by the optimization studies. As mentioned previously, all designs incorporated built-up "I" sections as a basic cross-section. The all-metal designs used machined T's for the chords. The reinforced designs used machined T's in which the caps were cut to a minimum gage. These caps were then reinforced with unidirectional boron composites to provide the required structural areas. The outer chords incorporated honeycomb stabilized extensions to provide an attachment capability. The inner chords included a honeycomb spacer to improve their torsional stability under compression loading. The webs of all designs were similar. They consisted of shear resistant all-metal webs stiffened with metal angles.

Analysis

Initially, all of the frames were sized using preliminary loads and hand analysis. These designs were then refined using an optimization program to develop the optimum structural materials distribution for both the all-metal and composite reinforced frame designs. The required frame cross-sections were computed automatically such that the frame weights were near optimum and no stress or gage limitations were exceeded.

The TES-222 computer program (Reference 1) was used to develop the material distribution in the frame designs. It incorporates a high speed finite element stress analyses program coupled with a direct search (nonlinear programming) technique. The program selected the proper gages and cross-sectional areas which created minimum weight designs. This was accomplished by producing a sequence of designs such that each was either lighter weight or exhibited less overstress than the previous design.

Assuming that portions of the frame would be buckling-critical, the buckling program, BUCLASP (Reference 1), was used to generate tables of buckling strain as a function of geometric parameters for each flange configuration. The TES-222 ingested these tables and performed a least-squares best-fit solution for each flange cross-section. When it was determined that flanges were not buckling-critical, a room temperature compression allowable of 5000 micro inches of strain was used in the reinforced designs. A room temperature allowable strain of 6000 micro inches was used in tension in the reinforced designs. In the all-metal designs the materials used had well established allowables which were used in their analyses.

Finite element models used for structural analysis and optimization of the frames were based on the frame idealization shown in Figure 3.0-5. All flange elements were idealized as rods, and all web elements which were not at corners as shear panels. The corner web elements were modeled or biaxial plane stress plates. Also, two plane stress triangles were used at each end of the central vertical support member.

In developing the minimum weight designs the frames were sized by two critical room temperature conditions, Side Wind Condition and Orbiter Ignition. These designs were also strength checked for three other conditions which occurred at elevated temperatures, as shown in Table 3.0-2. The stress distribution was developed around the frame for each of the loads with the TES-222 program as it produced the least weight designs. Typical data developed are shown for the outer members of the reinforced titanium and all-titanium frame designs in Figures 3.0-14 and -15. In all, fourteen computer runs were made in sizing and strength checking the frames. A summary of these runs is shown in Table 3.0-4.

The stress distributions established in the above analyses were used in conjunction with the allowables to establish the margins of safety for the designs. These analyses took into account the residual stresses set-up during fabrication. These stresses were based on the temperature difference between the adhesive cure temperature used for assembly and the service temperature of the specific design condition being considered. The temperatures used in the analyses of the frames are listed in Table 3.0-4. As noted in this table, two boron/epoxy reinforced aluminum frame designs were developed. One was based on being assembled with an adhesive that cured at 394°K (250°F) and one which cured at 450°K (350°F). The frame assembled at the lower cure temperature contained lower residual stresses and as a result was slightly lighter (3.3%). This frame although lighter was restricted to lower service temperatures due to the capability of the lower curing adhesive.

Frame Study Results

The prime considerations for determining the feasibility of the composite reinforced metal concept were potential weight savings and cost. In this program both all-metal and composite reinforced metal minimum weight frame designs were developed and compared to establish these parameters. Initially, a computer program was used to develop the optimum distribution of structural materials for the frame designs. Detail designs were then prepared incorporating these results. Total frame weights were based on these detail designs and were determined by adding the weights of the non-structural materials, such as dummy plies, adhesives, honeycomb and local doublers to the basic structural material weights. As a result of the optimizations performed on the frame designs their total weights were reduced and the weight savings were increased from approximately 20% on the preliminary designs to 25% on the final designs. The total weights did not include the lower frame members or center posts. These elements were not considered as a part of the basic frame, but were optimized as all-metal components during the design of the frames to insure they did not adversely effect the redistribution of loads.

The weight of the boron/epoxy reinforced titanium frame was increased from 30.4 kg (67.0 lbs) to 39.4 kg (86.9 lbs) by adding the weight of the non-structural materials. The weight of the all-titanium frame totaled 52.5 kg (116 lbs). A comparison of the two designs shows that a 25.4% weight saving was attained by using the reinforcement concept. The weight savings attained with the boron/epoxy reinforced aluminum concept when compared to the all aluminum design was 25%. When the reinforced aluminum design is compared to the all titanium design the weight savings is reduced to 12%. These comparisons are based on strength critical designs only. In general, the titanium designs were less stiff and deflected more under the same loading. If the stiffness of the frame becomes a greater consideration, which is probable as frame requirements become better defined, the reinforced aluminum design would become more competitive and could become the least weight design. A summary of the frame weights and their maximum deflections is shown in Table 3.0-5.

The cost to produce the full-scale frame designs were determined. A summary is shown in Table 3.0-6. In general, these results show that the aluminum frames are cheaper to produce than the equivalent titanium designs. The manufacturing cost of the titanium frames are appreciably greater than the aluminum frame. The material cost for the reinforced aluminum frame is higher than the reinforced titanium because it was determined during optimization that it required a greater amount of reinforcement to produce a least weight design. This difference in reinforcement cost was somewhat offset by the greater cost of the titanium. The tooling cost for the frames were approximately the same with the exception some additional hot sizing tools were required for the reinforced titanium design. The chords in this frame were machined to a minimum gage and could not be successfully rolled to their final geometry.

The weight savings were accomplished with a relatively small amount of boron. The reinforcement was incorporated in the chord areas which have well-defined load paths and permitted the boron to be used in an optimum (0°) orientation. As an example, the frame weight in the reinforced titanium design was reduced 29.5 lbs. using slightly less than 12 lbs. of boron composite. Weight savings demonstrated with composite reinforced metal concepts used in this study were accomplished at a cost of approximately \$441/kg (\$200/lb) and appear to be attractive for space schuttle application.

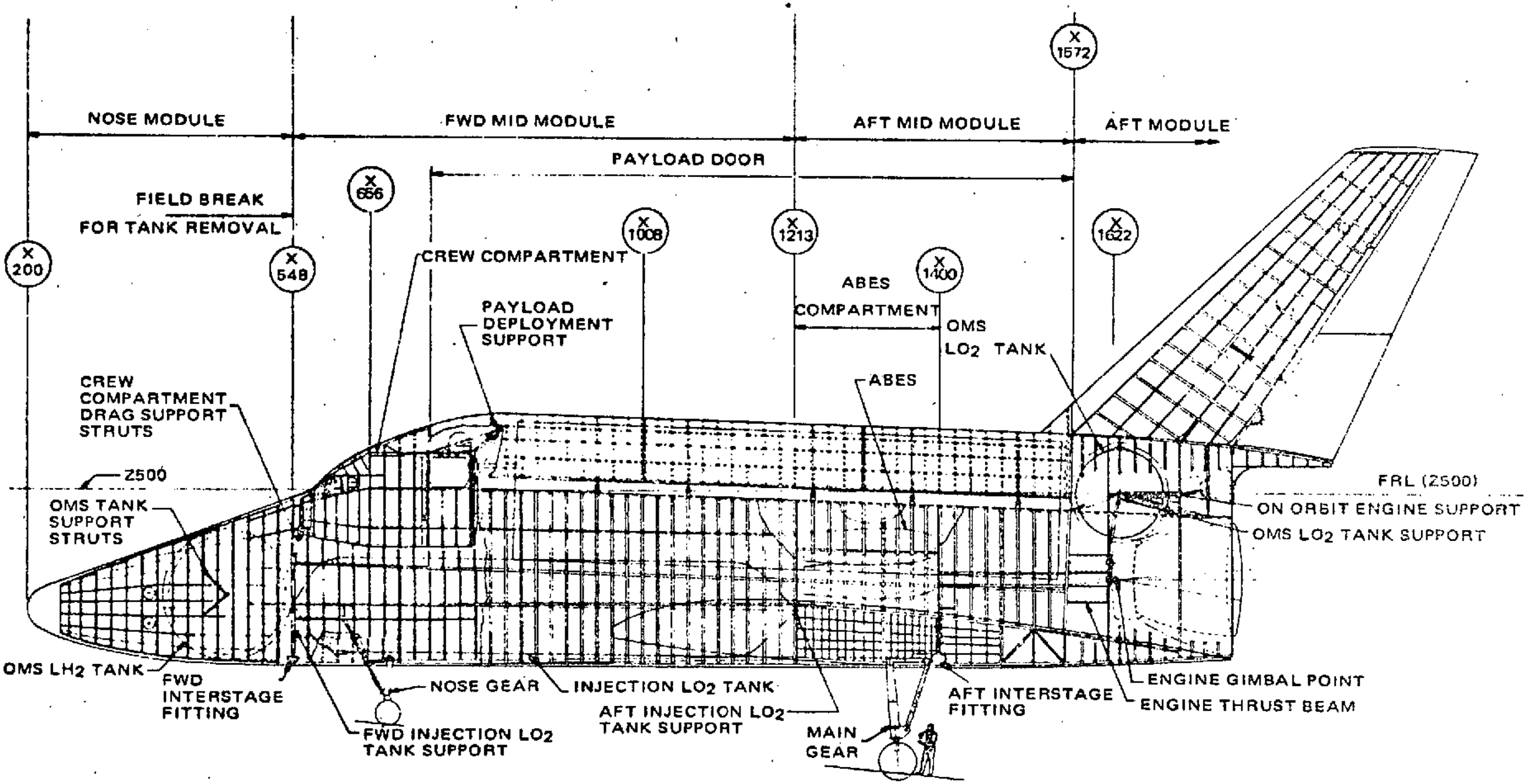


Figure 3.0-1: H-3T Orbiter – Structural Arrangement

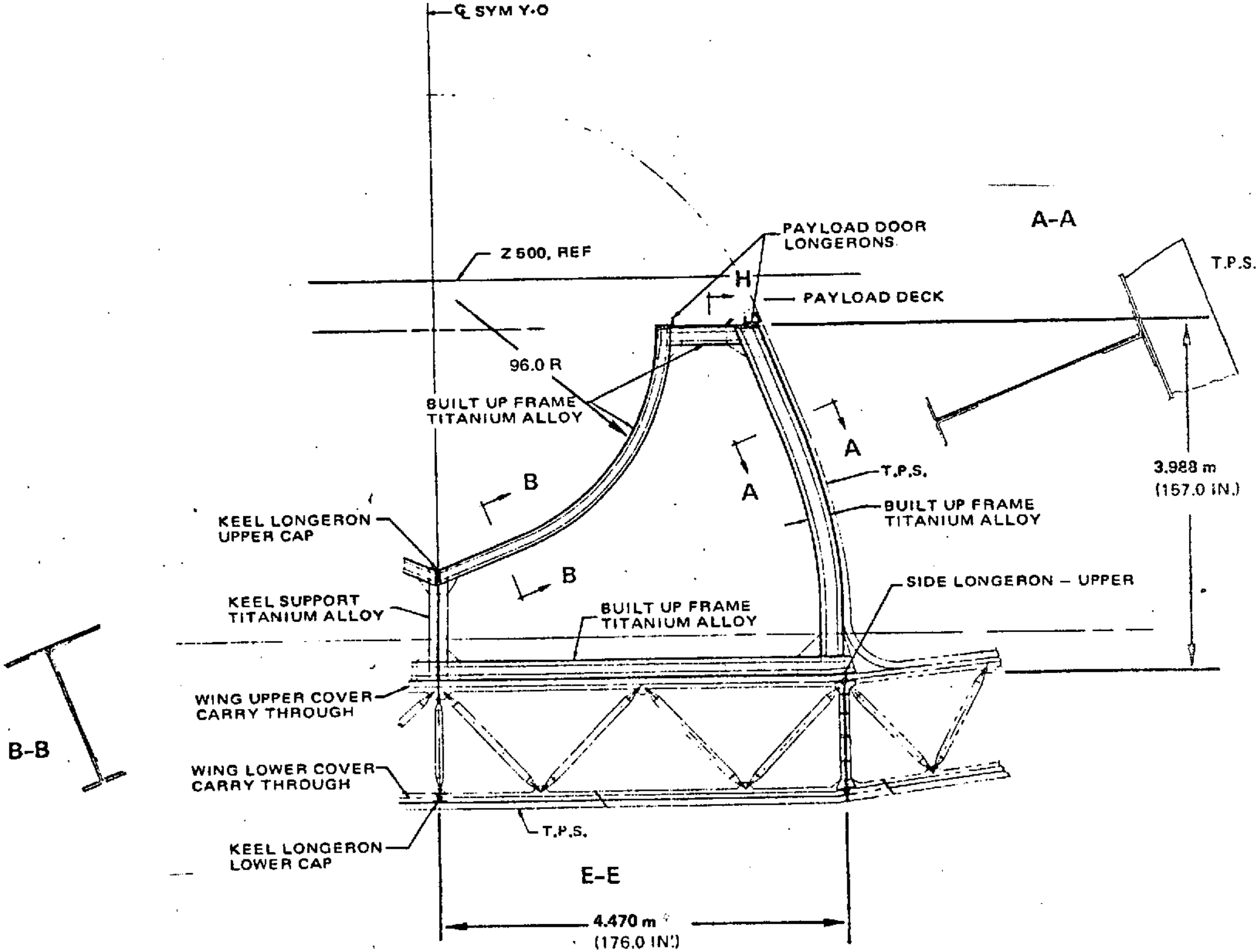


Figure 3.0-2: H-3T ORBITER–FRAME 1502

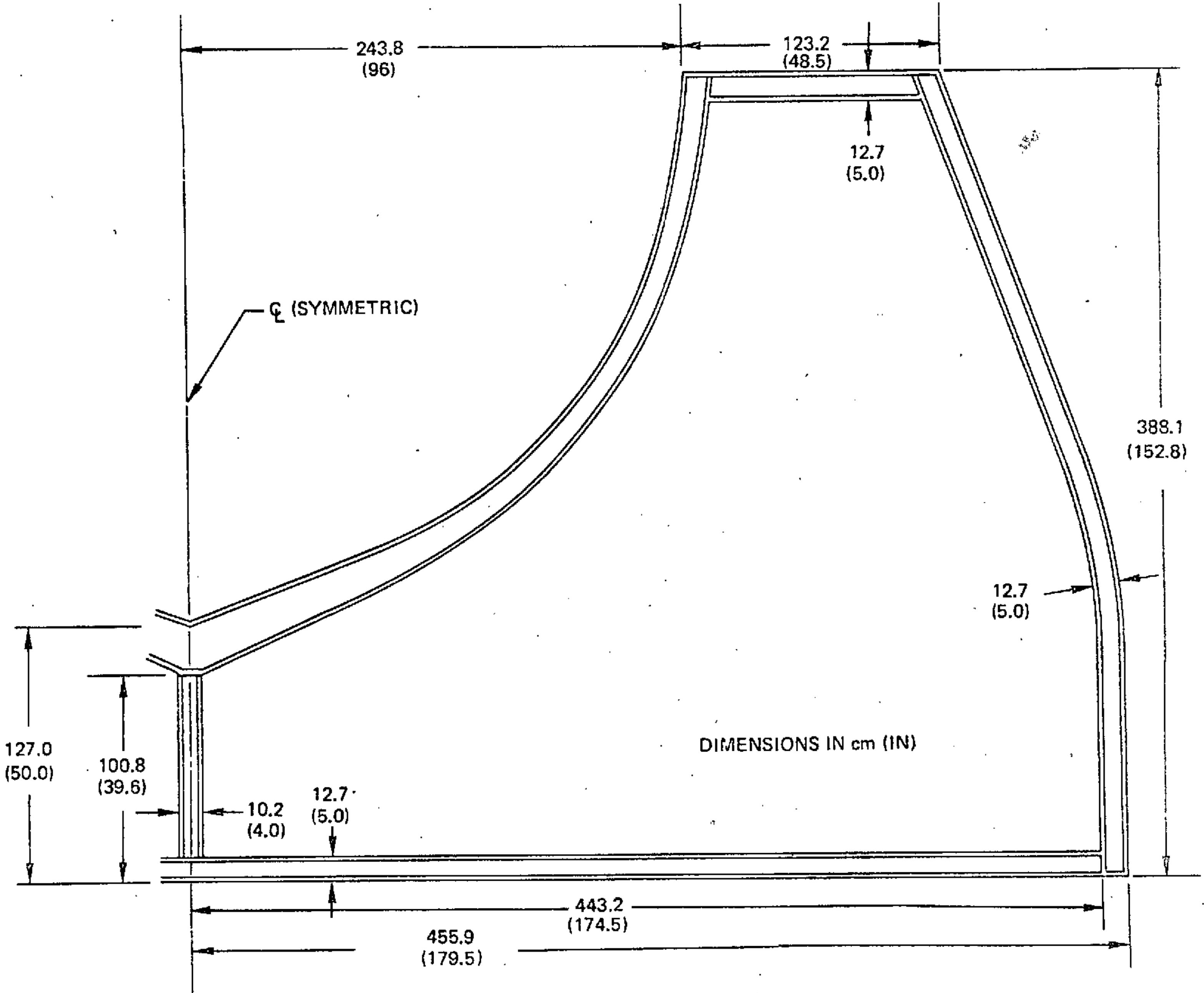


Figure 3.0-3: FRAME GEOMETRY

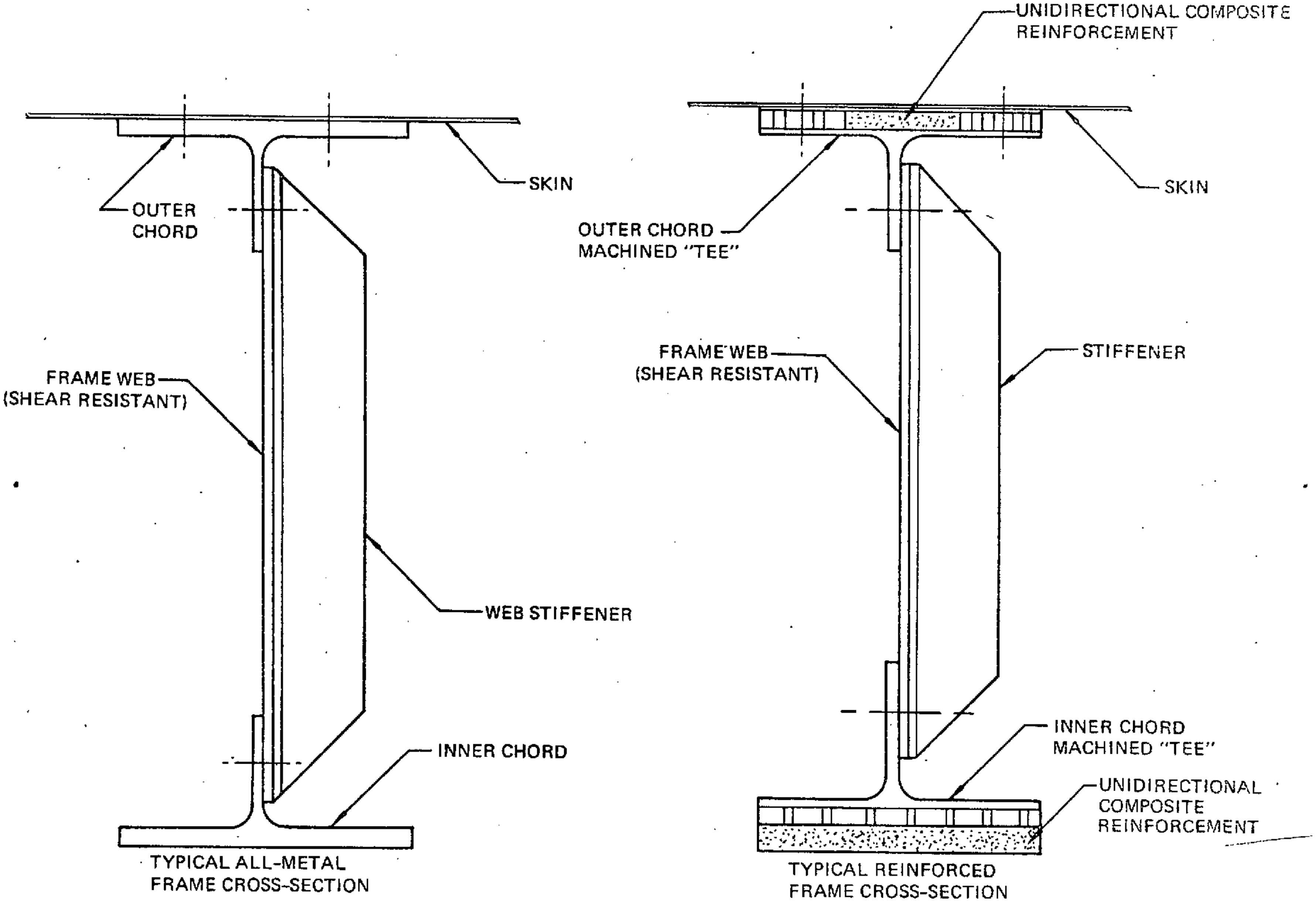


Figure 3.0-4: Frame Member Cross-Sections

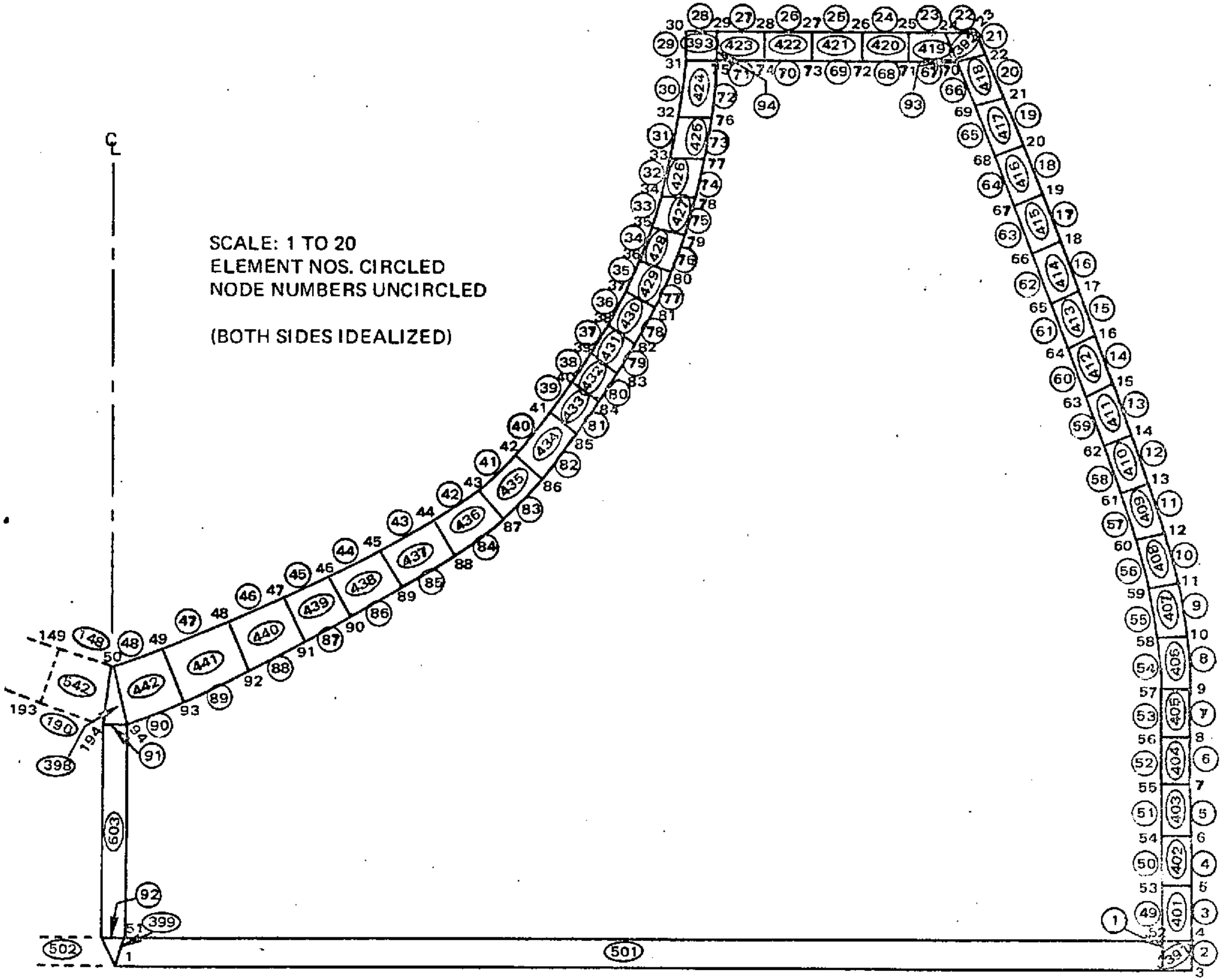


Figure 3.0-5: Frame Idealization for Structural Optimization

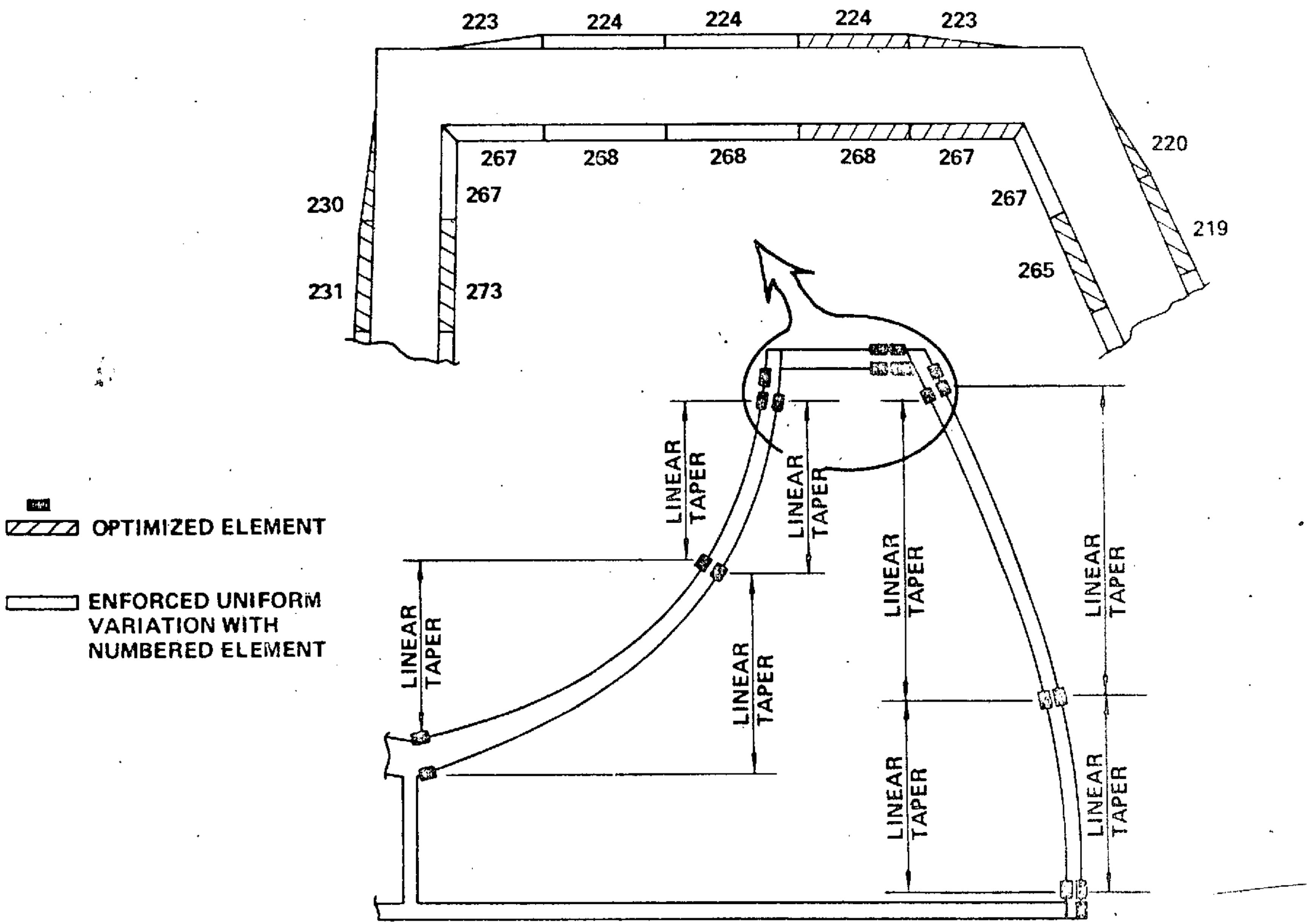


Figure 3.0-6: BORON OPTIMIZATION VARIABLES (REINFORCED FRAME ONLY)

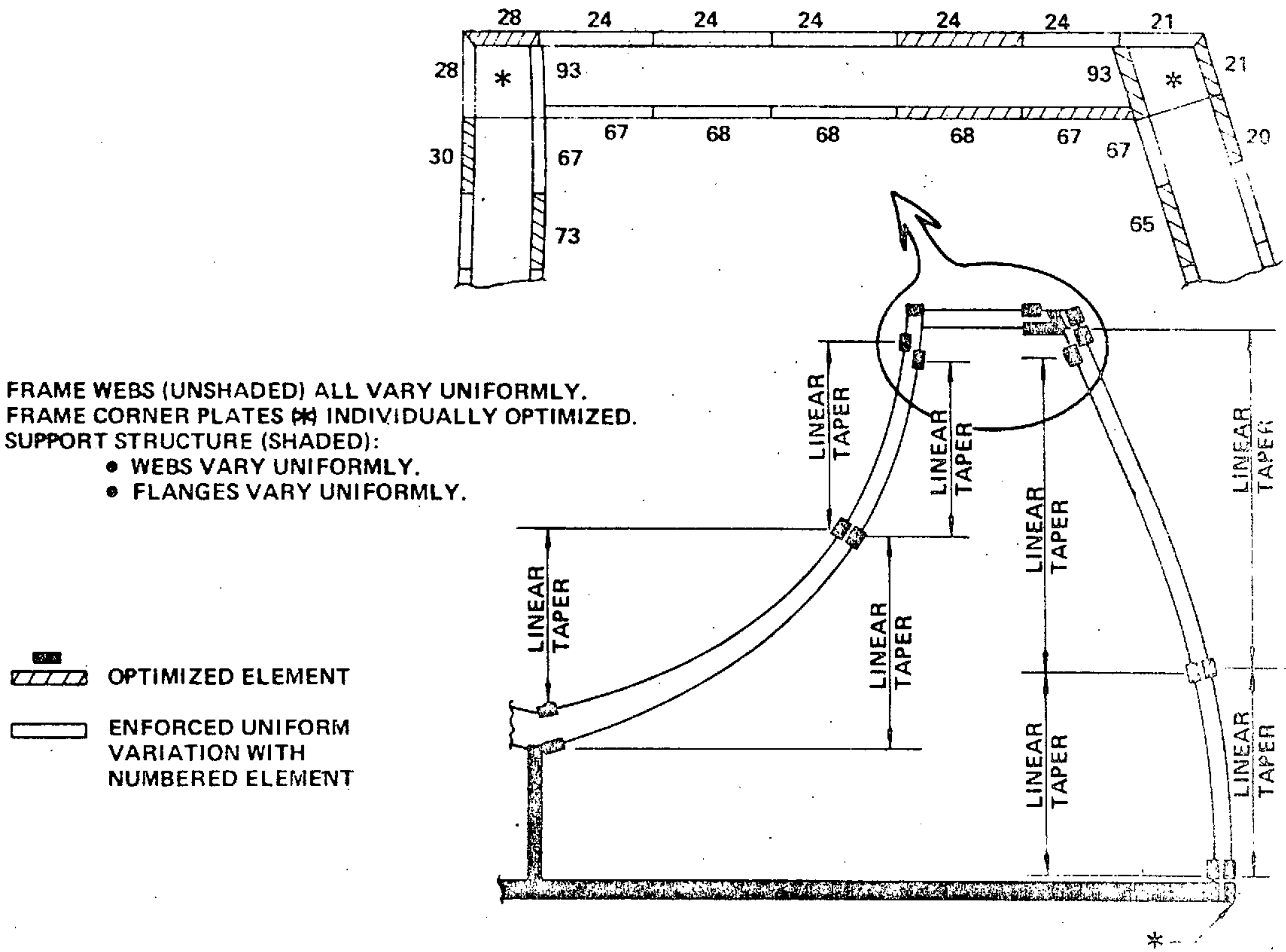


Figure 3.0-7: TITANIUN OPTIMIZATION VARIABLES (FOR ALL-METAL FRAME, AND FOR METAL PORTIONS OF REINFORCED FRAME)

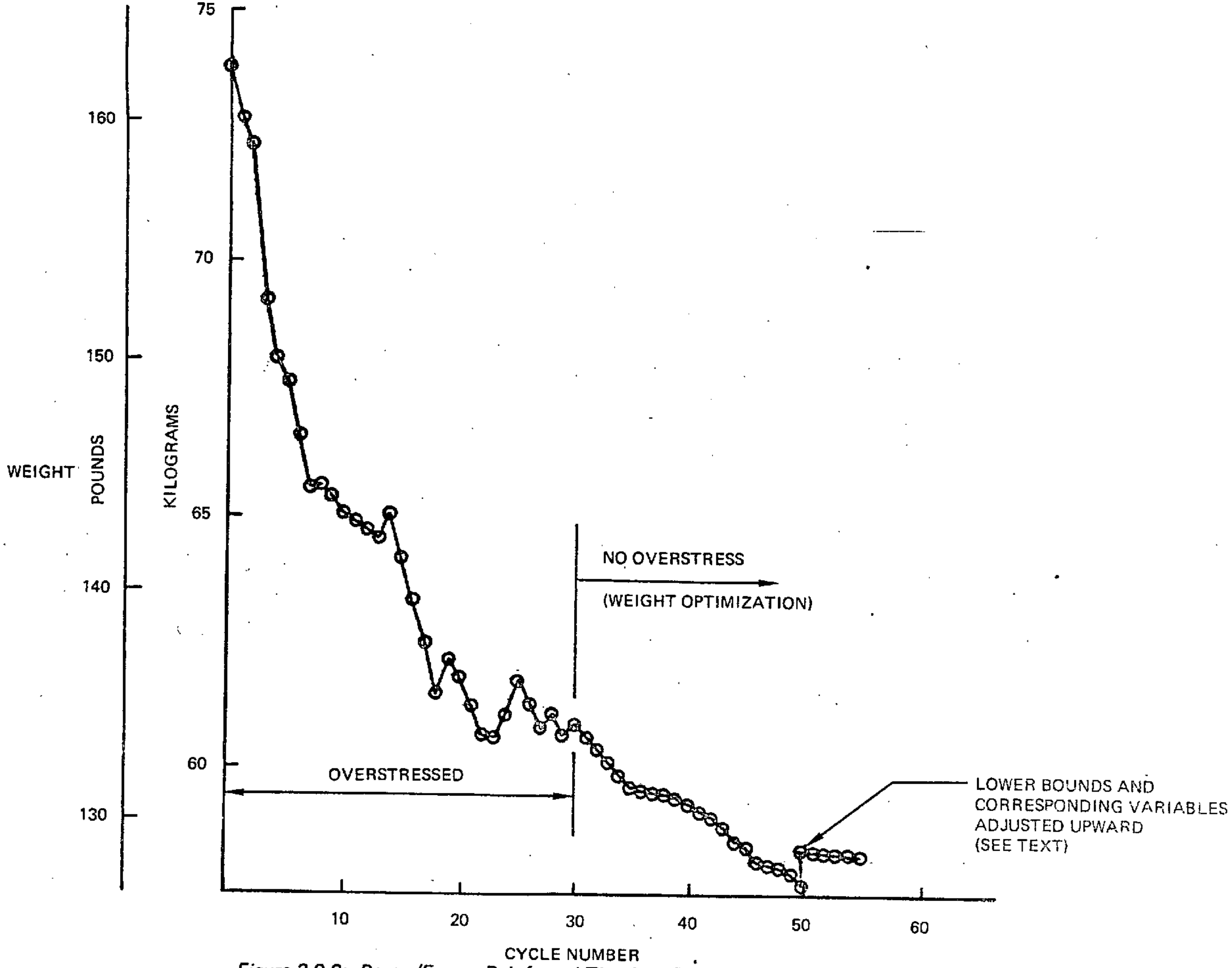


Figure 3.0-8: Boron/Epoxy Reinforced Titanium Frame Weight vs. Design Cycle

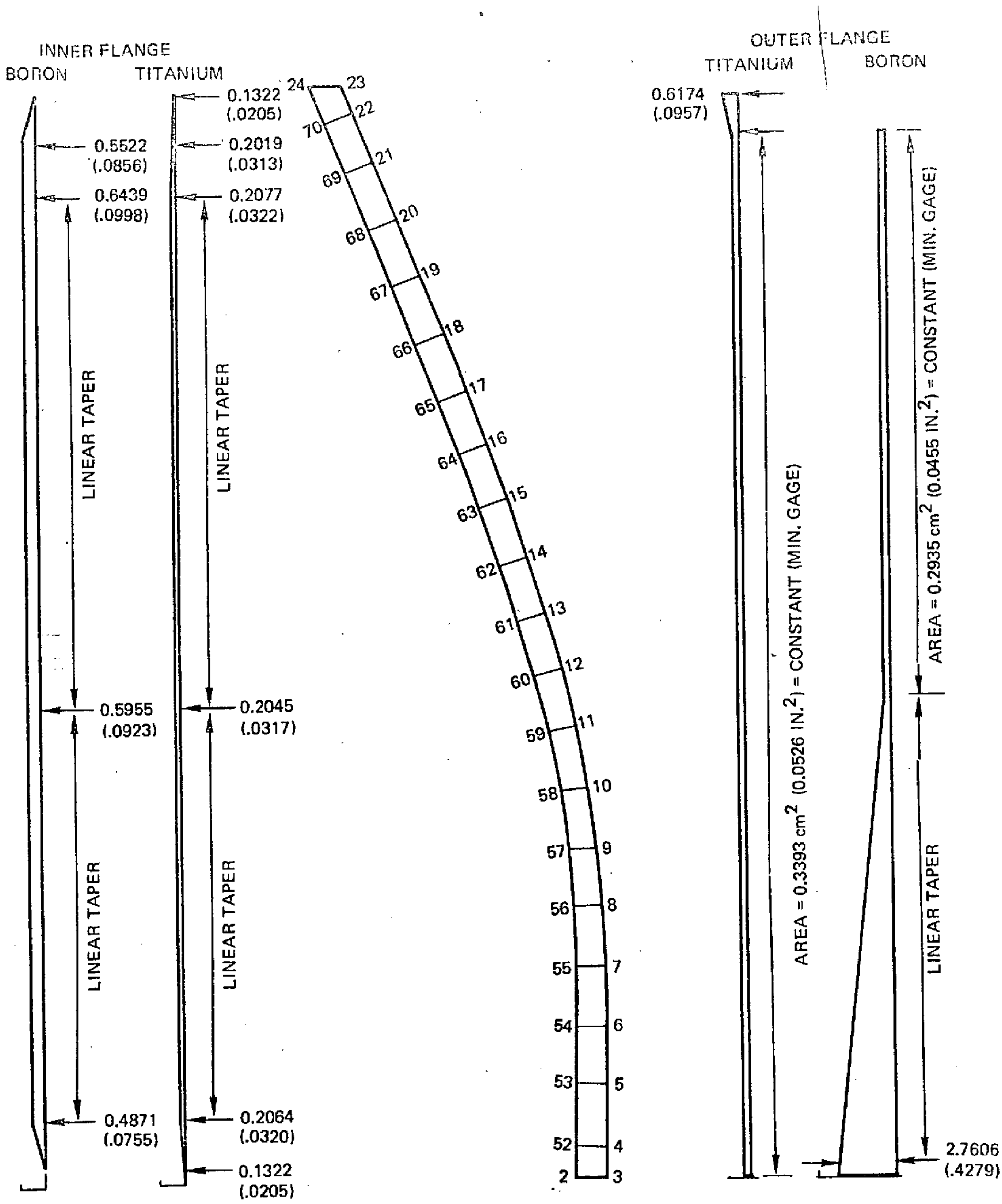


Figure 3.0-9: Boron/Epoxy Reinforced Titanium Frame — Flange Area Distribution cm^2 (In.^{2})

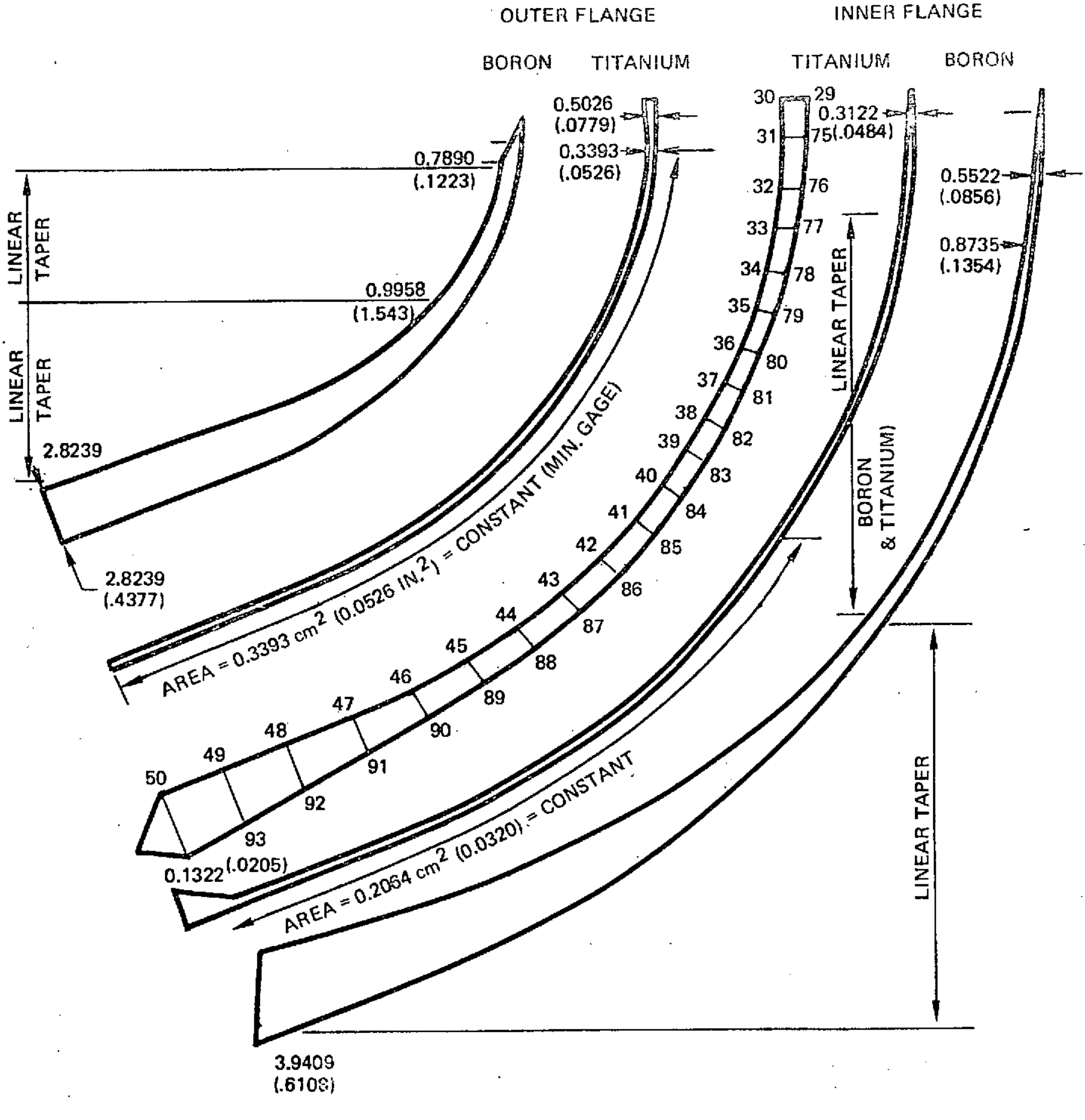


Figure 3.0-10: BORON/EPOXY REINFORCED TITANIUM FRAME – FLANGE AREA DISTRIBUTION cm^2 ($IN.^2$)

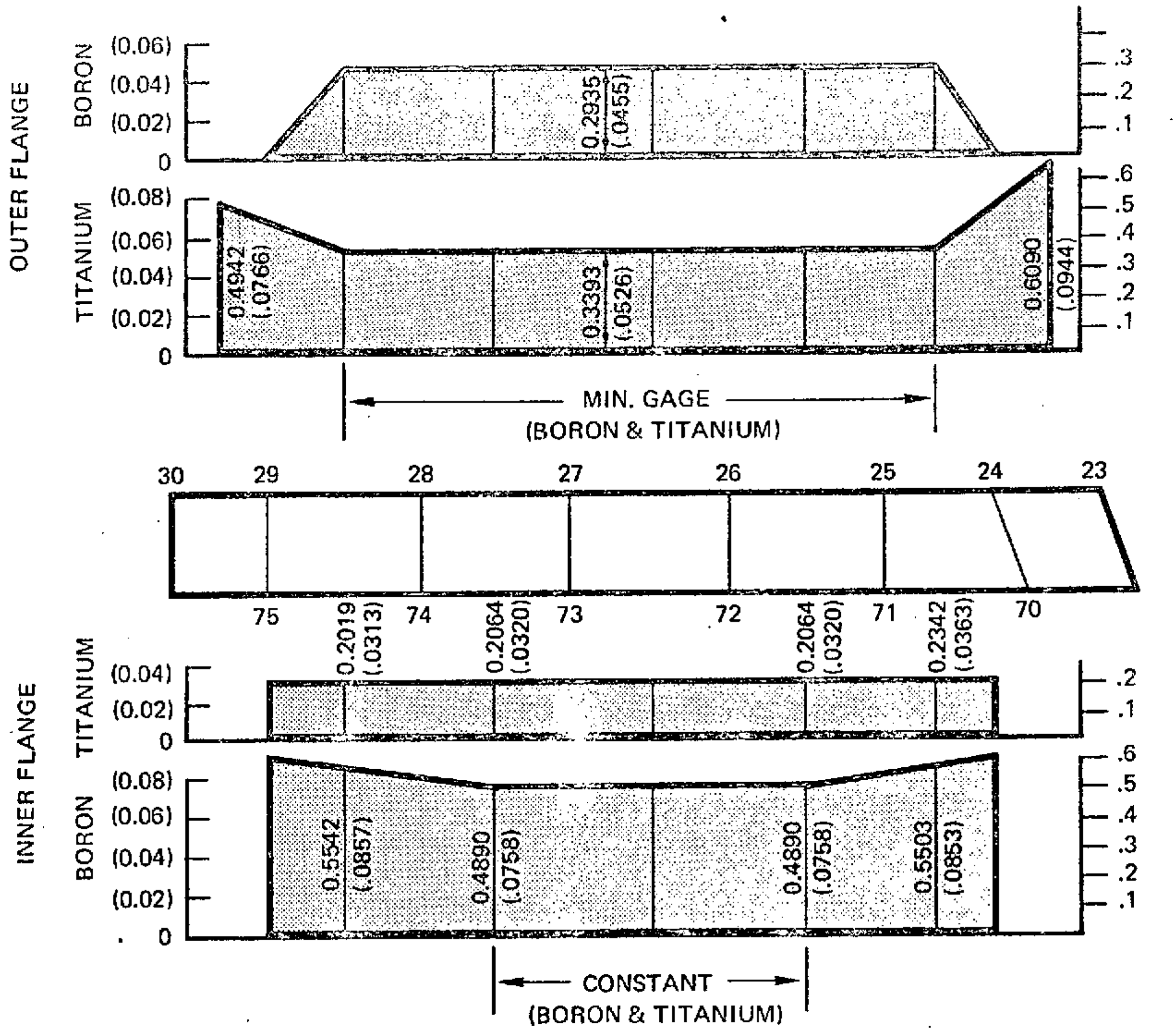


Figure 3.0-11: BORON/EPOXY REINFORCED TITANIUM FRAME – FLANGE AREA cm^2 (IN.^{2})

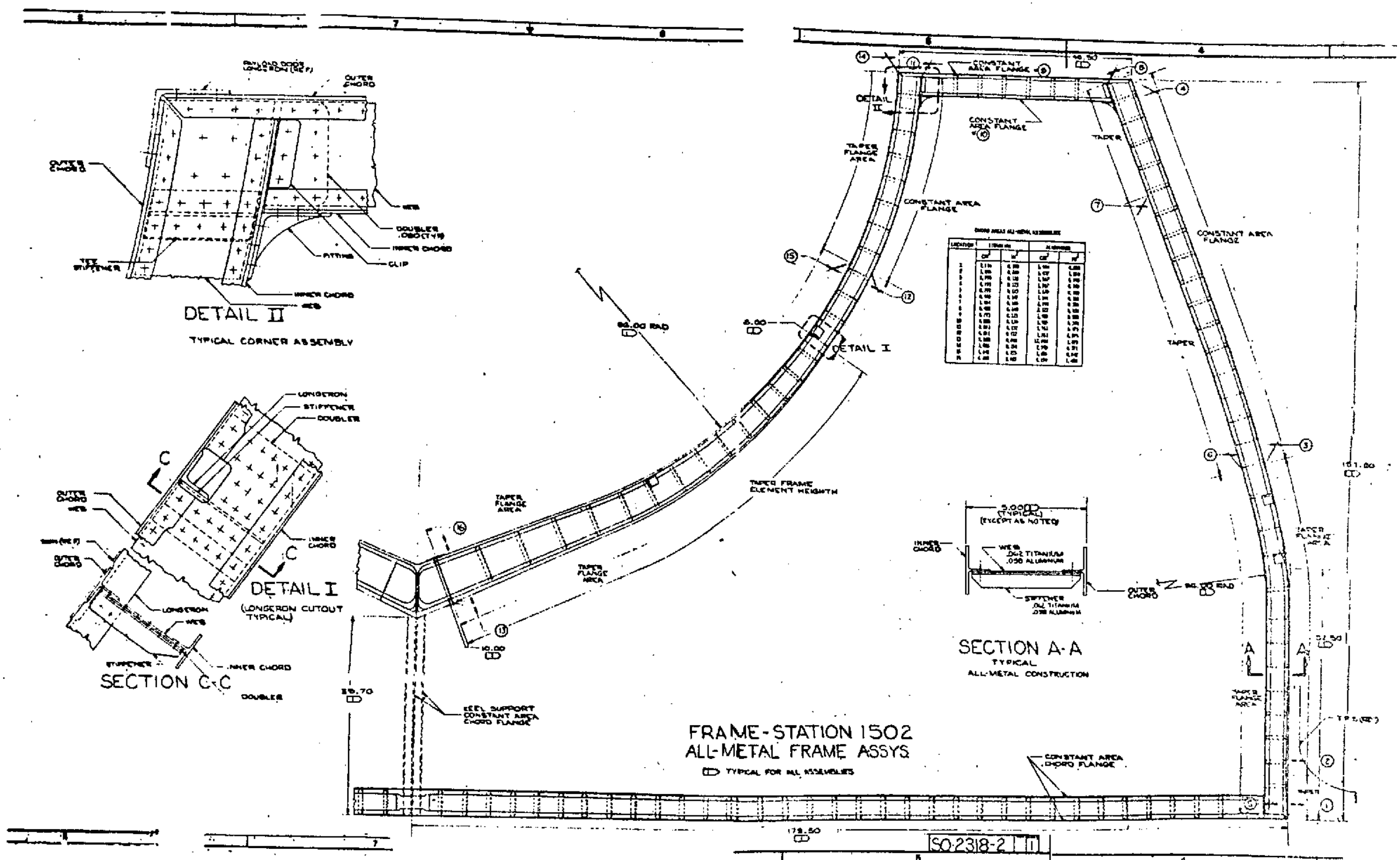


Figure 3.0-12 FRAME STATION 1502 ALL METAL FRAME ASSEMBLIES

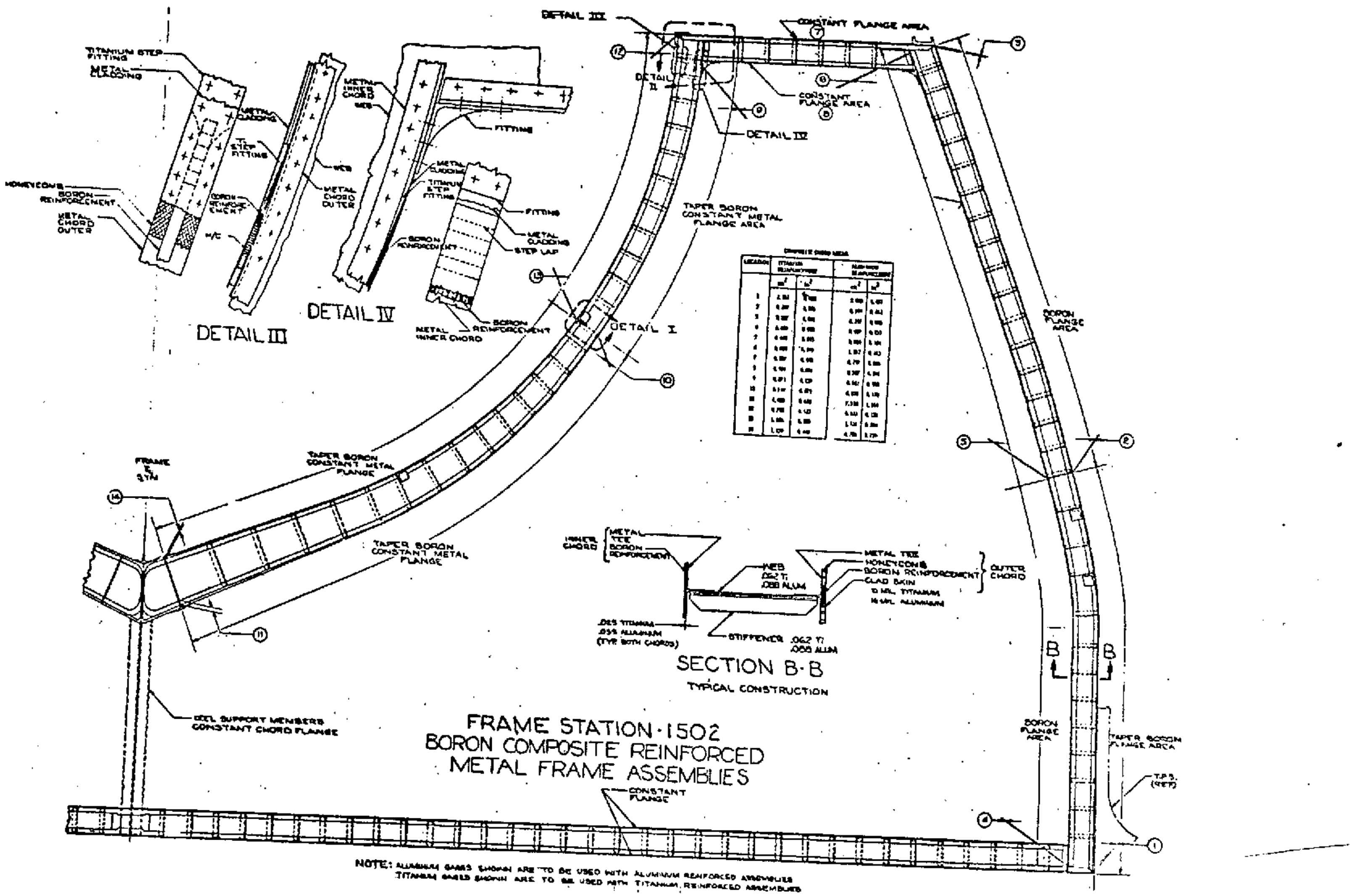


Figure 3.0-13: FRAME STATION - 1502

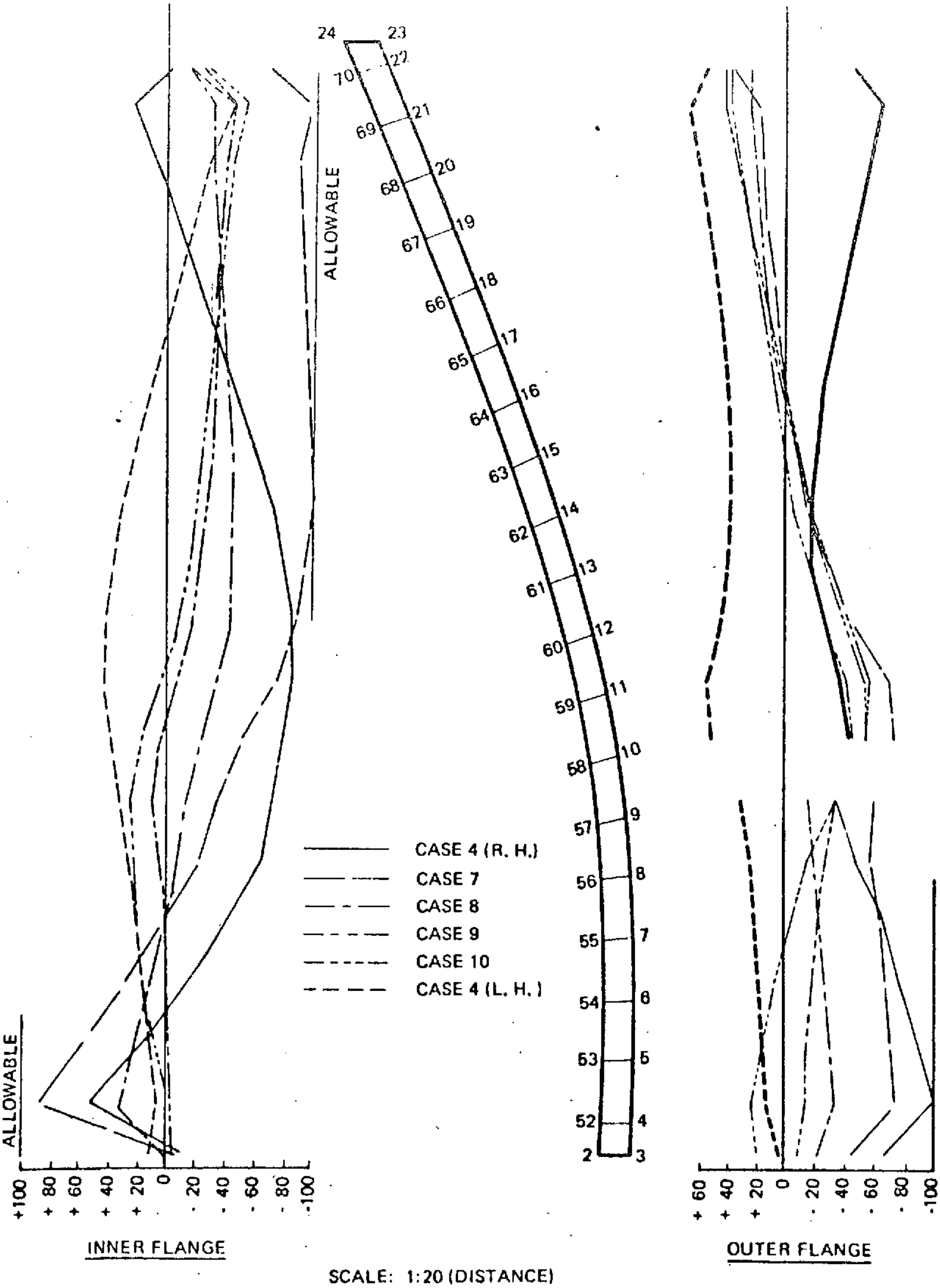


Figure 3.0-14: REINFORCED FRAME - FLANGE STRESS (KSI) DISTRIBUTION

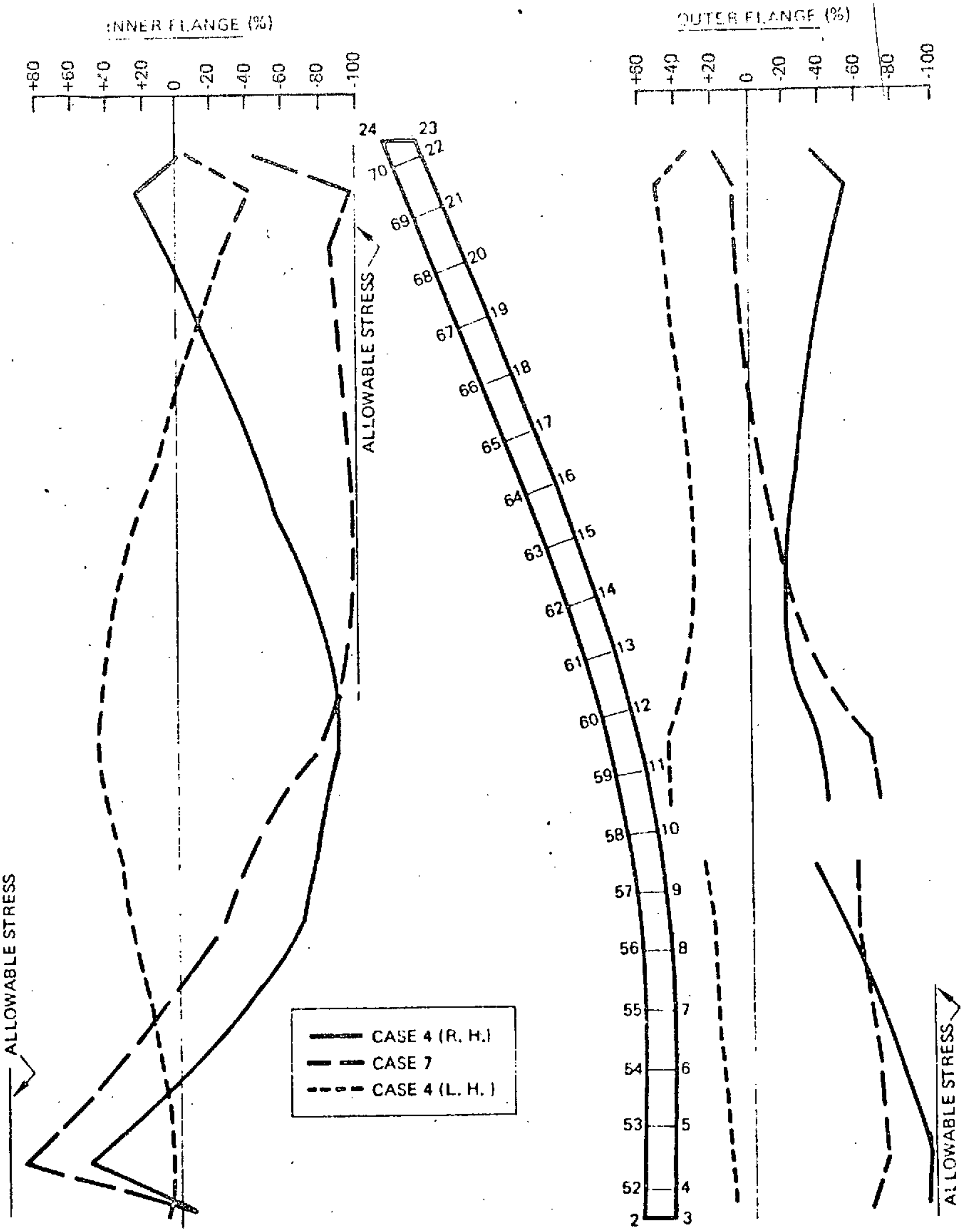


Figure 3.0-15: ALL TITANIUM FLANGE STRESS DISTRIBUTION

Table 3.0-1: FRAME MATERIAL SYSTEMS

DESIGN	MATERIALS	MAX. DESIGN TEMP.	
		°K	°F
1	ALL-METAL 6AL-4V TITANIUM	533	500
2	6AL-4V TITANIUM RIGIDITE 5505/4 METLBOND 329 ALUMINA BLAST + SILANE RINSE	464	375
3	6AL-4V TITANIUM 4 MIL BORON/SKYBOND 703 FM-34 POLYIMIDE ADHESIVE PASA GEL	533	500
4	ALL-METAL 7075-T6 ALUMINUM	394	250
5	7075-T6 ALUMINUM RIGIDITE 5505/4 METLBOND 329 ALUMINA BLAST + SILANE RINSE	394	250

Table 3.0-2: ***CRITICAL LOAD CONDITIONS FOR ORBITER FRAME 1502***

		MAXIMUM DESIGN TEMPERATURE					
		ALUMINUM & B/E-ALUM		TITANIUM & B/E-TITANIUM		TITANIUM & B/PI-TITANIUM	
CASE	LOAD DESCRIPTION	°K	°F	°K	°F	°K	°F
4	MAXIMUM aβ (+β) (SIDE WIND)	R.T.	R.T.	R.T.	R.T.	R.T.	R.T.
7	ORBITER ENGINE IGNITION	R.T.	R.T.	R.T.	R.T.	R.T.	R.T.
8	2.5 g PULLOUT	394°	250°	464°	375°	533°	500°
9	2 POINT TAIL DOWN, SPIN UP LANDING	394°	250°	464°	375°	533°	500°
10	2 POINT TAIL DOWN, SPRING BACK LANDING	394°	250°	464°	375°	533°	500°

Table 3.0-3: TYPICAL SPACE SHUTTLE FRAME PROBLEM DATA

	BORON/EPOXY REINFORCED TI FRAME	ALL-TITANIUM FRAME
NUMBER OF FINITE ELEMENTS	477	307
NUMBER OF NODE POINTS	206	196
NUMBER OF OPTIMIZED VARIABLES	46	26
NUMBER OF DEGREES OF FREEDOM	368	368
STIFFNESS MATRIX HALF BANDWIDTH	28	28
NUMBER OF DESIGN CYCLES	55	70

Table 3.0-4: SPACE SHUTTLE FRAME COMPUTER RUNS

RUN NO.	RUN TYPE*	FRAME CONSTRUCTION	TEMPERATURE				CASES
			OPERATING		REFERENCE (FABRICATION)		
			°K	°F	°K	°F	
1	OPT	ALL TITANIUM	294	70	294	70	4.7
2	SC	ALL TITANIUM	464	375	294	70	8, 9, 10
3	OPT	TITANIUM/BORON/EPOXY	294	70	450	350	4, 7
4	SC	TITANIUM/BORON/EPOXY	464	375	450	350	8, 9, 10
5	SC	ALL TITANIUM	589	600	294	70	8, 9, 10
6	SC	TITANIUM/BORON/P1	589	600	450	350	8, 9, 10
7	OPT	ALL ALUMINUM	294	70	294	70	4, 7
8	SC	ALL ALUMINUM (RUN NO. 7)	394	250	294	70	8, 9, 10
9	OPT	ALUMINUM/BORON/EPOXY	294	70	450	350	4, 7
10	OPT	ALUMINUM/BORON/EPOXY	294	70	394	250	4. 7
11	SC	ALUMINUM/BORON (RUN NO. 9)	394	250	450	350	8, 9, 10
12	SC	ALUMINUM/BORON (RUN NO. 10)	394	250	394	250	8, 9, 10
13	SC	ALUMINUM/BORON (RUN NO. 10)	347	165	394	250	8, 9, 10
14	SC	ALL ALUMINUM (RUN NO. 7 WITH WEB THICKNESS .224 (.088))	294	70	294	70	4, 7

*SC = STRESS CHECK OPT = OPTIMIZATION

Table 3.0-5: FRAME WEIGHT & DEFLECTION SUMMARY

FRAME CONSTRUCTION	WEIGHT		WEIGHT SAVINGS (%)	MAXIMUM DEFLECTION [1]	
	kg	lbs		cm	in
ALL TITANIUM (REF. 1)	52.6	116		29.03	11.43
B/E TITANIUM (REF. 1)	39.5	87	25.4	25.04	9.86
ALL ALUMINUM	61.7	136		22.68	8.93
B/E ALUMINUM	46.3	102	25.0	18.97	7.47

[1] AT NODES 33 & 133 DURING ORBITER IGNITION SEE FIG. 3.0-5

Table 3.0-6: COST SUMMARY/FRAME

FRAME CONSTRUCTION	MANUFACTURING COST ($)	MATERIAL COST ($)	TOOLING COST ($)	TOTAL COST	
				1ST VEHICLE	5TH VEHICLE
ALL TITANIUM	8,000	1,160	5,900	15,060	10,340
B/E TITANIUM	9,280	4,560	9,450	23,290	15,730
ALL ALUMINUM	4,800	102	5,900	10,802	6,082
B/E ALUMINUM	6,080	5,934	6,240	18,254	13,262

4.0 ELEMENT INVESTIGATIONS

Several structural elements were fabricated and tested to verify the allowables and evaluate the critical details used in the full-scale designs. These included composite - metal transition specimens tested in tension, chord crippling and column specimens and curved beams. The composite-metal transition tests demonstrated that the tension allowable (6000 micro strain) used with the boron/epoxy systems was realistic. Similar tests performed with the boron/polyimide composites failed low, which indicated local padding would be required in the transition areas to lower the strain levels. Chord crippling and column elements representative of the concepts used in the full-scale design were tested in compression. These results showed that allowables used in design could be attained with a high degree of confidence. The above tests were performed at both room temperature and at maximum service temperatures. Also, cyclic load tests were performed to insure that the life requirements of the orbiter could be met.

In addition to the basic tension and compression tests, curve beam elements were evaluated. These beams were representative of the construction use in the frame designs. They were 1.22 meters (40 ft) long and incorporated the boron/epoxy - titanium material system. Beams were successfully tested to room temperature, elevated temperature and cyclic requirements.

<u>Boron/Epoxy - Titanium</u>

In the full-scale designs all composite reinforcements terminated with chem-milled stepped titanium fittings. This provided a controlled means of introducing load to the composites and permitted conventional mechanical attachments to be used thru all-metal sections for making connections between frame members. Tests were performed to evaluate the load transfer capability between the boron/epoxy and titanium. These results proved conclusively that the tension allowable used in design was not limited by the transfer of load in the composite-metal transition region.

The load trans[illegible] properties of the transition region were developed using a ten-ply tensile [illegible]men as shown in Figure 4.0-1. The specimens were assembled from [illegible] five-ply laminates that were bonded to stepped titanium fittings. They were tested in a conventional test machine using hydraulic grips as shown in Figure 4.0-2. A tube furnace was installed around the specimen to develop elevated temperature data.

The initial specimens tested were used to evaluate four processes for preparing titanium for bonding. Included in this group were phosphate fluoride and Pasa Gel treatments widely used for polyimide bonding and an alumina blast with either a methyl ethyl ketone (MEK) wipe or a silane rinse (Union Carbide A-1100). The specimens that included step fittings prepared by chemical cleaning followed by Pasa Jel or phosphate fluoride conversion coatings failed at lower fiber stress levels than those specimens that were abrasively cleaned. The chemically prepared specimens also exhibited a larger scatter than those prepared by alumina blasting. In the later group those processed with a silane rinse developed higher tensile properties. The alumina blast with a silane rinse was therefore selected as the process that would be used in the balance of the program. A summary of the test data developed in this evaluation is shown in Table 4.0-1. Figure 4.0-3 shows a close-up of typical failed areas.

A series of specimens were made that incorporated a ply of Metlbond 329 adhesive on the steps of the end fittings as shown in Figure 4.0-4. These specimens were tested statically at both room and elevated temperature, and were also load and thermally cycled. Test results showed that specimens enriched with adhesive on the steps were superior to those made without the additional adhesive. A comparison of the static and thermally cycled specimens is shown in Figure 4.0-5. A summary of the cyclic test results is shown in Table 4.0-2.

The results of the testing performed in this portion of the program showed that a titanium-boron/epoxy load transition design was developed that met all of the required structural design requirements. This design included chem-milled stepped titanium fittings that were prepared for bonding by an alumina blast plus a silane rinse and incorporated a ply of Metlbond 329 on the steps. Transition specimens that included this design exceeded the tensile allowable by 22% and survived 400 load cycles at 2/3 design ultimate (2/3 of 2482 MN/m^2 (360 ksi) with negligible effects. The properties exhibited at the maximum design temperature of $464^{\circ}K$ ($375^{\circ}F$) were exceptional. Load and thermal cycling effects were minimal.

Elements representative of the chord areas in the full-scale boron/epoxy-titanium frame design were fabricated and tested. The three concepts shown in Table 4.0-3 were evaluated. The "A" concept was representative of an outside chord and incorporated stabilized extensions to provide for the attachment of TPS or fuselage skin panels. The "B" and "C" concepts were representative of two variations to improve the inside chord with torsional stability. The specimens incorporated a web plate to provide the same degree of stability to the outstanding leg of the chord "Tee" as provided by the web in the full-scale design. This plate was slightly shorter in length than the chord section to prevent it from directly picking up load by bearing on the loading heads during test. Specimens 19.0 cm (7.5 in) long were tested to obtain chord crippling data and some 74.9 cm (29.5 in) long were tested to develop column data. The metal area at the ends of the specimens was thickened to reduce the end strains and prevent composite brooming.

Typical chord element crippling specimens that were fabricated are shown in Figure 4.0-6. As shown in Table 4.0-3, two of each type were tested at room temperature. All of these specimens failed at loads above the design crippling load which was based on a crippling strain allowable of 6000 (6000 micro inches per inch).

Several additional Type "A" specimens were fabricated and tested under elevated temperatures and cyclic conditions. A summary of these results is shown in Table 4.0-4. The two specimens tested statically at $464^{\circ}K$ ($375^{\circ}F$) failed at loads above the 157 kN (35.3 kip) allowable load. Two specimens were load cycled 400 times to 2/3 design ultimate at $464^{\circ}K$ ($375^{\circ}F$) and were then loaded to failure.

These specimens failed at higher loads than the specimens that were not load cycled which indicated that the chord concepts could meet the safe life requirements without deteriorating their structural capability. Another set was thermal cycled between 219°K (-65°F) and 464°K (375°F) four hundred times. These specimens also were tested to failure and tested higher than those that were tested statically at temperature. These results also indicated that the frame safe life thermal cycle requirements could be met without deteriorating structural capability.

Two chord element column specimens were fabricated and tested. These speciments incorporated the outer chord configuration and were 74.9 cm (29.5 in) in overall length. Figure 4.0-7 shows the completed column specimens. The column specimens were tested and failed an average of 4% above their critical allowable load as summarized in Table 4.0-5.

Boron/Epoxy - Aluminum

The reinforced aluminum design used the same reinforcement strap concept as described previously for use in the reinforced titanium design. Since this data was already available it was not necessary to perform tensile tests to evaluate the capabilities of the composite - metal transition in this portion of the program.

Both column and crippling specimens incorporating boron/epoxy (5505/4) - 7075-T6 material system were fabricated and tested. Two sets of specimens were tested. One set was assembled with AF 126 adhesive at a 394°K (250°F) maximem cure temperature and one with Metlbond 329 adhesive at a 450°K (350°F) maximum cure temperature. The elements assembled at the lower cure temperature had lower residual stresses, but their maximum operational temperature was restricted to 347°K (165°F). Those bonded with Metlbond 329 at 450°K (350°F) had a use temperature of 394°K (250°F).

Three chord configurations were incorporated in the element specimens as shown in Table 4.0-6. The "A" configuration incorporated reinforcement in the center of the Tee and included honeycomb stabilized extensions to provide an attachment capability to the adjacent shell structure. A second concept incorporated a uniform reinforcement along the full width of the flange. A third configuration was similar to the previous one, except it incorporated a honeycomb spacer between the aluminum Tee and the reinforcement to improve the section torsional stability. The elements were assembled using a sequence which locked-in residual stresses of the same magnitude as expected in frame components. This consisted of machining the Tees and riveting the web plates to them prior to bonding. During bonding the ratio of composite/metal being assembled was approximately the same as expected in full frame components. As a result, the same magnitude of residual stresses were locked in during cool-down.

All of the chord element specimens tested developed strains at failure that exceeded their design requirements, except for the one of the "C" configuration specimens tested at temperature. A summary of these test results is shown in Tables 4.0-6 and -7. Typical failed crippling specimens are shown in Figure 4.0-8.

Several crippling specimens incorporating the "A" configuration cross-section were load and thermally cycled. Specimens were loaded to limit load 400 times and then to failure. Specimens were thermal cycled between 219°K (-65°F) and 347°K (165°F) or 394°K (250°F) 400 times and then loaded to failure. All of the specimens failed at loads above their design ultimate. A summary of the cyclic tests is shown in Table 4.0-8.

Two column specimens assembled at 394°K (250°F) and two assembled at 450°K (350°F) were tested. They all developed strains at failure of approximately 5000μ which exceeded their design requirements. A summary of these tests is shown in Table 4.0-9. The column specimens developed a bow of (0.12) inches because of thermal stresses established during bonding. Figure 4.0-9 shows two of these specimens back-to-back to illustrate the degree of distortion.

Boron/Polyimide - Titanium

Boron/polyimide composites were investigated to evaluate their potential as an elevated temperature (533°F plus) reinforcement material. Three available polyimide resins, Skybond 700, 703 and 710, were investigated along with variations in processing for each. The Skybond 703 was selected as the polyimide matrix to be used in following component evaluations.

Several structural elements were fabricated and tested to evaluate the critical details associated with the elevated temperature reinforcement concepts. These included tension strap tests to evaluate the load transfer capabilities between boron/polyimide laminates and titanium end fittings and crippling and column specimens to evaluate the compression load carrying capability of boron/polyimide reinforced titanium chord sections.

To evaluate the load transfer capability of the boron/polyimide - titanium transition several specimens as shown in Figure 4.0-1 were fabricated and tested. The end fittings were fabricated by chem-milling steps to the desired depth and then treating these surfaces with a pasa gel solution. The steps were then covered with a layer of FM-34 adhesive. Plies of "B" staged boron/Skybond 703 prepreg were then layed in-place. These 5-ply subassemblies were then bagged and cured (Reference 3). Two five-ply laminates were then bonded together with FM-34 and then post-cured to provide the finished specimen.

The transition specimens were tested in a standard test machine using hydraulic grips as shown previously in Figure 4.0-2. The first specimen was tested statically at room temperature and developed 4680 strain at failure. This was 22% below 6000 strain which was used as a tension allowable. This low value was not considered to be critical in a metal reinforced design, since it represented a local area that could be easily reinforced. In 8-foot curved beam tests discussed in a later section, failures were prevented from occurring in the transition section by using local reinforcement. A second specimen was cycled to limit load (4000)

400 times and then loaded to failure at room temperature. This specimen failed slightly above the one that was not cycled. Two specimens were then loaded to failure at 589°K (600°F). These specimens failed at an average strain of 2180 which was 27% below the elevated temperature requirement. Similar results were obtained in compression tests at both 561°K (550°F) and 589°K (600°F). Two additional specimens were therefore tested at 533°K (500°F), at which temperature successful results were obtained in compression. These specimens failed at an average strain of 2670 , which was 11% below the elevated temperature design allowable. A summary of the boron/polyimide transition tests is shown in Table 4.0-10.

Several chord crippling specimens incorporating the "A" configuration shown in Table 4.0-6 were tested as summarized in Table 4.0-11. As shown, both the static and load cycled specimens tested at room temperature developed strains at failure well above the crippling allowable of 6000 . The first specimen tested at elevated temperature, 589°K (600°F), failed 22% low. Additional specimens were therefore tested at lower temperatures, 561°K (550°F) and 533°K (500°F), in an attempt to establish the maximum temperature at which the boron/polyimide could satisfy design requirements. The specimen tested at 561°K (550°F) failed 8% low. Two specimens tested at 533°K (500°F) failed at an average strain of 3920 which was 31% above that required to meet design conditions.

Two column elements approximately 74.9 cm (in.) long were fabricated and tested. These specimens incorporated the same configuration as the crippling elements. They were tested at room temperature and failed at an average strain level of 5100 which was 7% above the column allowable used in the full scale frame designs.

Curved Beam Elements

Boron/epoxy (5505/4) reinforced titanium (6Al-4V Cond I) curved beam elements representative of the basic members used in the full scale frame design studies were evaluated. Four beam elements were fabricated and tested to evaluate fabrication capabilities and their ability to meet design requirements.

The curved beam design contained composite reinforced metal concepts and other typical critical details used in the full-scale frame design studies. It included typical frame member curvature, chord area tapering and end attachments. A detailed description of the curved beam element is shown in Figure 4.0-10.

The beam was designed with an approximate mean radius of curvature of 244 cm (96 inches). Its depth varied from 19.05 cm (7.5 inches) at the root to 12.7 cm (5.0 inches) at the tip. The chords incorporated titanium tees with flanges that were machined to a minimum gage of .063 cm (.025 inches) in their basic sections. This gage was increased to .254 cm (.10 inches) at the root ends of the tees to provide a higher factor of safety in the attachment area. The flanges were reinforced with unidirectional boron/epoxy laminates that matched the curvature of the tees and tapered in both thickness and width along their length. The inner chord reinforcement varied from 30 plies and 2.54 cm (1.0 inch) width at one end to 15 plies and 1.27 cm (.50 inches) width at the other. The outer chord reinforcement varied from 15 plies and 5.08 cm (2.0 inches) width at one end to a 5 plies and 3.81 cm (1.5 inches) width at the other. The inner chord incorporated flange extentions that were stabilized with high density honeycomb (.42 kg/m^3 (20 lb/ft^3)) to provide an attachment capability for installing shell structure.

The web of the beam was designed to be shear resistant at ultimate load. It consisted of a .178 cm (.07 inch) thick titanium plate stiffened with titanium angles of the same gage.

The curved beam was designed to be tested in the cantilevered configuration. The attachment at the support end was typical of the type of connection between frame members. All composites terminated with stepped titanium fittings in this area. Mechanical attachments were made through the resulting all metal sections to connect the beam to its support structure.

The metal details in the curved beam elements were fabricated using conventional titanium manufacturing techniques. These parts were then riveted together into an all metal assembly. Basic five-ply laminates incorporating titanium end fittings were fabricated. These laminates were stacked to the required ply thicknesses and assembled to the titanium substrate by bonding at elevated temperatures. Figure 4.0-11 shows the curved beam details prior to assembly. Figure 4.0-12 shows a completed beam.

The curved beam elements were tested to failure in a cantilevered configuration as shown in Figure 4.0-13. The beams were bolted to steel fittings through the all metal sections at their base. Load was applied at the opposite end with a hydraulic jack. Horizontal restraining bars were used to provide lateral support. In the first two tests, the lateral restraint was found to be inadequate because of tolerances and the tendency to peel the 10 mil cover-plates during cycling. In the last two beam tests, spacer blocks were used between the beam webs and the restraining bars. In the elevated temperature test, quartz lamps were used as a heat source.

The first two beams failed prematurely during cycling due to a flaw caused by poor drilling procedures and not providing the proper lateral support during test. These problems were corrected and the next two beams attained their design requirements. One beam was cycled to limit load 400 times. It was then loaded to failure at room temperature. It failed at a load of 33,805N (7,600 pounds) which was 8.5% above design ultimate. The last beam was first loaded to limit load at room temperature. It was then loaded to failure with its lower critical portion heated to $464^{\circ}K$ ($375^{\circ}F$). This beam failed at a load of 17,792 N

(4,000 lbs.) which was 14% above its elevated temperature design requirement. A summary of the curved beam element tests is shown in Table 4.0-12. A typical beam failure is shown in Figure 4.0-14.

The curved beam elements were representative of several full scale orbiter frames. The success achieved in building the curved beam elements demonstrated the ability to produce full scale orbiter frame designs using the composite reinforced metal concept.

The results obtained from the curved beam tests, after initial problem areas were corrected, demonstrated the ability of the composite reinforced metal frame concept to successfully meet structural requirements. A beam was cycled to limit load 400 times which met the safe life loading requirements of the orbiter vehicle. This beam as then loaded to failure at 8.5% above the design ultimate. One beam was heated at the base to 464°K (375°F) and then loaded to failure at 14% above its elevated temperature design requirement.

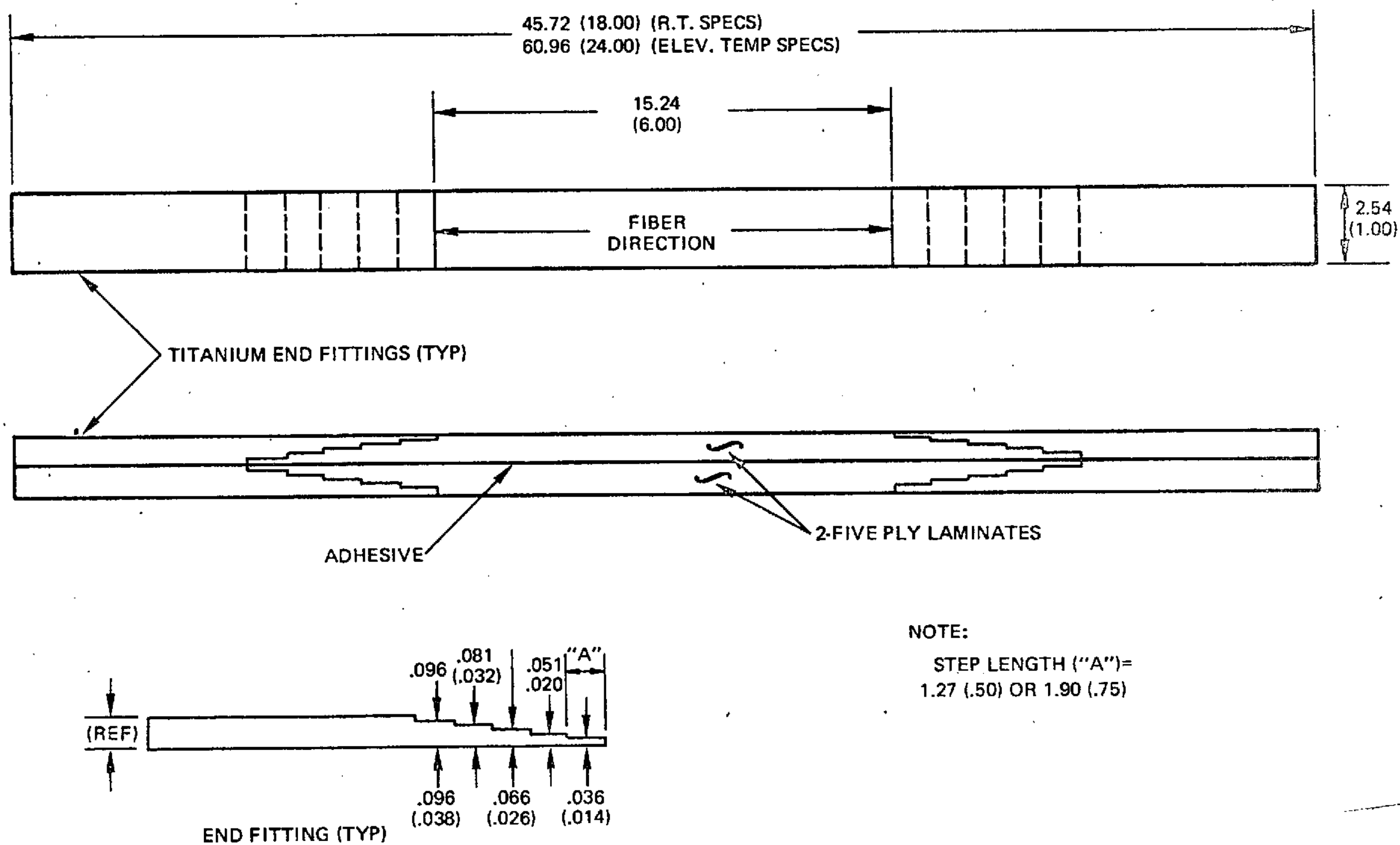


Figure 4.0-1: LOAD TRANSITION SPECIMEN

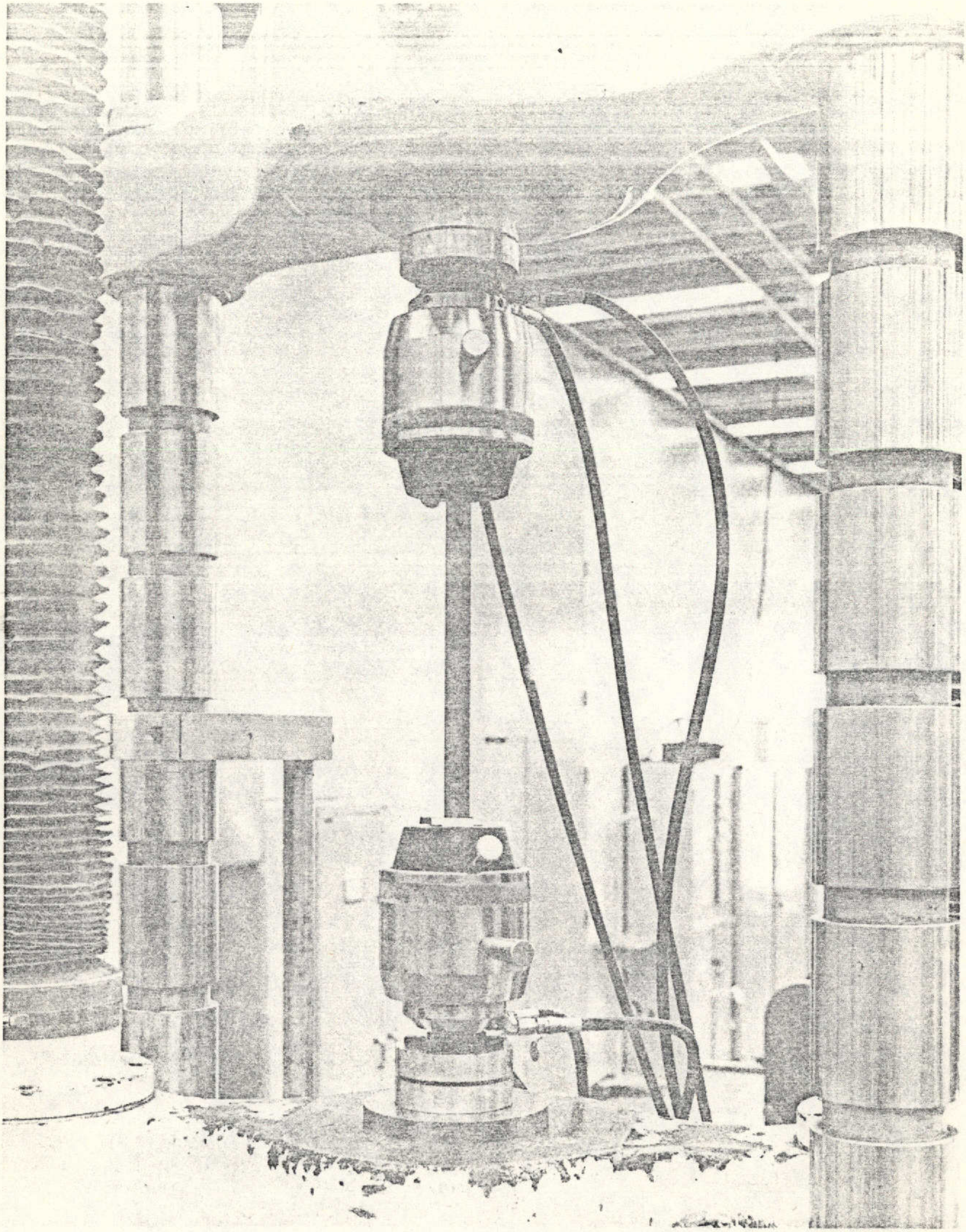


Figure 4.0-2: Room Temperature Load Transitions Specimen Test

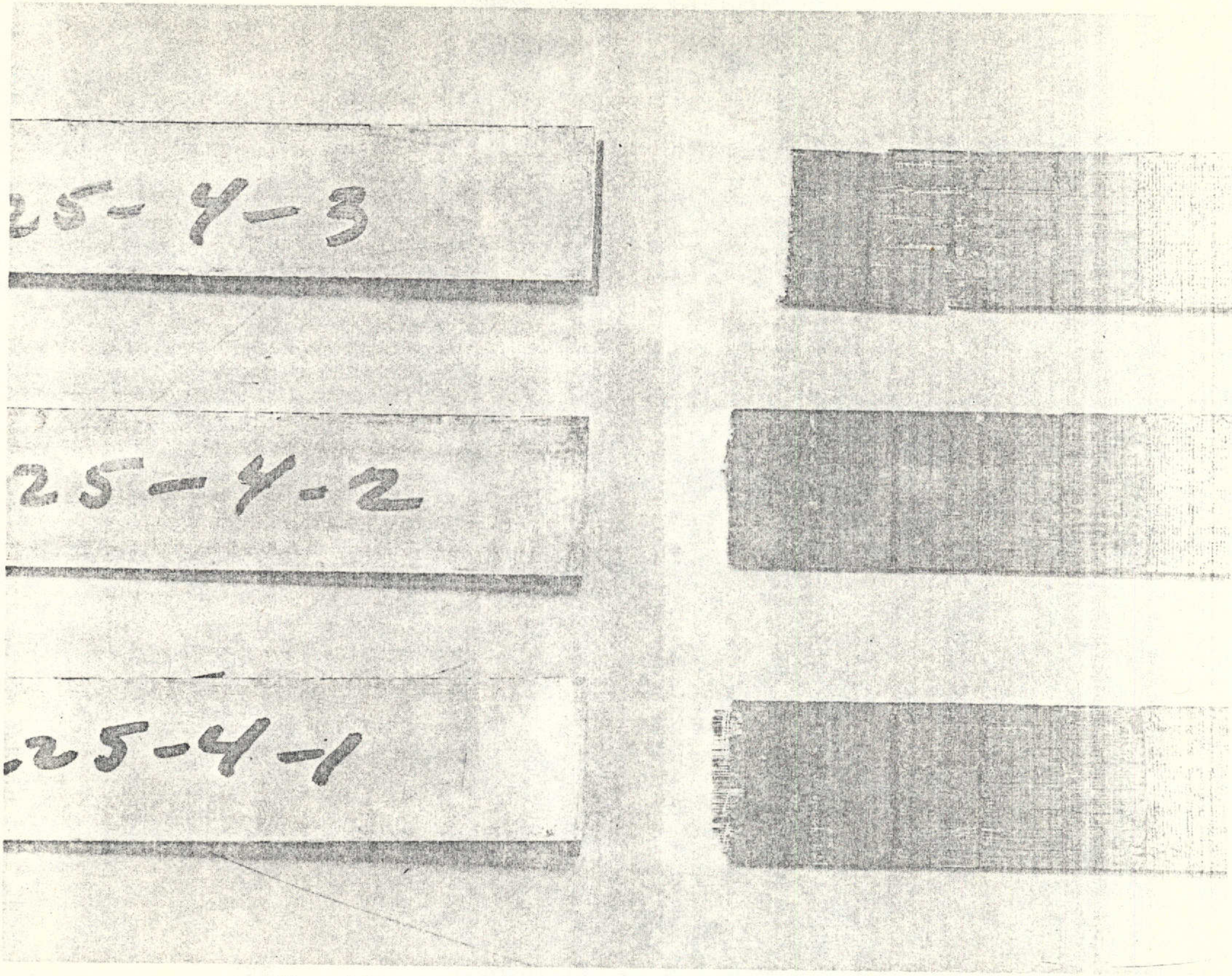


Figure 4.0-3: Load Transfer Speciments—Typical Failed Joint Areas

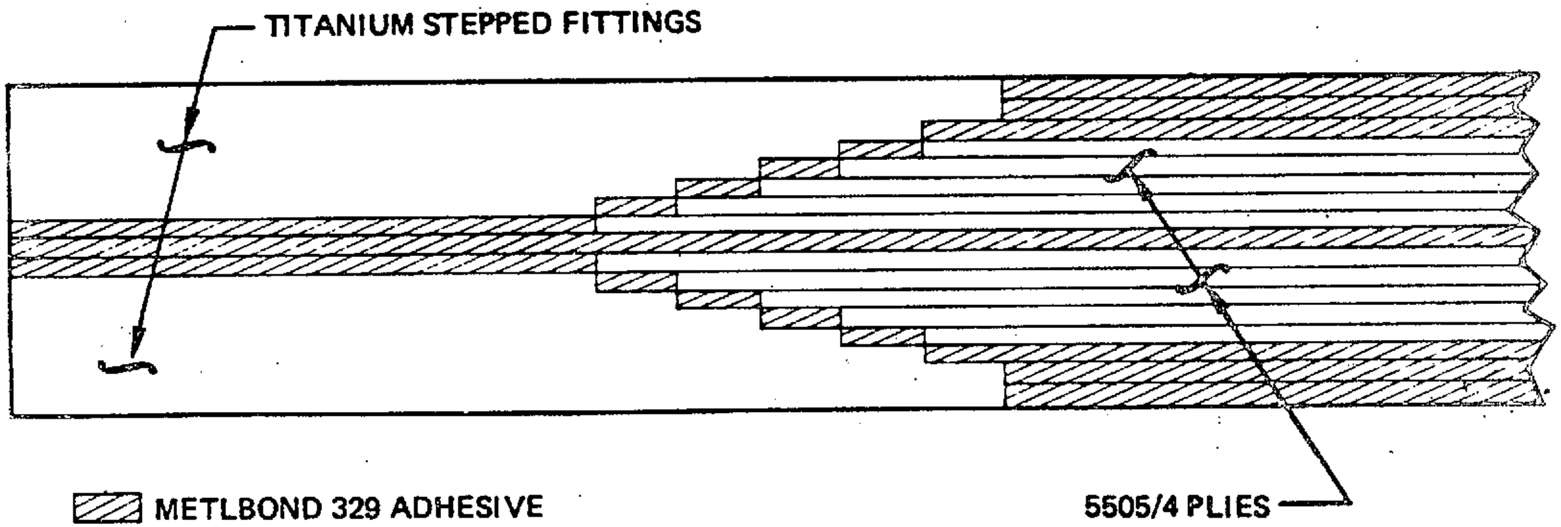


Figure 4.0-4: METAL-COMPOSITE TRANSITION-METLBOND 329 ON STEPS

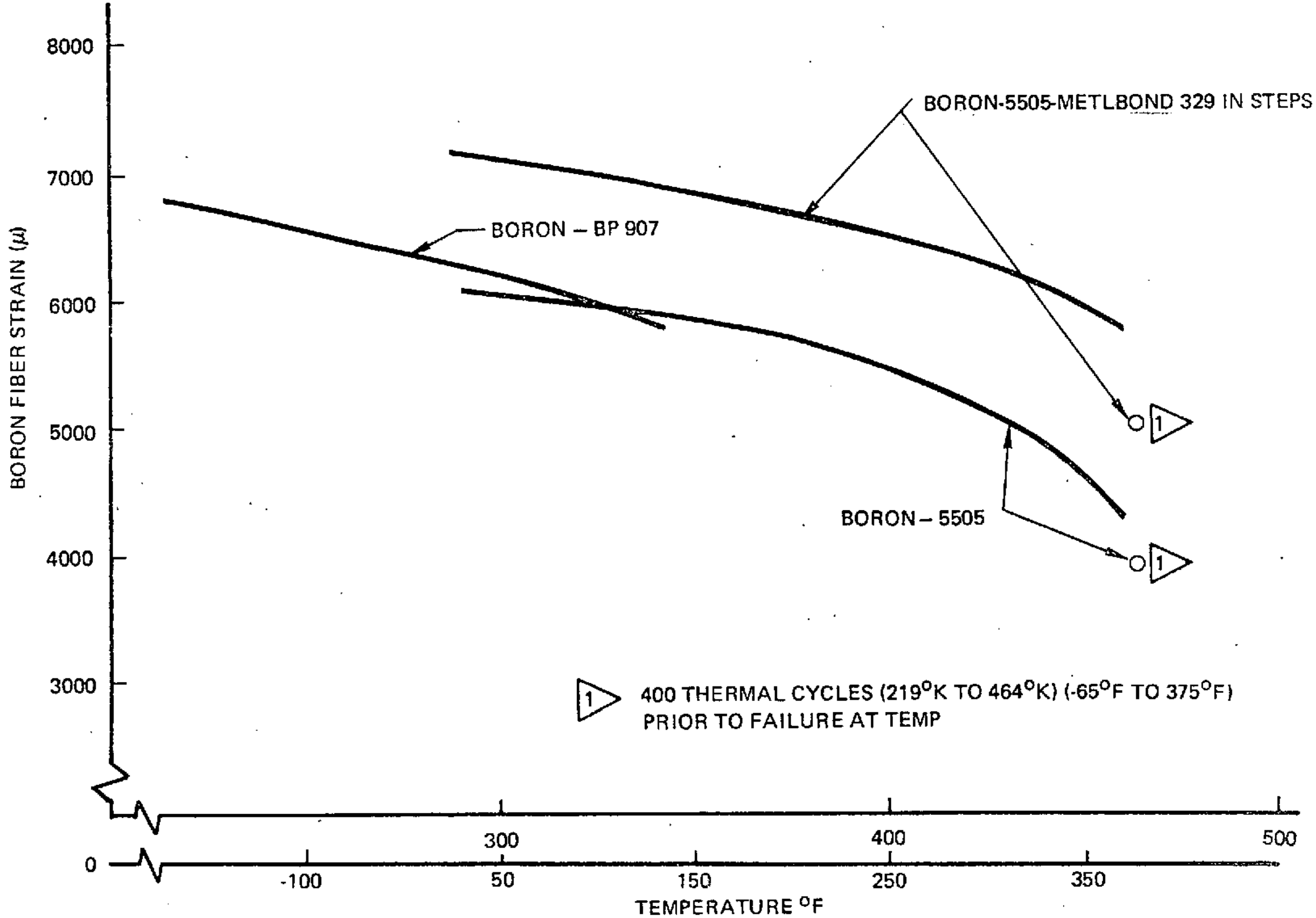


Figure 4.0-5: Composite-Metal Load Transition – Boron Fiber Strain at Failure

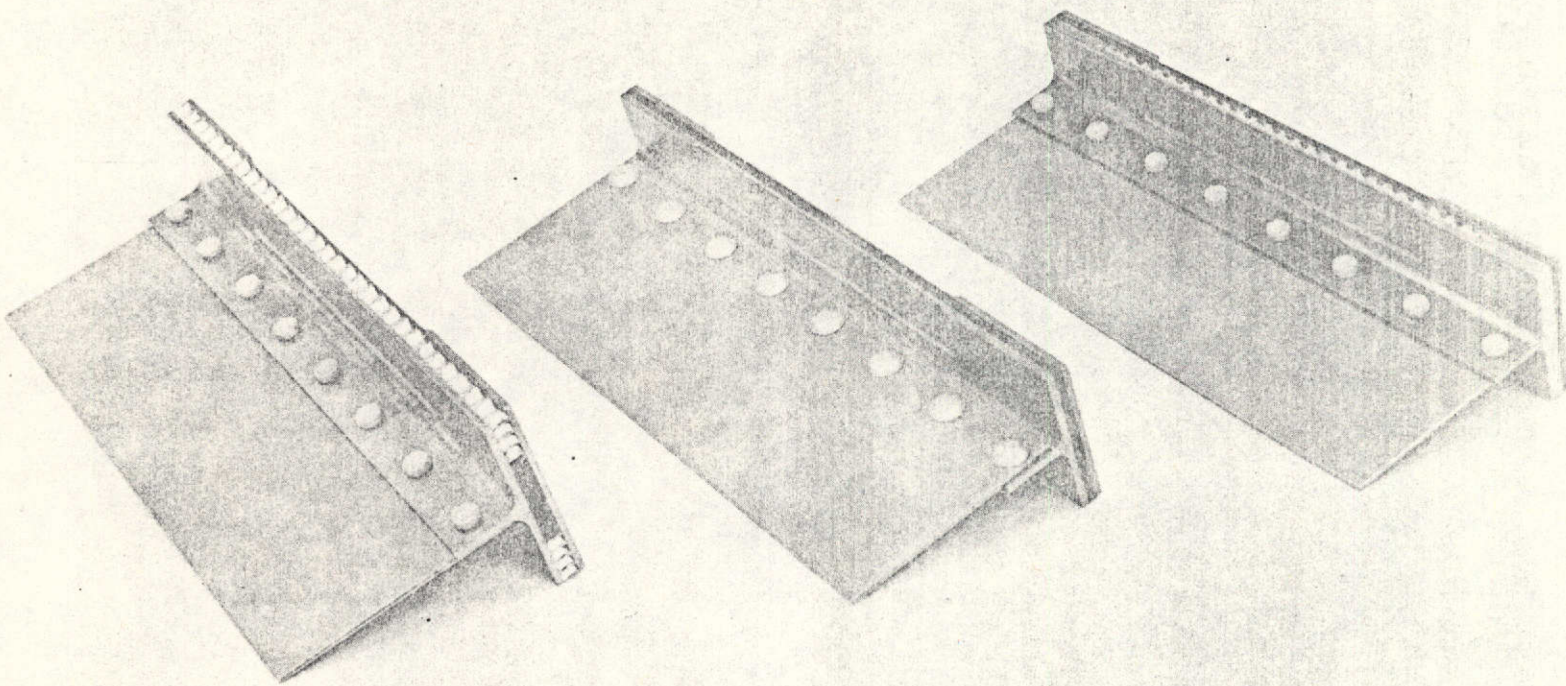


Figure 4.0-6: Chord Element Crippling Specimens

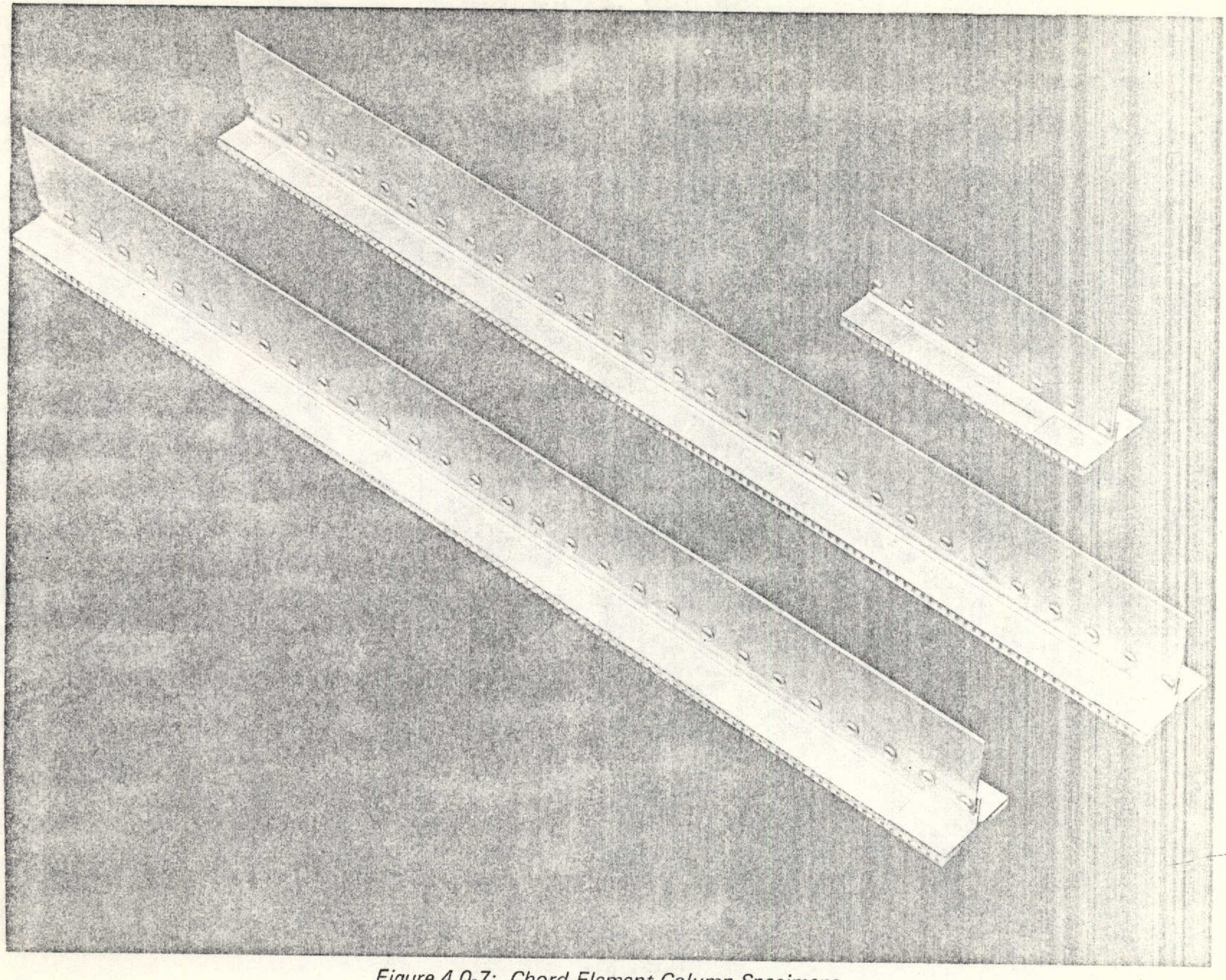


Figure 4.0-7: Chord Element Column Specimens

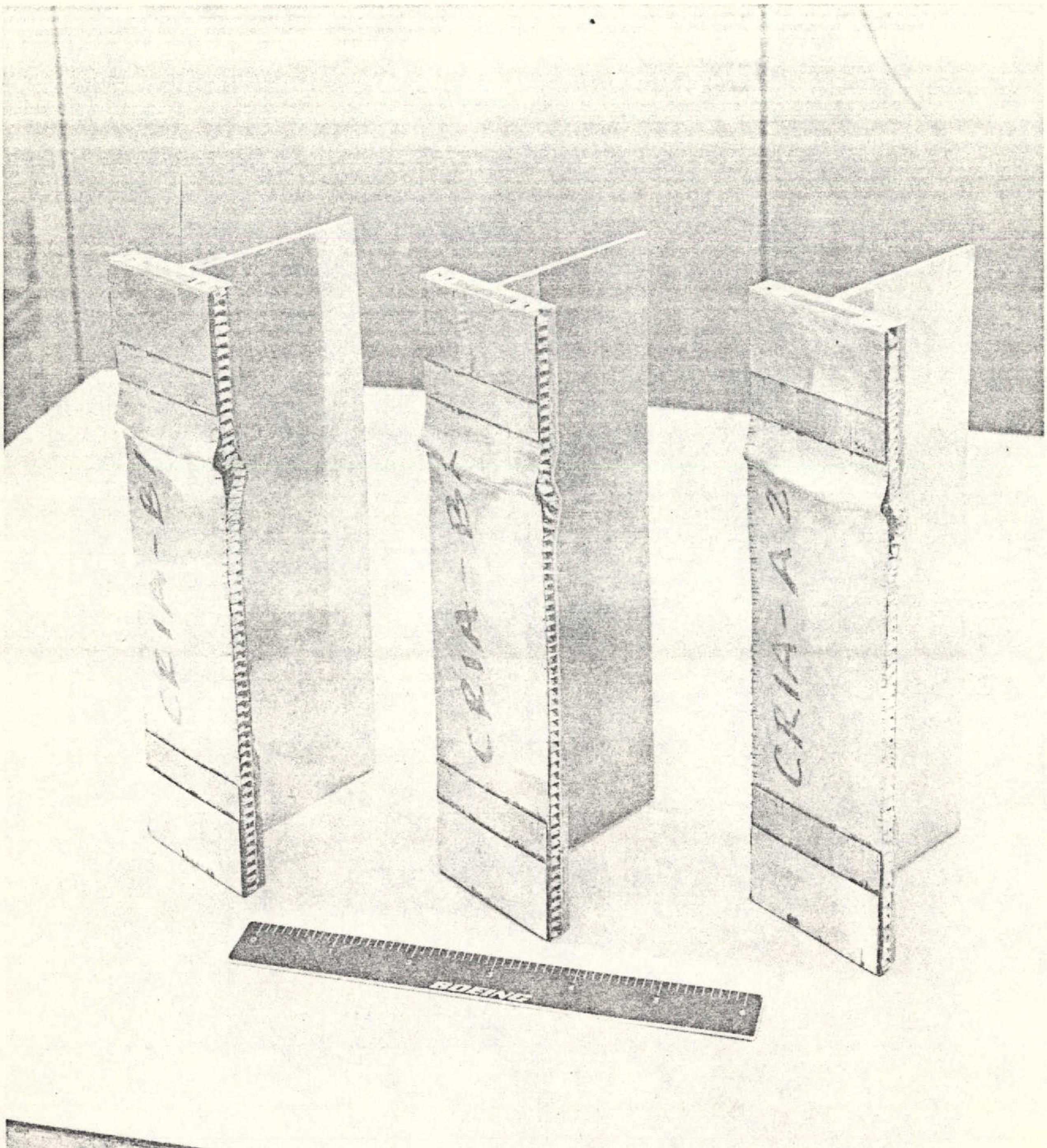


Figure 4.0-8: Failed Aluminum Chord Crippling Specimens – Boron/Epoxy

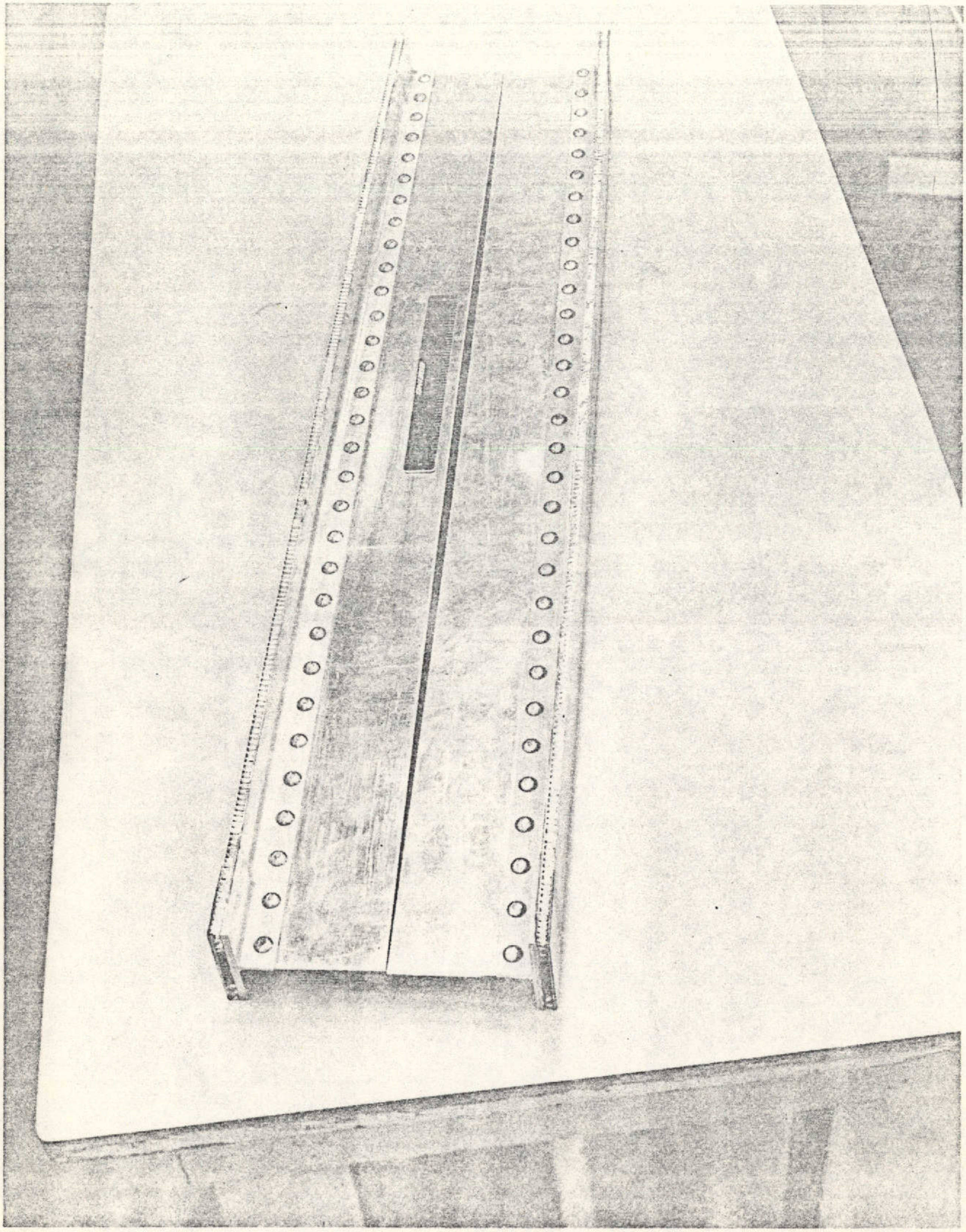


Figure 4.0-9: Column Elements Place Back-to-Back to Illustrate Degree of Thermal Distortion – Boron/Epoxy-Aluminum

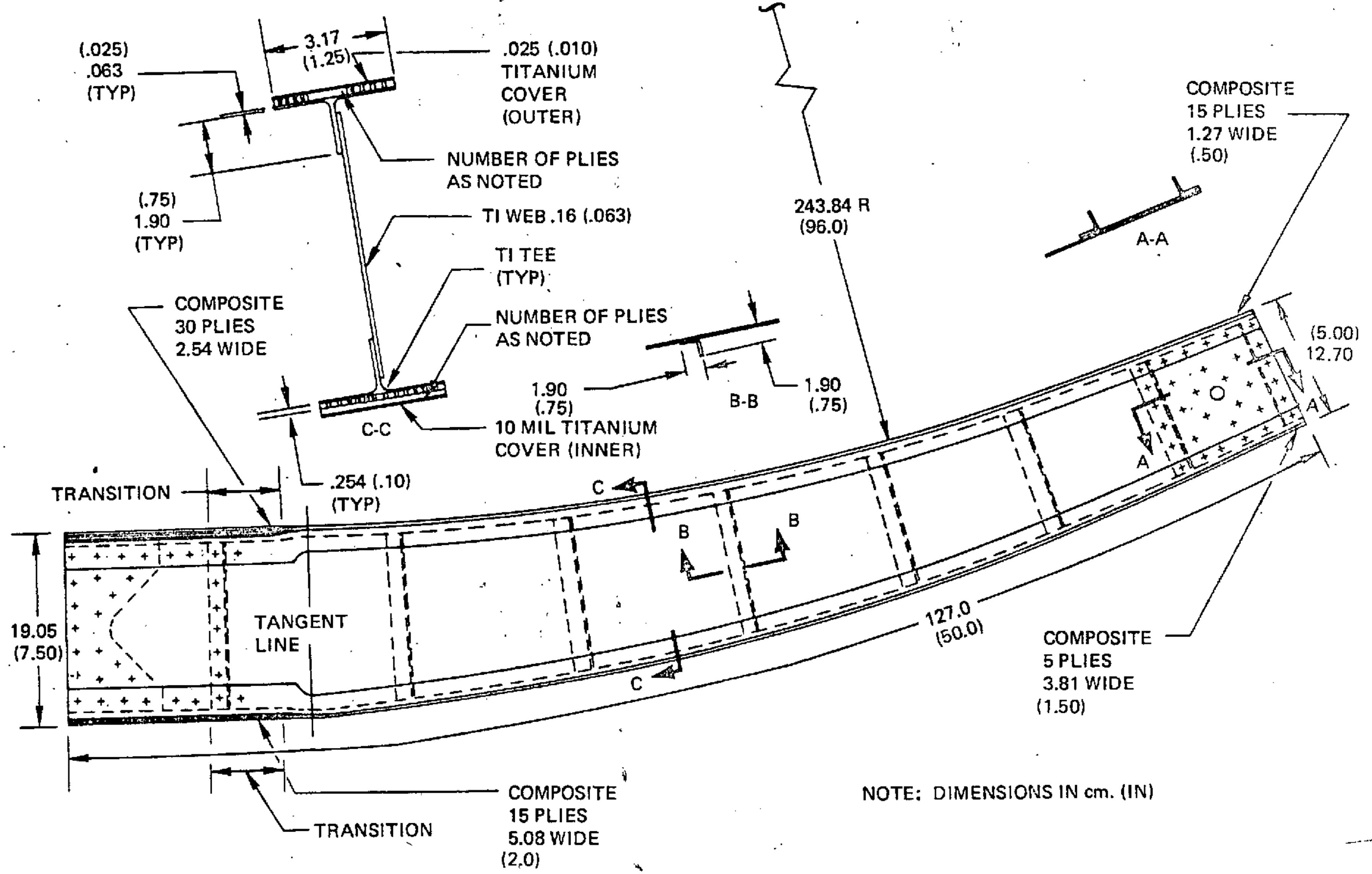


Figure 4.0-10: CURVED BEAM ELEMENT – BORON/EPOXY-TITANIUM

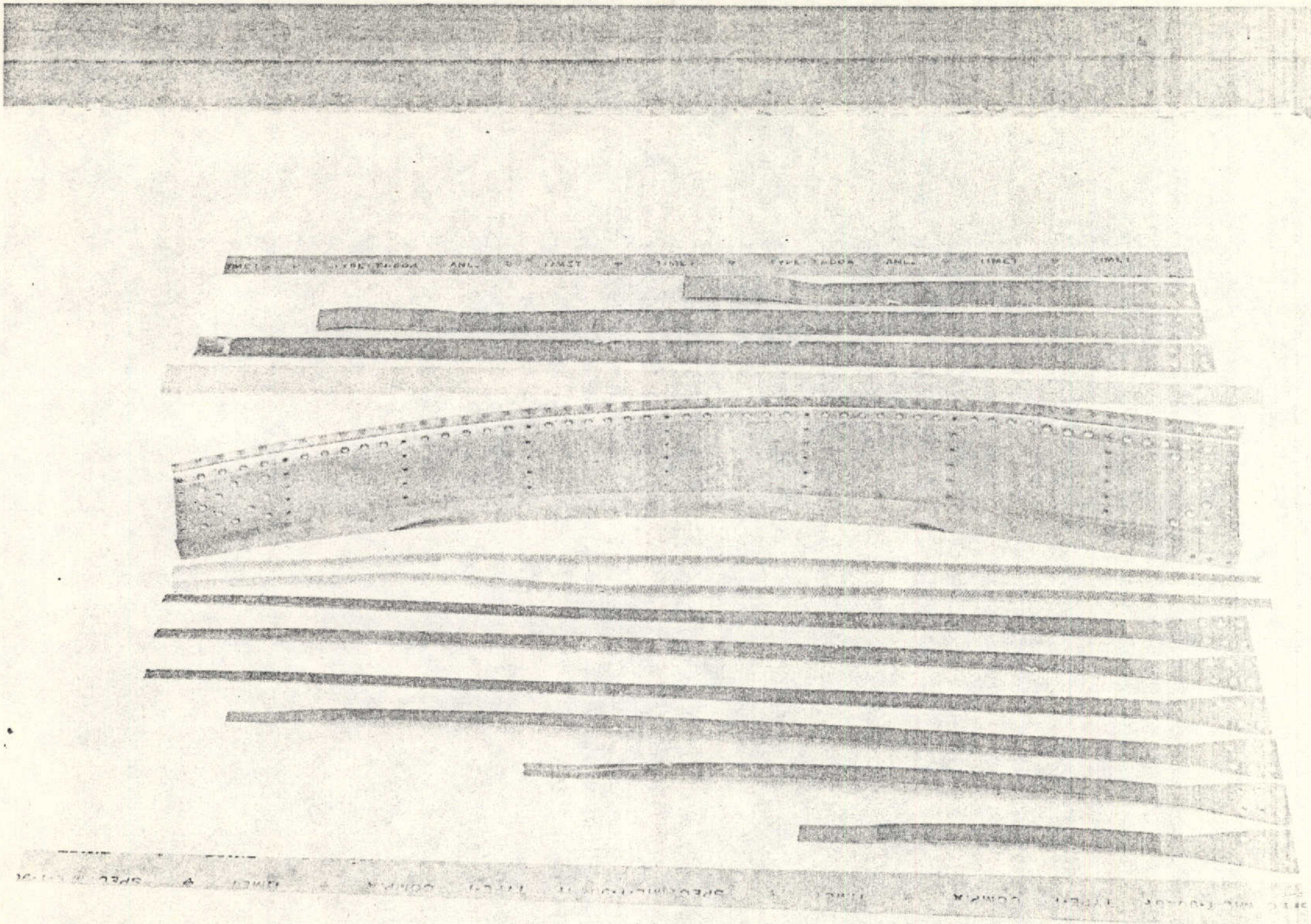


Figure 4.0-11: Curved Beam Details

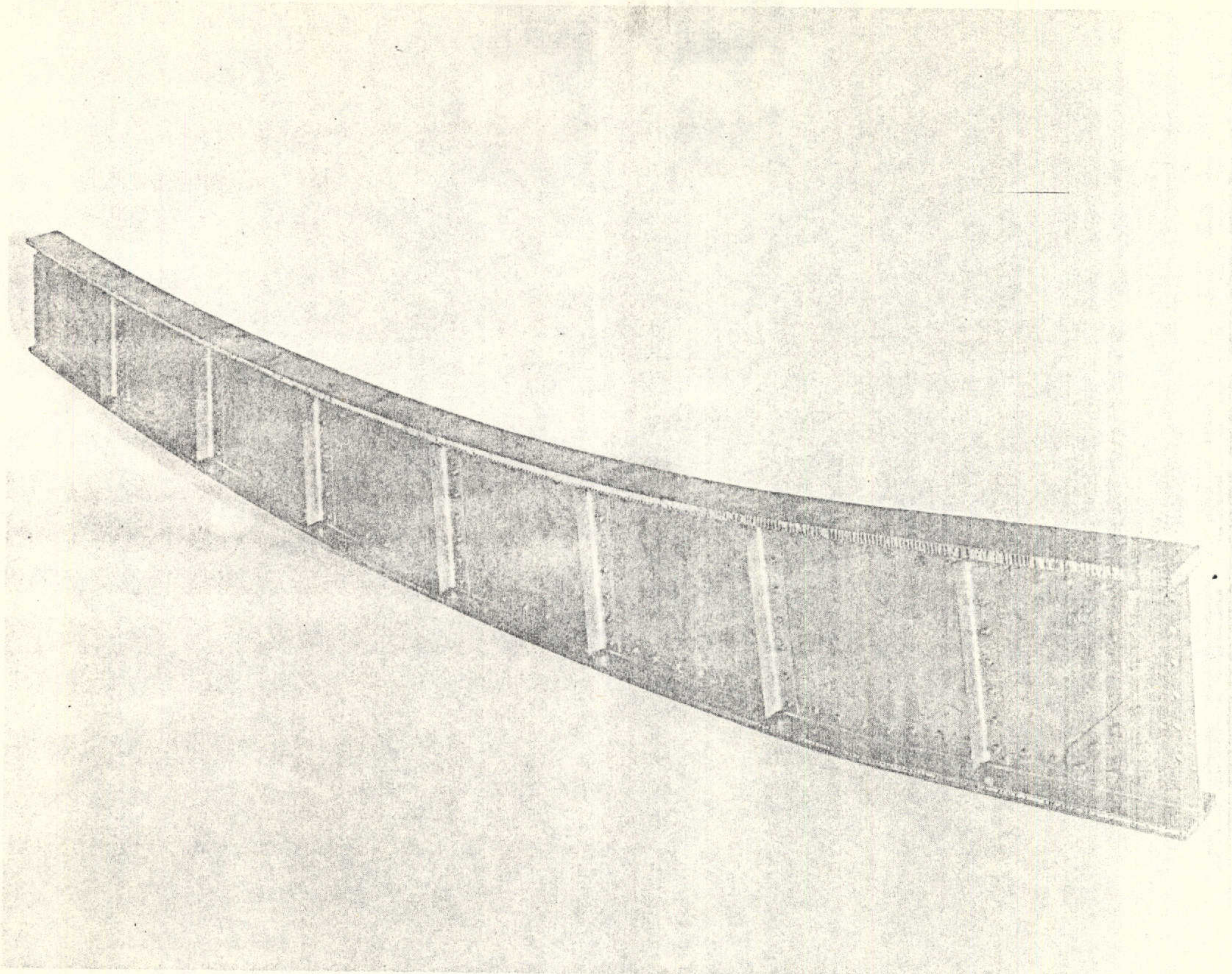


Figure 4.0-12: Curved Beam Element Assembly

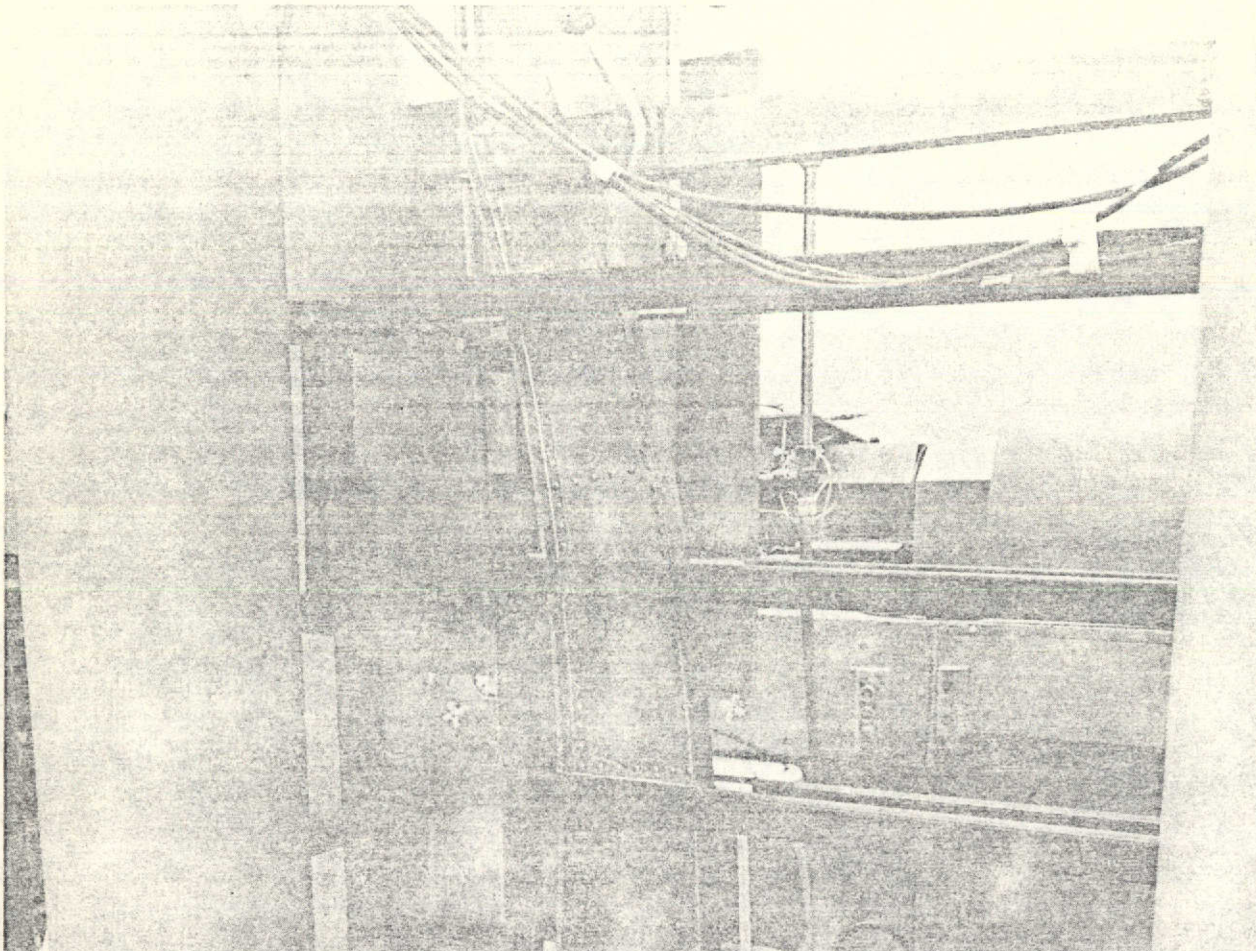


Figure 4.0-13: Test Set-Up Curved Beam

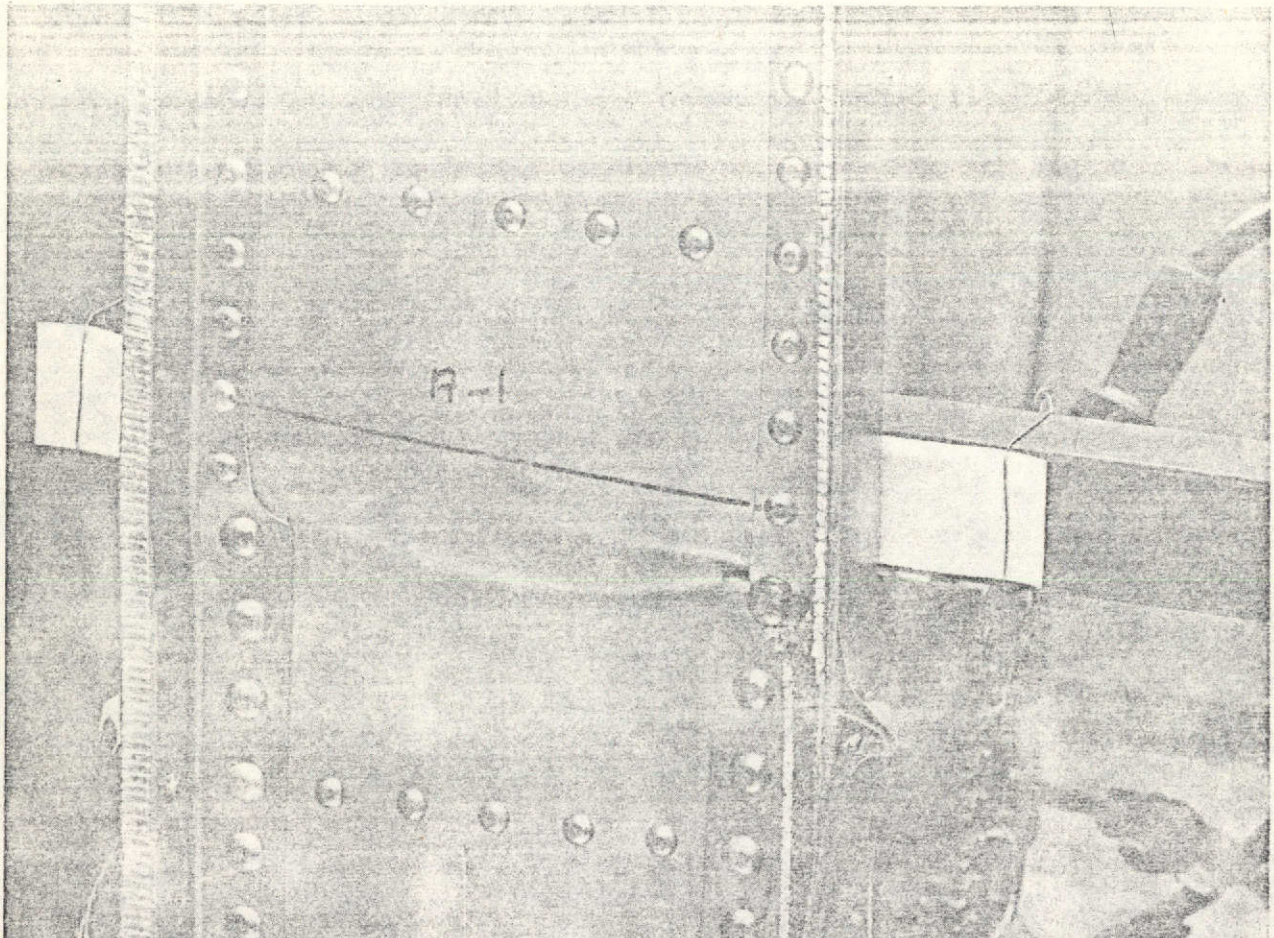


Figure 4.0-14: Failed Curved Beam No. 3

Table 4.0-1: TITANIUM SURFACE PREPARATION-LOAD TRANSFER TEST RESULTS

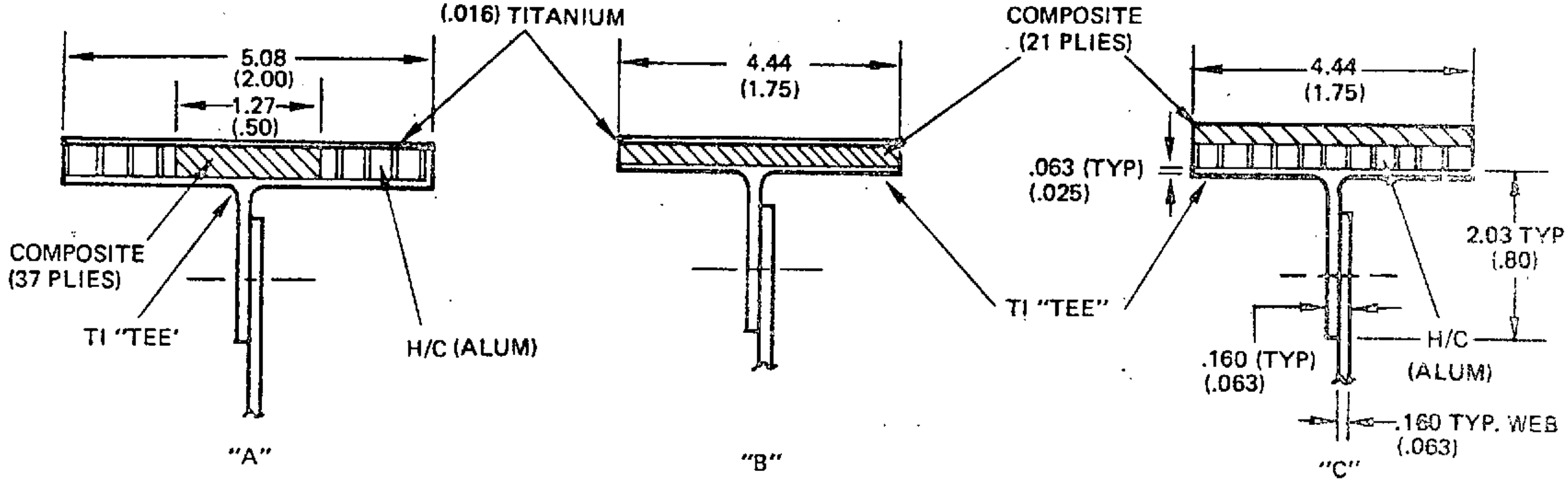
METAL PREPARATION	FAILURE STRAIN (μ)	GROUP AVERAGE (μ)
PHOSPHATE FLUORIDE	6150	5540
PHOSPHATE FLUORIDE	4930	
PHOSPHATE FLUORIDE	5530	
PASA JEL COATING	6430	5450
PASA JEL COATING	5000	
PASA JEL COATING	4930	
ALUMINA BLAST + M.E.K.	6000	5710
ALUMINA BLAST + M.E.K.	5770	
ALUMINA BLAST + M.E.K.	5350	
ALUMINA BLAST + SILANE	6500	6140
ALUMINA BLAST + SILANE	6000	
ALUMINA BLAST + SILANE	5930	

NOTE: LENGTH OF STEPS = 1.27 cm (0.5 IN.)

Table 4.0-2: Metal Composite Transition With Metlbond 329

SPEC.	R. T. LOAD CYCLES		400 THERMAL CYCLES @219 TO 464°K (-65 TO 375°F)	STATIC TEST TEMP °K (°F)	STATIC TEST BORON STRAIN AT FAILURE (μ)	AVE BORON STRAIN AT FAILURE (μ)
	% ULT (6000 μ)	NO.				
MB-1				R.T.	7230	7320
MB-2				R.T.	7400	
MB-3	67% ULT	400		R.T.	6880	7080
MB-4	67% ULT	400		R.T.	7270	
MB-5	67% ULT	400		464 (375)	5730	5920
MB-6	67% ULT	400		464 (375)	6100	
MB-7			400	464 (375)		5170
MB-8			400	464 (375)		

NOTE: LENGTH OF STEPS = 1.27 cm (.50 IN.)



NOTE: DIMENSIONS IN CM. (IN.)

Table 4.0-3: Boron/Epoxy-Titanium Chord Element Crippling

SPEC NO.	TYPE	ALLOWABLE CRIPPLING STRAIN (μ)	STRAIN AT FAILURE (μ)
1	A	6000	8370
2	"	6000	8000
3	B	6000	8130
4	"	6000	8300
5	C	6000	6880
6	"	6000	6950

ALL TESTING @ ROOM TEMPERATURE

Table 4.0-4: Chord Crippling Element — Elevated Temperature and Cyclic Tests

TEST SPEC. ③	DESIGN STRAIN (μ)	TEST TEMP. °K (°F)	TEST CYCLES	FAILURE STRAIN (μ)
1	6000	RT		8370
2	"	"		8000
3	4340 ①	464 (375)		4610
4	"	"		5350
5	"	"	400 @ LIMIT ②	6000
6	"	"	" "	6810
7	"	"	400 THERMAL (219 TO 464°K – 065 TO 375°F	6190
8	"	"	" " "	7210

① F_{CY} (Ti @ 464°K (375°F) = 73% F_{CY} (Ti @ RT)

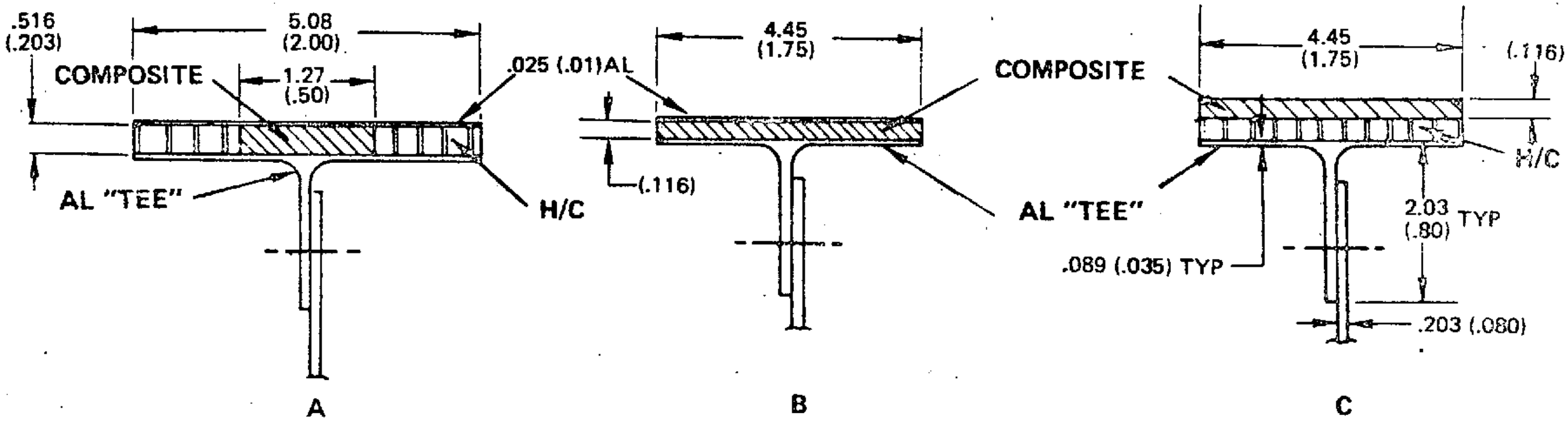
ϵ_{ULT} 464°K (375°F) = 73% ϵ_{ULT}(RT) = 4340μ

② ϵ_{LIMIT} = 2/3(4340) = 2890 @ 464°K (375°F)

③ TYPE "A"

Table 4.0-5: Column Tests Boron/Epoxy-Titanium

SPEC. NO.	COLUMN LENGTH cm (in)	TEST TEMPERATURE °K (°F)	TEST FAILURE STRAIN (μ)	ALLOWABLE STRAIN (μ)
1	74.9 (29.5)	296 (70)	4850	4767
2	74.9 (29.5)	296 (70)	5100	4767



NOTE: DIMENSIONS IN cm. (in.)

Table 4.0-6: Boron/Epoxy-Aluminum Chord Element Crippling

TYPE	FABRICATION TEMP °K (°F)	TEST TEMP	FAILURE STRAIN (μ)	ALLOWABLE STRAIN (μ)
A	394 (250)	R.T.	9453	5277
A	394 (250)	R.T.	8126	5277
A	450 (350)	R.T.	7490	5000
A	450 (350)	R.T.	9050	5000
B	394 (250)	R.T.	7313	5277
B	394 (250)	R.T.	7449	5277
B	450 (350)	R.T.	7137	5000
B	450 (350)	R.T.	7469	5000
C	450 (350)	R.T.	7015	5000
C	450 (350)	R.T.	7435	5000

Table 4.0-7: Boron/Epoxy-Aluminum Chord Element Elevated Temperature Crippling Tests

TYPE	FABRICATION TEMP °K (°F)	TEST TEMP °K (°F)	FAILURE STRAIN (μ)	ALLOWABLE STRAIN (μ)
A	394 (250)	347 (165)	6704	5340
A	394 (250)	347 (165)	5431	5340
A	450 (350)	394	6300	5020
A	450 (350)	394 (250)	5930	5020
B	394 (250)	347 (165)	5905	5340
B	394 (250)	347 (165)	5268	5340
B	450 (350)	394 (250)	5241	4960
B	450 (350)	394 (250)	5742	4960
C	450 (350)	394 (250)	5729	4960
C	450 (350)	394 (250)	4889	4960

Table 4.0-8: Boron/Epoxy-Aluminum Chord Element Cyclic Tests

CONFIG	FABRICATION TEMP °K (°F)	LOAD CYCLES (1)	THERMAL CYCLES	FAILURE STRAIN ($\mu\epsilon$)	ALLOWABLE STRAIN ($\mu\epsilon$)
A	394 (250)	400 CYCLES TO LIMIT LOAD		8464	5277
A	394 (250)	400 CYCLES TO LIMIT LOAD		8451	5277
A	394 (250)		400 CYCLES FROM 219° TO 347°K (-65 TO 165°F)	7410	5277
A	394 (250)		400 CYCLES FROM 219° TO 347°K (-65 TO 165°F)	7340	5277
A	450 (350)		400 CYCLES FROM 219° TO 394°K (-65 TO 165°F)	7556	5000
A	450 (350)		400 CYCLES FROM 219° TO 394°K (-65 TO 165°F)	7123	5000

(1) LIMIT LOAD = 2/3 ULTIMATE LOAD

NOTE: ELEMENTS FAILED STATICALLY AT ROOM TEMP AFTER CYCLING

Table 4.0-9: Boron/Epoxy-Aluminum Column Tests

COLUMN LENGTH cm (in)	FABRICATION TEMP °K (°F)	TEST TEMP	FAILURE STRAIN (μ)	ALLOWABLE STRAIN (μ)
74.9(29.5)	450(350)	ROOM TEMP	5106	4277
74.9(29.5)	450 (350)	ROOM TEMP	4970	4277
74.9(29.5)	394(250)	ROOM TEMP	5227	4340
74.9(29.5)	394(250)	ROOM TEMP	4685	4340

Table 4.0-10: Boron/Polyimide/Titanium Transition Tension Tests

TEST	RT LOAD CYCLES		STATIC TEST TEMP °K (°F)	FAILURE STRAIN (μ)	ALLOWABLE STRAIN (μ)
	% ULT	NUMBER			
STATIC			ROOM TEMP	4680	6000
LOAD CYCLES & STATIC	67	400	ROOM TEMP	5000	6000
STATIC			533 (500)	2670	3000
STATIC			589 (600)	2180	3000

NOTE: FM-34 APPLIED TO STEP AREAS. PASA GEL SURFACE TREATMENT USED ON ALL METAL BONDING AREAS

Table 4.0-11: BORON/POLYIMIDE–TITANIUM CHORD ELEMENT CRIPPLING TESTS

TYPE [1]	TEST CONDITION	FAILURE STRAIN (μ)	ALLOWABLE STRAIN (μ)
A	STATIC, ROOM TEMP	7300	5767
A	400 LIMIT LOAD CYCLES & STATIC AT ROOM TEMP	7610	5710
A	STATIC @ 589°K (600°F)	1950	2500
A	STATIC @ 561°K (550°F)	2290	2500
A	STATIC @ 533°K (500°F)	4650	2500
A	STATIC @ 533°K (500°F)	3190	2500

[1] See Table 4.0-6

Table 4.0-12: Curved Beam Element Tests – Boron/Epoxy-Titanium

BEAM NO.	TEST TEMPERATURE	ULTIMATE LOAD		FAILURE MODE	NUMBER LIMIT LOADS CYCLES
		DESIGN	TEST		
1	R.T.	31,136N (7,000 LB)		DELAMINATION OF TOP 5 PLIES ON COMPRESSION CHORD	30
2	R.T.	31,136N (7,000 LB)		COMPRESSION CHORD LATERAL FAILURE	17
3	R.T.	31,136N (7,000 LB)		COMPRESSION CHORD ADHESIVE FAILURE	1
	464°K(375°F)	15,568N (3,500 LB)	17,792N (4,000 LB)		
4	R.T.	31,136N (7,000 LB)	33,805N (7,600 LB)	COMPRESSION CHORD CRIPPLING	400

5.0 FULL SCALE HARDWARE DEVELOPMENT

Eight foot long curved beams representative of full scale frame members were fabricated and tested. They incorporated the same chord concepts and critical details proposed in the full scale designs.

Design

Three beam designs, each incorporating different material systems were evaluated. These systems were boron/epoxy reinforced aluminum, coron/epoxy reinforced titanium and boron/polyimide reinforced titanium which are specified in greater detail in Table 5.0-1. The evaluation testing included limit load cycling, ultimate loading at room temperature, and ultimate loading at elevated temperature.

Three detailed curved beam designs were developed that incorporated the material systems listed in Table 5.0-1. The maximum service temperature of each design was determined by the capabilities of the materials. The boron/epoxy reinforced aluminum was restricted to a maximum temperature of 394°K (250°F), the boron/epoxy reinforced titanium design was restricted to 464°K (375°F) and the boron/polyimide reinforced titanium was restricted to 533°K (500°F). The beams were assembled with adhesives that were compatible with these service temperatures.

The overall geometry of the three designs was the same. They were approximately 2.5 meters (8 feet) long and had an approximate 243.8 cm (96 inch) mean radius of curvature. Their depth varied from 25.4 cm (10.00 inches) at the root to 12.7 cm (5.00 inches) at the tip. The chords incorporated machined Tees which were riveted to metal webs. The caps of the Tees were machined to minimum gages which were .063 cm (.025 inches) for titanium and .089 cm (.035 inches) for aluminum. These thicknesses were increased at the root end of the beams to provide a higher factor of safety in the attachment areas. The flanges were reinforced with unidirectional laminates that matched the curvature of the Tees and tapered in thickness and width along their length. The inner chord reinforcement varied from a 30 ply thickness and 2.54 cm (1.00 inch) width on one end to a 15 ply thickness and 1.27 cm (0.50 inch) width at the other end. The outer chord reinforcement varied from 15 plies with a 5.08 cm (2.0 inch) width at one end to 5 plies and 2.54 cm (1.0 inch) width at the other end. The reinforcement laminates terminated with stepped titanium fittings to provide an all-metal section at the attachment end of the beam. Conventional mechanical attachments were used to attach the all-metal beam end to a base plate for test. This attachment was representative of the type of attachment between frame members used in the full-scale design. The outer chords of the beams incorporated flange extensions that were stabilized with high density honeycomb to provide an attachment capability which could be used for installing shell structure in the orbiter.

The webs of the beams were designed as stiffened all-metal plates that were shear resistant at ultimate loads. The titanium webs and stiffener angles were 0.16 cm (.063 inches) thick; the aluminum webs and angles were 0.203 cm (.080 inches) thick.

Detail drawings of the three beam designs were prepared and are shown in Figures 5.0-1, -2 and -3.

Analysis

Structural analyses were performed on boron/epoxy reinforced aluminum and boron/composite reinforced titanium 8-foot curved beams using the NASTRAN program. Strains and displacements due to fabrication, elevated temperatures and loads were determined.

The composite residual strains established during fabrication were determined and are shown in Figure 5.0-4. The beam materials were in a stress-free condition at the maximum cure temperature of the adhesive, but developed residual strains during cool-down due to differential thermal expansion. The boron/epoxy reinforced aluminum beams were analyzed for an assembly temperature that was 311°K (100°F) lower than used for the boron composite reinforced titanium beams. In spite of this, the higher thermal coefficient of expansion of aluminum caused residual strains in the boron composite that were approximately three times larger than in the reinforced titanium beams.

The strain distribution in the 8-foot curved beams were developed for the three following conditions; 1) 4448N (1000 lb.) tip load applied at room temperature, 2) 4448N (1000 lb.) tip load at room temperature plus residual strains, and 3) 4448N (1000 lb.) tip load applied at maximum service temperature plus residuals at this temperature. As a typical example, Figure 5.0-5 shows the strain distribution in the reinforced titanium beams for the above conditions. This data was used along with the allowable critical strain of the reinforcement to obtain the ultimate load of the beams. The allowable used, which was adjusted for adhesive stresses, was 4800μ. This strain is well within the elastic region of all the beam materials. Therefore, a multiple of the elastic strain developed with a 4448N (1000 lb.) load was used to determine the ultimate load of the beams using the following:

$$\text{Ultimate Load} = \frac{\text{Allowable Strain} - \text{Residual Strain}}{\text{Strain Due to 4448N (1000 lb.) Load}}$$

Using this relationship, the ultimate loads established for the beams were:

Reinforced Titanium Beams = 22,729N (5110 lbs.)

Reinforced Aluminum Beams = 18,700N (4220 lbs.)

Fabrication

To provide the benefits established in this program in a time period that is consistent with the space shuttle schedule, criteria specified that designs must utilize conventional materials and manufacturing processes that have demonstrated production capabilities. The eight foot curved beam designs incorporated materials and the bulk of the critical details proposed for use in the full-scale designs. The successful fabrication of the curved beams would therefore demonstrate an important aspect of this program; that is, the producibility of the filamentary composite reinforced metal frame concepts.

The eight-foot curved beams were fabricated as built-up metal and composite sub-assembly. A beam metal substrate was initially assembled using standard aluminum and titanium manufacturing processes. Reinforcing straps incorporating unidirectional plies and titanium end fitting were fabricated as separated details. The beam was then assembled by bonding the reinforcements onto the chords of the metal substrate. Figures 5.0-6 thru 5.0-11 show the beam details and various stages of beam assembly. Figure 5.0-12 shows a completed beam.

Test

The 8-foot curved beams were tested in a cantilevered configuration. The beams were bolted to a base plate and a horizontal load applied at the tip with a hydraulic jack as shown in Figure 5.0-13. Lateral support was provided by side bars used in conjunction with spacer blocks. The spacer blocks were covered with teflon tape to minimize friction forces during loading. The beams were drilled and bolted through their all-metal ends to steel fittings. These were bolted to a base plate (Figure 5.0-14) to mount the beam for test. The beam was loaded at its tip with a hydraulic jack as shown in Figure 5.0-15. The jack transmitted load through a flat ended clevis fitting to roller bearings mounted on the end of the beam which permitted free vertical movement when loaded in the horizontal direction.

To perform the elevated temperature tests, strip heaters were attached to the chords in the critical areas of the beam as shown in Figure 5.0-16. This area was then covered with insulation and power was supplied to the strip heaters to attain the desired test temperatures.

The initial beams were instrumented with several strain gages and electronic deflection indicators during test. After obtaining good correlation between test data and analysis, only minimum data was recorded in the remaining tests.

Beams of each design were cycled to limit load 400 times at room temperature. These beams were then loaded to failure. One boron/epoxy reinforced aluminum beam was tested at 394°K (250°F) and one boron/epoxy reinforced titanium beam was tested at 464°K (375°F). These beams were first loaded to limit at room temperature and then loaded to failure at elevated temperature.

The first boron/epoxy reinforced titanium beam was successfully limit load cycled 400 times at room temperature. This beam was then loaded to failure at room temperature at a load of 22,907N (5,150 lbs.). This was approximately 1% above its design ultimate load. A second beam of this design was loaded to limit load one time at room temperature. This beam was then heated to 464°K (375°F) in its critical region (near the base) and loaded to failure at a load of 17,347N (3900 lbs.). This was 53% above the load required to meet the full-scale elevated temperature design requirements.

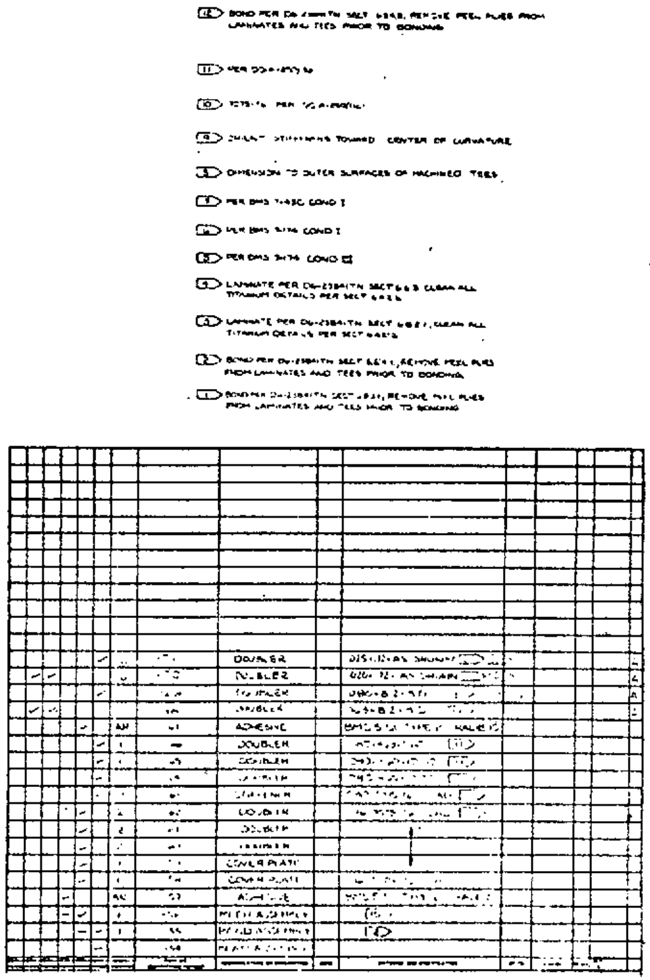
The first boron/epoxy reinforced aluminum beam was successfully limit load cycled 400 times at room temperature. This beam was then loaded to failure at room temperature at a load of 18,904N (4250 lbs.). This was 133N (30 lbs.) over its design ultimate. A second beam of this design was loaded to limit load one time at room temperature. This beam was then heated to 394°K (250°F) and loaded to failure at 21,350N (4800 lbs.). This improved capability at elevated temperature was predicted by analyses because of the reduction in residual stresses.

The first boron/polyimide reinforced titanium beam was limit load cycled. It failed after the tenth cycle. Examination of the failed surface indicated poor adhesion between the beam Tee and stepped titanium fittings due to poor surface preparation over a 3.08 cm (2.0 inch) length. Because of the premature failure the second beam was set-up to repeat the same test. This beam was successfully limit load cycled 400 times at room temperature. It was then loaded to failure at room temperature at a load of 23,130N (5200 lbs.). This was approximately 2% above design ultimate.

A summary of the 8-foot curved beam test results is shown in Table 5.0-2. A typical beam failure is shown in Figure 5.0-17. This failure occurred in the compression chord in a local crippling mode.

Evaluation

The results of the eight-foot curved beam investigations showed that the theoretical weight savings established in the full-scale design studies were feasible. Beams representative of the basic members in this design were fabricated using three different material systems. Test results obtained with the boron/epoxy reinforced aluminum beams were highly successful. They showed that the allowables and concepts used in the design studies were realistic. Results obtained with the boron/polyimide reinforced beams showed that additional development would be required with this material system before it could be utilized for space shuttle application.


DOUBLER
STIFFENER
ADHESIVE
COVER PLATE

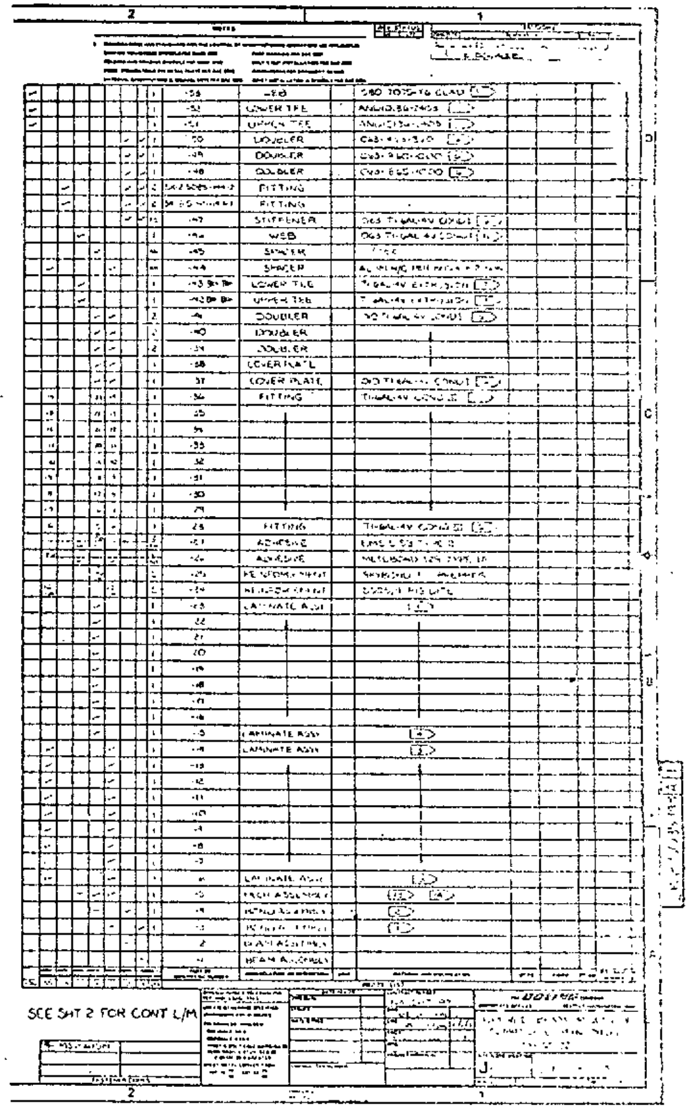

WEB
COVER TEE
UPPER TEE
DOUBLER
FITTING
STIFFENER
SPACER
COVER PLATE
ADHESIVE
LAMINATE ASSY
SEE SHT 2 FOR CONT L/M

Figure 5.0-1

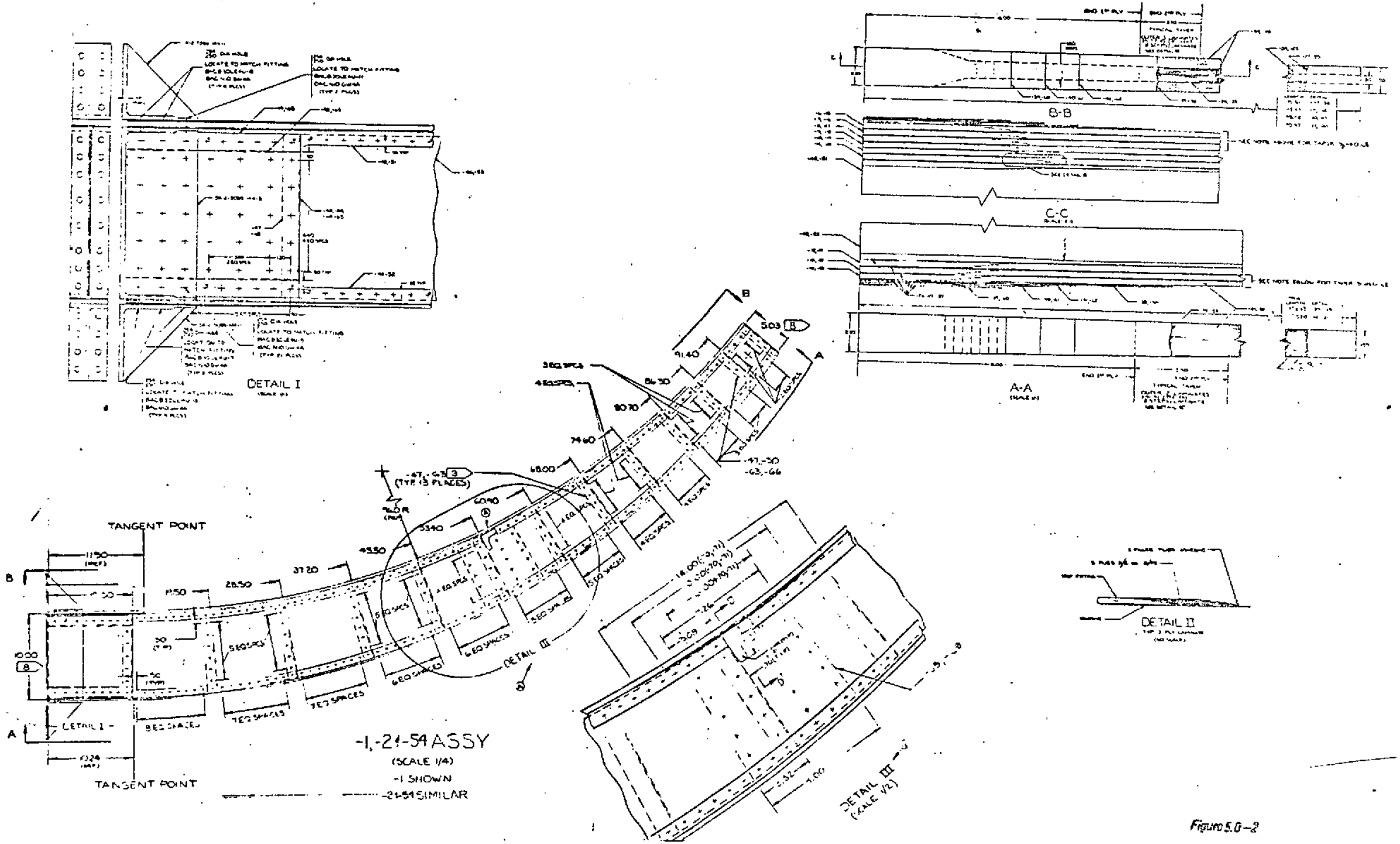

DETAIL I
B-B
C-C
A-A
TANGENT POINT
-1,-21-54 ASSY
(SCALE 1/4)
-1 SHOWN
-21-54 SIMILAR
TANGENT POINT
DETAIL III
DETAIL III
(SCALE 1/2)
DETAIL II

Figure 5.0-2

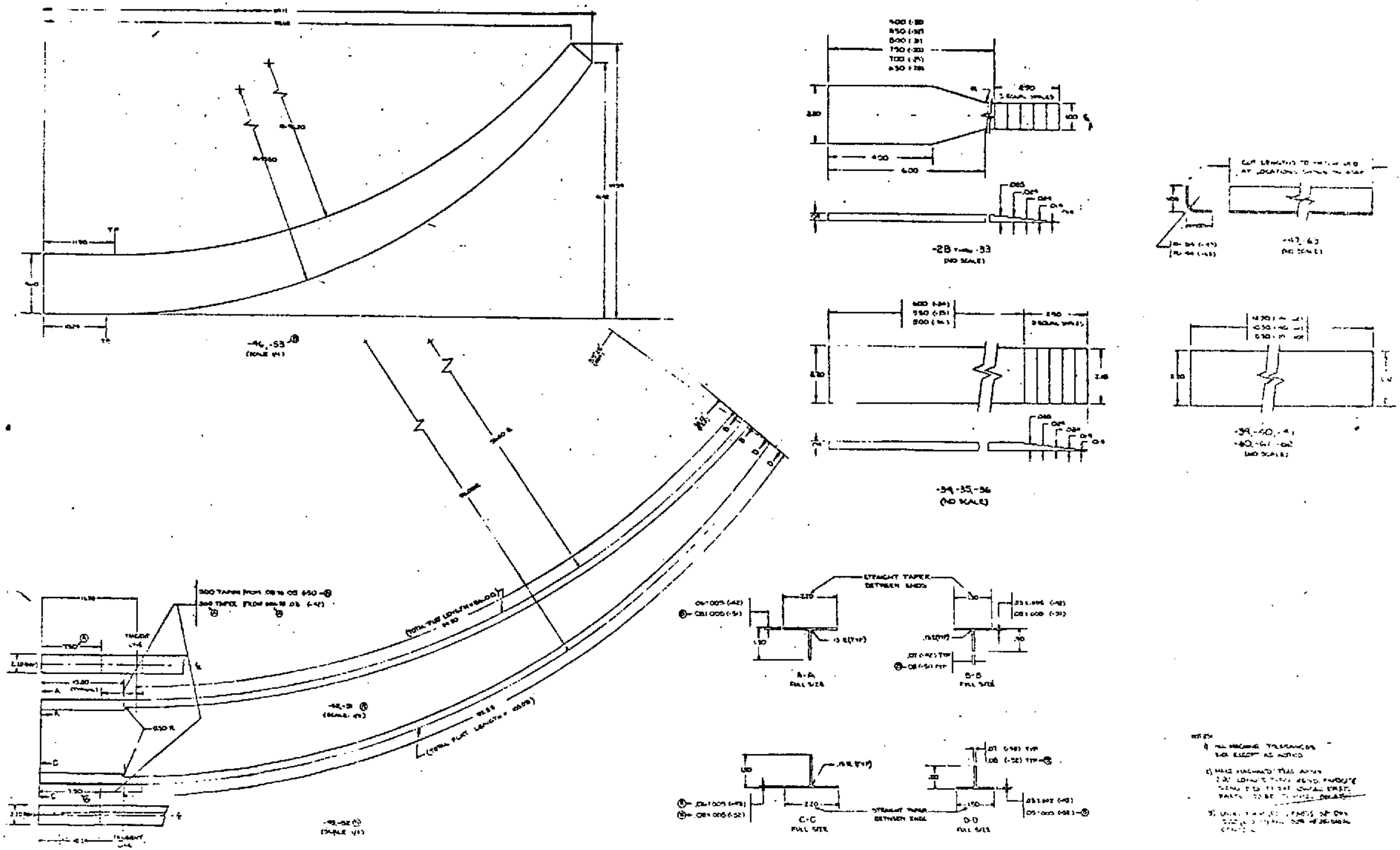

STRAIGHT TAPER BETWEEN ENDS
A-A
FULL SIZE
B-B
FULL SIZE
C-C
FULL SIZE
D-D
FULL SIZE
(NO SCALE)

Figure 5.0-3

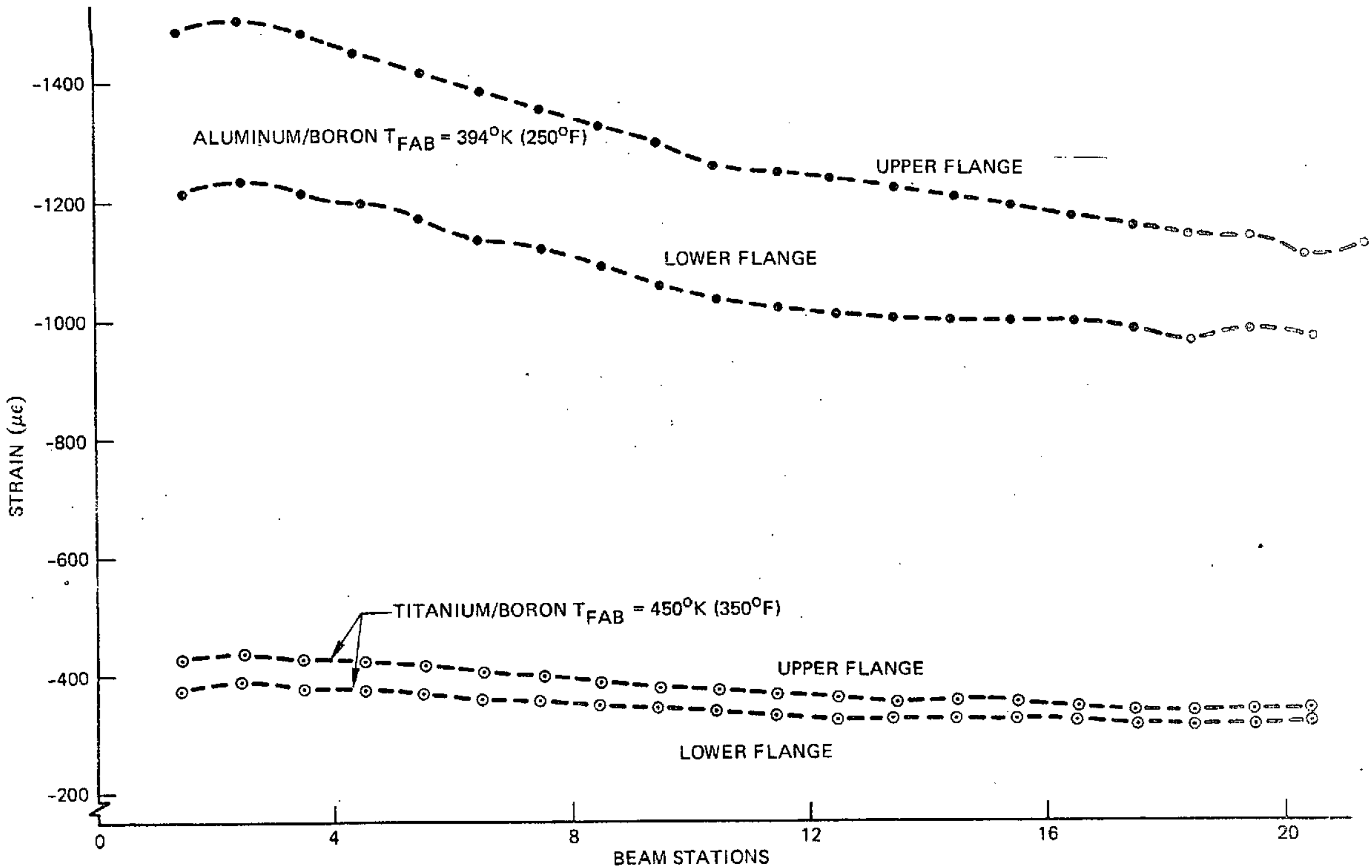


Figure 5.0-4: RESIDUAL FABRICATION STRAINS IN BORON COMPOSITE – 8-FOOT CURVED BEAMS

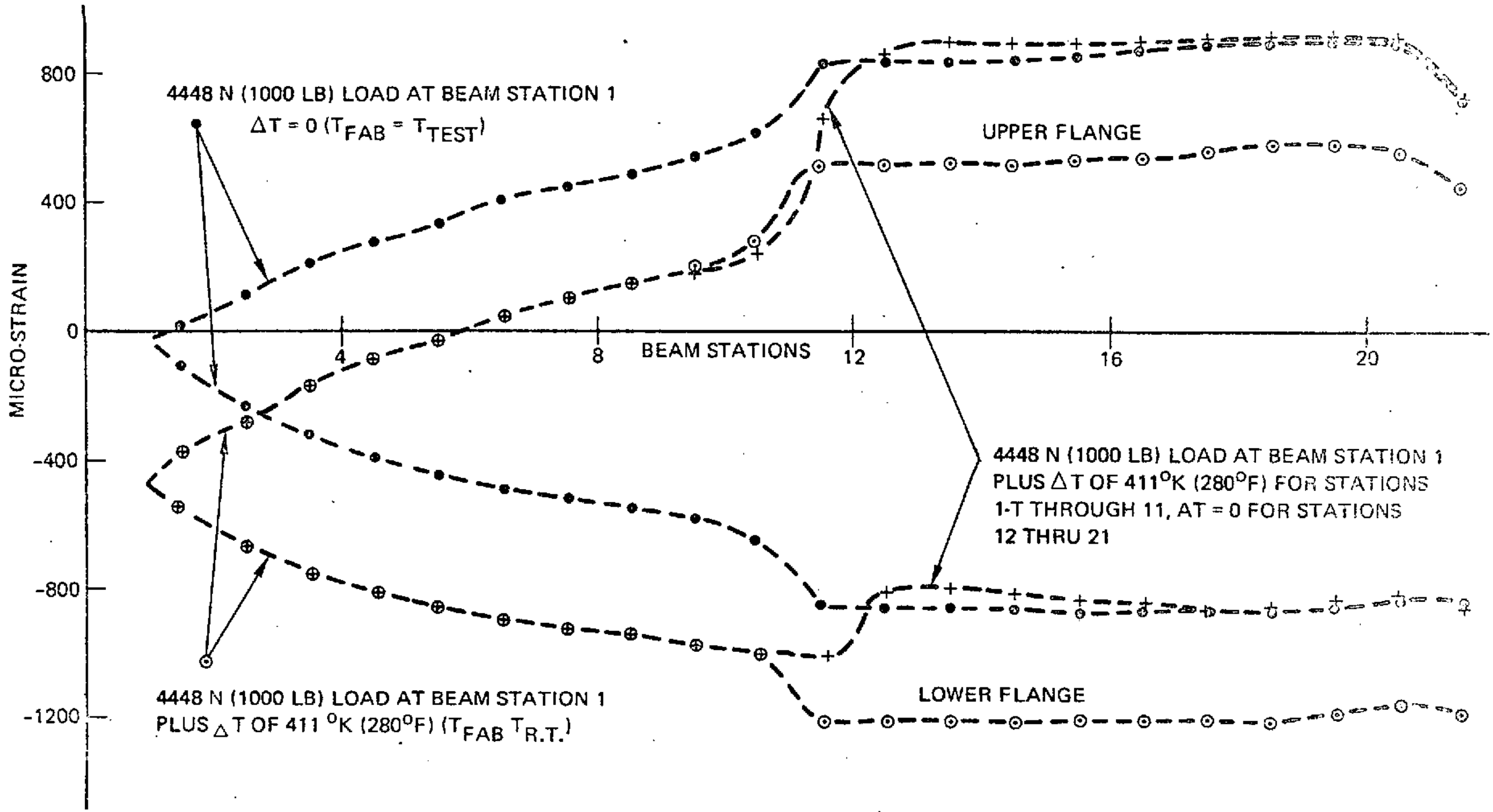


Figure 5.0-5: STRAIN DISTRIBUTION IN TITANIUM/BORON COMPOSITE BEAM

Figure 5.0-6: Metal Substrate Eight-Foot Curved Beam

Figure 5.0-7: Five-Ply Laminating Tool

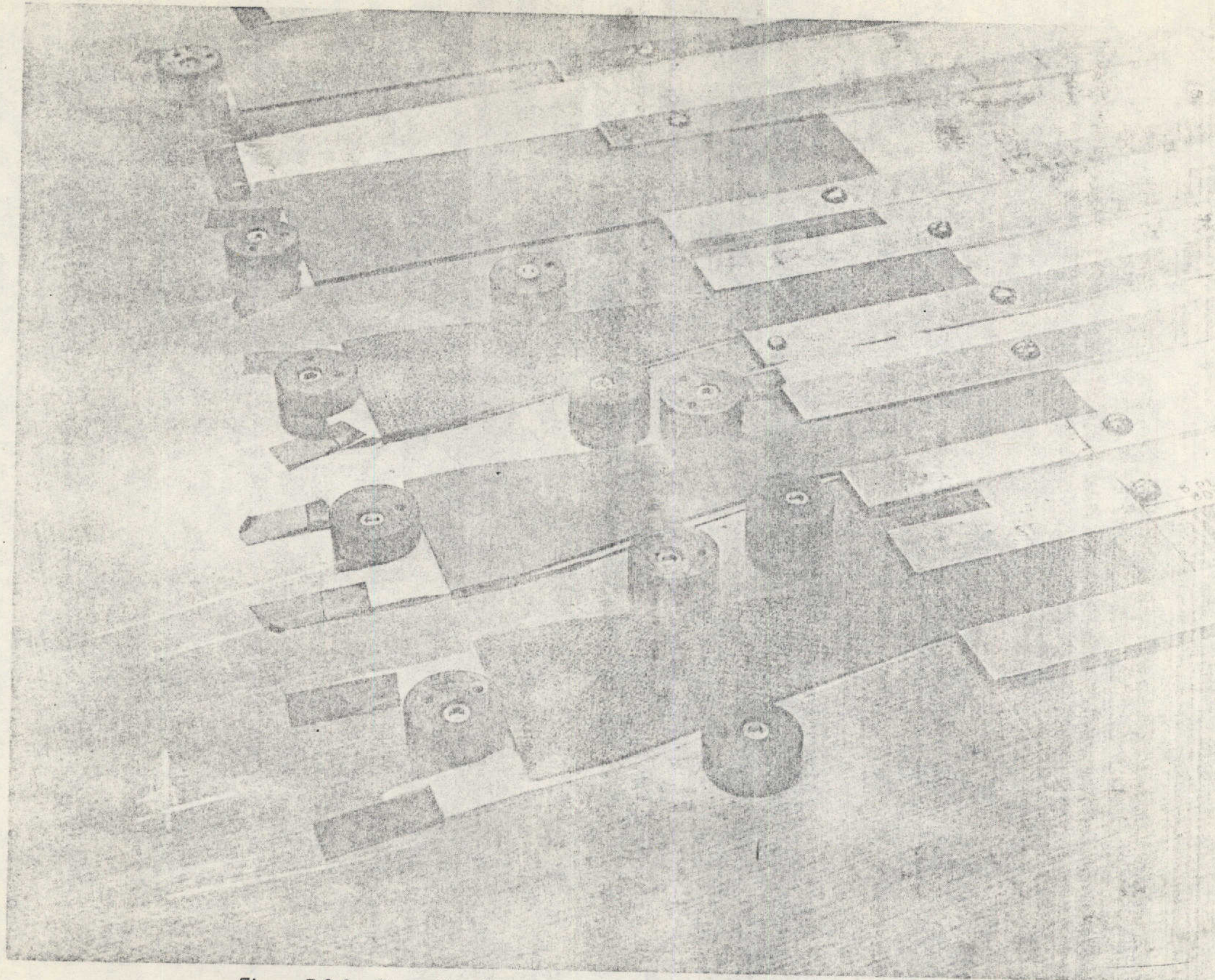


Figure 5.0-8: Close-Up of Five-Ply Laminates and Titanium End Fittings

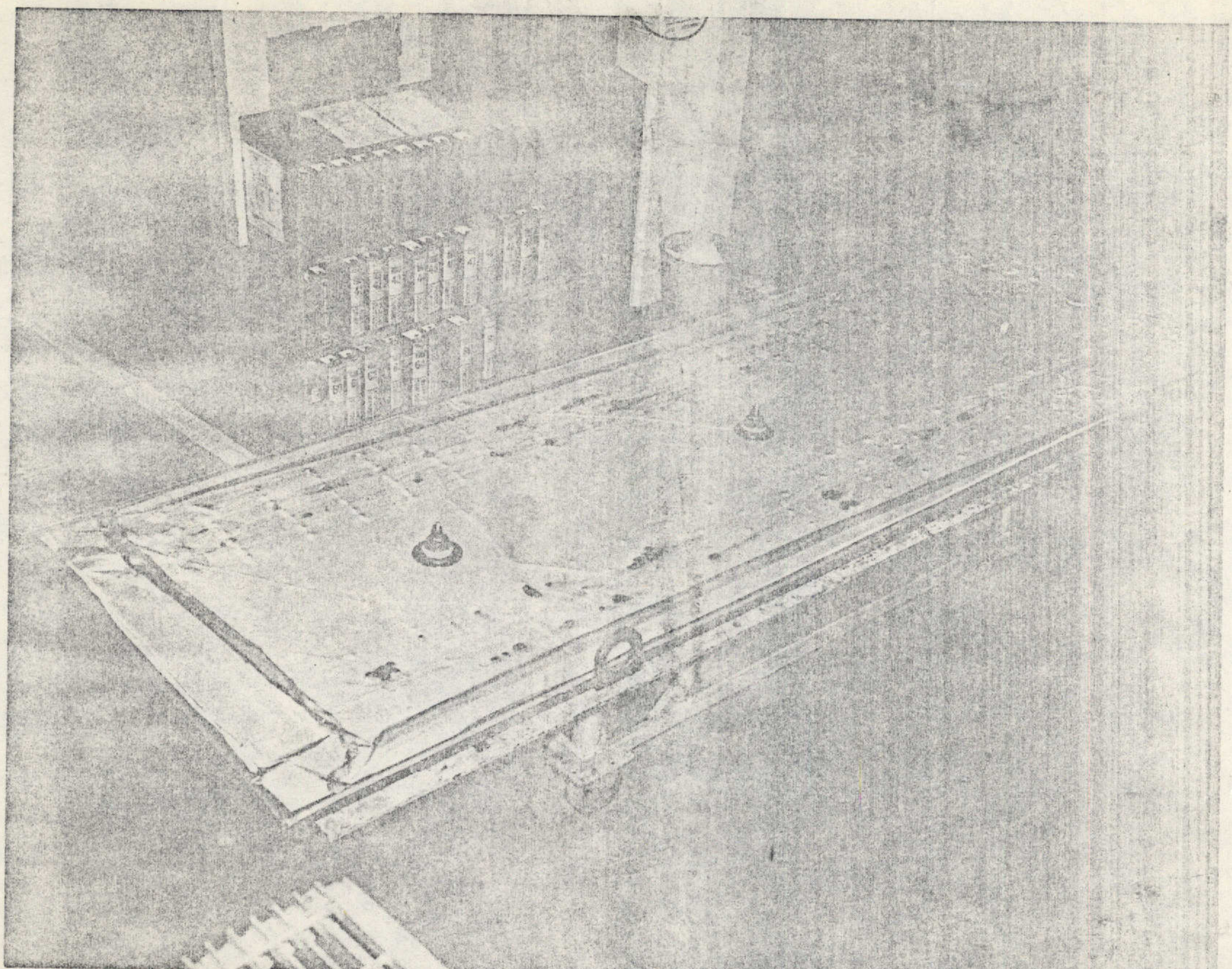


Figure 5.0-9: Bagged Reinforcing Straps—After Cure

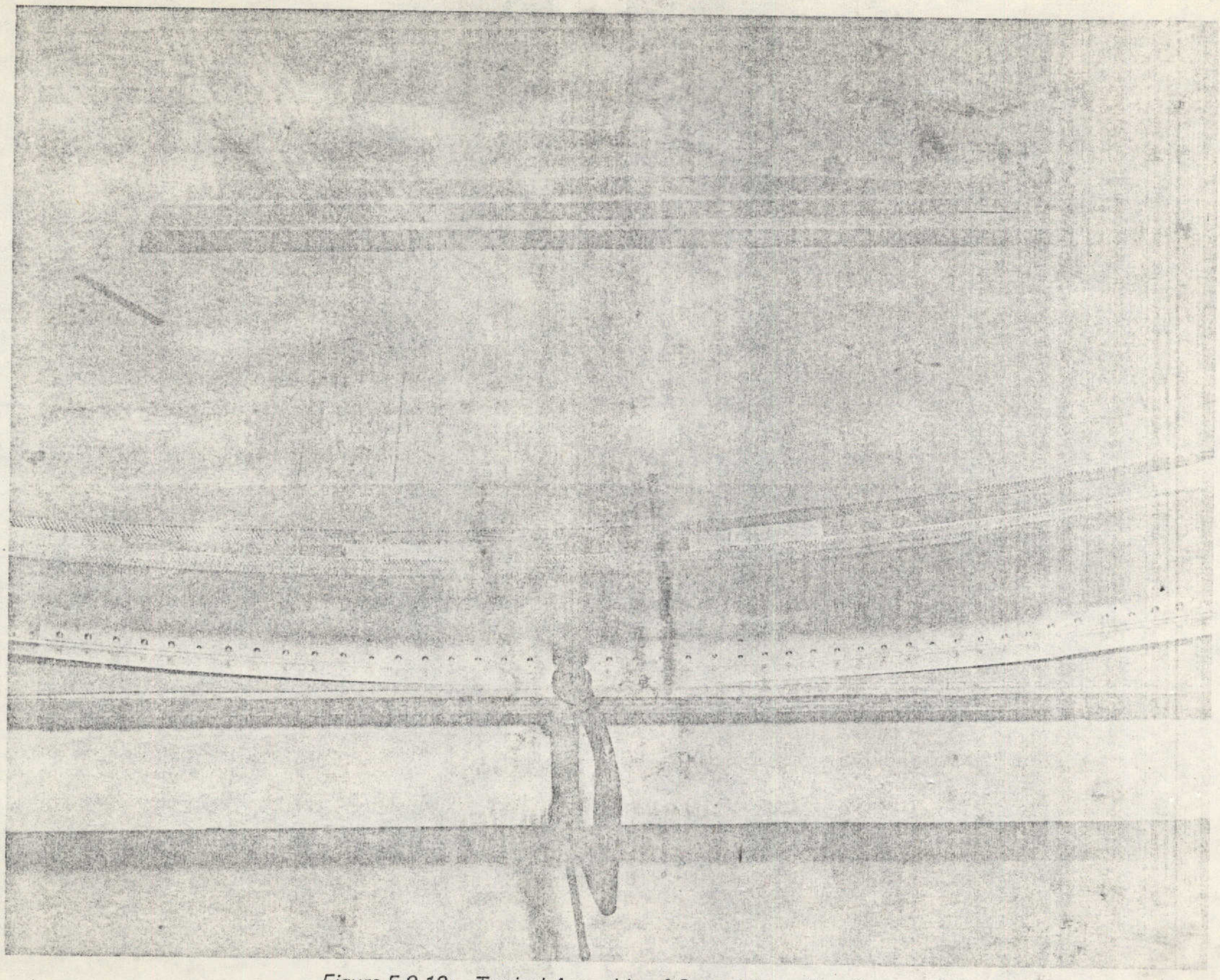


Figure 5.0-10: Typical Assembly of Curved Beam Details

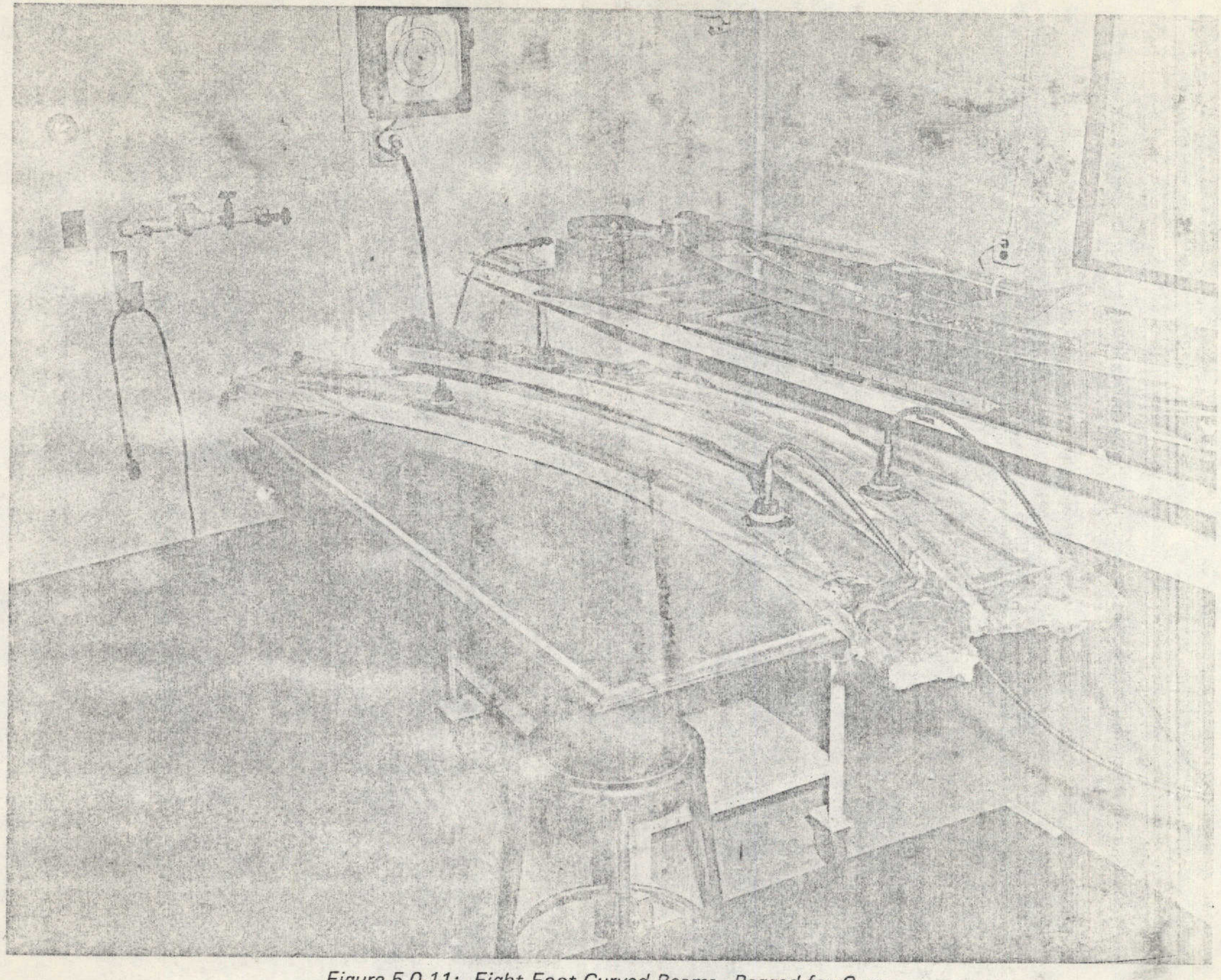


Figure 5.0-11: Eight-Foot Curved Beams—Bagged for Cure

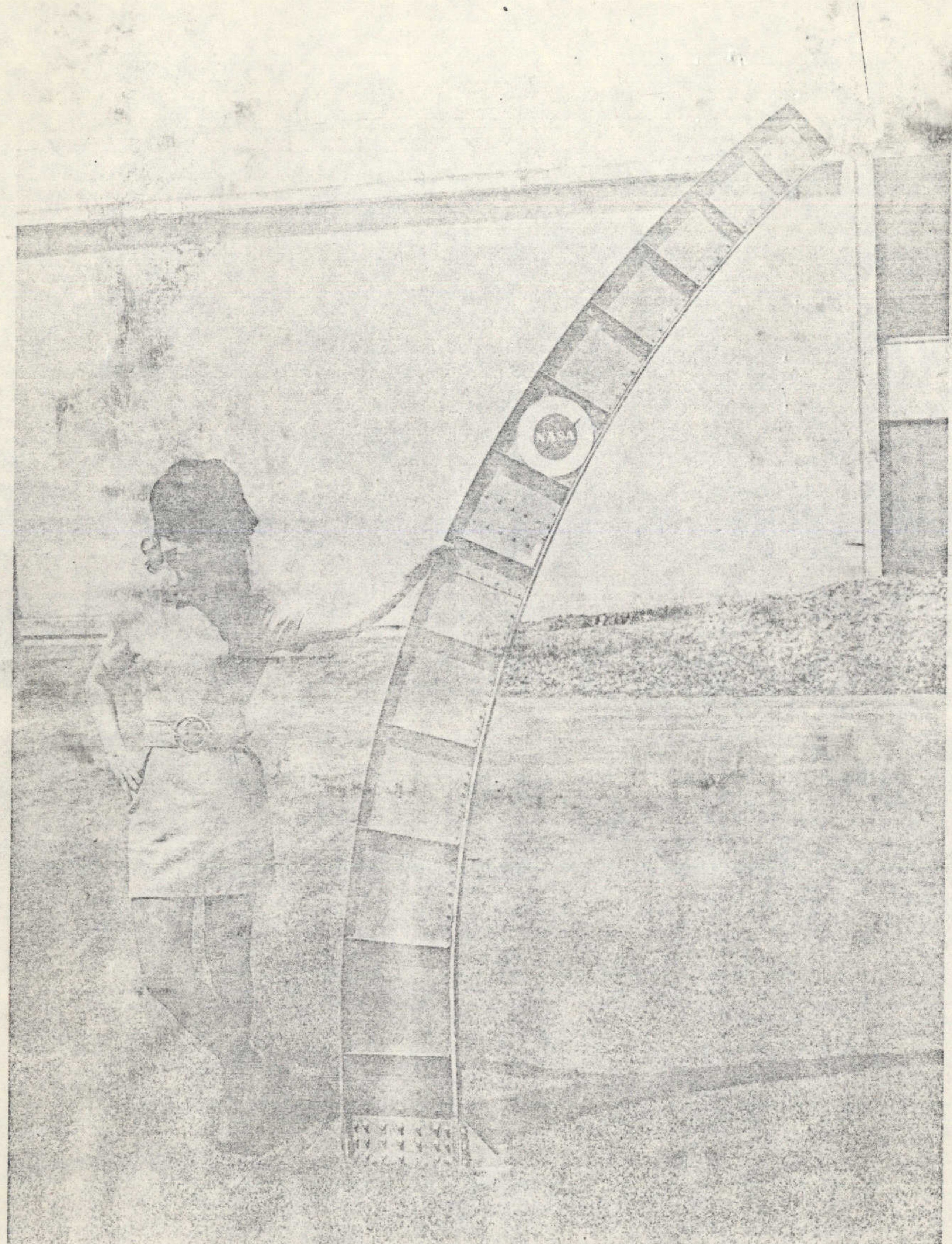


Figure 5.0-12: Eight-Foot Curved Beam

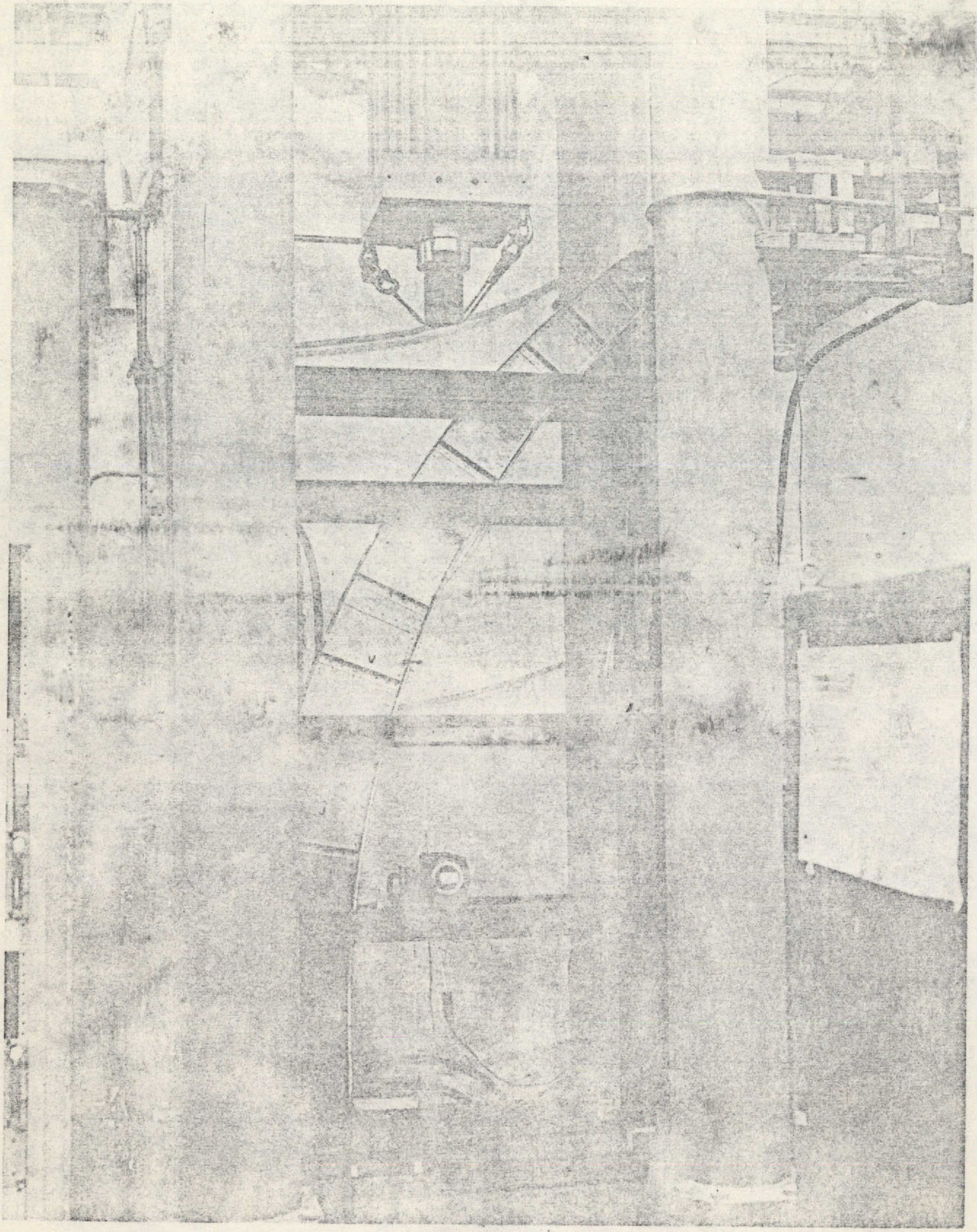


Figure 5.0-13: Eight-Foot Curved Beam—Test Set-Up

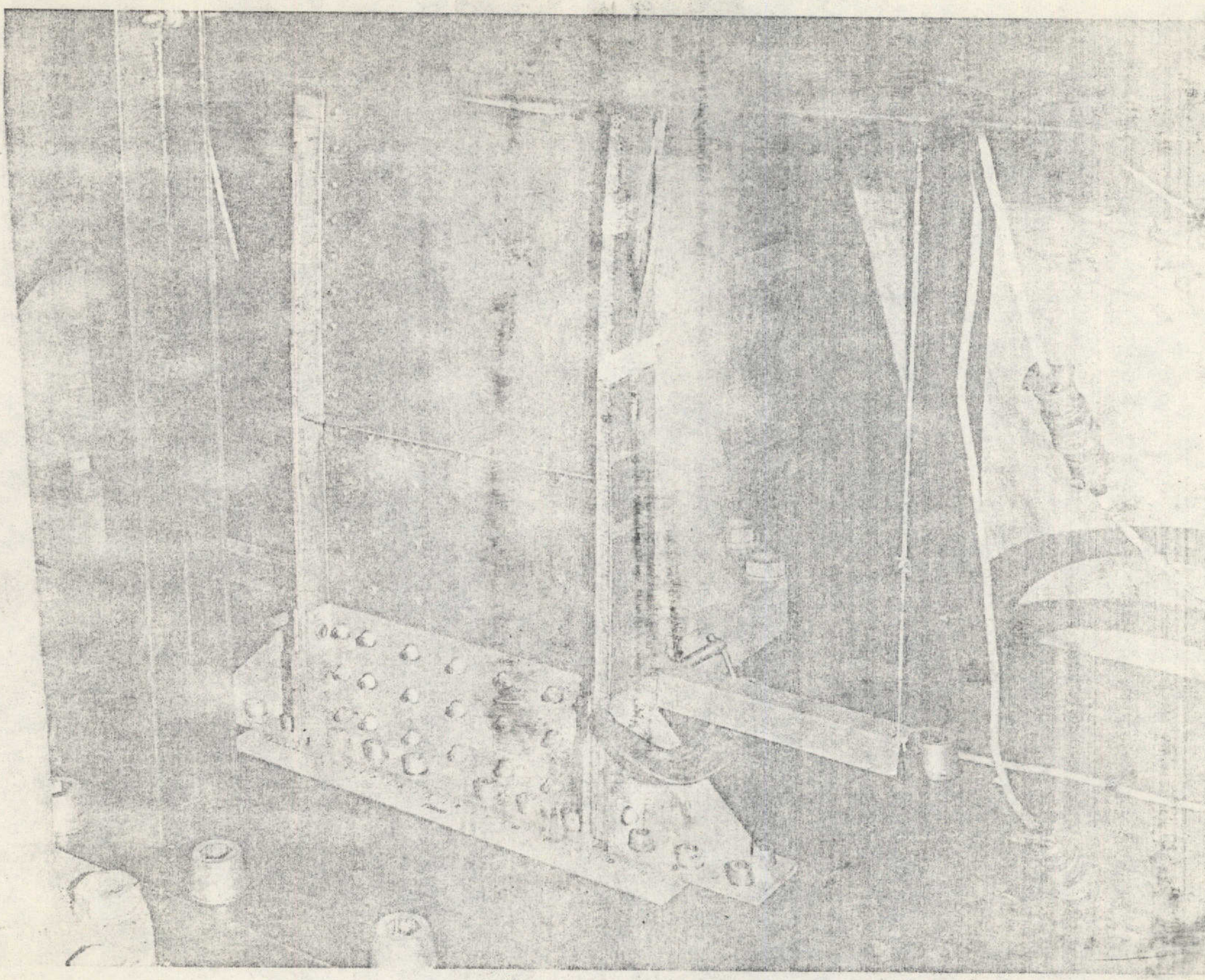


Figure 5.0-14: Eight-Foot Curved Beam—Baseplate Attachment

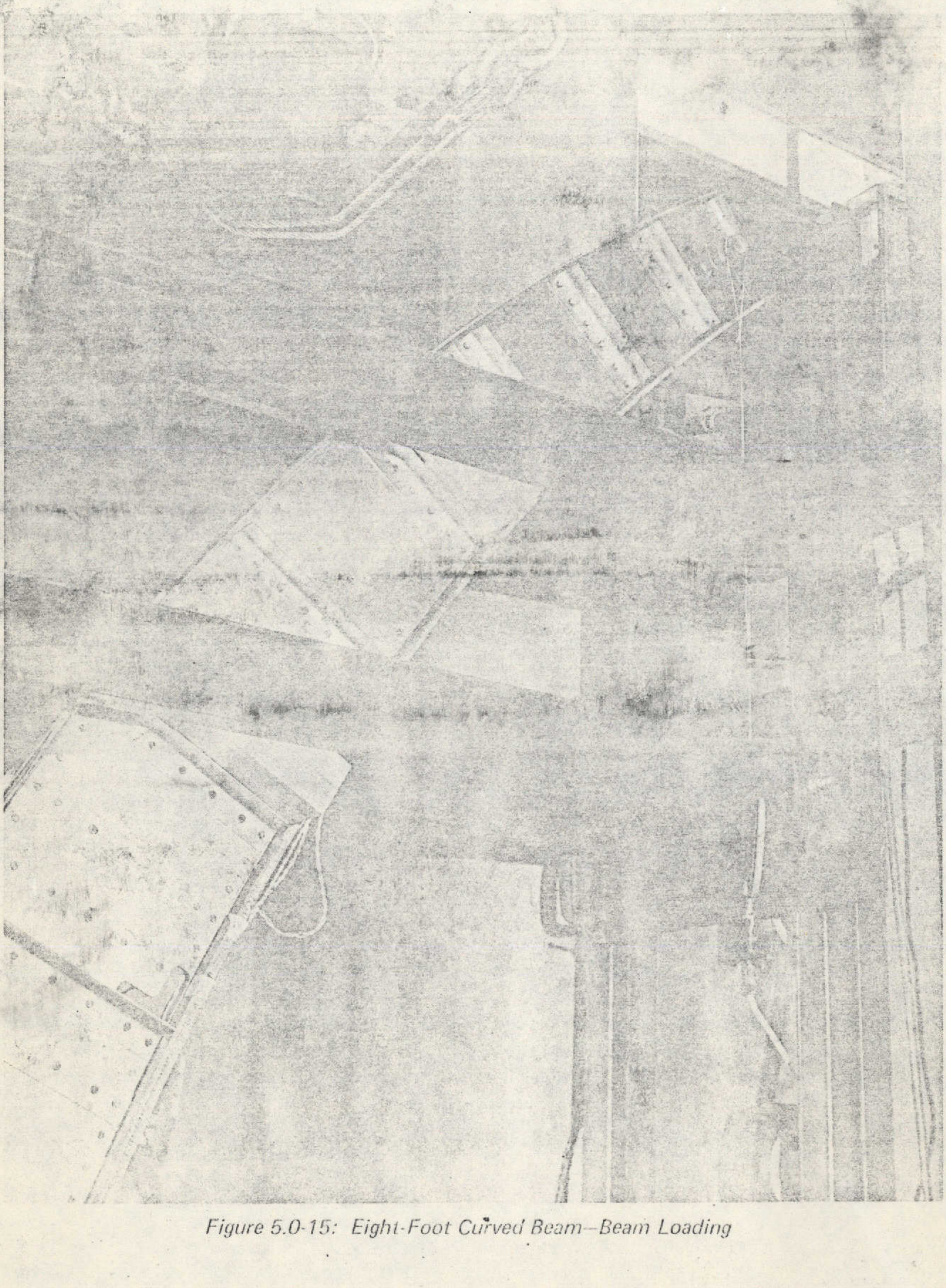


Figure 5.0-15: Eight-Foot Curved Beam—Beam Loading

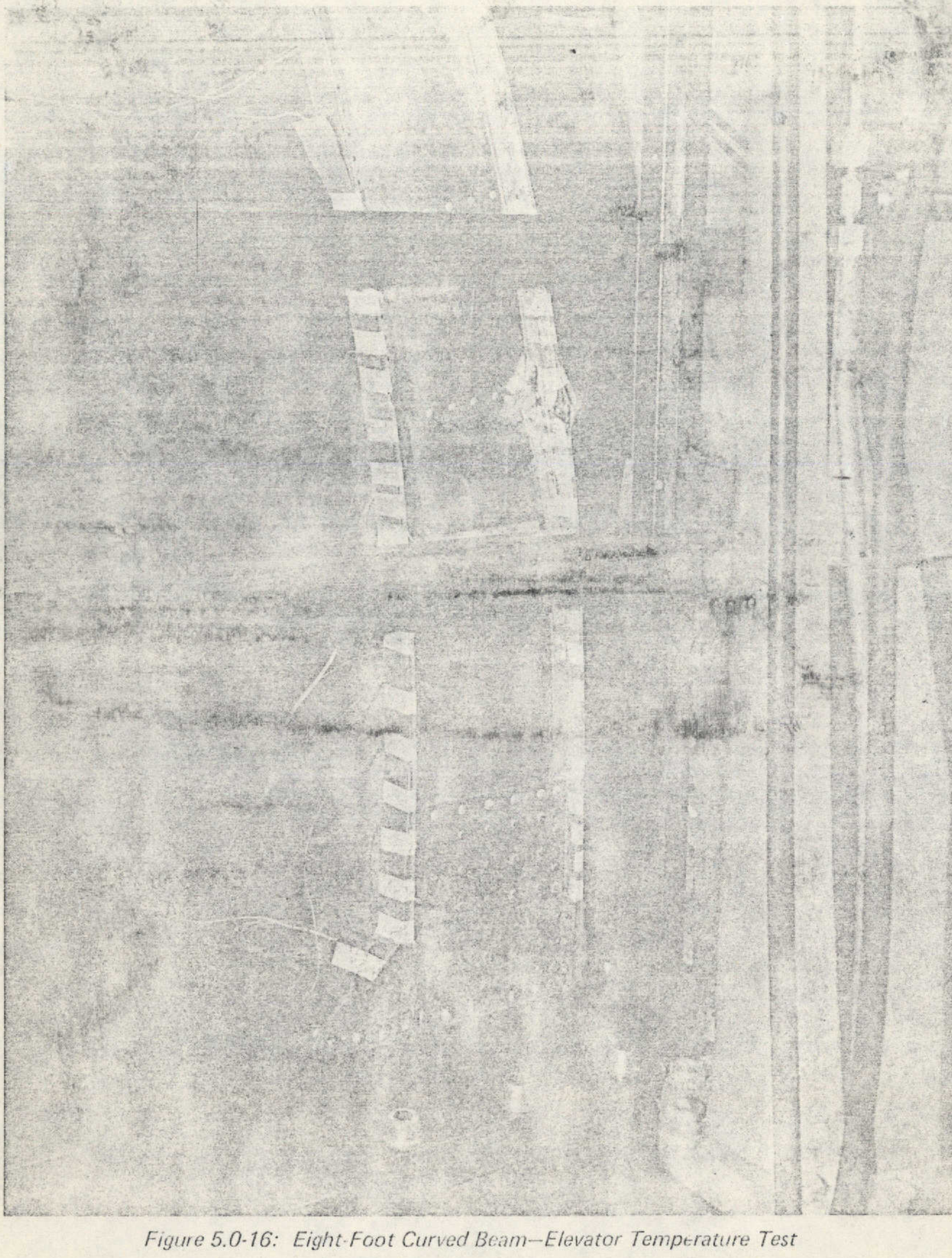


Figure 5.0-16: Eight-Foot Curved Beam—Elevator Temperature Test

C-2

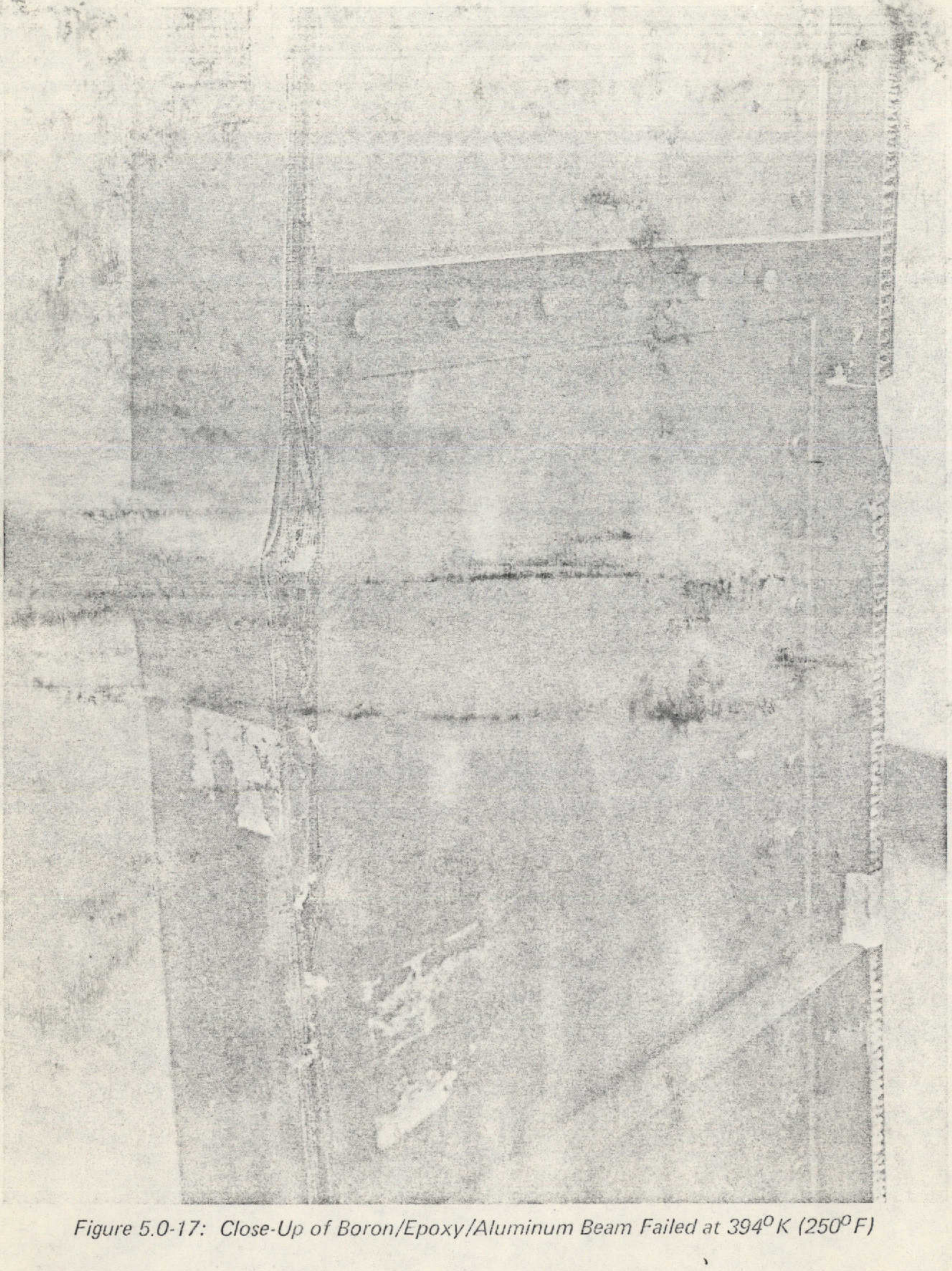


Figure 5.0-17: Close-Up of Boron/Epoxy/Aluminum Beam Failed at 394° K (250° F)

MATERIAL SYSTEMS	ADHESIVE	CURE CYCLE	POST CURE	MAX SERVICE TEMP	
				°K	°F
RIGIDITE 5505/4 7075-T6	METLBOND 329	408°K (275°F) FOR 3 HOURS	464°K (375°F) FOR 3 HOURS	394	250
RIGIDITE 5505/4 6AL-4V TITANIUM	METLBOND	450°K (350°F) FOR 90 MIN.	464°K (375°F) FOR 3 HOURS	464	375
BORON/SKYBOND 703 6 AL-4V TITANIUM	FM-34	450°K (350°F) FOR 2 HOURS	589°K (600°F) FOR 4 HOURS	533	500

Table 5.0-1: 8-FOOT CURVED BEAM DESIGNS

Table 5.0-2: 8-FOOT CURVED BEAM TEST RESULTS

DESIGN	TEST TEMP 2	NO. OF LIMIT LOAD CYCLES	ULTIMATE LOAD				FAILURE MODES
			DESIGN		TEST		
			N	lbs	N	lbs	
BORON/EPOXY TITANIUM	R.T.	400	22,765	5110	22,940	5150	COMPRESSION CHORD BUCKLING & TENSION CHORD DELAMINATION
BORON/EPOXY TITANIUM	R.T.						COMPRESSION CHORD BUCKLED
	464°K(375°F)		11,360	2555	17,370	3900	
BORON/EPOXY ALUMINUM	R.T.	400	18,800	4220	18,930	4250	COMPRESSION CHORD BUCKLED
BORON/EPOXY ALUMINUM	R.T.						COMPRESSION CHORD BUCKLED
	384°K(250°F)		9710	2110	21,380	4800	
BORON/POLYIMIDE TITANIUM	R.T.	10					DELAMINATION BETWEEN TI TEE AND TI STEPPED FITTING
BORON/POLYIMIDE TITANIUM	R.T.	400*	22,720	5110	23,165	5200	COMPRESSION CHORD BUCKLED

*LIMIT LOAD REDUCED TO 80% DUE TO INITIAL PREMATURE FAILURE

6.0 MODEL FRAME EVALUATION

A subscale model frame was designed, fabricated and tested to evaluate the filamentary composite reinforced metal frame concept in the same general frame configuation and under the same combined loading conditions proposed for use in the orbiter vehicle.

DESIGN

The model frame was designed as a half-frame configuration, but was supported during test in a manner which permitted it to act as full-frame under load. It's overall geometry was scaled down by a 1/3 factor. The element cross-sections were scaled by 1/2 factor which provided the minimum size at which reasonable details could be produced. As a result, the model frame was approximately 1.52 m (5 feet) along the base, 1.29 m (51 inches) high and the cross-sections of the majority of the elements were approximately 6.35 cm (2.5 inches) high. The design provided for the attachment of TPS panels and fuselage shell structure. It included additional critical details that were common to the full-size designs, such as curved and tapered beam elements, element connections, longeron interface provisions, and web clearance holes. The built-up cross-sections incorporated shear resistant titanium webs stiffened with titanium angles and chords reinforced with unidirectional boron/epoxy composites. The chords incorporated titanium "Tees" with caps machined to a minimum .063 cm (.025 inch) minimum gage. The outer chords incorporated honeycomb stabilized extensions to provide an attachment capability and the inner chords were reinforced uniformly along the width of the cap. The design of the model frame is shown in Figures 6.0-1A and -1B.

ANALYSIS

The NASTRAN program was used to perform a finite element stress analysis of the model frame. A model was constructed using approximately 155 nodes and 390 elements. Plate and chord elements were used to model the frame member cross-sections. The plates resisted in-plane stresses only and the chords axial stresses. The model of the test frame is shown in Figure 6.0-2.

In the analysis the frame was clamped at Nodes 371 and 377 and also at 378 and 380. These boundary conditions were selected to provide a configuration simulating the symmetry of the full frame with the half frame mode. Four locations were selected in the test frame which when loaded produced a structural response that simulated the full size frame under flight conditions. The four load points were at Nodes 652, 655, 656 and 657.

The analysis determined the combinations of jack loads that represented the Orbiter Ignition Condition and the Side Wind Condition. The Orbiter Ignition produced the highest stresses in the overall frame, while the Side Wind Condition provided the greatest structural challenge to the frame side member. The analysis established the stress distribution and frame deflections resulting from the above loadings. This theoretical data was compared to the experimental data obtained from the frame tests later in the program.

FABRICATION

The model frame consisted of four beam elements bolted together. Two of the elements were curved and two were straight. One of the straight beams, located at the top of the frame, was too short to make reinforcement practical and, therefore, was made using all titanium construction. The remaining three beams included composite reinforcement in their chord areas. After fabrication, the beams were bolted together into the desired frame configuration. Continuity between the beams was provided by steel fittings and titanium doublers. Bolts were installed through the fittings and ends of the beams which terminated with all metal sections. The webs were spliced using titanium corner doublers.

The beam elements consisted of a titanium substrate which was reinforced in the chord areas with unidirectional boron/epoxy composites. The basic titanium details consisted of two Tees located in the chord areas, a web plate which was riveted to the outstanding leg of the Tees and web angle stiffeners.

The titanium tees were produced from 6Al-4V titanium extrusions. They were machined to their final dimensions in the flat, then rolled to approximate contour, and then hot sized to final contour. The curved web plates and doublers were machined from 0.16 cm (.063 inches) 6Al-4V titanium sheet material on an end mill. The rectangular webs were cut to size with a large shear. The angle web stiffeners were formed using standard high temperature 90° dies. These angles were formed in meter lengths and then cut to size as required.

The beam metal details were assembled using monel rivets. The parts were clamped together and holes were drilled. The rivets were driven with a fixed rivet squeeze machine. The stiffener angles were installed after the laminates were bonded in place.

Figure 6.0-3 shows the completed titanium details assembled into the metal substrate used in the frame.

The beam elements in the subscale frame were reinforced with unidirectional boron/epoxy straps. The reinforcements varied in thickness from 10 plies to 30 plies from beam to beam and tapered from 20 plies to 30 plies in one beam. These variations were representative of the construction proposed in the full scale frame designs. Each of the reinforcement straps were made up from basic precured 5 ply laminates. These basic laminates were stacked up to the required thicknesses and bonded together. The thickness tapering was accomplished by cutting the lengths of the plies in the 5 ply laminates to a predetermined schedule. These laminates were stacked with the full length laminates in a sequence that provided the required thickness variation. The completed reinforcements terminated with stepped titanium end fittings which were bonded in-place during lamination, as shown in Figure 6.0-4.

The frame elements were assembled by bonding the matching metal and composite details. Each titanium subassembly was prepared for bonding by mechanically cleaning and priming the outer chord surfaces. The basic five ply laminate surfaces were prepared for bonding by removing their peel plies which had been incorporated during cure for their protection. Adhesive plies were placed between the laminates which were stacked to the required thickness and on the appropriate metal surfaces. The stacked plies, honeycomb and cover plate details were then assembled on both the upper and lower chords and held in place with the teflon tape. This whole assembly of parts was then enclosed in a tubular bag which was then sealed. This bag was then evaucated with shop vacuum. The bagged assembly was then placed in an autoclave and processed through the adhesive cure cycle. After cure the bag was removed and the beam was visually inspected. The web stiffeners were then drilled and riveted in place.

Conventional metal assembly techniques were used to connect the frame elements into the final frame configuration. Figure 6.0-5 shows the completed model frame. Since the ends of the beam elements terminated as all-metal sections, they were drilled and bolted as in conventional metal construction. The holes were drilled to match steel fittings which were used to provide continuity between the adjacent chord members. Titanium doublers were riveted and bolted in place to provide web continuity at the connections.

Figure 6.0-6 shows a typical corner connection. One of the frame load points was located at this corner and the hole for the load pin can be seen in the above figure.

TEST

Prior to test, the model test frame was instrumented with 15 electrical deflection indicators (EDI's), 18 single element strain gages, and 3 rosettes, as shown in Figure 6.0-2. The single element gages were used to measure chord strains, the rosettes to determine web sehars and the EDI's to determine frame deflections.

After being strain gaged the frame was installed in a test fixture. This fixture provided the lateral support normally provided by structure adjacent to a frame in actual vehicle construction. The center elements of the frame were bolted to reaction blocks. This set-up permitted the half frame model configuration to react as a full frame under load during test.

The model was tested in a horizontal position as shown in Figure 6.0-7. After being installed in the test fixture, strain gage circuits were completed and balanced, the EDI's were connected and the hydraulic load cells were installed. Six hydraulic jacks were attached to the model at four locations as shown in Figure 6.0-8. Loads were programmed to these jacks in a manner which simulated vehicle flight conditions. An SDS 910 computer was used to program all loads through the controllers. Data was recorded on tape and also was presented in real time on TV screens at the test site. This permitted the critical data to be plotted and monitored as testing progressed. Three programmed load tests were performed. Load was applied in increments. Strain gage, EDI, and load data was recorded at each increment.

Max Q Beta (Side Wind Condition) - Limit Load Test

The combination of loads applied to the frame to simulate the Max Q Beta-Limit Loads are shown in Figure 6.0-9. Strain gage data and frame deflections were recorded at 10% load increments up to the limit load values.

Orbiter Engine Ignition - Limit Load Test

The combination of loads applied to the model frame to simulate the Orbiter Ignition - Limit Loads are shown in Figure 6.0-10. Strain gage data and frame deflections were recorded at 10% load increments up to the limit load values.

Orbiter Engine Ignition - Ultimate Load Test

The combination of loads programmed to be applied to the model to achieve Orbiter Ignition - Ultimate Design Loads were 1-1/2 times greater than the above limit loads. Loads were applied in 10% increments up through 70% of ultimate. Loads were then applied at 5% increments until failure. Failure occurred at 8% above the design ultimate. Strain gage data and frame deflections were recorded at all load increments.

EVALUATION

The strain gage data and frame deflections obtained during the frame tests were compared to the theoretical predicted values obtained in the NASTRAN analysis. In general, excellent correlation data developed as shown for the Orbiter Ignition Limit Load condition in Figures 6.0-11 and -12. Maximum deflection deviation was less than 0.20 inches and strain deviation less than 8%.

The model scale frame was loaded to failure using the combination of loads simulating the orbiter ignition condition. Failure occurred at 8% above the design ultimate. The maximum chord strains developed during test at design ultimate were within 10% of the strain levels predicted by the NASTRAN analysis and at failure the maximum strains were approximately 3% above the design tension allowable. The maximum strain and failure occured at the location which the analyses predicted as the critical area in the frame. A close-up of the failure is shown in Figure 6.0-13.

[1] DIMENSIONS TO METAL TEE SURFACES OR THE INTERSECTION OF THEIR EXTENSIONS

[2] BOND (METLBOND 328 ADHESIVE) PER D6-23841 TN SECTION 6.6.1, CLEAN ALL TITANIUM DETAILS PER SECTION 6.4.3 (VACUUM BLAST AND SILANE RINSE), VAPOR DEGREASE CORE PER BAC 5408.

[3] 6AL-4V TITANIUM PER BMS 7-44 COND I

[4] ORIENTATE STIFFENERS TOWARD CENTER OF CURVATURE (31.0 R) ON -4 ASSY AND CUT LENGTH TO MATCH WEB HEIGHT

[5] COMPOSITE REINFORCEMENTS TO BE BUILT UP FROM BASIC 5 PLY LAMINATES TO THE NUMBER REQUIRED FOR LOCAL REINFORCEMENT. BASIC 5 PLY LAMINATES WILL INCORPORATE 5 PLIES OF 5505/4 BORON AND ONE DUMMY PLY OF METLBOND 329.

[6] QUANTITIES SHOWN IN ASSEMBLY BLOCKS

[7] 6AL-4V TITANIUM PER BMS 7-174 COND III

[8] 6AL-4V TITANIUM PER BMS 7-174 COND I

[9] 4130 STEEL PER BMS 7-32F (180-200 ksi)

[10] USE NAS 1104-10 BOLTS THRU -32 & REINFORCED TEE

[11] VAPOR DEGREASE AFTER MACHINING, APPLY ZINC CHROMATE PRIMER TO ALL SURFACES.

[12] DRILL .750-.757 DIA HOLE THRU

-4	-3	-2	-1	-0	QTY REQD	PART OR IDENTIFYING NUMBER	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	NOTE
			✓		1	-51	FILLER	.40 x .60 x .063 [8]	
			✓		1	-50	FILLER	.50 x .70 x .063 [8]	
			✓		1	-49	DOUBLER	1.85 x 1.00 x .063 [8]	
	✓				1	-48	DOUBLER	1.60 x 2.50 x .063 [8]	
	✓				1	-47	DOUBLER	1.60 x 2.50 x .063 [8]	
			✓		1	-46	DOUBLER	1.60 x 3.25 x .063 [8]	
					1	-45	DOUBLER	1.80 x 3.00 x .063 [8]	
			✓		2	-44	FITTING	[9]	[11]
			✓		2	-43	FITTING	[9]	[11]
			✓		2	-42	FITTING	[9]	[11]
					1	-41	DOUBLER	.063 [8]	
					1	-40	DOUBLER	.063 [8]	
			✓		1	-39	CLIP	.08 [8]	
			✓		1	-38	FITTING	[9] OR EQUIV	[11]
			✓		1	-37	FITTING	[5] OR EQUIV	[11]
			✓		1	-36	DOUBLER	.063 [8]	
			✓		1	-35	CLIP	.08 [8]	
			✓		1	-34	DOUBLER	.063 [8]	
			✓		1	-33	FITTING	[5] OR EQUIV	[11]
			✓		1	-32	FITTING	[9] OR EQUIV [10]	[11]
		✓			1	-31	DOUBLER	.063 [8]	
			✓		3	-30	FITTING	[9] OR EQUIV	[11]
			✓		1	-29	FITTING	[9] OR EQUIV	[11]
			✓		1	-28	CLIP	.08 [8]	
			✓		1	-27	DOUBLER	.063 [8]	
		✓			1	-26	DOUBLER	.063 [8]	
✓					1	-25	TAPERED INNER CHORD REINFORCEMENT	.125 x .500 x 10 x 15 PLIES 5505/4 [5]	
✓					1	-24	TAPERED OUTER CHORD REINFORCEMENT	.50 x .600 x 20 x 30 PLIES 5505/4 [5]	
✓					1	-23	WEB PLATE	.063 [8]	
✓					1	-22	INNER TEE	[3]	
✓					1	-21	OUTER TEE	[3]	
	✓				1	-20	WEB PLATE	.063 [8]	
	✓				1	-19	INNER TEE	[3]	
	✓				1	-18	OUTER TEE	[3]	
		✓			1	-17	INNER COMPOSITE REINFORCEMENT	.25 x 550 x 15 PLY 5505/4 [5]	
		✓			1	-16	OUTER COMPOSITE REINFORCEMENT	.50 x 550 x 30 PLY 5505/4 [5]	
		✓			1	-15	WEB PLATE	.063 [8]	
		✓			1	-14	INNER TEE	[3]	
		✓			1	-13	OUTER TEE	[3]	
5		6	4		[6]	-12	INNER CHORD STEPPED FITTING	.062 [7]	
			✓		1	-11	INNER COMPOSITE REINFORCEMENT	.125 x 550 x 10 PLY 5505/4 [5]	
10		12	6		[6]	-10	OUTER CHORD STEPPED FITTING	.062 [7]	
			✓		1	-9	OUTER COMPOSITE REINFORCEMENT	.50 x 600 x 20 PLY 5505/4 [5]	
19	5	23	21		[6]	-8	STIFFENER	.063 [8] [4]	
			✓		1	-7	WEB PLATE	.063 [8]	
			✓		1	-6	INNER TEE	[3]	
			✓		1	-5	OUTER TEE	[3]	
-				✓	1	-4	CURVED FRM ELEMENT	[2]	
	-			✓	1	-3	TOP FRM ELEMENT		
		-		✓	1	-2	SIDE FRM ELEMENT	[2]	
			-	✓	1	-1	BOT FRM ELEMENT	[2]	
					-	SO-E51B	MODEL FRAME ASSY		

LIST OF MATERIAL

THE BOEING COMPANY

SUBSCALE MODEL FRAME

Figure 6.0-1a: Sheet 1

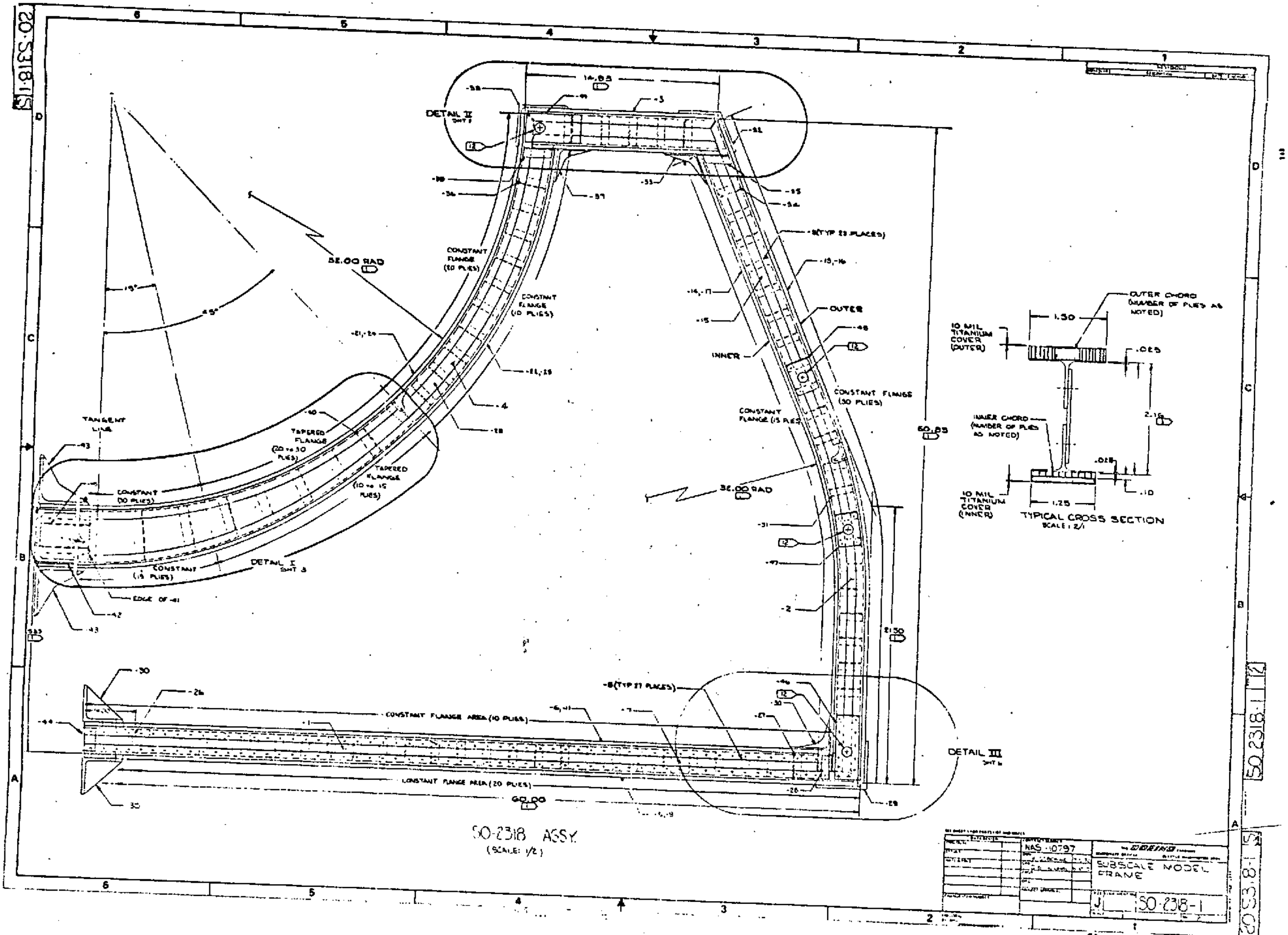


Figure 6.0-1b: Sheet 2

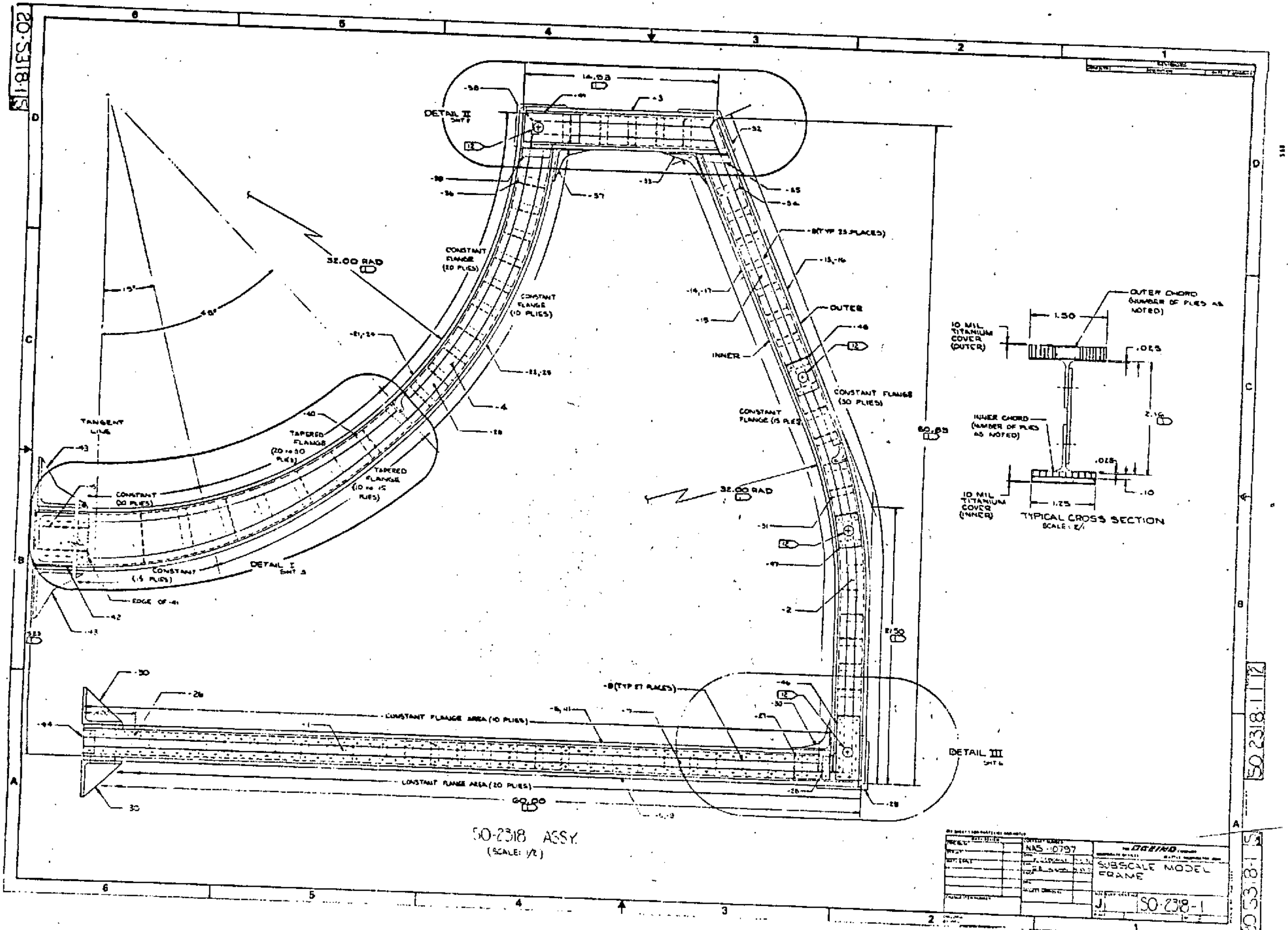


Figure 6.0-1b: Sheet 2

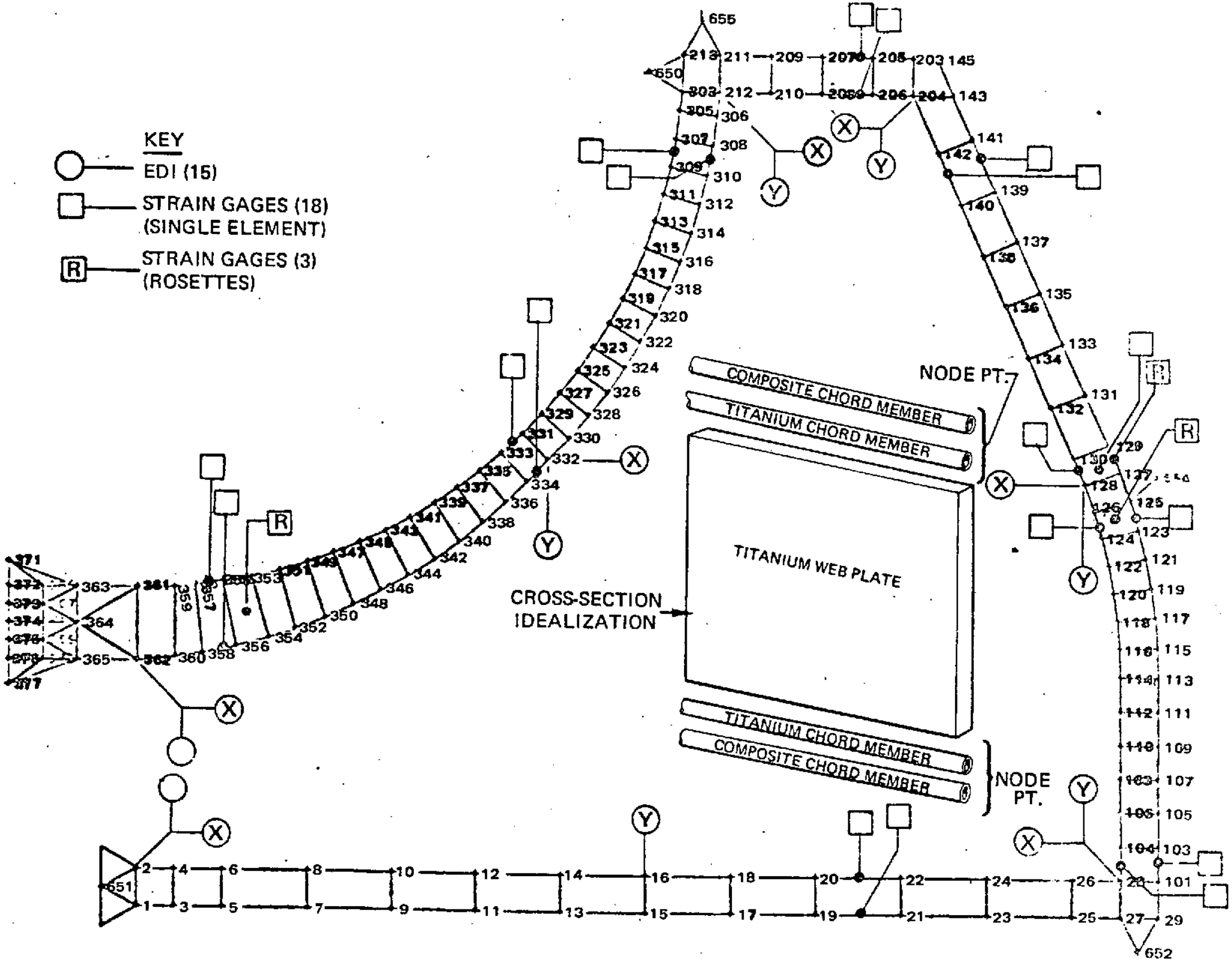


Figure 6.0-2: Model Grame Idealization

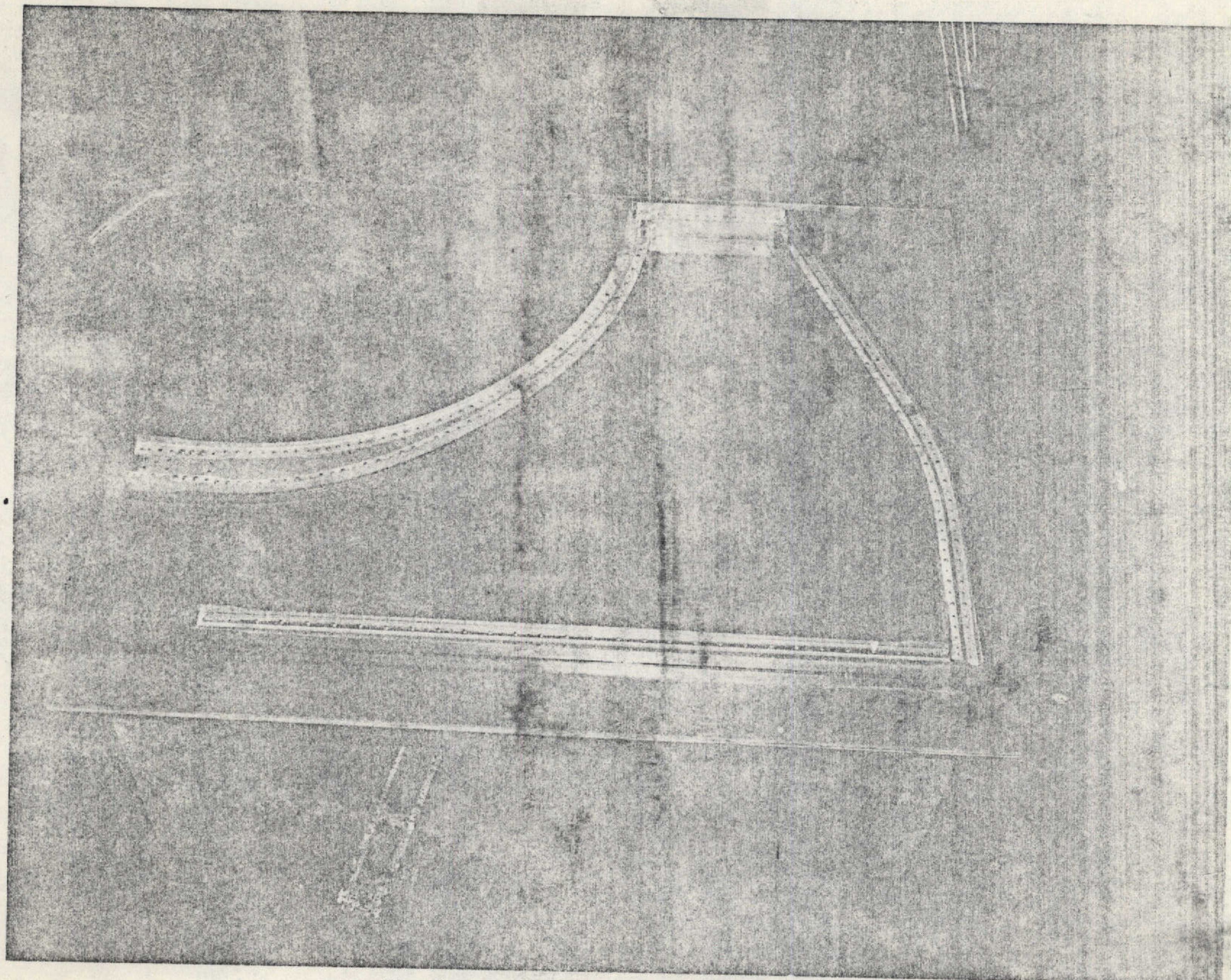


Figure 6.0-3: Model Frame Titanium Details

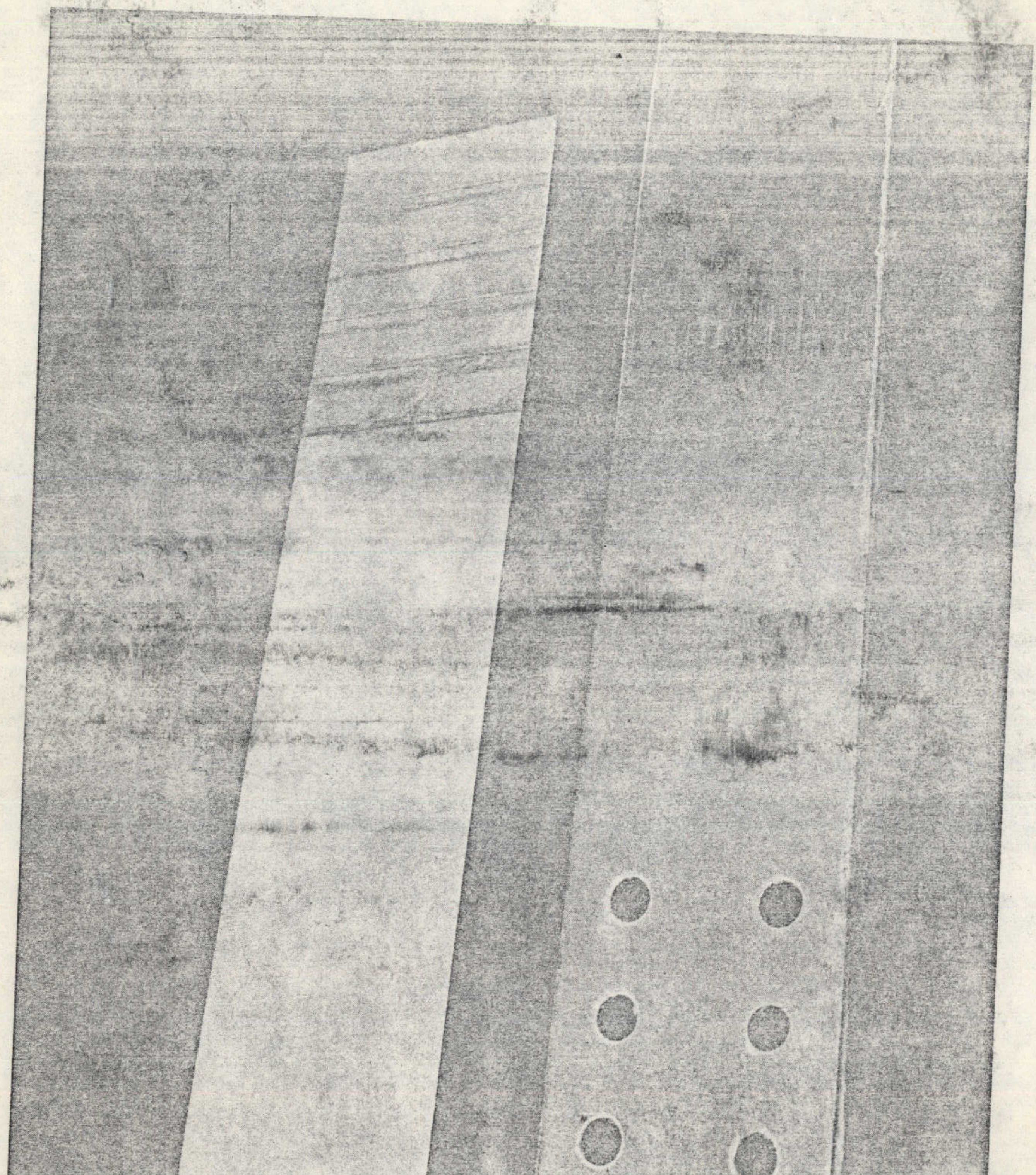


Figure 6.0-4: Basic Five Ply Laminate

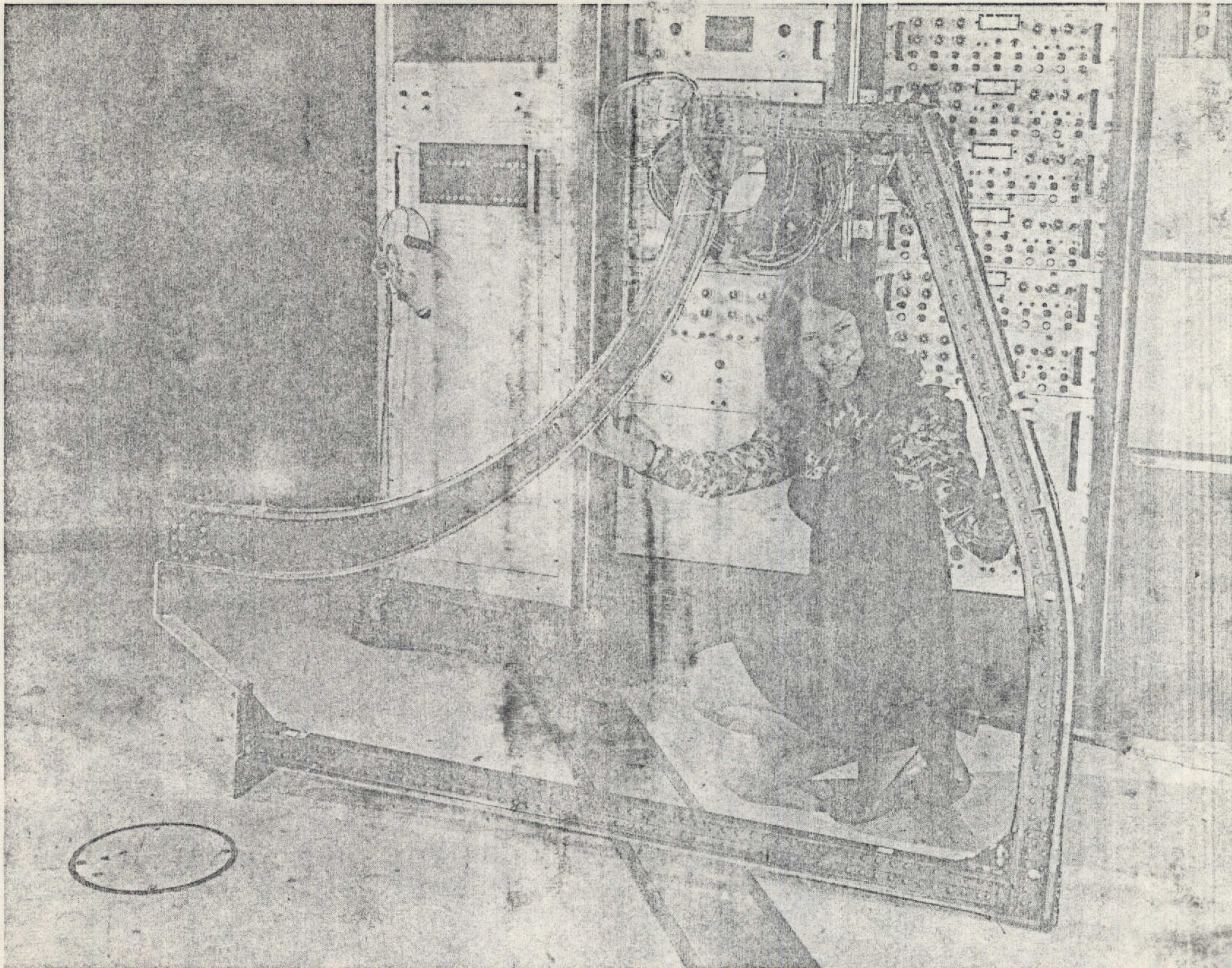


Figure 6.0-5: Model Frame Assembly

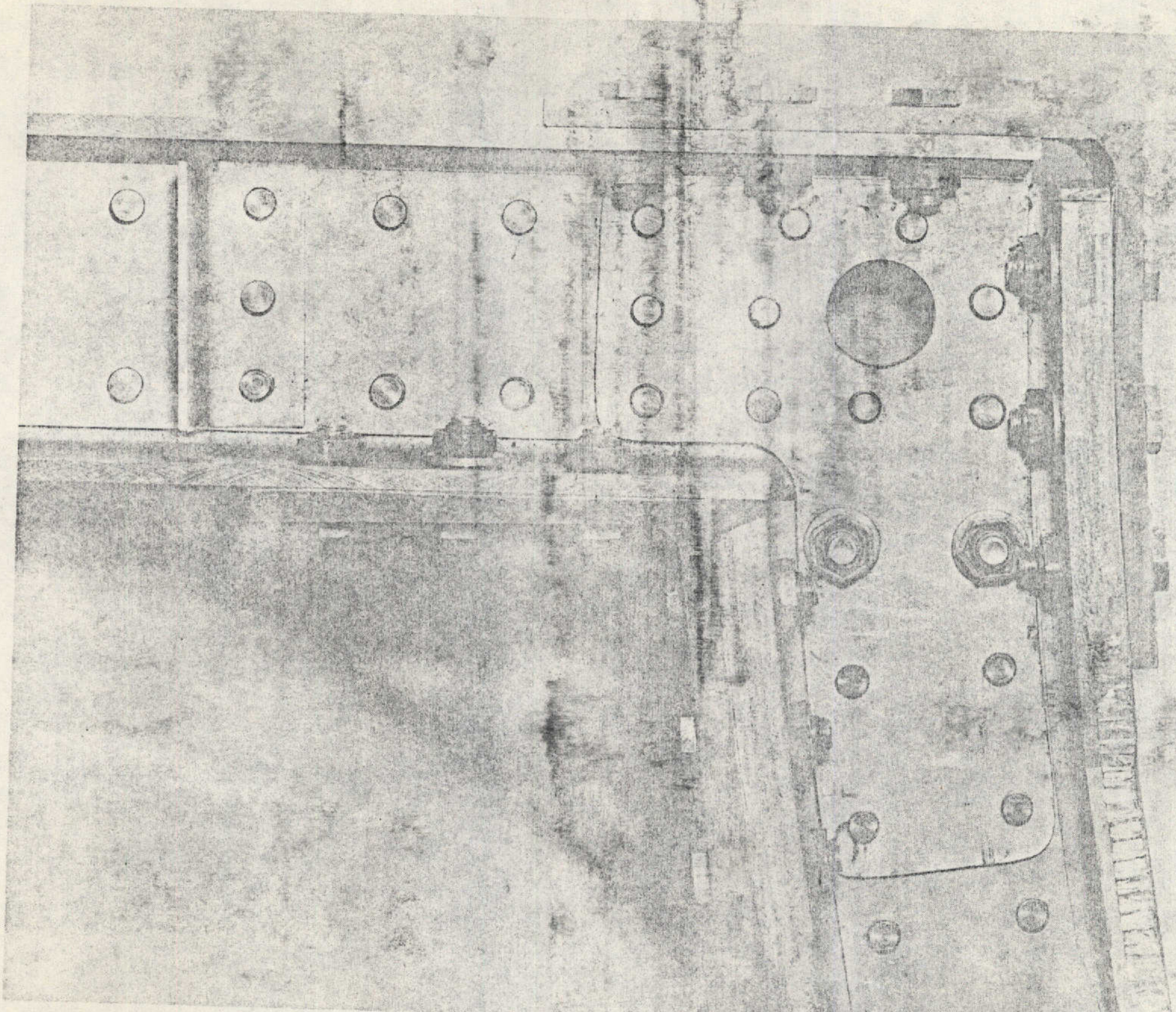


Figure 6.0-6: Model Frame Corner Detail—Stiffener Side

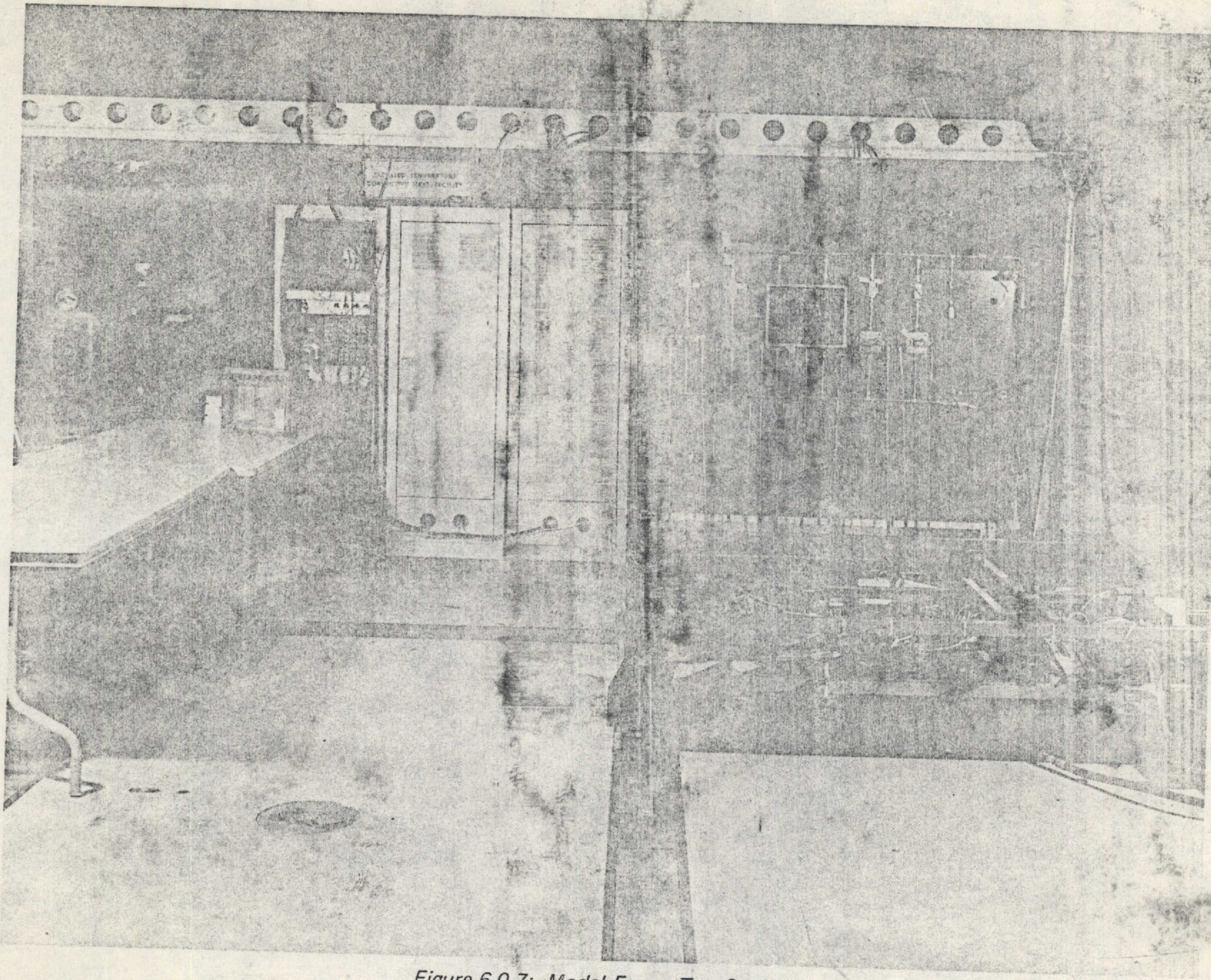


Figure 6.0-7: Model Frame Test Set-Up

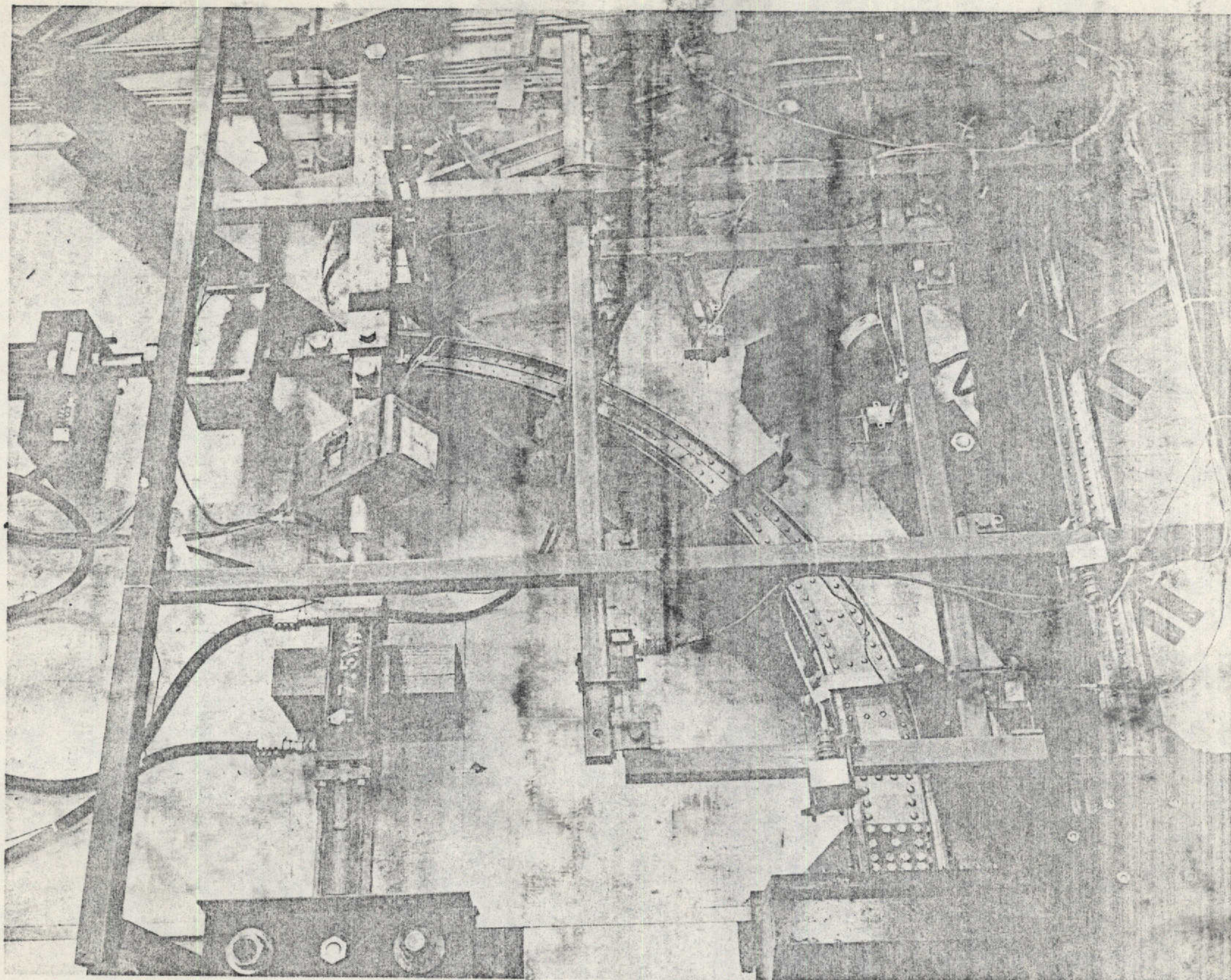


Figure 6.0-8: Close-Up Model Frame Test Set-Up

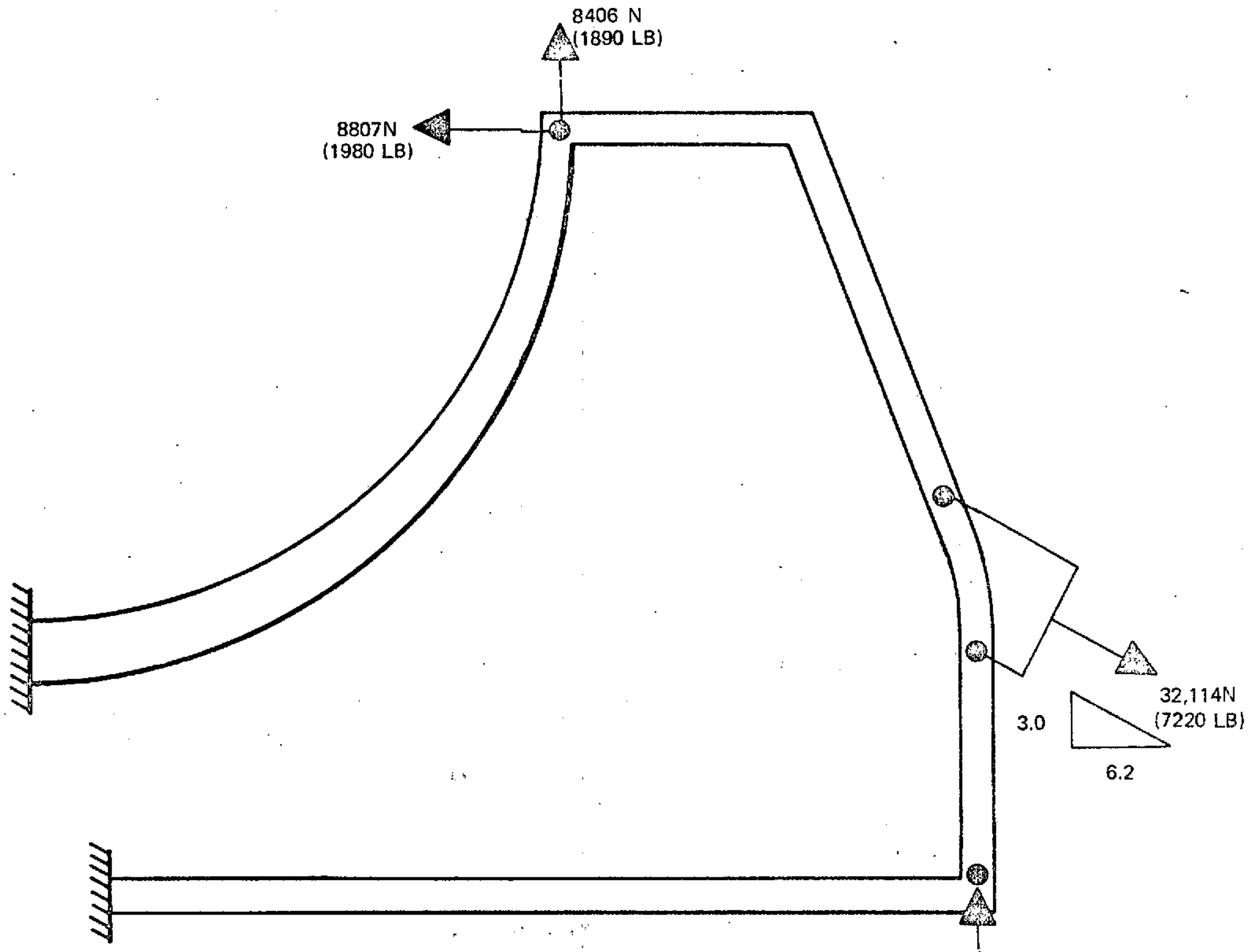


Figure 6.0-9: Max Q Beta – Limit Loads

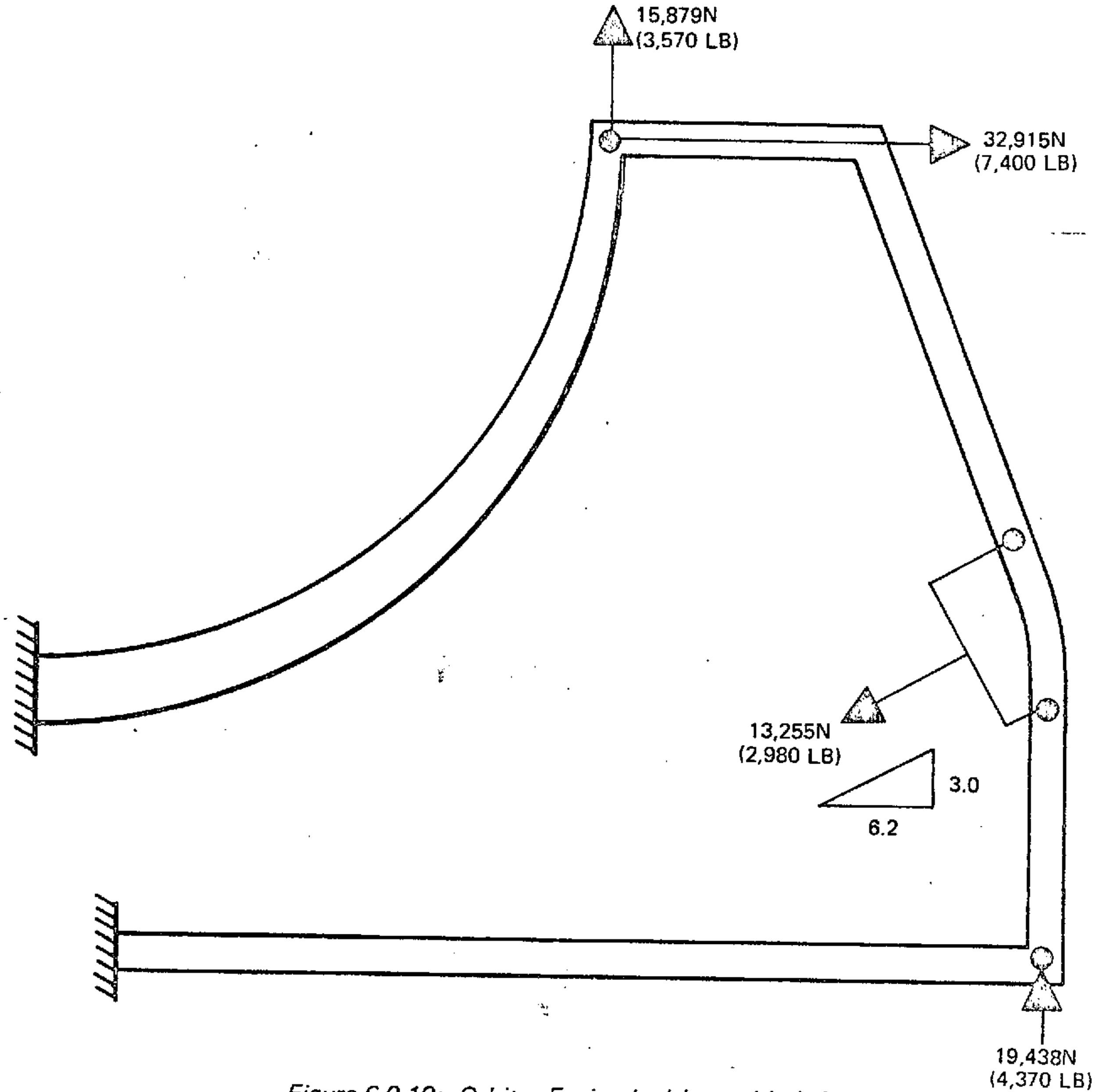


Figure 6.0-10: Orbiter Engine Ignition – Limit Loads

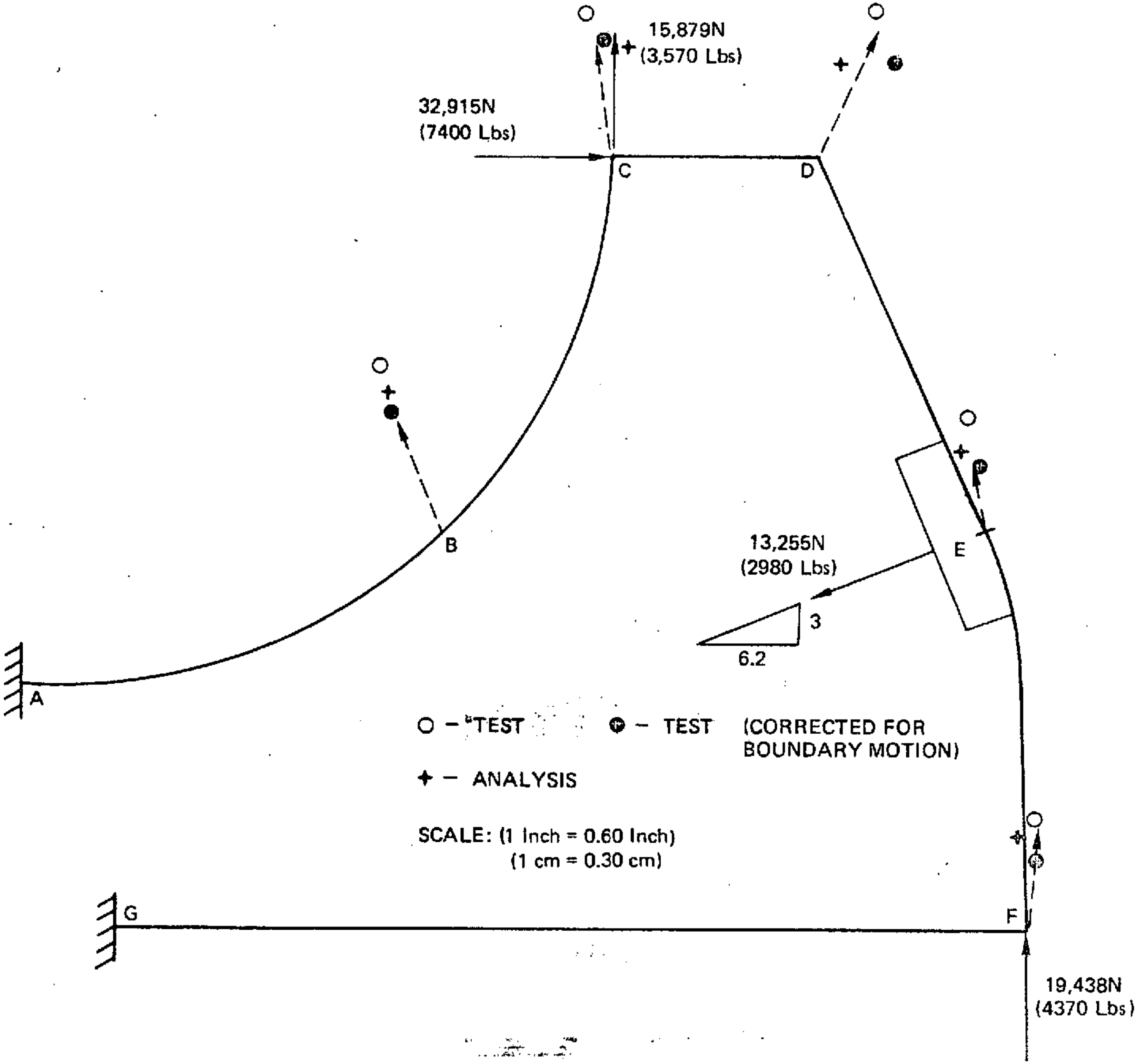


Figure 6.0-11: Frame Displacements — Orbiter Ignition - - Limit Load

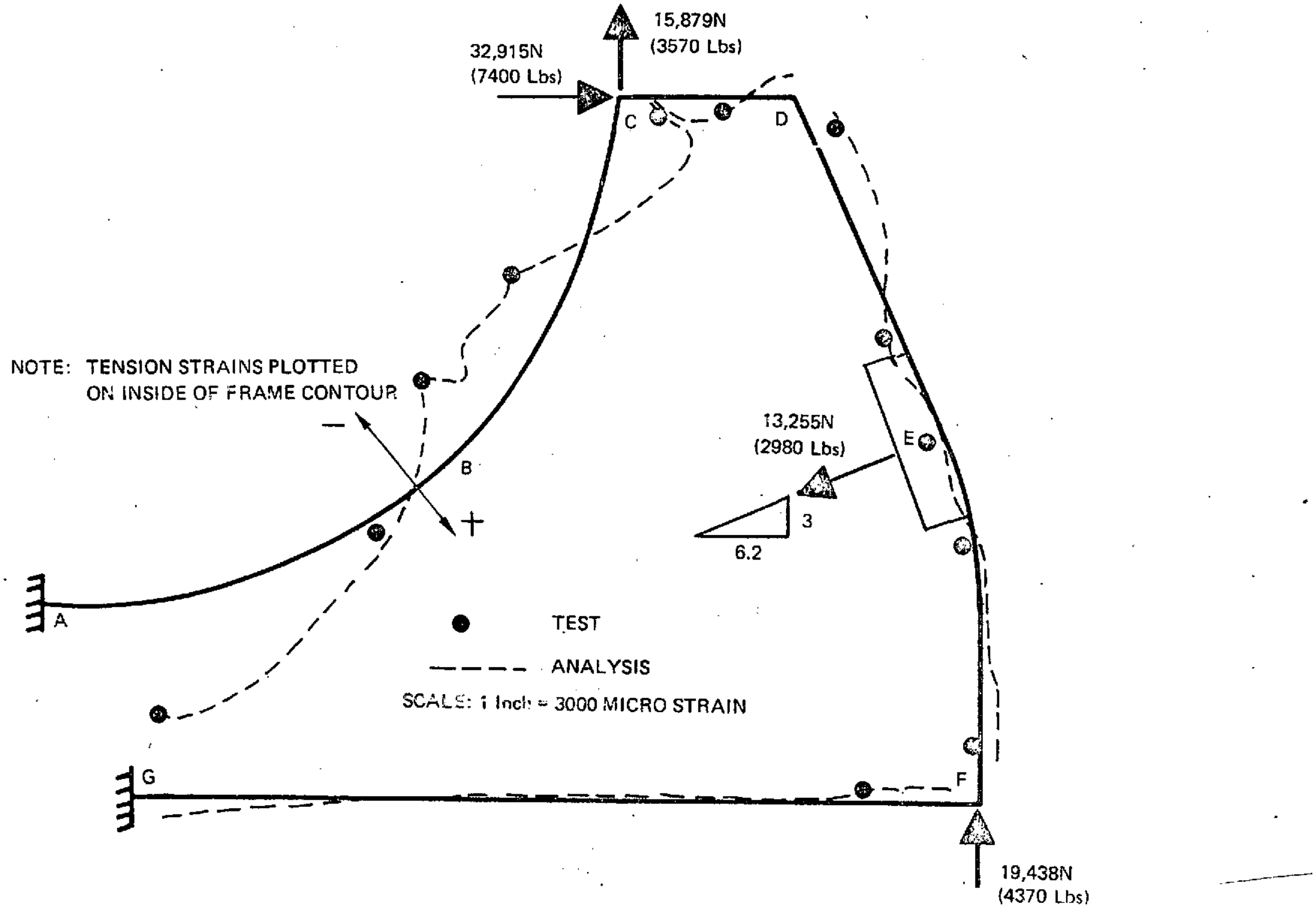


Figure 6.0-12: Frame Strains in Inner Flanges – Orbiter Ignition – Limit Load

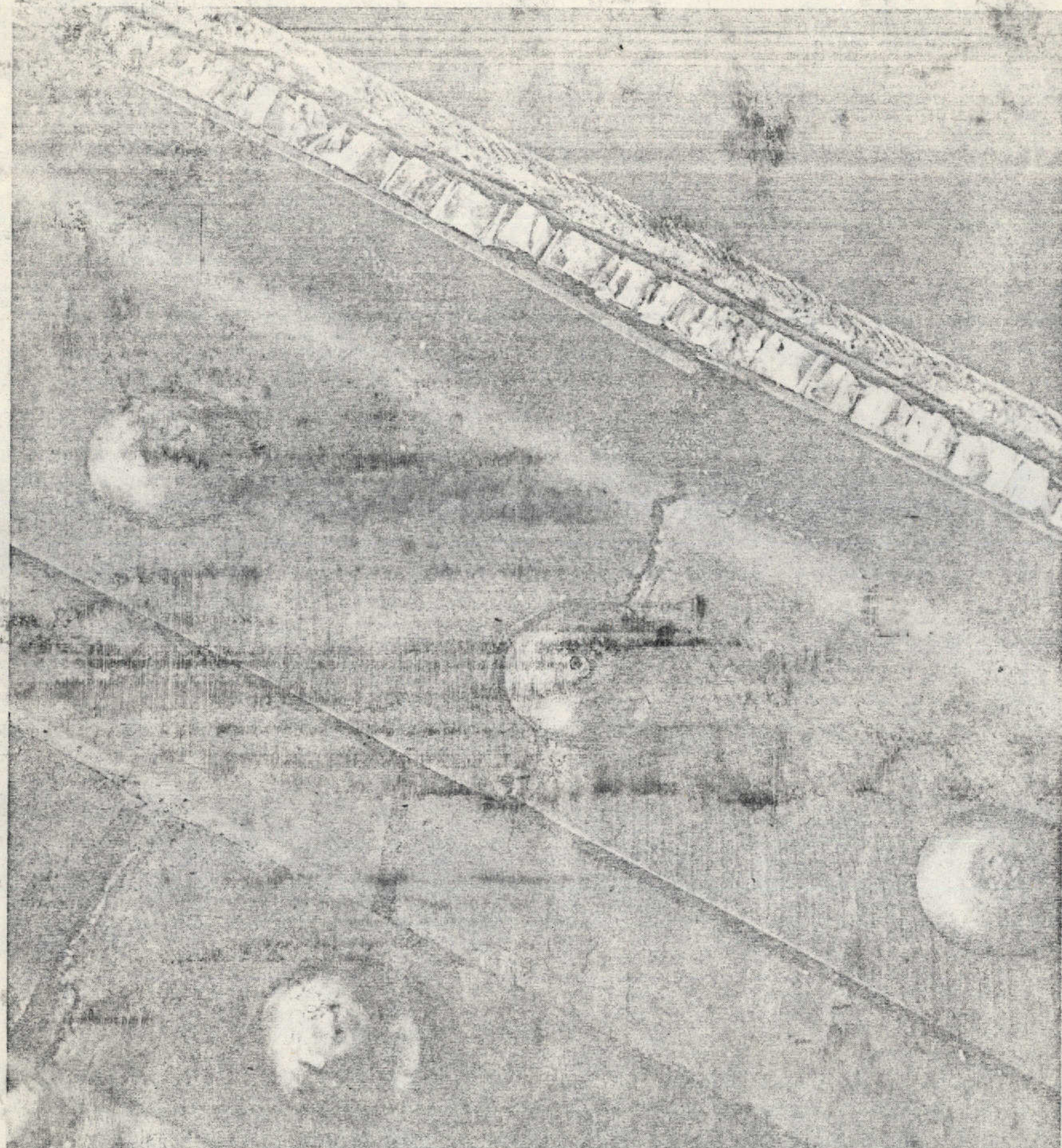


Figure 6.0-13: Model Frame Failure

7.0 PROGRAM CONCLUSIONS

Theoretical studies were performed which indicated that the composite reinforced metal concept can provide a 25% weight saving when used in the design of space shuttle orbiter frames. Experimental tests on both structural elements and components verified that the allowables used in developing these designs were attainable with available material systems, concepts and associated manufacturing processes.

Tests performed on elements showed that concepts proposed in the full scale designs that incorporated the boron/epoxy reinforced aluminum material system can meet the static and cyclic load orbiter design conditions. These concepts and material system can successfully be used up to 394°K (250°F) and meet the thermal cycling requirements.

Test performed on elements incorporating the boron/epoxy reinforced titanium system also met the orbiter static load, cyclic load, elevated temperatures up to 464°K (375°F) and thermal cyclic design requirements.

Tests performed with the boron/polyimide reinforced titanium system were somewhat successful at room and temperatures up to 533°K (500°F). This material system will require additional development to refine the materials and associated processes in order to establish the confidence required to seriously consider it for orbiter applications.

In addition to the material systems, the element and component tests established that concepts and associated manufacturing processes proposed in the full-scale design were feasible. Composite-metal transition load transfer capabilities were developed that met design requirements. The ability to use composites in an efficient manner by tapering them in both width and thickness was successfully demonstrated. Reinforced components were successfully fabricated that incorporated the curvature required by orbiter frame members.

Finally, a subscale model frame was fabricated and tested. The results obtained demonstrated without any uncertainty that a complex orbiter frame incorporating the filamentary composite reinforced metal concept can be built and function successfully under realistic combined orbiter load conditions.

REFERENCES

1. Phase I - Frame Design & Development, NAS 1-10797, Evaluation of a Metal Fuselage Frame Selectively Reinforced with Filamentary Composites for Space Shuttle Application.

2. Phase II - Curved Beam Element Evaluation, NAS 1-10797, Evaluation of a Metal Fuselage Frame Selectively Reinforced with Filamentary Composites for Space Shuttle Application.

3. Phases III & IV - Subscale Model Frame, NAS1-10797, Evaluation of a Metal Fuselage Frame Selectively Reinforced with Filamentary Composites for Space Shuttle Application.