N73-23873

REPORT MDC E0783

DESIGN, PROCESS DEVELOPMENT, MANUFACTURE, TEST AND EVALUATION OF BORON-ALUMINUM FOR SPACE SHUTTLE COMPONENTS

FOURTH QUARTERLY REPORT

Nasa, MSFC
(A&TS-MS-L6)

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

MCDONNELL DOUGLAS
CORPORATION

COPY NO. 2

DESIGN, PROCESS DEVELOPMENT, MANUFACTURE, TEST AND EVALUATION OF BORON-ALUMINUM FOR SPACE SHUTTLE COMPONENTS

10 MARCH 1973 | MDC E0783

FOURTH QUARTERLY REPORT

Prepared for
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812
under
Contract NAS 8-27735
by

R.A. Garrett, et al

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

Saint Louis, Missouri 63166 (314) 232-0232

MCDONNELL DOUGLAS CORPORATION

TABLE OF CONTENTS

LIST OF PAGES

FOREWORD

The work reported herein was accomplished by the McDonnell Douglas Astronautics Company - East (MDAC-E), St. Louis, Missouri under sponsorship of the Research and Process Technology Division, Product Engineering and Process Technology Laboratory of the George C. Marshall Space Flight Center (MSFC), National Aeronautics and Space Administration (NASA). Mr. R. L. Nichols, S&E-PT-MXS, is the NASA MSFC Contracting Officer Representative (COR); the contract identification is NAS 8-27735, "Design, Process Development, Manufacture, Test and Evaluation of Boron-Aluminum For Space Shuttle Components", dated 29 June 1971.

The program is being performed by the Advanced Composites Group, MDAC-E, with Mr. R. A. Garrett serving as Program Manager. The materials and processes development work is under the direction of Mr. J. T. Niemann. Mr. O. R. Otto is responsible for the strength analyses and testing effort and Mr. N. M. Brown directs all design and fabrication coordination effort. The tooling and manufacturing work is under the direction of Mr. R. E. Heinrich. Their contributions to this report are gratefully acknowledged.

1.0 INTRODUCTION, SUMMARY AND PROGRAM STATUS

This Fourth Quarterly Report describes the activities during the fourteenth month through the twentieth month on the design, process development, manufacture, test and evaluation of boron-aluminum for Space Shuttle components under NASA Contract NAS 8-27735. The objective of this program is development of sufficient technology to permit application of boron-aluminum to Space Shuttle components with high confidence. In addition to the acquisition of a significant quantity of mechanical property and process technology data, the realization of this objective will be further demonstrated by fabrication and test of a 1.22m (48 inch) x 1.83m (72 inch) boron-aluminum compression panel capable of distributing a point load of 1555 kN (350,000 lbs) into a uniform running load within a peaking factor of 1.3 at a temperature of 589°K (600°F). Small component testing has been performed by MDAC-E to verify the compression panel design; however, testing of the full size Compression Panel Assembly will be accomplished by MSFC following panel design, fabrication and delivery by MDAC-E.

The contracted effort includes the following five program phases:

Phase I - Materials Evaluation
Phase II - Design Studies
Phase III - Process Technology Development
Phase IV - Fabrication and Assembly
Phase V - Test and Evaluation

The work accomplished during the first thirteen months was described in References (1), (2), and (3), and included effort in each of the five program phases. Phase III effort was reported as complete in Reference (3). During this reporting period, Phase I work was also completed, with Phases II, IV and V very near completion.

Activity during the fourth quarter under Phase I, Materials Evaluation, has included further evaluation of incoming monolayer and bilayer boron-aluminum tape (supplied by Amercom, Inc.), as well as the completion of the remainder of mechanical property specimen fabrication and testing. An additional 45 kg (100 lbs) of boron-aluminum tape has been received and evaluated in this quarter; the total amount received to date is approximately 172 kg (380 lbs). All material required to complete this program has been received and only replacement material shipments are expected in the future.

All material utilized by MDAC-E in pack layups has passed all tests, including peel tests; however, diffusion bond delaminations in bilayer tape have occurred in some edge locations on the Compression Panel skin. This material fault is further described in Section 2.1, Materials Evaluation, and in Section 2.4, Fabrication and Assembly. Due to the tight mechanical filament-to-matrix lock in multilayer diffusion bonded boron aluminum, present techniques including peel tests and ultrasonic C-scan to inspect for an adequate diffusion bond between adjacent foils are not adequate. Further development is needed in this area. No further diffusion bonded bilayer tape will be utilized until an adequate inspection technique is found.

All boron-aluminum mechanical property element tests have been performed in Phase I; the test results exceed design allowables in all cases.

Phase II work in Design Studies has centered in support of Stringer, Component Panel and Compression Panel fabrication, with some additional work in the Truss Web Beam design. In the design of the truss web beam, rectangular tubes will be utilized to reduce the weight penalty associated with end fitting design for circular tubes. These rectangular tubes, although less efficient than circular tubes for local crippling loads, allow a simpler and lighter splice design where two or more tubes intersect. Titanium interleaves are included in these designs to increase local bearing strength without suffering a loss in longitudinal strength by cross plying.

As reported in Reference (3), all Phase III Process Technolgy Development work has been completed. Since that time, effort has been expended in this area to analyze tension test results of Quality Assurance coupon test specimens which are placed in each bonding pack for bond cycle degradation evaluation.

In Phase IV, Fabrication and Assembly, both the Stringer Test Assembly and the Component Panel Test Assembly were completed during this reporting period and sent to the Laboratory for structural testing. Further, following successful completion of these tests, significant progress has been made in the fabrication and assembly of the Compression Panel Assembly, which will be delivered to MSFC for testing at 600°F. For the Compression Panel, all non-boron aluminum detail parts have been completed (frames, clips, fittings, etc.) and the following boron-aluminum parts have been completed:

a) One Compression Panel Skin

1.22m (48 inch) x 1.83m (72 inch)

10 plies to 62 plies in thickness
up to 4 plies of 8 mil 6Al-4V titanium

b) One Compression Panel Hat Section Centerline Stringer
   1.83m (72 inch) long
   21 plies to 52 plies in thickness
   up to 5 plies of 8 mil 6Al-4V titanium

c) Two Compression Panel Hat Section Stringers "C"
   1.83 (72 inch) long
   5 plies to 23 plies in thickness
   up to 5 plies of 8 mil 6Al-4V titanium

d) Two Compression Panel Hat Section Stringers "A"
   1.83m (72 inch) long
   12 plies to 20 plies in thickness
   up to 6 plies of 8 mil 6Al-4V titanium

Only two stringers (Stringer "B") remain to be fabricated and assembly of the completed stringers and skins has already begun. Completion and delivery of the Compression Panel to MSFC is expected in early April, 1973.

Testing under Phase V, Test and Evaluation, has been performed on both the Stringer Test Assembly at room temperature and on the Component Panel Test Assembly at room temperature and 600°F. In both tests, ultimate design load was exceeded without failure and the Compression Panel design has now been fully verified. The load distribution in the Component Panel Test at 600°F was in very good agreement with the distribution as predicted by MDAC-E analysis; we have full confidence that the load distribution at the distributed load end in the Compression Panel test, when performed by MSFC, will be uniform within a peaking factor far less than the contract requirement of 30 percent. A significant milestone in the development of boron aluminum technology was achieved with these complex test assemblies which are the first simulated vehicle structures to demonstrate design ultimate load in a 600°F test environment.

2.0 PROGRESS DURING THE FOURTH QUARTER

During this reporting period, work has been completed in Phase I, Materials Evaluation, and is very near completion in Phase II, Design Studies. All Compression Panel drawings have been completed under Phase II. Phase III, Process Technology Development, has been previously reported as completed. Under Phase IV, Fabrication and Assembly, two boron-aluminum test structures have been completed (Stringer Test Assembly and Component Panel Test Assembly), and the Compression Panel Assembly is nearing completion. Structural tests of the Stringer Test Assembly at room temperature and the Component Panel Test Assembly at 600°F by MDAC-E under Phase V, Test and Evaluation, were fully successful and verified the Compression Panel design; both structures sustained design ultimate loads (equivalent) with only minor structural damage.

The work accomplished in each phase is described in detail below.

2.1 Phase I - Materials Evaluation

The work to be accomplished under Phase I includes both review and characterization of incoming boron-aluminum monolayer and bilayer tape as supplied by Amercom, Inc., and generation of sufficient mechanical property data for compression panel design purposes.

2.1.1 Evaluation of Incoming Material - Approximately 172 kg (380 lbs) of boron-aluminum monolayer and bi-layer tape have been received and inspected. With the exception of several pounds of replacement material, all material procured for use on the program has been received. To date, a total of 20.68 kg (46 lbs) or 12% of the total has been rejected for failure to meet MDAC-E specification MMS 584 requirements. The causes for rejection included the following: poor diffusion bonds - 7.7 kg (17 lbs), surface irregularities - 11 kg (24.2 lbs), and low strength - 2 kg (4.5 lbs).

Since the onset of this program, monolayer bond quality has improved markedly and is not now a major cause for the rejection; bilayer material requires additional development at present. Surface finish has not been a problem, but other surface irregularities such as filament spacing, cross-overs and cleanliness, represent the major reasons for rejection, and more significantly, quality in this area has not improved during the program. Strength and volume content control have not been significant problems.

Although monolayer diffusion bond quality is now considered adequate, serious problems have been encountered in fabricating components from bilayer material. In recent months delaminations have been observed in bonded structures and traced to poor diffusion bonds in bilayer foils. These defective foils had passed the hand peel tests used to check bond quality. Because of the fiber interlocking action of bilayer, detection of weak diffusion bonds in this material by peel testing is unreliable. Therefore, a study is now underway to develop new techniques for detecting weak bonds in bilayer foils. Methods being considered include localized heating to induce differential straining and local bulging of the matrix at poorly bonding areas and vacuum gripping to induce failure of weak diffusion bonds. Until a satisfactory test technique is developed, the use of bilayer will be restricted to non-critical applications.

2.1.2 Mechanical Property Test Results - All mechanical property element tests required for the compression panel design have been completed. Test reports for these tests, prepared by the laboratory, are currently being reviewed. Final results and evaluation of these tests will be included in the Final Report. These tests are summarized below:

Longitudinal Tension
Transverse Tension
Longitudinal Compression
Transverse Compression
Rail Shear
Diagonal Tension
Crippling
Interlaminar Shear
Tensile Tests of $\pm 45°$ Laminates
Compressive Tests of $\pm 45°$ Laminates

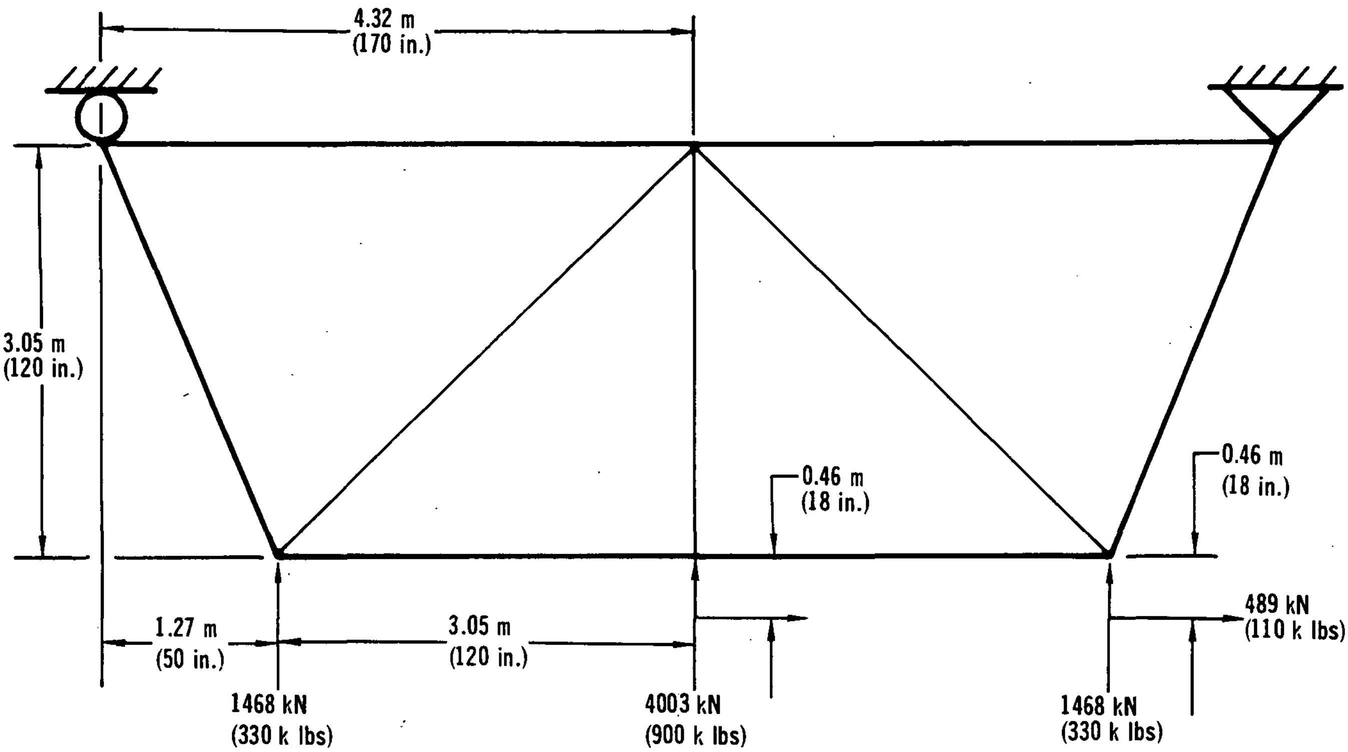
2.2 Phase II - Design Studies

In Phase II, Design Studies, components and assemblies are to be designed and analyzed to be representative of full scale hardware. The components and assemblies to be designed include a 1.22m x 1.83m (48 inch x 72 inch) compression panel, a thrust structure beam of truss design, a thrust structure beam of shear web design, and a component panel and a stringer test assembly design to be used for panel design verification testing. Of these tasks, all are complete with the exception of the truss and shear web thrust structure beam designs, which are now nearing completion.

2.2.1 Final Compression Panel Design - The design of the Compression Panel has been finalized and all Engineering drawings have been released to Manufacturing for fabrication and assembly; progress in this area is described in Section 2.4. The final design for the Compression Panel is identical with that described in Reference (3) with one exception. An alloy steel thrust plate has been incorporated in place of the boron aluminum thrust plate shown in Reference (3) to reduce program cost; this steel thrust plate was also utilized in the successful Component Panel Test Assembly test described in Section 2.5.

2.2.2 Thrust Structure Truss Web Beam Design and Analysis - The truss beam design is proceeding using the geometry and loading conditions as described in Figure 2-1. Basically the truss beam design utilizes a 4.5 inch x 9.0 inch rectangular cross section for the major loaded members with other tubes being sized to fit these members in the intersection areas. The rectangular tubes consist of flat, tapered upper and lower plates joined to channel section edge members by spotwelding. Additional plies and titanium interleaves are introduced in the upper and lower plates in splice areas to increase the local bearing allowable. The plates also increase in width at joints to obtain the surface areas for mechanically attaching the tubes together to affect the joint splices. A detail layout is being prepared for detail analysis and review prior to the submittal of the study results.

Both circular and rectangular tube designs have been evaluated. Preliminary analytical studies have been conducted to determine the most efficient design configuration for both circular and rectangular cross-section tubes. To aid in these studies, two computer programs were written for use on the direct access Sigma 7 digital computer system. Computer program TUBE was written to optimize circular tubes while computer program RECTANGLE was written to optimize



TRUSS BEAM GEOMETRY AND APPLIED LOADS

FIGURE 2-1

rectangular tubes. These programs determine geometrical proportions which maximize axial compressive strength for a given cross sectional area. Currently, emphasis is being placed on rectangular shaped members because the joint design is greatly simplified. Although circular tubes are lighter than rectangular tubes, this weight difference is more than balanced by complex and heavy fittings required to join circular tubes.

The method of analysis used to determine the allowable axial compressive strength for a unidirectional boron aluminum circular tube includes both local and general instability failure modes. For long columns, stability is determined using the Euler formula. For short columns, the Johnson parabola formula is used because it allows an interaction of flexural and local crippling failure modes. Equations used in this analysis are given below.

Long Column Stability - Euler Formula (Ref 4)

$$\sigma_e = \frac{\pi^2 E_L r^2}{2L^2}$$

The allowable column stress, σ_{COL}, is defined as:

$$\sigma_{COL} = \sigma_e \quad \text{for } \frac{L}{r} \geq \pi\sqrt{\frac{E_L}{\sigma_{cr}}}$$

<u>Short Column Stability - Johnson Formula (Ref 4)</u>

$$\sigma_c = \sigma_{cr}\left(1 - \frac{\sigma_{cr}L^2A}{4\pi^2E_LI_{CG}}\right)$$

$$\sigma_{COL} = \sigma_c \quad \text{when } \frac{L}{r} < \pi\sqrt{\frac{E_L}{\sigma_{cr}}}$$

Local stability (crippling) strength, σ_{cr}, is determined using the formula, Ref 5 ,

$$\sigma_{cr} = \frac{\gamma K\phi\sqrt{E_LE_T}}{2(r/t)} \leq F_{co}$$

Where

$$K = 2[3(1 - \mu_{TL}\mu_{LT})]^{-1/2}$$

And

$$\phi = \frac{2G_{LT}}{\sqrt{E_LE_T}}(1 + \mu_{TL}\mu_{LT})^{1/2}$$

or

$$\phi = 1, \text{ whichever is lower}$$

$$\gamma_o = 1 - 0.901\ (1 - e^{-\theta})$$

$$\theta = \frac{1}{16}\sqrt{\frac{r}{t}} \quad \text{(for unidirectional orthotropic tubes)}$$

Terms used in the previous equations are defined below:

F_{co} - Compressive stress cutoff, psi

E_L - Longitudinal compressive modulus, psi

E_T - Transverse tensile modulus, psi

G_{LT} - Shear Modulus, psi

μ_{LT} - Major Poisson's ratio

μ_{TL} - Minor Poisson's ratio

r - Tube radius, in.

t - Tube thickness, in.

L - Effective column length, in.

A - Cross sectional area of the tube, in.^{2}

I_{CG} - Moment of inertia, in.^{4}

The method of analysis used to determine the allowable axial compressive strength of rectangular tubes is similar to that used for circular tubes. Both local and general instability failure modes are considered and both long and short column formulae are used. Equations used in the analysis of rectangular tubes are given below:

Long Column Stability - Euler Formula

$$\sigma_e = \frac{\pi^2 E_L I_{MIN}}{L^2 A}$$

where

I_{MIN} = Minimum moment of inertia, in.^{4}

The allowable column stress, σ_{col}, is defined as:

$$\sigma_{col} = \sigma_e \qquad \text{When} \quad L/\sqrt{\frac{I_{MIN}}{A}} \geq \pi \sqrt{\frac{2E_L}{F_{cc}}}$$

Short Column Stability - Johnson Formula

$$\sigma_c = F_{cc} \left(1 - \frac{F_{cc} L^2 A}{4\pi^2 E_L I_{MIN}} \right)$$

$$\sigma_{col} = \sigma_c \qquad \text{When} \quad L/\sqrt{\frac{I_{MIN}}{A}} < \pi \sqrt{\frac{2E_L}{F_{cc}}}$$

Crippling strength, F_{CC}, of rectangular tubes is determined by the following equation,

$$F_{CC} = \frac{\sum_{i=1}^{4} F_{CC_i} b_i t_i}{\sum_{i=1}^{4} b_i t_i}$$

where

F_{CC_i} - No-edge-free crippling strength of ith element, psi (based on most recent crippling test results)

b_i - Length of ith element, in.

t_i - Thickness of ith element, in.

Using these methods of analysis, studies were initiated to determine optimum geometrical proportions for circular and rectangular tubes capable of sustaining the various applied compressive loads for members defined in the truss web study. Results from these studies indicated that circular boron aluminum tubes are substantially lighter than rectangular tubes. However, preliminary analysis of end fitting details for both types of members, indicated that weight of circular tube end fittings is considerably higher than for rectangular tubes. Further, in order to design reasonable joints for the circular tube truss concept, it was necessary to substantially compromise optimum tube geometry, resulting in increased tube weight. Therefore, to obtain an overall minimum weight design, the rectangular tube concept was selected for the truss web design. Detail analysis of member sizes, including joint details, is now in progress.

2.3 Phase III - Process Technology Development

All specific tasks, investigations and studies planned for Phase III, Process Technology Development, have been completed. Effort will continue to be expended to provide necessary in-process coordination and consultation in support of the remaining Manufacturing activity. Appropriate data which may be developed during this Manufacturing support phase will be reported as available; all Phase III work will be summarized in the Final Report.

2.4 Phase IV - Fabrication and Assembly

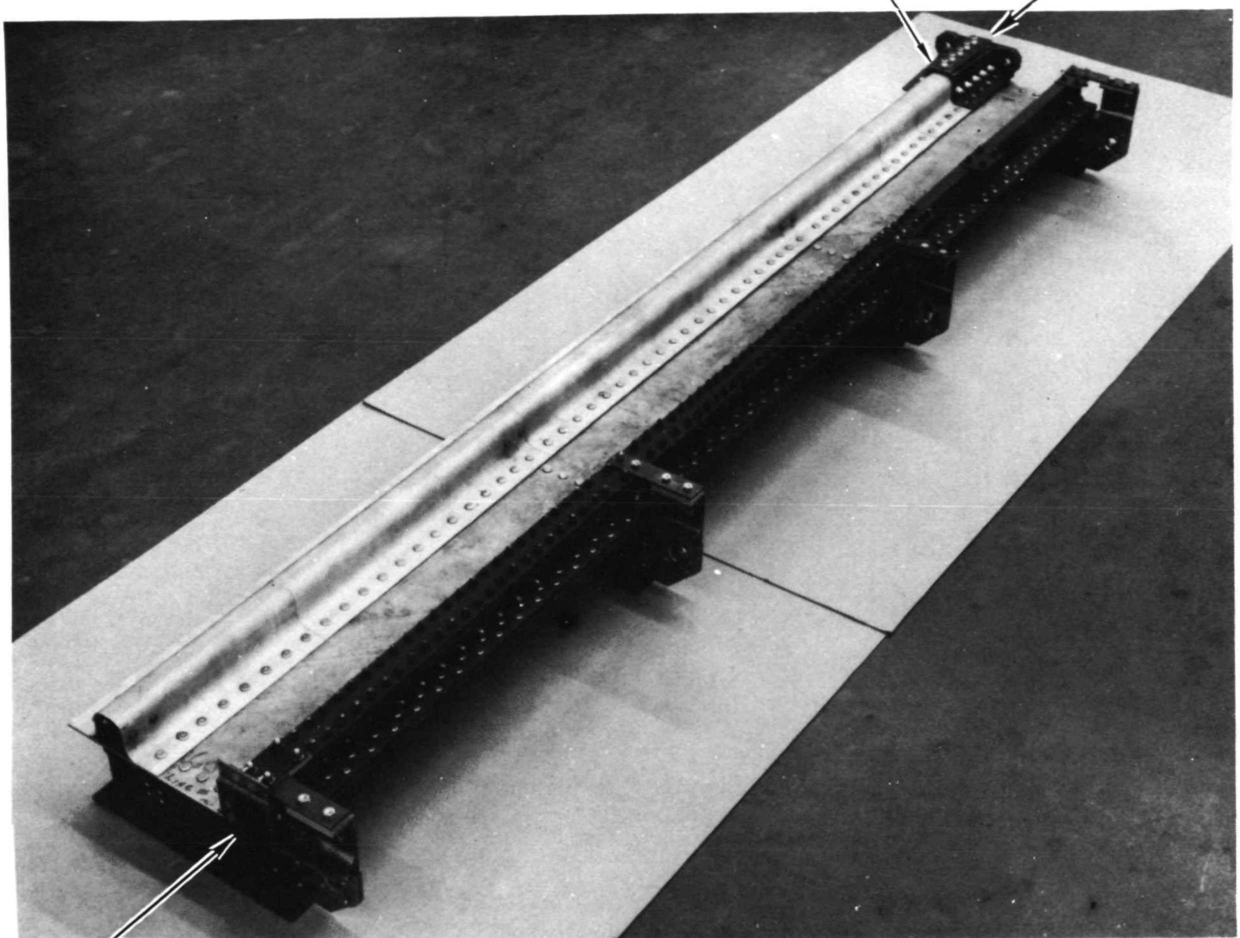
Both the Stringer Test Assembly and the Component Panel Test Assembly were completed during this reporting period. The fabrication of these assemblies is further described in Section 2.4.1 and 2.4.2 respectively. Significant progress has also been made in the fabrication and assembly of the Compression Panel Assembly, which will be delivered to MSFC. For the Compression Panel, all nonboron-aluminum detail parts have been completed (frames, clips, fittings, etc.).

Only two stringers (Stringer "B") remain to be fabricated and assembly of the completed stringers and skins has already begun. Completion and delivery of the Compression Panel to MSFC is expected in early April 1973; further discussion of the Compression Panel fabrication is presented in Section 2.4.3.

2.4.1 Stringer Test Assembly Fabrication - The stringer test assembly as shown in Figure 2-2 was completed and delivered to the laboratory for testing. This assembly consisted of a 12 ply boron aluminum skin of $\pm 45°$ cross ply orientation and a full length panel stringer identical in design to the outboard stringer of the compression panel assembly. A sheet metal stringer assembly attached to the skin served as a load introduction distribution member to simulate the loading of the compression panel assembly.

The fabrication of the first boron-aluminum composite stringer, as reported in the third quarterly period (Ref. 3), resulted in a lack of bond. Investigation to determine the cause of this lack of bond indicated the need to incorporate an automatically controlled bonding cycle to minimize temperature extremes and variations experienced previously in manual control. Also, it was found that the control thermocouples of this particular cycle were reading erroneously high; consequently the maximum temperature attained was marginally low for adequate bonding. A complete check and calibration on the equipment and trial cycles were made to verify the bonding cycle prior to resumption of fabrication. Since the resumption of fabrication, all parts subjected to the bonding cycle now under automatic control have been successfully bonded.

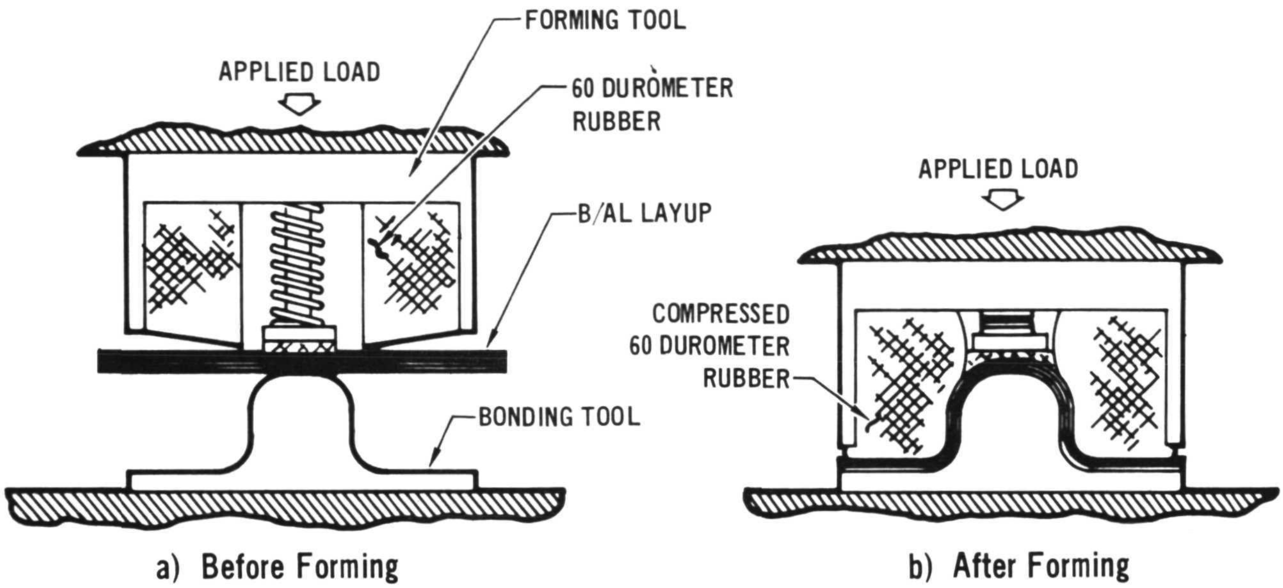
Of major importance to the successful fabrication of the composite stringer was the forming technique employed. A tooling concept was developed to permit simultaneous mechanical forming of all hat section monolayers prior to bonding as opposed to the layer by layer hand forming technique previously used. The tooling



COMPLETED STRINGER TEST ASSEMBLY

FIGURE 2-2

schematic, shown in Figure 2-3, consists of a "C" shaped metal frame with shaped rubber inserts which when used with a press brake enables forming of a flat pack assembly to fit snugly on the bonding tool. The forming steps are shown in Figures 2-4 through 2-6. These figures show the development tool configuration from which a production tool was fabricated (Figure 2-7). As shown in these figures, all material including cover sheets, slip and spacer sheets for the bonding pack are formed together as a unit. Clamps are affixed to the forming and bonding tools prior to release of the press brake pressure to insure retention of external pressure on the pack until the pack is welded and vacuum is attained. Figure 2-8 illustrates the clamped assembly during the welded operation. The stringer fabricated for the stringer test assembly using this forming method is shown in



A FLAT PACK LAY-UP IS MADE CONSISTING OF COPPER-COATED BORON/ALUMINUM MONOLAYER FOILS, TITANIUM FOIL INTERLEAVES, STOP-OFF COATED SLIP SHEETS AND AN OUTER ENVELOPE SHEET. THIS LAY-UP IS THEN PLACED IN A BRAKE PRESS ON THE BONDING TOOL AS SHOWN IN (a). PRESSURE THEN IS APPLIED AS IN (b) TO FORM THE ENTIRE LAY-UP. FORMING PRESSURE IS MAINTAINED WHILE THE OUTER ENVELOPE SHEET IS WELDED ALL AROUND THE PERIPHERY OF THE BONDING TOOL. THE INTERIOR OF THE WELDED PACK IS EVACUATED AND THE FORMING PRESSURE THEN RELEASED. ATMOSPHERIC PRESSURE HOLDS THE LAY-UP TO THE TOOL AND PREVENTS SPRINGBACK OF THE B/AL AND TITANIUM FOILS.

MECHANICAL FORMING OFFERS THE FOLLOWING ADVANTAGES:

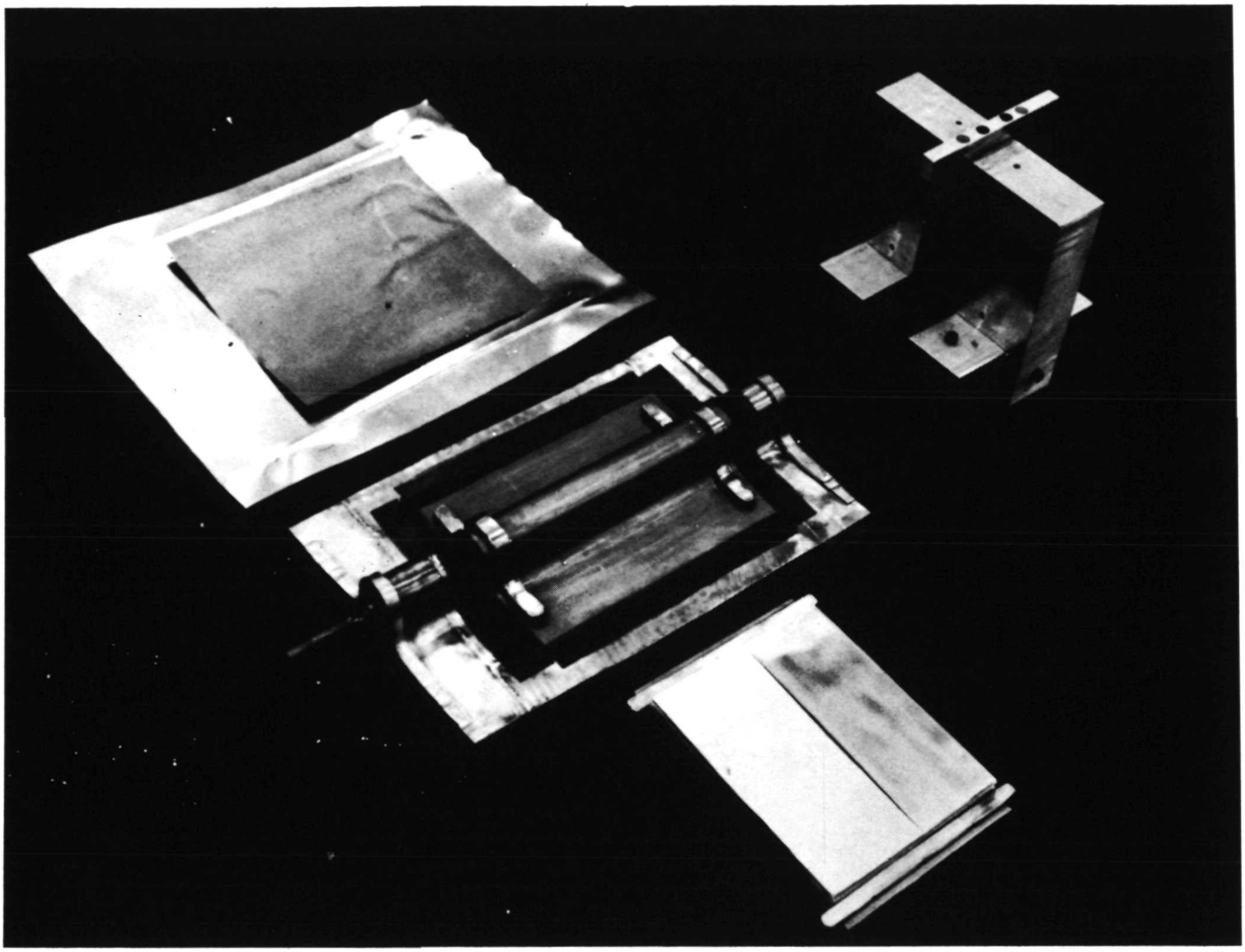
1. SUBSTANTIAL REDUCTION OF LAY-UP COSTS
2. HIGHER QUALITY OF FINAL PRODUCT BY VIRTUE OF BETTER CONTROL OF RADIUS CONTOUR AND CONTACT BETWEEN PLIES
3. PERMITS INCLUSION OF TITANIUM ALLOY INTERLEAVES – SPRINGBACK OF TITANIUM CANNOT BE PREVENTED IN HAND LAY-UP OPERATIONS.

MECHANICAL FORMING SCHEMATIC

FIGURE 2–3

Figure 2-9. All stringers for the test component panel and full compression panel to date, have been fabricated using this forming technique.

Mechanical forming has consistently produced the stringer hat sections with intimate material contact and bonding through out the cross section. Titanium interleaves and cross plying in shaped sections, which previously had been major problems in shaped sections due to spring back, are practical designs considerations utilizing the mechanical forming with the eutectic bonding process. A typical cross section is shown in Figure 2-10.

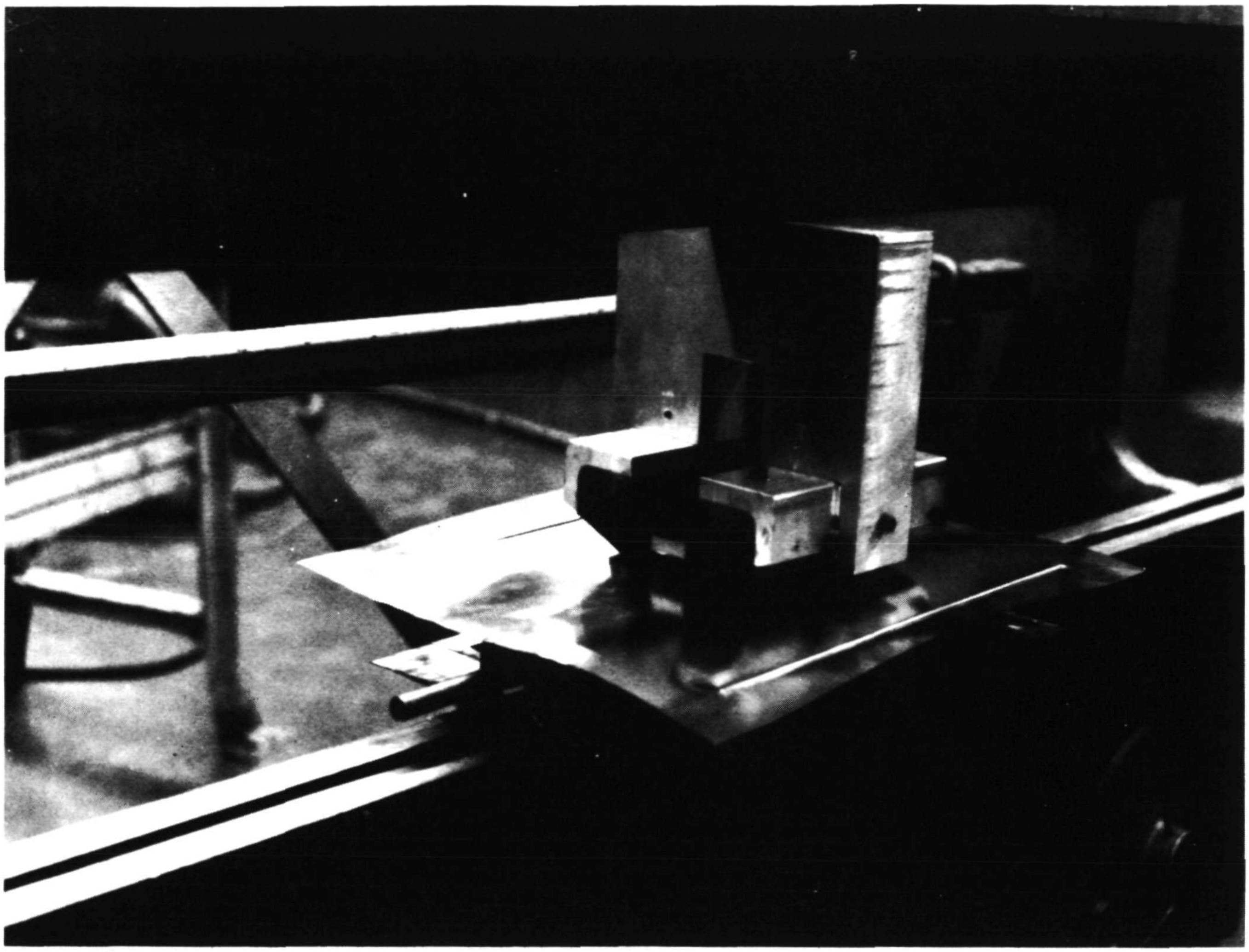


DETAILS FOR MECHANICAL FORMING HAT SECTION

FIGURE 2-4

The stringer test assembly was assembled using Hy-Lok fasteners. Drilling was accomplished using a Branson ultrasonic unit with diamond core drills. This unit requires very rigid mounting, consequently is stationary, requiring the parts be moved into position for drilling each hole. Although the drilling time and drill life using this technique is superior to other methods, the set-up time is a major drawback. Attempts were unsuccessful to make the ultrasonic unit portable due to the mounting ridigity requirements.

2.4.2 Component Panel Test Assembly Fabrication - The component test assembly, as shown in Figure 2-11, was completed and delivered to the laboratory for testing. This assembly is identical to the first bay of the compression panel test assembly consisting of a varying thickness composite skin and seven (7) stringers of tapering cross section with a steel thrust plate in the load introduction area

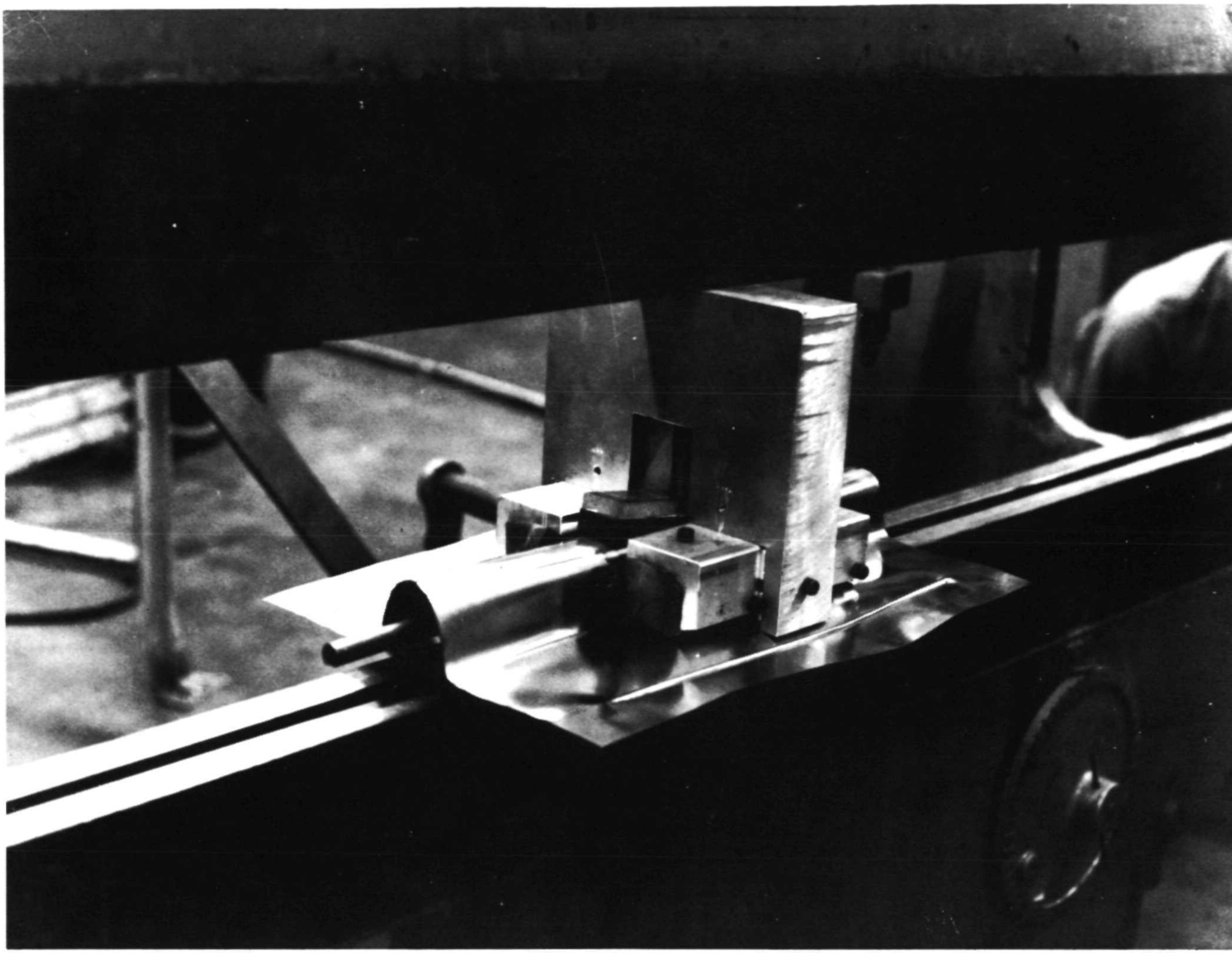


HAT SECTION FLAT PACK IN POSITION FOR MECHANICAL FORMING

FIGURE 2–5

and two sheet metal ring assemblies supporting the panel.

This assembly was fabricated and assembled using the same processes described in Section 2.4.1. Use of the mechanical forming and automated bonding cycle produced quality parts. The use of the ultrasonic drilling unit was discarded during the fabrication of this assembly as attempts to make the unit portable were not successful and set up time for rigidly mounted drill unit became prohibitive. A DeSoutter rack feed drill using high speed drills was substituted and although tooling for support of the drill unit was primitive and frequent changing of drills was required (approximately one drill was used per hole), the total drilling time was substantially reduced. Using this method an acceptable hole could be generated in two minutes in this assembly. This technique proved reliable and efficient; consequently it has been adopted for the remaining assembly work.



FORMED HAT SECTION

FIGURE 2-6

Inspection of the skin for this assembly revealed some delaminations in the bilayer material at the edges. Ultrasonic C scans of the skin showed the delamination to be localized and after assembly would be reinforced by stringer attachments. The delaminations were judged acceptable as is.

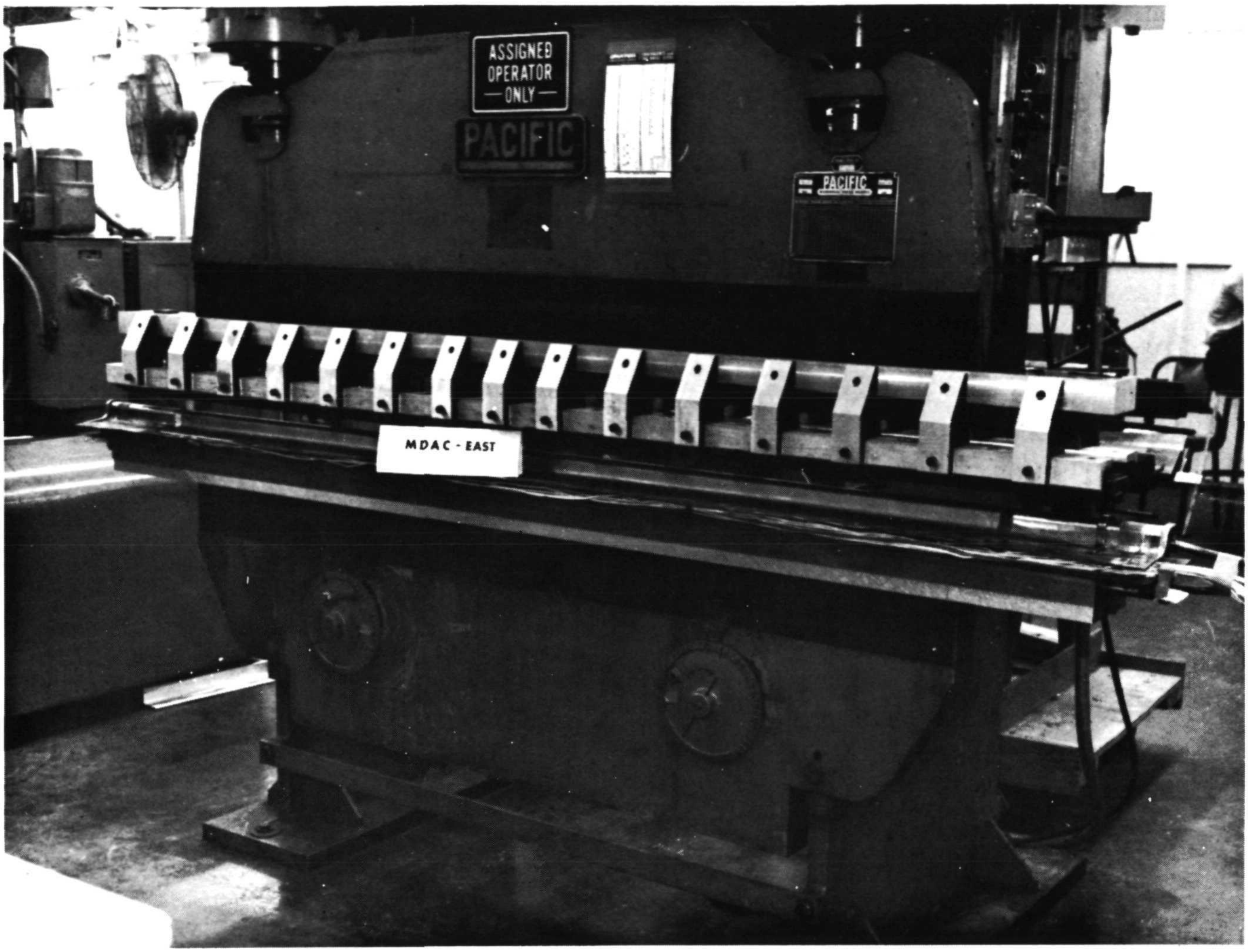
2.4.3 <u>Compression Panel Fabrication</u> - The fabrication of the compression panel detail parts and assembly is well under way with five stringers and the full panel skin fabricated as described below:

a) One Compression Panel Skin

1.22m (48 inch) x 1.83 m (72 inch)

10 plies to 62 plies in thickness

up to 4 plies of .008 6Al-4V titanium



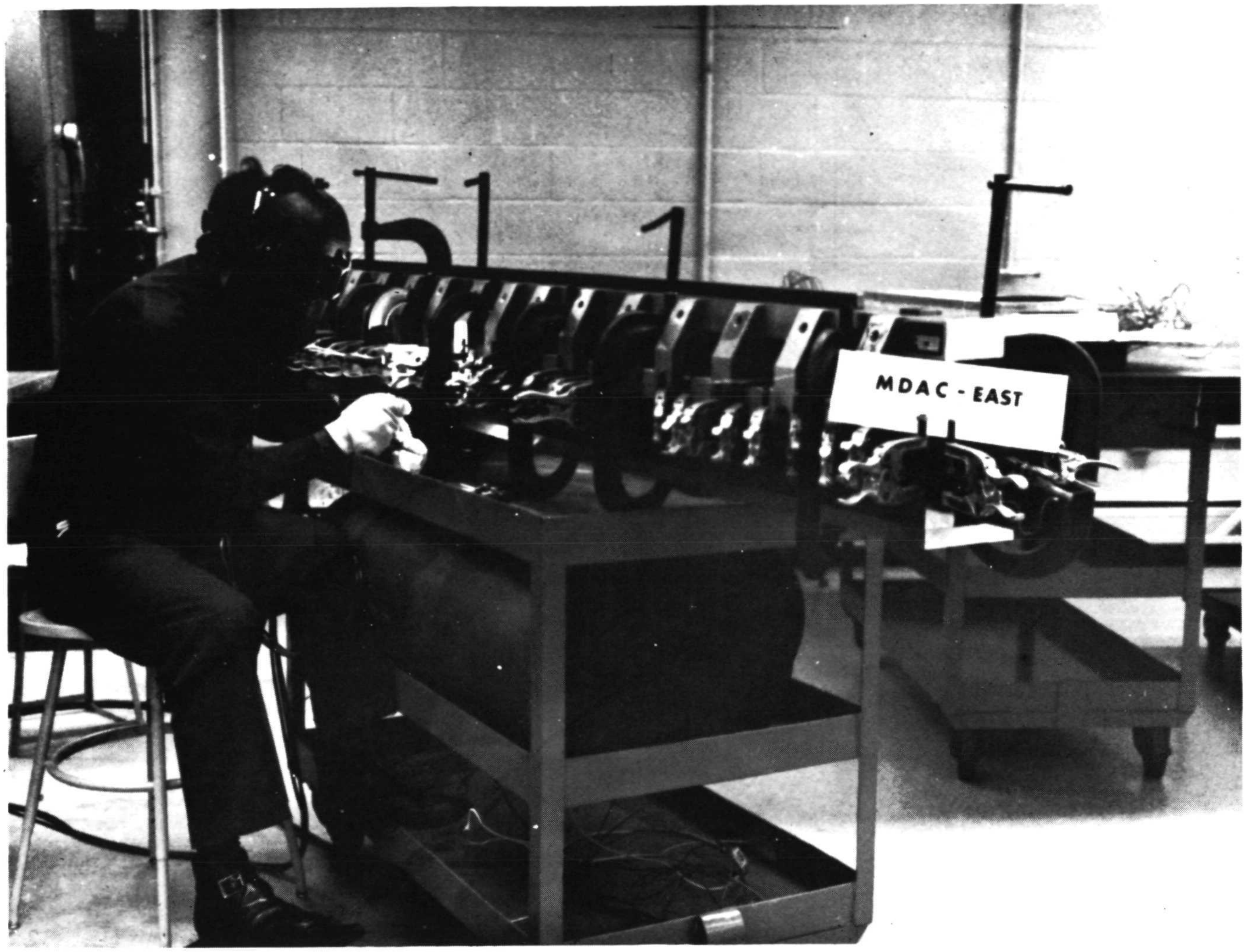
STRINGER FORMING TOOL

FIGURE 2–7

b) One Compression Panel Hat Section Centerline Stringer
   1.83m (72 inch) long
   21 plies to 52 plies in thickness
   up to 5 plies of .008 6Al-4V titanium

c) Two Compression Panel Hat Section Stringers "C"
   1.83m (72 inch) long
   5 plies to 23 plies in thickness
   up to 5 plies of .008 6Al-4V titanium

d) Two Compression Panel Hat Section Stringers "A"
   1.83m (72 inch) long
   12 plies to 20 plies in thickness
   up to 6 plies of .008 6Al-4V titanium



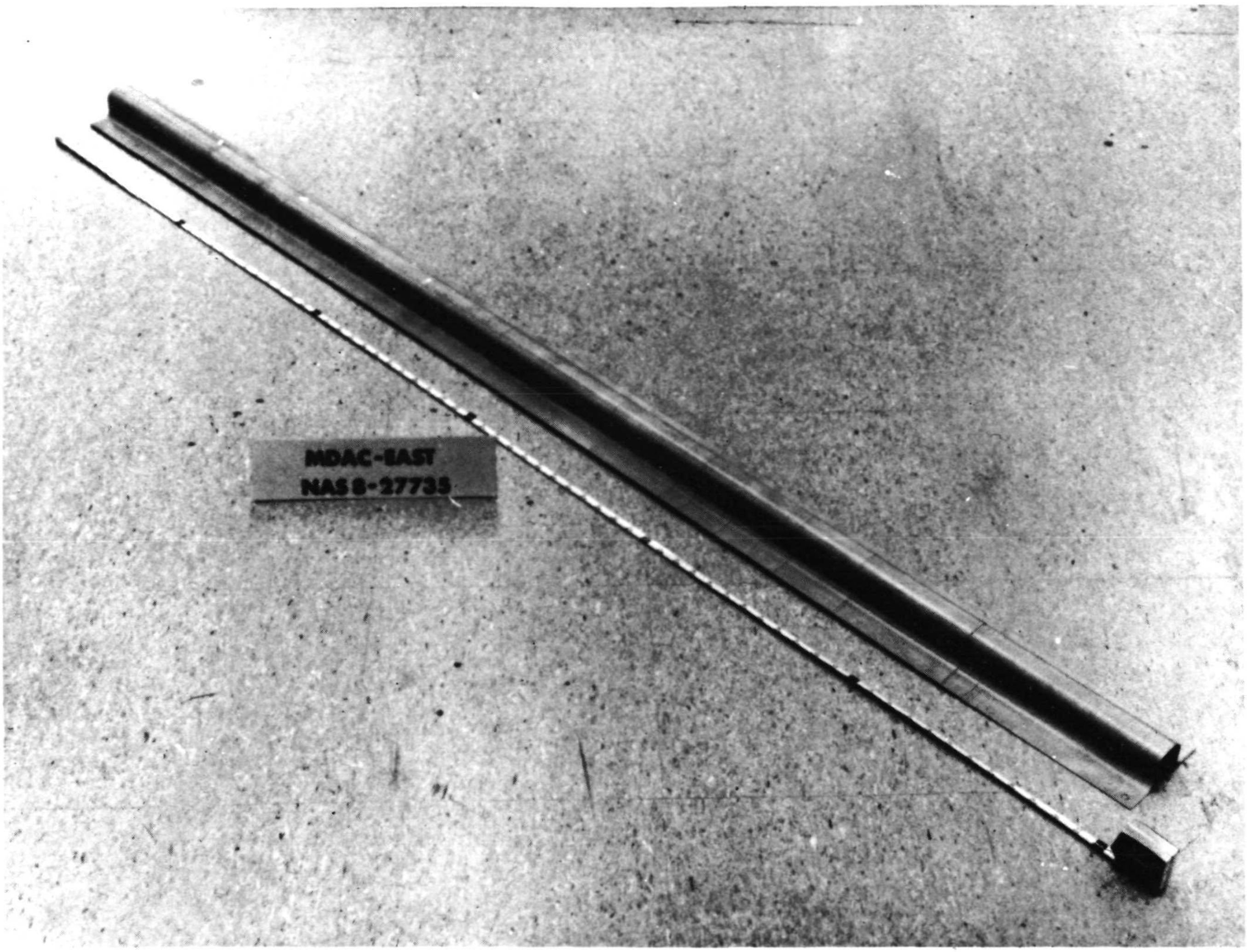
WELDING OF FORMED STRINGER PACK

FIGURE 2-8

Two "B" configuration stringers remain to be bonded. All other detail parts have been fabricated. The bonding and assembly is proceeding at a brisk pace and panel completion in early April 1973 is expected.

The stringer and skin for this assembly were fabricated using the forming and bonding processes as described in Sections 2.4.1 and 2.4.2. Drilling for the assembly of the panel is being accomplished using high speed drills with the Desoutter rack feed drill. This technique is proving to be economical and efficient with high quality holes routinely being produced.

Of major concern on this assembly, to date, is diffusion bond delaminations found in the tapered boron aluminum skin. The bilayer material used in the skin was found to be delaminated in several edge areas. These delaminations were similar to, but more prominent than, the component panel skin delaminations discussed in

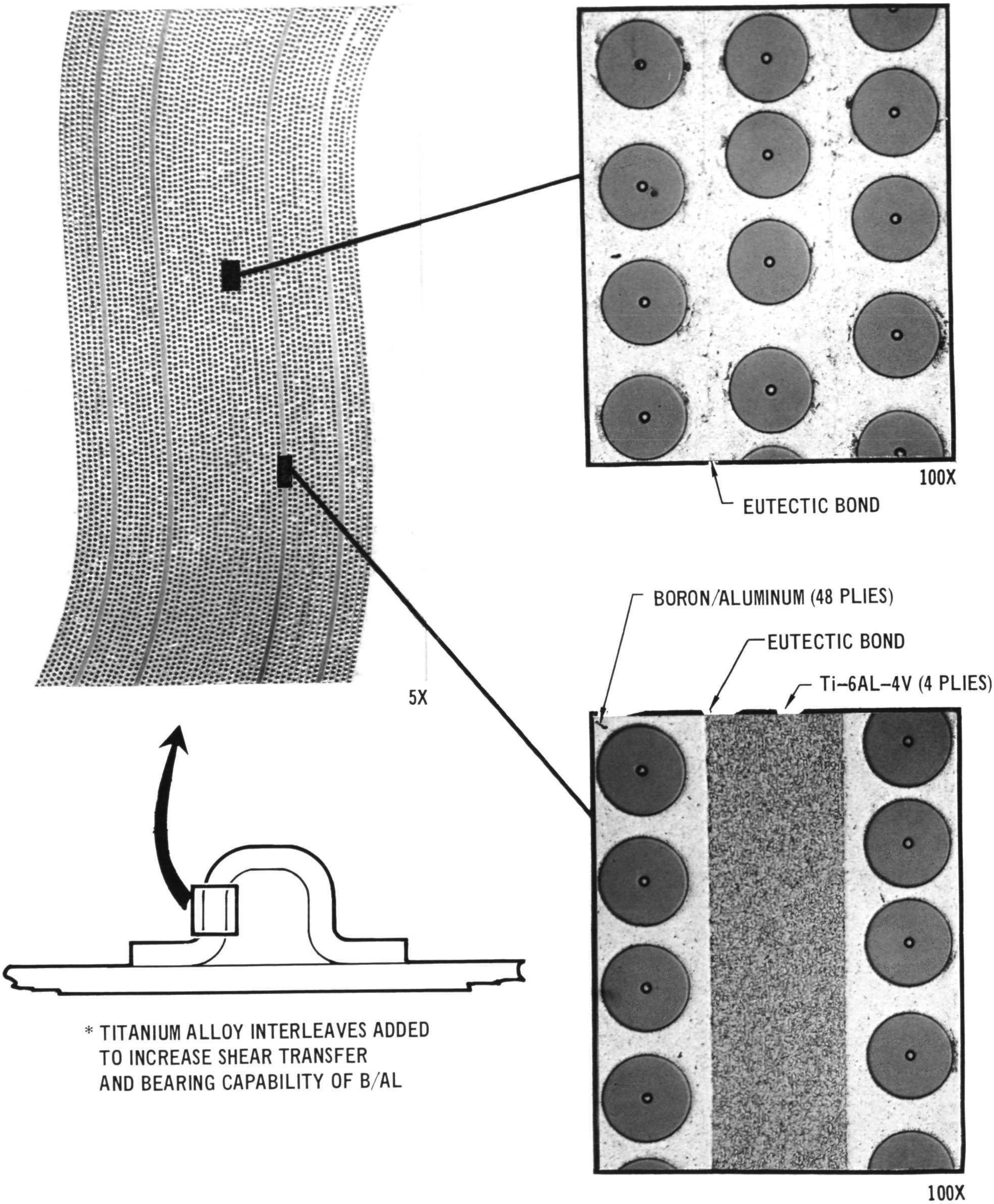


MONOLAYER MECHANICAL FORMING PRODUCES SOUND B/Al STRINGER

FIGURE 2–9

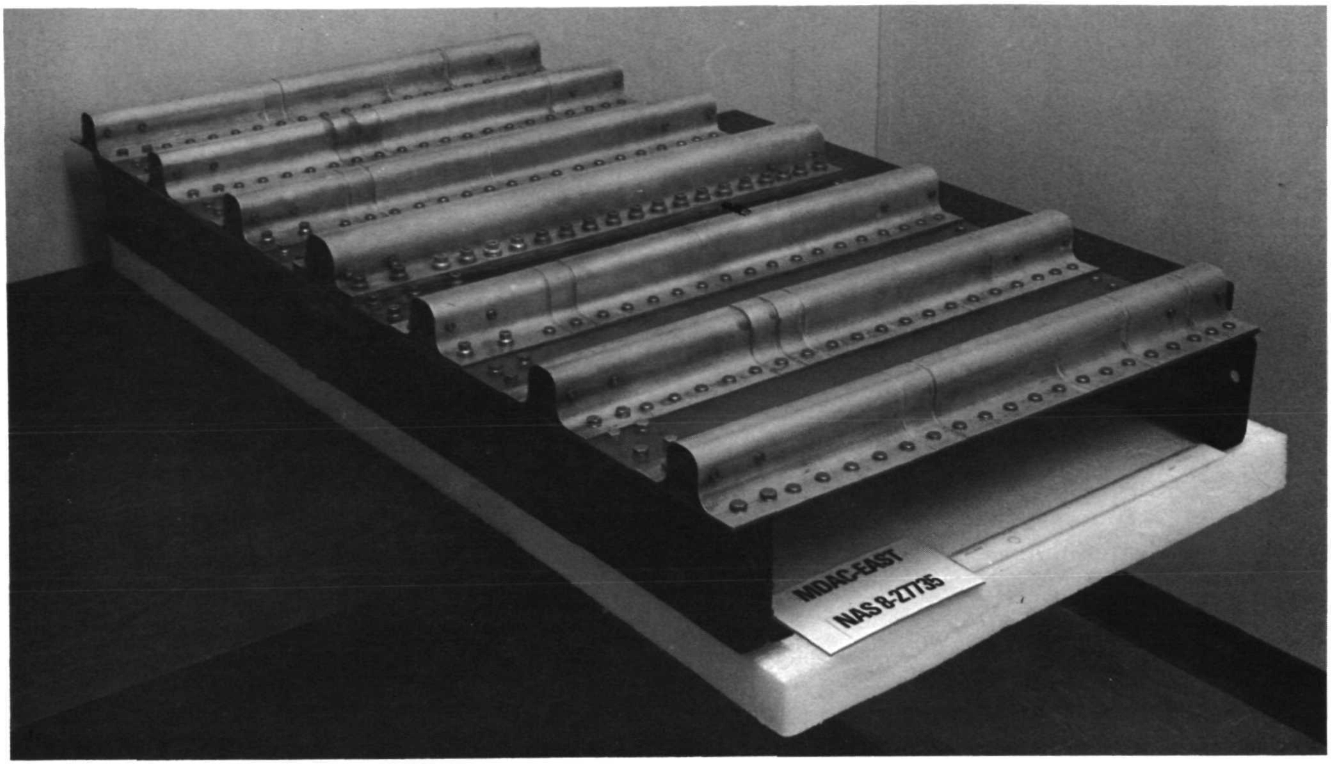
Section 2.4.2. Ultrasonic C scans of the skin indicated these delaminations to be in localized areas at the skin edges and assembly operations are proceeding. Care is being taken during the assembly operations to prevent propagation of the delaminations. Repair methods such as spotwelding, adhesive bonding and auxiliary straps are being considered for possible use if found necessary after all assembly operations on the skin have been completed.

It is believed that these defective diffusion bonds in the bilayer material existed in incoming material as supplied by Amercom, Inc. but were not discoverable using available techniques. It is the nature of multilayer diffusion bonded material to form a mechanical lock between the foil and filaments, making detection of lack of diffusion bond (especially when the joint is tight) very difficult.

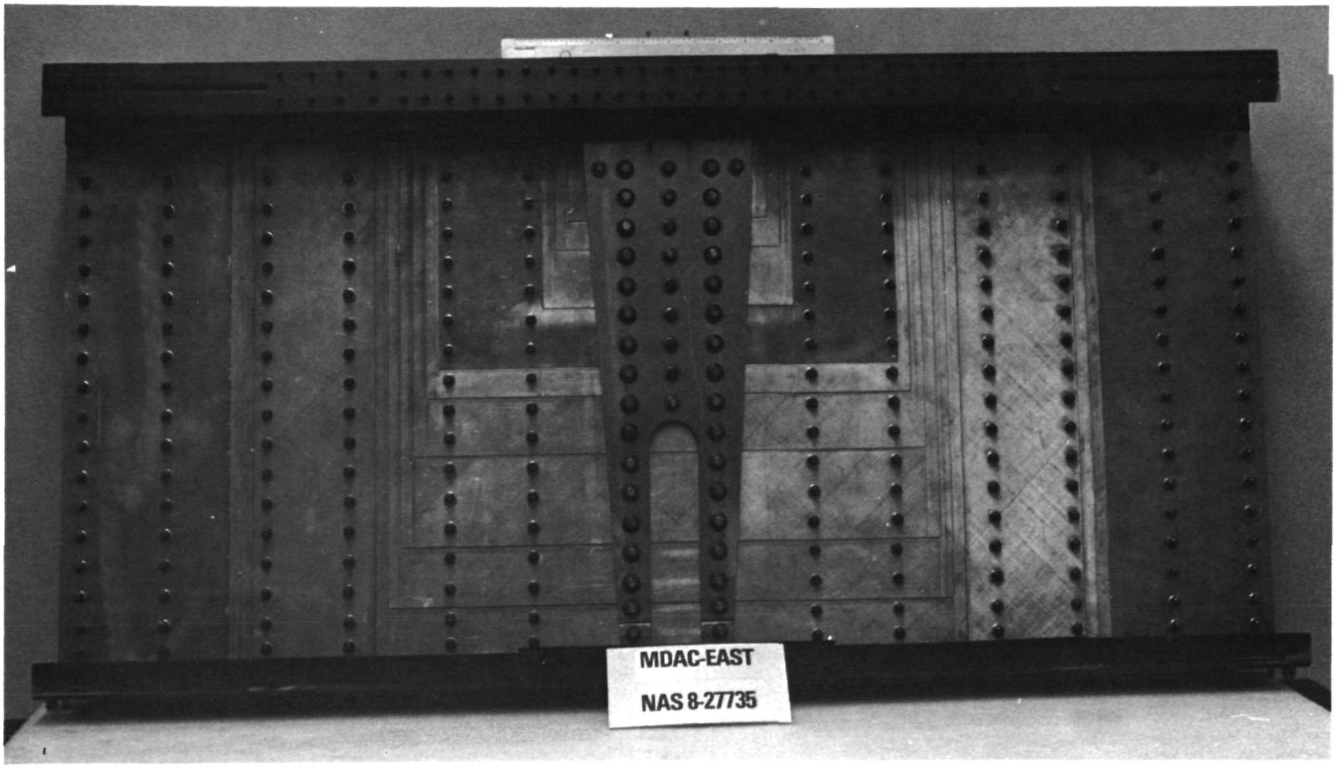


CROSS-SECTION THROUGH CENTER-LINE STRINGER OF COMPONENT PANEL

FIGURE 2–10



STRINGER SIDE



SKIN SIDE

COMPLETED COMPONENT PANEL ASSEMBLY

FIGURE 2–11

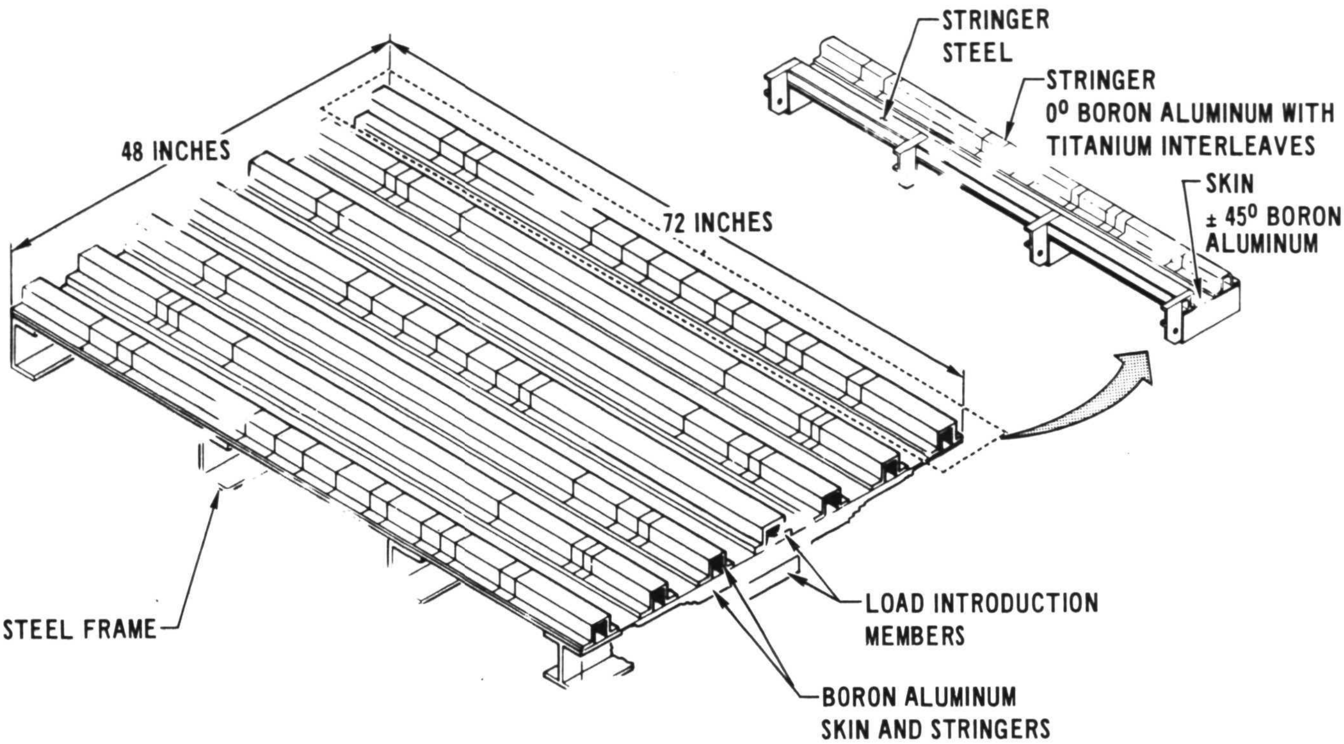
Bilayer material on hand is being subjected to a series of inspection tests to verify the soundness of the diffusion bond. Although the material passes currently-used peel test techniques, it is apparent that more exhaustive testing technqiues are required to insure that the material is of consistent high quality. Until these inspection techniques are developed the use of bilayer material is being restricted to noncritical applications.

2.5 Phase V - Test and Evaluation

The 4 ft. by 6 ft. boron aluminum Compression Panel contains many unique design features including titanium interleaves, internal and external boron aluminum ply terminations, and tapered thickness stringers and skin. In addition, the concentrated load applied at one end reacted by a uniformly distributed load at the opposite end causes complex internal loads. No composite structure has been designed and tested for shear lag loading in the past, particularly at an elevated temperature of 600°F. For these reasons, it was advisable to fabricate and test structural components which verify primary structural features of the Compression Panel. Two components were chosen. One was a stringer assembly to demonstrate the overall axial compressive strength of a long element of the panel. The stringer assembly is described in Section 2.5.1. The other structural test article was a Component Panel. It is an exact duplicate of one-third of the Compression Panel at the concentrated load end. Test of the Component Panel verified internal loads distribution. Component Panel test results are described in Section 2.5.2.

2.5.1 Boron Aluminum Stringer Assembly - The three span 72-inch long tapered boron aluminum stringer column specimen shown in Figure 2-12 was selected to verify the design and analysis of stringers on the compression panel. This specimen was successfully tested at room temperature to 80K and 100K during two different loading sequences without failure. Axial load was applied to the unidirectional boron aluminum stringer of this test assembly by shear load using a 12 ply $\pm 45°$ boron aluminum skin. It will be shown that the 100K load level demonstrates ultimate strength of the outboard stringer on the compression panel when loaded to 50K at 600°F. In addition, this is the first major boron aluminum test article to utilize titanium interleaves eutectically bonded to the boron aluminum. Results of this test showed that the use of titanium interleaves significantly increased shear strength and fastener strength of unidirectional boron aluminum stringers.

Design loads for the outboard stringer on the compression panel are shown in Figure 2-13. These loads occur at a temperature of 600°F. The maximum shear



ACCOMPLISHED OBJECTIVES

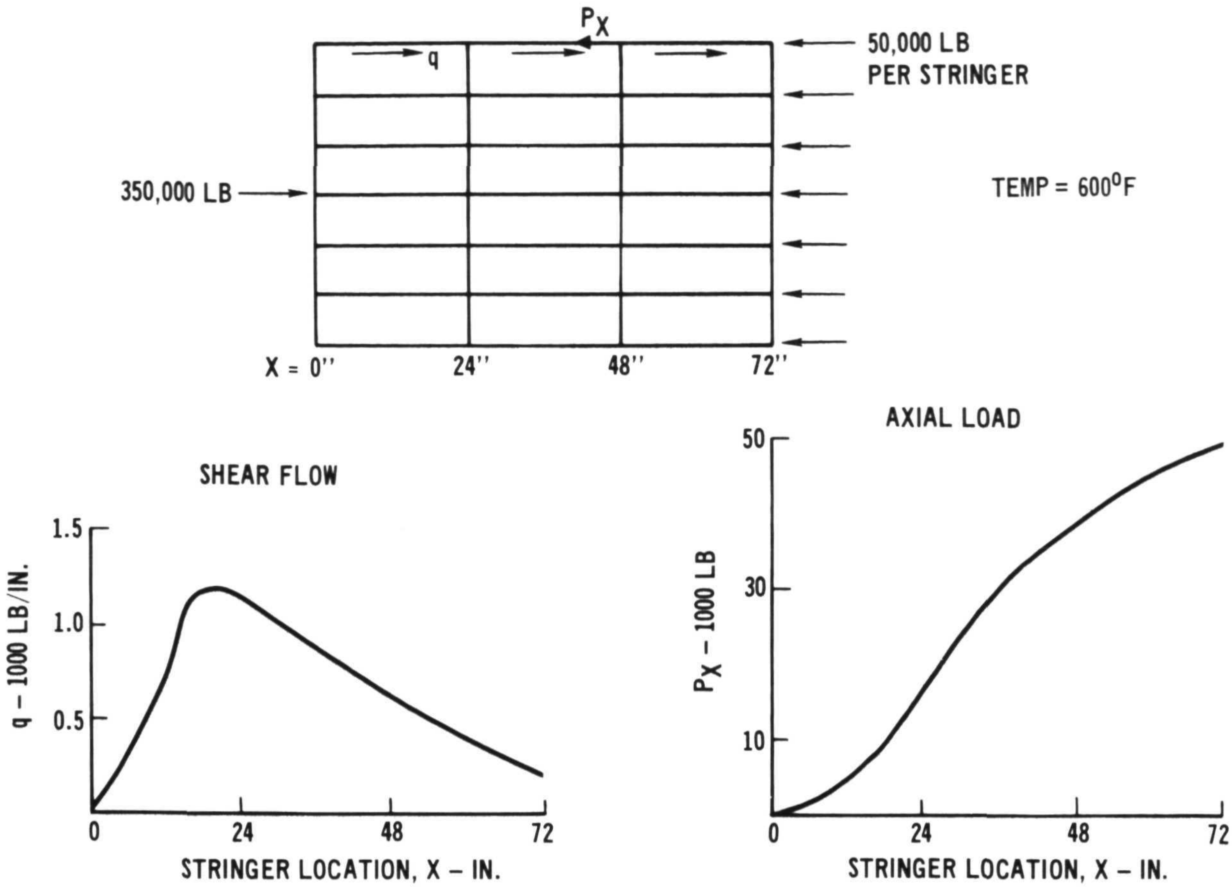
- DEMONSTRATE COLUMN CAPABILITY OF STRINGER INCLUDING CRIPPLING
- VERIFY THAT TITANIUM INTERLEAVES INCREASE IN-PLANE SHEAR STRENGTH
- VERIFY THAT TITANIUM INTERLEAVES INCREASE BEARING STRENGTH

STRINGER ASSEMBLY AIDED EVALUATION OF COMPRESSION PANEL DESIGN

FIGURE 2-12

flow occurs at approximately 20 inches from the unloaded end of the stringer, while the maximum axial compressive load occurs at the stringer closeout. The small predicted shear flows shown for the area near the distributed load end of panel indicate that the internal loads distribution required to achieve a nearly-uniform reaction load (50,000 lb per stringer) has been accomplished in less than the full panel length.

The stringer for the stringer assembly test is identical to the outboard stringer planned for the compression panel. Therefore, it is designed for loads shown on Figure 2-13 which occur at 600°F. Analysis showed that a unidirectional boron aluminum stringer, if sized to carry the axial compressive load, would possess insufficient in-plane shear strength to carry the shear loads. Therefore, one 8 mil titanium ply was added over the entire length and a 15 in. long ply was



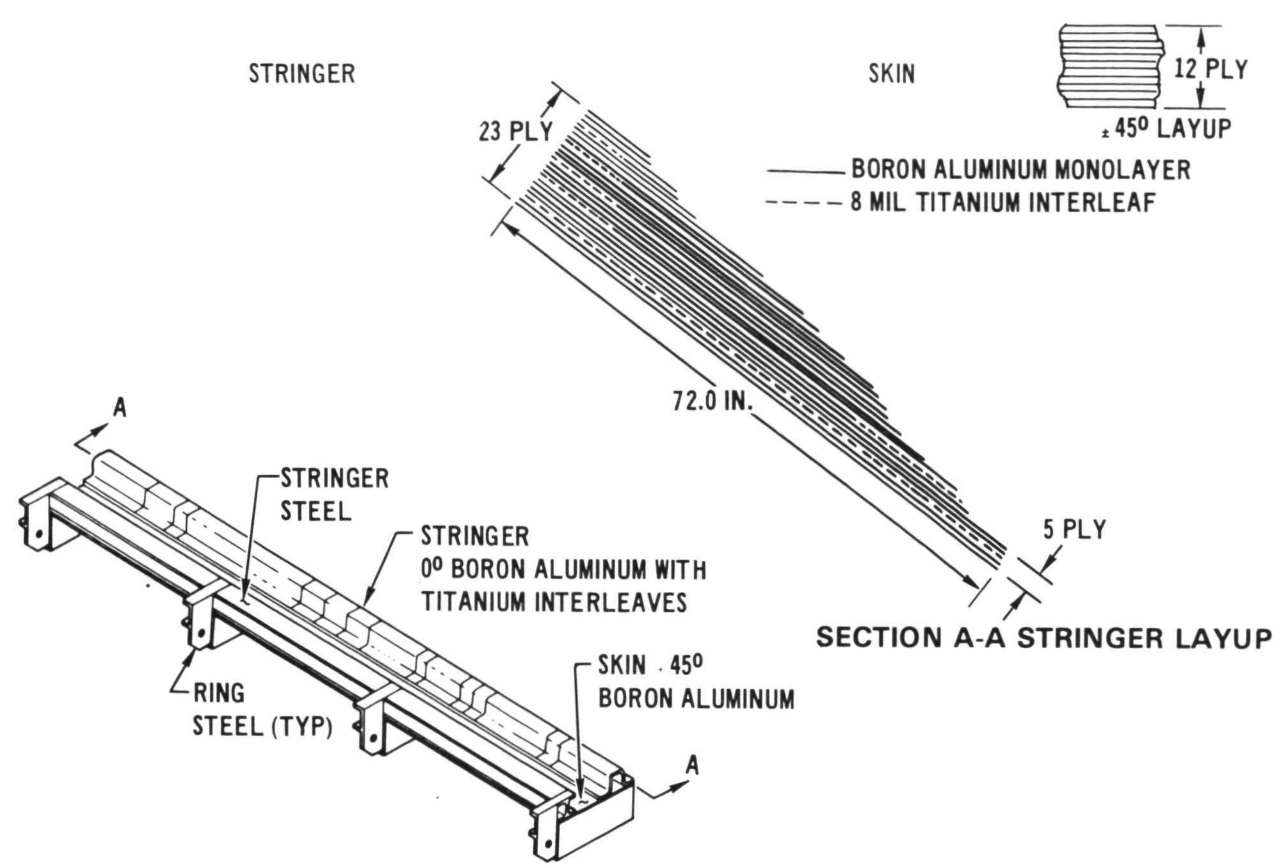
DESIGN LOADS FOR STRINGER ON COMPRESSION PANEL

FIGURE 2–13

added near the thin end of stringer as shown in Figure 2-14. Additional titanium plies are used at the opposite end to provide sufficient bearing strength for the close-out fitting loads. Note that the boron aluminum and titanium plies can be terminated internally if the terminations are staggered. A minimum of 1/2 inch was used. The external ply terminations were selected to meet the axial load and stiffness requirements of stringer.

The skin used in this test assembly (Figure 2-14) is slightly different than the skin for this region on the compression panel. For the compression panel, eight plies of ± 45 degree boron aluminum are used with two plies of titanium. The titanium plies are located on the outer surface to maximize panel buckling strength.

The allowable shear flow which can be applied to a stringer with boron aluminum plies only and to a boron aluminum stringer with titanium interleaves is shown in Figure 2-15. Without titanium interleaves, the stringer could not



SIGNIFICANT FEATURES OF BORON-ALUMINUM STRINGER ASSEMBLY

FIGURE 2-14

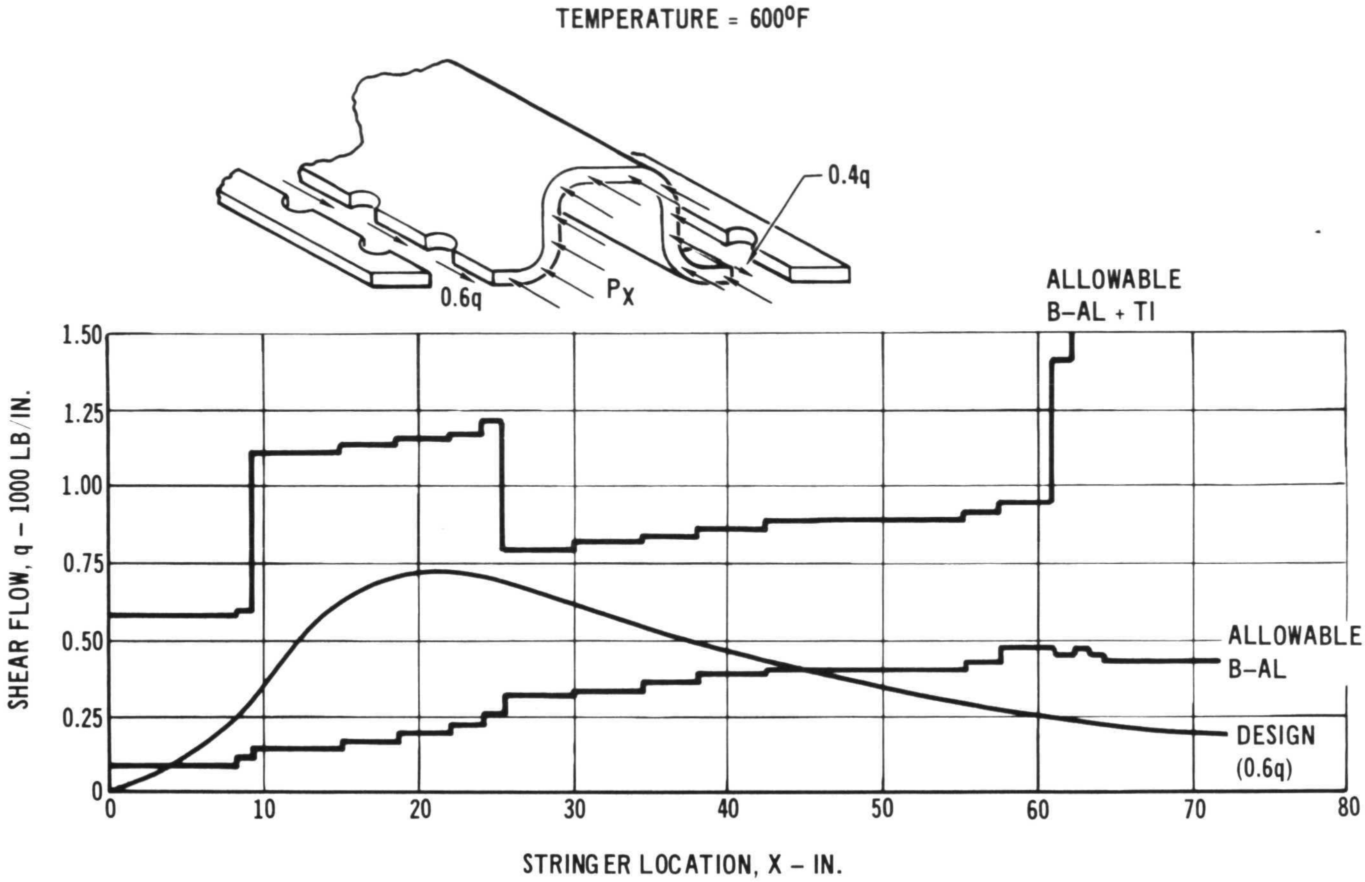
sustain the design shear flow over half the stringer length.

The design shear flow curve is for 60% of the total shear flow at any location along the stringer. This is based on analysis which showed the maximum shear flow going into any one leg of the stringer to be 60% of the total shear flow.

The structure which was fabricated and tested is shown in Figure 2-2. It consists of a boron aluminum stringer and a steel stringer which are attached to a section of boron aluminum skin. Four equally spaced lateral frames and a stringer close out fitting make up the remainder of the assembly. All attachments have been made using HI-LOK mechanical fasteners.

The lateral frames are steel channel members and the close out fitting is a machined steel part attached to the boron aluminum stringer with 25 fasteners.

Figure 2-16 shows the boron aluminum stringer assembly located in test machine. Note the turn buckle arrangement used to provide lateral support without restricting axial motion of the stringer.



TITANIUM PLIES USED TO INCREASE IN-PLANE
SHEAR STRENGTH

FIGURE 2-15

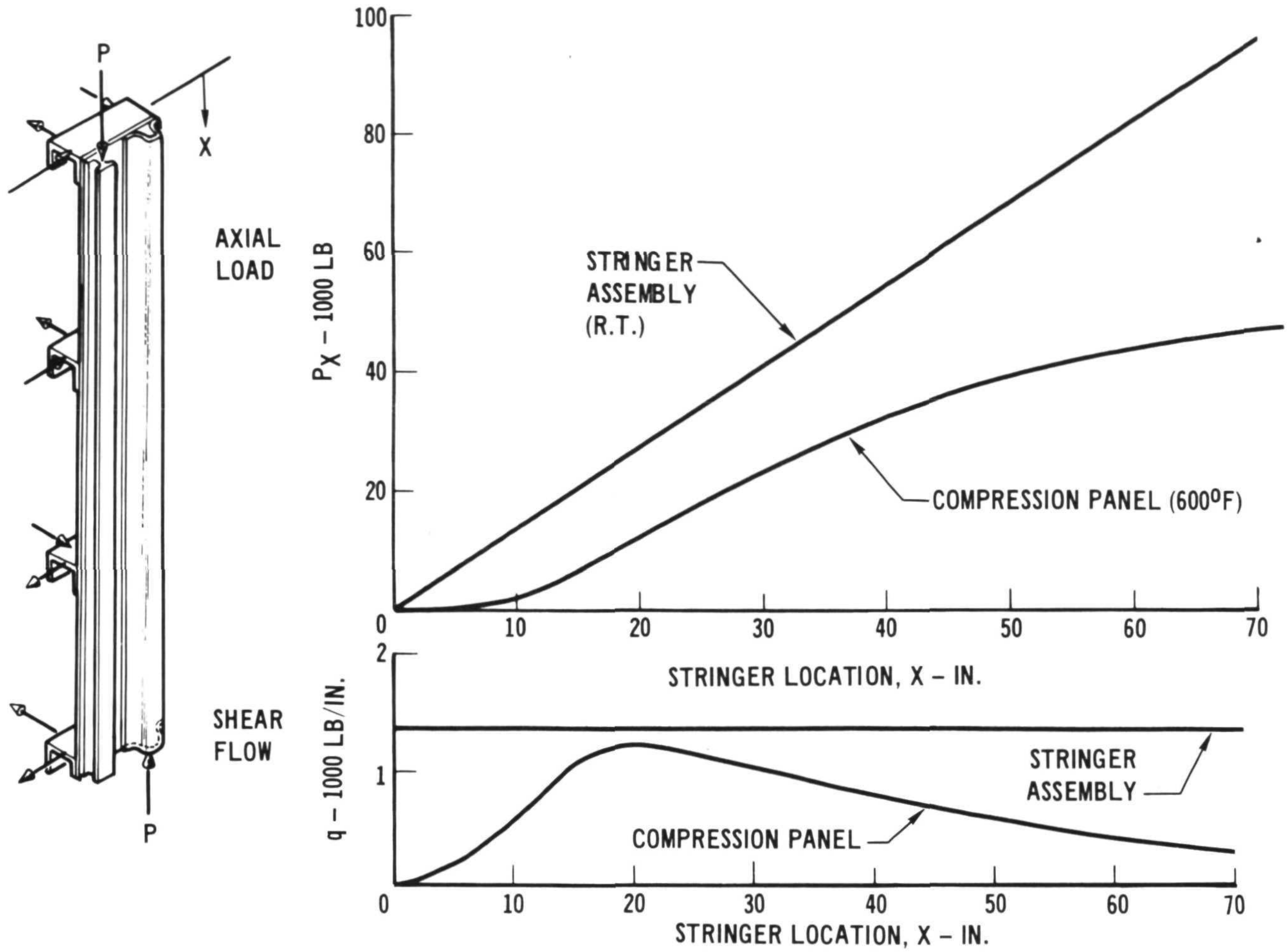
The assembly was loaded twice at room temperature without failure. During the first test, the maximum axial load applied to the stringer was 80K. In the second test, the maximum load was 100K. When the stringer successfully carried 100K at room temperature, ultimate strength was demonstrated of a similar stringer on the compression panel at 600°F.

Room temperature loads for the boron aluminum stringer on the stringer assembly and the 600°F design loads for the stringer on the compression panel are compared in Figure 2-17. The shear flow for the stringer assembly test is essentially constant over the entire length (72") and does not peak as does the shear flow on the compression panel. The boron aluminum stringer for the stringer assembly test is the same as the outboard stringer for the compression panel. However, axial loads at various locations along the stringer are not necessarily the same for both the stringer assembly and compression panel due to loading differences.

STRINGER ASSEMBLY IN TEST MACHINE

FIGURE 2-16

Strain gages for the stringer assembly were located as shown in Figure 2-18. In addition, three deflection gages were located midway between each frame for recording deflection of the stringer normal to the skin. A fourth deflection gage was used to record overall shear deformation of the panel.



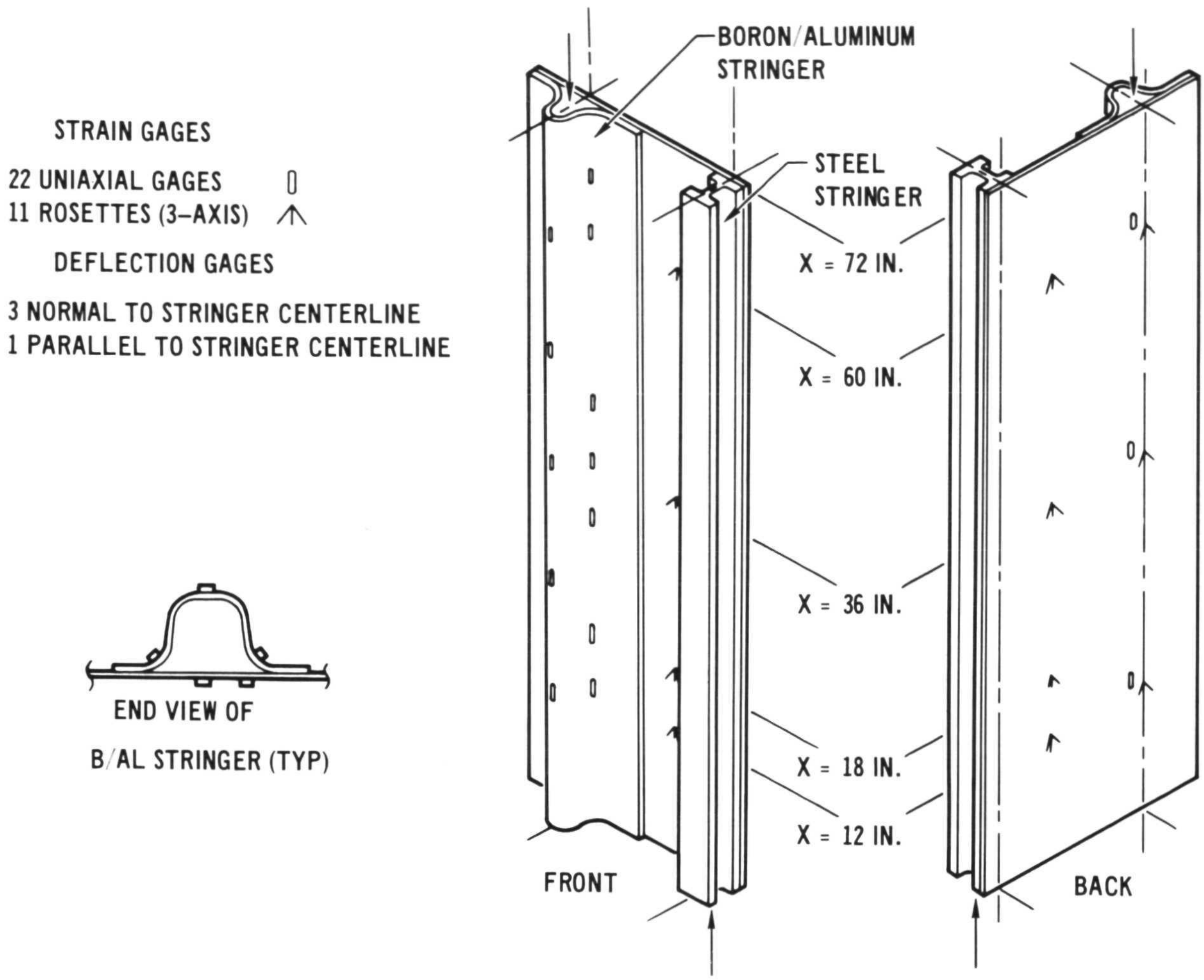
STRINGER ASSEMBLY LOADS

FIGURE 2–17

The eleven strain rosettes were all located on the ±45° skin to determine the complex state of strain in the skin. The portion of skin between stringers had back to back gages in each bay for determining any skin buckling during loading. That portion of the skin beneath the boron aluminum stringer had an additional strain rosette in each bay to determine the shear strain in the skin between the attachment legs of the stringer.

Nineteen of the 22 uniaxial strain gages were located on the boron aluminum stringer parallel to the direction of the applied load. Gages were located on both the crown of the stringer and the attachment legs to detect any bending of the stringer. The other three uniaxial gages were located on the skin to aid in evaluation of shear distribution between the two legs of stringer.

The uniaxial strain gages located on the stringer cross-section were used to

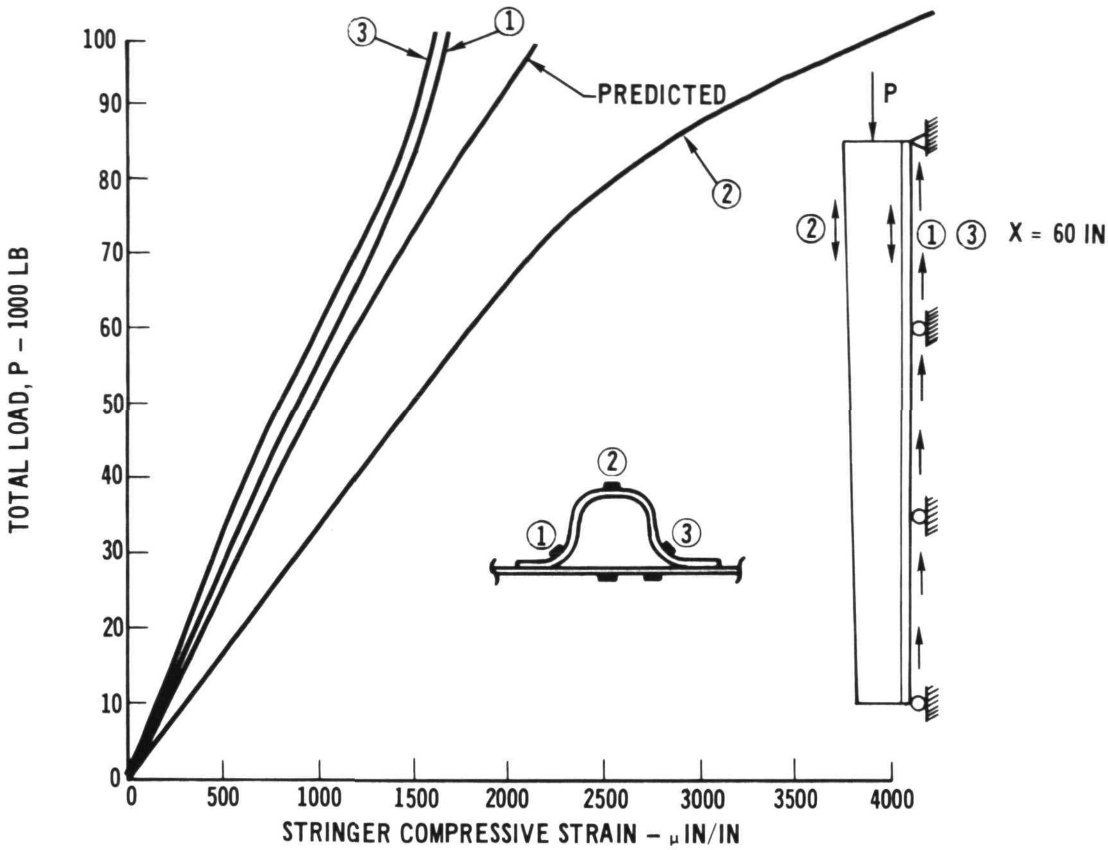


STRAIN AND DEFLECTION GAGES MONITOR RESPONSE DURING TEST

FIGURE 2-18

determine the presence of bending as well as axial load. Figure 2-19 shows strain readings taken from three such gages located 12 inches from the highly loaded end of the stringer. A predicted load-strain curve for the stringer under pure axial load is shown also. There was considerable difference between the compressive strain measured by the gage on the crown of the stringer and the gages located near the attachment legs. This indicates that the stringer cross section at this location was subjected to bending as well as axial load.

Figure 2-20 illustrates the stringer deflected shape under 100,000 lbs load. The thick end portion of the stringer was subjected to significant bending as discussed previously. The high bending strains in this region of the stringer were attributed to an initial curvature in the stringer caused either during stringer



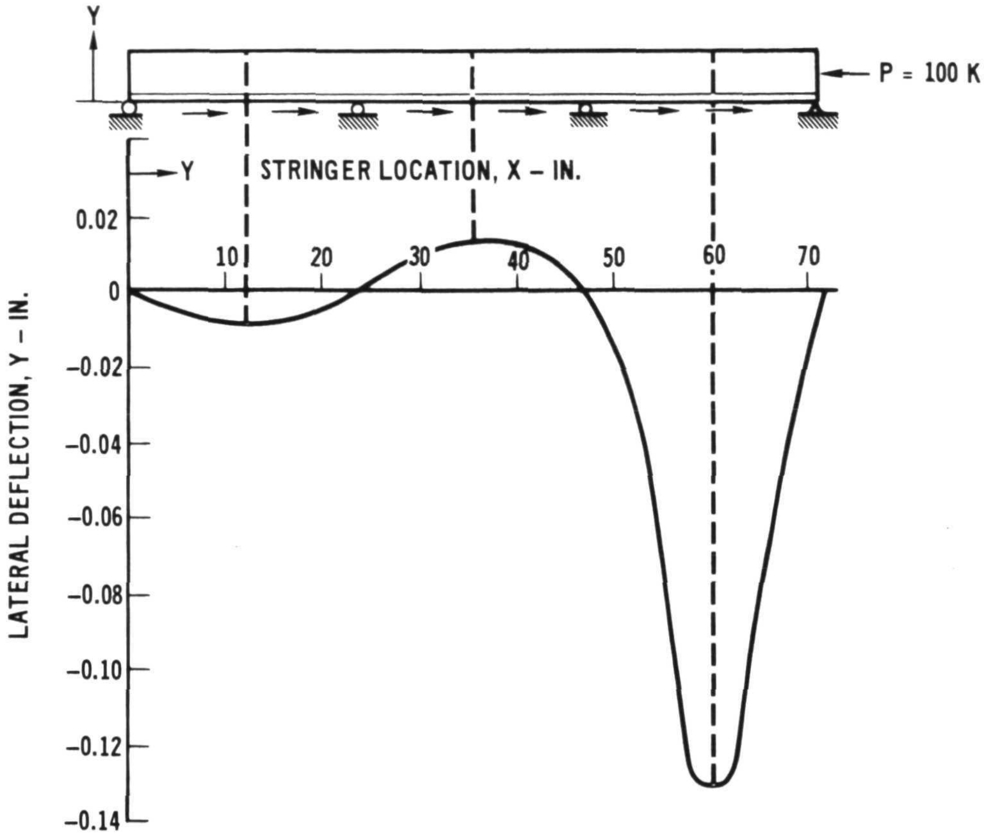
STRAIN GAGE DATA SHOW STRINGER BENDING STRESSES

FIGURE 2–19

fabrication or induced into the specimen by the lateral support adjustment struts in the test setup. It can be shown that an initial eccentricity of .04 inches is sufficient to produce the bending strains observed during this test. After testing it was demonstrated that these support struts could be easily hand-adjusted to this eccentricity.

Figure 2-21 shows the 600°F predicted axial load curve used to design the stringer on the compression panel. Also shown is the allowable load curve for the stringer based on recent crippling tests. Crippling specimen for these tests had the same cross section as the stringer. This curve does not include a reduction for long column effects since they are small for these stringer thicknesses and frame spacings. The allowable load curve markedly exceeds the predicted curve at most locations due to improvements in actual crippling strength over predicted values used to design the stringer.

The lower portion of Figure 2-21 shows the room temperature axial loads carried by the stringer during the actual stringer assembly test along with the

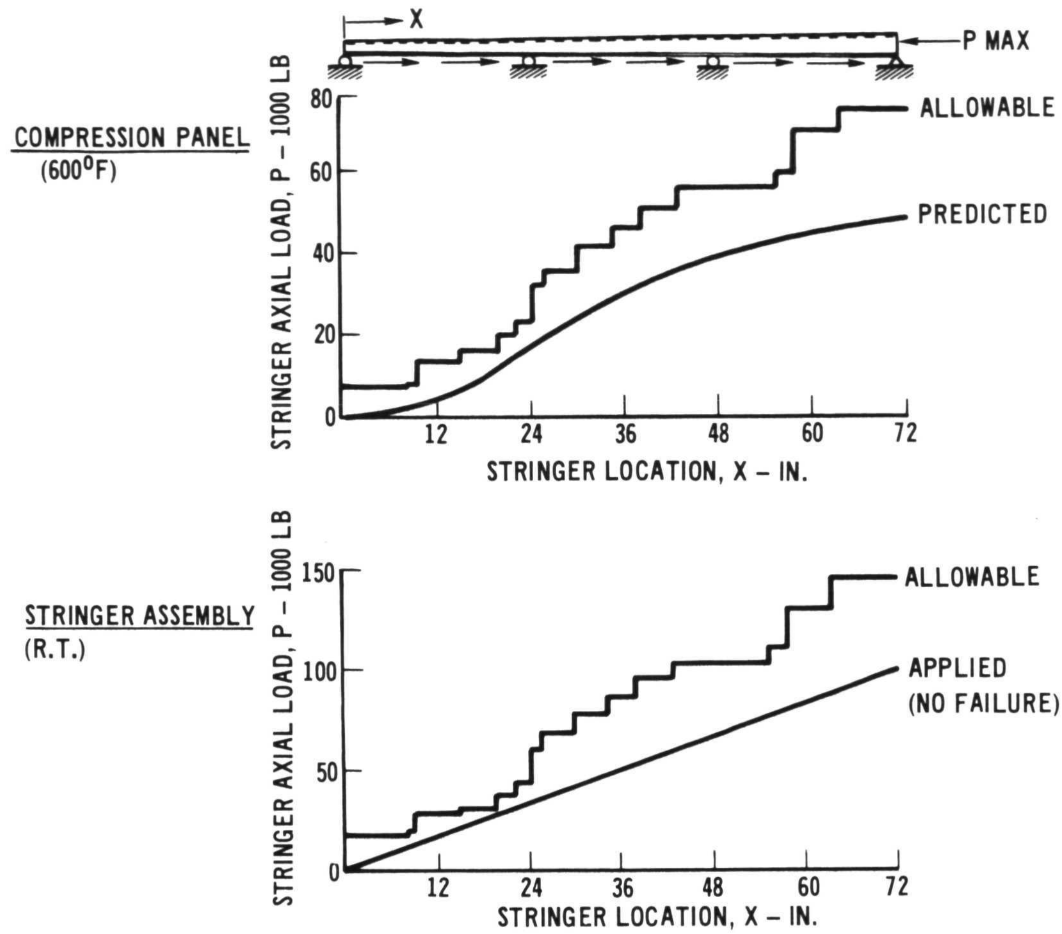


DEFLECTION GAGES VERIFY STRINGER BENDING

FIGURE 2-20

allowable load curve based on recent room temperature crippling tests. Again, crippling specimen used to determine the allowable curve had the same cross section as the actual stringer. In the thin end of the stringer, at 100,000 lb load on the assembly, the applied stringer loads were almost the same as the allowable loads. The stringer did not fail at this load level. The critical region on the stringer during test is about the same as expected for the stringer on the compression panel. It occurs approximately 20 inches from the thin end of the stringer.

In-plane shear strength of the boron aluminum stringer at room temperature both with and without titanium interleaves is shown in Figure 2-22. Since the applied stringer shear flow is essentially linear for the stringer assembly, the margin between allowable and applied shear flows in the thin end of the stringer is smaller than for the same location on the compression panel stringer at 600°F. Therefore the contribution of titanium interleaves for increasing in-plane shear strength was adequately shown over a portion of the stringer length.

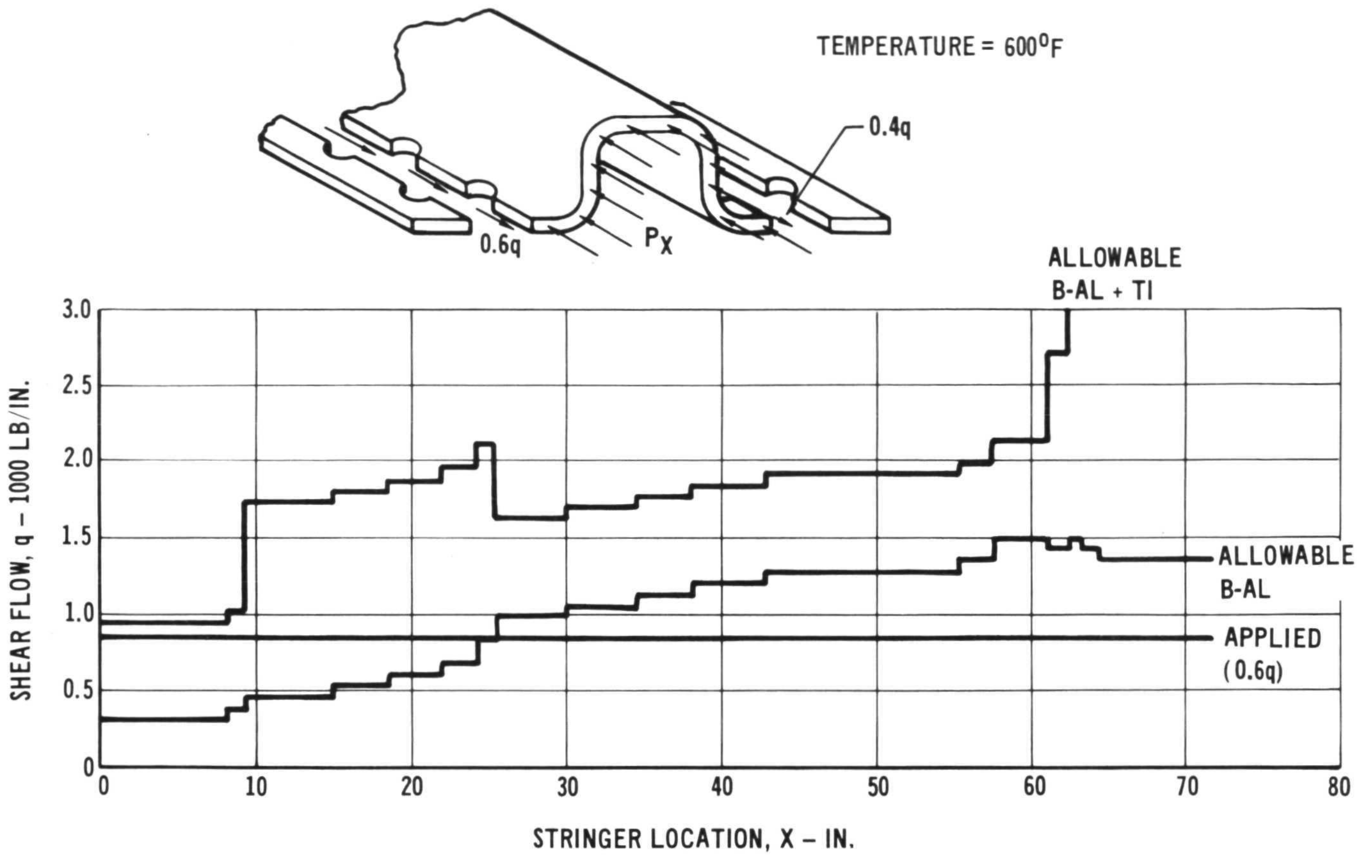


ULTIMATE COLUMN STRENGTH OF BORON ALUMINUM STRINGER VERIFIED BY TEST

FIGURE 2–21

Figure 2-23 illustrates the use of titanium interleaves to increase the allowable fastener load in the leg of the stringer. The load introduced at the fastener is reacted by both the boron aluminum and titanium and must be sheared into the main portion of the stringer. As shown, the load in the boron aluminum layers may be sheared into the stringer by way of the titanium plies as well as through the boron aluminum plies themselves. Since the titanium shear allowable is considerably above that of the unidirectional boron aluminum, the shear-out strength of the joint is greatly increased.

The stringer closeout fitting, Figure 2-24 simulates a typical load introduction splice joint. All loads in the stringer are transferred to the end fitting thru 25 fasteners. In this case, loads are applied to the fastener on both sides resulting in a double shear condition for the boron aluminum stringer.



IN–PLANE SHEAR STRENGTH OF STRINGER AT
ROOM TEMPERATURE

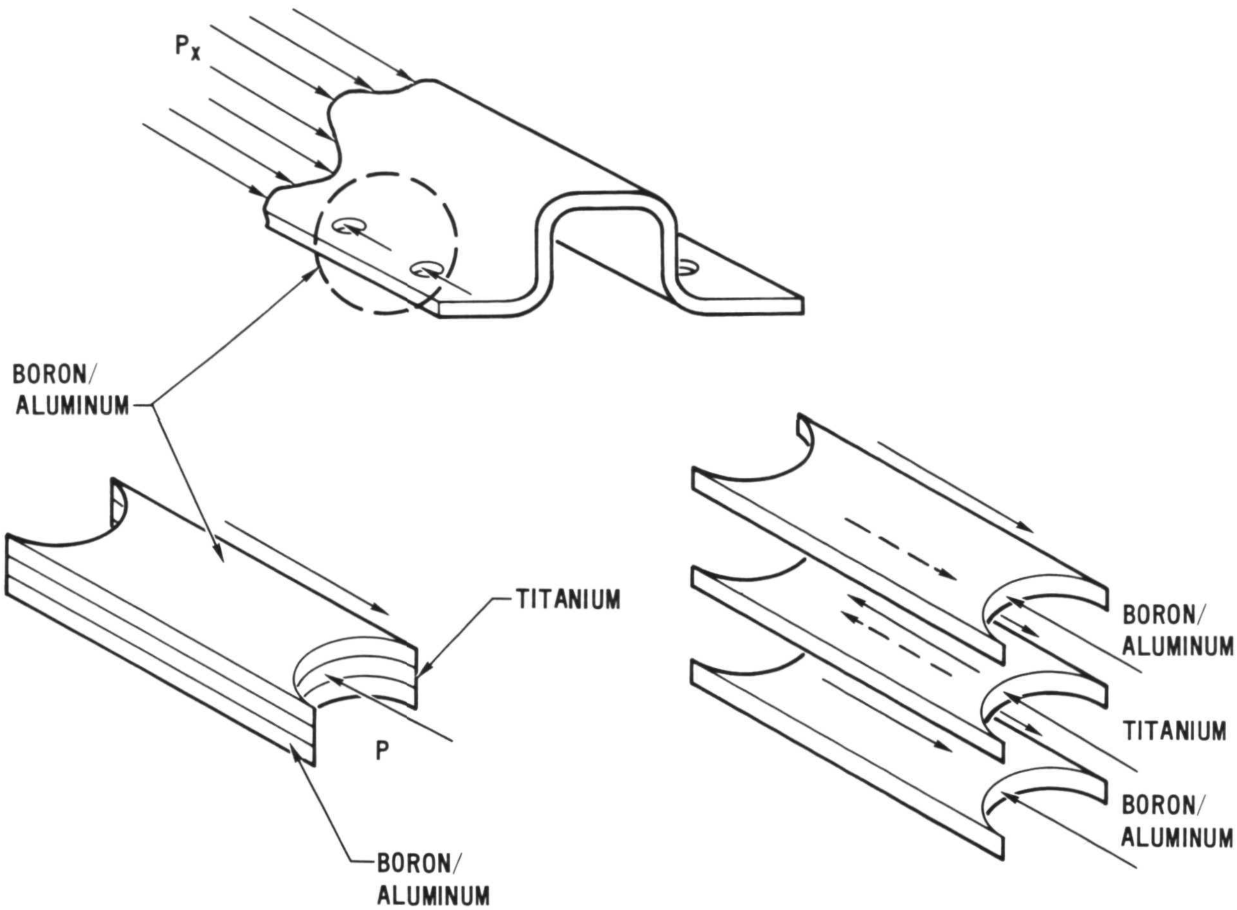
FIGURE 2–22

The end fitting extends beyond the panel skin and stringer to ensure that the entire load in the assembly is reacted at the steel end fitting.

Predicted fastener allowables for unidirectional (0°) boron aluminum are shown in Figure 2-25. Curves are for boron aluminum only and for boron aluminum combined with five, .008 in. thick annealed 6Al-4V titanium plies. The latter curve applies to stringer closeout fitting region where 5 titanium plies are used.

The point designated closeout fitting represents the load experienced by each of the 25 fasteners in the closeout region of the stringer when the total load was 100,000 lb. This assumes each fastener is carrying an equal portion of the total load. Since no failures occurred in the stringer, predicted ultimate strength of the joint was not completely proven.

The other point shown represents the average of three unidirectional boron aluminum, titanium interleaf lug tests at room temperature. The actual lug specimens were made up of 28 plies of 0° boron aluminum and eight, .012 in. thick titanium plies. Their average failing load was 14,000 lb. To plot these results



TITANIUM AND BORON ALUMINUM SHARE FASTENER BEARING LOADS
(Single Shear)

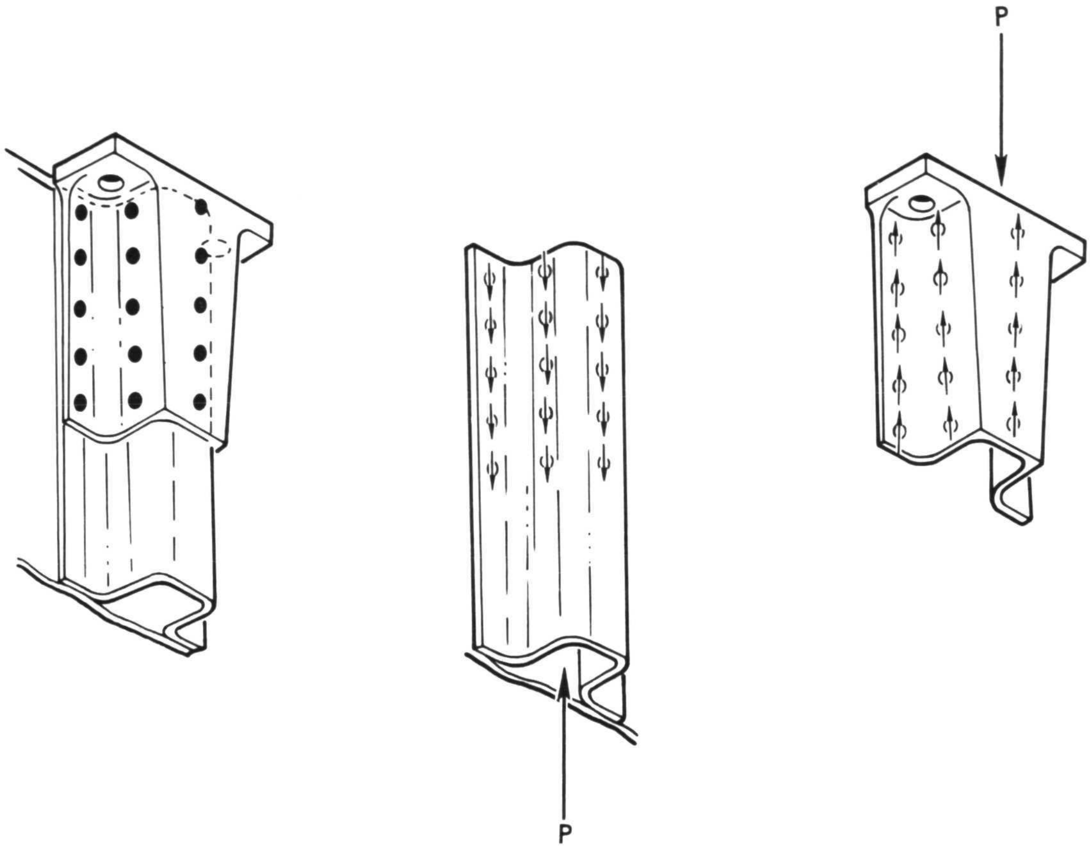
FIGURE 2-23

on this curve, the failing load and number of boron aluminum plies was scaled down so that the thickness of titanium was equivalent to five .008 in. thick titanium plies.

In summary, a considerable amount of significant data were obtained from the stringer assembly. Fabrication procedures necessary to construct a long stringer with tapered thickness and containing titanium interleaves were developed. In addition, several structural features incorporated in the stringer were demonstrated including the following:

- o Unidirectional boron aluminum can be used as stringers
- o Titanium interleaves increase in-plane shear strength
- o Titanium interleaves increase fastener bearing strength.

2.5.2 Boron Aluminum Component Panel - The compression panel will experience very high internal shear and compressive loads when subjected to the concentrated ultimate

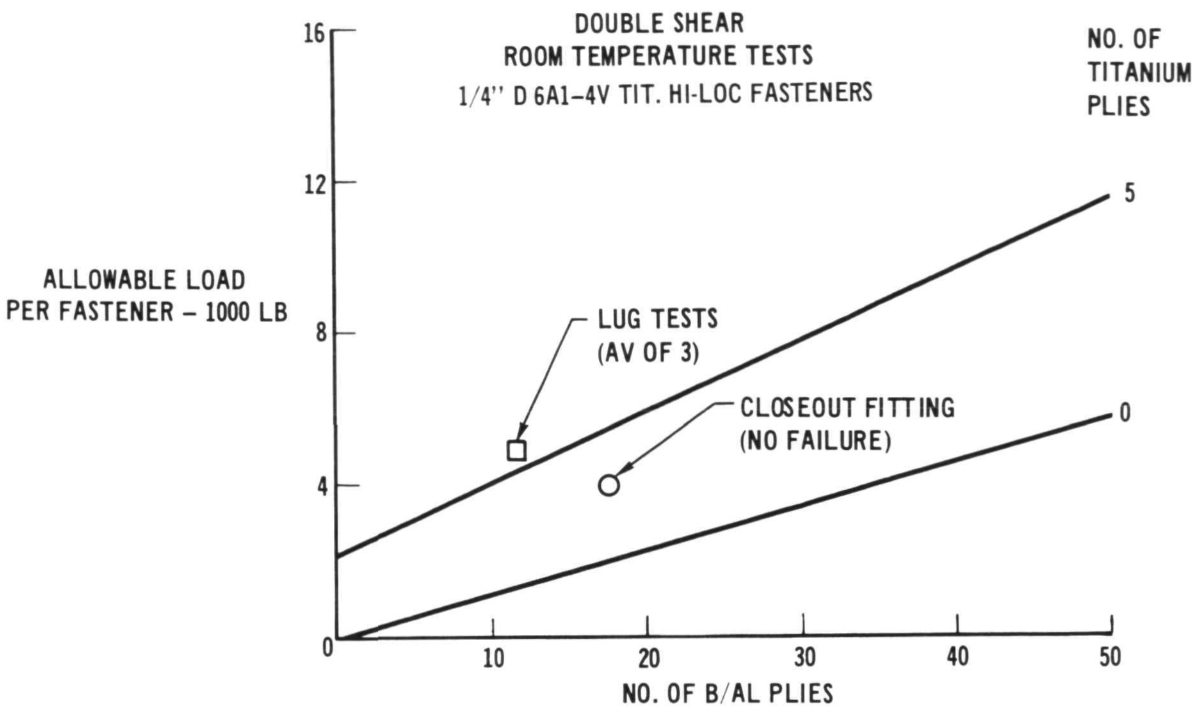


STRINGER CLOSEOUT FITTING

FIGURE 2-24

load of 350K at 600°F. Since no composite structures have experienced this type of loading and the unique design features incorporated in panel had not been proven, the component panel shown in Figure 2-11 was fabricated and tested. The panel is two feet long and four feet wide. It is an exact duplication of the highly loaded first bay at the concentrated load end of Compression Panel. Seven unidirectional boron aluminum stringers carry the axial compressive load and a ±45 degree cross-plied skin carries the shear load. With the exception of the centerline stringer which is constant thickness in this bay, both the stringers and skin are tapered in thickness to achieve an efficient design.

Very high shear loads exist in this bay of the compression panel. Unidirectional boron aluminum stringers sized to carry axial compressive loads possess insufficient in-plane shear strength to carry the applied shear loads. Therefore, 8 mil titanium interleaves were added to the stringers to provide the required shear and bearing strengths as shown in Figure 2-26. The titanium interleaves and boron aluminum plies



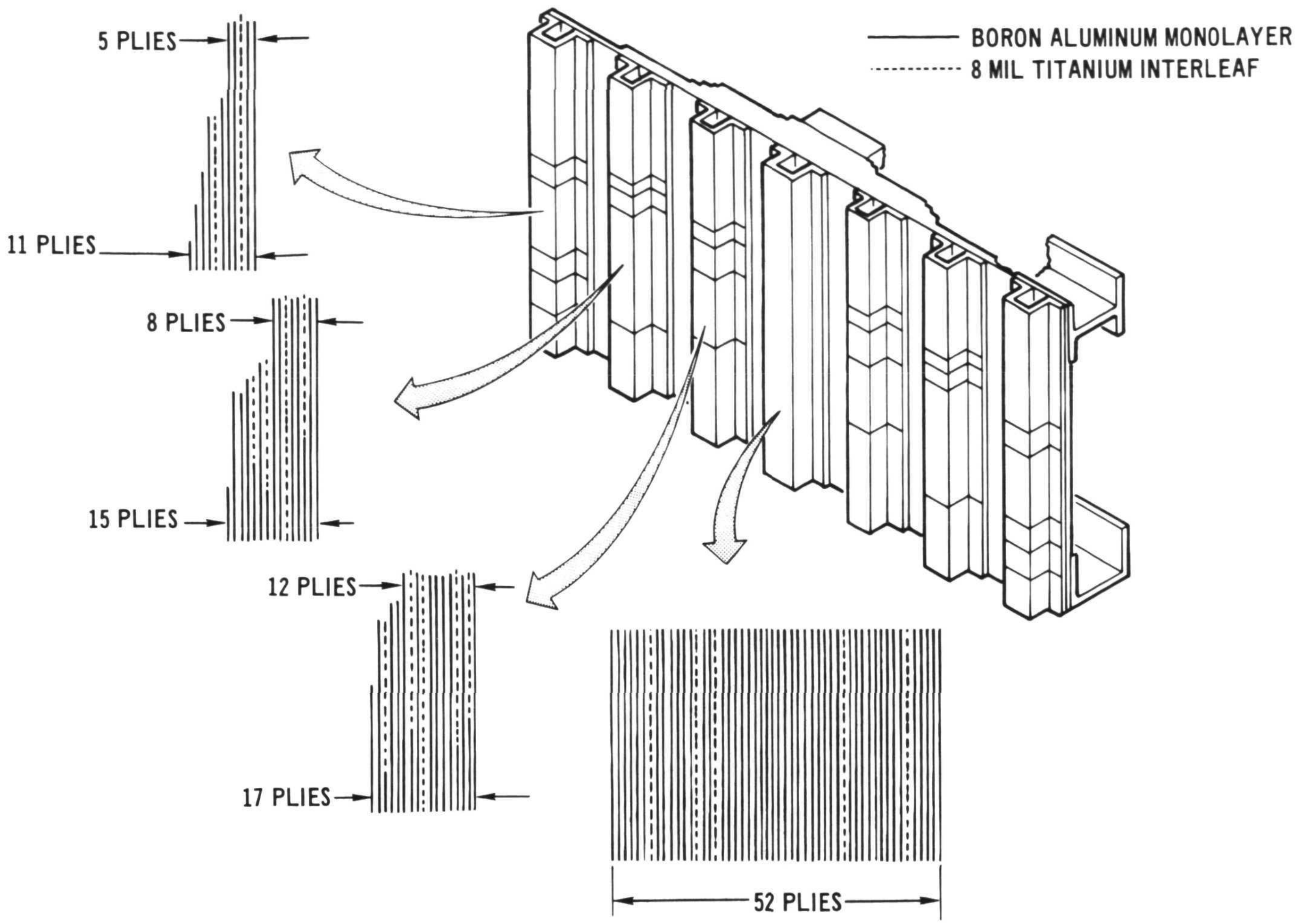
ANALYTICAL PROCEDURES FOR PREDICTING BEARING STRENGTH
PARTIALLY VERIFIED BY TEST

FIGURE 2–25

are eutectically bonded simultaneously in one operation. The number of interleaves required at a particular location on a stringer was determined from the applied shear flow at that location.

The component panel skin shown in Figure 2-11 is the same as that planned for the first bay of compression panel. The skin is made up of both $\pm 45°$ boron aluminum plies and some titanium interleaves. Skin thickness is designed to carry the shear flow occurring at various locations on the panel. The entire skin is eutectically bonded during a single bond cycle. All tapering of the skin occurs on one side. This permits the skin to be bonded on a flat tool and provides a flat surface for attaching stringers.

Figure 2-27 shows the panel skin before assembly. Skin thickness varies from a maximum of 58, $\pm 45°$ boron aluminum plies with four titanium interleaves at the load introduction end to a thickness of 24, $\pm 45°$ boron aluminum plies with three titanium interleaves at distributed end of panel.

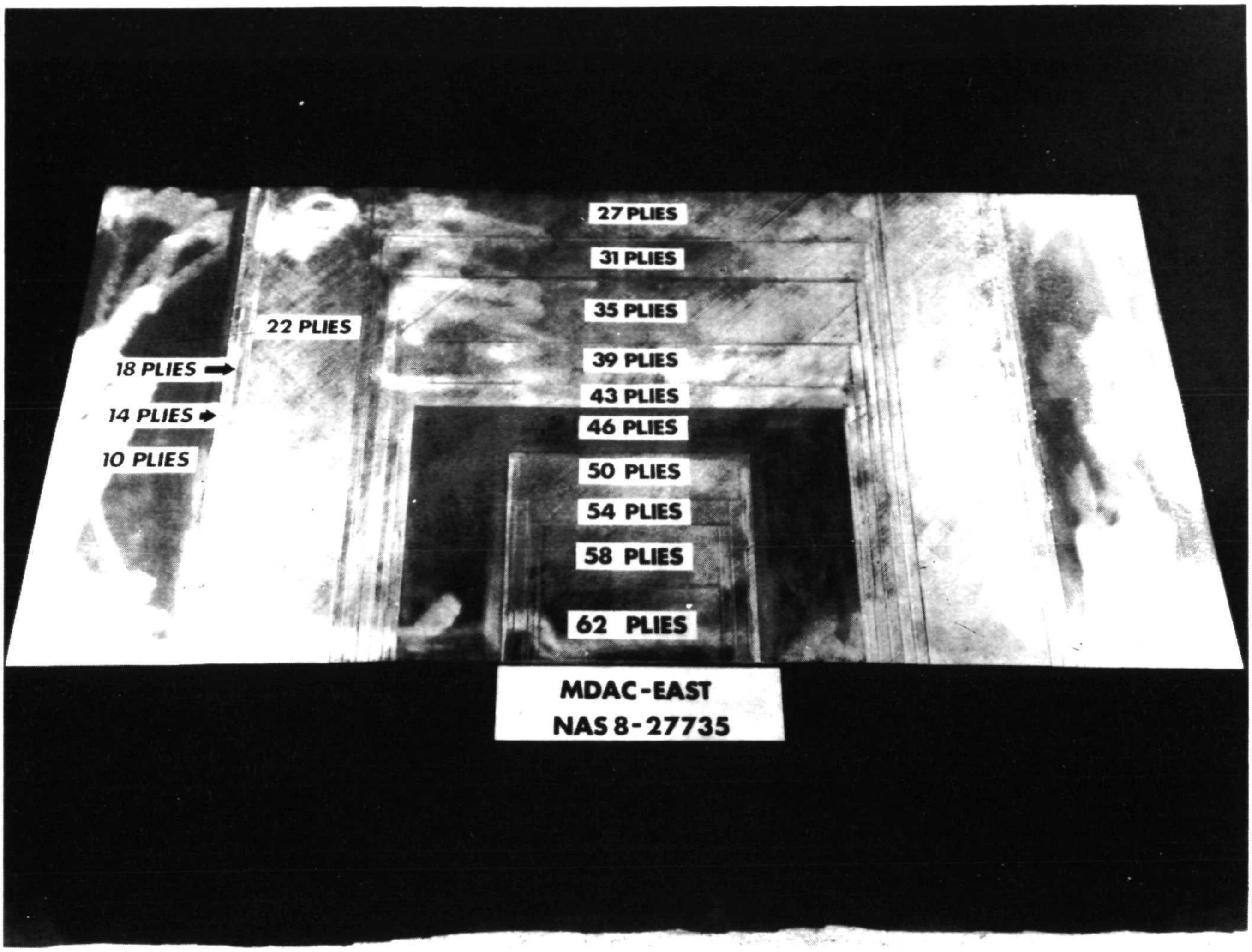


TITANIUM INTERLEAVES ARE ADDED TO STRINGERS TO PROVIDE NECESSARY SHEAR AND BEARING STRENGTH

FIGURE 2-26

The Component Panel is shown installed in test machine in Figure 2-28. The panel was supported on steel beams under each stringer to provide an elastic foundation for the panel. These beams were designed to simulate the stiffness of the remaining portion of the compression panel. Load was applied by the rectangular shaped loading head at the top of the panel.

Two separate tests were conducted on the panel. During the first test conducted at room temperature, the maximum applied load was 300K. Approximately 70 strain gages attached to the skin and stringers and 10 deflection gages were used to monitor response of panel. The second test was conducted at a temperature of 600°F. The majority of strain gages were inoperative for this test because they did not withstand the several hour exposure to 600°F temperature. However, the deflection



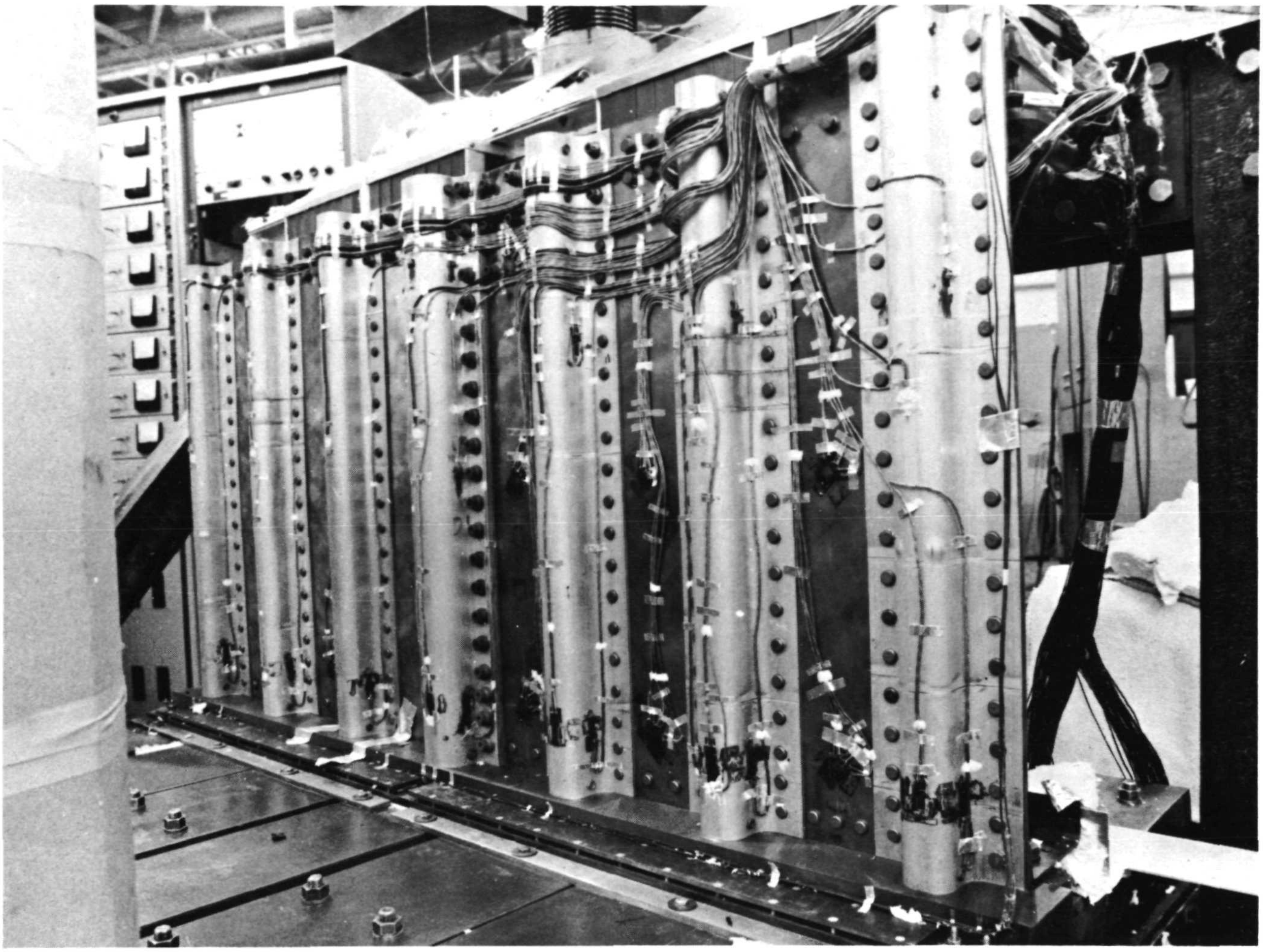
COMPONENT PANEL SKIN BEFORE ASSEMBLY

FIGURE 2-27

gages functioned properly and were sufficient to verify structural integrity and load distribution.

Although design ultimate load was 350K at 600°F, the panel actually was tested to 400K or 115% of design ultimate load. The test was then stopped due to limitations of the test machine. Examination of the panel after test showed indications of the beginnings of crippling failures on the outboard stringers. These can be observed in Figure 2-28.

Figure 2-29 shows in detail one of the outboard stringers on the component panel after the 600°F test. The local blister on the surface indicates the beginning of a crippling failure. The opposite outboard stringer contains a similar blister. It is estimated that some additional load above the 400K level could



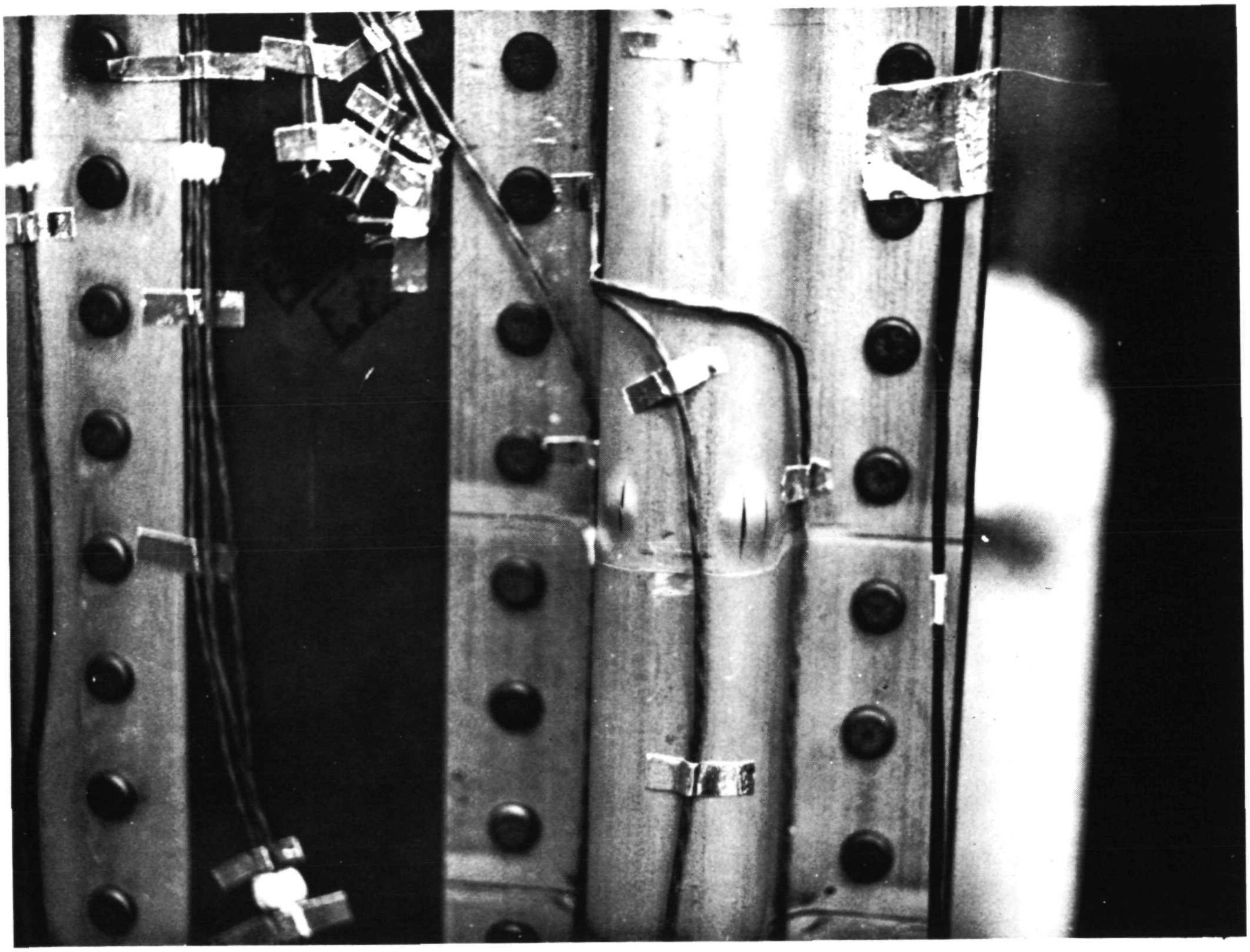
COMPONENT PANEL IN TESTING MACHINE

Figure 2-28

have been carried by the panel before a complete crippling failure of outboard stringers would have occurred.

In Figure 2-30 the predicted and measured loads distribution for the component panel when subjected to 350K at 600°F are shown. For comparison, the loads distribution predicted at this location for the complete compression panel are shown also. The good agreement between predicted and measured loads for the component panel increases confidence in procedures used for design and analysis.

A comparison of reactions from the room temperature (RT) and 600°F component panel is shown in Figure 2-31. The 350K room temperature reactions were calculated based on distribution at 300K. The outboard stringers carry more of the total load at RT than they do at 600°F. This difference in loads distribution is attributed



CRIPPLING FAILURE OF STRINGER EMINENT

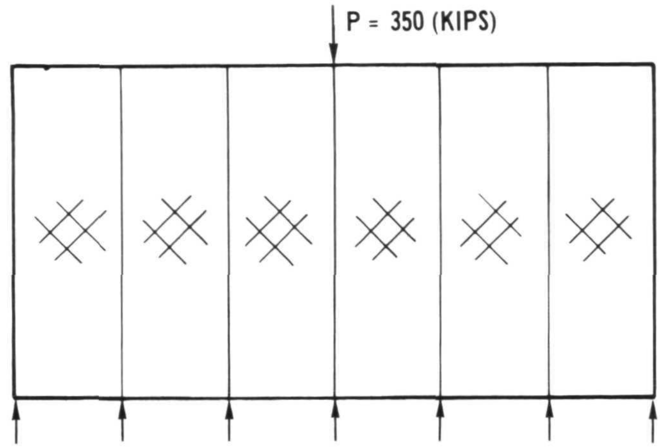
FIGURE 2-29

primarily to the higher ratio of skin shear stiffness to stringer axial stiffness at room temperature than at 600°F.

In summary, many unique design features incorporated in the compression panel were verified by the component panel test program. Also, the ability of a boron aluminum structure to sustain a complex shear lag load distribution was demonstrated. In addition, it was proven that analytical tools, such as finite element programs, for conventional materials and structures can be successfully applied to analysis of composite structures. Other specific accomplishments include:

- o Capability to design B/Al load redistribution structures for 600°F environment
- o Additional strength at minimum weight provided by titanium interleaves

LOADS DISTRIBUTION
($600^{\circ}F$)



PREDICTED – COMPRESSION PANEL	17.8	34.7	49.7	145.5	49.7	34.7	17.8
– COMPONENT PANEL	23.0	37.2	48.0	133.5	48.0	37.2	23.0
MEASURED – COMPONENT PANEL	23.6	–	–	135.0	45.0	40.0	21.2

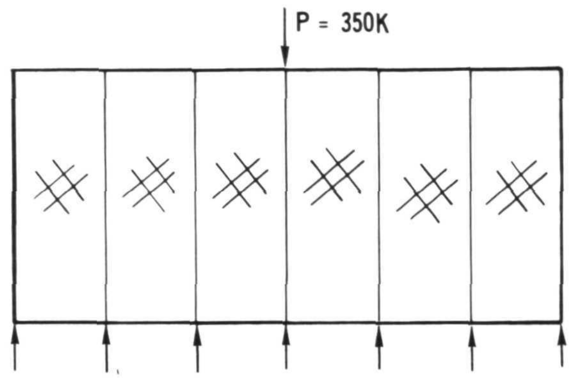
STRUCTURAL INTEGRITY

MAXIMUM TEST CONDITION: P = 400K (115% DUL)
TEMPERATURE = $600^{\circ}F$
CRIPPLING FAILURES BEGINNING ON OUTBOARD STRINGER

PREDICTED LOADS DISTRIBUTION AND STRUCTURAL INTEGRITY OF COMPONENT PANEL VERIFIED BY TEST AT $600^{\circ}F$

FIGURE 2–30

  - o In-plane shear strength
  - o Fastener bearing strength
  - o Overall improvement in apparent ductility
- o Design and fabrication of tapered B/Al stringers with titanium interleaves
- o Design and fabrication of contoured B/Al skins with titanium interleaves
- o B/Al stringer closeout fitting design
- o Panel thrust post area design using mix of both composite and conventional materials
- o General improvement in overall B/Al manufacturing and design technology.



STRINGER LOAD (KIPS)							
PREDICTED (600°F)	23.0	37.2	48.0	133.5	48.0	37.2	23.0
600°F TEST	23.6	–	–	135.0	45.0	40.0	21.2
RT TEST	27.6	–	–	115.6	46.0	45.4	24.0

PROPERTY COMPARISON	E_L^C (10^6 PSI)	G_{xy} (10^6 PSI)	G_{xy}/E_L^C
RT	32.0	9.4	0.293
600°F	25.8	6.7	0.259

COMPONENT PANEL OUTBOARD STRINGER LOADS HIGHER
FOR ROOM TEMPERATURE TEST THAN 600°F TEST

FIGURE 2–31

3.0 REFERENCES

1. Garrett, R. A., et al., "Design, Process Development, Manufacture Test and Evaluation of Boron-Aluminum for Space Shuttle Components", First Quarterly Report, Contract No. NAS8-27735, McDonnell Douglas Corporation, Report MDC E0491, dated 10 November 1971.

2. Garrett, R. A., et al., "Design, Process Development, Manufacture Test and Evaluation of Boron-Aluminum for Space Shuttle Components", Second Quarterly Report Contract No. NAS8-27735, McDonnell Douglas Corporation, Report MDC E0555, dated 10 March 1972.

3. Garrett, R. A., et al., "Design, Process Development, Manufacture Test and Evaluation of Boron-Aluminum for Space Shuttle Components", Third Quarterly Report Contract No. NAS8-27735, McDonnell Douglas Corporation, Report MDC E0650, dated 10 August 1972.

4. "Military Standardization Handbook: "Metallic Materials and Elements for Aerospace Vehicle Structures", MIL-HDBK-5B, Volume 1, September 1971.

5. Corvelli, N., and R. Carri, "Evaluation of Boron-Epoxy-Reinforced Titanium Tubular Truss for Application to a Space Shuttle Booster Thrust Structure", NASA TND-6778, June 1972.

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

Saint Louis, Missouri 63166 (314) 232-0232

MCDONNELL DOUGLAS
CORPORATION