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VOLUME IV ◆ REPAIRABILITY

GENERAL DYNAMICS
Convair Division

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VOLUME IV ◆ REPAIRABILITY

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Prepared by
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FOREWORD

The following final report describes work performed on NASA Contract NAS 8-27738 by the Convair Division of General Dynamics Corporation. The work was administered by the Materials Division of the Astronautics Laboratory, George C. Marshall Space Flight Center, Huntsville, Alabama 35812. Mr. F. P. LaIacona was the NASA project officer.

The program was conducted by the Advanced Composites Group at Convair, San Diego, California. Primary contributors to the program were:

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This report covers the repairability portion of the contract from 1 October 1973 to 30 July 1974.

Jack L. Christian

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Program Manager

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SUMMARY

This portion of the program was performed to determine the repairability of boron/aluminum structural components. Previous program reports defined design and manufacturing criteria necessary for the successful application of these composites and verified their applicability through structural testing. This report demonstrates that metal matrix composite material, damaged in service, can be repaired by techniques that are not very different from those currently in use for conventional materials.

A list of repair guidelines was prepared to aid in determining the proper repair techniques for a given structure. These guidelines included specifying types of repair material and their applicability, corrosion prevention procedures, design criteria, and inspection criteria.

Six sets of boron/aluminum structural components were repaired and tested to compare as-fabricated and repaired performance. The specimens included a honeycomb-stiffened panel, elastically buckled tubes, a skin/stringer panel, a tube combining bending and tension, a splice joint specimen, and a tension field panel. All but one set of specimens, when repaired, exceeded the strength of the original specimens; the repairs resulted in an average weight increase per structure of 9%, and an average performance increase of 27%.

SECTION 1

INTRODUCTION

The application of advanced composites, both resin and metal-matrix, to aircraft and missile structure has become prevalent in recent years. It is clear that these high-strength, low-weight composite materials will find additional structural applications on future aerospace vehicles. Previous test articles from this and other government and industry programs (References 1-6) have demonstrated that boron/aluminum technology has progressed sufficiently to be considered for use on Space Shuttle. In fact, partly because of the present program, boron/aluminum tubular struts have already been baselined for the Space Shuttle Orbiter.

1.1 PROGRAM OBJECTIVES

The objectives of this program were to compare the use of boron/aluminum (B/Al) in Space Shuttle application with other structural materials and to evaluate material properties, processing techniques, and fabrication characteristics of B/Al to develop sufficient technology to permit application of B/Al for Space Shuttle structural components with a high degree of confidence.

The main portion of the program (References 1, 2) included the design of three thrust structure components for the Space Shuttle, the testing of subcomponent specimens to verify design and joint fabrication concepts, and culminated in the design and fabrication of two components: a 1 by 0.96m (40 by 38 in.) shear beam weighing 35.4 kg (78 lb) designed for service at 366K (200F), and a 2 by 0.7m (80 by 29 in.) compression panel weighing 20.2 kg (44.4 lb) and capable of service up to 589K (600F). These structures successfully demonstrated that B/Al structural components could be fabricated and assembled using modified sheet metal technology and today's factory equipment. The successful testing of the shear beam component to 110% of design ultimate load is described in Reference 7.

The objective of the repairability phase of the program was both to determine a basic repair approach for metal matrix structures and to demonstrate the applicability of this approach through actual repair testing. A repairability review board, composed of design, material, and processing personnel formulated the repair approaches and selected six sets of failed specimens to be repaired and retested. Each selected specimen had its previous testing history recorded, and a photograph was made of the failed specimen. A second photograph was taken after specimen repair to visually demonstrate the repair technique. A third photograph was then taken after the specimen was retested so that comparisons could be made regarding the type and location of failure before and after repair.

1.2 ORGANIZATION

This report is divided into four volumes. The first volume (Reference 1) details the design, stress analysis, and subcomponent testing of structures examined during the program. Specifically, designs are presented for 9.2 by 3.1m (30 by 10 ft) and 1.0 by 0.96m (40 by 38 in.) shear beams, a 9.2 by 3.1m (30 by 10 ft) truss, and 3.1 by 3.1m (10 by 10 ft) and 2.0 by 0.7m (80 by 29 in.) compression panels as well as several subcomponent specimens. The second volume (Reference 2) contains material characterization, process development, process and material specifications or guidelines, and manufacturing procedures used in the fabrication of component and subcomponent test articles. The third volume (Reference 7) discusses the component testing on the full-scale shear beam test specimen, and compares the B/Al design of the component with comparable performance structures made from aluminum and titanium. This fourth volume describes the repair techniques for B/Al aluminum developed on this program.

1.3 REPAIRABILITY BACKGROUND

Previous to this program, General Dynamics had performed selected repair studies on three structural components made from metal-matrix composites (References 2, 3, and [illegible]). These repair studies, as well as the repair of numerous sub-element specimens, formed the basis on which this program was developed.

1.3.1 REPAIR OF CRIPPLED B/Al ADAPTER. (Reference 3) A PRIME adapter for the Atlas Missile was made in 1968 using B/Al. The composite section of this adapter was 1.5m (5 ft) in diameter and 1.2m (4 ft) high. The hat stringer reinforced cross-plied skin initially failed at 133% of design ultimate load by crippling of three stringers and the skin panels between the hats. Aluminum straps were riveted over the damaged area, and the structure was retested to 100% of design ultimate load without failure.

1.3.2 REPAIR OF DAMAGED B/Al-Ti COMPRESSION PANEL. (Reference 8) A 1.2 by 0.6m (4 by 2 ft) compression panel consisting of eight unidirectional B/Al hats welded to a titanium skin was to be subjected to 589K (600F) compression testing. During heat-up, portions of the panel attained a temperature in excess of 811K (1000F). This overheating caused buckling of three stringers on one side of the panel.

The buckled stiffeners were successfully straightened using the application of heat and pressure to the skin/stiffener. Because it was not possible to obtain perfectly straight stringer flanges and because of the possibility that the boron was degraded due to local overheating, it was decided to reinforce the skin flanges of the three damaged stringers.

Five boron/aluminum angles, $[0_6]$, 1.09 mm (0.04 in.) thick were hot formed. The angles were attached to the stringers by means of rivets and adhesive bonding. Hexcel 951 material was used for the bonding operation. A 0.81 mm (0.032 in.) titanium doubler was added to the skin side of the panel. The repaired panel was later successfully tested at 589K (600F).

1.3.3 REPAIR OF CRIPPLED B/Al HAT SECTION. (Reference 2) A 0.24 cm (0.1 in.) thick B/Al hat, 48 cm (18 in.) long, was tested in compression at 589K (600F). A post test evaluation disclosed that the testing arrangement did not provide the desired end fixity. The specimen had acted as the center of a 2m (78 in.) column of undetermined fixity. For this reason, a second crippling test was run.

The previously failed B/Al stringer was disassembled and cut to approximately 30.3 cm (12 in.) for retesting. The crippled section was reformed into the desired configuration at 755K (900F) using wooden tools and graphite lubricant. The hat was resistance welded to a 10-ply 0 ± 45° skin and retested at 589K (600F). The specimen failed at 133% of design ultimate load.

1.4 NEW TECHNOLOGY

In compliance with the New Technology clause of the contract, personnel assigned to work on the program were advised, and periodically reminded, of their responsibilities in the prompt reporting of items of New Technology. In addition, reports generated as a result of the contract work were reviewed by the Program Manager as a further means of identifying items to be reported.

Response was made to all inquiries by the company-appointed New Technology Representative, and when deemed appropriate, conferences were held with the New Technology Representative to discuss new developments arising out of current work that could lead to New Technology items. The New Technology Representative has the responsibility for transmitting reportable items of New Technology to the Technology Utilization Officer, as well as the annual and final reports specified in the Clause.

The Contractor believes the performance of personnel associated with the contract has been consistent with the requirements of the New Technology clause.

SECTION 2

REPAIRABILITY GUIDELINES

The following list of guidelines was used during the repairability studies. These guidelines were intended for application to structures fabricated from 50 v/o B/6061 Al. The applicability of these guidelines was continually assessed during the repairability program.

2.1 FIELD REPAIRS

Primary consideration shall be placed on the application of in situ field repairs; however it may be necessary to remove specialized items to repair facilities.

2.2 REPAIR MATERIALS

The following materials may be considered for use in B/Al repairs.

a. Aluminum — limited to applications between 211K (-80F) and 422K (300F).

b. Resin Composites — limited to maximum resin composite use temperature.

c. Titanium, Steel, B/Al — no limits.

2.3 CORROSION PRODUCTS

All corrosion products shall be mechanically removed prior to repair. If boron fibers are exposed in a joint area, special handling may be necessary. The same corrosion prevention system used with the parent structure shall be applied to the repair. If no corrosion system is in use on the parent structure, and boron fibers are exposed or the repair uses material other than B/Al, a corrosion prevention system compatible with the use temperature shall be applied.

2.4 TEMPERATURE LIMITATIONS

The following guidelines shall be used for maximum temperature usage during repairs.

a. Heat treated B/Al — maximum applied temperature, 422K (300F).

b. As-Received B/Al — maximum applied temperature, 783K (950F).

Note: If the repaired structure contains brazed, soldered, or adhesive joints, temperature limitations may be imposed by the joint.

c. Cross-Ply Laminate — if hot forming is necessary, the repair should be performed between 700-783K (800-950F).

The use of a Temple Stick or other temperature monitoring device is recommended when attempting elevated temperature repairs to ensure that maximum temperature limits are not exceeded; overheating of components during attempted repair will result in severe structural strength degradation of the component.

2.5 DAMAGE/REPAIR (l/t) RATIO

As a general rule, the area of damage is not as critical as is the thickness of composite in which the damage is contained. General guidelines were prepared for patches (on skins) and straps (on beams) as given in Figure 2-1. The guideline could be used for repair on one or both sides of the damaged structure.

2.6 REPAIR OR REPLACEMENT

It is not possible to present general guidelines that specify at what point structures should be replaced rather than repaired. Several individual factors must be taken into account; these include extent of damage, economics, complexity of the part, and location of the part (primary or secondary structure).

2.7 NONDESTRUCTIVE INSPECTION

All structures must first be visually examined; if possible, radiogr[illegible]hould also be made in the damaged area (including the area surrounding the da[illegible] The radiography is important because it can reveal subsurface filament dama[illegible]t cannot be observed by any other means. There will be some composite thickne[illegible], above which radiographs will not be useful; however, this thickness has not been specified. Dye penetrant inspection would be useful in areas where surface cracks may occur, and it should be used to assist in determining the extent of cracking.

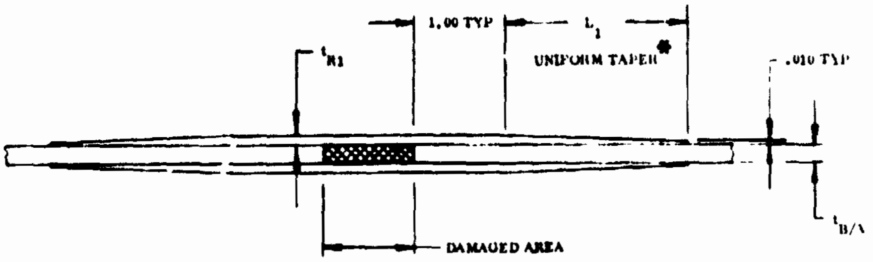
2.8 WEIGHT PENALTY TOLERANCE

No specific guidelines can be given on the weight penalty that can be tolerated for a given repair. This factor is dependent on the total efficiency of the structure.

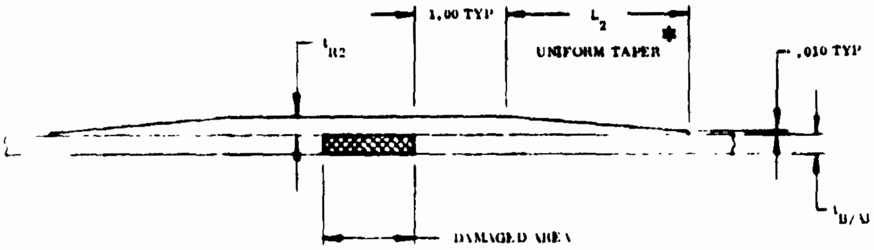
2.9 CUTTING OF DAMAGED MATERIAL

Existing structures should be used whenever possible, and damaged material will only be cut out and removed when absolutely necessary.

CASE I BOTH SIDES ACCESSIBLE



CASE II ONE SIDE ACCESSIBLE



Where the repair patch thickness is:

$$t_{R1} = \frac{1}{2} \times K_m \times t_{B/Al} \qquad t_{R2} = K_m \times t_{B/Al}$$

and the taper length is:

$$L_1 = \frac{1}{2} \times K_\ell \times t_{B/Al} \qquad L_2 = K_\ell \times t_{B/Al}$$

* Taper not required on Boron/Aluminum or Boron/Epoxy where $t_R \leq .05$ in.

REPAIR MATERIAL	K_m	
	"0°" Laminate	"±45°" Laminate
BORON/ALUMINUM	1.0	1.0
TITANIUM 6Al-4V	2.0	1.5
ALUMINUM 2024-T3	3.0	2.5
BORON/EPOXY	1.0	1.0

SHEAR STRENGTH OF REPAIR-TO-STRUCTURE JOINT (psi)	K_ℓ	
	"0°" Laminate	"±45°" Laminate
1000	160	80
2000	80	40
3000	55	27
4000	40	20
5000	32	16

Note: For clarity, only English units are shown.

Figure 2-1. Guidelines for B/Al Patch Repair

SECTION 3

COMPONENT REPAIRS

Six sets of specimens were selected for repair and subsequent re-testing. Selection of the specimens was based on the type of specimen, nature of the required repair, and the availability of previous test history. Repairs were made using, where applicable, the ground rules established in Section 2. Photographic records were maintained of specimens before, during, and after repair and subsequent re-testing. Attempts were made to test the repaired specimens under the same conditions used in the original testing.

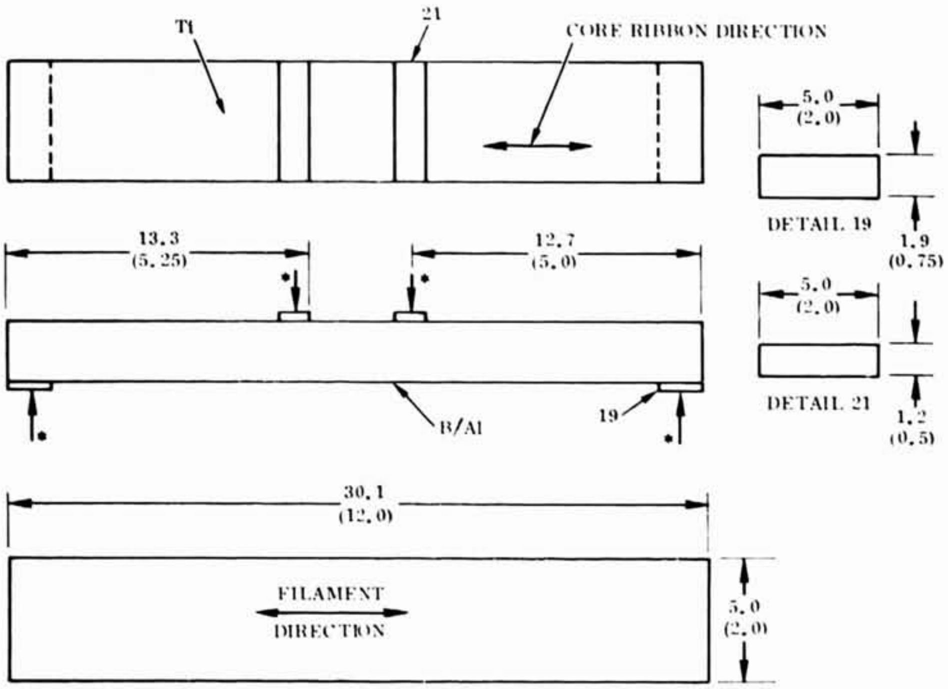
3.1 SANDWICH BEAM TEST

A sandwich beam specimen was designed originally to demonstrate the strength of boron/aluminum (B/Al) when used as face sheet material on a honeycomb sandwich (Reference 9). The sandwich beam test enabled the face sheets to develop the highest possible strength due to both the stabilizing action of the core and the introduction of uniform loads.

The original specimen configuration is shown in Figure 3-1. The overall dimensions of the beam were 30.1 by 5.0 by 2.5 cm (12 by 2 by 1 in.). The load introduction tabs were made from 6061-T6 aluminum. The compression skin was made from 6Al-4V titanium, the core from 3.1 mm (0.125 in.) cell diameter by 0.06 mm (0.0023 in.) thick aluminum honeycomb, and the tension skin from a 0.51 mm (0.020 in.) thickness of 0.1 mm (4.0 mil) boron reinforced aluminum. The panel was bonded together using FM-123 adhesive. It was assumed that a facing sheet tensile stress of 1207 MPa (175 ksi) would be developed; using this as the design value, a failure load of 13.7 kN (3090 lb) was anticipated. The specimen failed by a tensile fracture of the B/Al skin; the actual failure load was 15.8 kN (3545 lb), which corresponds to a tensile stress of 1306 MPa (189.5 ksi) in the tension skin.

The specimen, shown in the damaged condition in Figure 3-2, was selected for this program because it represents a severely damaged skin section.

The repair splice, consisting of a 0.76 mm (0.030 in.) thick section of 0.1 mm (4 mil) unidirectional B/Al, was adhesively bonded to the 0.51 mm (0.020 in.) thick B/Al skin with FM-123 adhesive. The splice section was 15.2 cm (6 in.) in length and conformed to the l/t ratio outlined in Section 2. The beam, prior to bending, was straitened as much as possible at room temperature using a flat press. A capillary adhesive, Hysol 9313, was used on the honeycomb at crack surfaces and at the titanium/honeycomb interface. This adhesive was used to strengthen the honeycomb core and the titanium compression skin/aluminum honeycomb core interface where separation had occurred during initial testing. The repaired beam with the splice in place is shown in Figure 3-3.



NOTE: DIMENSIONS IN CM (in.)
*LOADS

Figure 3-1. B/Al Sandwich Beam Specimen

Figure 3-2. Failed Sandwich Beam Specimen. The Boron Aluminum tension skin failed at a stress of 1306 MPa (189.5 ksi). (136410)

Figure 3-3. Repaired Sandwich Beam Specimen. A 0.76 mm (0.030 in.) splice plate has been adhesively bonded over the failed section. (136864)

The repaired sandwich beam specimen was re-tested in an identical manner to the original test. The specimen failed at a load of 18.7 kN (4147 lb), which corresponded to a tensile stress of 1531 MPa (222 ksi), a 16.5% increase in strength over the original specimen. In addition, the failure, shown in Figure 3-4, was forced away from the initial failure. The actual cause for specimen failure was shearing of the aluminum core and subsequent tearing of the tension skin at one of the reaction points.

The specimen readily showed that honeycomb-stiffened B/Al structure could be easily repaired, even when damage to both the face sheets and core was severe. Table 3-1 gives a comparison of performance characteristics between the original and repaired specimen. In an actual structural application, for a damaged area similar to that on the sandwich beam specimen, the dimensions of the splice would be similar to those used on the specimen; however, this would only represent a fraction of a percent of the part weight. It is therefore felt that B/Al, when used as a core-stiffened skin, could be repaired when damaged at no strength penalty and no significant weight penalty.

3.2 ELASTIC BUCKLING TUBES

Two B/Al tubes, previously used in buckling tests (Reference 6) were selected for repairability testing on this program. One tube was 63.5 cm (25 in.) in length and the other tube was 76.2 cm (30 in.) in length. The original buckling loads for these tubes are shown in Table 3-2. Because the tubes were only tested in the elastic

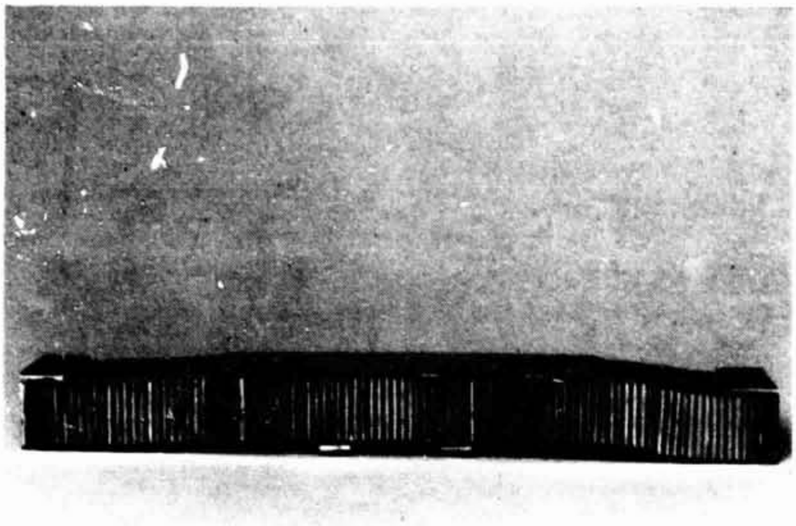


Figure 3-4. Retested B/Al Sandwich Beam Specimen. The repaired beam failed at 1531 MPa (222 ksi), a strength increase of 16.5% over the initial structure. (136994)

Table 3-1. Sandwich Beam Performance

Specimen	Weight g (lb)	Weight Difference g (lb)	% Weight Change	Strength MPa (ksi)	Strength Difference MPa (ksi)	% Strength Change
Original specimen	245 (0.54)	—	—	1306 (189)	—	—
Repaired specimen	262 (0.58)	17 (0.037)	6.5	1531 (222)	227 (33)	16.5

Table 3-2. Elastic Buckling of B/Al Tubes

Tube Length cm	(in.)	L/D	Initial Buckling Load kN	(lb)	Buckling Load, Damaged kN	(lb)
63.5	25	25.4	37.8	8500	26.7	6000
76.2	30	30.3	22.3	5000	16.5	3700

range, there was no permanent deformation in the tubes. There is, however, always a chance that thin-walled tubes could be crushed during service or due to abusive handling. To simulate this abusive handling, the tubes were crushed in a vise. Photographs showing the tubes before and after the damage are presented in Figures 3-5 and 3-6. The damaged tubes were then tested in the same fixture used for initial testing. The results, shown in Table 3-2, indicate a decrease in elastic strength of approximately 28%.

The two damaged B/Al tubes were repaired by reforming the damaged portions at 788K (950F). The re-forming die consisted of two steel blocks, each with a groove 1.27 cm (0.5 in.) in radius, machined on facing surfaces. The blocks were sufficiently long to completely cover the damaged area of the tubes. Originally, aluminum dies were tried; however, they were not sufficiently strong to reform the tubes, but instead yielded under pressure.

Both the steel blocks and the tubes were coated with Everlube Corporation's T-50 graphite lubricant to minimize friction during forming. The steel blocks were externally heated to 788K (950F) in a furnace and then clamped around a tube. The clamps were slowly tightened to bring the tube back to its original roundness. Forming was continued until the temperature of the steel dies dropped below 505K (450F), at which point the blocks were reheated and the operation repeated. Thermocouples mounted at each end of the tube indicated that the temperature at the tube ends did not rise above 505K (450F); therefore, the soldered end caps were not disturbed during repair.

In actual field repairs of this type (for tubes crushed during abusive handling), an external heating unit could be locally applied to the steel dies, and the tubes repaired in situ.

An example of this technique was demonstrated when a 3.8 cm (1.5 in.) diameter tube, similar to those to be used in the mid-fuselage of the Space Shuttle, was repaired. This tube had been deformed during autoclave diffusion bonding because of defective tooling. The tube was formed to its design shape in a manner similar to that described above.

Figure 3-7 shows the two repaired test specimens as well as the repaired mid-fuselage tube.

The repaired tubes were then re-tested in the same manner as was used in initial testing. The results are reported in Table 3-3. Although the buckling loads are greater for the repaired tubes than for the damaged tubes (by 8 to 17%), they are still less than the initial buckling loads for the undamaged tubes (by about 20%). This indicated that reforming of the damaged portions of the tube did not constitute an acceptable repair; therefore, the two B/Al tubes were repaired again using thin stainless-steel sheet material wrapped twice around the periphery of the tubes and bonded in place using type 2216 adhesive. The 63.5 cm (25 in.) long tube had two strips of 3.8 cm (1.5 in.)

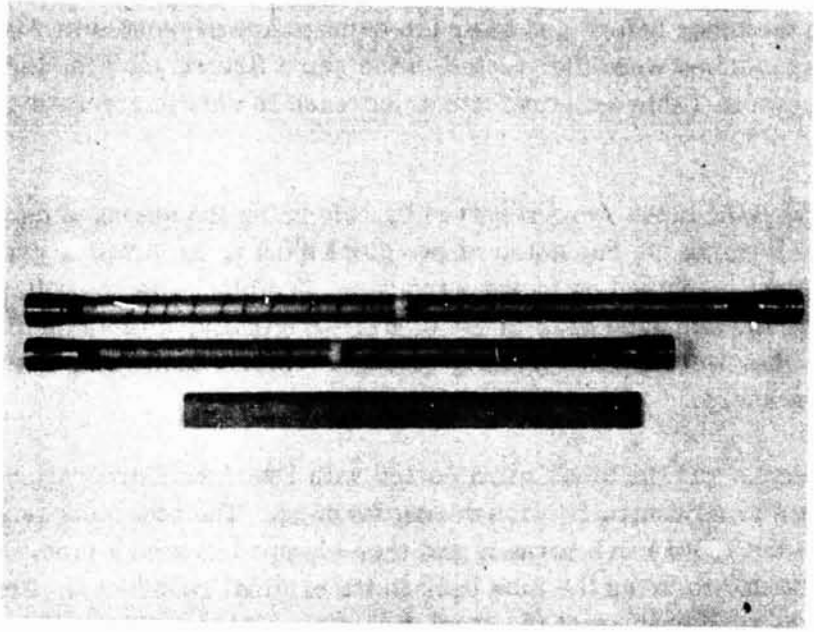


Figure 3-5. B/Al Tubes Prior to Damage (136478)

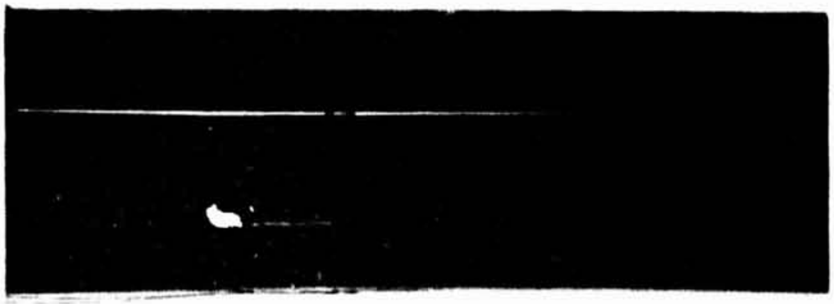


Figure 3-6. B/Al Tube After Damage (diameter at center of the column decreased 10%) (062574)

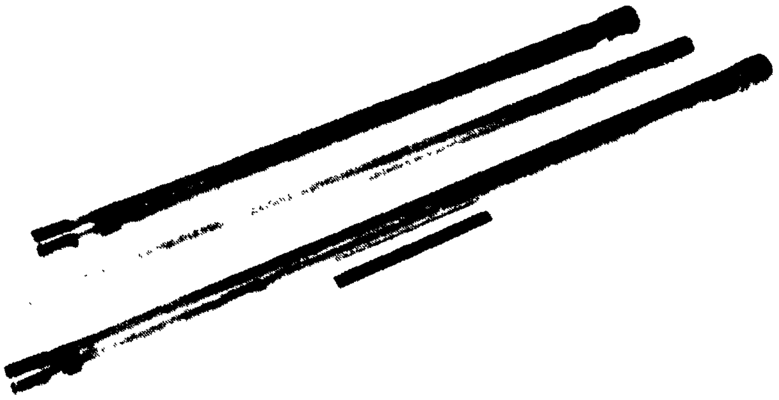


Figure 3-7. Crushed B/Al Tubes Repaired by forming at 788K (950F) (137203)

Table 3-3. Elastic Buckling of Repaired B/Al Tubes

Tube Length		L/D	Initial Buckling Load		Buckling Load Damaged Tubes		Buckling Load Repaired Tubes		Buckling Load Wrap Repaired Tubes		Weight Gain
cm	(in.)		kN	(lb)	kN	(lb)	kN	(lb)	kN	(lb)	(%)
63.5	25	25.4	37.8	8500	26.7	6000	31.7	7100	32.7	7400	6
76.2	30	30.3	22.3	5000	16.5	3700	17.9	4000	20.1	4500	11

wide by 0.15 mm (0.006 in.) thick stainless-steel foil wrapped around the tube twice and adhesively bonded and cured at 333K (140F) for one hour. The foils were separated by 2.54 cm (1.0 in.) as shown in Figure 3-8.

The weight of the tube before the repair was 253 grams. The weight of the tube after the repair was 268 grams, for a 6% weight gain. The 76.2 cm (30 in.) long tube was similarly repaired, but consisted of a 10.2 cm (4 in.) long by 0.15 mm (0.006 in.) thick stainless-steel sheet bonded at the center of the tube as shown in Figure 3-8. The weight before repair was 257 grams. The weight after repair was 286 grams for a 11% weight gain.

After the stainless-steel wrap repairs were made, the tubes were again re-tested for buckling strength; the results are reported in Table 3-3. The stainless-steel wrap repair resulted in an additional improvement in the buckling strength capability of the B/Al tubes; however, the buckling strength is still less than was initially obtained for the undamaged tubes (by 10 to 13%). It is believed that with minor modifications the wrap repair method is capable of restoring full buckling strength capabilities to damaged B/Al tubes.

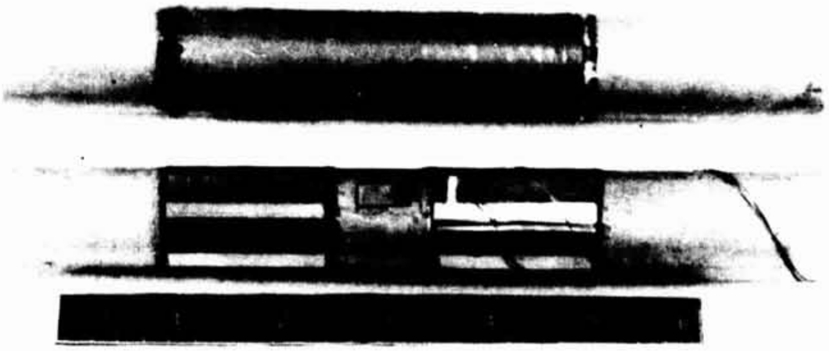


Figure 3-8. Foil Reinforced B/Al Tubes (138226)

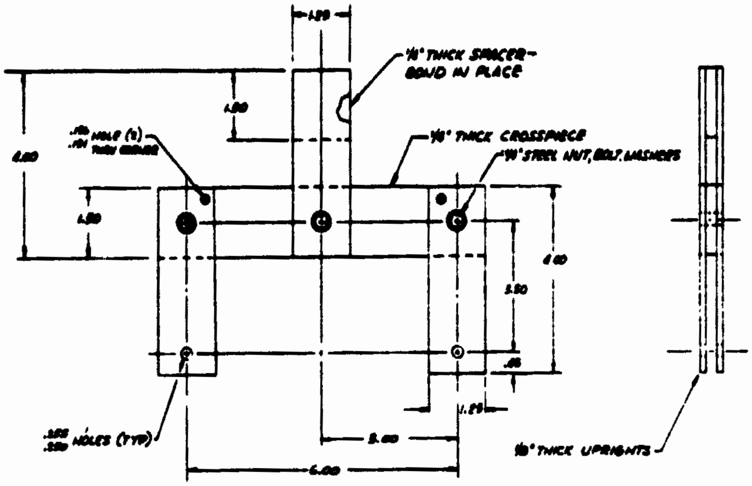
3.3 SHEET STRINGER SPECIMEN

A B/Al sheet-stringer specimen tested as a subcomponent demonstration article during development and fabrication of a B/Al adapter for the PRIME missile (Reference 3) was also selected for the repairability program. The test specimen consisted of a unidirectional B/Al hat section stringer resistance spot welded to a 0-90 crossply B/Al skin. Details of the test specimen and test fixture and attachments are shown in Figure 3-9.

The subcomponent test specimen was initially loaded to produce tension on the B/Al stringer to evaluate horizontal shear capability, which was design critical. The specimen was loaded in increments to failure, which occurred at 1730 newtons (386 pounds). The initial failure mode was horizontal shear calculated to be 5.65 MN/m^2 (8170 psi) at the skin radius on one side of the specimen. The skin failure was not catastrophic; therefore, the specimen was reversed and loaded again, this time to produce compression in the curved top of the B/Al hat section. Loading progressed in increments, with some evidence of yielding in the failed area, to 1770 newtons (399 pounds) load, at which time the shear upright collapsed and the top cap was forced to buckle as shown in Figure 3-10. The ability of the stringer to carry nearly limit loads after an initial shear failure was highly encouraging and again illustrated the post-buckling capability of B/Al composite material.

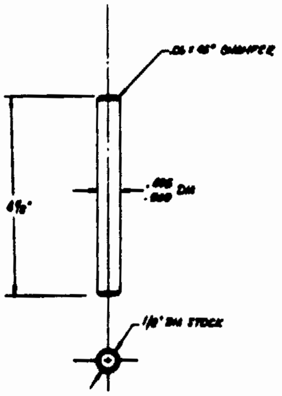
The technique developed for repair of the B/Al sheet stringer specimen consisted of reforming the hat into a straight configuration and then bonding and riveting on aluminum doublers to reinforce the side walls and flanges of the hat as shown in Figure 3-11.

Prior to making the repairs, the unit was disassembled; this included the aluminum end plug, the fasteners that held the aluminum tee, and also the tee. The procedure for straightening the B/Al hat was to hot size the affected area using soft dies and a



LOADING RIG

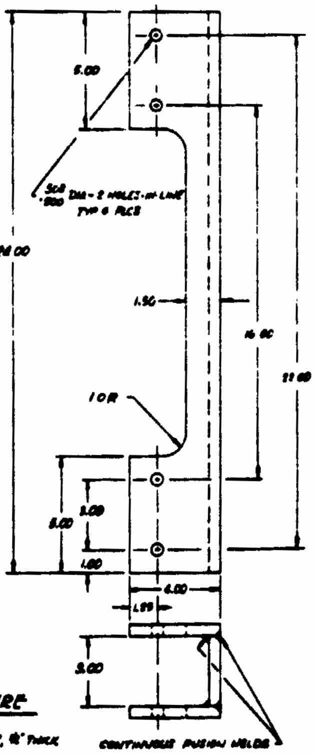
7075-T6 OR 2024-T62 ALUMINUM



LOADING PIN (2 REQ'D)

SAE 4130 STEEL, 125 KSI UTS MIN

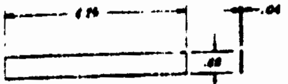
SCALE 1/1



HOLDING FIXTURE

ASTM A-7, SAE 1020 OR EQUIVALENT STEEL PLATE, ½" THICK

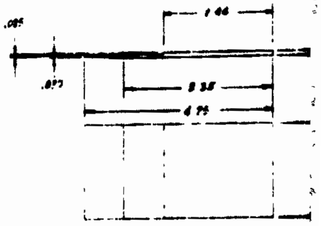
SCALE ½



RIVET DOUBLER (4 REQD)

7075-T6 ALUMINUM

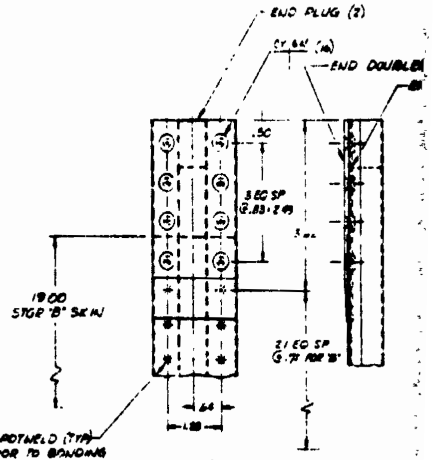
FOR STGR 'B' ONLY



END DOUBLER (2 REQ'D)

7075-T6 ALUMINUM

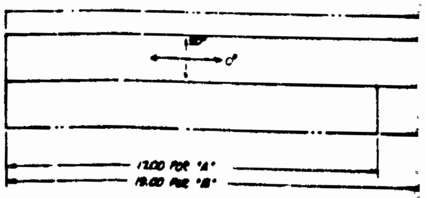
FOR STGR 'B' ONLY



DETAIL A

TYP BOTH ENDS STGR 'B'

BOND END PLUG, END DBLR & RIVET DBLR PER NOTE 1



CUTTING PLAN FOR SKINS FROM SEGMENT OF PANEL NA-616

½ SCALE

FOLDOUT FRAME

(

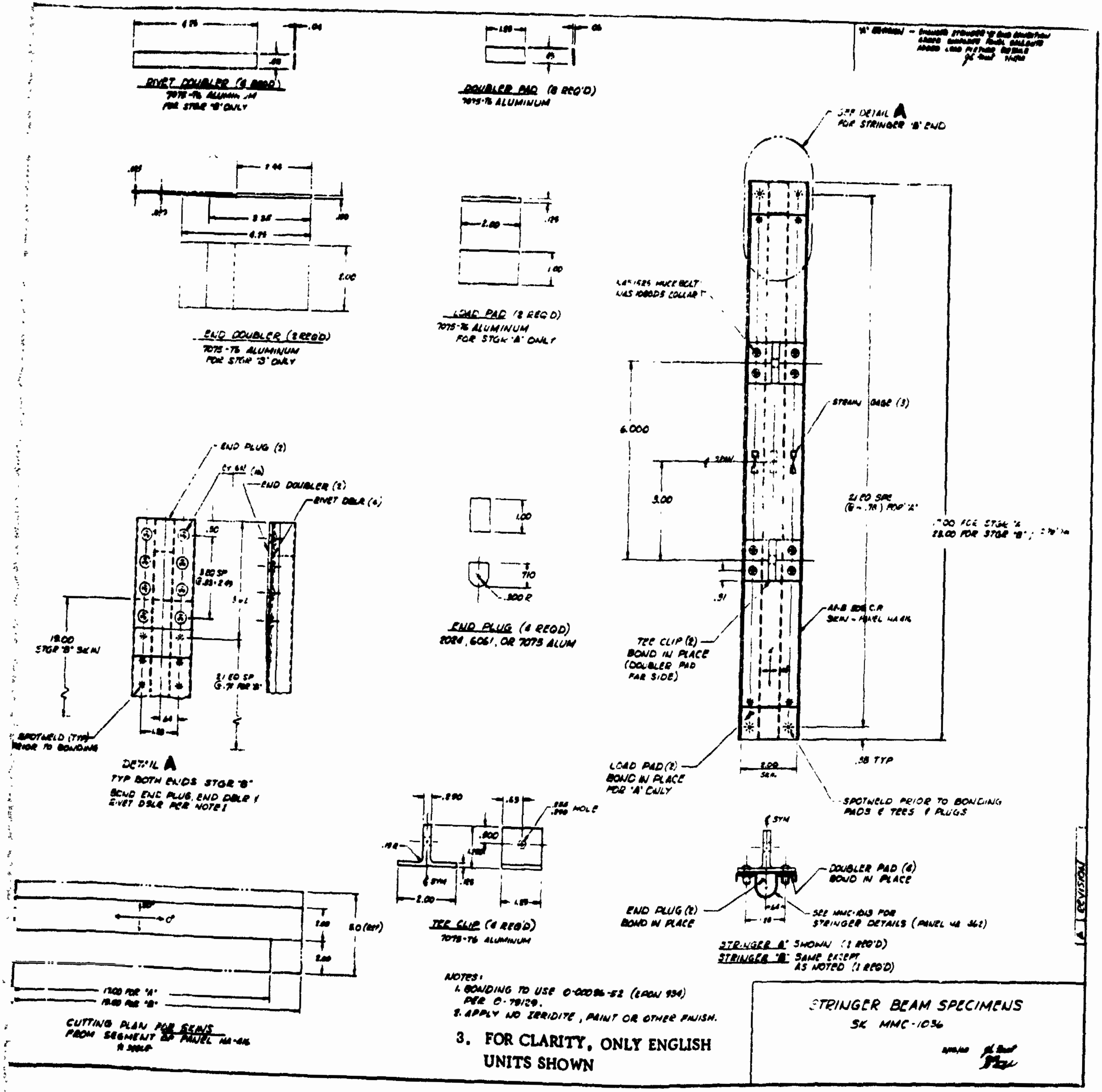


Figure 3-9. Sheet Stringer Specimen

FOLDOUT FRAME

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

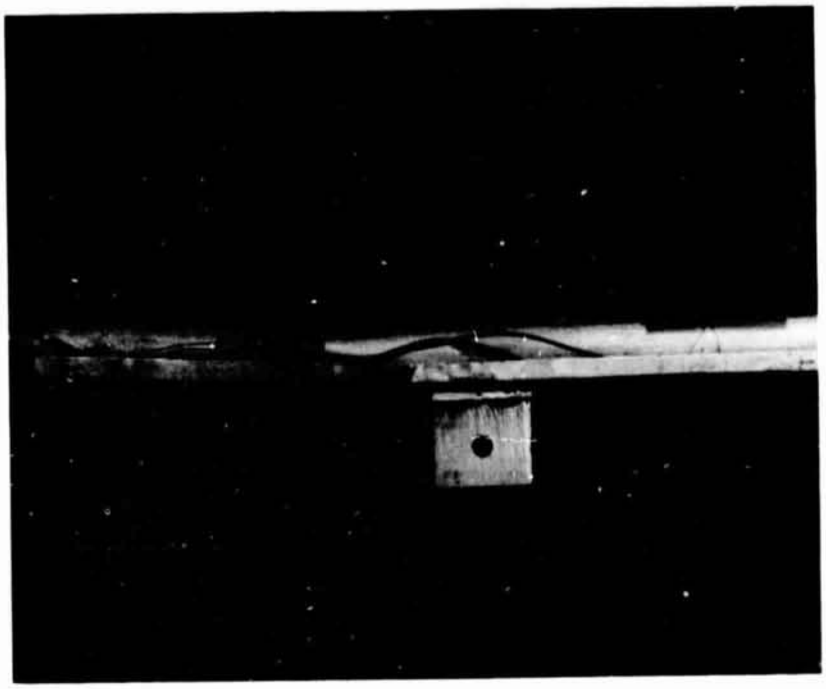
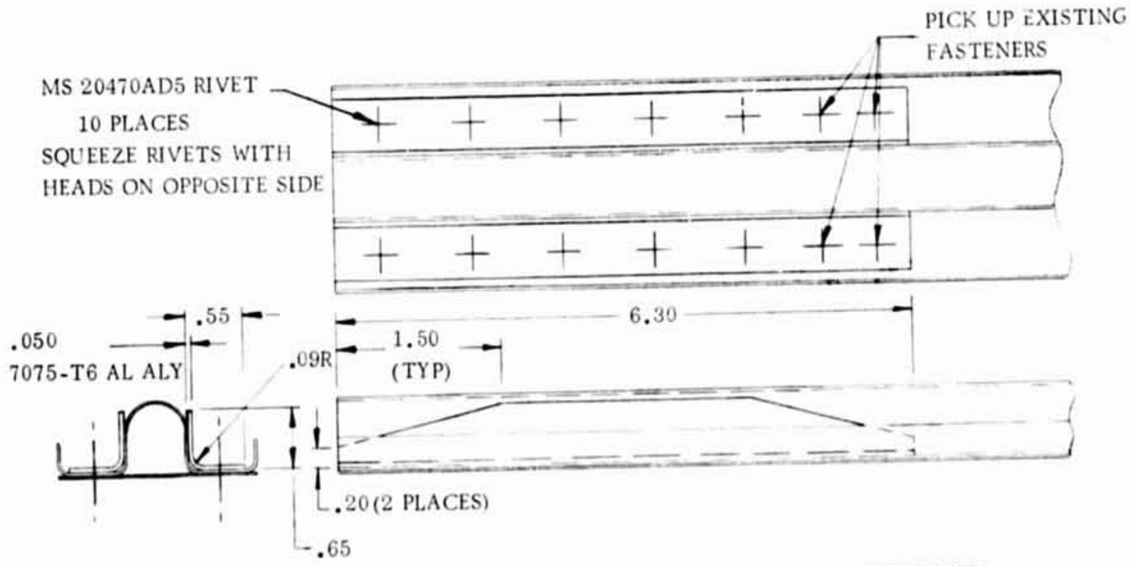


Figure 3-10. Failed Hat Crippling Specimen (13 7951)



NOTES: 1. BOND ANGLES TO STIFFENER USING HYSOL 394.1 PRIOR TO INSTALLING RIVETS.

2. MAINTAIN .24 MIN. EDGE DISTANCE ON ALL FASTENERS.

3. FOR CLARITY, ONLY ENGLISH UNITS SHOWN

Figure 3-11. Repair Plan for Hat Crippling Specimen heat lamp capable of raising the temperature of the part to 674K (750F). The form tools, which were made from hardwood, were sprayed with Form Kote T-50. The male die was inserted into the hat and a female die was then placed on the outside contour. Mild pressure was used in reforming the damaged portion of the hat.

After the straightening operation the part was cleaned and reassembled. Holes were punched using a 2.4 mm (3/32 in.) Whitney punch.

The stiffener angles were made from 7075-T6 aluminum and the 2.54 cm by 5.08 cm by 6.3 mm (1.00 by 2.00 by 0.25 in.) aluminum pad was made from 2024 ST. The part was then bonded with Hysol 394.1 adhesive. After bonding, the 2.4 mm (3/22 in.) holes were brought to size and rivets installed. The repaired B/Al sheet stringer specimen is shown in Figure 3-12.

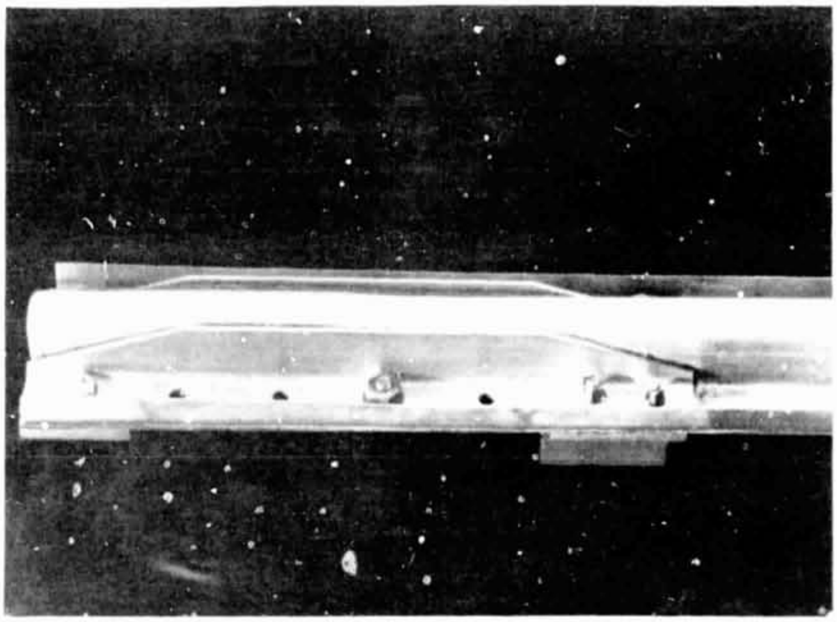


Figure 3-12. Repaired Sheet Stringer Specimen Prior to Riveting (139287)

The repaired sheet stringer specimen was then retested using the same fixtures and test method as was used in the initial testing (Figure 3-13). The specimen was first loaded to produce tension on the B/Al stringer. Failure occurred at 1766 newtons (398 pounds), which is 3% higher than the original failure load. Again the failure was not catastrophic, and the specimen was reversed and loaded again, this time to produce compression in the B/Al hat section. Failure occurred at 2120 newtons (477 pounds), which is a 20% higher load than obtained in the initial test. The test data are summarized in Table 3-4, and Figure 3-14 is a photograph showing failure of the repaired specimen. The repair of the B/Al sheet stringer was obviously very successful.

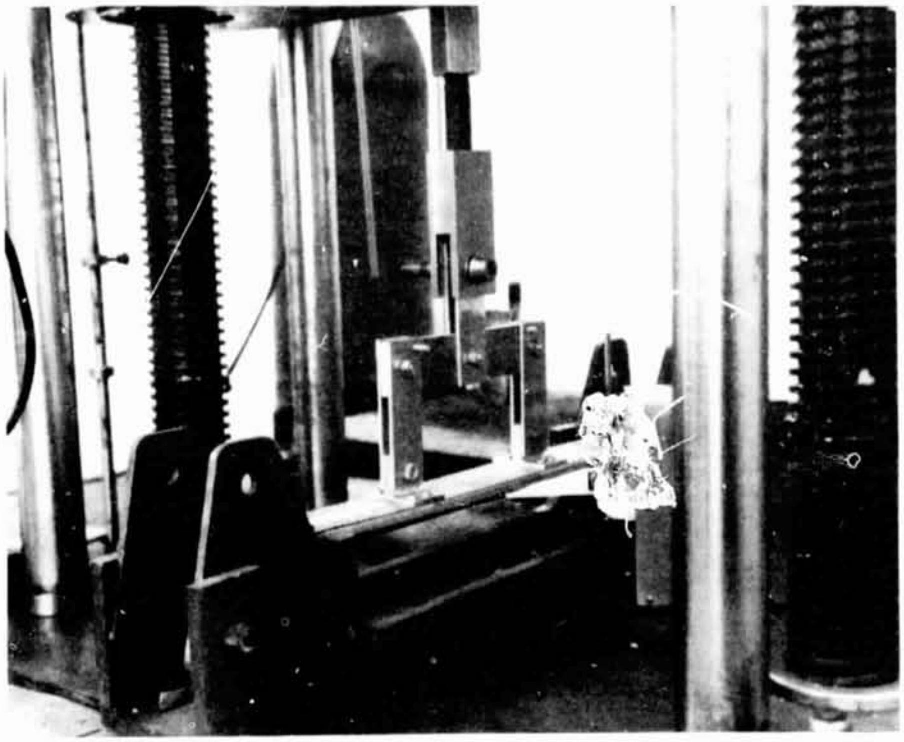


Figure 3-13. Testing of Repaired B/Al Sheet-Stringer Specimen (139369)

Table 3-4. B/Al Sheet-Hat Stringer Performance

	Weight		Weight Change	Failure Loads in Tension		%	Failure Loads Compression		%
Specimen	g	(lb)	(%)	N	(lb)	Change	N	(lb)	Change
Original	249	(0.54)		1730	(386)		1770	(399)	
Repaired	279	(0.61)	+12	1766	(398)	+3	2120	(477)	+20

3.4 BORON/ALUMINUM TUBE

The 1 m (40 in.) long 5.7 cm (2.25 in.) diameter B/Al tube was originally fabricated under contract to the Lockheed Missiles and Space Company. After the tube was built, the truss concept for the C-4 was abandoned in favor of a thin graphite/epoxy shell design. Thereafter, Lockheed furnished Convair the B/Al tube in exchange for the test data. The initial testing was accomplished under a Convair IRAD program. The tube was tested in combined tension and bending (the end fittings were drilled 0.44 cm (0.174 in.) off center to induce a bending load in addition to the tension loading). Failure occurred at 108,000N (24,400 lb) of load. Figure 3-15 is a photograph of the failed tube.

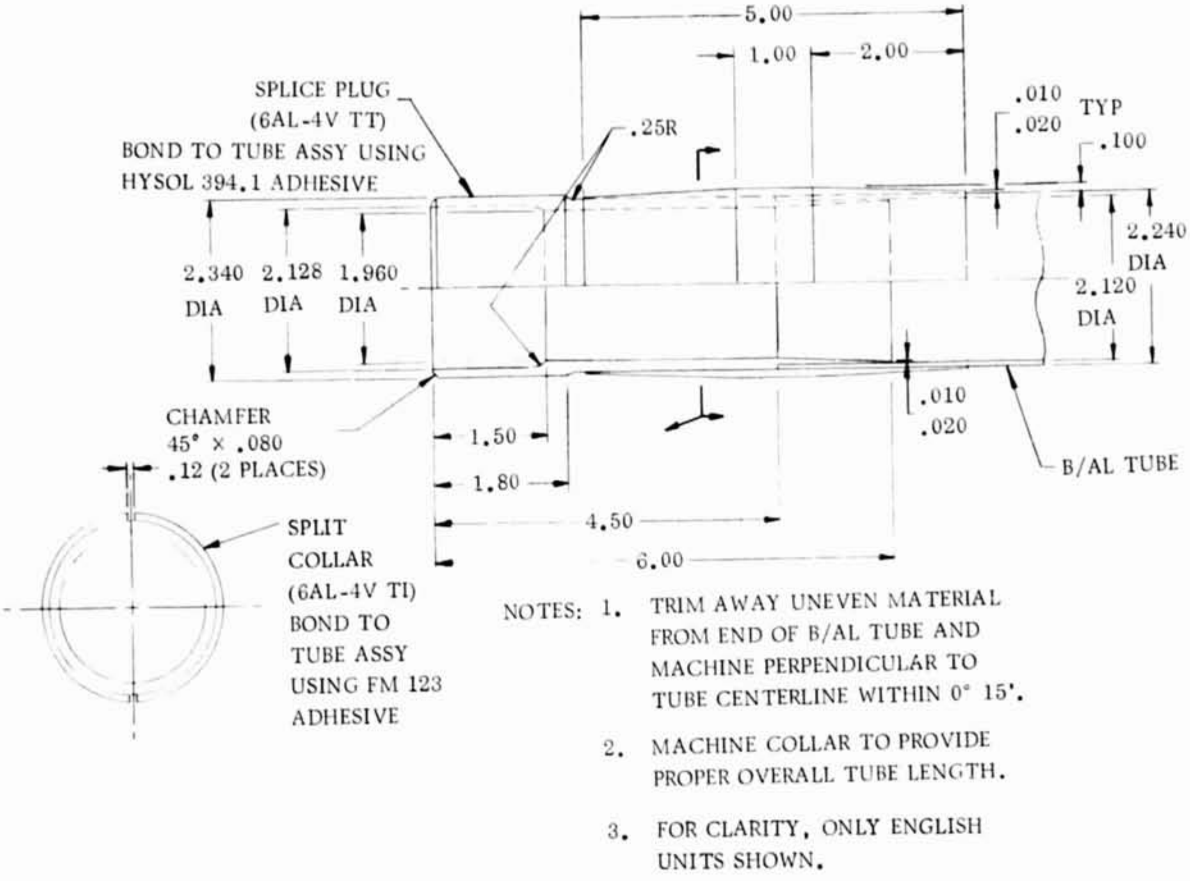
Figure 3-14. Retested B/Al Sheet Stringer Specimen (139858)

Figure 3-15. Failed B/Al Tube (137950)

The B/Al tube was repaired according to the plan shown in Figure 3-16. The uneven material was trimmed away from the broken end of the B/Al tube with a diamond router. The titanium splice plug and split collar were machined from titanium 6Al-4V alloy. The parts were then prepared for adhesive bonding.

The B/Al tube was etched with the standard Forest Products Laboratory aluminum etch. The splice plug and split collar were etched with a nitric/hydrofluoric mixture, followed by a phosphate/fluoride rinse. The splice plug was bonded into the tube with Hysol E.A. 394.1 and allowed to cure. The split collar was then bonded with American Cyanamide's FM-123 adhesive for one hour at 393K (250F). Figure 3-17 is a photograph of the repaired B/Al tube.

The repaired B/Al tube was tested in the same manner and with the same fixtures and test machine as was used in the initial testing. Failure occurred at 191,000N (42,900 lb) of load at the unrepaired end of the specimen, as shown in Figure 3-18. A summary of the test data is given in Table 3-5. The results indicate that satisfactory adhesive bond repairs can be accomplished in large diameter B/Al tubes.



NOTES:
1. TRIM AWAY UNEVEN MATERIAL FROM END OF B/AL TUBE AND MACHINE PERPENDICULAR TO TUBE CENTERLINE WITHIN 0° 15'.
2. MACHINE COLLAR TO PROVIDE PROPER OVERALL TUBE LENGTH.
3. FOR CLARITY, ONLY ENGLISH UNITS SHOWN.

Figure 3-16. Repair Plan for B/Al Tube Specimen

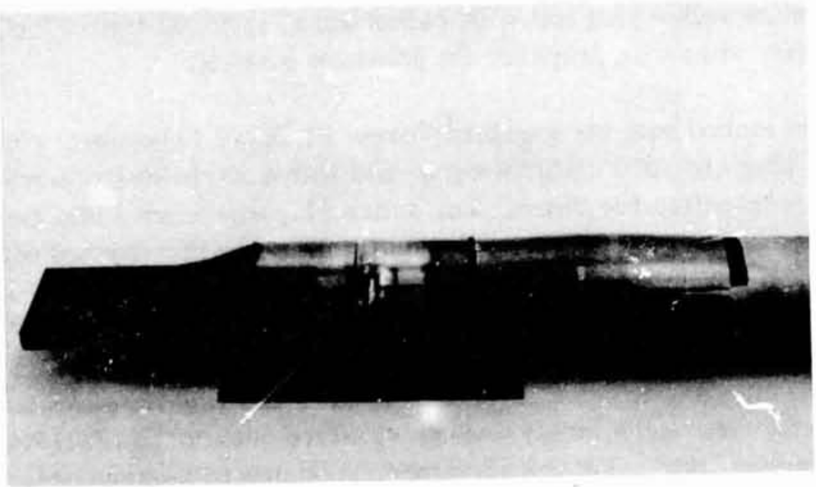


Figure 3-17. Repaired End of B/Al Tube (13 9633)

Figure 3-18. Failed B/Al Tube After Repair and Retest (13957)

Table 3-5. B/Al Tube Performance

	Weight		Weight	Tension/Bending Failure Loads		%
Specimens	kg	(lb)	Change (%)	N	(lb)	Change
Original	1.29	(2.84)		108,000	(24,400)	
Repaired	1.49	(3.27)	+15	191,000	(42,900)	+76

3.5 WEB SPLICE

The primary purpose of the web splice joint subcomponent test was to establish a splice/joint allowable to verify the joint strength used in the design of the shear web beam (Reference 1). The web splice test specimen was configured from a 5 mm (0.20 in.) thick web with 2.5 mm (0.10 in.) thick splice plates on both web faces. Both the web and splice material were ± 45° crossply B/Al. The spotwelded joint was sized to have sufficient shear load transfer capability to support shear flows of 5250 N/cm (3000 lb/in.) predicted for the center bays of the full-scale shear beam. The design ultimate strength of this joint was 120,000N (27,000 lb) or for equal distribution of load, 20,000N (4500 lb) per double shear spotweld. With the spotwelds on 3.81 cm (1.5 in.) centers, this strength equates with an expected maximum ultimate shear flow of 5250 N/cm (3000 lb/in.).

Two B/Al web splice test specimens were installed in test fixtures (one of which is shown in Figure 3-19) and tested in tension (double shear of the spotwelds). Failure of one specimen occurred at 100,085N (22,500 lb) of load. The failed test specimen is shown in Figure 3-20.

Double lap shear specimens were cut from B/Al that was originally purchased to develop weld schedules for the original web splice subcomponent. This material was cleaned and the original weld schedule verified by welding three specimens and then static testing them to failure. The failure loads were 9,600 lb, 8,650 lb, and 8,400 lb,

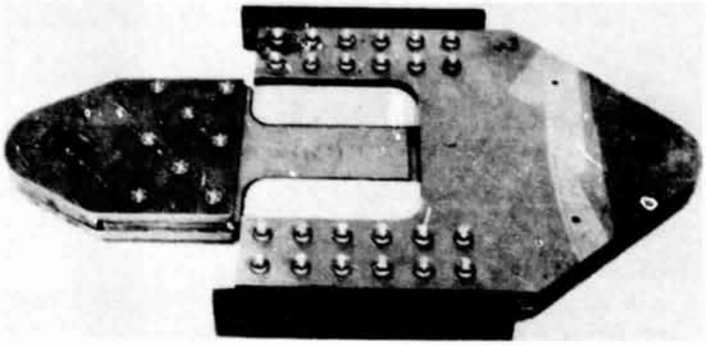


Figure 3-19. Web Splice Test Specimen and Fixture (122407B)

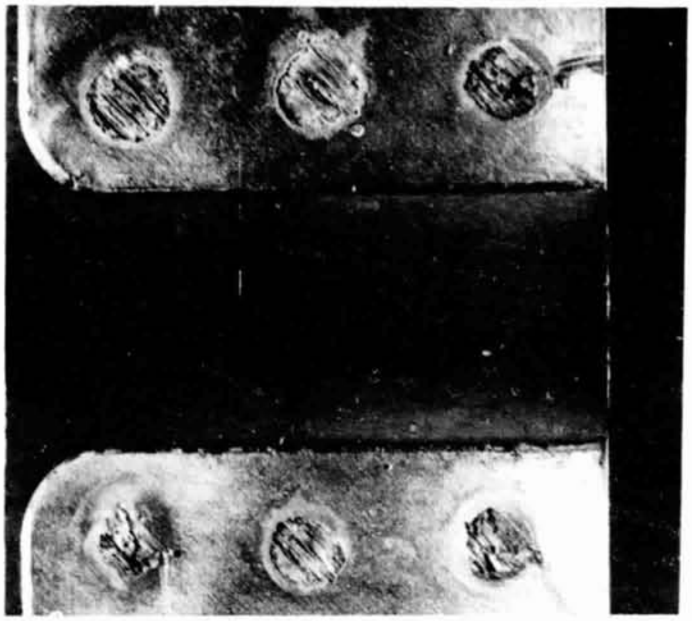


Figure 3-20. Failed Spotwelded Web Splice Test Specimen (136409)

which compare favorably with the average failure load of 8,400 lb for the original schedule. Weld specimens were cut from the second failed web splice subcomponents. Attempts to weld these specimens at locations coincident with the original sheared spot weld met with no success.

The remaining web splice specimen was repaired by welding at locations between the original spot welds. This meant there were only four welds in the specimen compared to the original six. Also the inability to clean the mating surfaces on the unfailed side of the original specimen probably precluded the formation of good resistance welds in two locations.

The spotweld repaired web splice specimen was installed in the same test fixture and tested in the same manner as was used in the original test. Failure occurred by shearing of the spotwelds at 34,400N (7750 lb). This was 65% less than the load obtained in the original test which indicated that repair of the web splice specimen by spotwelding was unsuccessful. It was then decided to repair the specimen using mechanical fasteners. Six holes (three on each side) were drilled through the B/Al splice joint at the location of the original spot welds and 0.635 cm (1/4 inch) steel bolts were installed. Figure 3-21 is a photograph of the bolted repair specimen. The bolted repair specimen was then tested in the same manner as previous tests. Failure occurred by shearing of one of the ± 45° crossplied B/Al splice plates at the bolt holes as shown in Figure 3-22. Failure load was 157,800N (35,500 lb), which is a 58% higher load than was obtained for the original spotwelded web splice specimen. A summary of the performance of the web splice specimen is shown in Table 3-6. The bolted repair was quite successful since it improved load carrying ability by 58% with only a 4% weight penalty.

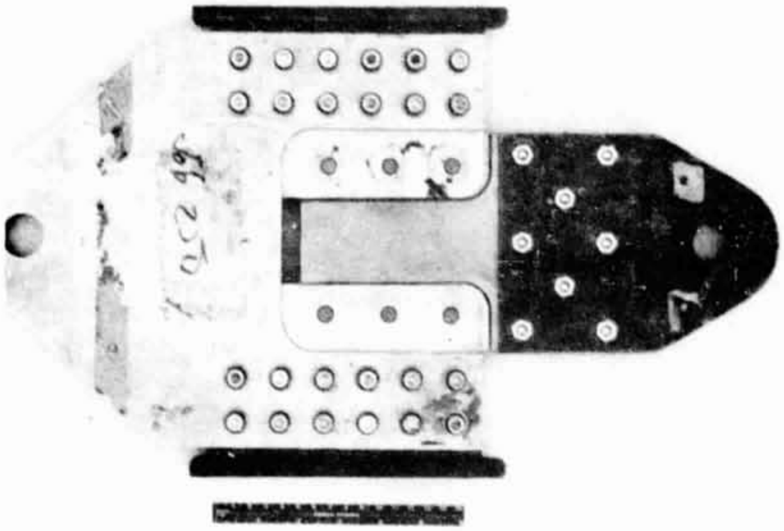


Figure 3-21. Photograph of Bolted Repair of Web Splice Specimen (140262)

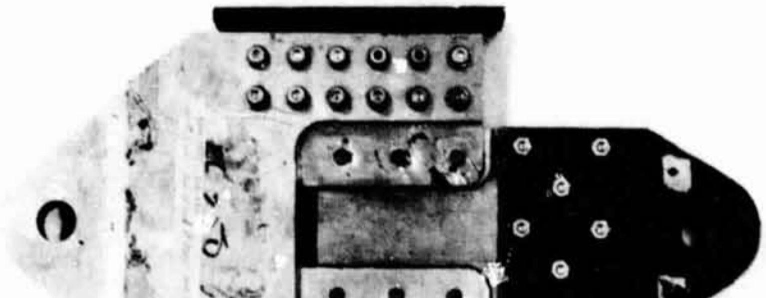


Figure 3-22. Failed Web Splice Specimen (Bolted Repair) (140312)

Table 3-6. Performance of B/Al Web Splice Specimens

Specimen	Weight kg	(lb)	Weight Change (%)	Failure Load N	(lb)	% Change
Original Spotwelded	0.84	(1.86)		100,085	(22,500)	
Spotweld Repair	0.84	(1.86)	0	34,400	(7,750)	-65
Bolted Repair	0.88	(1.94)	4	157,800	(35,500)	+58

3.6 B/Al TENSION FIELD PANEL

The ±45° B/Al tension field panel selected for repairability studies was one of two tension field test specimens originally fabricated and tested to determine the tension field properties of 0.254 cm (0.100 in.) thick B/Al shear web material. Two Z-section stiffeners, fabricated from unidirectional B/Al, were positioned to isolate the tension field panel from the test fixture. The stiffeners were sized to provide simple support to the panel and withstand secondary compressive loads. The aspect ratio was approximately 2:1. The tension field panel was tested in a "picture frame" test fixture, Figure 3-23, on a universal testing machine. Initial buckling of the specimen occurred at 334,000N (75,000 lb) and failure occurred at 369,000N (83,000 lb) of load. Details of the original test are given in Reference 1.

Figure 3-23. Tension Field Test in Progress (122589B)

The failed ±45° B/Al tension field specimen selected for repairs is shown in Figure 3-24. Primary failure was a crack through one of the bolts tying the Z-section stiffener to the web. The proposed repair procedure (Figure 3-25) was to resistance weld a series of titanium sheets together in a mirror image of the damaged area (and the surrounding test fixture) and to then adhesively bond this doubler to the specimen.

The four layers of the titanium doubler were resistance welded together and bonded to the panel. During adhesive bonding, pressure was inadvertently applied to the unsupported Z-section stiffeners, thereby damaging them. The panel with the damaged stiffeners is shown in Figure 3-26.

The stiffeners were subsequently repaired by straightening of the unfailed stiffener [by forming in a closed die fixture at 533K (500 F)] and adhesively bonding an aluminum doubler onto the failed stiffener. Figure 3-27 is a photograph of the repaired tension field panel.

The repaired panel was then installed into the same universal testing machine and tested in the same manner as was used in the initial test. The results are summarized in Table 3-7, which indicates a very satisfactory repair was achieved. The failure was docile in nature, consisting of splitting of the B/Al web material, as is shown in Figure 3-28.

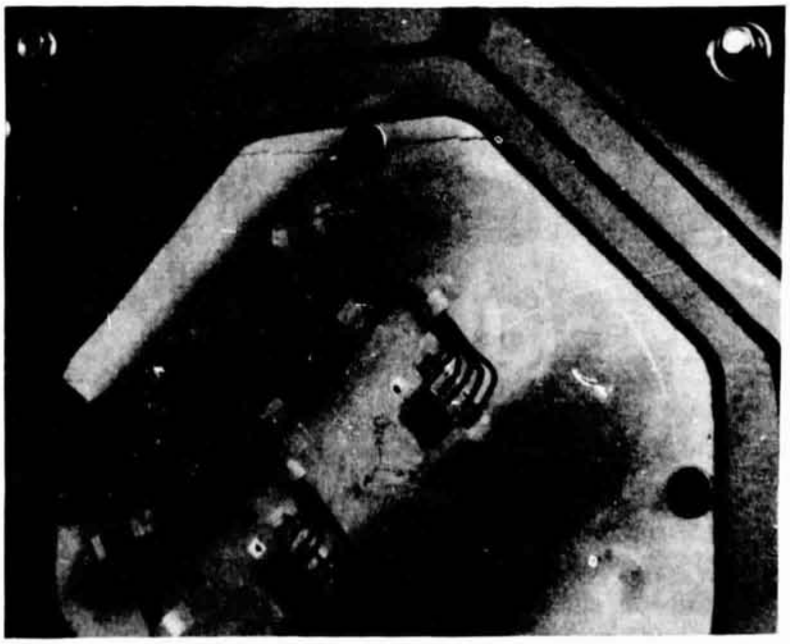
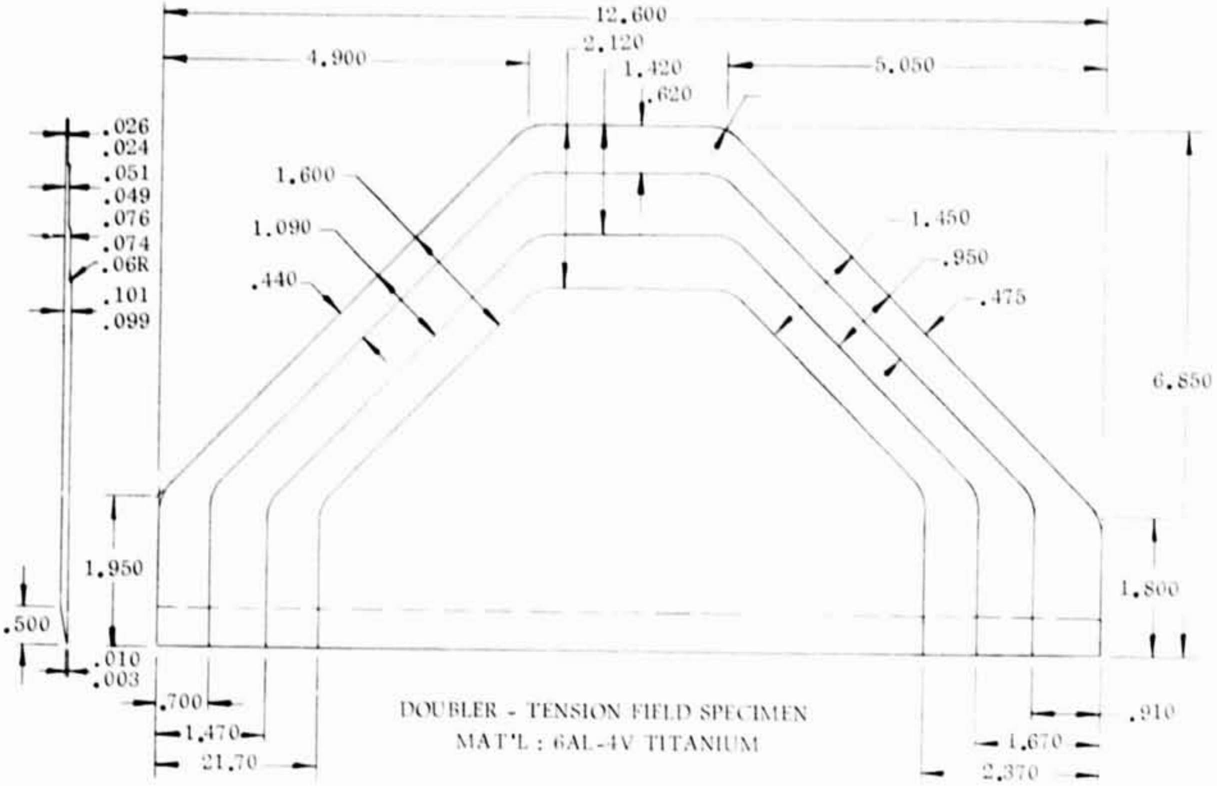


Figure 3-24. Failed Tension Field Panel (12 2588B)



Note: For clarity, only English units are shown.

Figure 3-25. Repair Plan for Tension Field Panel

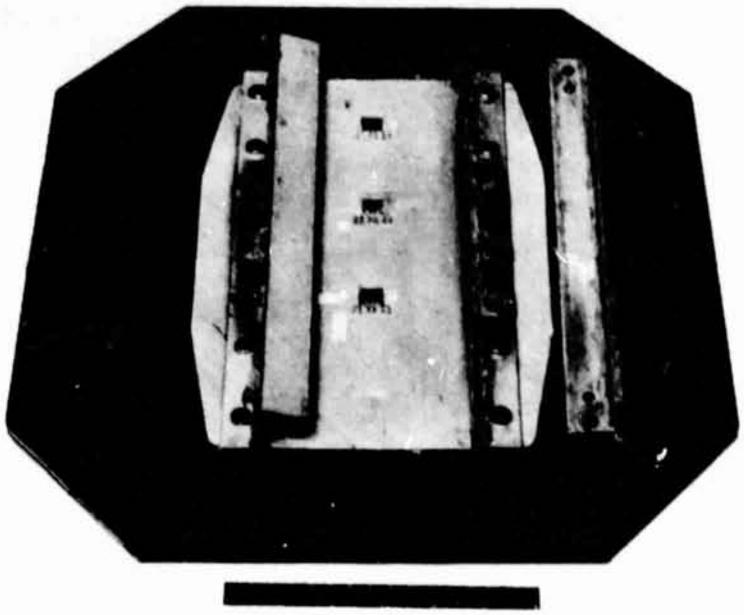


Figure 3-26. Damaged B/Al Tension Field Specimen (140311)

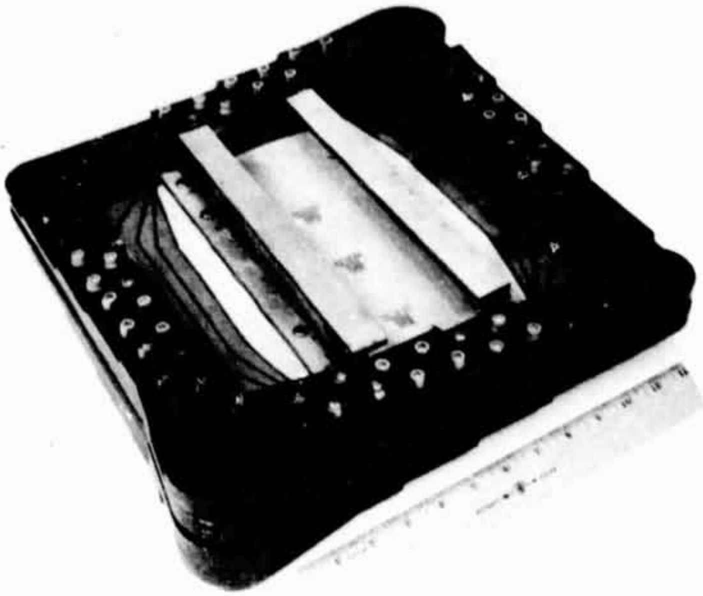


Figure 3-27. Repaired B/Al Tension Field Panel (140691)

Table 3-7. Performance of B/Al Tension Field Panel

	Weight	Weight	Buckling Load	%	Failing Load	%
Specimen	kg (lb)	Change (%)	newtons (lb)	Change	newtons (lb)	Change
Original	3.36 (7.39)		334,000 (75,000)		369,000 (83,000)	
Repaired	3.69 (8.12)	+10	378,000 (85,000)	+13	521,000 (117,200)	+41

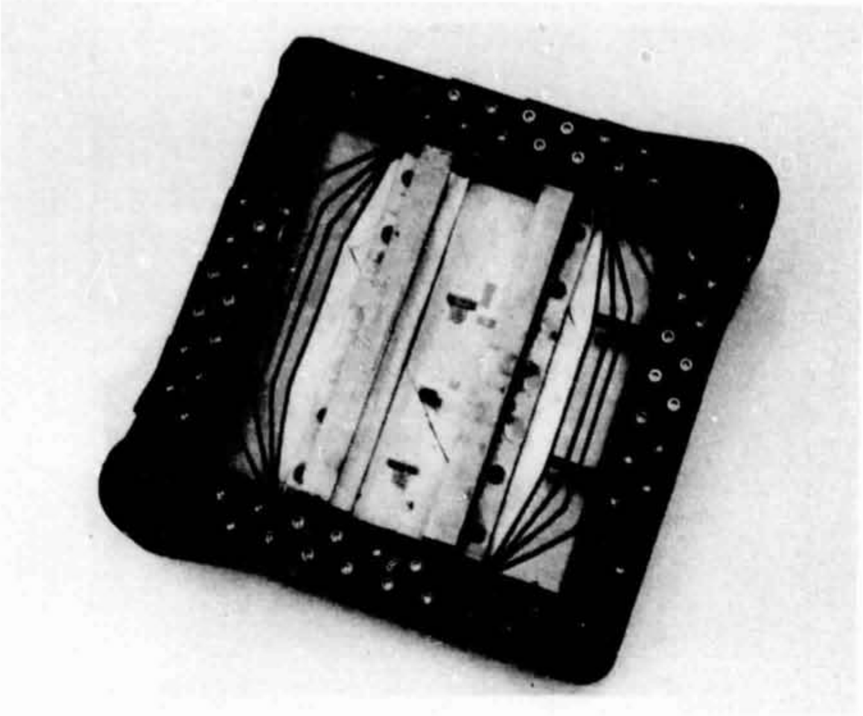


Figure 3-28. Failure of Repaired B/Al Tension Field Panel (140708)

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

The program has demonstrated that boron/aluminum (B/Al) structures can be successfully repaired with techniques similar to those currently used for conventional materials. Repair materials consisted of aluminum, titanium, steel, resin composites, or B/Al, and repair techniques included adhesive bonding, mechanical fastening, and reforming. Demonstration of the repair techniques were performed on the seven specimens listed in Table 4-1.

Table 4-1. Summary of Repairability Results

Specimen	Weight Change %	Load Change %
Sandwich Beam	+ 6.5	+ 16.5
B/Al Tube (63.5 cm long)	+ 6	- 13
B/Al Tube (76.2 cm long)	+ 11	- 10
Sheet Stringer	+ 12	+ 20
B/Al Tube (1 m long)	+ 15	+ 76
Web Splice	+ 4	+ 58
Tension Field Panel	+ 10	+ 41
Average	9	27

The average weight penalty incurred for these specimens was 9%; however, this resulted in a performance increase over the as-fabricated specimens of 27%.

In addition to demonstrating repairability techniques, this program has served to identify the "weak link" in the selected components; by repairing these areas, the composite structures were capable of higher performance than originally demonstrated. This points out the need for further work to develop optimum designs so that greater advantage can be taken of the light weight and high performance of B/Al components.

The program also demonstrated that the 'shelf-life' of B/Al is similar to that of other metals. The specimens selected for this program were from two to seven years old, and had been left in an unprotected state after their initial test. No deleterious effects such as corrosion damage, damage from residual stresses, or fiber matrix interaction were observed, thus giving increased confidence and credibility to the use of B/Al composites.

Based on the results of this program (including those results discussed in References 1, 2, and 7), it is recommended that B/Al structures be considered when high load intensities will be encountered. The fabrication can be accomplished with today's technology and existing shop equipment and personnel. Using sheet metal fabrication techniques, these composite structures can be fabricated at a reasonable cost. If damaged in service the components can be readily repaired using simple repair techniques.

SECTION 5

REFERENCES

1. Miller, M. F., Christian, J. L., and Wennhold, W. F., Design, Manufacture, Development, Test, and Evaluation of Boron/Aluminum Structural Components for Space Shuttle, Volume I, Design and Analysis, GDCA-DBG73-006, NASA Contract NAS8-27738, August 1973.

2. Miller, M. F., Christian, J. L., and Wennhold, W. F., Design, Manufacture, Development, Test, and Evaluation of Boron/Aluminum Structural Components for Space Shuttle, Volume II, Materials and Processing, GDCA-DBG73-006, NASA Contract NAS8-27738, August 1973.

3. Schaefer, W. H., Christian, J. L., et al, Evaluation of the Structural Behavior of Filament Reinforced Metal Matrix Composites, AFML-TR-69-36, January 1969.

4. Schaefer, W. H., Aluminum-Boron F-106 Engine Access Door Design and Test Evaluation, Convair Aerospace Division Report GDC-ERR-1514, August 1970.

5. Schaefer, W. H., Wennhold, W., et al, Composite Fuselage Development, Convair-San Diego report to General Dynamics, Fort Worth, for Air Force Contract F33C15-70-C-1494, 1969.

6. Forest, J. D., et al, Advanced Composite Applications for Spacecraft and Missiles, Volume I — Structural Development, Volume II — Material Development, AFML-TR-71-186, March 1972.

7. Spier, E. E., and Miller, M. F., Design, Manufacture, Development, Test, and Evaluation of Boron/Aluminum Structural Components for Space Shuttle, Volume III, Test Analysis, GDCA-DBG73-006, NASA Contract NAS8-27738, February 1974.

8. Wennhold, W. F., Evaluation of a Metal Fuselage Panel Selectively Reinforced with Filamentary Composites for Space Shuttle Applications, NASA Contract NAS1-10766, November 1973.

9. Miller, M. F, Schaefer, W. H., and Weisinger, M. D., Development of Improved Metal Matrix Fabrication Techniques for Aircraft Structures, AFML-TR-71-181, July 1971.