

CONTRACT NAS8-20125

# COMMON BULKHEAD JOINT DEVELOPMENT AND EVALUATION

## FINAL REPORT

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Huntsville, Alabama

**Prepared by:** MARTIN COMPANY  
A DIVISION OF MARTIN MARIETTA CORPORATION  
Denver, Colorado

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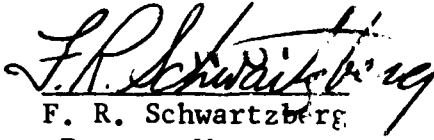
COMMON BULKHEAD JOINT DEVELOPMENT  
AND EVALUATION  
FINAL REPORT

July 1966

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DENVER, COLORADO

FOREWORD

This final report, in accordance with Paragraph F 3 of Exhibit A to Contract NAS8-20125, is submitted to the Marshall Space Flight Center, Methods Development Branch, Manufacturing Engineering Laboratory. The MSFC technical representative for this work was Mr. B. K. Davis.

This program was comprised of three phases:

- Phase I - Development of an Optimized Welded Joint
- Phase II - Analysis of Joints Under Compression
- Phase III - Comparison of a Combination Welded-Bonded Joint with the Optimized Welded Joint

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## I. INTRODUCTION

In the field of advanced composite structures, one of the most versatile design concepts is the honeycomb sandwich composite. Structures of this type have been successfully used in airplane, missile, space vehicle, and naval applications. The principal advantages of honeycomb composites are based on their high strength- and modulus-to-weight ratios. For example, honeycomb composites have been used in booster structures as load-carrying members where resistance to vibration and flutter were important design criteria.

Honeycomb sandwich composites possess inherent design versatility since a wide range of properties can be achieved by variation in core materials, thickness, cell size, faceplate material, and thickness of plates. Stainless steel, aluminum, or phenolic/glass are presently used as cell materials, and faceplates are made from wood, reinforced plastics, stainless steel, and aluminum.

The present Saturn booster system design employs a honeycomb structure as the common bulkhead between liquid oxygen and liquid hydrogen tanks. In this application, the honeycomb sandwich acts both as a load-bearing structure and as an insulator between the two cryogenic fluids. The faceplates are made of aluminum, and the core is made of phenolic-impregnated glass cloth.

The manufacture of large honeycomb structures presents several fabrication problems that can be identified from a consideration of the Saturn bulkhead. In the presently used fabrication technique, large pie-shaped sections of aluminum are welded to form a full-sized dome. A second dome is similarly fabricated. After welding, the two dome sections are carefully fitted to a honeycomb core. Because of the distortion that occurs during welding, fitup is extremely difficult. Attempts are made to contour the honeycomb for the best possible fit. The bonding is made difficult because of (1) the problems in handling the large structure and (2) the warping resulting from the welding process. Slight mismatch between honeycomb core and faceplates causes areas in which poor bonding or no bonding is achieved. Repair of an area of unsatisfactory bonding is essentially impossible in the approach as described.

One of the new concepts of fabrication proposed for the bulkhead is to divide the dome into a number of prebonded gore segments. Each segment is made by forming the sheet stock to the desired contour and then bonding the faceplates to the core material. The segments are then welded to make the full-sized dome. This concept of bulkhead fabrication offers several important advantages over the previously described approach. Bonding of gore sections is much simpler than performing the same operation on large parts. Also, domes fabricated by the gore section approach have the advantage of permitting repair, if necessary, by replacement of gore panel composites.

Inherent in the development of the prebonded gore section method is a requirement for a satisfactory welded joint to connect the components. The objectives of Contract NAS8-5463 were to develop a welded joint and to develop techniques for forming gore faceplates and honeycomb sections.

The objectives of this work (NAS8-20125) were to optimize the welded joint design using a structural analysis approach and obtain experimental data for various combinations of geometries and material to confirm the analytically obtained design.

During the program it was discovered that although the scientific design approach could be substituted for the empirical design approach, a more serious problem in the application of the welded honeycomb joint arose. That was the problem of successful fabrication of hardware articles using this concept. Work being performed in another program showed that the difficulties associated with fabrication of hardware articles severely limit the feasibility of welding large prebonded honeycomb sections.

As a result of this observation, preliminary work toward evaluation of a combination bonded-welded joint, which would be a superior method for fabricating common bulkhead structures, was initiated.

## II. PHASE I - DEVELOPMENT OF AN OPTIMIZED WELDED JOINT

The objective of Phase I was to establish an optimized honeycomb weld joint design using three aluminum alloys (2014-T6, 2219-T87, and 7106-T6) with skin thicknesses of 0.032 and 0.055 in. Specifically, the following was required to optimize the joint:

- 1) Selection of weld filler material and establishment of weld processing;
- 2) Determination of mechanical properties at ambient and cryogenic temperatures required for joint design;
- 3) Determination of weld land and core gap width effects;
- 4) Structural analysis of joint design;
- 5) Selection of specific joint geometries for each alloy and thickness.

### A. WELD PROCESSING

A discussion regarding selection of weld filler material held between Martin Company personnel and the NASA Project Engineer resulted in the following selections:

| <u>Alloy</u> | <u>Filler</u> |
|--------------|---------------|
| 2014-T6      | 4043          |
| 2219-T87     | 2319          |
| 7106-T6      | 5180          |

The welding technique agreed upon for the subject thicknesses was the automatic tungsten-inert-gas process. It was requested that water-chilled holddown fixturing be used for this program.

Based on preliminary data on mechanical properties, the fabrication problems associated with welding honeycomb panels, and the theoretical joint efficiency, a land/skin thickness ratio of 2.5 was selected for the Phase I work. This ratio gives the following skin and weld land thicknesses:

| <u>Skin</u><br><u>Thickness (in.)</u> | <u>Weld Land</u><br><u>Thickness (in.)</u> |
|---------------------------------------|--------------------------------------------|
| 0.032                                 | 0.080                                      |
| 0.055                                 | 0.138                                      |

The following materials were received from NASA stock for use in this program:

| <u>Alloy</u> | <u>No. Sheets</u> | <u>Size</u>                |
|--------------|-------------------|----------------------------|
| 2014-T6      | 3                 | 4 ft by 8 ft by 0.100 in.  |
| 2014-T6      | 3                 | 4 ft by 8 ft by 0.140 in.  |
| 2219-T87     | 3                 | 4 ft by 8 ft by 0.090 in.  |
| 2219-T87     | 3                 | 4 ft by 8 ft by 0.180 in.  |
| 7106-T6      | 1                 | 6 ft by 12 ft by 0.125 in. |
| 7106-T6      | 1                 | 4 ft by 6 ft by 0.125 in.  |
| 7106-T6      | 3                 | 4 ft by 8 ft by 0.250 in.  |

Initial weld panel preparation was achieved by mechanically milling to the desired weld land thickness. However, the cost and time associated with this technique were excessive. Since actual hardware is chemically milled, subsequent panels were satisfactorily prepared in this manner. Surface condition and dimensional accuracy were adequately maintained.

Because of Martin's extensive experience with welding of aluminum alloys, the work associated with optimizing the welding process was reduced to confirming variables to achieve desired weld strength and appearance. An actual weld optimization program was far beyond the scope of this program; we attempted to merely confirm that our process would result in satisfactory welds.

Welding was achieved using a Sciaky Zero-Error Power Supply equipped with an Airline automatic welding fixture. The direct current, straight-polarity TIG process was used. Gas protection primarily consisted of helium combined with a small quantity of argon. The holddown fixtures were water-cooled steel with aluminum shims, as required. All panels were vapor degreased, alkali cleaned, and deoxidized before welding.

Tables 1 thru 6 present data showing the effect of weld processing variables on the weld appearance and strength. Note that the variations in control settings were minor; as a result, the variation in strength was also rather small. Where no comments regarding appearance are given, all welds exhibited good penetration and appeared satisfactory.

Data for 0.080-in. 2014-T6 showed that variation in voltage between 11 and 12 v while current was varied between 76 and 90 amp resulted in a spread in average tensile strength of only 3.5 ksi (Table 1). In all cases, good penetration and weld bead appearance was obtained. The typical weld strength was approximately 51 to 52 ksi. Similar behavior was exhibited for the 0.138-in. material except that typical weld strength was decreased to about 47 ksi (Table 2).

Optimization of the 2219-T87 alloy was also achieved using minor variations in weld settings. For both thicknesses, the spread in tensile strength was about 5 ksi. In all cases, good penetration and weld bead shape was achieved (Tables 3 and 4).

In the optimization of 0.080-in. 7106-T6 aluminum alloy, it was noted that the quantity of gas coverage affected the appearance of the weld bead. A rough appearing, slightly oxidized weld bead was obtained in many cases. The weld strength was virtually unaffected by the variations in control settings, although the penetration varied from light to medium (Table 5). The thicker gage (0.138 in.) material exhibited similar behavior except that the gas coverage selected was sufficient to produce clean weld beads in all cases. The average weld strength was almost 5 ksi higher than for the thinner gage (Table 6).

**Table 1 Weld Optimization for 0.080-in. 2014-T6 Aluminum Alloy  
Using Cooled Fixturing\***

| Panel No. | Voltage (v) | Current (amp) | Speed (ipm) | Feed (ipm)      | Ultimate Strength (ksi) |
|-----------|-------------|---------------|-------------|-----------------|-------------------------|
| 1         | 11.0        | 76            | 20          | 30              | 51.3 (4) <sup>†</sup>   |
| 2         | 11.0        | 80            | 20          | -- <sup>‡</sup> | 52.6 (4)                |
| 3         | 11.0        | 80            | 20          | 48              | 51.1 (5)                |
| 4         | 11.0        | 84            | 20          | 50              | 51.4 (5)                |
| 5         | 11.0        | 90            | 20          | 60              | 52.7 (5)                |
| 6         | 11.5        | 78            | 20          | -- <sup>‡</sup> | 49.2 (4)                |
| 7         | 11.5        | 80            | 20          | -- <sup>‡</sup> | 49.7 (7)                |
| 8         | 11.5        | 80            | 20          | -- <sup>‡</sup> | 49.8 (4)                |
| 9         | 11.5        | 83            | 20          | -- <sup>‡</sup> | 49.8 (4)                |
| 10        | 12.0        | 78            | 20          | 50              | 52.4 (5)                |
| 11        | 12.0        | 82            | 20          | 50              | 51.3 (5)                |

\*Filler: 0.063-in.-dia 4043; automatic TIG welded, direct current, straight polarity; gas protection: 50 cfh helium + 1.5 cfh argon; backup: water-cooled metallic.

<sup>†</sup>Number in parentheses is number of replicate tensile specimens tested to obtain average value.

<sup>‡</sup>Feed rate varied during welding

**Table 2 Weld Optimization for 0.138-in. 2014-T6 Aluminum Alloy  
Using Cooled Fixturing\***

| Panel No. | Voltage (v) | Current (amp) | Speed (ipm) | Feed (ipm) | Ultimate Strength (ksi) |
|-----------|-------------|---------------|-------------|------------|-------------------------|
| 1         | 11.0        | 118           | 14          | 32         | 47.5 (5) <sup>†</sup>   |
| 2         | 11.0        | 125           | 14          | 38         | 47.1 (3)                |
| 3         | 11.0        | 125           | 20          | 38         | 46.9 (2)                |
| 4         | 11.5        | 118           | 14          | 30         | 47.7 (5)                |
| 5         | 11.5        | 120           | 14          | 32         | 45.5 (4)                |

\*Filler: 0.063-in.-dia 4043; automatic TIG welded, direct current, straight polarity; gas protection: 50 cfh helium + 1.5 cfh argon; backup: water-cooled metallic.

<sup>†</sup>Number in parentheses is number of replicate tensile specimens tested to obtain average value.

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Table 3 Weld Optimization for 0.080-in. 2219-T87 Aluminum Alloy  
Using Cooled Fixturing\*

| Panel No. | Voltage (v) | Current (amp) | Speed (ipm) | Feed (ipm) | Ultimate Strength <sup>†</sup> (ksi) |
|-----------|-------------|---------------|-------------|------------|--------------------------------------|
| 1         | 11.5        | 78            | 20          | 45         | 50.7                                 |
| 2         | 11.5        | 78            | 20          | 47         | 50.4                                 |
| 3         | 11.5        | 80            | 20          | 60         | 51.7                                 |
| 4         | 12.0        | 70            | 20          | 34         | 47.7                                 |
| 5         | 12.0        | 70            | 20          | 38         | 46.3                                 |
| 6         | 12.0        | 72            | 20          | 40         | 49.2                                 |
| 7         | 12.0        | 74            | 20          | 42         | 45.9                                 |
| 8         | 12.0        | 74            | 20          | 42         | 48.7                                 |
| 9         | 12.0        | 74            | 20          | 45         | 49.2                                 |
| 10        | 12.0        | 76            | 20          | 48         | 48.7                                 |
| 11        | 12.0        | 78            | 20          | 50         | 48.2                                 |

\*Filler: 0.063-in.-dia 2319; automatic TIG welded, direct current, straight polarity; gas protection: 50 cfh helium + 1.5 cfh argon; backup: water-cooled metallic.

<sup>†</sup> Average of five replicate tensile tests.

Table 4 Weld Optimization for 0.138-in. 2219-T87 Aluminum Alloy  
Using Cooled Fixturing\*

| Panel No. | Voltage (v) | Current (amp) | Speed (ipm) | Feed (ipm) | Ultimate Strength (ksi) |
|-----------|-------------|---------------|-------------|------------|-------------------------|
| 1         | 11.0        | 108           | 14          | 25         | 44.4 (6) <sup>†</sup>   |
| 2         | 11.0        | 110           | 14          | 20         | 44.6 (3)                |
| 3         | 11.5        | 110           | 14          | 30         | 44.5 (5)                |
| 4         | 11.5        | 112           | 14          | 30         | 46.1 (5)                |
| 5         | 11.5        | 114           | 14          | 30         | 41.1 (5)                |
| 6         | 11.5        | 115           | 14          | 38         | 45.1 (5)                |
| 7         | 11.5        | 122           | 14          | 35         | 41.3 (5)                |
| 8         | 11.5        | 125           | 14          | 42         | 43.5 (5)                |
| 9         | 12.0        | 110           | 14          | 30         | 42.6 (5)                |

\*Filler: 0.063-in.-dia 2319; automatic TIG welded, direct current, straight polarity; gas protection: 50 cfh helium + 1.5 cfh argon; backup: water-cooled metallic.

<sup>†</sup> Number in parentheses is number of replicate tensile specimens tested to obtain average value.

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Table 5 Weld Optimization for 0.080-in. 7106-T6 Aluminum Alloy Using Cooled Fixturing\*

| Panel No. | Voltage (v) | Current (amp) | Feed (ipm) | Gas Protection (cfh) | Appearance <sup>†</sup> | Ultimate Strength <sup>‡</sup> (ksi) |
|-----------|-------------|---------------|------------|----------------------|-------------------------|--------------------------------------|
| 1         | 11.0        | 78            | 40         | 65 He + 2 Ar         | LP, OB                  | 50.4                                 |
| 2         | 11.0        | 80            | 40         | 60 He + 2 Ar         | LP, OB                  | 51.0                                 |
| 3         | 11.0        | 80            | 42         | 65 He + 2 Ar         | LP, CB                  | 51.0                                 |
| 4         | 11.0        | 80            | 45         | 60 He + 2 Ar         | LP, OB                  | 50.4                                 |
| 5         | 11.0        | 82            | 48         | 65 He + 2 Ar         | MP, OB                  | 50.5                                 |
| 6         | 11.0        | 84            | 46         | 65 He + 2 Ar         | MP, OB                  | 50.4                                 |
| 7         | 11.0        | 86            | --         | 65 He + 2 Ar         | MP, OB                  | 50.4                                 |
| 8         | 12.0        | 85            | 62         | 50 He + 4 Ar         | MP, OB                  | 50.7                                 |

\*Filler: 0.063-in.-dia 5180; automatic TIG welded, direct current, straight polarity; speed: 20 ipm; backup: water-cooled metallic.

<sup>†</sup>LP - light penetration;  
MP - medium penetration;  
OB - slightly oxidized, rough bead surface;  
CB - clean, smooth bead surface.

<sup>‡</sup>Average of five replicate tensile tests.

Table 6 Weld Optimization for 0.138-in. 7106-T6 Aluminum Alloy Using Cooled Fixturing\*

| Panel No. | Voltage (v) | Current (amp) | Speed (ipm) | Feed (ipm) | Appearance <sup>†</sup> | Ultimate Strength <sup>‡</sup> (ksi) |
|-----------|-------------|---------------|-------------|------------|-------------------------|--------------------------------------|
| 1         | 10.0        | 125           | 14          | 40         | MP, CB                  | 55.4                                 |
| 2         | 11.0        | 108           | 10          | 30         | LP, CB                  | 54.9                                 |
| 3         | 11.0        | 115           | 14          | 30         | LP, CB                  | 55.6                                 |
| 4         | 11.0        | 120           | 20          | 45         | LP, CB                  | 55.4                                 |
| 5         | 11.0        | 125           | 14          | 50         | MP, CB                  | 55.4                                 |
| 6         | 12.0        | 120           | 20          | 55         | MP, CB                  | 55.4                                 |

\*Filler: 0.063-in.-dia 5180; automatic TIG welded, direct current straight polarity; gas protection: 65 cfh helium + 1.5 cfh argon; backup: water-cooled metallic.

<sup>†</sup>LP - light penetration;  
MP - medium penetration;  
CB - clean, smooth bead surface.

<sup>‡</sup>Average of five replicate tensile tests.

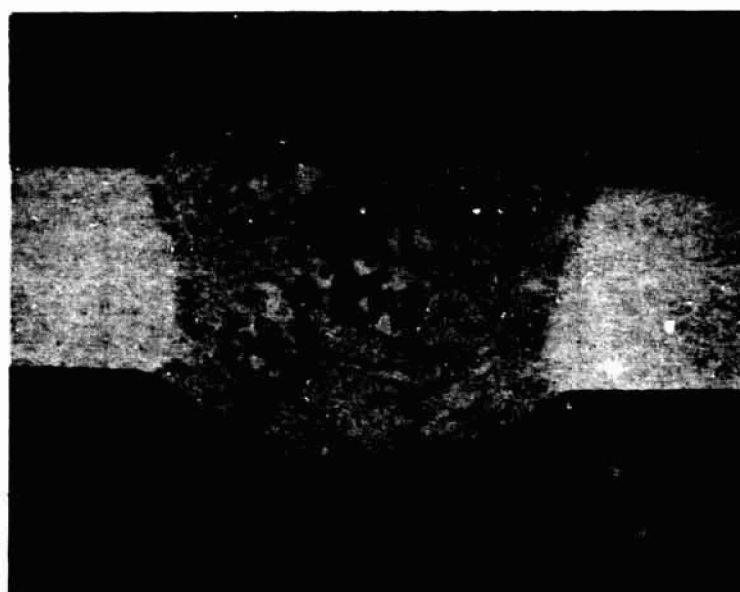
As a result of these studies, the following welding schedules were selected for preparation of weld panels using cooled fixturing:

| Alloy    | Thickness (in.) | Voltage (v) | Current (amp) | Speed (ipm) | Feed (ipm) | Gas Protection (cfh) |
|----------|-----------------|-------------|---------------|-------------|------------|----------------------|
| 2014-T6  | 0.080           | 11.0        | 85            | 20          | 50         | 50 He + 1.5 Ar       |
|          | 0.138           | 11.0        | 120           | 14          | 32         | 50 He + 1.5 Ar       |
| 2219-T87 | 0.080           | 11.5        | 80            | 20          | 50         | 50 He + 1.5 Ar       |
|          | 0.138           | 11.5        | 113           | 14          | 30         | 50 He + 1.5 Ar       |
| 7106-T6  | 0.080           | 11.0        | 82            | 20          | 48         | 65 He + 2 Ar         |
|          | 0.138           | 11.0        | 125           | 14          | 50         | 65 He + 2 Ar         |

Using these optimized settings, weld panels were prepared for the purpose of determining mechanical properties at room and cryogenic temperatures. These data are presented in the following section. Weld panels were radiographed to confirm quality and metallographically inspected. Photomicrographs of weld structures are shown in Fig. 1. In all cases, structures were normal for as-welded aluminum alloys. No evidence of eutectic melting or overheating was apparent in the heat affected zones of the 2000 series alloys.

During the program, it was determined that the weld schedule information obtained using cooled backup fixtures would not be totally adequate for preparing composite panels where the honeycomb core would act as an insulating material. Therefore, to better represent the conditions for hardware fabrication, additional weld panels using an insulating backup were prepared. Honeycomb core material, although a natural choice for a backup material, could not withstand the fixture pressure necessary for holding panels during welding. An alternative material, asbestos sheet, was used quite successfully.

Experimental results are presented in Tables 7 thru 9. It was found that virtually no change in feed or speed was required. However, current and voltage levels obtained using a cooled backup were often excessive.



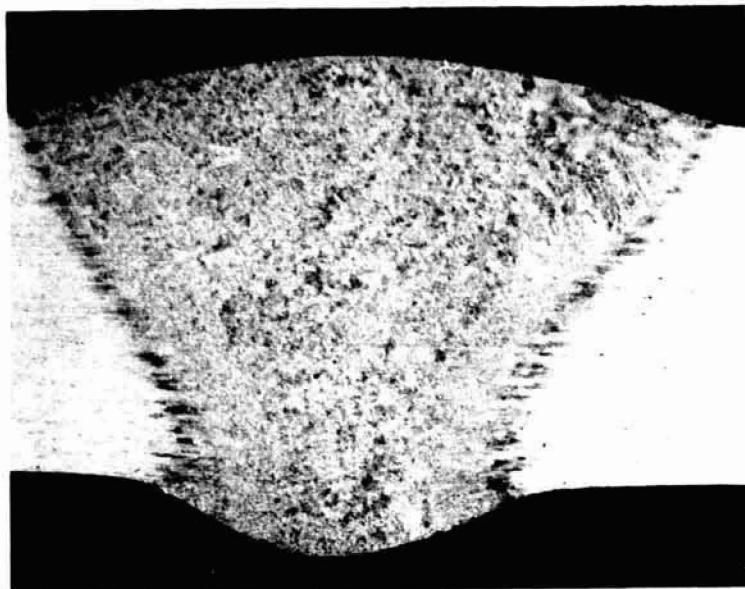
12.2X



200X

(a) 0.080-in. 2014-T6

Fig. 1 Photomicrographs of Aluminum Alloy Welds



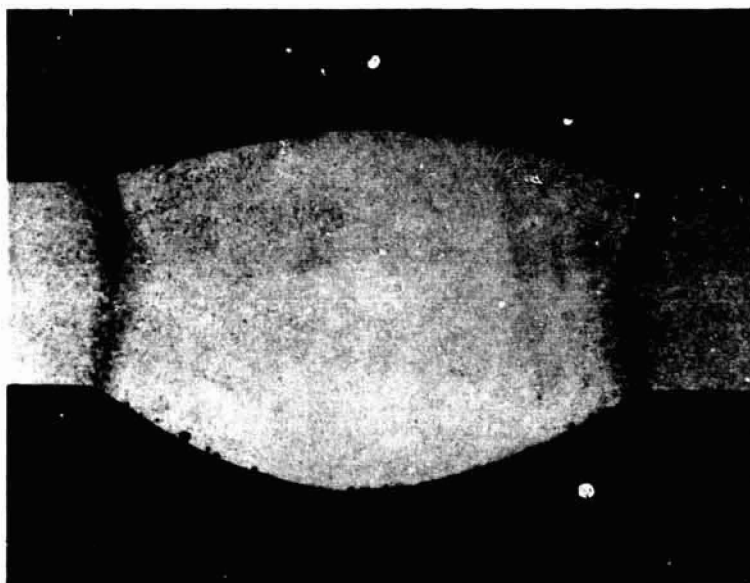
12.2X



200X

(b) 0.138-in. 2014-T6

Fig. 1 (cont)



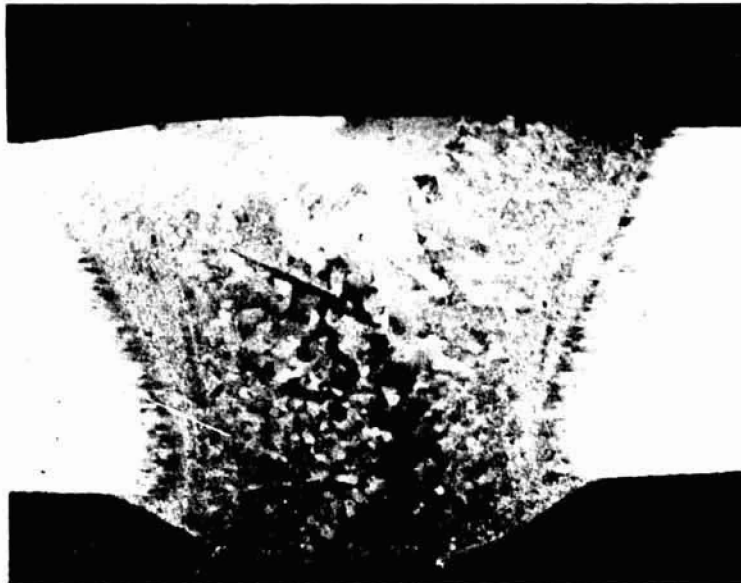
12.2X



200X

(c) 0.080-in. 2219-T87

Fig. 1 (cont)



12.2X



200X

(d) 0.138-in. 2219-T87

Fig. 1 (cont)



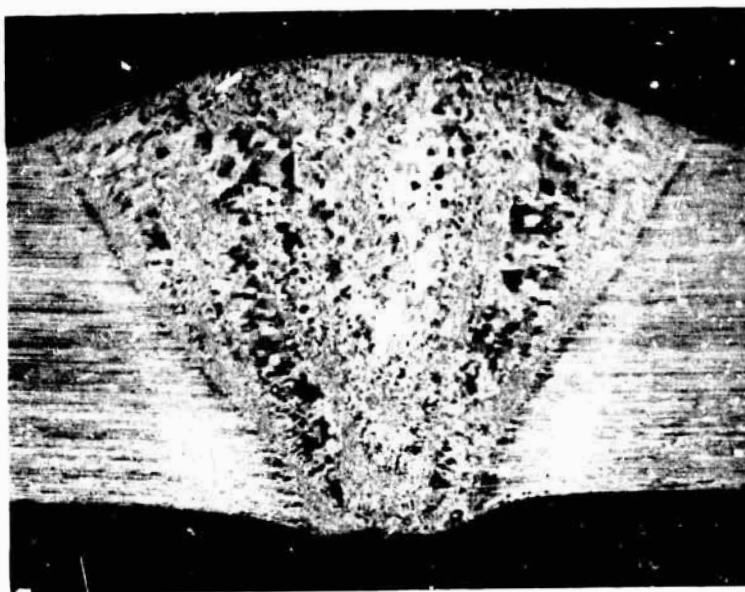
12.2X



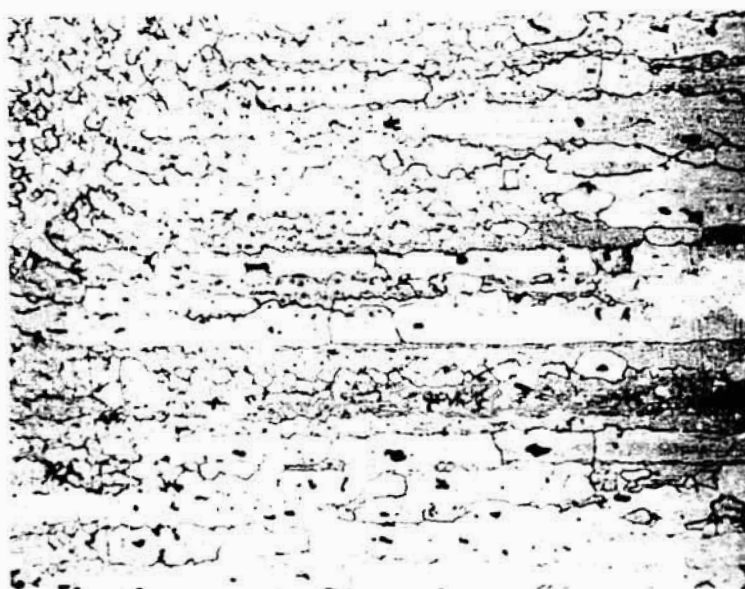
200X

(e) 0.080-in. 7106-T6

Fig. 1 (cont)



12.2X



200X

(f) 0.138-in. 7106-T6

Fig. 1 (concl)

The data for 0.080-in. 2014-T6 aluminum alloy indicate that the current must be decreased from 85 to 73 amp. Tensile strength attainable was reduced slightly. In the thicker gage (0.138-in.) material, control settings did not require appreciable change. No significant strength reduction was apparent (Table 7).

The 2219-T87 results (0.080-in. sheet) showed that both voltage and current could be reduced with only a minor loss of strength. In the thicker gage material, a decreased voltage combined with increased current could achieve tensile strength equivalent to the cooled backup tests (Table 8).

For the 7106-T6 material, a combination of reduced voltage and current and reduced voltage only were selected for welding the 0.080- and 0.138-in. sheets, respectively. It was found that cleaning the wire immediately before welding resulted in improved weld strength. Subsequent welding experience showed that increased gas coverage would give clean beads without the necessity for extra cleaning of the wire (Table 9).

Table 7 Weld Optimization for 2014-T6 Aluminum Alloy Using Insulated Fixturing\*

| Panel No.                                                                                                                                                                                                                                                                                                                                                                                                                         | Voltage (v) | Current (amp) | Feed (ipm) | Appearance <sup>†</sup> | Ultimate Strength, (ksi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|---------------|------------|-------------------------|--------------------------|
| 0.080-in. Sheet                                                                                                                                                                                                                                                                                                                                                                                                                   |             |               |            |                         |                          |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 68            | 40         | LP                      | 43.9 (5) <sup>‡</sup>    |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 70            | 50         | MP                      | 48.2 (5)                 |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 73            | 50         | MP                      | 48.8 (5)                 |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 78            | 52         | HP                      | 45.0 (4)                 |
| 0.138-in. Sheet                                                                                                                                                                                                                                                                                                                                                                                                                   |             |               |            |                         |                          |
| 1                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 110           | 40         | IP                      | 27.9 (3)                 |
| 2                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 117           | 45         | LP                      | 40.9 (5)                 |
| 3                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 120           | 40         | LP                      | 45.3 (5)                 |
| 4                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 125           | 50         | MP                      | 46.8 (5)                 |
| 5                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10.5        | 130           | 45         | HP                      | 46.8 (5)                 |
| *Filler: 0.063-in.-dia 4043; automatic TIG welded, direct current, straight polarity; gas protection: 50 cfh helium + 1.5 cfh argon; backup: asbestos sheet; speed: 20 ipm.<br><br><sup>†</sup> IP - incomplete penetration;<br>LP - light penetration;<br>MP - medium penetration;<br>HP - heavy penetration.<br><br><sup>‡</sup> Number in parentheses in number of replicate tensile specimens tested to obtain average value. |             |               |            |                         |                          |

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Table 8 Weld Optimization for 2219-T87 Aluminum Alloy Using Insulated Fixturing\*

| Panel No.                                                                                                                                                                                                                                                                                                                                                                                                 | Voltage (v) | Current (amp) | Feed (ipm) | Appearance† | Ultimate Strength (ksi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|---------------|------------|-------------|-------------------------|
| 0.080-in. Sheet                                                                                                                                                                                                                                                                                                                                                                                           |             |               |            |             |                         |
| 1                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 60            | 40         | IP          | 19.5 (1)*               |
| 2                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 65            | 40         | LP          | 50.4 (5)                |
| 3                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 70            | 40         | MP          | 49.5 (4)                |
| 4                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 75            | 40         | MP          | 45.0 (5)                |
| 5                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 80            |            | HP          | 45.6 (5)                |
| 0.138-in. Sheet                                                                                                                                                                                                                                                                                                                                                                                           |             |               |            |             |                         |
| 1                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 110           | 35         | IP          | 19.5 (5)                |
| 2                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 120           | 35         | LP          | 45.0 (5)                |
| 3                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 125           | 35         | MP          | 45.2 (5)                |
| 4                                                                                                                                                                                                                                                                                                                                                                                                         | 10.0        | 135           | 35         | HP          | 41.7 (5)                |
| *Filler: 0.063-in.-dia 2319; automatic TIG welded, direct current, straight polarity; gas protection: 50 cfh helium + 1.5 cfh argon; backup: asbestos sheet; speed: 20 ipm.<br><br>†IP - incomplete penetration;<br>LP - light penetration;<br>MP - medium penetration;<br>HP - heavy penetration.<br><br>*Number in parentheses is number of replicate tensile specimens tested to obtain average value. |             |               |            |             |                         |

Table 9 Weld Optimization for 7106-T6 Aluminum Alloy Using Insulated Fixturing\*

| Panel No.                                                                                                                                                                                                                                                                                                       | Voltage (v) | Current (amp) | Gas Protection (cfh) | Remarks†                 | Ultimate Strength (ksi) |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|---------------|----------------------|--------------------------|-------------------------|
| 0.080-in. Sheet                                                                                                                                                                                                                                                                                                 |             |               |                      |                          |                         |
| 1                                                                                                                                                                                                                                                                                                               | 10          | 75            | 50 He + 1.5 Ar       | Cleaned wire, MP, OB     | 44.8                    |
| 2                                                                                                                                                                                                                                                                                                               | 10          | 75            | 65 He + 2 Ar         | Cleaned wire, MP, OB     | 45.9                    |
| 0.138-in. Sheet                                                                                                                                                                                                                                                                                                 |             |               |                      |                          |                         |
| 1                                                                                                                                                                                                                                                                                                               | 10          | 125           | 65 He + 2 Ar         | As-received wire, MP, OB | 48.8                    |
| 2                                                                                                                                                                                                                                                                                                               | 10          | 125           | 65 He + 2 Ar         | Cleaned wire, MP, CB     | 52.3                    |
| *Filler: 0.063-in.-dia 5180; automatic TIG welded, direct current, straight polarity; backup: asbestos sheet; feed: 45 ipm; speed: 20 ipm.<br><br>†MP - medium penetration;<br>OB - slightly oxidized, rough bead surface;<br>CB - clean, smooth bead surface.<br><br>*Average of five replicate tensile tests. |             |               |                      |                          |                         |

## B. MECHANICAL PROPERTIES

All six combinations of materials and thicknesses were hardness tested, spectrographically analyzed, and tensile tested at room temperature to confirm that materials satisfied applicable requirements.

In addition, cryogenic ( $-320^{\circ}\text{F}$ ) mechanical properties were also determined.

Weld panels, prepared using the optimized schedule (cooled backup), were machined into tensile coupon form and also tested at 70 and  $-320^{\circ}\text{F}$ .

Tensile properties of parent metal and welds are summarized in Table 10. Detailed data are given in Appendix Tables A-1 thru A-6. Test results are in good agreement with data contained in the literature.

Table 10 Summary of Tensile Properties for Parent Metal and Welded Aluminum Alloys

| Alloy    | Temperature<br>( $^{\circ}\text{F}$ ) | Thickness<br>(in.) | Parent Metal Properties       |                            |                   | Welded Properties             |                            |
|----------|---------------------------------------|--------------------|-------------------------------|----------------------------|-------------------|-------------------------------|----------------------------|
|          |                                       |                    | Ultimate<br>Strength<br>(ksi) | Yield<br>Strength<br>(ksi) | Elongation<br>(%) | Ultimate<br>Strength<br>(ksi) | Yield<br>Strength<br>(ksi) |
| 2014-T6  | 70                                    | 0.080              | 69.8                          | 63.1                       | 10.0              | 52.7                          | 34.9                       |
|          | -320                                  | 0.080              | 83.2                          | 75.9                       | 11.5              | 60.1                          | 57.3                       |
|          | 70                                    | 0.138              | 72.1                          | 67.6                       | 12.8              | 48.5                          | 34.3                       |
|          | -320                                  | 0.138              | 87.7                          | 81.1                       | 14.5              | 57.4                          | 57.0                       |
| 2219-T87 | 70                                    | 0.080              | 69.6                          | 57.3                       | 9.0               | 47.7                          | 29.6                       |
|          | -320                                  | 0.080              | 88.1                          | 76.8                       | 10.1              | 56.1                          | 53.9                       |
|          | 70                                    | 0.138              | 68.2                          | 56.9                       | 11.2              | 45.3                          | 26.7                       |
|          | -320                                  | 0.138              | 86.0                          | 75.4                       | 13.0              | 59.6                          | 49.0                       |
| 7106-T6  | 70                                    | 0.080              | 56.5                          | 48.8                       | 9.3               | 51.1                          | 38.1                       |
|          | -320                                  | 0.080              | 78.0                          | 66.0                       | 12.4              | 61.5                          | 57.3                       |
|          | 70                                    | 0.138              | 62.7                          | 55.7                       | 10.8              | 54.5                          | 38.1                       |
|          | -320                                  | 0.138              | 86.1                          | 75.6                       | 15.9              | 61.5                          | 58.3                       |

To perform a structural analysis of the composite joints, the following additional mechanical property information was required:

- 1) Compression modulus data for aluminum alloy 2014-T6;
- 2) Tensile strength of honeycomb core material;
- 3) Modulus or spring constant of honeycomb core in tension and compression;
- 4) Moment of inertia of core stiffened skin.

Details of test procedure and results are given in the following paragraphs.

Small compression blocks using an  $L/D^*$  ratio of two were machined from various samples of 2014-T6 plate stock (0.340 to 0.500 in. thick). Specimens were tested at 70°F in both the longitudinal and transverse grain directions. Resistance strain gages were used to provide data to approximately 2% total strain. A typical graph of stress vs tangent modulus is given in Fig. 2. Agreement between various lots of material was very good.

For determining the honeycomb core tensile strength, 2-in. cubes of HRP honeycomb were bonded to 0.500-in.-thick aluminum faceplates using HT-424 adhesive. Faceplates were drilled and tapped to accommodate standard testing machine pull rods. Specimens were carefully checked to assure dimensional accuracy. Only specimens exhibiting a length variation of less than 0.002 in. were considered satisfactory for test. Test data are given below:

#### Tensile Strength of Honeycomb Core

##### Stress (psi)

815

803

768

825

802 (Average)

---

\* $L/D$  ratio is defined as length divided by minor dimension of cross section.

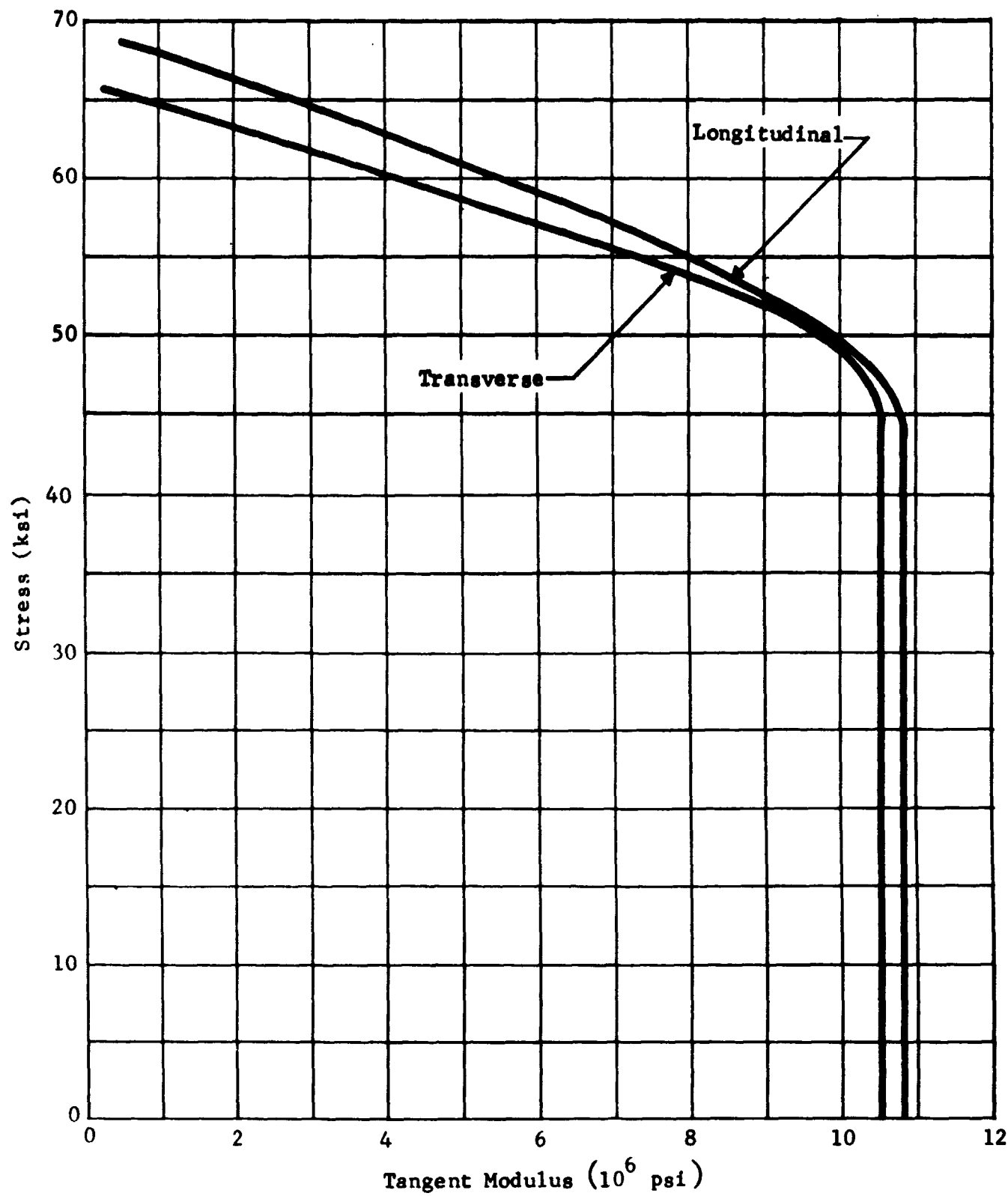


Fig. 2 Stress vs Compressive Tangent Modulus for 2014-T6 Aluminum Alloy (0.340-in. Thick)

Figure 3 shows typical specimens before and after testing.

Modulus determinations were obtained using a similar specimen. Initially, data were obtained under compression loading for simplicity of testing. Self-aligning compression heads were employed; deflection was measured with a dial gage. The average modulus value obtained was 64,000 psi. Using this value in the structural analysis, the agreement between theoretical and experimental results was not sufficiently close to satisfy our expectations of the ability of our analytical model to predict behavior. Since the core is subject to tensile loading, additional tests were performed to determine whether the tensile modulus agrees with that obtained under compression loading. The test apparatus for tensile loading is shown in Fig. 4. A Gaertner dual-scope extensometer was used to precisely determine deflection at each increment of load. It was determined that the tensile modulus (94,000 psi) significantly exceeded the compression value. The higher value gave good agreement between theory and experiment.

During the structural analysis it was determined that a corrected moment of inertia accounting for the increased stiffening resulting from the bonded core was required. It was decided to achieve this result empirically rather than analytically. A simple three-point loading beam specimen of 0.055-in.-thick 2014-T6 bonded to 1-in.-thick honeycomb core was used.

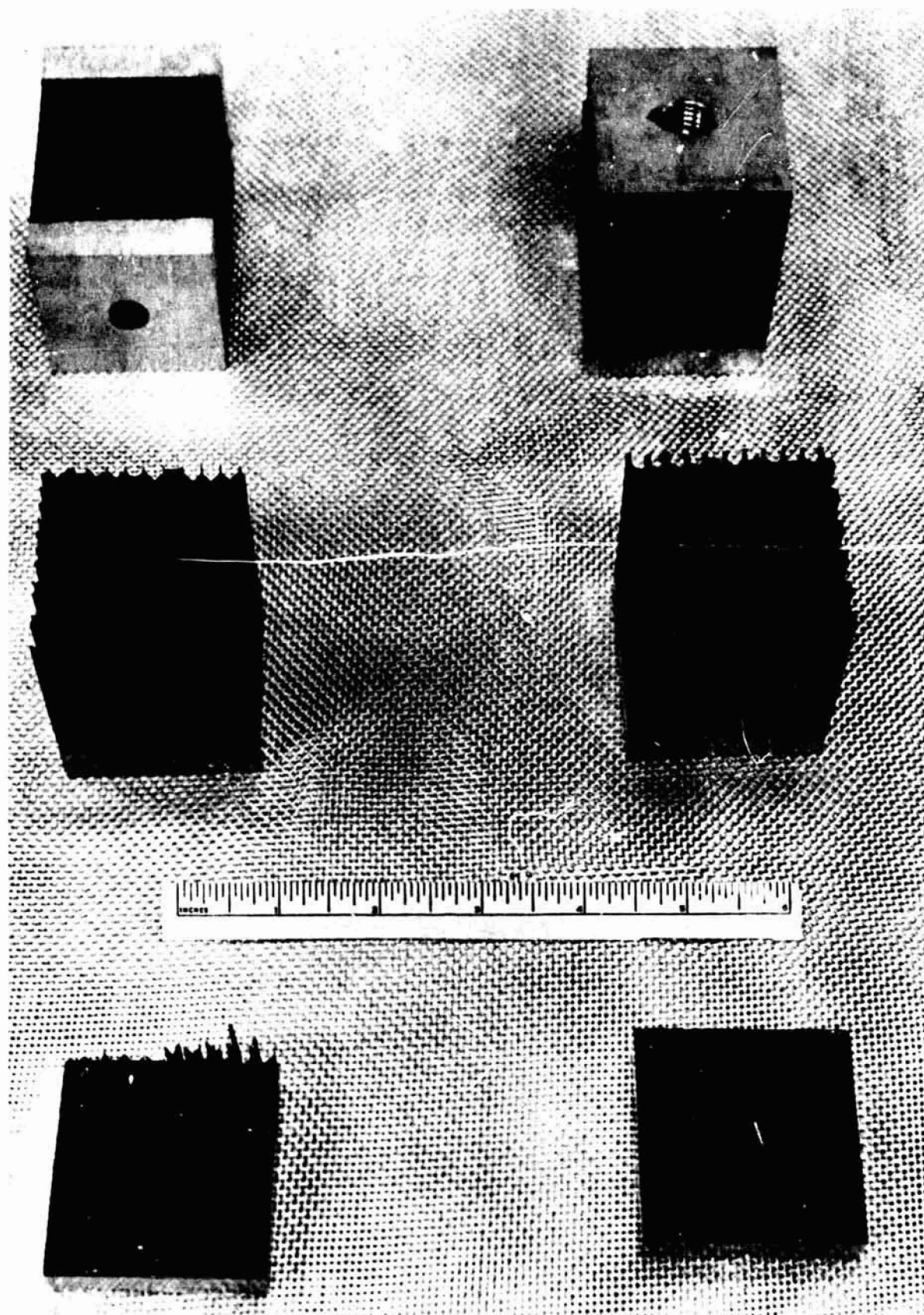


Fig. 3 Honeycomb Core Specimens, Before and After Testing

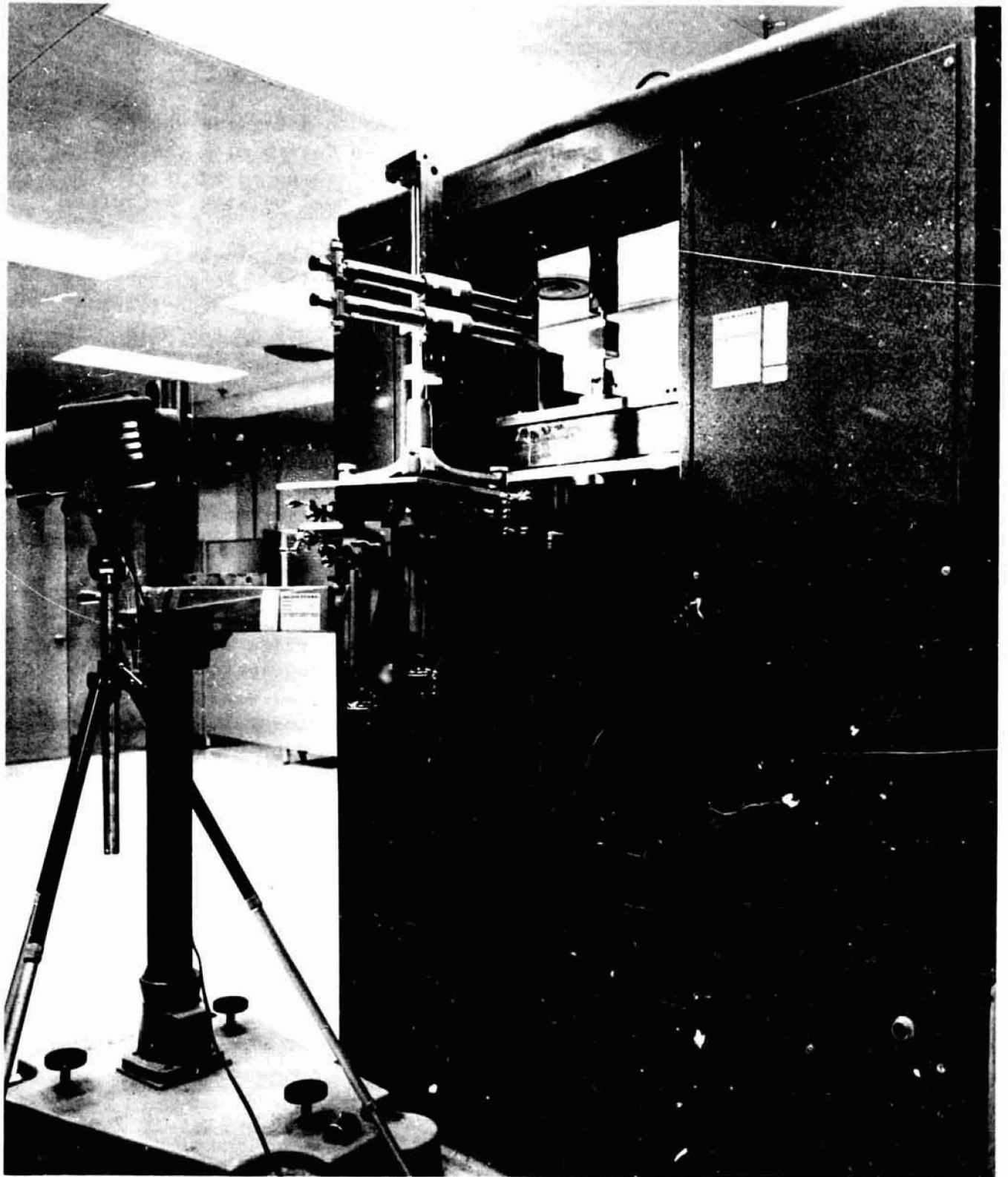


Fig. 4 Test Apparatus for Determining Tension Modulus of Honeycomb Core

### C. WELD LAND AND CORE GAP WIDTH EFFECTS

The effect of land width was studied to determine whether this parameter was an important factor in design from the thermal standpoint. Panels were thermocouple instrumented to provide temperature vs time behavior during an actual welding operation.

Panels were prepared by chemical rather than mechanical milling to be more representative of actual service. To perform the welding under conditions representative of hardware fabrication, it was attempted to use unbonded honeycomb core as the weld backup instead of the metal chill bars normally used. It was found that the fixtures used for test-panel welding could not be used with the 1-in.-thick honeycomb backup. An alternative material, asbestos sheet, was used successfully. Preliminary welding showed that the schedules established for metal backup were not suitable for the insulating material. As described in Section A of this chapter, additional weld optimization was performed for the alternative backup.

Time/temperature history during welding was obtained for all alloys and thicknesses. Thermocouples were located 0.25, 0.50, 0.75, 1.00, and 1.25 in. from the weld centerline as shown in Fig. 5. Temperature vs time curves were autographically recorded. Land widths (distance from centerline) evaluated were 1.25, 1.50, and 2.00 in. A summary of experimental data is presented in Table 11. In several cases thermocouple failures were encountered. However, adjacent data points are sufficient to characterize the shape of the curve for these cases. These studies showed that variation in land width appears to be a minor variable in establishing the effect of weld heating on the adhesive. This study served to emphasize the importance of determining the time/temperature degradation of the adhesive for intelligent selection of minimum weld gap width.

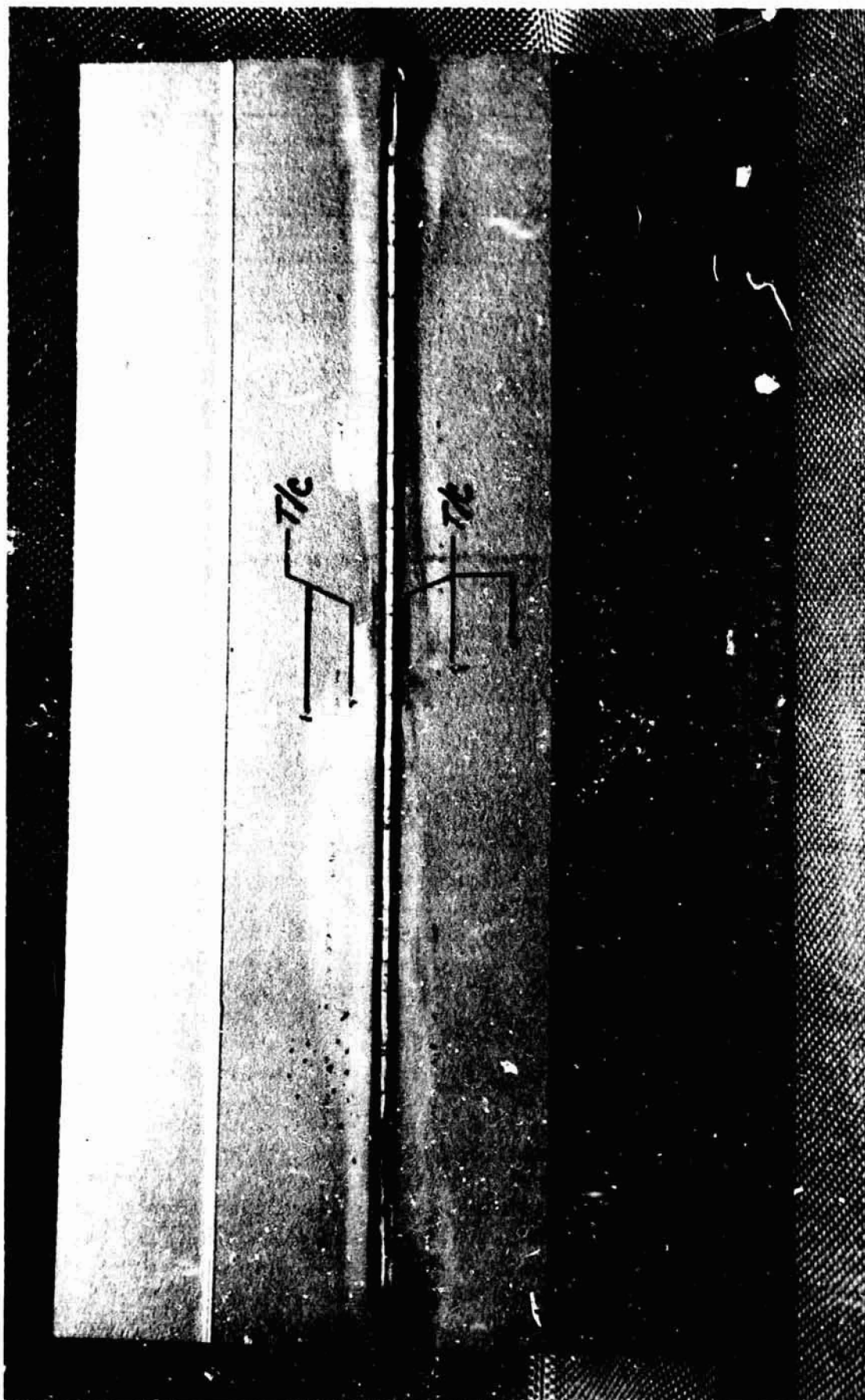


Fig. 5 Thermocouple Locations on Typical Weld Panel for Land-Width Studies

Table 11 Summary of Peak Temperatures from Time/Temperature History Data

| Material | Thickness | Land Width<br>(in.) | Peak Temperature at Indicated Distance from Weld Centerline (°F) |       |       |
|----------|-----------|---------------------|------------------------------------------------------------------|-------|-------|
|          |           |                     | ½ in.                                                            | ¾ in. | 1 in. |
| 2014-T6  | 0.080     | 1½                  | 465                                                              | --    | 246   |
|          |           | 1½                  | 515                                                              | --    | 242   |
|          |           | 2                   | 530                                                              | 380   | 325   |
| 2014-T6  | 0.138     | 1½                  | 530                                                              | 395   | 348   |
|          |           | 1½                  | 560                                                              | 335   | --    |
|          |           | 2                   | 598                                                              | 405   | 255   |
| 2219-T87 | 0.080     | 1½                  | 540                                                              | 330   | 230   |
|          |           | 1½                  | 490                                                              | 345   | --    |
|          |           | 2                   | 545                                                              | 260   | --    |
| 2219-T87 | 0.138     | 1½                  | 602                                                              | --    | 342   |
|          |           | 1½                  | 595                                                              | 395   | --    |
|          |           | 2                   | 588                                                              | --    | 342   |
| 7106-T6  | 0.080     | 1½                  | 498                                                              | 415   | 300   |
|          |           | 1½                  | 485                                                              | 305   | --    |
|          |           | 2                   | 488                                                              | 268   | 270   |
| 7106-T6  | 0.138     | 1½                  | 560                                                              | 375   | 287   |
|          |           | 1½                  | 550                                                              | --    | 320   |
|          |           | 2                   | 560                                                              | 377   | --    |

An autoresistance heating technique simulating the weld cycle was used to thermally degrade the adhesive. A Research, Inc Data-Track temperature programmer was used for this work. Thermal cycles were selected from the time/temperature data obtained from welding actual panels. Exposure specimens consisted of two 0.080-in.-thick 2014-T6 aluminum alloy strips, with a reduced section width, 0.500-in., bonded with a single ply of HT-424 film adhesive to give a bond thickness of 0.007 to 0.008 in. Both strips are simultaneously heated according to a predetermined thermal cycle program. Temperature was monitored and controlled using chromel-alumel couples. Good agreement was obtained between the program trace and monitored record. The central 1 in. of the exposure specimen was found to exhibit  $\pm 10^\circ\text{F}$  temperature uniformity. Exposure times were varied from 5 to 20 sec. Peak temperatures ranged from 400 to 600°F. Figure 6 shows the apparatus used for making thermal exposures.

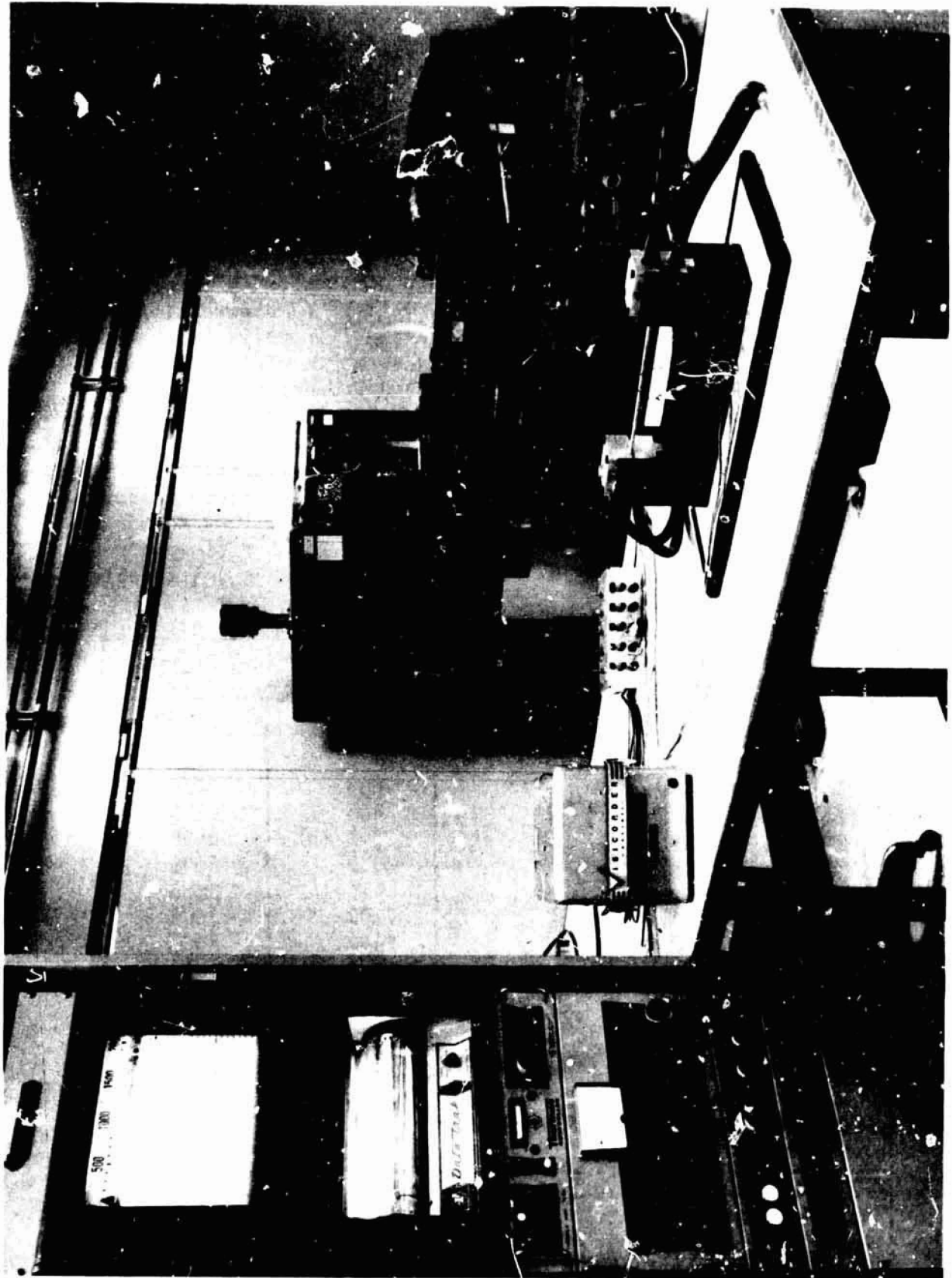


Fig. 6 Thermal Exposure Test Apparatus

After exposure, specimens were carefully slotted into the adhesive on opposite sides,  $\frac{1}{2}$  in. apart, to produce lap shear specimens with an effective bond area of 0.25 sq in. Figure 7 shows the various steps in assembly of a typical shear specimen.

Mechanical property testing was conducted at 70 and -320°F on both unexposed control and thermal exposure specimens. Test results are summarized in Table 12 and Fig. 8 and 9. The data at 70°F show that 400°F and 450°F exposures resulted in very little change in strength, probably a result of postcuring occurring during the heat cycle to offset any effects of degradation. Above this temperature, strength decreased significantly. Tests conducted at -320°F showed no change in strength after 400°F exposure. Above this temperature, strength properties decreased. It appears that the cryogenic mechanical property test is a more severe measure of degradation than the room temperature test. Based on the test results, a maximum adhesive temperature of 400°F is recommended. This value includes a built-in safety factor, since the exposure time in the tests is somewhat longer than encountered in the welding process. Unless a number of weld repairs were required, the 400°F maximum is somewhat conservative.

Table 12 Summary of Thermal Degradation Data

| Exposure Temperature (°F)                                                                                                                                               | Exposure Time (sec) | Shear Strength (psi) (a) |        |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|--------------------------|--------|
|                                                                                                                                                                         |                     | 70°F                     | -320°F |
| 70                                                                                                                                                                      | --                  | 3130                     | 3720   |
| 400                                                                                                                                                                     | 5                   | 2840                     | 3350   |
|                                                                                                                                                                         | 10                  | 2845                     | 3480   |
|                                                                                                                                                                         | 20                  | 2845 (b)                 | 3690   |
|                                                                                                                                                                         | 5                   | 2850                     | 3600   |
| 450                                                                                                                                                                     | 10                  | 2670                     | 3530   |
|                                                                                                                                                                         | 20                  | 2700                     | 2600   |
|                                                                                                                                                                         | 5                   | 2440                     | 3060   |
|                                                                                                                                                                         | 10                  | 2130 (c)                 | 2990   |
| 500                                                                                                                                                                     | 20                  | 2050                     | 2240   |
|                                                                                                                                                                         | 5                   | 2210                     | 2560   |
|                                                                                                                                                                         | 10                  | 1490 (d)                 | 2460   |
|                                                                                                                                                                         | 20                  | 1560                     | 2110   |
| 550                                                                                                                                                                     | 5                   | 1670 (e)                 | 1870   |
|                                                                                                                                                                         | 10                  | 1700                     | 1890   |
|                                                                                                                                                                         | 20                  | 1180                     | 1760   |
|                                                                                                                                                                         | 5                   |                          |        |
|                                                                                                                                                                         | 10                  |                          |        |
|                                                                                                                                                                         | 20                  |                          |        |
| (a) Average of triplicate tests.<br>(b) Two test results.<br>(c) Single test result.<br>(d) Excessive bond line thickness.<br>(e) Specimens overheated during exposure. |                     |                          |        |

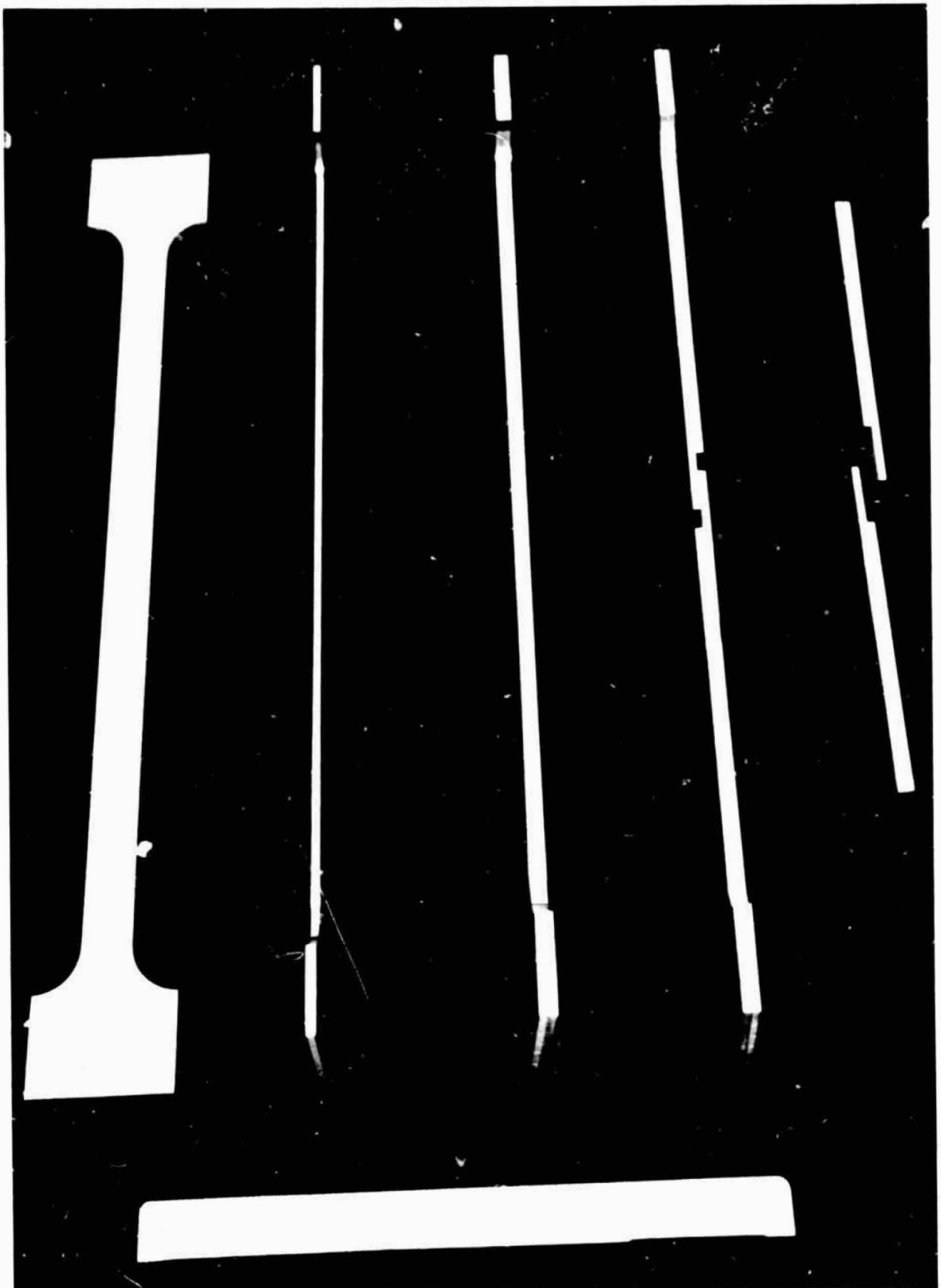


Fig. 7 Thermal Exposure Specimen Showing Various Stages of Fabrication and Test

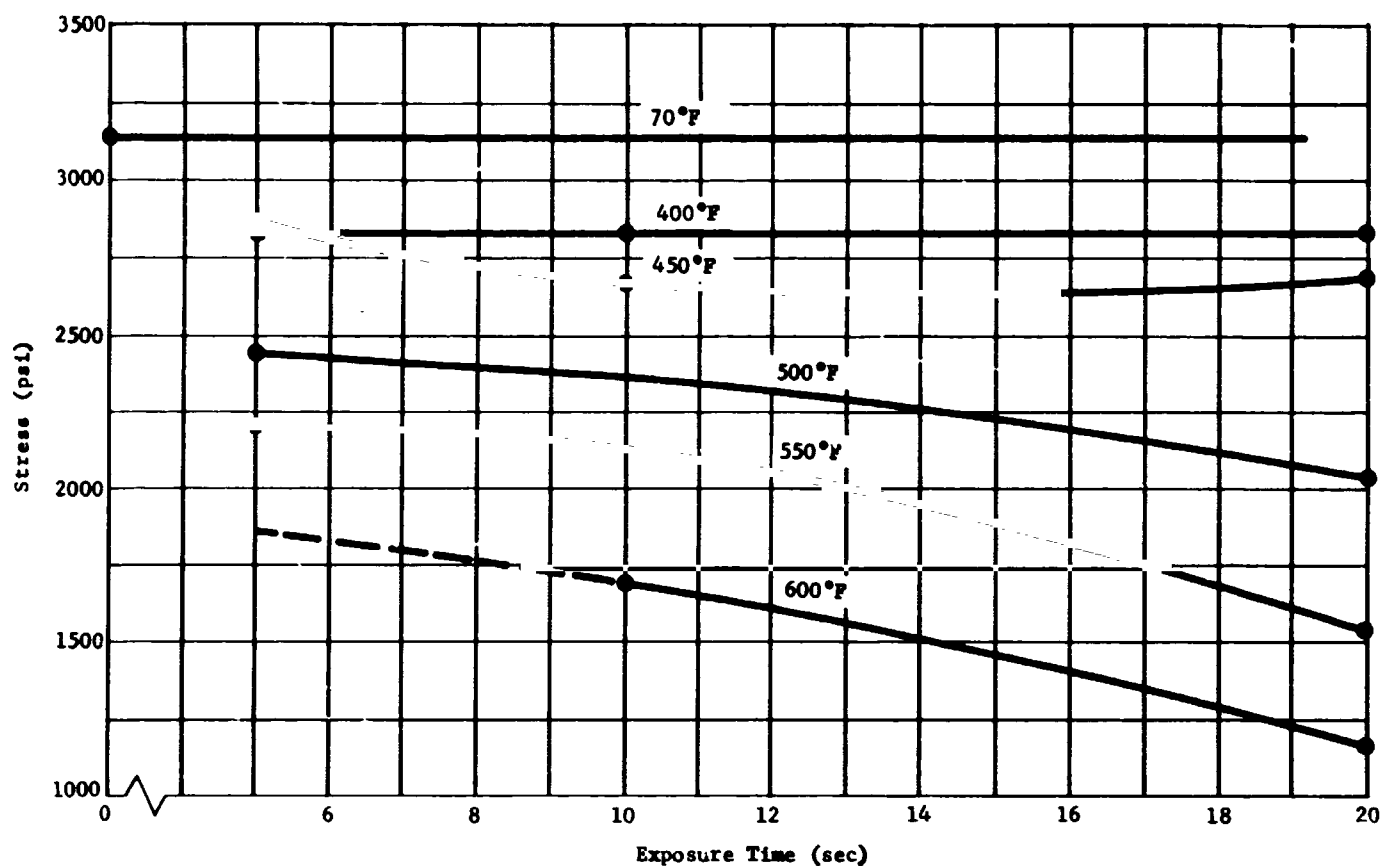


Fig. 8 Lap Shear Strength vs Exposure Time for Thermally Exposed Specimens Tested at 70°F

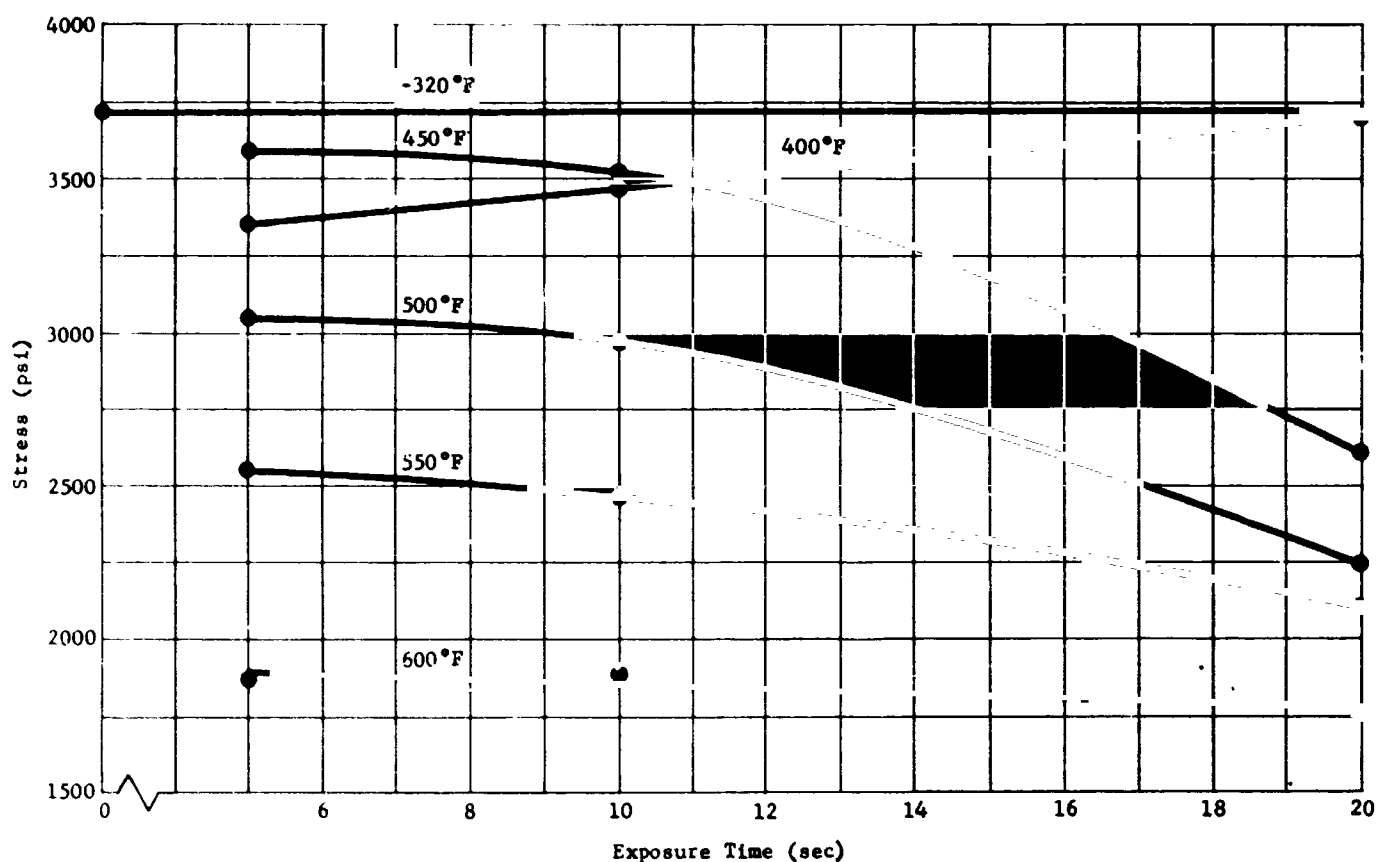


Fig. 9 Lap Shear Strength vs Exposure Time for Thermally Exposed Specimens Tested at -320°F

#### D. STRUCTURAL ANALYSIS OF JOINT DESIGN

The purpose of this work was to maximize the efficiency of sandwich joints subject to compression by a systematic analytical investigation of certain variables that include the effects of land width, gap width, and eccentricity of load path through the land. Development of an analytical model of general validity would preclude the necessity of optimization by empirical means, when a particular skin thickness is altered.

##### 1. Development of Mathematical Model

The analytical approach is based on computation of bending and bond stresses for three zones of the composite assembly. The Region I (gap zone) is considered a beam-column supported only at its ends. Regions II (land area with honeycomb support) and III (skin area with honeycomb support) are considered beam-columns of different stiffness resting on an elastic foundation.

To compute bending and bond stresses for individual sandwich facings, the symmetrical action (Fig. 10) of the facings must be considered.

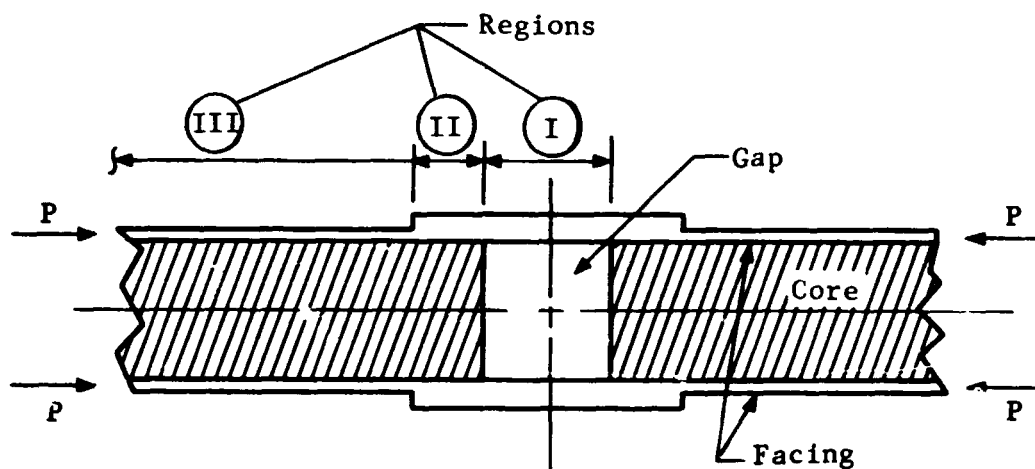


Fig. 10 Sandwich Assembly Cross Section

Throughout the development of this model, it is assumed that the core is acting as an elastic foundation with modulus ( $k$ ), and that there is no bond failure. It is also assumed that the beam of Region I has some initial curvature, i.e., it displays known imperfections. To simplify handling of the eccentricity for the model, the actual situation, characterized by Fig. 11(a) was idealized by applying an external moment,  $P_e$ , as shown in Fig. 11(b),

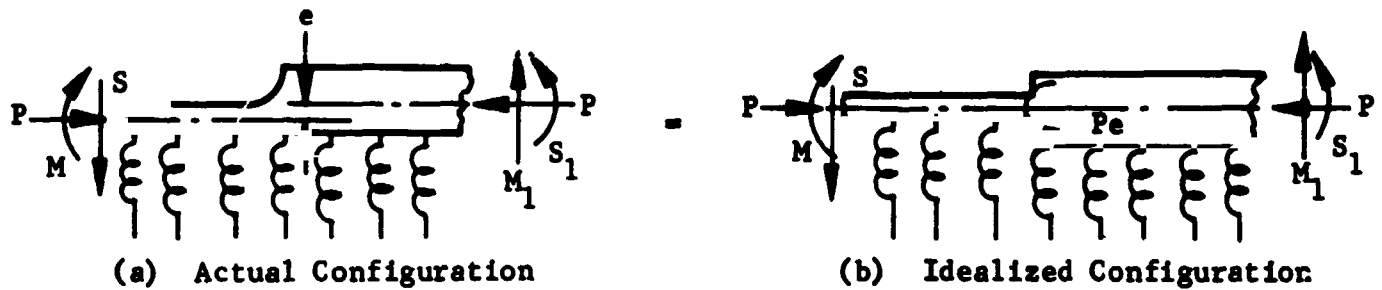


Fig. 11 Idealized Eccentricity

The sign convention\* and free-body diagram of an axially loaded beam on an elastic foundation is shown in Fig. 12. Moment equilibrium for the freebody is given by

$$\frac{dM}{dx} - P \frac{dy}{dx} - Q_v = 0, \quad [1]$$

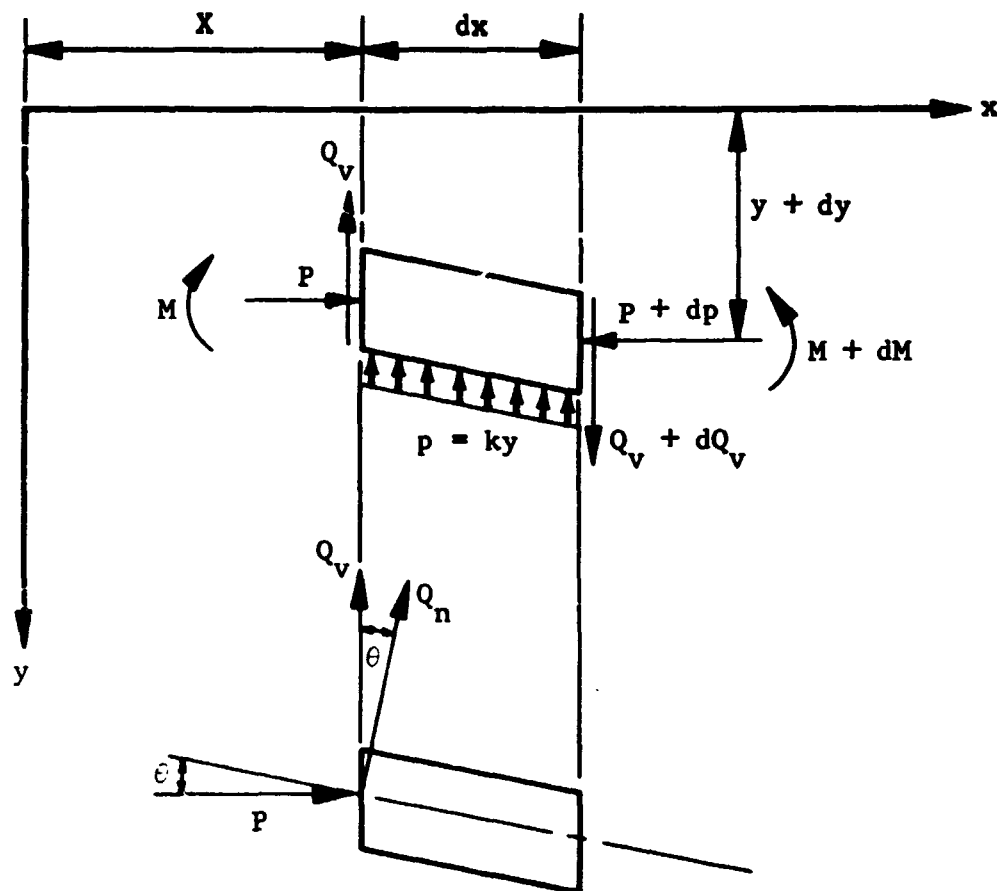


Fig. 12 Sign Convention and Free-Body Diagram for Axially Loaded Beam on Elastic Foundation

\*Nomenclature for this analysis is given in Table 13

and, we note that

$$Q_n = Q_v \cos \theta + P \sin \theta \approx Q_v + P \frac{dy}{dx} = \frac{dM}{dx}, \quad [2]$$

this approximation being valid for sufficiently small slopes,  $\frac{dy}{dx}$ .

Table 13 Nomenclature for Mathematical Model

| Symbol     | Definition                 |
|------------|----------------------------|
| y          | Deflection of beam         |
| x          | Running coordinate of beam |
| M          | Bending moment             |
| $Q_n$      | Normal shear force         |
| $Q_v$      | Vertical shear force       |
| P          | Axial force                |
| E          | Young's modulus            |
| I          | Moment of inertia          |
| k          | Foundation modulus         |
| $\epsilon$ | Amplitude of imperfection  |
| $l$        | Gap length                 |
| a          | Length of Region II        |

Vertical force equilibrium demands that

$$\frac{dQ_v}{dx} = ky, \quad [3]$$

and, within the framework of the Euler-Bernoulli beam theory, we have

$$M = -EI \frac{d^2 y}{dx^2}. \quad [4]$$

Combining Eq [1], [3], and [4], we obtain the differential equation of the elastic line of the beam;

$$\frac{d^4 y}{dx^4} + \frac{P}{EI} \frac{d^2 y}{dx^2} + \frac{k}{EI} y = 0. \quad [5]$$

The solution of Eq [5] is obtained in the usual manner. Face wrinkling is not considered to be a mode of failure in the skin gages used, since  $2\sqrt{kEI} > P$  in this case (verified by preliminary tests), then we may write the solution of Eq [5] as

$$y = (C_1 e^{\beta x} + C_2 e^{-\beta x}) \cos \alpha x, \\ + (C_3 e^{\beta x} + C_4 e^{-\beta x}) \sin \alpha x, \quad [6]$$

where

$$\alpha = \sqrt{\sqrt{\frac{k}{4EI}} + \frac{P}{4EI}},$$

and

$$\beta = \sqrt{\sqrt{\frac{k}{4EI}} - \frac{P}{4EI}}.$$

If we assume that the portion of the facing not attached to the core (Region I) has an initial imperfection characterized by  $y_0 = \frac{\epsilon}{2} \left(1 - \cos \frac{2\pi}{\ell} x\right)$ , then its deflection,  $y = y_0 + y_1$ , is given by solving the equation

$$EI \frac{d^2 y_1}{dx^2} = -P (y_0 + y_1) - M_0 \quad (\text{see Fig. 13}). \quad [7]$$

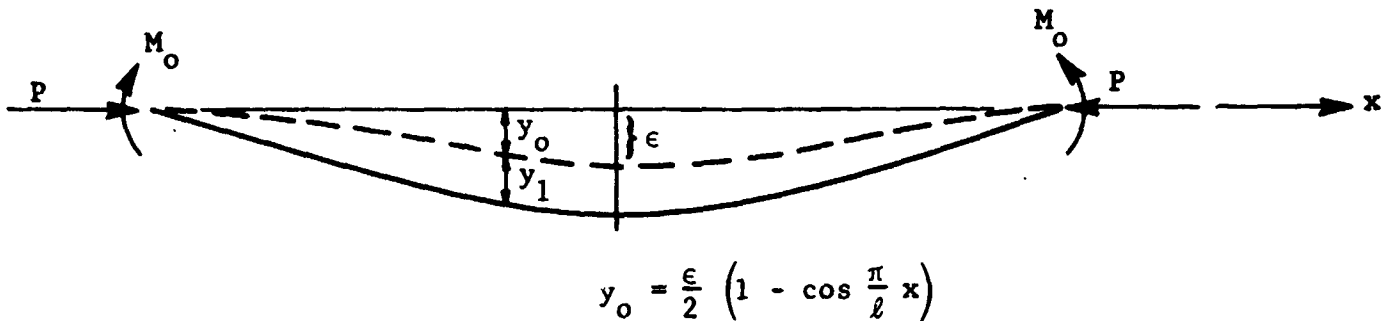


Fig. 13 Axially Compressed Beam with Initial Imperfection and End Moment

Solving Eq [7], we have

$$y_1 = A \cos \lambda x + B \sin \lambda x - \frac{M_o}{P} - \frac{\epsilon}{2} - \frac{\frac{\epsilon}{2}}{1 - \frac{4\pi^2}{\lambda^2 \ell^2}} \cos \frac{2\pi}{\ell} x, \quad [8]$$

where

$$\lambda^2 = \frac{P}{EI}.$$

At  $x = 0$ , we require

$$EI \frac{d^2 y_1}{dx^2} = -M_o,$$

and at  $x = \frac{\ell}{2}$  we have, by symmetry,

$$\frac{dy}{dx} = 0.$$

These conditions, when imposed on Eq [8], result in

$$A = \frac{M_o}{P} - \frac{\frac{4\pi^2}{\lambda^2 \ell^2} \frac{\epsilon}{2}}{1 - \frac{4\pi^2}{\lambda^2 \ell^2}};$$

$$B = A \tan \lambda \frac{\ell}{2}.$$

With these constants, and with Eq [8], we can calculate the slope at  $x = 0$ . It is

$$\left( \frac{dy_1}{dx} \right)_{x=0} = \lambda B = \left( \frac{\lambda M_o}{P} - \frac{\frac{4\pi^2}{\lambda^2 \ell^2} \frac{\epsilon}{2}}{1 - \frac{4\pi^2}{\lambda^2 \ell^2}} \right) \tan \lambda \frac{\ell}{2}. \quad [9]$$

Based on examination of typical weld panels, an initial imperfection of approximately 0.010 in. was selected for calculations. This value is not considered significant compared to the effects of axial load eccentricity ( $P \times e$ ) caused by change in face sheet thickness.

Figure 14 will be used to designate the coordinates required for synthesis of the entire problem. Adapting Eq [6] to Region III, and letting  $x_3$  take negative values ( $x_3 \leq 0$ ), we have,

$$y = e^{\beta x_3} (C_5 \cos \alpha x_3 + C_6 \sin \alpha x_3). \quad [10]$$

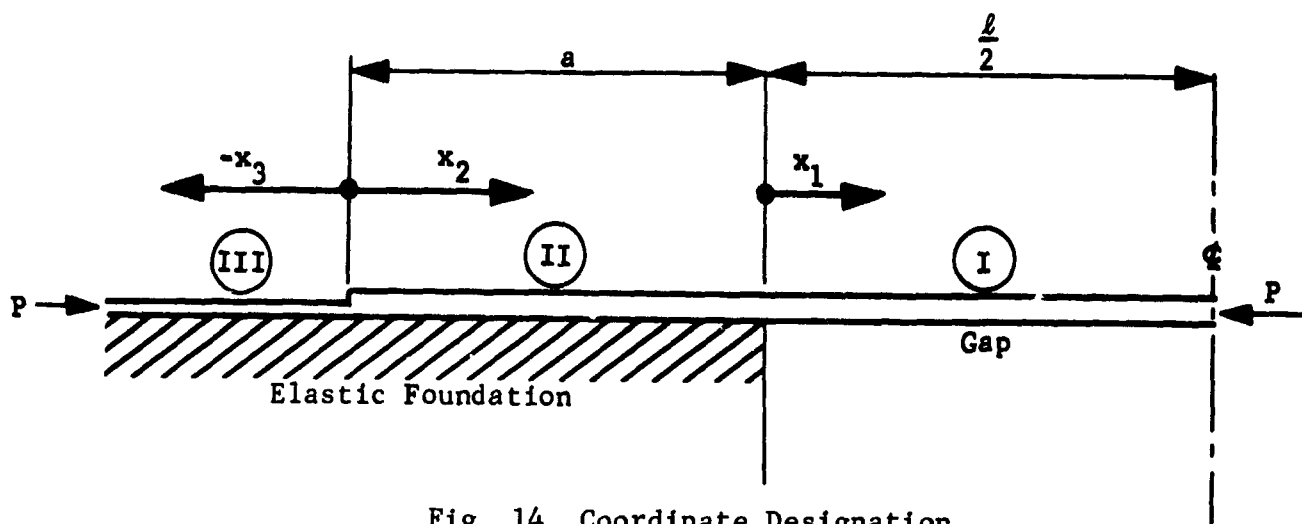


Fig. 14 Coordinate Designation

To arrive at Eq [10], we have made the implicit assumption that deflections, slopes, etc, vanish for  $x_3 \rightarrow -\infty$ ; i.e., boundary conditions at the left end of this beam will not influence the results of this calculation.

Adapting Eq [6] to Region II, we have

$$y = \left( C_1 e^{\beta x_2} + C_2 e^{-\beta x_2} \right) \cos \alpha x_2 + \left( C_3 e^{\beta x_2} + C_4 e^{-\beta x_2} \right) \sin \alpha x_2. \quad [11]$$

Continuity of deflection, slope, moment, and shear at  $x_3 = x_2 = 0$  demands that

$$\left. \begin{aligned} (y)_{x_2=0} &= (y)_{x_3=0}, \\ \left(\frac{dy}{dx_2}\right)_{x_2=0} &= \left(\frac{dy}{dx_3}\right)_{x_3=0}, \\ (EI)_2 \left(\frac{d^2 y}{dx_2^2}\right)_{x_2=0} &= (EI)_3 \left(\frac{d^2 y}{dx_3^2}\right)_{x_3=0}, \\ (EI)_2 \left(\frac{d^3 y}{dx_2^3}\right)_{x_2=0} &= (EI)_3 \left(\frac{d^3 y}{dx_3^3}\right)_{x_3=0} \end{aligned} \right\} \quad [12]$$

At  $x_2 = a$  and  $x_1 = 0$ , we require continuity of slope, moment, and shear:

$$\left. \begin{aligned} \left(\frac{dy}{dx_2}\right)_{x_2=a} &= \left(\frac{dy}{dx_1}\right)_{x_1=0}, \\ (EI)_2 \left(\frac{d^2 y}{dx_2^2}\right)_{x_2=a} &= -M_0, \\ \left[ (EI)_2 \frac{d^3 y}{dx_2^3} + p \frac{dy}{dx_2} \right]_{x_2=0} &= 0. \end{aligned} \right\} \quad [13]$$

If we substitute the solutions of Eq [10] and [11] into the continuity conditions of Eq [12] and [13], we obtain, in conjunction with Eq [9], seven linear equations in the seven unknowns  $C_1, C_2, C_3, C_4, C_5, C_6$ , and  $M_0$ , thus ensuring a unique solution to the problem.

This solution results in complete information about stresses and deflections if geometry, material properties, and load are given. In particular, it is possible to calculate the normal bond stresses between the core and facing, given by the expression  $\sigma_b = ky(x)$ .

## 2. Application of Mathematical Model

To use the mathematical model previously described, additional mechanical property data were obtained.

The moment of inertia was calculated as follows:

$$I = \frac{1}{12} \frac{bh^3}{(1 - U^2)}.$$

By using the deflection formula

$$\Delta = \frac{Pl^3}{48EI},$$

and substituting for I, we obtain

$$h^3 = \frac{Pl^3 \cdot 12 (1 - U^2)}{48 E b \Delta}.$$

Since b is made equal to unity, the equation reduces to

$$h^3 = \frac{Pl^3 \cdot 12 (1 - U^2)}{48 E \Delta}.$$

By measuring deflection in the three-point loaded beam test using 0.055-in. aluminum stiffened with 1-in. core, an effective thickness (h) of 0.0675 in. was obtained. In other words, the core had an effective thickness of 0.0125 in.

The seven simultaneous equations were programed for computer solution.

Initial solutions for the geometries evaluated under Contract NAS8-5463 were compared with actual test data. The test results for Contract NAS8-5463 composite panels were not sufficient to provide a rigorous confirmation of the computer solution because deflection data were not obtained for these panels. The calculated stress in the core predicted from the model was compared with the tensile strength of the core.

To provide a more rigorous confirmation of the model, a test panel was constructed using the same dimensions as those evaluated in Contract NAS8-5463. Dimensions were as follows:

- 1) Skin thickness, 0.125 in.;
- 2) Land thickness, 0.340 in.;
- 3) Land width, 1.750 in. (from centerline);
- 4) Gap width, 1 in.;
- 5) Core thickness, 2 in.;
- 6) Width, 9 in.;
- 7) Height, 9 in.

Deflections under incremental compressive loading were taken at  $\frac{1}{2}$ -in. intervals along a plane 2 in. from the edge of the panel. The relation between experimental and analytically determined deflections is shown in Fig. 15. Note that the agreement is particularly outstanding. The failing load was 108,000 lb (6000 lb/in. of width). The maximum deflection, 0.0072 in., was obtained before failure at a 100,000-lb load. This deflection is equal to a core stress of 676 psi or approximately 85% of the core tensile strength.

To obtain a better value for core stress, a second panel was continuously loaded, rather than incrementally loaded, and deflection was autographically recorded to obtain maximum deflection at the failing load. With this technique, a core stress of 771 psi (or more than 95% of fracture stress) was obtained at failure.

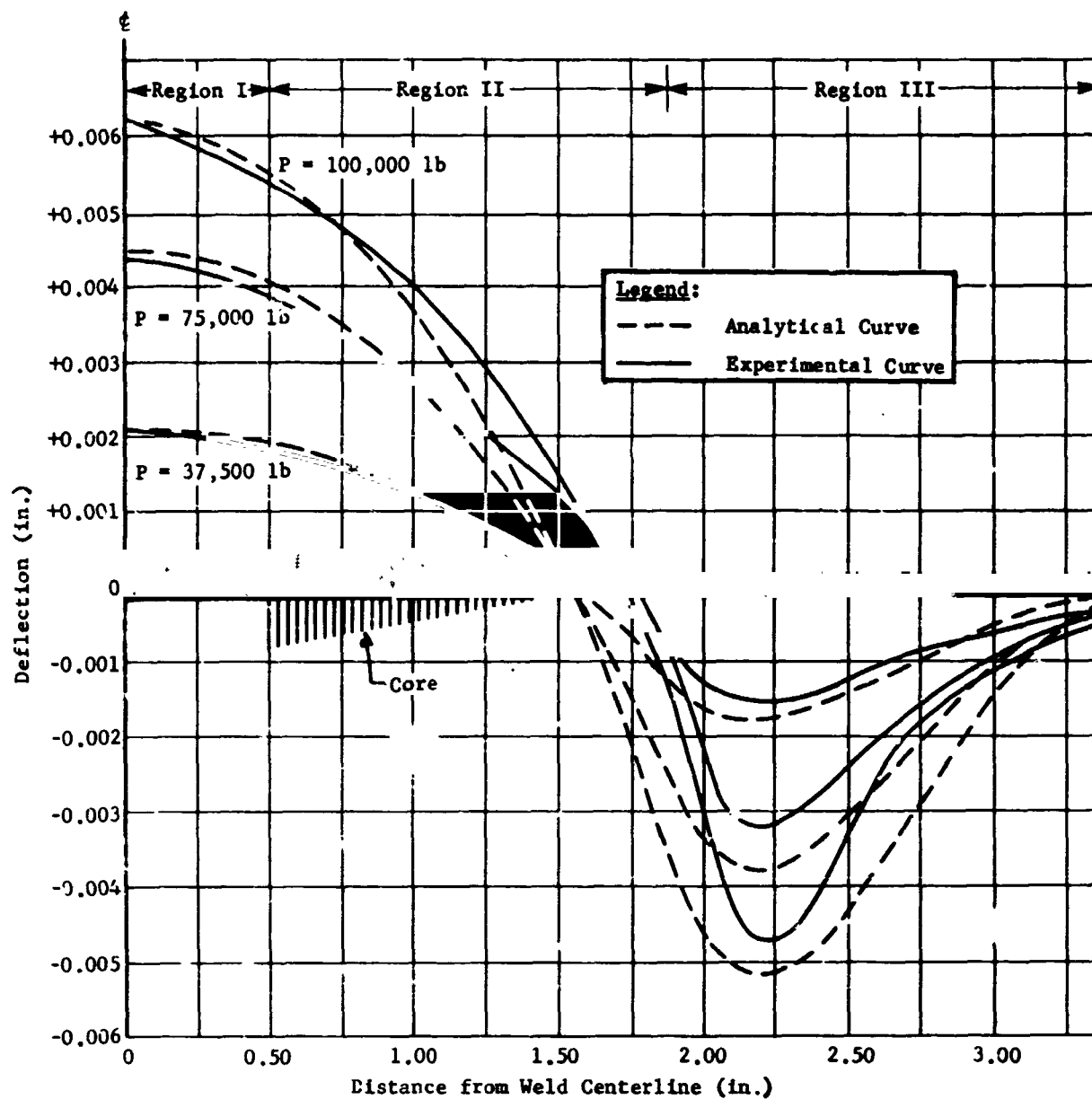


Fig. 15 Comparison of Analytical and Experimental Deflection Data for 2-in.-Thick Honeycomb Panel

### E. DESIGN OF OPTIMIZED JOINT

The design of optimized joints was performed for the six material and thickness combinations. The important parameters to be selected were: (1) land/skin thickness ratio; (2) gap width; and (3) land width.

Land/skin thickness ratio was selected considering design allowable values. For example, Martin Company design allowable for welded 2014-T6 aluminum alloy is 25,000 psi; the parent metal allowable is 67,000 psi. The ratio of these stresses is very close to 2.5. Normal design practice at Martin Company is to use a land/skin ratio equal to 2.5 for 2014-T6. Aluminum alloy 2219-T87 also exhibits a similar stress ratio and would be used in design with a land/skin thickness ratio of 2.5. The stress ratio for 7106-T6 is somewhat closer to 2.0. However, to obtain a basis for comparison between different alloys and because of the danger of buckling failure at a 2.0 land/skin ratio, the value of 2.5 was selected for all three alloys.

Gap width selection was dictated by two factors:

- 1) Minimum gap from adhesive degradation considerations;
- 2) Maximum gap from column buckling considerations.

The minimum gap value was selected to maintain peak temperature to no more than 400°F. From the time/temperature data summarized in Table 11, it is shown that a gap of 1.5 in. is sufficient to limit peak temperature to acceptable limits. Our analysis of the data indicates that for thicknesses less than 0.100 in., a gap width of 1.30 in. should be acceptable; for thicknesses above 0.100 in., a width of 1.40 in. should suffice.

The maximum gap width was selected using the column buckling formula:

$$P = \frac{\pi^2 EI}{l^2}.$$

The critical lengths for the thin (0.090 in.) and thick (0.138 in.) land were 1.43 and 2.38 in., respectively.

The tolerance for selection of gap width in the thinner design was quite small (minimum = 1.30 in. vs maximum = 1.43 in.). A value of 1.40 in. was selected to avoid the danger of adhesive degradation. For the thicker design, a value of 1.5 in. was selected. This value gives great freedom from buckling instability.

Land width was selected by obtaining an optimum relationship among the following important factors:

- 1) Minimum deflection at edge of core (Region I to Region II junction);
- 2) Minimum deflection near edge of land (Region III);
- 3) Minimum positive moment at edge of core;
- 4) Minimum weight.

A series of computer runs was made to obtain deflection data for various land widths with fixed gap and load for both land thicknesses. A stress level of 56,000 psi was selected to give deflections typical of those expected in the vicinity of instability.

Figure 16 shows deflection data for four land width values of the 0.138-in. land thickness design. As shown in the diagram, the land widths of 2.10 and 2.00 in. give low deflections at points A and B. In addition, the moment is minimal. However, weight is high. For the 1.75-in. land width, deflection is high. At a land width of 1.85 in., an intermediate value of deflection is obtained. Figure 17 summarizes the data in a manner that permits selection of the optimum width. This diagram plots deflection at point A, moment at point A, and maximum deflection in Region III. The land width value that gives minimum deflection at point A, minimum deflection adjacent to the junction of Regions II and III, minimum moment at point A, and minimum weight is the goal of our selection. However, as shown by Fig. 17, this is impossible to achieve. An analysis of the modes of joint failure suggested that the value of the point of maximum deflection in Region III should be kept as small as possible. As shown by the graph, this value varies little with width. It should be further noted that the moment value is rather small over the entire range of land widths. Selection of the land width was made by proportionate weighing of the various parameters affecting performance. For the thicker design, a land width value of 1.95 in. was selected. Similarly, an optimum land width of 1.55 in. was selected for the thinner composite panel (Fig. 18 and 19).

The results of the design optimization are summarized in Table 14.

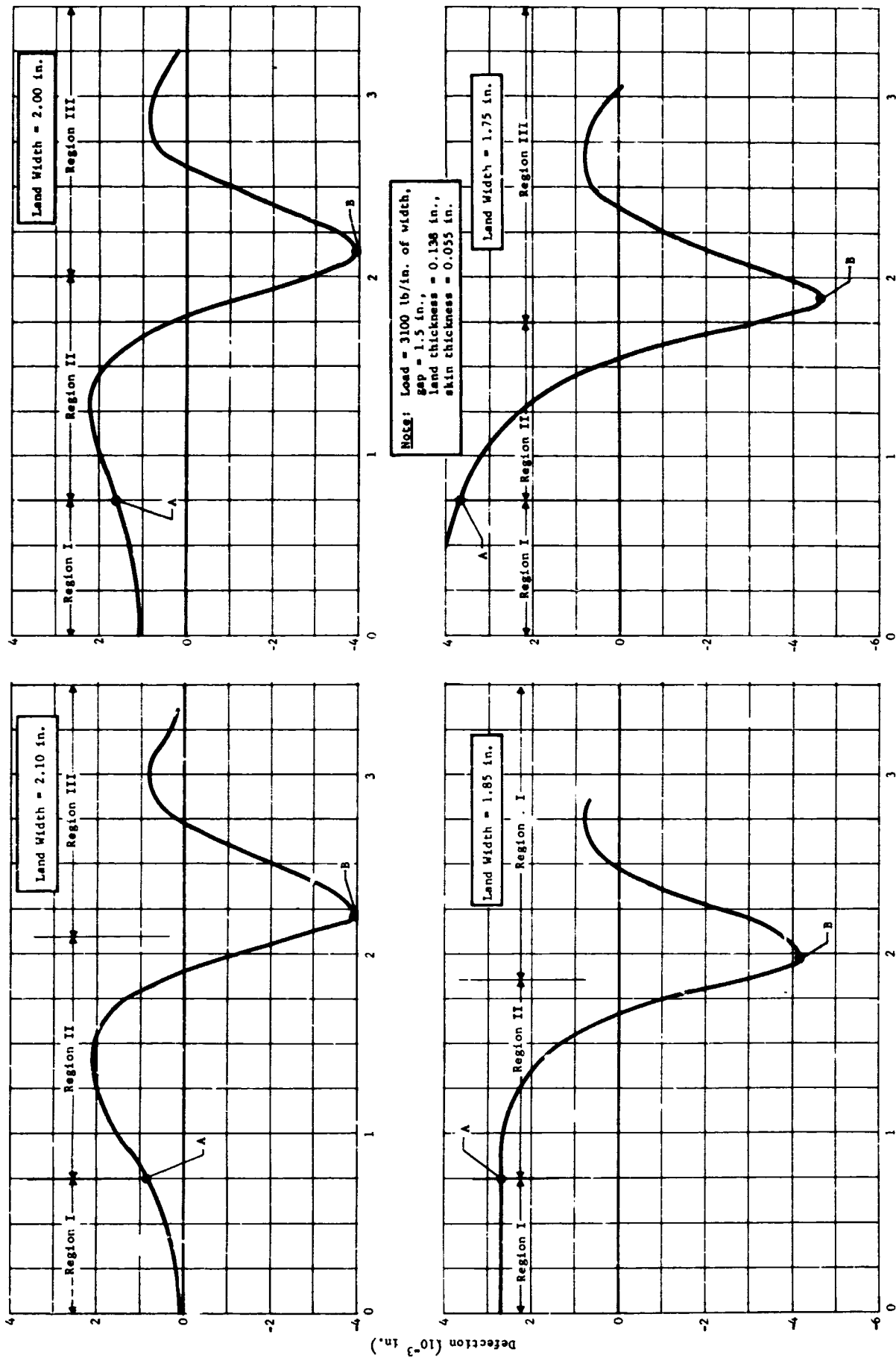


Fig. 16 Deflection Data for Various Land Widths (Thicker Design)

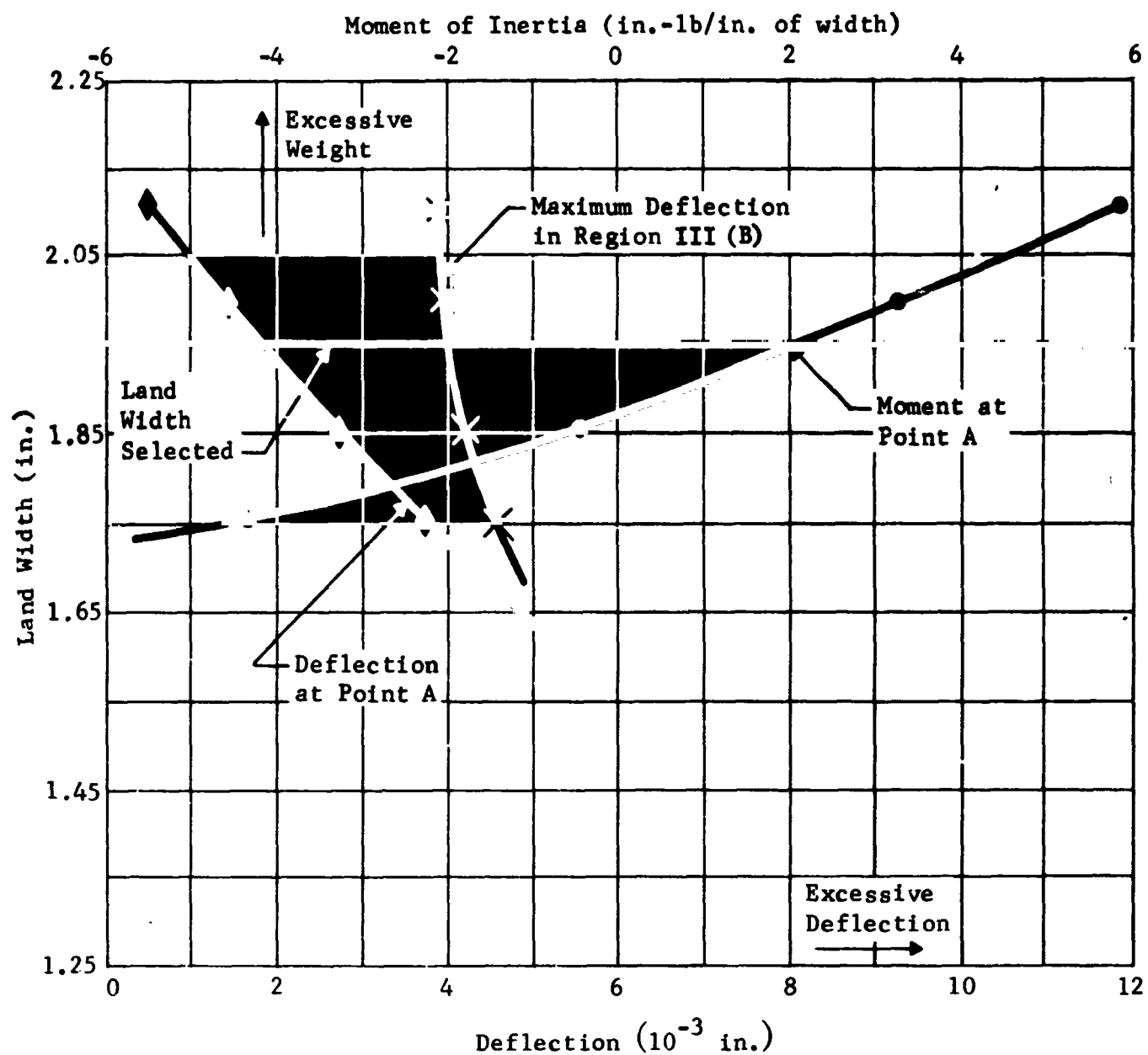


Fig. 17 Summary of Deflection and Moment Data (Thicker Design)

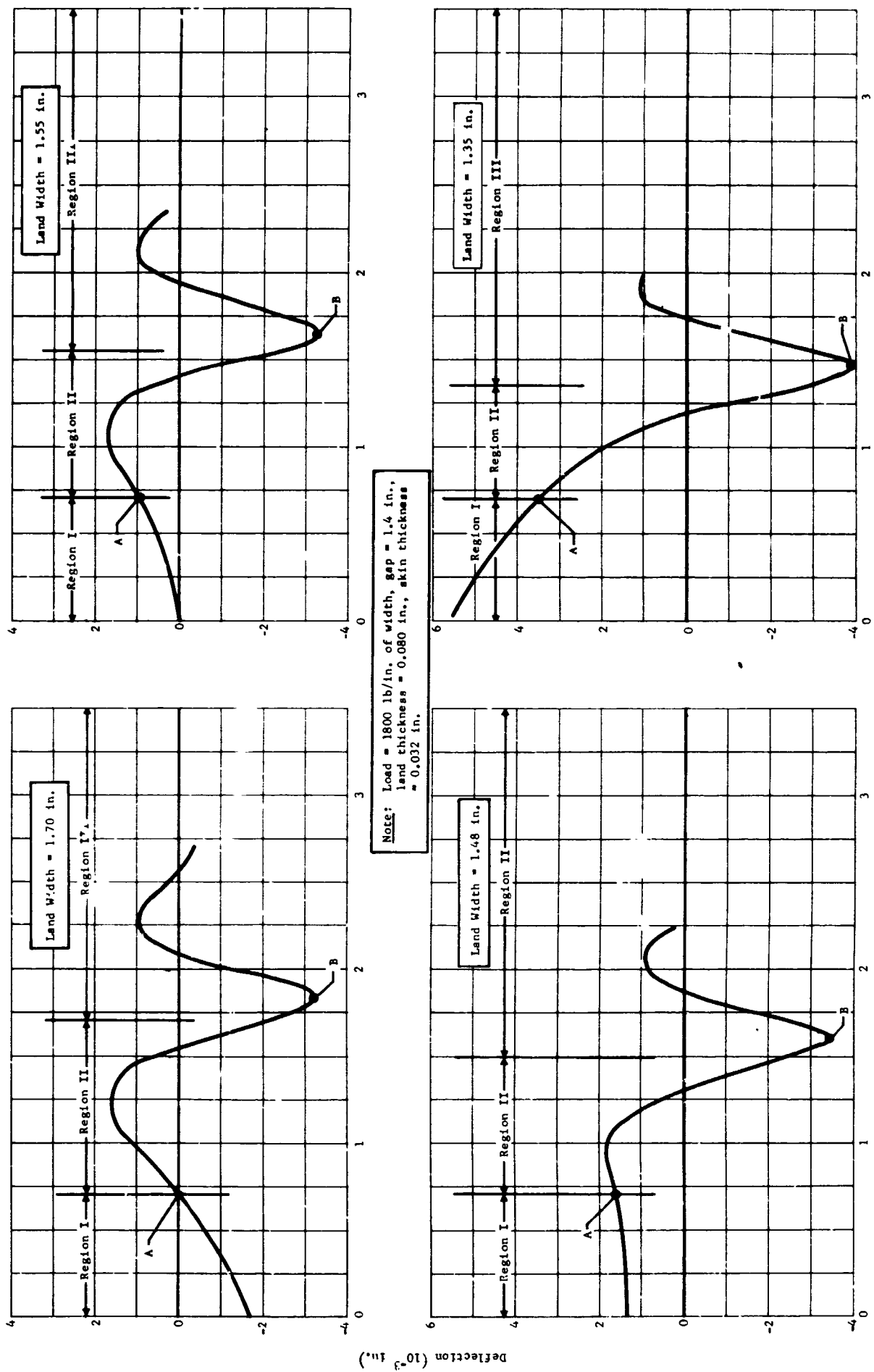


Fig. 18 Deflection Data for Various Land Widths (Thinner Design)

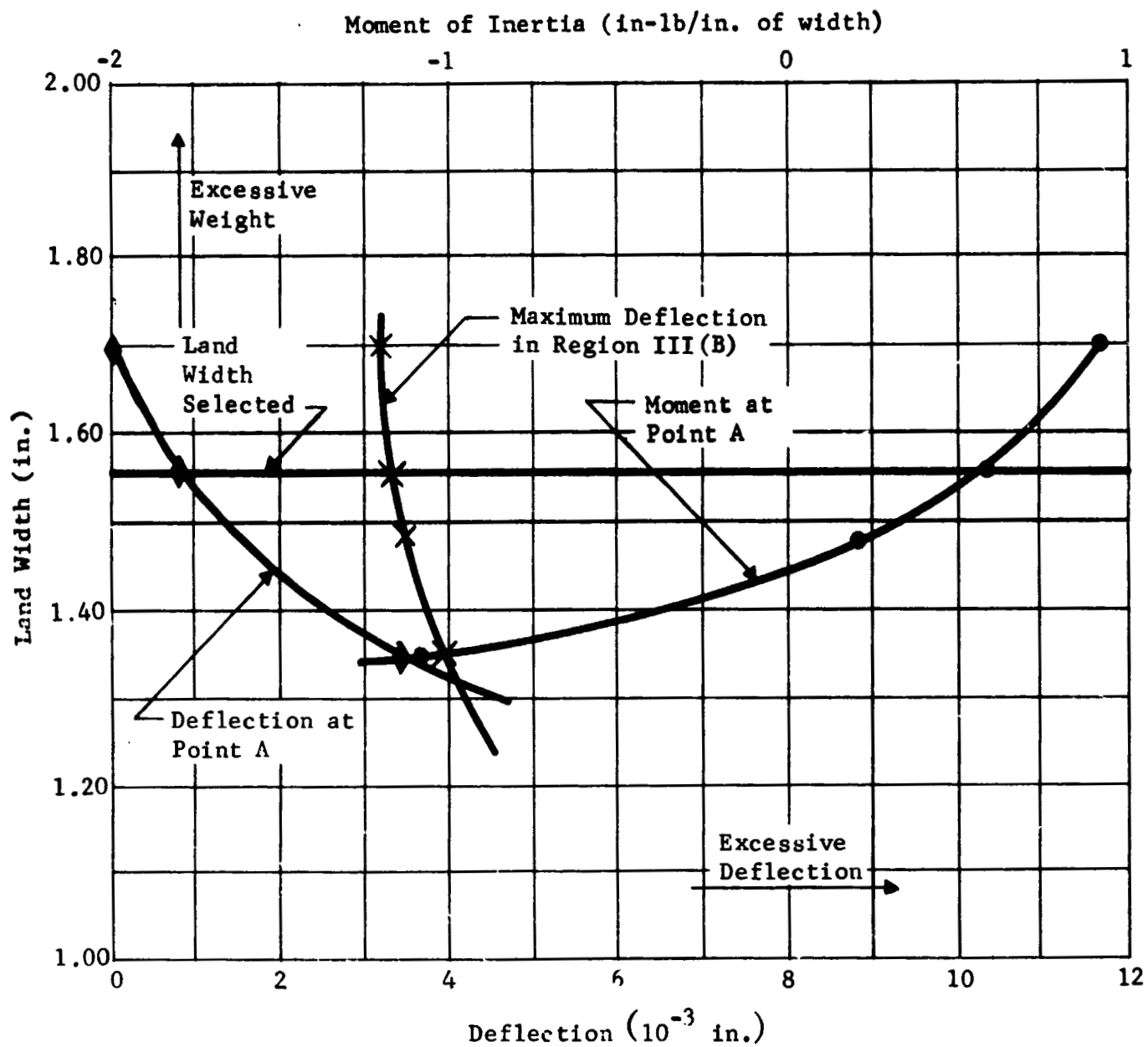


Fig. 19 Summary of Deflection and Moment Data (Thinner Design)

Table 14 Design Optimization of Welded Joint

| Skin Thickness (in.) | Land Thickness (in.) | Land/Skin Ratio | Gap Design                                    |                                                |                    | Land Width (in.) |
|----------------------|----------------------|-----------------|-----------------------------------------------|------------------------------------------------|--------------------|------------------|
|                      |                      |                 | Minimum Gap from Thermal Considerations (in.) | Maximum Gap from Buckling Considerations (in.) | Gap Selected (in.) |                  |
| 0.032                | 0.080                | 2.5             | 1.30                                          | 1.43                                           | 1.40               | 1.55             |
| 0.055                | 0.138                | 2.5             | 1.40                                          | 2.38                                           | 1.50               | 1.95             |

Additional computer runs were made to predict failure loads and modes for each specimen design.

The thin design was shown to exhibit a critical stress for failure because of plastic deformation (interface buckling) at the junction of Regions II and III of approximately 62,000 psi using an iterative process to obtain a modulus and stress combination that falls on the experimentally determined tangent modulus curve. Calculations of column buckling indicate failure could occur at approximately 71,000 psi. Because of the close similarity of these values, it cannot be determined whether failure is expected because of column buckling across the gap or interface buckling.

The thicker design would be expected to exhibit failure because of interface buckling at a stress of approximately 65,000 psi. Column buckling would not occur until a stress of almost 200,000 psi was attained. Therefore, failure was predicted to occur because of interface buckling at approximately 65,000 psi.

### III. PHASE II - ANALYSIS OF JOINTS UNDER COMPRESSION

The objectives of Phase II of this research were to experimentally determine the behavior of optimum designed honeycomb joints for the six combinations of materials and thicknesses under compressive loading and to compare this behavior with that predicted by our design studies.

The optimum design selected in Phase I was used for this work.

#### A. FABRICATION

To simulate the actual processing for composite structures, chemical milling was used to obtain the weld lands in the composite panels. Chemical milling of the 2014-T6 material in the laboratory gave panels that met our thickness tolerances of  $\pm 0.002$ ,  $-0.001$  in. Chemical milling of the 2219 and 7106 material in our factory resulted in nonuniformity of final thickness, probably due to operator error. Fortunately, chemical milling was ceased at a thickness exceeding the maximum tolerance. Panels were not subjected to an additional chemical milling cycle because nonuniform thickness cannot be corrected using chemical milling. Therefore, panels were mechanically milled to final dimensions. Milled panels were 12x24 in., containing the full land width centered on the longitudinal axis. Panels were split into 6x24-in. sections before bonding. To ensure good bonding behavior, each panel was carefully cleaned in an acid solution (acidified sodium dichromate solution); core material was vapor degreased. Each panel was carefully measured to determine thickness; mated panels were hand selected to give uniform thickness of the composite. To achieve uniform pressure during the bonding cycle, the skin thickness area was shimmed to within 0.001-in. of the weld land thickness. As shown in Fig. 20, two half panels were butted together for bonding. The gap spacing was obtained by using a precision machined spacer bar during the positioning of the core and faceplates. After positioning, platen pressure was applied, the spacer bar was removed, and the bond heating cycle was initiated.

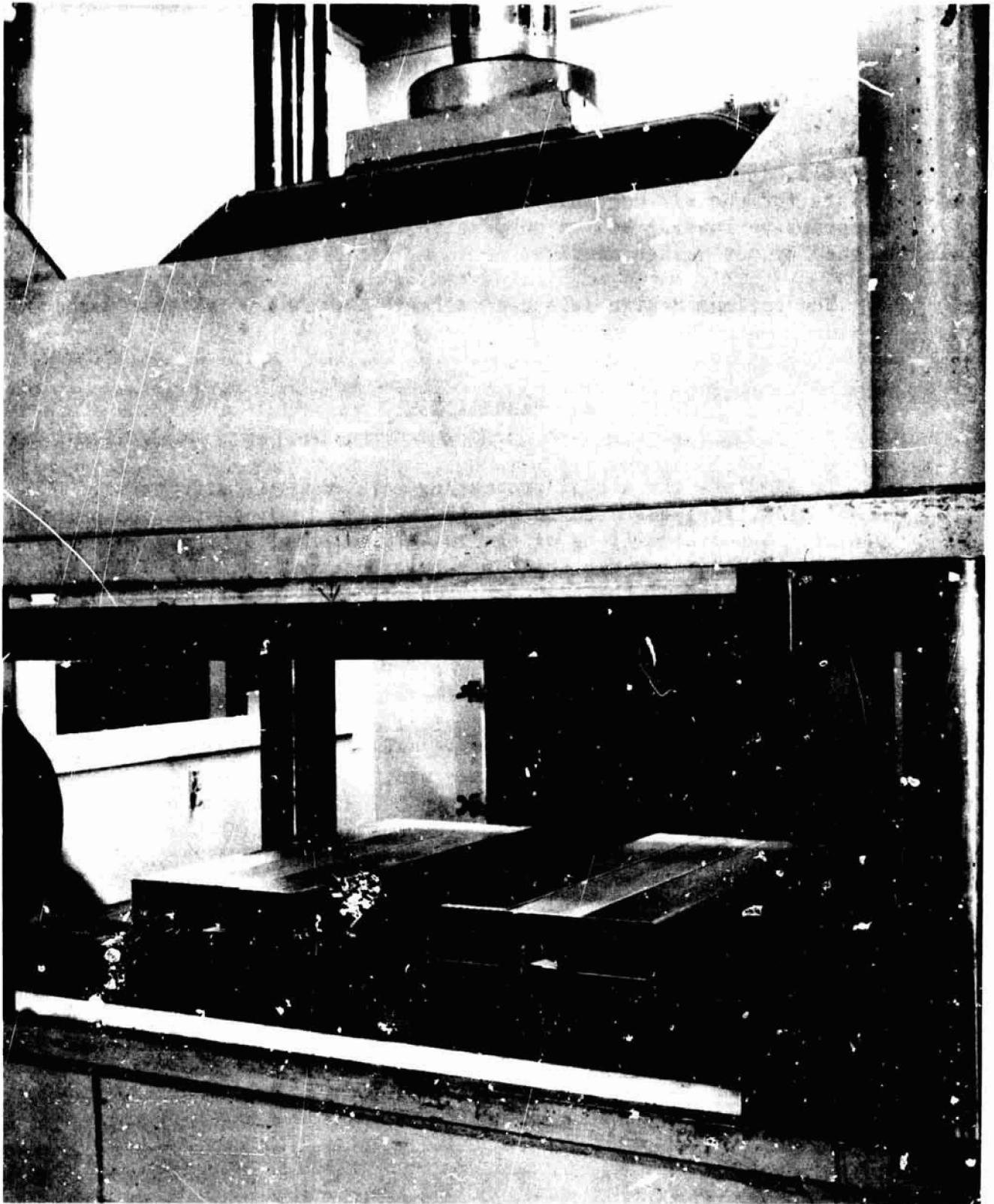


Fig. 20 Four 6x24-in. Panels Ready for Bonding

Bonding was achieved in a 150-ton plastic molding press incorporating 3-ft square heated platens. Four 6x24-in. sections were bonded in each thermal cycle. This provides sufficient material for four finished 9x9-in. panels. Two layers of HT424 adhesive were used for each bonded surface. A 50-psi pressure was maintained during heating and cooling. The thermal cycle was as follows:

- 1) Heating - Average rate of 10°F/minute;
- 2) Cure - 60 minutes at 350°F;
- 3) Cooling - Free cooling average rate of less than 1°F/minute.

The adhesive was laid up within five minutes after removal from the storage refrigerator. Layup was also performed on an ambient temperature platen to preclude the possibility of premature curing during layup.

After bonding, matched half panels were welded using the automatic TIG process. Welding schedules were checked using practice panels. It was determined that the schedules established using the insulated backup flat panels were close to those required for welding of composite panels, but required a small increase in current level to account for slightly different chilling characteristics of the fixturing. After welding, 9-in. square panels were machined from the 12x24-in. assembly.

## B. TEST TECHNIQUES

Testing was performed using the modified ASTM-364-61 compression fixture described in our previous work.\* Figure 21 shows this device. For cryogenic testing, -320°F, the entire fixture was placed in a flat-bottomed insulated container.

The compression test fixture was aligned using composite panels instrumented with strain gages mounted on opposite faces. The fixture was adjusted until uniform strain was achieved in both faces. Several different panels were used for alignment checking. The fixture was maintained in the aligned position. All room temperature testing was performed using noninstrumented panels. A similar alignment procedure was used for cryogenic testing. However, approximately half of the composite panels were tested using strain gages for alignment confirmation. No evidence of loss of alignment was noted.

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\*A. A. Ezra et al.: Explosive Forming and Welding of Honeycomb Sandwich Material, Final Report. Martin-CR-64-36. Martin Company, Denver, Colorado, October 1964.

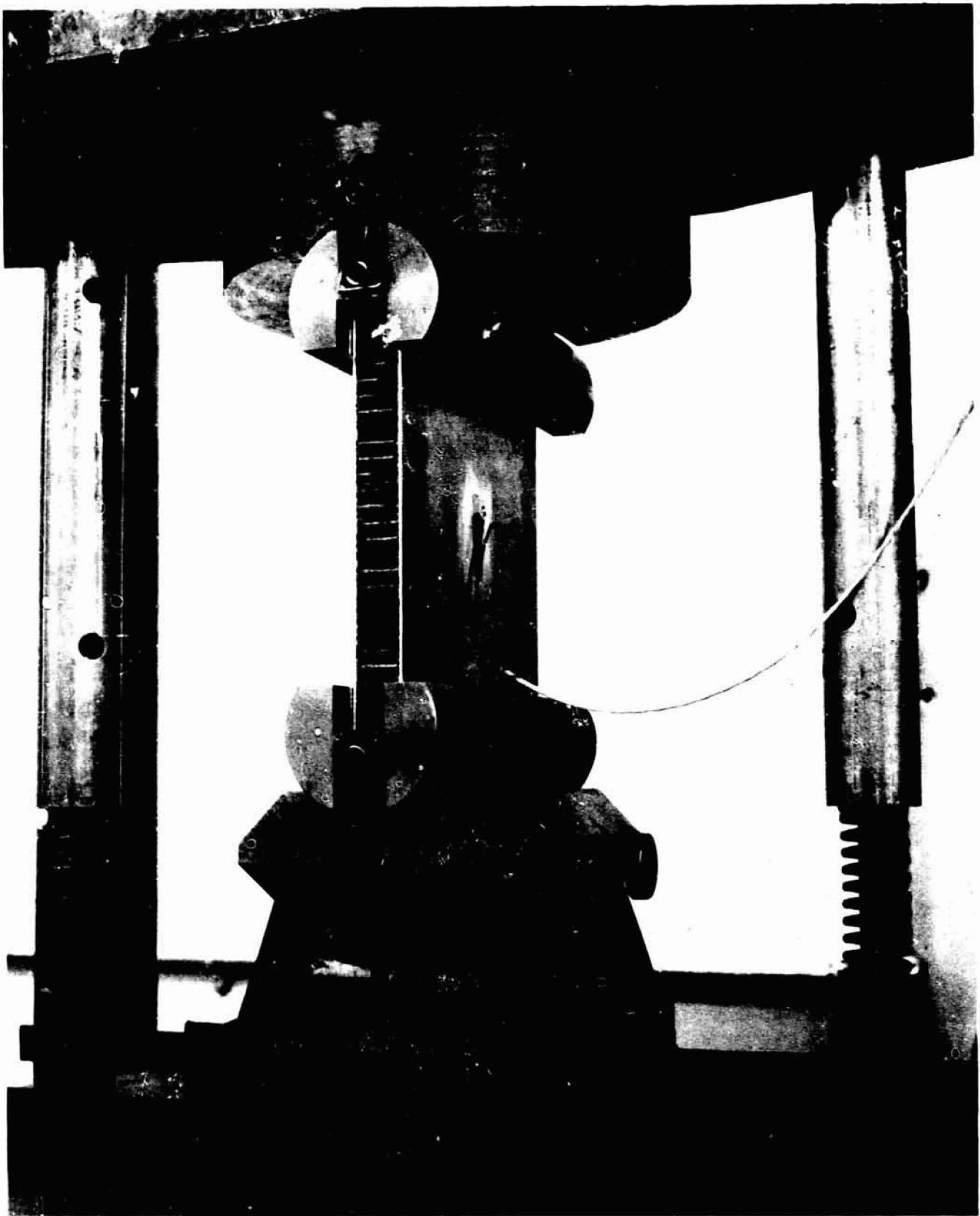


Fig. 21 Compression Test Fixture

Testing was performed at a constant platen speed of 0.003 to 0.005 in./minute.

### C. TEST RESULTS AND DISCUSSION

Test results for each alloy are summarized in Tables 15 thru 17, which give failing load, skin stress, and type of failure. Three types of failures or combinations were encountered. These are:

- 1) Interface buckling;
- 2) Column buckling;
- 3) Adhesive failure.

Figures 22 thru 26 show the various types of failures encountered. Figure 22 shows the interface buckling failure exhibited by 16 of the 18 thick-gage specimens tested. The remaining two samples (both 7106-T6 tested at -320°F) displayed adhesive failures (Fig. 23). However, stress at failure was not significantly lower than that observed for the third specimen that did not fail adhesively.

The thinner-gage specimens exhibited column buckling, interface buckling, or a combination of both, as shown in Fig. 24, 25, and 26, respectively. No adhesive failures were observed.

Comparison of experimental with predicted behavior gave excellent results. The predictions, although made for all three alloys, apply primarily to the 2014-T6 composition because compression tangent modulus data were obtained only for this alloy. Therefore, the predicted failure stresses would be expected to be high for the other two lower-strength alloys.

The prediction for the thick specimens was for interface buckling to occur at a skin stress of 65,000 psi. Experimental results confirmed predictions in that all specimens failed in the mode predicted.\* Failure stress for the 2014-T6, 68,700 psi (avg), was quite close to the prediction. The other two alloys failed at decreasing stresses in proportion to their strength.

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\*Adhesive failure must be excluded from consideration because it is not predictable.

Table 15 Compressive Strength of 2014-T6 Composite Panels

| Land Thickness<br>(in.)                                          | Failure Load<br>( $10^3$ lb) | Skin Stress<br>(ksi) | Type of<br>Failure* |
|------------------------------------------------------------------|------------------------------|----------------------|---------------------|
| 70°F                                                             |                              |                      |                     |
| 0.138                                                            | 72.3                         | 73.2                 | I                   |
|                                                                  | 69.3                         | 70.1                 | I                   |
|                                                                  | 62.0                         | <u>62.7</u>          | I                   |
|                                                                  |                              | 68.7 Avg             |                     |
| 0.080                                                            | 30.3                         | 54.3                 | I&C                 |
|                                                                  | 34.5                         | 57.3                 | I&C                 |
|                                                                  | 33.8                         | <u>59.7</u>          | I&C                 |
|                                                                  |                              | 57.1 Avg             |                     |
| -320°F                                                           |                              |                      |                     |
| 0.138                                                            | 80.0                         | 80.9                 | I                   |
|                                                                  | 82.5                         | 83.3                 | I                   |
|                                                                  | 80.8                         | <u>81.7</u>          | I                   |
|                                                                  |                              | 82.0 Avg             |                     |
| 0.080                                                            | 30.0                         | 52.2                 | C                   |
|                                                                  | 38.0                         | 66.0                 | I&C                 |
|                                                                  | 40.5                         | <u>70.4</u>          | I                   |
|                                                                  |                              | 62.9 Avg             |                     |
| *I = interface buckling failure;<br>C = column buckling failure. |                              |                      |                     |

Table 16 Compressive Strength of 2219-T87 Composite Panels

| Land Thickness<br>(in.)                                          | Failure Load<br>(10 <sup>3</sup> lb) | Skin Stress<br>(ksi) | Type of<br>Failure* |
|------------------------------------------------------------------|--------------------------------------|----------------------|---------------------|
| 70°F                                                             |                                      |                      |                     |
| 0.138                                                            | 65.0                                 | 65.7                 | I                   |
|                                                                  | 59.8                                 | 60.5                 | I                   |
|                                                                  | 56.5                                 | <u>57.1</u>          | I                   |
|                                                                  |                                      | 61.1 Avg             |                     |
| 0.080                                                            | 28.8                                 | 48.7                 | I                   |
|                                                                  | 33.0                                 | 55.7                 | I                   |
|                                                                  | 28.0                                 | <u>48.7</u>          | C                   |
|                                                                  |                                      | 51.0 Avg             |                     |
| -320°F                                                           |                                      |                      |                     |
| 0.138                                                            | 75.0                                 | 75.8                 | I                   |
|                                                                  | 78.3                                 | 79.1                 | I                   |
|                                                                  | 74.5                                 | <u>75.3</u>          | I                   |
|                                                                  |                                      | 76.7 Avg             |                     |
| 0.080                                                            | 39.0                                 | 67.8                 | C                   |
|                                                                  | 34.8                                 | 60.5                 | I                   |
|                                                                  | 39.8                                 | <u>67.2</u>          | I                   |
|                                                                  |                                      | 65.2 Avg             |                     |
| *I = interface buckling failure;<br>C = column buckling failure. |                                      |                      |                     |

Table 17 Compressive Strength of 7106-T6 Composite Panels

| Land Thickness<br>(in.)                                                                                          | Failure Load<br>(10 <sup>3</sup> lb) | Skin Stress<br>(ksi) | Type of<br>Failure* |
|------------------------------------------------------------------------------------------------------------------|--------------------------------------|----------------------|---------------------|
| 70°F                                                                                                             |                                      |                      |                     |
| 0.138                                                                                                            | 52.8                                 | 53.4                 | I                   |
|                                                                                                                  | 56.5                                 | 57.1                 | I                   |
|                                                                                                                  | 55.0                                 | <u>55.6</u>          | I                   |
|                                                                                                                  |                                      | 55.4 Avg             |                     |
| 0.080                                                                                                            | 28.8                                 | 50.0                 | C                   |
|                                                                                                                  | 27.8                                 | 48.3                 | C                   |
|                                                                                                                  | 26.3                                 | <u>50.4</u>          | C                   |
|                                                                                                                  |                                      | 49.6 Avg             |                     |
| -320°F                                                                                                           |                                      |                      |                     |
| 0.138                                                                                                            | 65.5                                 | 66.2                 | A                   |
|                                                                                                                  | 66.0                                 | 66.7                 | I                   |
|                                                                                                                  | 64.5                                 | <u>65.2</u>          | A                   |
|                                                                                                                  |                                      | 66.0 Avg             |                     |
| 0.080                                                                                                            | 23.0                                 | 40.0†                | C                   |
|                                                                                                                  | 34.8                                 | 60.5                 | I&C                 |
|                                                                                                                  | 37.0                                 | <u>68.5</u>          | I                   |
|                                                                                                                  |                                      | 64.5 Avg<br>of 2     |                     |
| *I = interface buckling failure;<br>C = column buckling failure;<br>A = adhesive failure.<br><br>†Excessive gap. |                                      |                      |                     |



Fig. 22 Interface Buckling Failure of 0.138-in.-Thick Specimen



Fig. 23 Adhesive Failure of 0.138-in.-Thick Specimen (7106-T6)



Fig. 24 Column Buckling Failure of 0.080-in.-Thick Specimen



Fig. 25 Interface Buckling Failure of 0.080-in.-Thick Specimen



Fig. 26 Combination Interface and Column Buckling Failure of  
0.080-in.-Thick Specimen

The 0.138-in.-thick specimens tested at  $-320^{\circ}\text{F}$  all showed increased strengthening and, except for the two 7106-T6 specimens that exhibited adhesive failure, the interface buckling mode was noted.

The close similarity of the predicted skin stress for interface (62,000 psi) vs column buckling (71,000 psi) precluded selection of a failure mode in the 0.080-in.-thick specimens. Test results showed that failure for the 2014-T6 occurred at 57,000 psi. The other alloys failed at slightly lower stresses. Our inability to predict failure mode was confirmed by evaluation of the types of failure: column, interface, and combination buckling.

Cryogenic testing of the 0.080-in.-thick specimens showed strengthening with reduction in temperature. One specimen (7106-T6) showed column failure at 40,000 psi. An examination of the dimension data showed that the gap (1.50 in.) exceeded the estimated critical column buckling length of 1.43 in. Other specimens were very close to the design value of 1.40 in.

#### IV. PHASE III - COMPARISON OF A COMBINATION WELDED-BONDED JOINT WITH THE OPTIMIZED WELDED JOINT

The purpose of the Phase III research was to determine the efficiency of a combination welded-bonded joint compared to the optimized welded joint developed and evaluated in Phases I and II.

The following factors guided design of this joint:

- 1) Weld joint design strength = 25,000 psi;
- 2) Weld joint to be butt type with skin thickness of 0.055-in. (no weld lands);
- 3) Two reinforcement materials would be used, 7075-T6 aluminum alloy and AISI 301 full hard stainless steel;
- 4) Core and adhesive to be the same as used in Phase II;
- 5) Joint is to occur in one face sheet only.

##### A. MECHANICAL PROPERTIES AND JOINT DESIGN

The principal requirement for preliminary design of a combination welded-bonded joint was to evaluate the effect of adhesive bond reinforcement on the weld strength.

Four weld panels of 0.063-in.-thick 2014-T6 were prepared using existing weld schedules. Three panels were shaved to provide a flat surface for adhesive bonding. Tensile tests performed on as-welded coupons gave the following results:

| Condition                | Ultimate Strength* (ksi) |
|--------------------------|--------------------------|
| As-Welded, Bead Intact   | 56.2                     |
| As-Welded, Bead Shaved   | 41.2                     |
| *Average of three tests. |                          |

Tensile specimens were prepared with an adhesively bonded (HT 424 adhesive) reinforcing strip across the weld. It was recommended by NASA that a maximum reinforcement thickness of 0.040-in.

be used to preclude machining the core to accommodate the reinforcement. Test results are summarized in Table 18.

Table 18 Effect of Adhesively Bonded Reinforcement\*  
on the Weld Strength of 0.063-in. 2014-T6  
Aluminum

| Reinforcement Material                            | Thickness (in.) | Tensile Strength (ksi) | Type of Failure |
|---------------------------------------------------|-----------------|------------------------|-----------------|
| 7075-T6                                           | 0.032           | 67.7                   | Peel            |
| 7075-T6                                           | 0.025           | 57.2                   | Peel            |
| 7075-T6                                           | 0.020           | 55.2                   | Tensile         |
| 301 FH                                            | 0.010           | 68.1                   | Peel            |
| 301 FH                                            | 0.006           | 57.5                   | Tensile         |
| *2-in. wide doubler; bonded with HT-424 adhesive. |                 |                        |                 |

The data show that as reinforcement thickness is decreased, tensile strength also decreases. A transition from adhesive peel failure to a tensile failure through the reinforcement occurs with reduction in thickness. The joint strength for the 0.032-in. 7075-T6 and 0.010-in. 301 FH stainless steel reinforced specimens is within a few thousand psi of the typical parent metal strength for 2014-T6. Optimization of the reinforcement by varying both doubler width and thickness was beyond the scope of this program. Therefore, the 0.032-in. 7075-T6 and 0.010 301 FH were selected for panel fabrication. In addition, it was planned to prepare a few panels reinforced with 0.025-in. 7075-T6 to determine whether stabilization of the joint by the underlying core material gives improved strength.

## B. FABRICATION

Faceplate material (2014-T6) was chemically milled from 0.063 to 0.055 in. Welding schedules were optimized for the 0.055-in. gage. Weld panels were carefully welded to provide minimum mismatch. After welding and radiographic inspection, panels were machined to remove the top surface of the weld bead.

The entire bonding operation was performed in a single cycle.

Figure 27 is a schematic diagram of the layup for bonding. Panels were bonded as 10x10-in. sections and then machined to final 9x9-in. size.

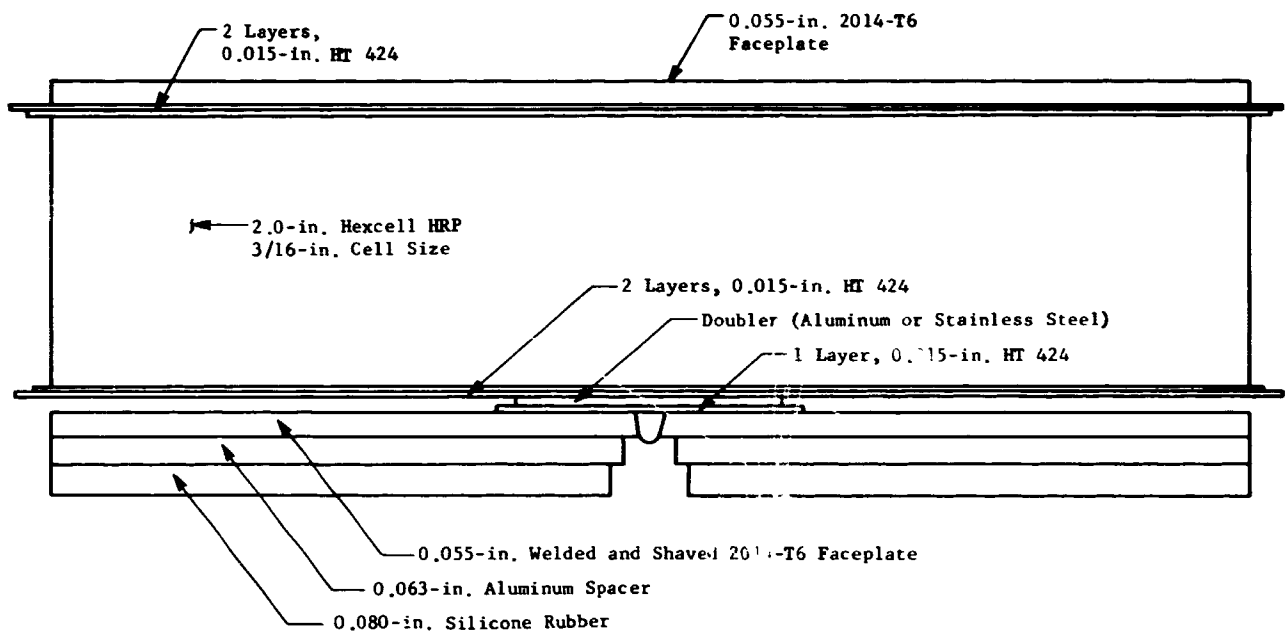


Fig. 27 Schematic of Phase III Panel Layup

### C. TEST RESULTS AND DISCUSSION

Testing of the Phase III panels was achieved using the same techniques previously described for the Phase II panels.

Test results are given in Table 19. Results showed that in all cases the skin stress exceeded that found in Phase II thick gage specimens. Very little difference in strength as a function of reinforcement material and thickness was observed. A substantial strengthening occurred at low temperatures.

Two types of failures were encountered. The bulk of the specimens failed due to bending at the edge of the reinforcing strip (Fig. 28). Several specimens failed adjacent to the slot in the test fixture (Fig. 29).

It is interesting to note that the Phase III specimens were not optimized, but designed on the basis of very limited mechanical property data. However, the test results showed strength superiority compared to the optimized Phase II specimens.

Table 19 Compressive Strength of Welded-Bonded 2014-T6 Composite Panels

| Reinforcement                                                                                                                                                                                                                                                     |                 | Load (10 <sup>3</sup> lb) | Skin Stress (ksi) | Type of Failure* |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|---------------------------|-------------------|------------------|
| Material                                                                                                                                                                                                                                                          | Thickness (in.) |                           |                   |                  |
| 70°F                                                                                                                                                                                                                                                              |                 |                           |                   |                  |
| 301 FH                                                                                                                                                                                                                                                            | 0.010           | 72.0                      | 72.8              | B                |
|                                                                                                                                                                                                                                                                   |                 | 73.3                      | 74.0              | A                |
|                                                                                                                                                                                                                                                                   |                 | 75.3                      | 76.0              | A                |
|                                                                                                                                                                                                                                                                   |                 | 64.3                      | 65.0              | B                |
|                                                                                                                                                                                                                                                                   |                 | 68.0                      | <u>68.8</u>       | B                |
|                                                                                                                                                                                                                                                                   |                 |                           | 71.3 Avg          |                  |
| 7075-T6                                                                                                                                                                                                                                                           | 0.025           | 71.5                      | 72.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | 73.8                      | 74.6              | A                |
|                                                                                                                                                                                                                                                                   |                 | 72.0                      | <u>72.8</u>       | A                |
|                                                                                                                                                                                                                                                                   |                 |                           | 73.2 Avg          |                  |
| 7075-T6                                                                                                                                                                                                                                                           | 0.032           | 65.3                      | 66.0              | A                |
|                                                                                                                                                                                                                                                                   |                 | 69.5                      | 70.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | 66.8                      | 67.5              | A                |
|                                                                                                                                                                                                                                                                   |                 | 72.5                      | 73.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | 72.5                      | <u>73.2</u>       | A                |
|                                                                                                                                                                                                                                                                   |                 |                           | 70.0 Avg          |                  |
| -320°F                                                                                                                                                                                                                                                            |                 |                           |                   |                  |
| 301 FH                                                                                                                                                                                                                                                            | 0.010           | 58.2                      | 58.8              | †                |
|                                                                                                                                                                                                                                                                   |                 | 88.0                      | 88.9              | B                |
|                                                                                                                                                                                                                                                                   |                 | 92.3                      | 93.2              | B                |
|                                                                                                                                                                                                                                                                   |                 | 91.3                      | 92.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | 93.0                      | <u>93.9</u>       | A                |
|                                                                                                                                                                                                                                                                   |                 |                           | 92.1 Avg of 4     |                  |
| 7075-T6                                                                                                                                                                                                                                                           | 0.025           | 92.9                      | 93.8              | A                |
|                                                                                                                                                                                                                                                                   |                 | 85.0                      | <u>85.8</u>       | A                |
|                                                                                                                                                                                                                                                                   |                 |                           | 89.8 Avg          |                  |
| 7075-T6                                                                                                                                                                                                                                                           | 0.032           | 86.8                      | 87.7              | A                |
|                                                                                                                                                                                                                                                                   |                 | 89.3                      | 90.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | 88.3                      | 89.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | 91.3                      | 92.2              | A                |
|                                                                                                                                                                                                                                                                   |                 | <u>91.3</u>               | <u>92.2</u>       | A                |
|                                                                                                                                                                                                                                                                   |                 | 89.4                      | 90.3 Avg          |                  |
| *A = Bending failure initiating at end of reinforcement;<br>B = Failure adjacent to slot in test fixture.<br>†Failure on unwelded side due to unsymmetrical construction of panel; unwelded face sheet was approximately 0.010-in. longer than welded face sheet. |                 |                           |                   |                  |



Fig. 28 Bending Failure in Welded-Bonded Specimen Originating at Edge of Reinforcement

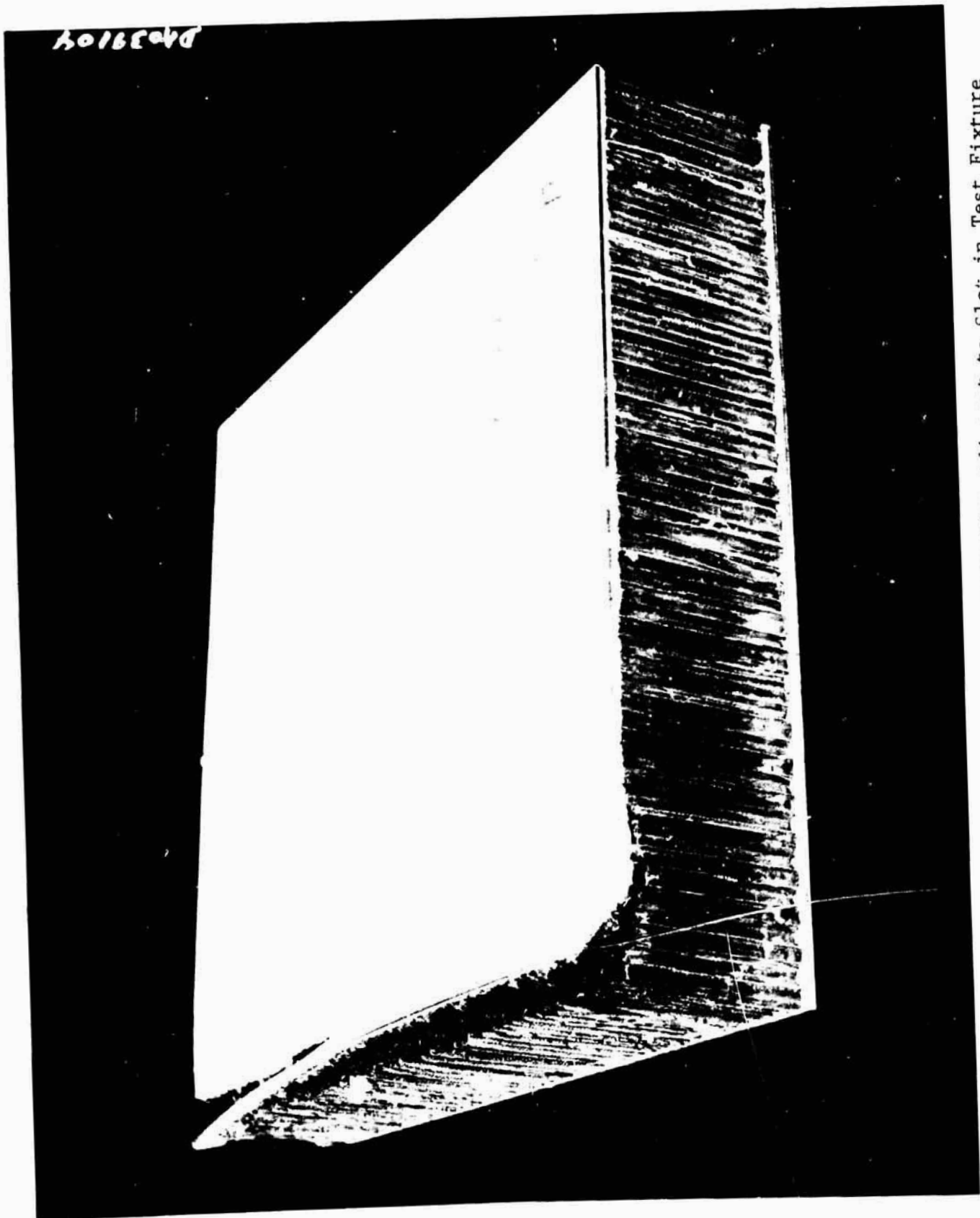


Fig. 29 Failure in Welded-Bonded Specimen Originating Adjacent to Slot in Test Fixture

## V. CONCLUSIONS AND RECOMMENDATIONS

The research performed in Phases I and II of this work confirm that the structural analysis approach can be used to design optimum welded composite joints. Experimental confirmation of predicted performance showed excellent agreement between theory and experiment. Actual property data obtained for two designs of three different alloys showed that the compressive strength of panels with a 0.138-in. land thickness closely checked predicted strength. The strength prediction for the thin panels was slightly higher than experimental data.

Results from the not fully optimized welded-bonded panels designed and tested in Phase III showed higher strength than the Phase II welded panels.

The most serious problem encountered in applying the prebonded common bulkhead appears to be fabrication. In our work, it was noted that careful precautions were required to obtain high-quality flat panels. The problems reported in making the large structure are even more severe. From our observations, fabrication of structural items using the Phase III design would be much simpler.

As a result of our research under NASA Contracts NAS8-5463 and NAS8-20125, several items requiring additional research have been identified. These are as follows:

- 1) Bond line thickness effects for various supported film adhesives;
- 2) Ribbon orientation effects;
- 3) Tensile behavior of composite sections;
- 4) Behavior under cyclic and sustained loading.

**Martin-CR-66-47**

**APPENDIX**

Table A-1 Tensile Properties of Parent Metal, 2014-T6 Aluminum Alloy

| Temperature<br>(°F) | Thickness<br>(in.) | Ultimate Tensile<br>Strength (ksi) | Yield Strength,<br>0.2% Offset (ksi) | Elongation<br>(% in 2 in.) |
|---------------------|--------------------|------------------------------------|--------------------------------------|----------------------------|
| 70                  | 0.080              | 68.6                               | 62.2                                 | 8.0                        |
|                     |                    | 70.3                               | 63.2                                 | 10.5                       |
|                     |                    | 70.4                               | 63.8                                 | 11.0                       |
|                     |                    | 69.7                               | 63.2                                 | 10.0                       |
|                     |                    | 69.8                               | 63.1                                 | 10.5                       |
|                     |                    | <u>69.8 Avg</u>                    | <u>63.1 Avg</u>                      | <u>10.0 Avg</u>            |
| -320                | 0.080              | 83.8                               | 75.9                                 | 11.0                       |
|                     |                    | 83.2                               | 76.2                                 | --                         |
|                     |                    | 84.0                               | 76.9                                 | --                         |
|                     |                    | 81.2                               | 73.5                                 | 12.0                       |
|                     |                    | 83.7                               | 77.2                                 | --                         |
|                     |                    | <u>83.2 Avg</u>                    | <u>75.9 Avg</u>                      | <u>11.5 Avg</u>            |
| 70                  | 0.138              | 72.1                               | 68.0                                 | 13.0                       |
|                     |                    | 72.1                               | 67.4                                 | 12.5                       |
|                     |                    | 71.8                               | 67.6                                 | 12.5                       |
|                     |                    | 72.1                               | 67.6                                 | 13.5                       |
|                     |                    | 72.2                               | 67.5                                 | 12.5                       |
|                     |                    | <u>72.1 Avg</u>                    | <u>67.6 Avg</u>                      | <u>12.8 Avg</u>            |
| -320                | 0.138              | 88.0                               | 83.5                                 | --                         |
|                     |                    | 88.6                               | 82.4                                 | 14.0                       |
|                     |                    | 88.4                               | 82.7                                 | 15.0                       |
|                     |                    | 85.2                               | 74.0                                 | --                         |
|                     |                    | 88.4                               | 82.7                                 | --                         |
|                     |                    | <u>87.7 Avg</u>                    | <u>81.1 Avg</u>                      | <u>14.5 Avg</u>            |

Table A-2 Tensile Properties of Parent Metal, 2219-T87 Aluminum Alloy

| Temperature<br>(°F) | Thickness<br>(in.) | Ultimate Tensile<br>Strength (ksi) | Yield Strength,<br>0.2% Offset (ksi) | Elongation<br>(% in 2 in.) |
|---------------------|--------------------|------------------------------------|--------------------------------------|----------------------------|
| 70                  | 0.080              | 70.0                               | --                                   | 9.0                        |
|                     |                    | 69.8                               | 57.8                                 | 9.5                        |
|                     |                    | 69.1                               | 56.9                                 | 7.5                        |
|                     |                    | 69.4                               | 57.1                                 | 9.5                        |
|                     |                    | 69.5                               | 57.3                                 | 9.5                        |
|                     |                    | <u>69.6 Avg</u>                    | <u>57.3 Avg</u>                      | <u>9.0 Avg</u>             |
| -320                | 0.080              | 87.8                               | 76.9                                 | 8.5                        |
|                     |                    | 88.0                               | 76.7                                 | 10.5                       |
|                     |                    | 88.6                               | 77.2                                 | 9.5                        |
|                     |                    | 88.0                               | 76.8                                 | 11.5                       |
|                     |                    | 88.0                               | 76.6                                 | 10.5                       |
|                     |                    | <u>88.1 Avg</u>                    | <u>76.8 Avg</u>                      | <u>10.1 Avg</u>            |
| 70                  | 0.138              | 68.9                               | 57.1                                 | 11.0                       |
|                     |                    | 68.9                               | 57.1                                 | 10.5                       |
|                     |                    | 68.2                               | 56.5                                 | 11.5                       |
|                     |                    | 68.4                               | 56.8                                 | 11.5                       |
|                     |                    | 68.2                               | 56.9                                 | 11.5                       |
|                     |                    | <u>68.2 Avg</u>                    | <u>56.9 Avg</u>                      | <u>11.2 Avg</u>            |
| -320                | 0.138              | 85.8                               | 74.4                                 | 13.0                       |
|                     |                    | 85.7                               | 74.4                                 | 14.0                       |
|                     |                    | 86.3                               | 78.5                                 | 13.0                       |
|                     |                    | 85.8                               | 74.7                                 | --                         |
|                     |                    | 86.3                               | 75.0                                 | 12.0                       |
|                     |                    | <u>86.0 Avg</u>                    | <u>75.4 Avg</u>                      | <u>13.0 Avg</u>            |

Table A-3 Tensile Properties of Parent Metal, 7106-T6 Aluminum Alloy

| Temperature<br>(°F) | Thickness<br>(in.) | Ultimate Tensile<br>Strength (ksi) | Yield Strength,<br>0.2% Offset (ksi) | Elongation<br>(% in 2 in.) |
|---------------------|--------------------|------------------------------------|--------------------------------------|----------------------------|
| 70                  | 0.080              | 55.4                               | 48.4                                 | 7.0                        |
|                     |                    | 58.5                               | 50.8                                 | 10.5                       |
|                     |                    | 57.9                               | 50.5                                 | 10.0                       |
|                     |                    | 56.4                               | 48.2                                 | 11.5                       |
|                     |                    | 54.2                               | 46.0                                 | 7.5                        |
|                     |                    | <u>56.5 Avg</u>                    | <u>48.8 Avg</u>                      | <u>9.3 Avg</u>             |
| -320                | 0.080              | 77.4                               | 65.0                                 | 16.0                       |
|                     |                    | 79.4                               | 67.2                                 | 12.5                       |
|                     |                    | 78.5                               | 66.8                                 | 10.0                       |
|                     |                    | 77.6                               | 65.3                                 | 14.0                       |
|                     |                    | 76.9                               | 65.9                                 | 9.5                        |
|                     |                    | <u>78.0 Avg</u>                    | <u>66.0 Avg</u>                      | <u>12.4 Avg</u>            |
| 70                  | 0.138              | 62.8                               | 55.7                                 | 11.5                       |
|                     |                    | 62.5                               | 55.4                                 | 11.0                       |
|                     |                    | 62.3                               | 55.3                                 | 9.5                        |
|                     |                    | 62.4                               | 55.5                                 | 11.0                       |
|                     |                    | 63.7                               | 56.5                                 | 11.0                       |
|                     |                    | <u>62.7 Avg</u>                    | <u>55.7 Avg</u>                      | <u>10.8 Avg</u>            |
| -320                | 0.138              | 85.5                               | 73.7                                 | 16.0                       |
|                     |                    | 85.9                               | 74.0                                 | 16.5                       |
|                     |                    | 88.1                               | 82.8                                 | --                         |
|                     |                    | 86.1                               | 74.2                                 | 17.5                       |
|                     |                    | 85.1                               | 73.5                                 | 13.5                       |
|                     |                    | <u>86.1 Avg</u>                    | <u>75.6 Avg</u>                      | <u>15.9 Avg</u>            |

Table A-4 Tensile Properties of Welded 2014-T6 Aluminum Alloy\*

| Temperature<br>(°F)                                       | Thickness<br>(in.) | Ultimate Tensile<br>Strength (ksi) | Yield Strength<br>0.2% Offset (ksi) |
|-----------------------------------------------------------|--------------------|------------------------------------|-------------------------------------|
| 70                                                        | 0.080              | 52.2                               | 35.2                                |
|                                                           |                    | 52.7                               | 34.0                                |
|                                                           |                    | 53.8                               | 35.5                                |
|                                                           |                    | 53.8                               | 34.5                                |
|                                                           |                    | 51.1                               | 35.1                                |
|                                                           |                    | 52.7 Avg                           | 34.9 Avg                            |
| -320                                                      | 0.080              | 59.8                               | 57.6                                |
|                                                           |                    | 61.3                               | 56.9                                |
|                                                           |                    | 58.9                               | 57.2                                |
|                                                           |                    | 59.3                               | 57.5                                |
|                                                           |                    | 61.0                               | 57.3                                |
|                                                           |                    | 60.1 Avg                           | 57.3 Avg                            |
| 70                                                        | 0.138              | 47.0                               | 34.5                                |
|                                                           |                    | 49.8                               | 34.3                                |
|                                                           |                    | 48.7                               | 34.2                                |
|                                                           |                    | 48.5 Avg                           | 34.3 Avg                            |
| -320                                                      | 0.138              | 55.7                               | --                                  |
|                                                           |                    | 57.3                               | 57.1                                |
|                                                           |                    | 55.8                               | --                                  |
|                                                           |                    | 59.3                               | 56.0                                |
|                                                           |                    | 58.8                               | 57.9                                |
|                                                           |                    | 57.4 Avg                           | 57.0 Avg                            |
| *DC automatic TIG welded, straight polarity; 4043 filler. |                    |                                    |                                     |

Table A-5 Tensile Properties of Welded 2219-T87 Aluminum Alloy\*

| Temperature<br>(°F) | Thickness<br>(in.) | Ultimate Tensile<br>Strength (ksi) | Yield Strength, 0.2%<br>Offset (ksi) |
|---------------------|--------------------|------------------------------------|--------------------------------------|
| 70                  | 0.080              | 50.2                               | 30.9                                 |
|                     |                    | 47.9                               | 29.9                                 |
|                     |                    | 48.7                               | 29.8                                 |
|                     |                    | 47.3                               | 28.6                                 |
|                     |                    | 43.8                               | 29.3                                 |
|                     |                    | 48.4                               | 29.2                                 |
|                     |                    | 47.7 Avg                           | 29.6 Avg                             |
| -320                | 0.080              | 56.4                               | 53.4                                 |
|                     |                    | 58.2                               | 54.2                                 |
|                     |                    | 55.6                               | 52.8                                 |
|                     |                    | 58.2                               | 55.1                                 |
|                     |                    | 52.3                               | --                                   |
|                     |                    | 56.1 Avg                           | 53.9 Avg                             |
| 70                  | 0.138              | 47.0                               | 26.9                                 |
|                     |                    | 45.1                               | 26.4                                 |
|                     |                    | 45.0                               | 27.0                                 |
|                     |                    | 43.9                               | 25.8                                 |
|                     |                    | 45.3 Avg                           | 26.7 Avg                             |
|                     |                    |                                    |                                      |
| -320                | 0.138              | 59.3                               | 49.6                                 |
|                     |                    | 60.1                               | 49.1                                 |
|                     |                    | 59.4                               | 48.6                                 |
|                     |                    | 59.0                               | 48.6                                 |
|                     |                    | 60.2                               | 49.0                                 |
|                     |                    | 59.6 Avg                           | 49.0 Avg                             |

\*DC automatic TIG welded; 2319 filler.

Table A-6 Tensile Properties of Welded 7106-T6 Aluminum Alloy\*

| Temperature<br>(°F) | Thickness<br>(in.) | Ultimate Tensile<br>Strength (ksi) | Yield Strength, 0.2%<br>Offset (ksi) |
|---------------------|--------------------|------------------------------------|--------------------------------------|
| 70                  | 0.080              | 50.5                               | 38.0                                 |
|                     |                    | 52.4                               | 38.8                                 |
|                     |                    | 51.2                               | 38.0                                 |
|                     |                    | 51.1                               | 38.0                                 |
|                     |                    | 50.9                               | 38.2                                 |
|                     |                    | <u>50.3</u>                        | <u>37.5</u>                          |
|                     |                    | 51.1 Avg                           | 38.1 Avg                             |
| -320                | 0.080              | 60.2                               | 57.6                                 |
|                     |                    | 61.2                               | 57.7                                 |
|                     |                    | 64.4                               | 58.4                                 |
|                     |                    | 65.1                               | 55.7                                 |
|                     |                    | 59.3                               | 57.9                                 |
|                     |                    | <u>58.6</u>                        | <u>56.7</u>                          |
|                     |                    | 61.5 Avg                           | 57.3 Avg                             |
| 70                  | 0.138              | 55.3                               | 39.1                                 |
|                     |                    | 54.0                               | 37.5                                 |
|                     |                    | 55.2                               | 38.6                                 |
|                     |                    | 54.3                               | 37.7                                 |
|                     |                    | <u>53.8</u>                        | <u>37.5</u>                          |
|                     |                    | 54.5 Avg                           | 38.1 Avg                             |
| -320                | 0.138              | 63.2                               | 58.6                                 |
|                     |                    | 58.8                               | 58.2                                 |
|                     |                    | 60.1                               | 57.9                                 |
|                     |                    | 61.8                               | 58.2                                 |
|                     |                    | <u>63.6</u>                        | <u>58.9</u>                          |
|                     |                    | 61.5 Avg                           | 58.3 Avg                             |

\*DC automatic TIG welded; 5180 filler; naturally aged 30 days.