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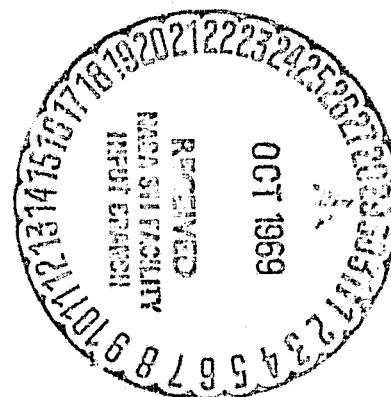
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# RESEARCH STUDY TO DEVELOP MEANS OF MANUFACTURING BONDING CLIPS, BRACKETS AND JOINTS, AND PRESSURE SEALING JOINTS WITH UNIFORM STRESS DISTRIBUTION

by

Harold A. Evensen



FINAL REPORT

Contract NAS8-21380

Covering Period 29 February 1968 - 1 July 1969

25 September 1969

WHITTAKER CORPORATION  
Research & Development/San Diego  
Advanced Composites Engineering  
3540 Aero Court  
San Diego, California 92123

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
George C. Marshall Space Flight Center  
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#### FOREWORD

This report was prepared by Whittaker Corporation, Research and Development Division (WRD), San Diego, California, under Contract NAS 8-21380, entitled "Research Study to Develop Means of Manufacturing Bonding Clips, Brackets and Joints, and Pressure Sealing Joints with Uniform Stress Distribution." This program was administered by the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama. Mr. William J. Miller was the Contracting Officer and Mr. H. M. Walker was the Project Officer. Mr. Walker maintained close coordination with WRD during the course of this program, and provided valuable guidance during its conduct.

This report was released by the authors for publication on 17 September 1969.

Work was conducted at WRD under the general direction of Mr. Boris Levenetz, Manager, Advanced Composites Engineering, and Dr. Kenneth R. Berg, Chief, Structural Design and Analysis Group. Dr. Harold A. Evensen served as Principal Investigator, taking over these duties from Mr. Stephen Feher in December, 1968.

## ABSTRACT

This study program is part of an effort by NASA to develop improved joint manufacturing and design techniques. Specifically, means of attaining uniform adhesive shear stress distributions in double-lap bonded joints were investigated, and a joint design criterion was developed. For straight-lap, stepped-lap and scarf joints, this criterion was shown to be independent of adhesive properties and adherend shear stiffness.

It was shown that reduction of adhesive peak shear stresses can be accomplished if several general design rules are followed:

- (a) The local strains in the adherends must match as closely as possible at each point on the bondline.
- (b) The adherend thickness shear stiffness should be reduced as much as the overall application constraints will permit.
- (c) The adhesive shear strength should be high; its ductility should be as high as the overall joint deformation constraints will permit.

Full exploitation of these reduced peak shear stresses further requires that the shear strengths of the adherends and the adherend-to-adhesive interfaces exceed that of the adhesive.

The unique tailoring capabilities of fiber composite materials were shown to be applicable in realizing the optimum designs suggested by the design criterion. With judicious choice of layup patterns, joint strength was shown to be improved without affecting the geometry of the stepped-lap or straight-lap configurations. Procedures for tailoring composite adherend properties are discussed in the report.

In support of the study, an improved analysis of straight-lap joints was conducted, accounting for adherend shear properties and adhesive nonlinearities. These factors were shown to be important to the

performance of adhesive joints in fiber composite materials. A finite-element program was employed to study the stepped-lap joint and to verify the simplified design criterion developed in this investigation.

Joint designs developed under this study were fabricated and tested. The observed relative strengths were found to be in good agreement with the predicted relative strengths, and the effects of several fabrication parameters were noted. A photoelastic study was conducted. It was shown that adherend shear deformations preclude accurate determination of adhesive stresses, but the technique is still applicable when visual monitoring of salient features of the stress field is required.

This report includes recommendations for improved joint design procedures. A suggested study of the effects of joint fabrication parameters is outlined; and a procedure for adhesive characterization, based on the analytic results, is proposed. Computer programs for analysis of lap joints with nonlinear adhesive and finite adherend shear stiffness are included in the appendices.

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## NOMENCLATURE

### Adherend and Adhesive Parameters

|                       |                                                    |
|-----------------------|----------------------------------------------------|
| $G, \gamma, \tau$     | Shear Modulus, strain, stress                      |
| $E, \epsilon, \sigma$ | Tensile Modulus, strain, stress                    |
| $\Omega$              | Adhesive nonlinearity parameter                    |
| $\nu$                 | Poisson's ratio                                    |
| $u$                   | Local displacement parallel to load axis           |
| $v$                   | Local displacement normal to load axis             |
| $t$                   | Thickness                                          |
| $b$                   | Joint width                                        |
| $L$                   | Joint lap length                                   |
| $2P$                  | Total applied load                                 |
| $P_1(x), P_2(x)$      | Total cross sectional reaction forces in adherends |
| $\theta$              | Bondline inclination with respect to load axis     |

### Coordinates and Subscripts

|         |                                                             |
|---------|-------------------------------------------------------------|
| $x$     | Parallel to load axis                                       |
| $y$     | Normal to load axis                                         |
| $s$     | Parallel to bondline                                        |
| $n$     | Normal to bondline                                          |
| $\xi$   | Vertical position in doubler with respect to bonding face   |
| $\beta$ | Vertical position in mainplate with respect to bonding face |
| $1$     | Pertaining to the mainplate                                 |
| $2$     | Pertaining to the doubler                                   |
| $a$     | Pertaining to the adhesive                                  |
| $o$     | Pertaining to the bonding face                              |

## SECTION 1

### INTRODUCTION

The joining technology is currently a major obstacle to full utilization of high strength aerospace materials. The reliability of mechanical joints must be obtained at the expense of material load bearing capability, due to the concentrations of stress in the joint. Adhesive bonding, on the other hand, has the advantage that any joint strength can theoretically be developed (being a function of bonded area rather than material notch sensitivity). However, conventional adhesive joining configurations do not take full advantage of adhesive or adherend capabilities. The lap-joint configurations usually encountered in adhesive bonding have their origins in the riveted and welded-joint technology, and are not ideally suited to match the properties of adhesives. Conventional simple-lap joints, for example, often develop less than 20% of the adhesive strength capability because adherend strain mismatches result in severe adhesive stress concentrations. Simple expedients, such as adhesive grading and tapering of the doublers, have significantly improved adhesive joint behavior, but investigations of these latter approaches have been of an empirical nature and few guide lines for general design of adhesive lap joints have been established.

Effective application of modern adhesives requires development of advanced adhesive joining concepts, designed to utilize both adhesive and adherend properties to fullest advantage. A fundamental understanding of the mechanical behavior in adhesive joints is necessary if these concepts are to be accepted and incorporated into the technology.

The objective of the research program presented in this report is the development of manufacturing methods and procedures, as well as design allowables required to obtain optimum utilization of the unique characteristics of adhesive or bonding agents. Specifically, methods were investigated during the program for attaining uniform shear stress distribution throughout the bonding agent in the bonded or adhesive joint. A combined analytical and experimental study has been performed to accomplish this objective.

This study is a sequel to contract NAS 8-20376, "Research Study of Common Bulkhead and Manufacturing Technology Improvement Program for Saturn Stages", 10 July 1967. In the earlier study, it was suggested that optimum joint designs could be tailored to the environmental, geometric, and material constraints of a particular joining requirement. The present study, initiated 29 March 1968, further investigates this possibility. Since the most obvious optimization criterion is the development of uniform adhesive shear stress, this objective has been pursued with particular intensity during the program. A revised scope of work was approved 21 April 1969. This revision was granted in light of findings of the preliminary study, in which it was found that better adherend strain matching could be accomplished if the adherends were properly varied, not only in cross-sectional area, but in cross-sectional tensile modulus. This new aspect of joint design could not be fully investigated using homogeneous adherends; and it was natural, in view of WRD background, to consider the unique tailoring capabilities of composite materials as a means of accomplishing the required modulus changes. An extended scope of work was approved 10 June 1969 that included the effects of adherend shear stiffness and adhesive nonlinearities on the adhesive shear stress. Since composite materials are particularly amenable to simultaneous tailoring of tensile and shear stiffness, the study ultimately focused on the application of these materials in high-strength joints. NASA interest in joining of boron-epoxy and titanium provided an additional stimulus.

This report discusses the program in two parts: A preliminary study that covered effort prior to the revision, and a composite design study that covered the revised program effort. A simplified optimization procedure was developed and has been demonstrated to lead to stronger bonded joints. Given the particular geometric and property constraints, an optimum doubler geometry and property makeup can be developed. This optimum configuration then serves as a guide for design of the practical configuration. Designs developed from this criterion have been analyzed with the aid of a finite element computer program and have been fabricated and tested in tensile shear. Using this criterion, joints can be designed that develop lower adhesive shear stresses for the same applied load.

The photoelastic technique, developed and applied in the preliminary study, has been shown to be most effective in joint configuration having homogeneous adherends with no abrupt changes in cross-section. When composite materials or materials with low shear moduli are used, the photoelastic method gives apparent peak shear stresses that are substantially lower than the actual values. With the aid of the analysis developed herein, this technique can still be used in the practical monitoring of adhesive stresses in joints of simple geometry.

A preliminary survey of bonded joint design was performed and is included in Appendix A for reference.

## SECTION 2

### PRELIMINARY STUDY

In this portion of the program, eighteen double-lap joint configurations were designed, fabricated and tested. The results were correlated with a numerical analysis that was performed with the aid of a finite element computer program. A concurrent photoelastic study was performed, and the apparent adhesive shear distributions obtained from this study were compared with those predicted by the finite-element program. A computerized parameter study was performed that involved eleven double-lap joint configurations; and a simplified joint optimization criterion was developed from basic strength-of-materials considerations.

Information obtained from this preliminary study led to the investigation of the applications of composite material to joint design. This will be discussed in a later section.

#### Preliminary Straight Lap Specimens

Preliminary straight-lap joints were designed, fabricated and evaluated for two adhesive thicknesses and two adhesive systems. The parameters considered were:

##### 1. Adhesives

- (a) Narmco Type 7343
- (b) Narmco Metlbond 328

## 2. Bondline Thickness

- (a) .004 inch
- (b) .008 inch

Table 2-I and Figure 2-1 summarize the joint configurations and test results. In view of the relatively small scatter and high failure stresses obtained with Metlbond 328, the decision was made to use this adhesive in all further studies.

### Selection of a Brittle Adhesive

Metlbond 328 is particularly well-suited to this study, since it is a brittle adhesive with a relatively high shear modulus.

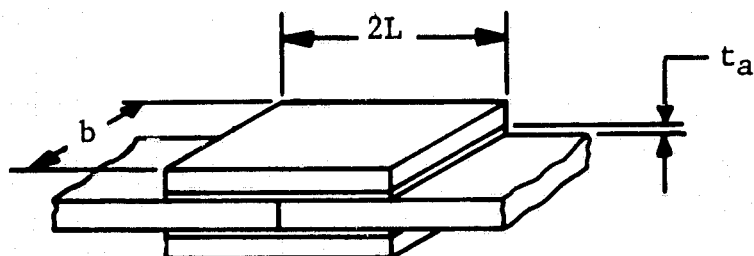
When tensile-shear tests are used to evaluate the magnitude of adhesive shear stress concentrations, it is desirable that the joints fail immediately when the maximum shear stress exceeds the adhesive ultimate shear stress. A joint incorporating a ductile adhesive would not fail when this occurs because peak stresses would tend to be relieved by the flow of the adhesive. A brittle adhesive, on the other hand, would fracture under the same load condition with very little flow. Typical shear stress distributions in a brittle adhesive (a) and a ductile adhesive (b) are shown in Figure 2-2. Because of the stress relieving action, a ductile adhesive having relatively low yield strength may fail at a significantly higher total applied load than a joint of the same dimensions, but incorporating a brittle, high-strength adhesive. However, if the shear stress concentrations could be reduced through proper joint design, the high-strength adhesive would obviously be the more desirable of the two.

The properties of Metlbond 328 were evaluated by Berg<sup>[1]</sup> and are summarized in Table 2-II and Figure 2-3. This film adhesive is supplied on a glass-cloth carrier, and achieves a .005-inch bondline thickness with a cure pressure of 15-25 psi at 375°F.

TABLE 2 - I

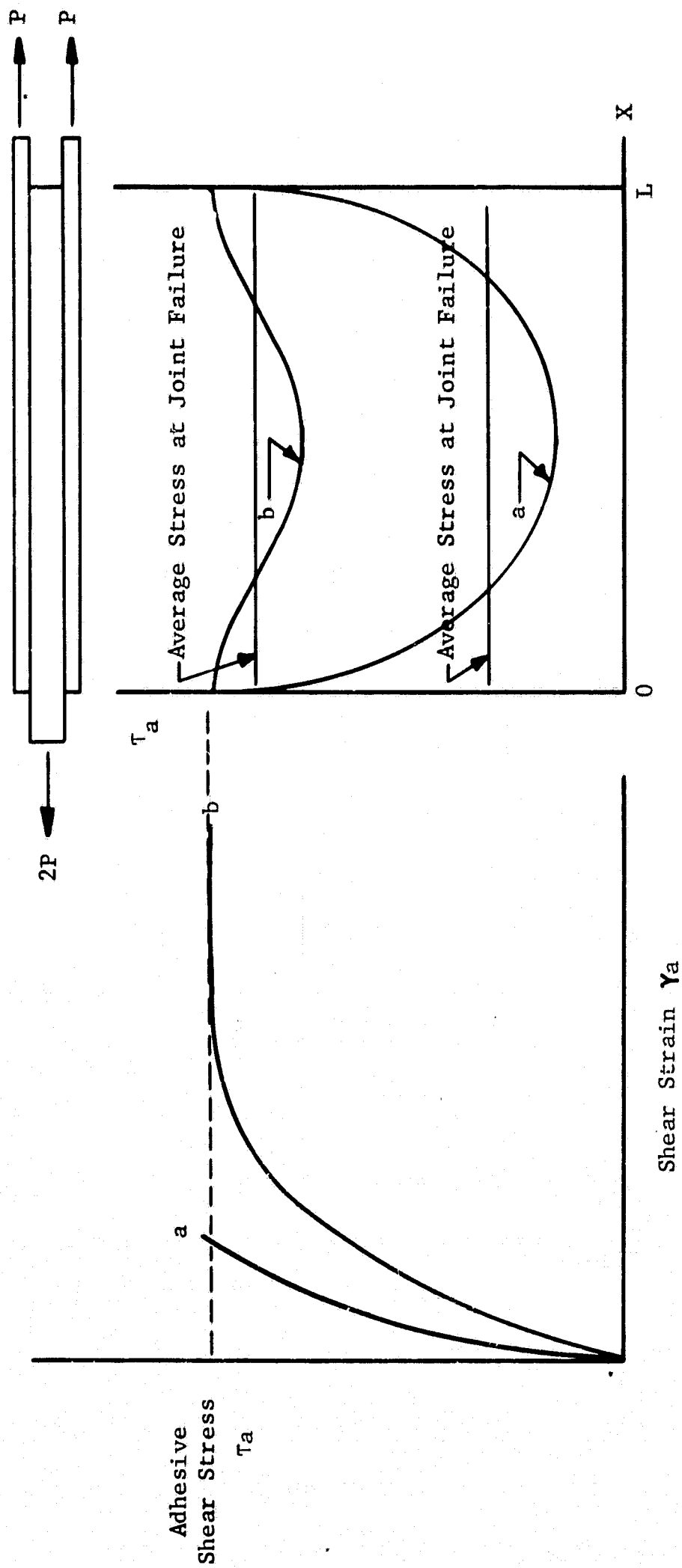
SUMMARY OF TENSILE-SHEAR FAILURE TESTS FOR  
STRAIGHT-LAP ALUMINUM JOINTS

| SPECIMEN | ADHESIVE        | BONDLINE         |                |                        | FAILURE<br>LOAD LB | AVERAGE FAILURE<br>SHEAR STRESS psi | COMMENTS            |
|----------|-----------------|------------------|----------------|------------------------|--------------------|-------------------------------------|---------------------|
|          |                 | LENGTH<br>2L IN. | WIDTH<br>b IN. | THICKNESS<br>$t_a$ IN. |                    |                                     |                     |
| 328-1    | Metlbond<br>328 | 2                | 1              | .004                   | 7800               | 3925                                | Mounting<br>Failure |
| 328-2    | ↕               | 2                | 1              | .004                   | 7900               | ±0.6%                               |                     |
| 328-3    | ↕               | 2                | 2              | .004                   | —                  |                                     |                     |
| 328-4    | Metlbond<br>328 | 2                | 1              | .008                   | 7900               | 3970                                |                     |
| 328-5    | ↕               | 2                | 1              | .008                   | 8000               | ±0.6%                               |                     |
| 328-6    | ↕               | 2                | 1              | .008                   | 7900               |                                     |                     |
| L100-1   | Narmco<br>7343  | 2                | 1              | .004                   | 300                | 174                                 |                     |
| L100-2   | ↕               | 2                | 1              | .004                   | 305                | ±18.7%                              |                     |
| L100-3   | ↕               | 2                | 1              | .004                   | 440                |                                     |                     |
| L100-4   | Narmco<br>7343  | 2                | 1              | .008                   | 640                | 313                                 |                     |
| L100-5   | ↕               | 2                | 1              | .008                   | 590                | ±4.2%                               |                     |
| L100-6   | ↕               | 2                | 1              | .008                   | 650                |                                     |                     |



Doubler thickness .0625"  
Mainplate thickness .125"  
Material 2024-T3

Figure 2-1. Straight-Lap Joint Configuration



(a) Stress Strain Curve (b) Bondline Shear Stress Distribution

Figure 2-2. Effects of Adhesive Stress-Strain Properties on Adhesive Stress-Distributions in a Bonded Joint.

TABLE 2-II

SUMMARY OF PROPERTIES OF METLBOND 328 ADHESIVE<sup>[1]</sup>

| TENSION                  |                              | SHEAR                    |                              |
|--------------------------|------------------------------|--------------------------|------------------------------|
| ULTIMATE STRENGTH<br>ksi | MODULUS $\times 10^8$<br>psi | ULTIMATE STRENGTH<br>ksi | MODULUS $\times 10^8$<br>psi |
| 6.7                      | .81                          | 7.46                     | .176                         |

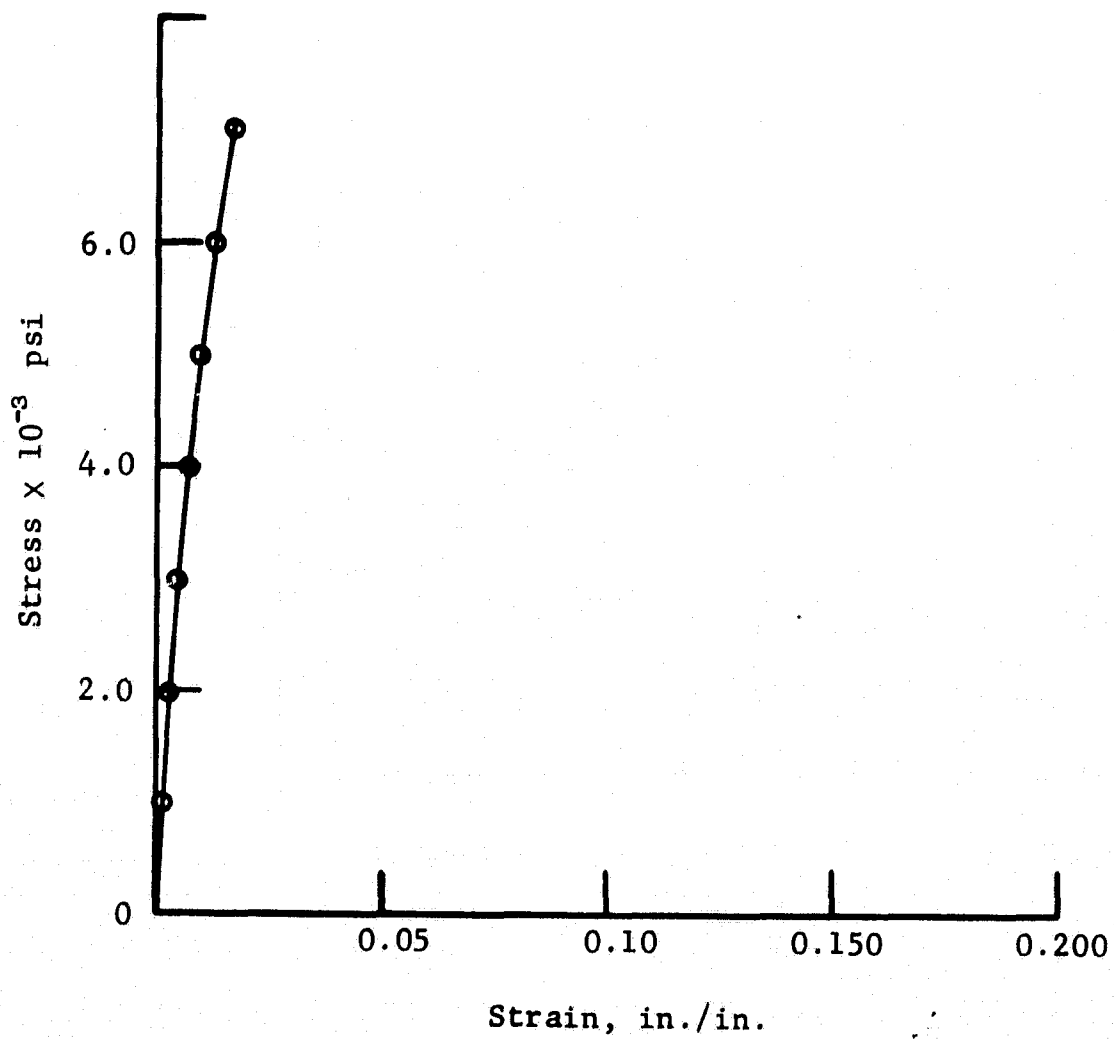


Figure 2-3. Bulk-Tensile Stress-Strain Curve for Metlbond 328 Adhesive<sup>[1]</sup>.

### Preliminary Step-Tapered Specimen

Step-tapered aluminum joints were designed, fabricated, and evaluated, using Metlbond 328 adhesive and the two bondline thicknesses: .004-inch and .008-inch. Table 2-III and Figure 2-4 summarize the joint configurations and test results. One specimen from each group was prepared for later photoelastic determination of the adhesive stress distribution. The destructive test results indicated that step-tapering led to only small (five percent) increases in joint strength, although reduction of the doubler leading-edge thickness is a technique often used to improve the joint strength. It is evident from this result that the variation of doubler thickness must proceed according to a definite rule if the joint strength is to be improved. The criterion by which this and other variations are accomplished is an important goal of this study.

### Finite-Element Computer Study

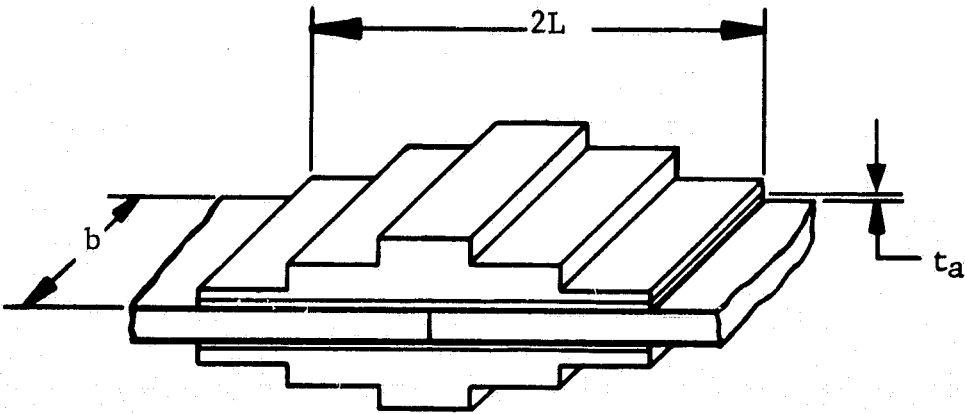
In order to evaluate the effect of specimen geometry, adhesive properties, adherend properties, and boundary conditions on the joint strength, a finite element computer program was adapted to the analysis of bonded joints. In this preliminary study, a so-called "three-point" element was used as the basic building block. This finite-element approach would permit consideration of advanced composite materials in complex joint configurations, and would provide a verification of the design criteria developed in this research program. In application, the joint is simulated by a structure consisting of small triangular elements joined at their vertices. The joint stress distributions are then obtained, to a very good approximation, by assuming uniform stresses in the triangular elements and satisfying the required force and displacement boundary conditions.

A computerized parameter study was performed on the eleven joint configurations listed in Table 2-IV. The adhesive shear stress distributions are summarized in Figures 2-5 through 2-14, and a Case 1 comparison between

Table 2-III

SUMMARY OF TENSILE SHEAR FAILURE TESTS FOR  
STEP-TAPERED ALUMINUM JOINTS

| SPECIMEN | ADHESIVE        | BONDLINE         |                |                        | FAILURE<br>LOAD LB | AVERAGE FAILURE<br>SHEAR STRESS psi | COMMENTS          |
|----------|-----------------|------------------|----------------|------------------------|--------------------|-------------------------------------|-------------------|
|          |                 | LENGTH<br>2L IN. | WIDTH<br>b IN. | THICKNESS<br>$t_a$ IN. |                    |                                     |                   |
| 328-7    | Metlbond<br>328 | 2                | 1              | .004                   | —                  | 3700<br>$\pm 0.7\%$                 | Photo-<br>elastic |
| 328-8    | ↓               | 2                | 1              | .004                   | 7350               |                                     |                   |
| 328-9    | ↓               | 2                | 1              | .004                   | 7450               |                                     |                   |
| 328-10   | Metlbond<br>328 | 2                | 1              | .008                   | 7250               | 3612<br>$\pm 0.3\%$                 | Photo-<br>elastic |
| 328-11   | ↓               | 2                | 1              | .008                   | 7200               |                                     |                   |
| 328-12   | ↓               | 2                | 1              | .008                   | —                  |                                     |                   |



Three Equal Steps  
Doubler Thickness: .0625"  
Mainplate Thickness: .125"  
Material 2024-T5

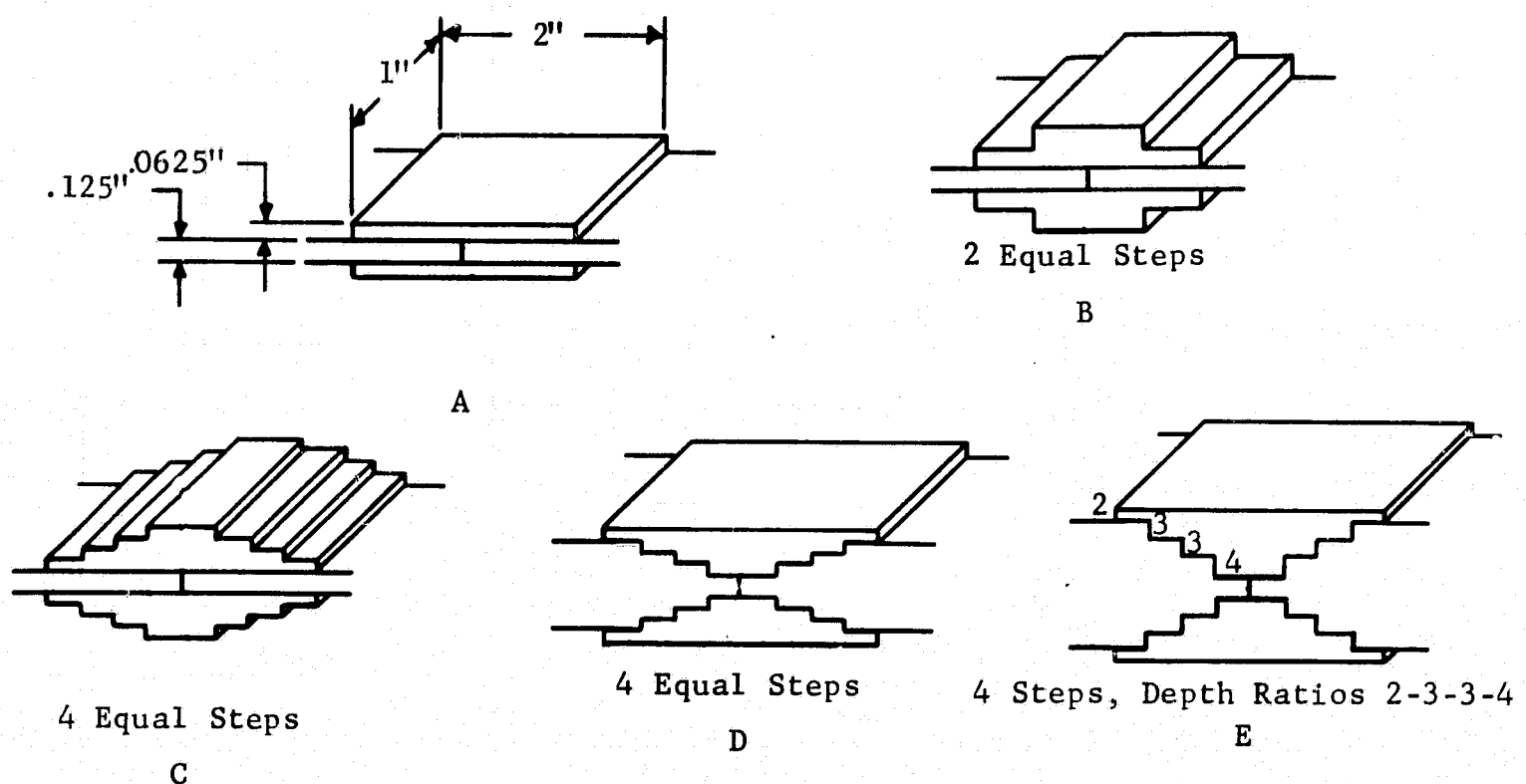
Figure 2 -4. Step-Tapered Aluminum Joint Configuration.

TABLE 2-IV

## SUMMARY OF FINITE-ELEMENT JOINT STUDY

| CASE | MAINPLATES  | DOUBLERS | TYPE                  | MAXIMUM STRESS<br>CONCENTRATION $\tau_{\max}/\tau_{\text{av}}$ |
|------|-------------|----------|-----------------------|----------------------------------------------------------------|
| 1    | Aluminum    | Aluminum | A                     | 5.00                                                           |
| 2    | Aluminum    | Aluminum | A<br>(.008" Bondline) | 3.70                                                           |
| 3    | Aluminum    | Aluminum | B                     | 5.00                                                           |
| 4    | Aluminum    | Aluminum | C                     | 5.00                                                           |
| 5    | Aluminum    | Aluminum | D                     | 3.75                                                           |
| 6    | Boron-Epoxy | Aluminum | D                     | 3.65                                                           |
| 7    | Boron-Epoxy | Titanium | D                     | 2.85                                                           |
| 8    | Boron-Epoxy | Steel    | D                     | 3.65                                                           |
| 9    | Boron-Epoxy | Aluminum | E                     | 2.90                                                           |
| 10   | Boron-Epoxy | Titanium | E                     | 2.35                                                           |
| 11   | Boron-Epoxy | Steel    | E                     | 3.35                                                           |

Adhesive: Metlbond 328, thickness .004"



the computer analysis and the classical analysis is presented in Figure 2-15. The computer analysis is believed to be more nearly correct in this case, since the classical analysis does not account for the stress-relieving effect of adherend shear deformations.

It is evident, from review of Table 2-IV and Figures 2-5 through 2-15, that judicious choice of joint geometry, materials and bondline thickness can lead to significant reductions in maximum bondline shear stresses. While the stepped-doubler concepts (Cases 3 and 4) produce little improvement over the straight-lap joint of Case 1, the stepped-bondline approaches have definite merit. As Cases 5 through 11 demonstrate, adhesive shear stresses are further reduced by proper alteration of step depths and material properties. The aluminum-aluminum combination of Case 5 (Figure 2-8), for example, will not develop the adhesive strength as well as the titanium boron/epoxy combination of Case 7 (Figure 2-10). Case 7 in turn can be improved by changes of step depth, as typified by Case 10 (Figure 2-13).

It should be emphasized that the finite element program was not considered the goal of this preliminary study. The preliminary study, with the aid of this program, has demonstrated the potential benefits to be gained from a more practical design criterion that would specify an optimum material and geometry combination, given the design constraints. Once this criterion has been developed, the resulting designs can be further evaluated, using this program, if desired.

#### Photoelastic Determination of Adhesive Shear Stresses

Two joints with step-tapered doublers were evaluated nondestructively, using photoelastic techniques described in [2]. In agreement with the finite-element results of Table 2-IV, the photoelastic evaluation reveals no discernible reduction of maximum stress concentration when the step-tapered doublers are employed.

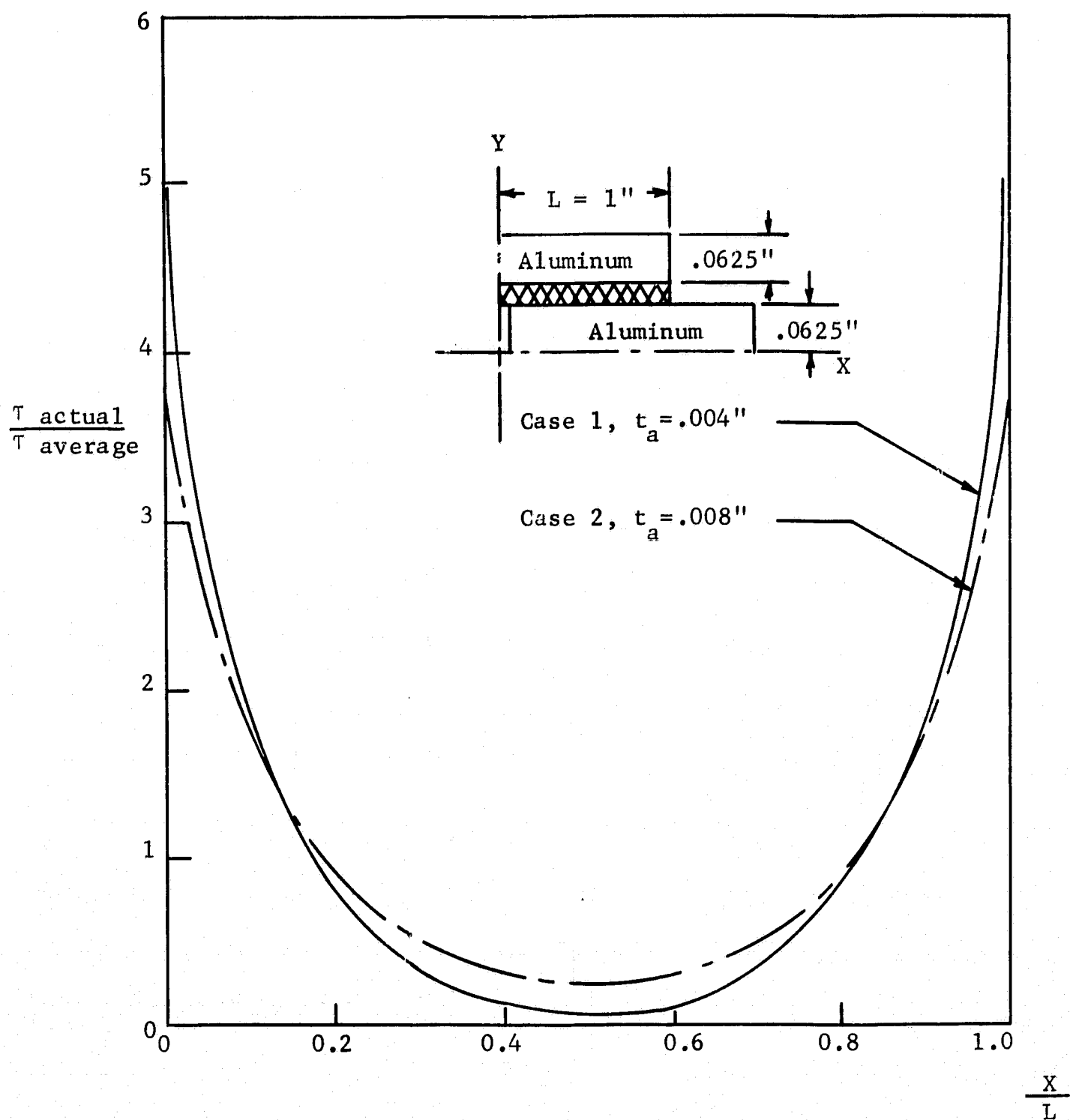


Figure 2-5. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Cases 1 and 2.

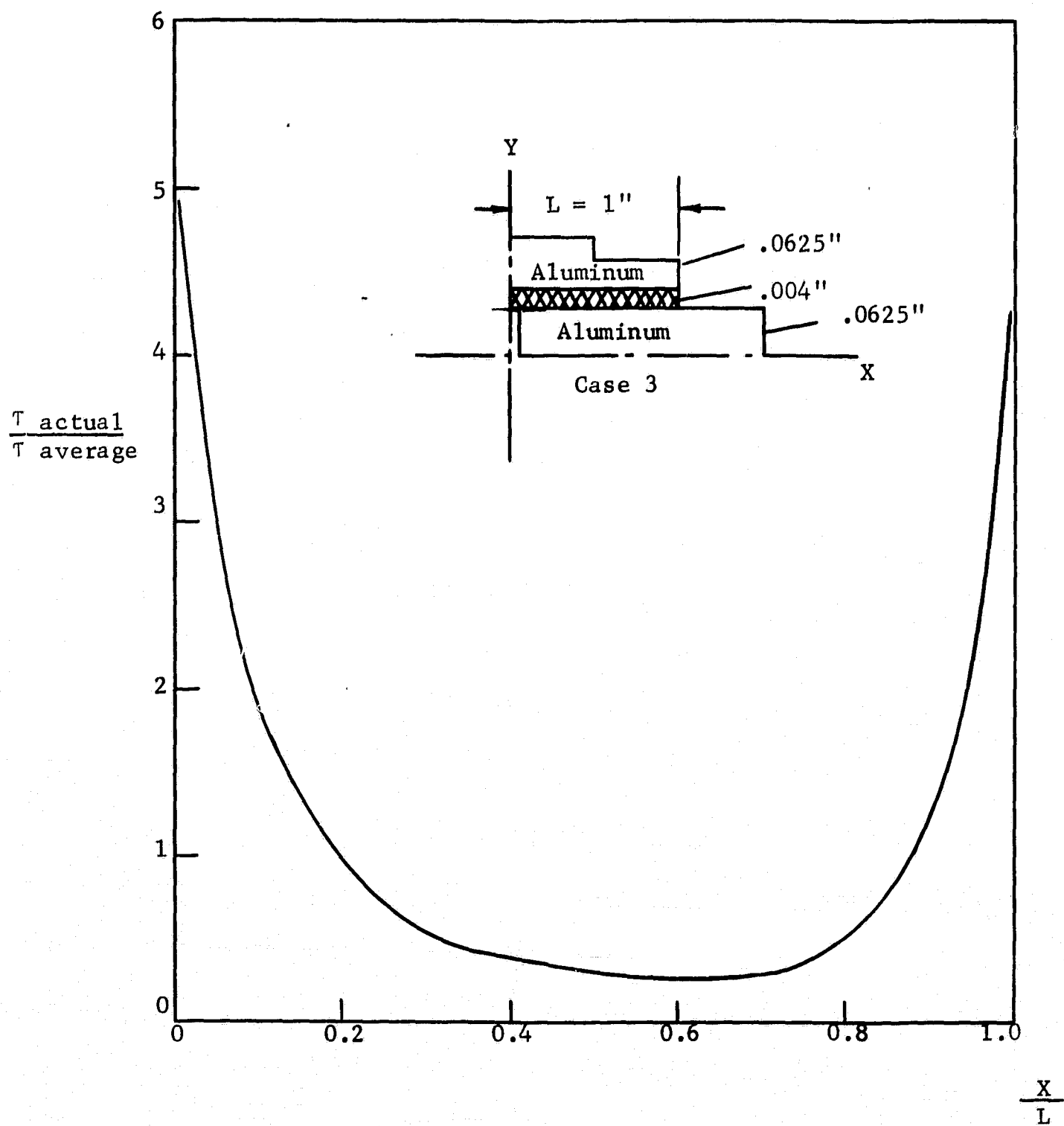


Figure 2-6. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 3.

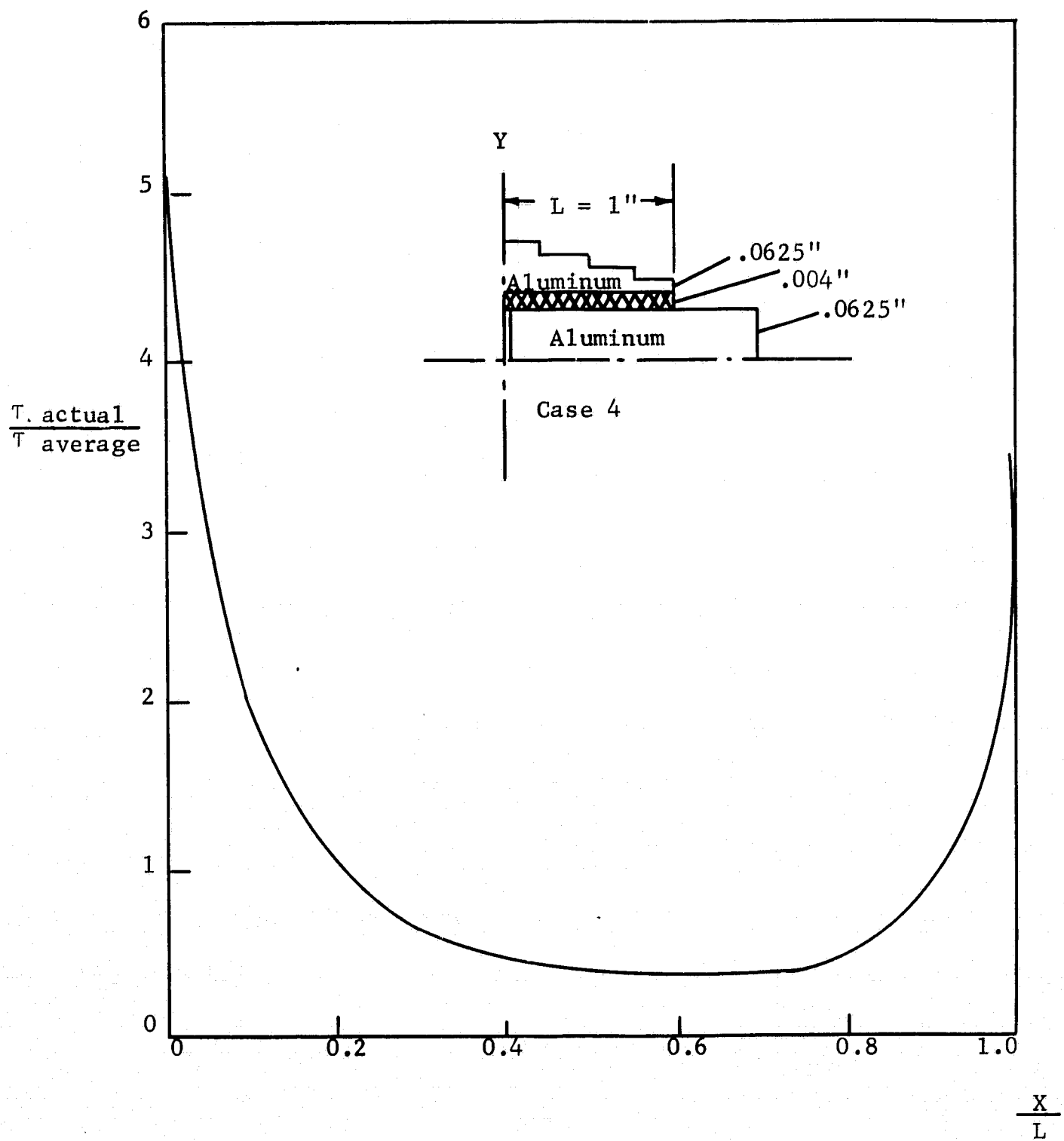


Figure 2-7. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 4.

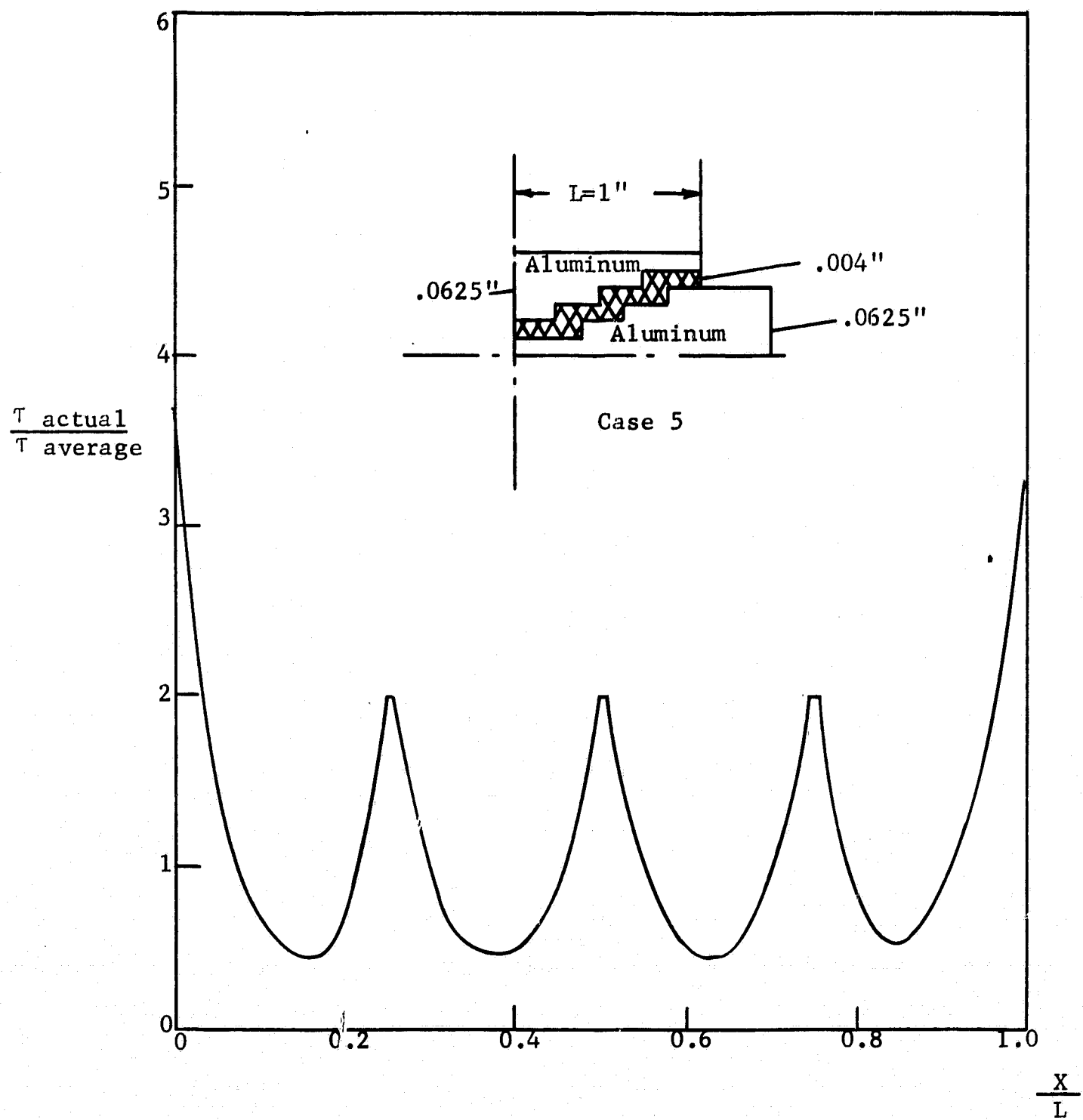


Figure 2-8. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 5.

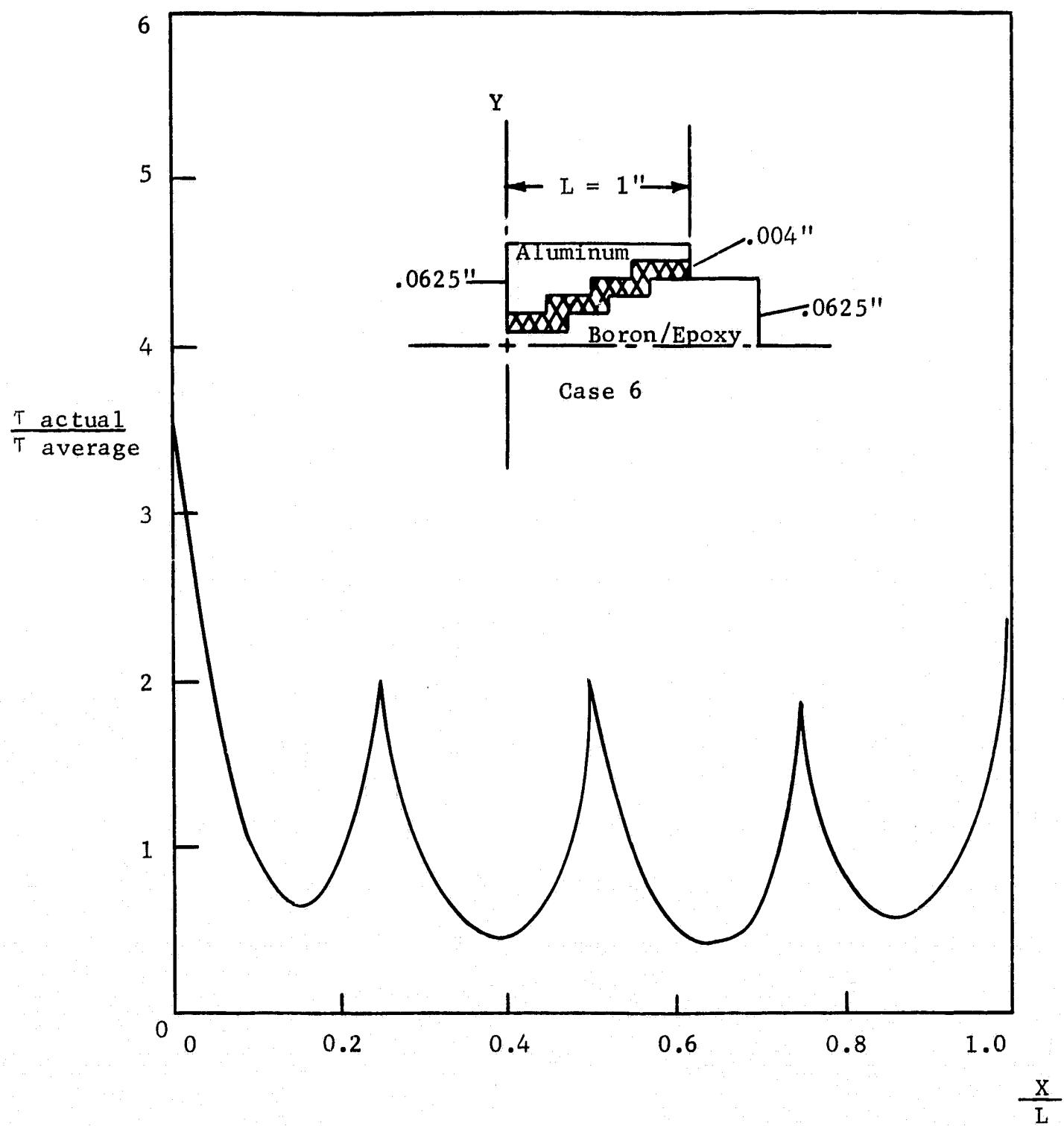


Figure 2-9. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 6.

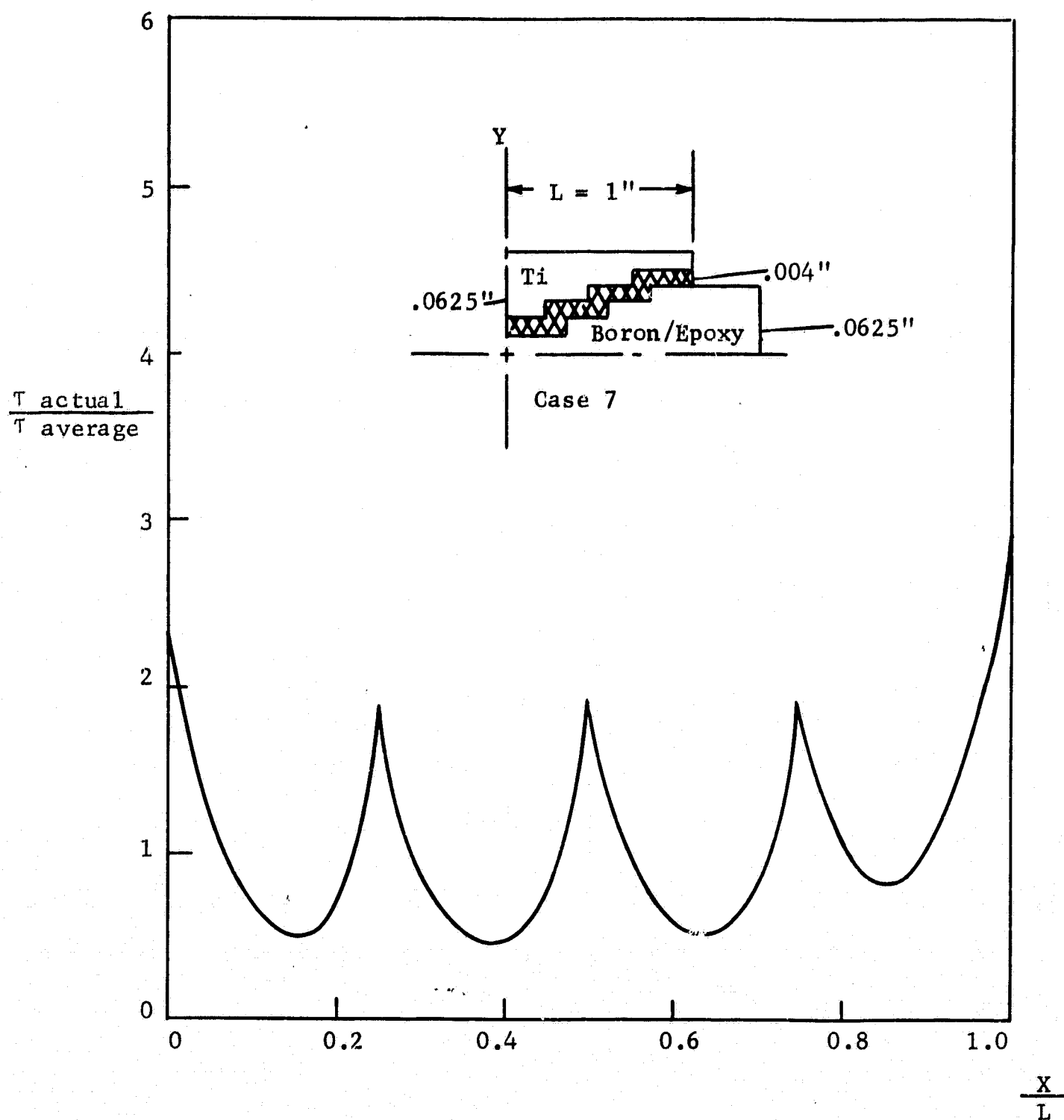


Figure 2-10. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 7.

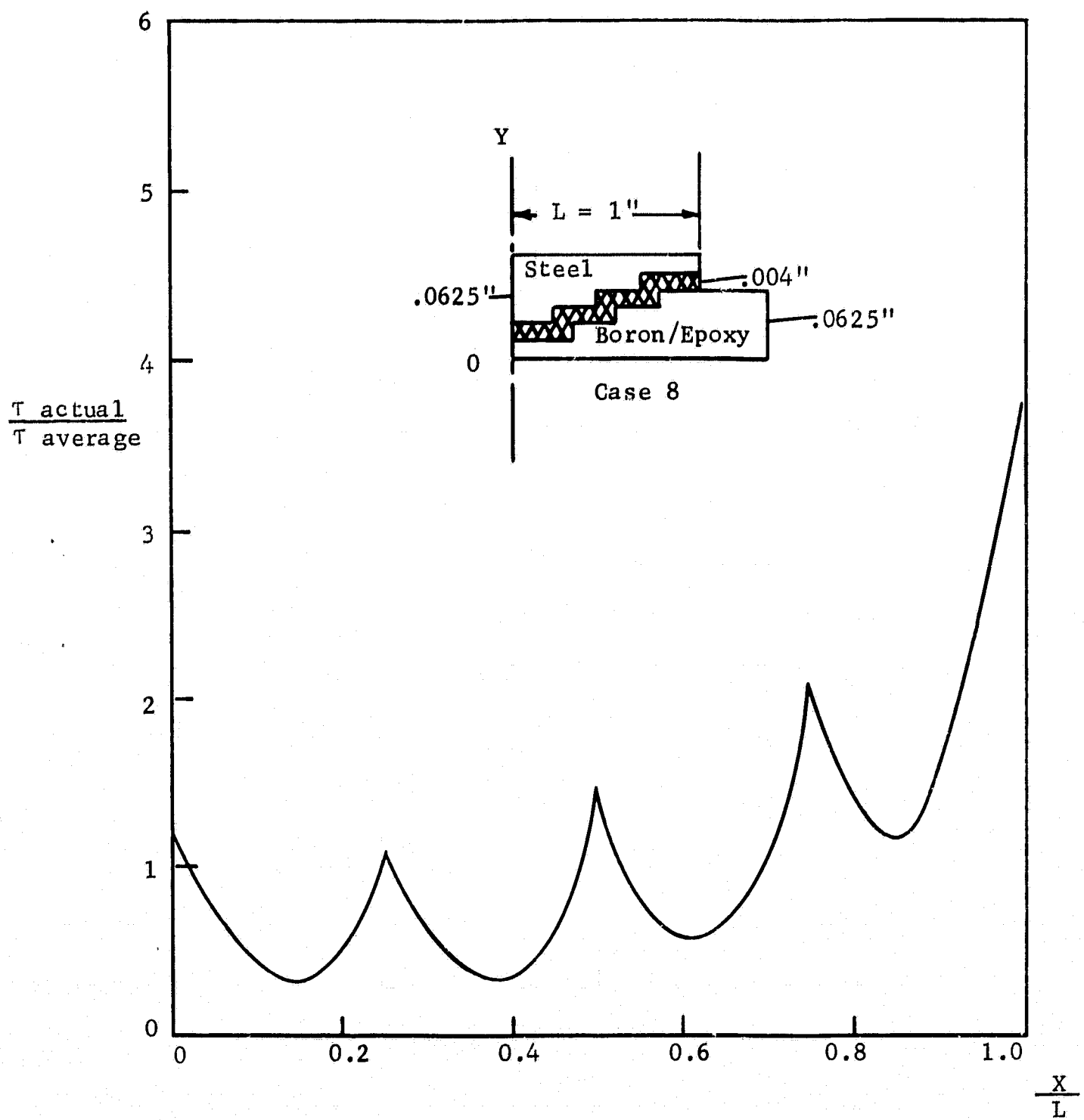


Figure 2-11. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 8.

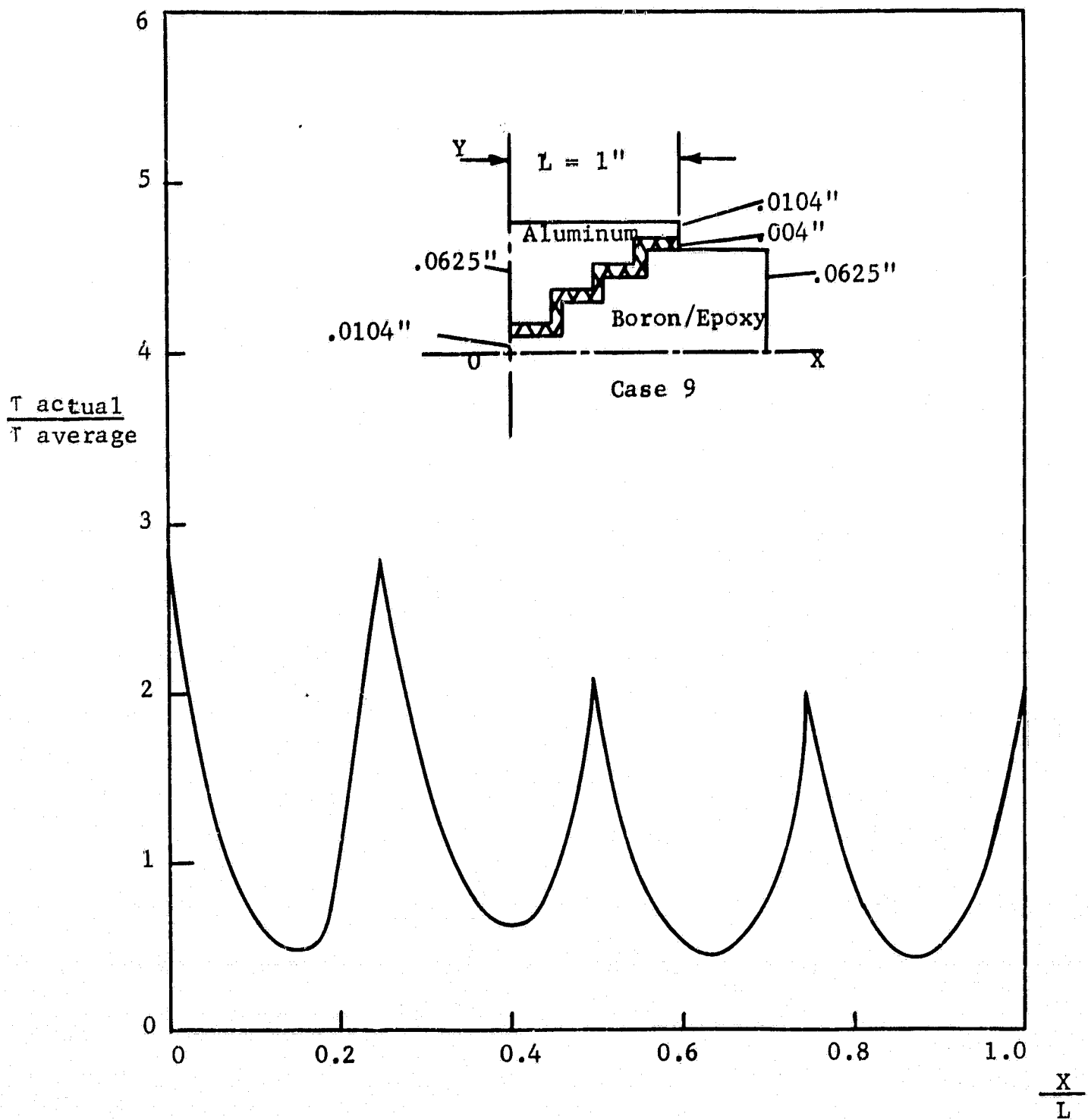


Figure 2-12. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 9.

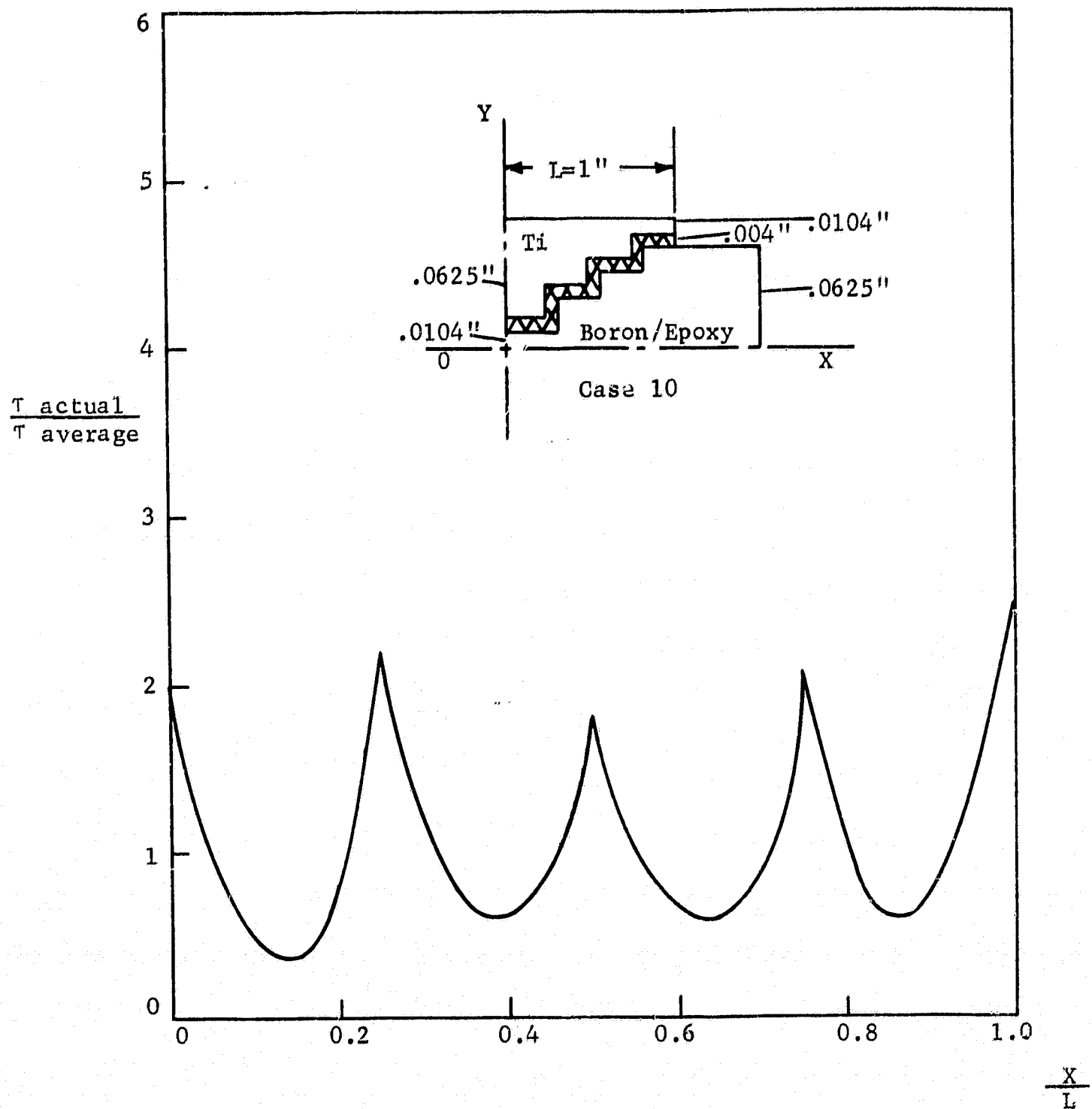


Figure 2-13. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 10.

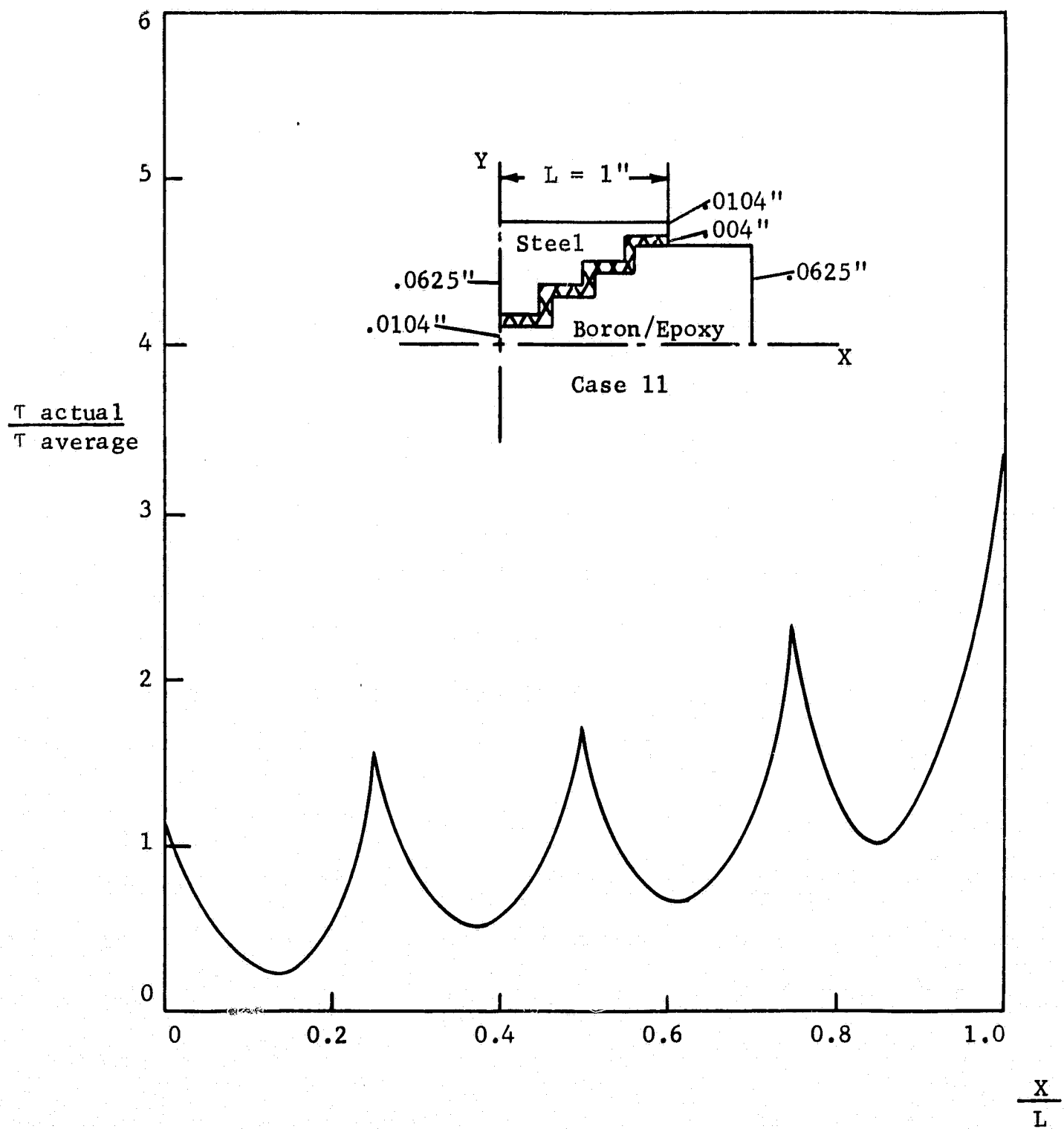


Figure 2-14. Shear Stress Distribution Along the Bondline of a Double-Lap Joint. Case 11.

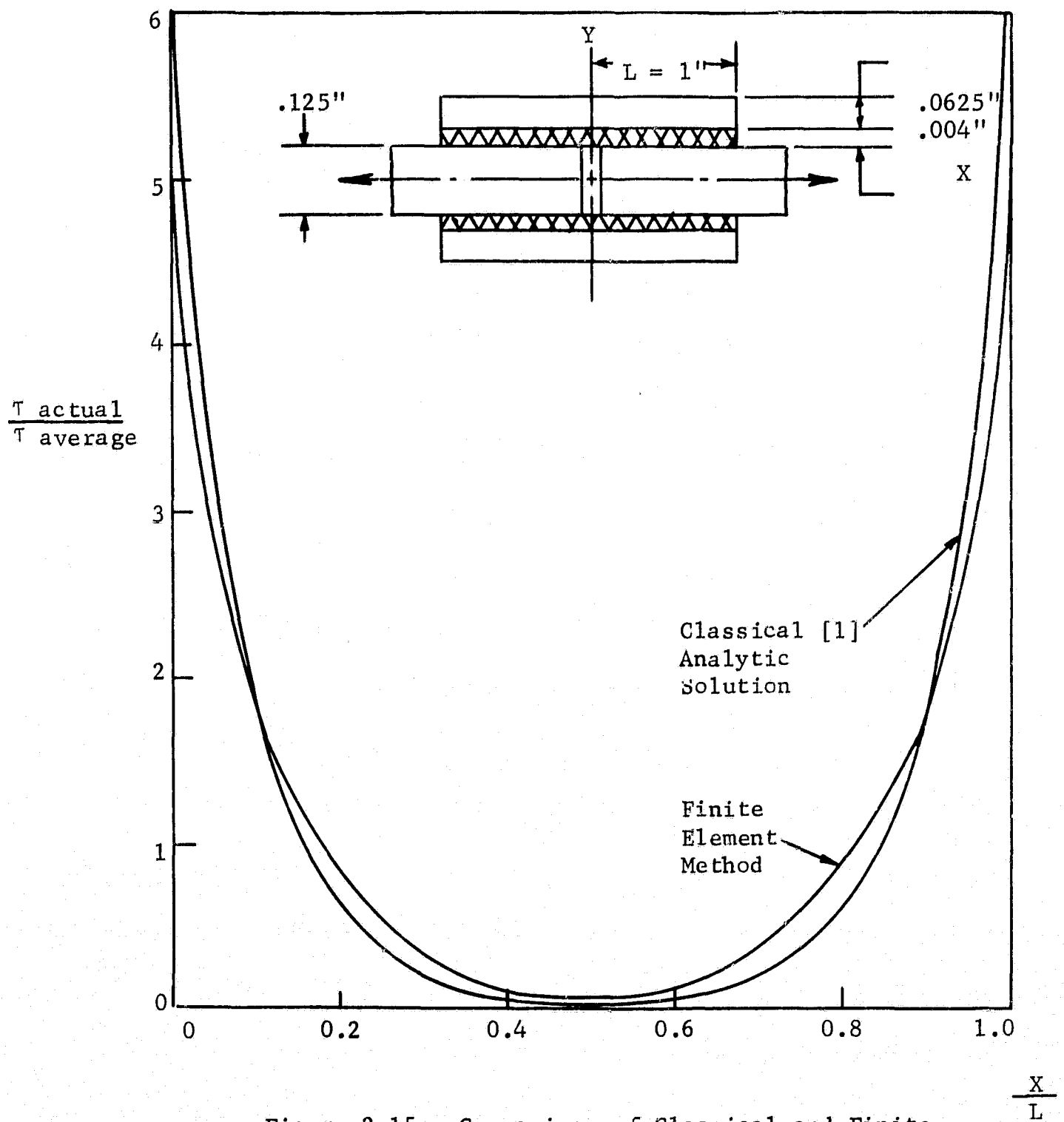


Figure 2-15. Comparison of Classical and Finite-Element Solutions for Shear Stress Distribution Along the Bondline of a Double-Lap Joint.

The photoelastic method itself was evaluated, using the finite-element computer developed for joint analysis. A typical photostress application is shown in Figure 2-16. Photoelastic material is bonded to the outer facing of the doubler, and the quantity actually measured photoelastically is the tensile strain at this surface. According to classical analysis, when the doubler has an infinite shear modulus the adhesive shear stress can be obtained from differentiation of the surface tensile stress  $\sigma_x$ . Actually, the finite shear deformations in the doubler cause the strains on the outer face to differ from the desired strains at the bonding face. Since the "apparent" adhesive shear stress is deduced from the derivative of this erroneous measurement, a departure from the actual shear stress distribution may be expected. This phenomenon is demonstrated in Figure 2-17, where possible "apparent" and actual adhesive shear stresses are determined from adherend tensile stresses measured on the inner and outer surfaces of the doubler.

Finite-element comparisons of the tensile stresses at the bondline and at the photoelastic interface are presented in Figures 2-18 through 2-27. Note that the tensile stresses are well-matched at points removed from cross-sectional changes, but may differ appreciably at steps either in the doubler (Figures 2-19 and 2-20) or in the bondline (Figures 2-21 through 2-27). Even in the straight-lap joint (Figure 2-18, it is evident that the character of the peak stresses at the ends of the doubler cannot be accurately determined with this technique. Since the adhesive shear stresses are deduced from the derivatives of these tensile stresses, the discrepancies can be accentuated even further.

On the basis of the finite element analysis, it can be asserted that the photoelastic technique has merit when qualitative features of the adhesive shear are to be monitored, and when the joint geometry does not include adhesive steps. Areas of high-adhesive shear stress can be located by noting regions of high fringe density in the photoelastic display. The use of the photoelastic technique is questionable, however, when attempts are made to actually evaluate these shear stresses.

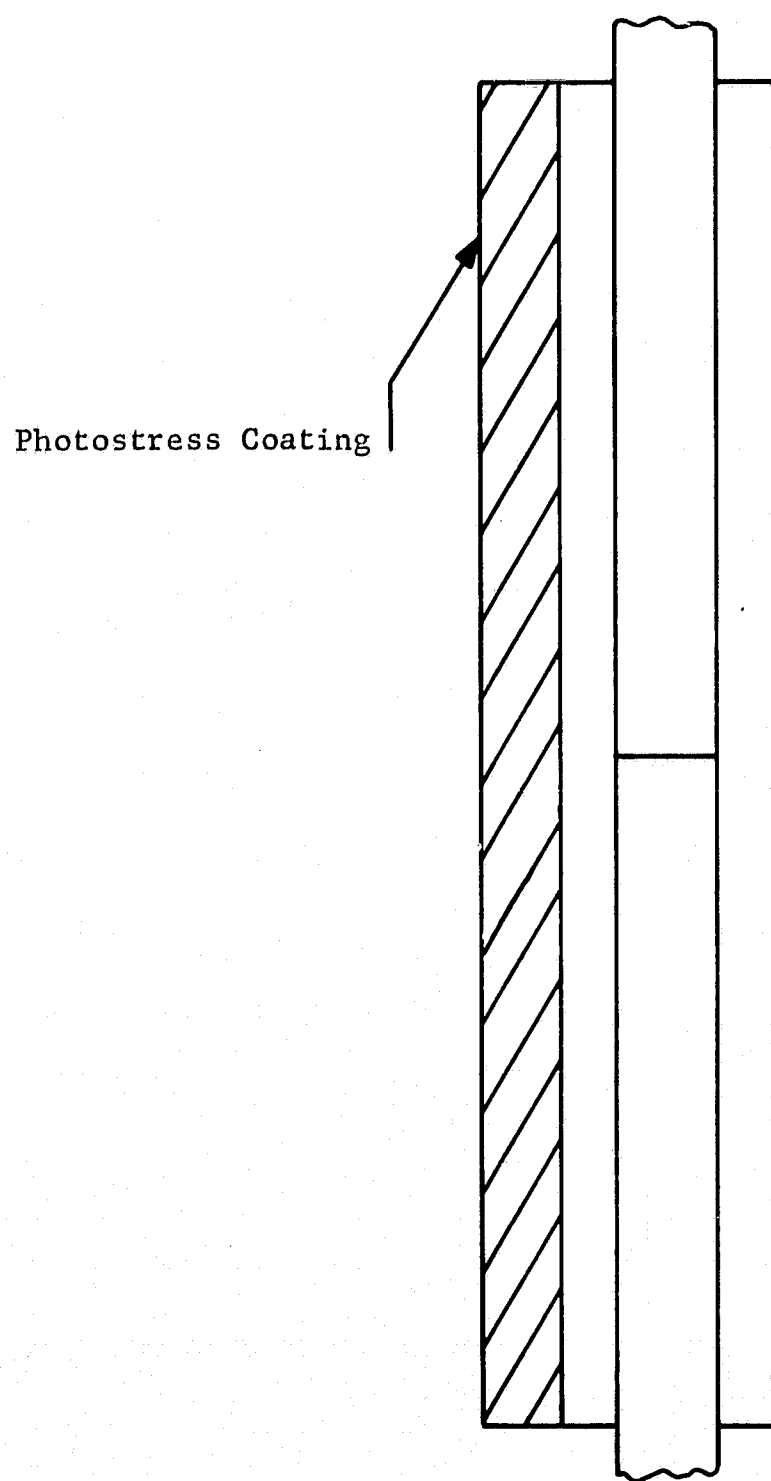


Figure 2-16. Straight-Lap Joint, Prepared for Photoelastic Study. Case 1.

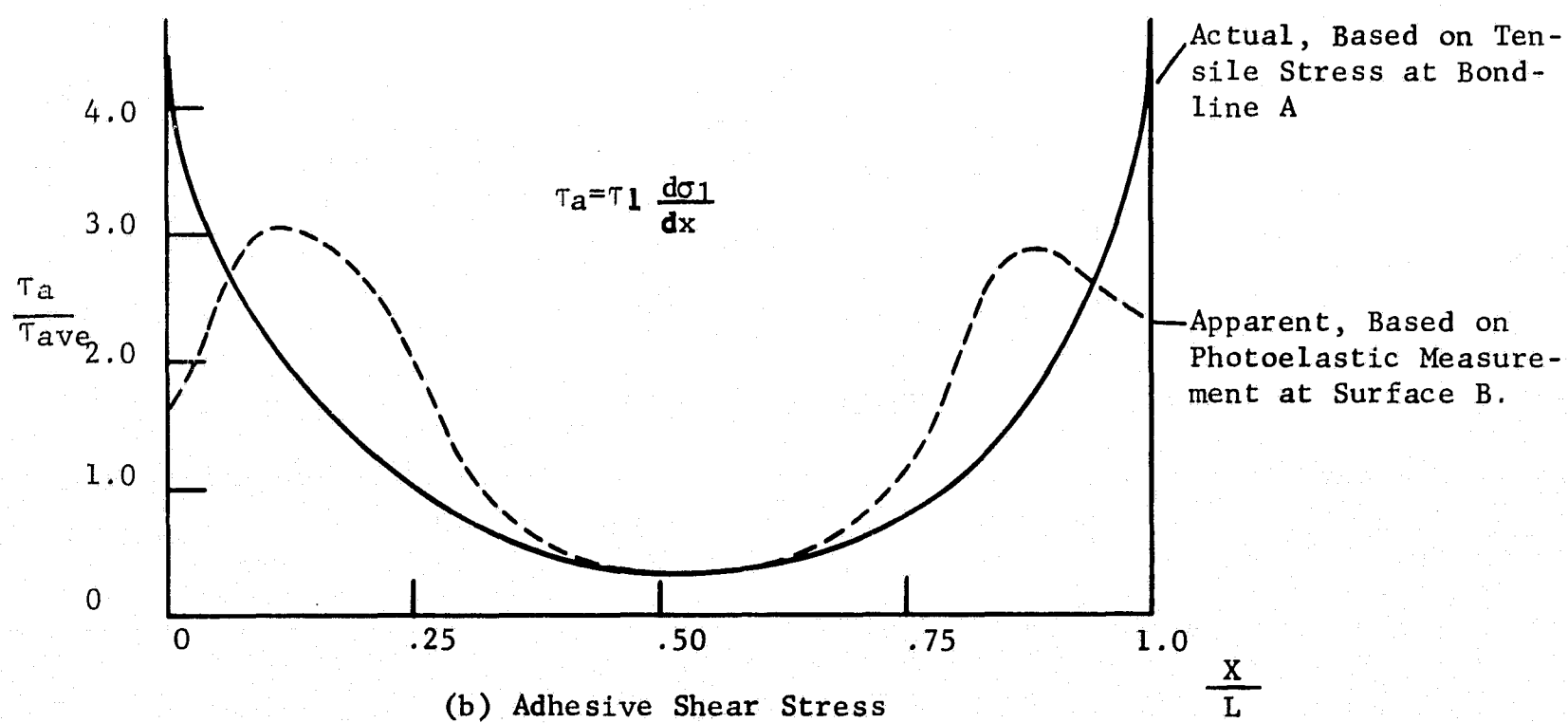
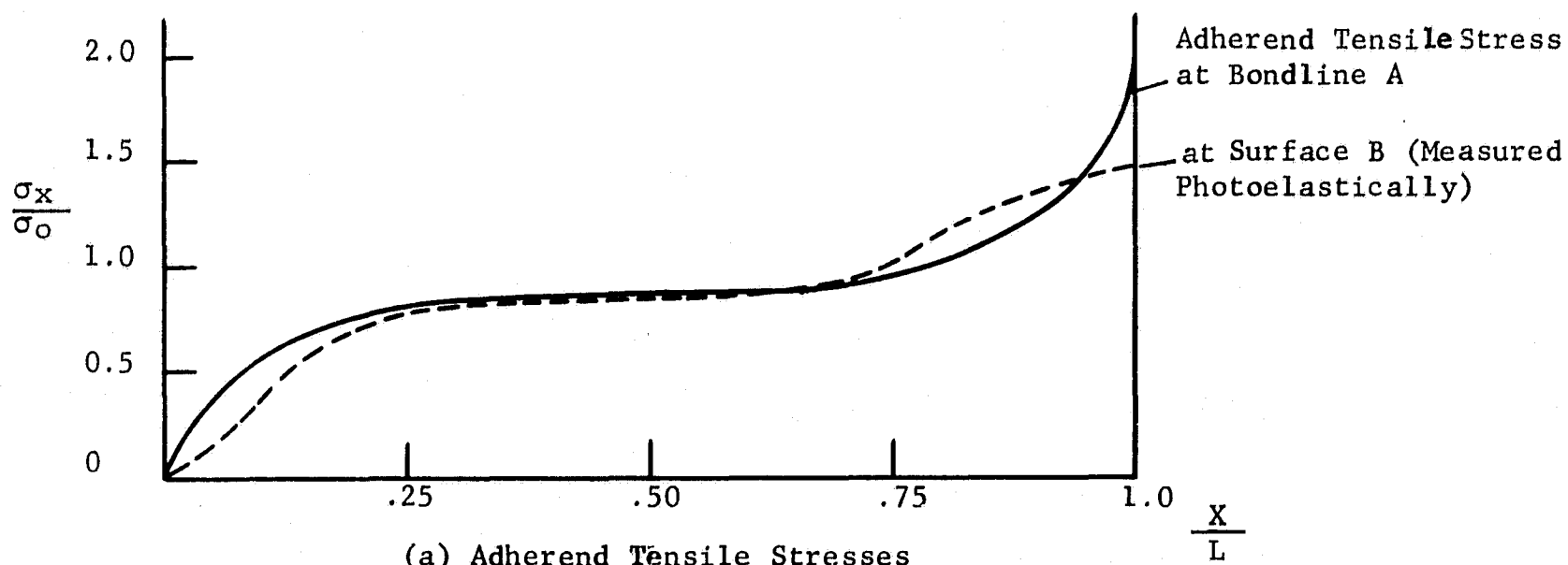
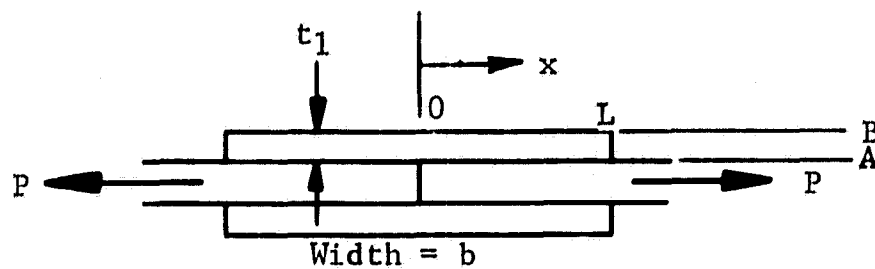


Figure 2-17. Demonstration of Photoelastic Method for Determining Adhesive Shear Stress.

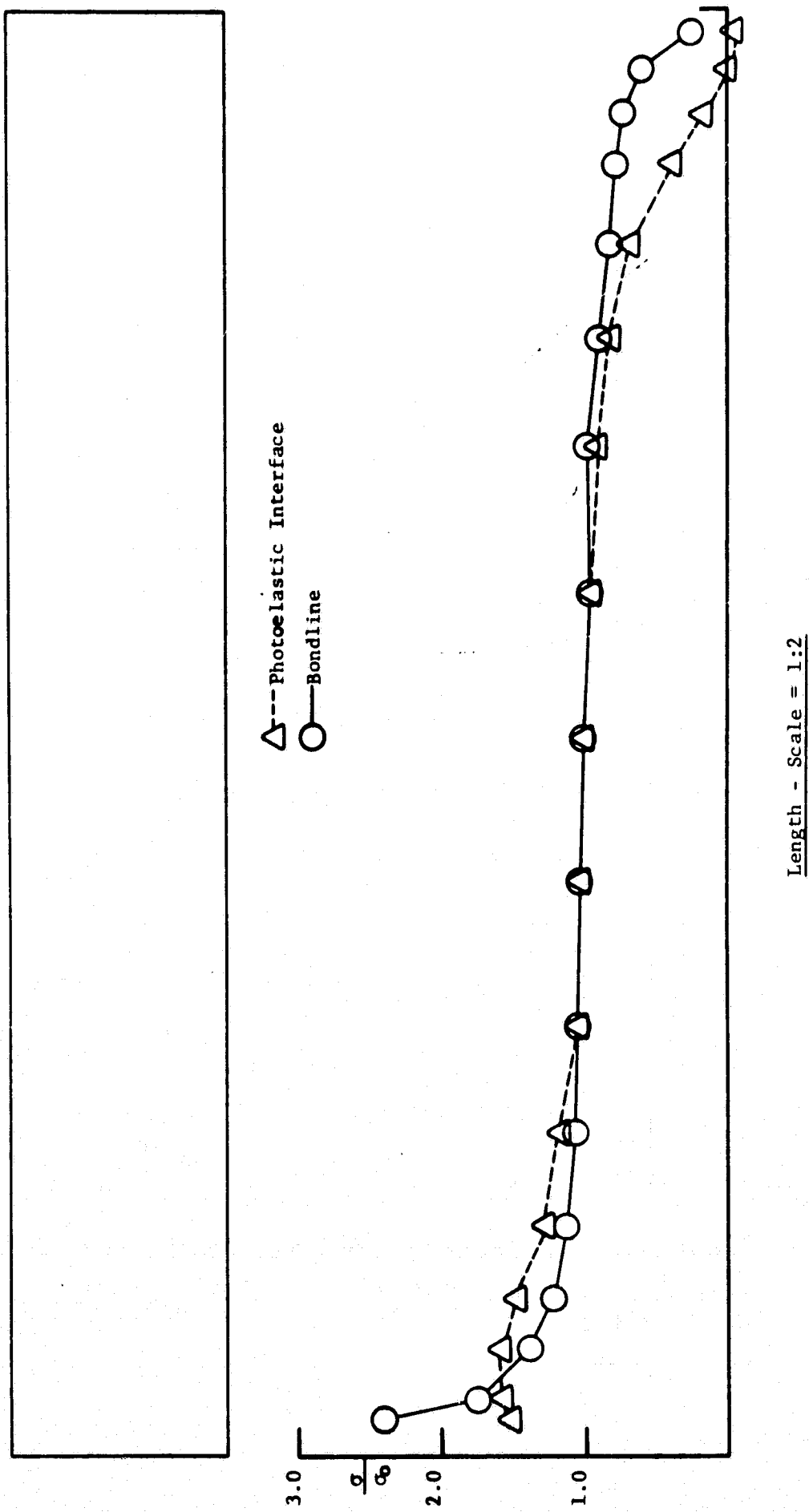


Figure 2-18. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Cases 1 and 2.

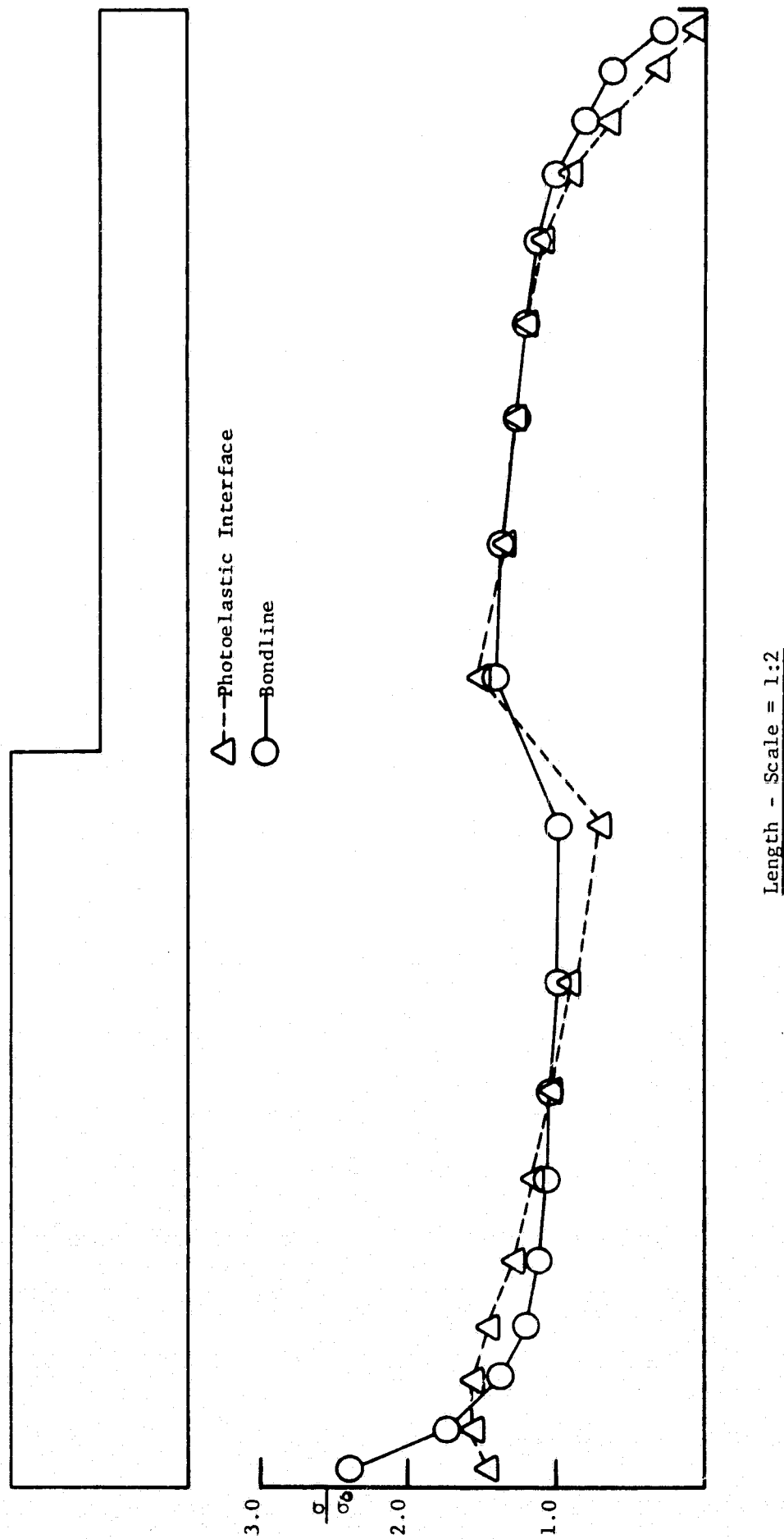


Figure 2-19. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 3.

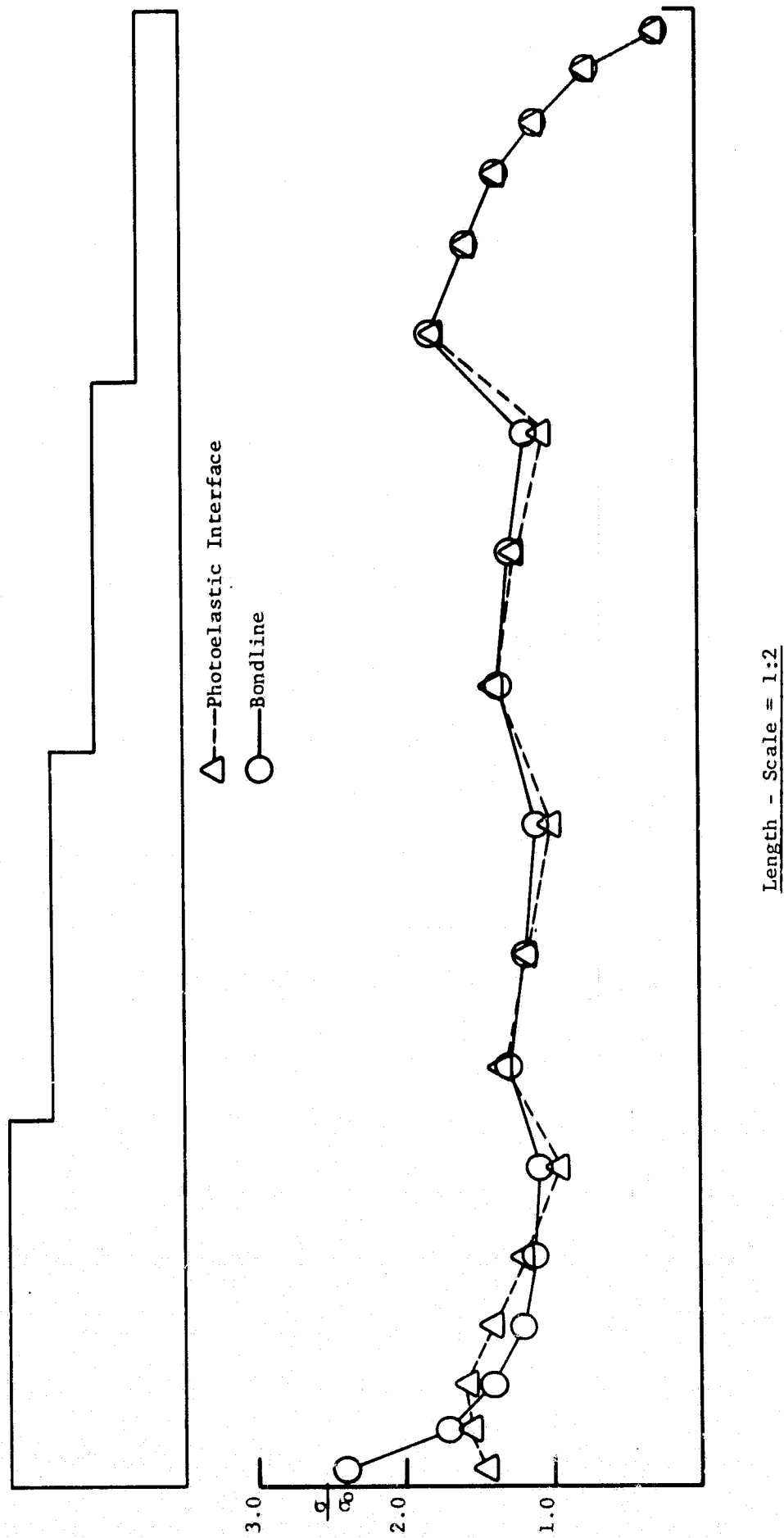


Figure 2-20. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 4.

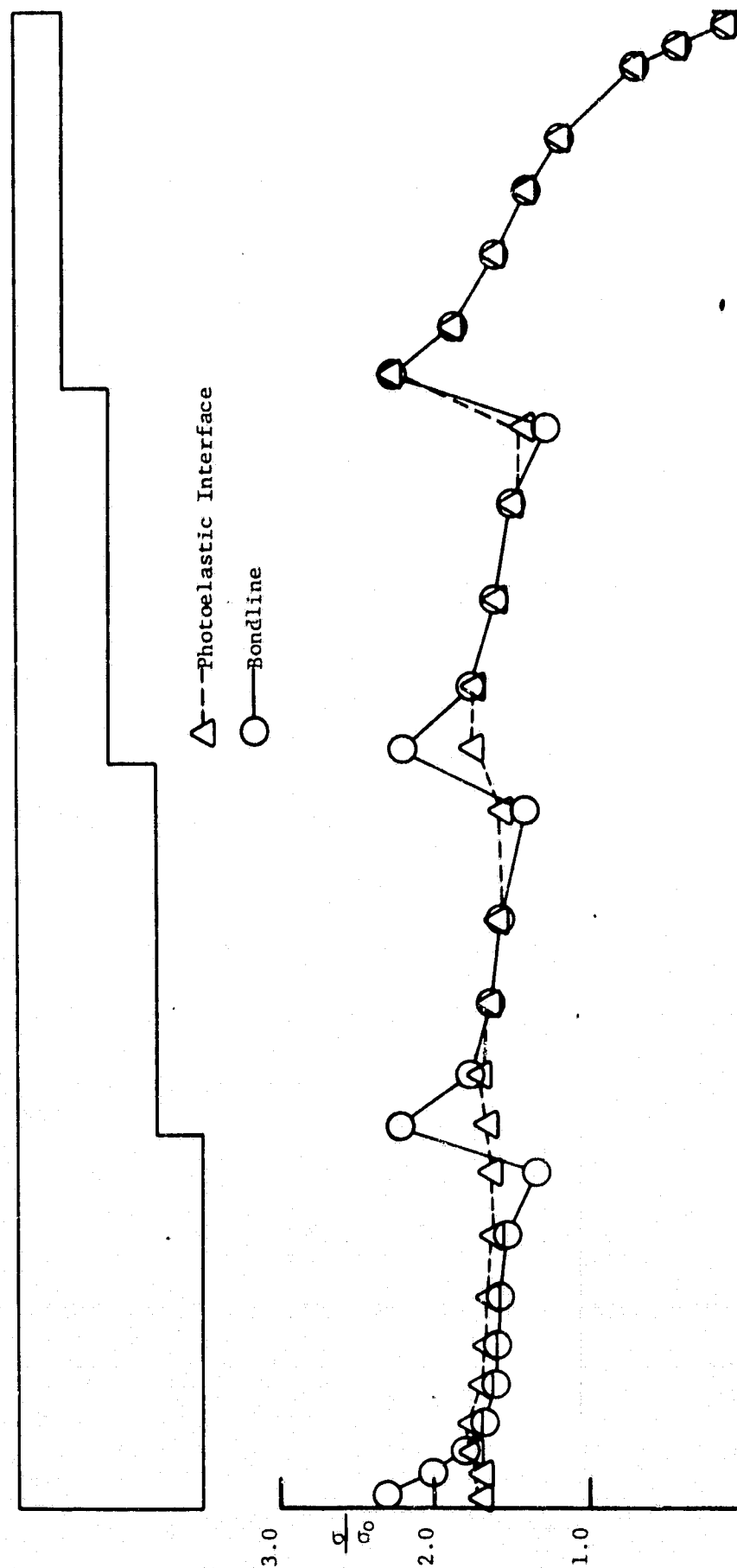


Figure 2-21. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 5.

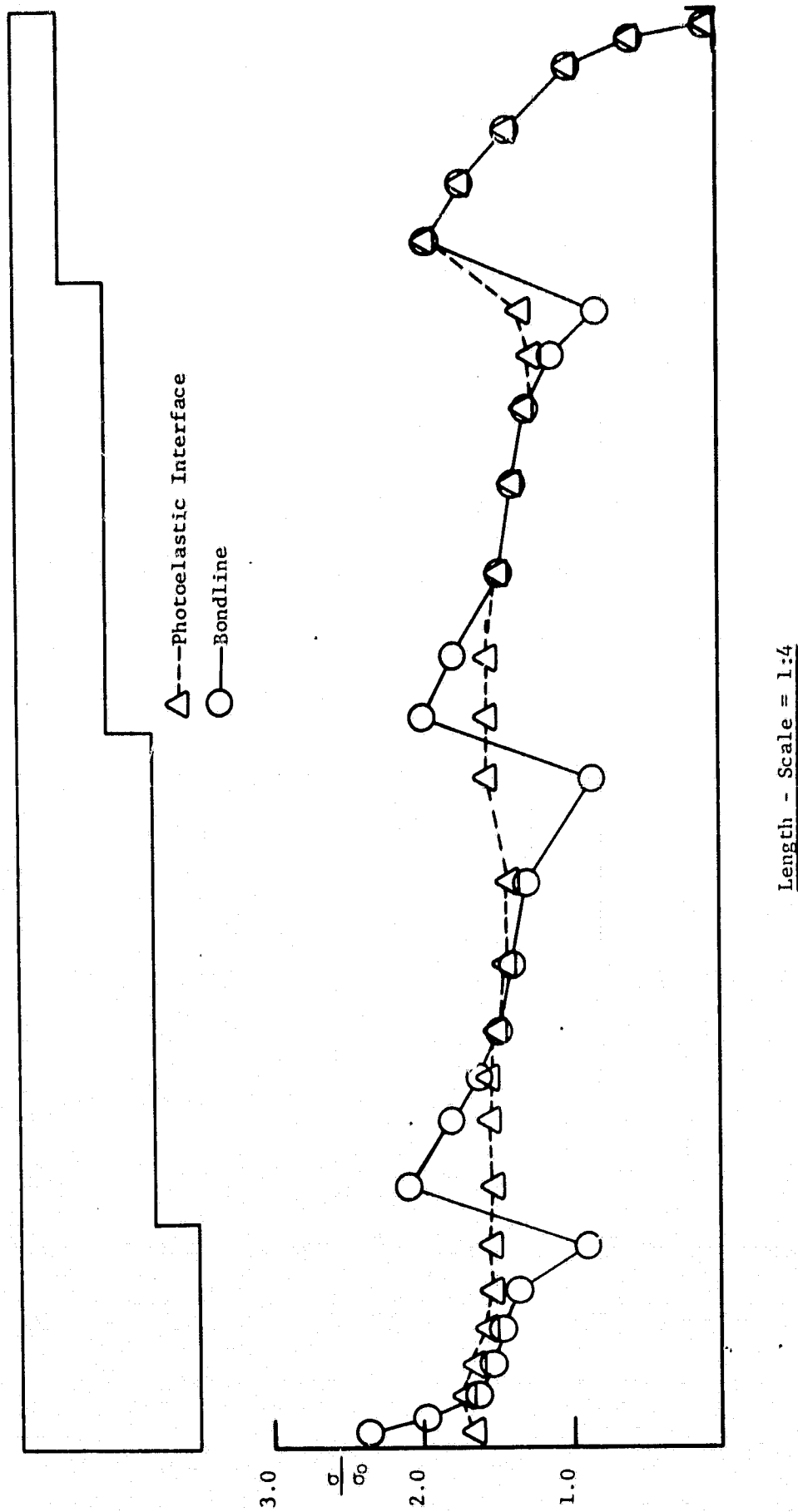
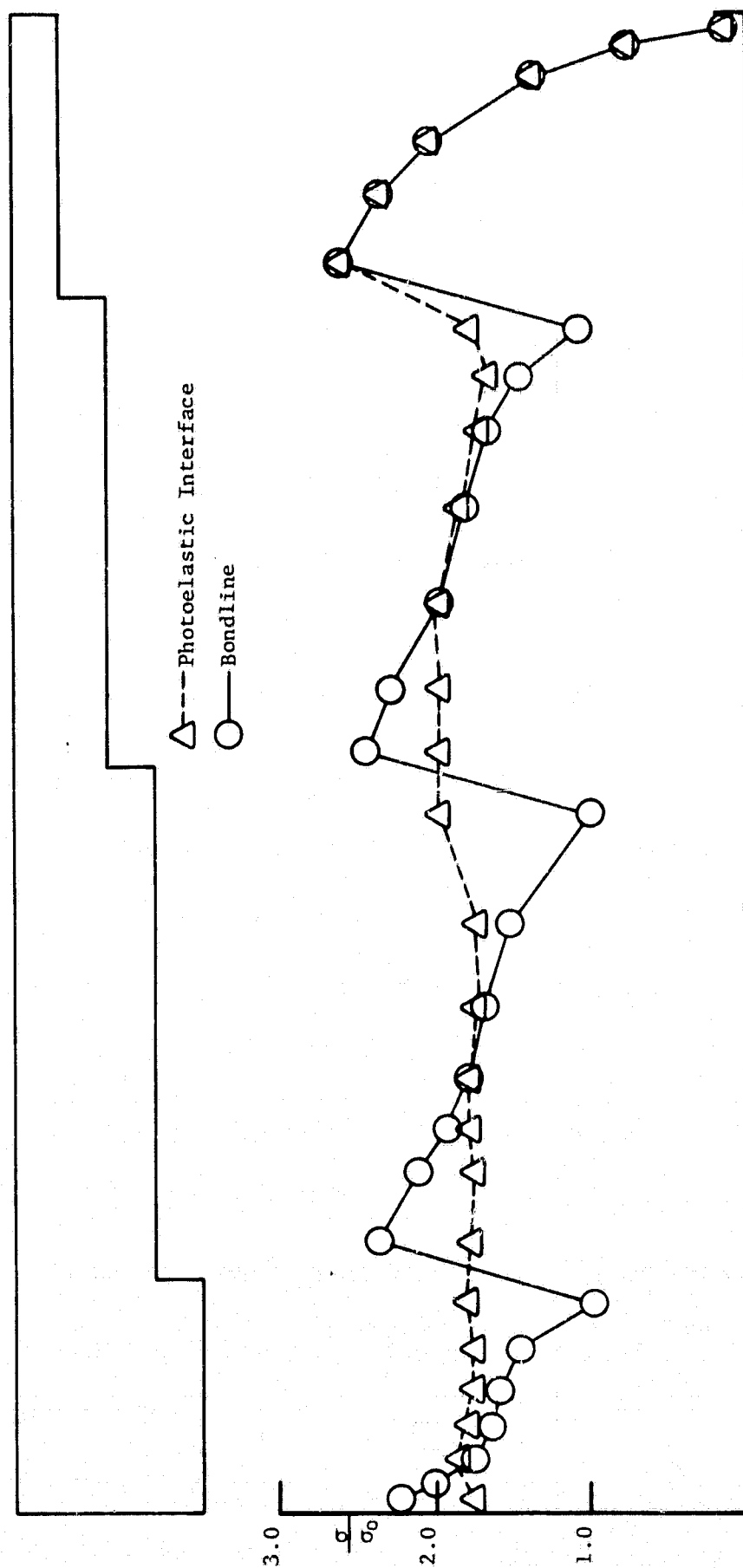


Figure 2-22. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 6.



Length - Scale = 1:4

Figure 2-23. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 7.

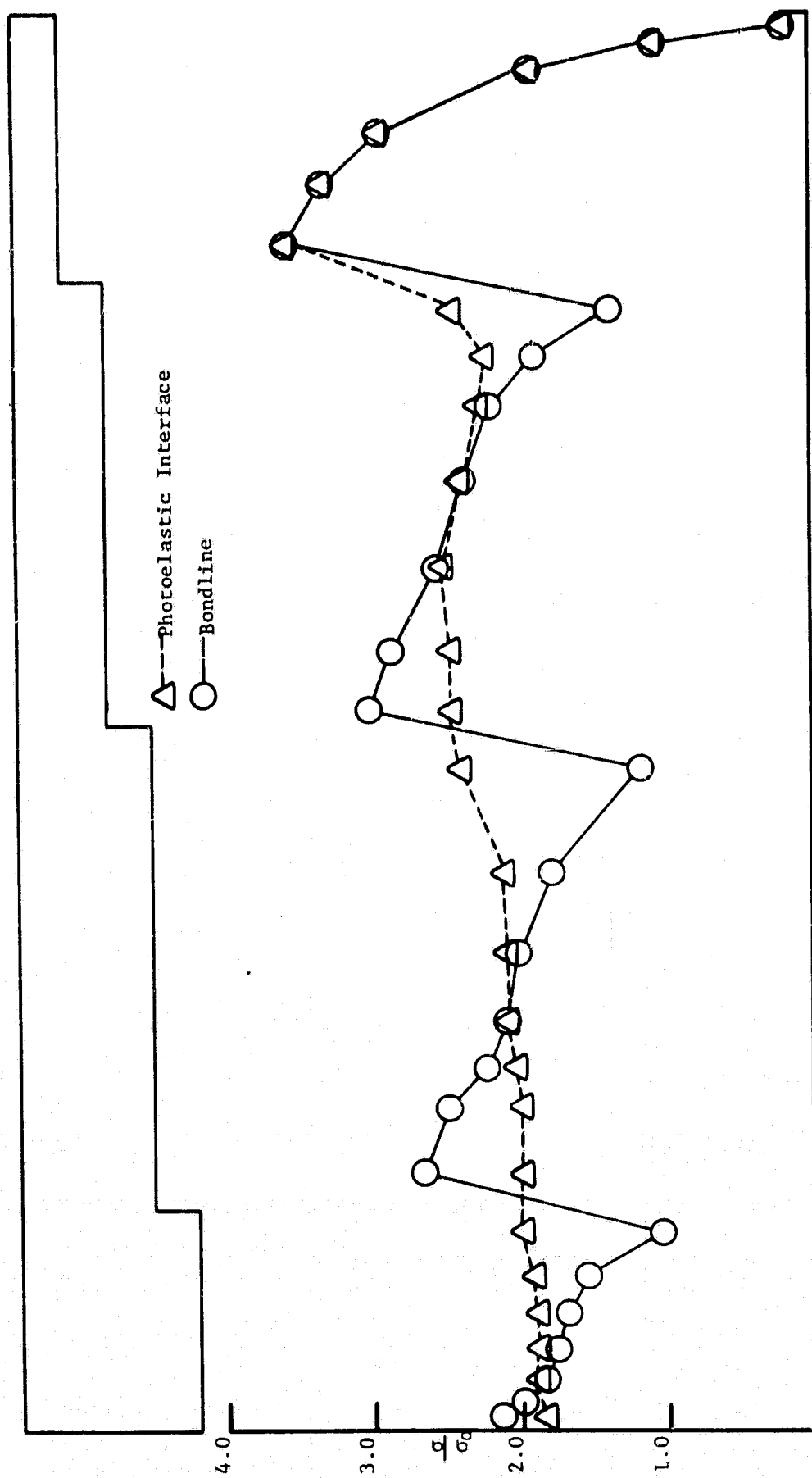


Figure 2-24. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 8.

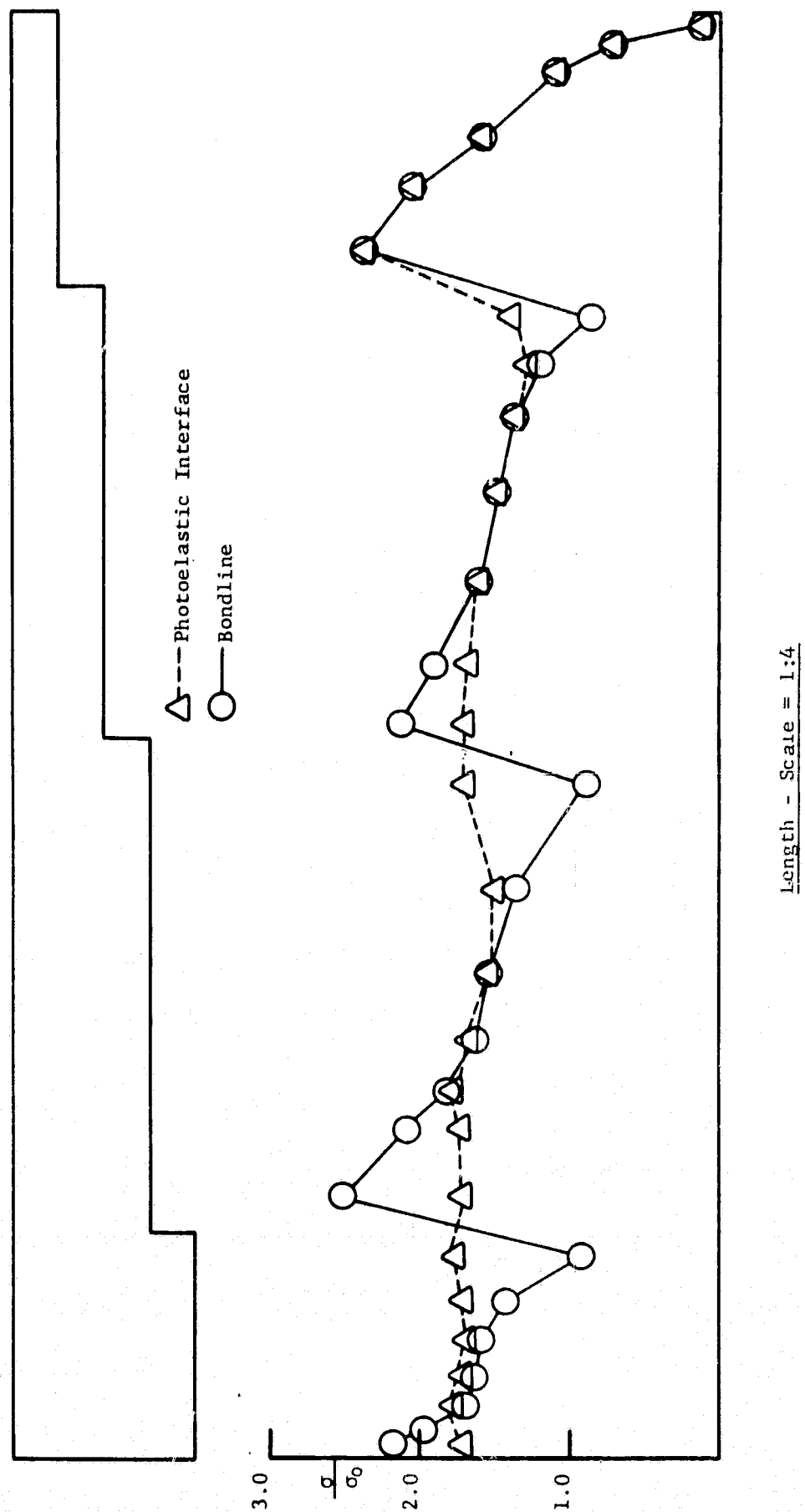
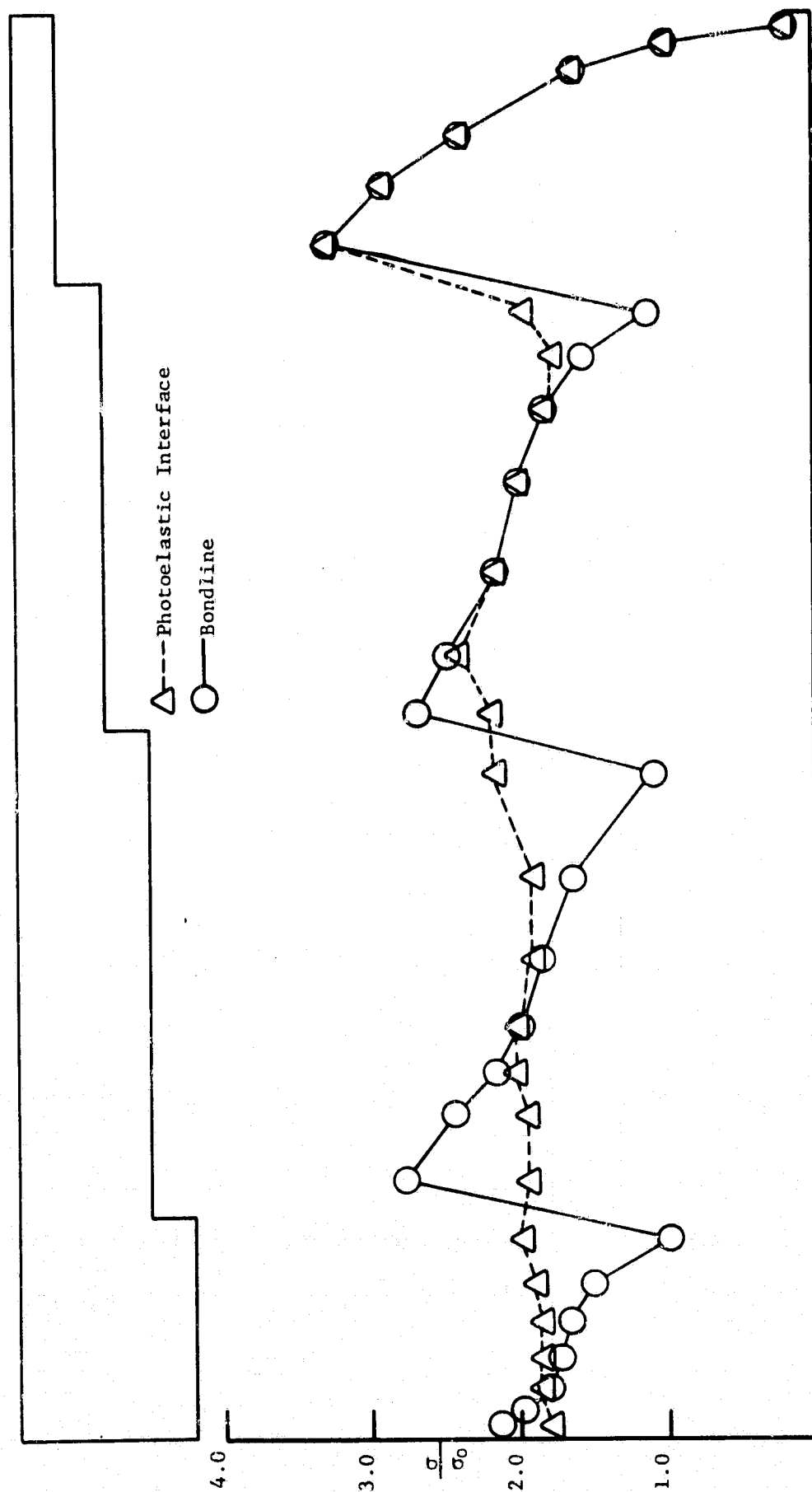


Figure 2-25. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 9.



Length - Scale = 1:4

Figure 2-26. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 10.

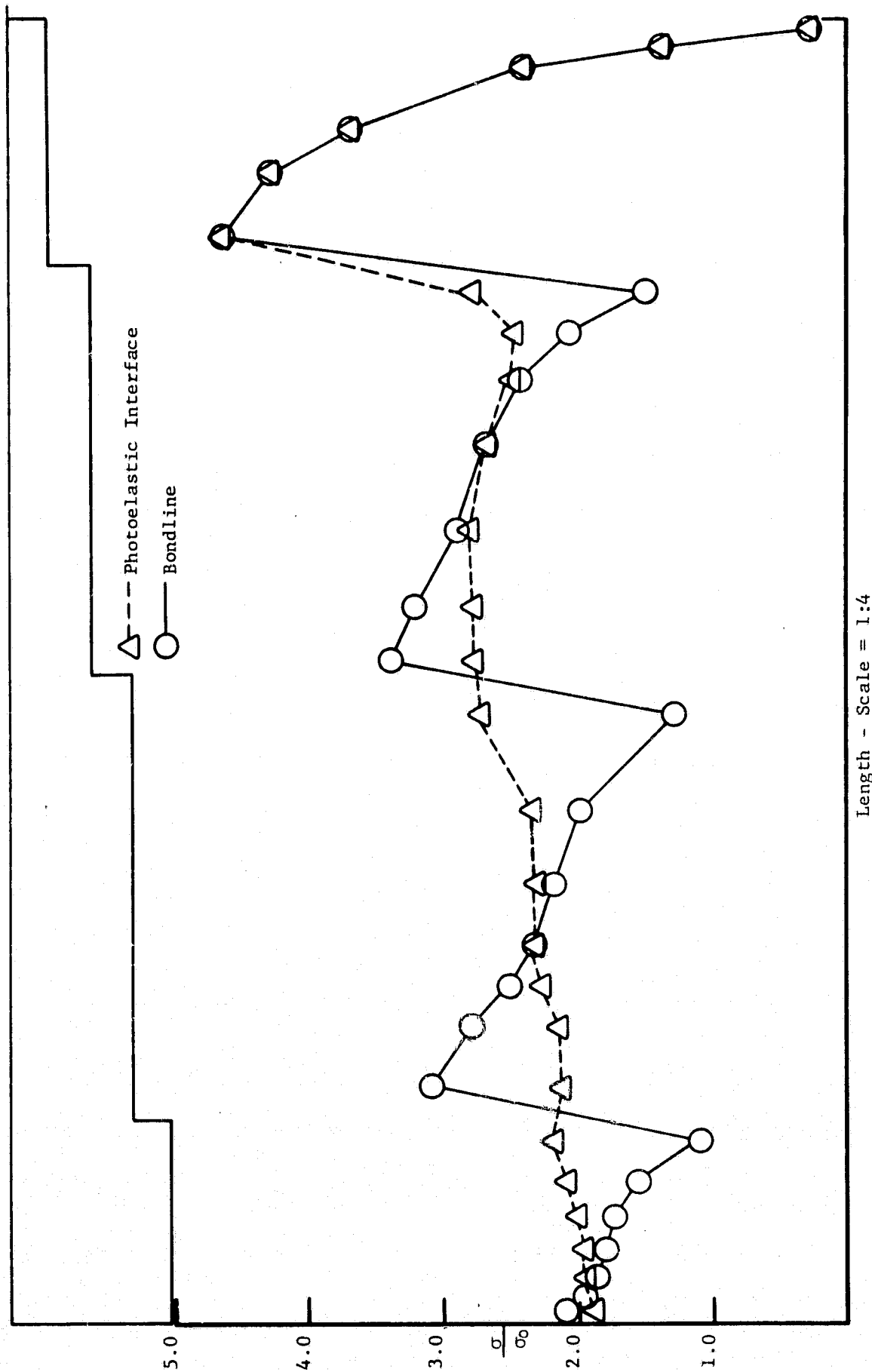


Figure 2-27. Comparison of Tensile Stress Distributions at the Doubler Bondline and Photoelastic Interface. Case 11.

### SECTION 3

#### SIMPLIFIED JOINT DESIGN CRITERION

A design criterion was developed in this preliminary phase, for analysis of the symmetrical double-lap joint. The Goland-Reissner<sup>[3]</sup> assumptions formed the basis for this strength-of-materials approach, specifically:

- (a) The shear stiffness of the adherends are large compared with those of the adherend, i.e.,

$$\frac{1}{10} \frac{t_a}{E_a} \geq \frac{t}{E}, \quad \frac{1}{10} \frac{t_a}{G_a} \geq \frac{t}{G}$$

where  $t_a, G_a, E_a$  represent the thickness, shear modulus and tensile modulus of the adhesive and  $t, G, E$  represent the same properties of either adherend.

- (b) All stresses remain below the proportional limit.
- (c) Adherends and adhesive materials are homogeneous and isotropic.
- (d) Joints are loaded in simple static tension.

- (e) Adhesive shear strains are uniform through the bondline thickness.

In the analysis outlined herein, the adherend shear moduli are assumed large, so that tensile strains in the adherend are nearly constant throughout the adherend thickness. This assumption is reasonably correct for metallic adherends, but will be modified later when typical composite adherends are studied.

#### Analysis

Consider the symmetrical double-lap joint shown schematically in Figure 3-28. This joint has a width  $b$ , overlap length  $L$ , and different properties in the main plate (1) and doublers (2). The joint is subjected to a load  $2P$ . A small element of width  $\Delta x$  and bondline slope angle  $\theta$  is considered in Figure 3-28b.

From equilibrium (Figure 3-28b) the relation between the adherend tensile loads and adhesive shear stresses are obtained:

$$\begin{aligned} \frac{dP_1}{dx} &= b \frac{\tau_a}{\cos^2 \theta}, \text{ or } P_1 = b \int_0^x \frac{\tau_a}{\cos^2 \theta} dx \\ \frac{dP_2}{dx} &= -b \frac{\tau_a}{\cos^2 \theta}, \text{ or } P_2 = b \int_x^L \frac{\tau_a}{\cos^2 \theta} dx \end{aligned} \quad (1)$$

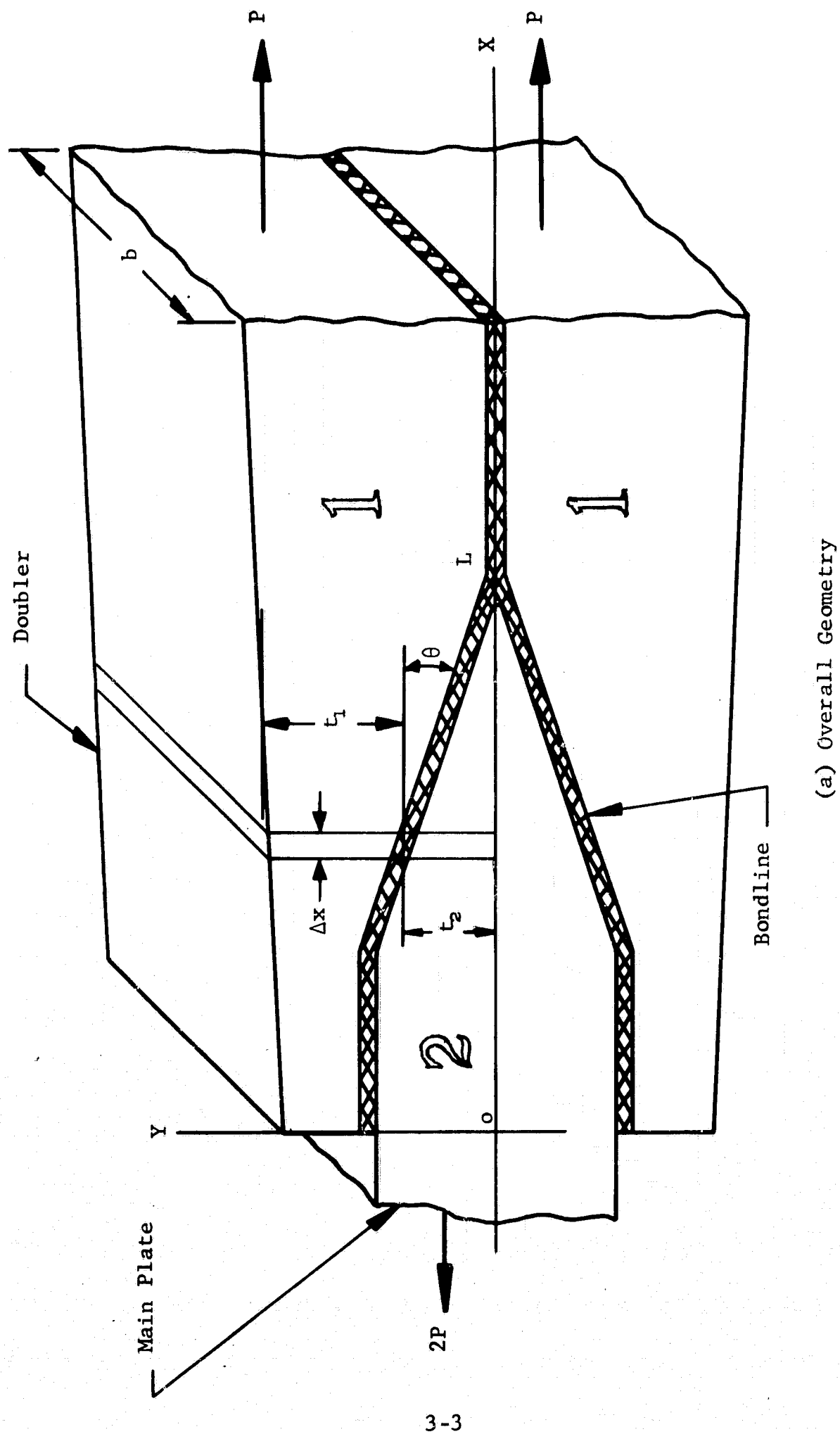
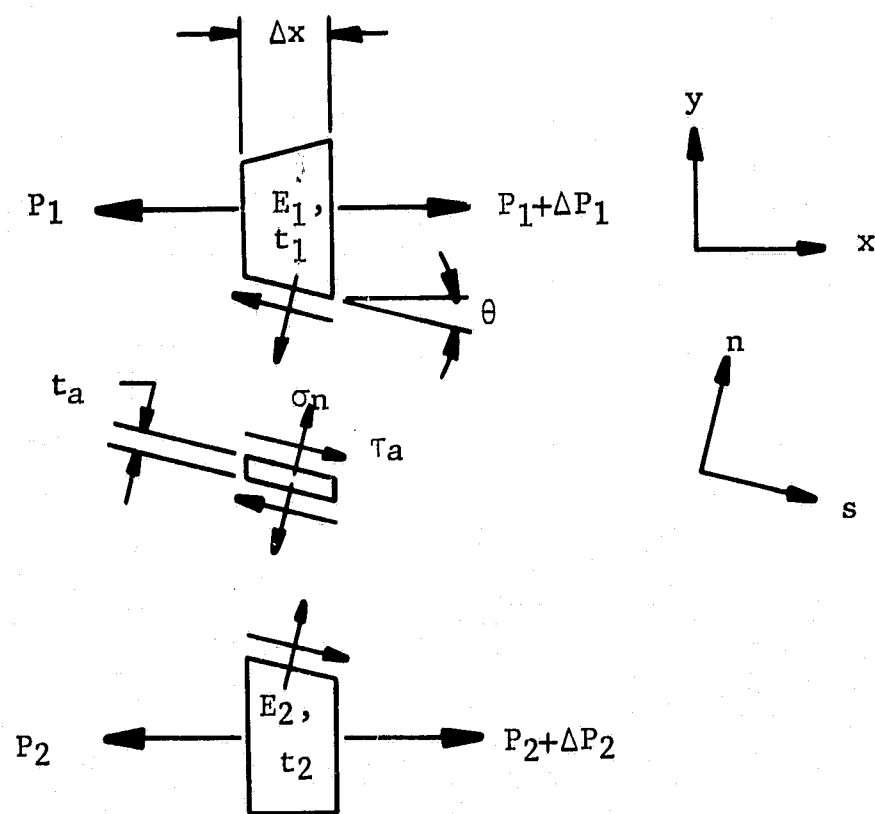


Figure 3-28a Double-Lap Joint Configuration.  
Bondline Thickness Constant



(b) Infinitesimal Element

Figure 3-28.b Double-Lap Joint Configuration.  
Bondline Thickness Constant.

The strains  $\epsilon_{xx}, \epsilon_{yy}, \gamma_{xy}$  in each adherend are found from the plane-stress assumption

$$\begin{aligned}\epsilon_{xx1} &= \frac{\partial u_1}{\partial x} = \frac{\sigma_{x1}}{E_1} = \frac{P_1}{t_1 b E_1} ; \epsilon_{yy1} = \frac{\partial v_1}{\partial y} = -\nu_1 \frac{P_1}{t_1 b E_1} \\ \gamma_{xy1} &= \frac{\partial u_1}{\partial y} + \frac{\partial v_1}{\partial x} = 0 \\ \epsilon_{xx2} &= \frac{\partial u_2}{\partial x} = \frac{\sigma_{x2}}{E_2} = \frac{P_2}{t_2 b E_2} ; \epsilon_{yy2} = \frac{\partial v_2}{\partial y} = -\nu_2 \frac{P_2}{t_2 b E_2} \\ \gamma_{xy2} &= \frac{\partial u_2}{\partial y} + \frac{\partial v_2}{\partial x} = 0\end{aligned}\quad (2)$$

Transformed to the  $s, n$  coordinate system oriented with respect to the bondline, the strains  $\epsilon_{ss}, \epsilon_{nn}, \gamma_{sn}$  are found:

$$\begin{aligned}\epsilon_{ss1} &= \epsilon_{xx1} (\cos^2 \theta - \nu_1 \sin^2 \theta) \\ \epsilon_{nn1} &= \epsilon_{xx1} (\sin^2 \theta - \nu_1 \cos^2 \theta) \\ \gamma_{sn1} &= \epsilon_{xx1} \left( \frac{1 + \nu_1}{2} \sin 2\theta \right) \\ \epsilon_{ss2} &= \epsilon_{xx2} (\cos^2 \theta - \nu_2 \sin^2 \theta) \\ \epsilon_{nn2} &= \epsilon_{xx2} (\sin^2 \theta - \nu_2 \cos^2 \theta) \\ \gamma_{sn2} &= \epsilon_{xx2} \left( \frac{1 + \nu_2}{2} \sin 2\theta \right)\end{aligned}\quad (3)$$

Since the adhesive shear stress is uniform through the bondline, the adhesive shear strain  $\gamma_a$  is defined by the displacements  $u_{s1}$  and  $u_{s2}$  of the adherends:

$$\gamma_a = \frac{u_{s1} - u_{s2}}{t_a} \quad (4)$$

If the adhesive material is homogeneous through its entire volume, it is evident that the adhesive can be in a state of uniform shear stress along the bondline only if the shear strain is independent of  $s$ , i.e.,

$\frac{\partial \gamma_a}{\partial s} = 0$ , or in terms of the adherend strains (Equation 4):

$$\frac{\partial \gamma_a}{\partial s} = \frac{1}{t_a} \left( \frac{\partial u_{s1}}{\partial s} - \frac{\partial u_{s2}}{\partial s} \right) = \frac{1}{t_a} \left( \epsilon_{ss1} - \epsilon_{ss2} \right) = 0 \quad (5)$$

The design criterion for uniform shear stress  $\tau_a$  in the adhesive can then be obtained from Equations (5), (3) and (2):

$$\frac{P_1}{t_1 b E_1} \left( \cos^2 \theta - \nu_1 \sin^2 \theta \right) = \frac{P_2}{t_2 b E_2} \left( \cos^2 \theta - \nu_2 \sin^2 \theta \right) \quad (6)$$

Equation (6) is merely a mathematical statement of the well-known fact that adhesive shear strains can be made more nearly uniform if the tensile strains in the adherends can be matched more precisely. This strain-matching criterion is actually employed intuitively when leading edges of doublers are tapered — a common practice. Assuming adherends of like material, for example, the large load  $P \sim P_1$  in the mainplate at this leading edge is best accommodated by a very thin doubler. In this particular case, the criterion (6) for the doubler design becomes

$$\frac{P_1}{t_1} = \frac{P_2}{t_2} \quad (7)$$

where the adherend loads  $P_2$  and  $P_1$  are determined by (1). This criterion has been satisfied more-or-less intuitively in past applications.

Substituting (1) into (6) and recalling that the shear stress  $\tau_a$  is postulated constant, the design criterion for uniform adhesive shear stress is

$$\begin{aligned} \tau_a \left( \frac{1}{t_1 E_1} \int_0^x \frac{dx}{\cos^2 \theta} \right) (\cos^2 \theta - \nu_1 \sin^2 \theta) \\ = \tau_a \left( \frac{1}{t_2 E_2} \int_x^L \frac{dx}{\cos^2 \theta} \right) (\cos^2 \theta - \nu_2 \sin^2 \theta) \quad (8) \end{aligned}$$

Note that the criterion (8) was developed assuming infinite adherend shear moduli. The abrupt changes of adherend thickness would require diffusion of stresses through shear transfer, and Equation (8) would be less accurate in these regions. Since finite shear moduli have an attenuating effect on the adherend tensile strains, the criterion (8) should yield conservative designs in such cases.

### Illustrative Examples

Application of (8) will be discussed with the aid of several examples. The question will be posed as follows: Given a mainplate of constant width  $b$ , specified material properties  $E_2(x), \nu_2(x)$ , and specified geometry  $t_2(x), \theta_2(x)$ , determine the optimum doubler properties  $E_1(x), \nu_1(x)$  and/or geometry  $t_1(x), \theta_1(x)$ .

#### (a) Double-Lap Butt Joint, Straight Mainplate, Titanium

In this case,  $E_2 = 16 \times 10^6$  psi,  $\nu_2 = .33$ ,  $\theta_2 = 0$ ,  $t_2 = .10$  inches are assumed. The ideal configurations for

aluminum ( $E_1=10 \times 10^6$  psi,  $\nu_1=.33$ ), titanium, and steel ( $E_1=30 \times 10^6$  psi,  $\nu_1=.33$ ) doublers are shown in Figure 3-29. Theoretically, an infinite thickness is required at the point  $x=L$ , but this condition is mitigated by the shear deformations in the doubler at this point. Current practices can obviously be improved by tapering the leading edges of the doubler, and by using reduced-modulus filler in the gap between the main plates. These facts have already been recognized, of course, but Equation (8) provides a theoretical basis for the alterations.

(b) Double-Scarf Joint, Tapered Mainplate, Titanium Mainplate

In this case,  $E_2=16 \times 10^6$  psi,  $\nu_2=.33$ ,  $t_2=.10$  inches and  $\theta_2(x)=\theta_{20}=\text{constant}$  are assumed. The ideal configurations for aluminum, titanium and steel doublers are shown in Figure 3-30. Note that the standard doubler configuration is optimum for like materials only. Dissimilar adherend materials require modified doubler geometries.

(c) Double-Lap Butt Joint, Stepped Bondline, Titanium Mainplate, Standard Doubler Geometry

In this case, the joint geometry is specified, and only the doubler modulus can be varied. The ideal doubler modulus is plotted as a function of bondline position in Figure 3-31a. The shear lag problem

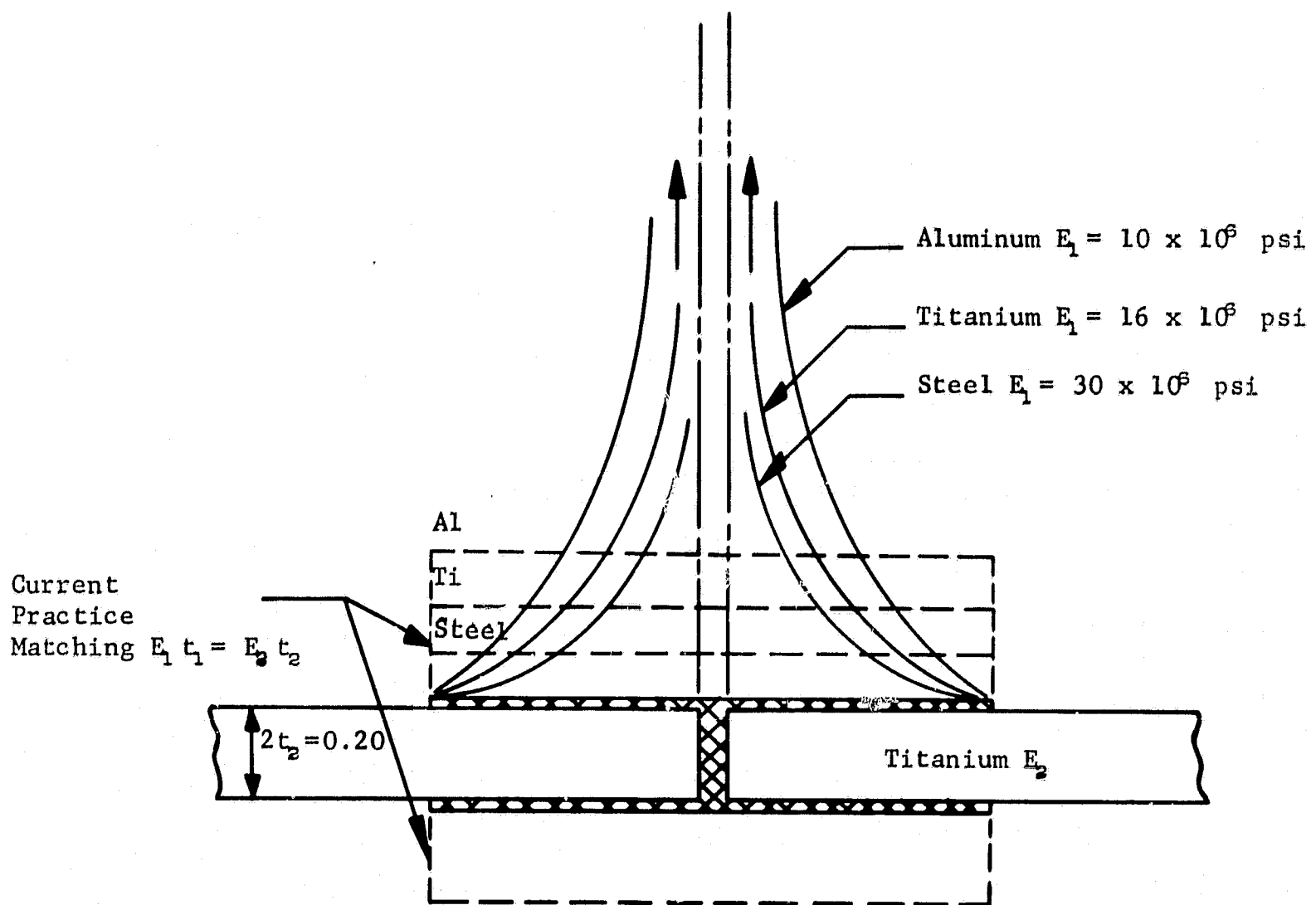


Figure 3-29. Optimum Doubler Configuration for Double-Lap Joint, Compared with Current Practice.

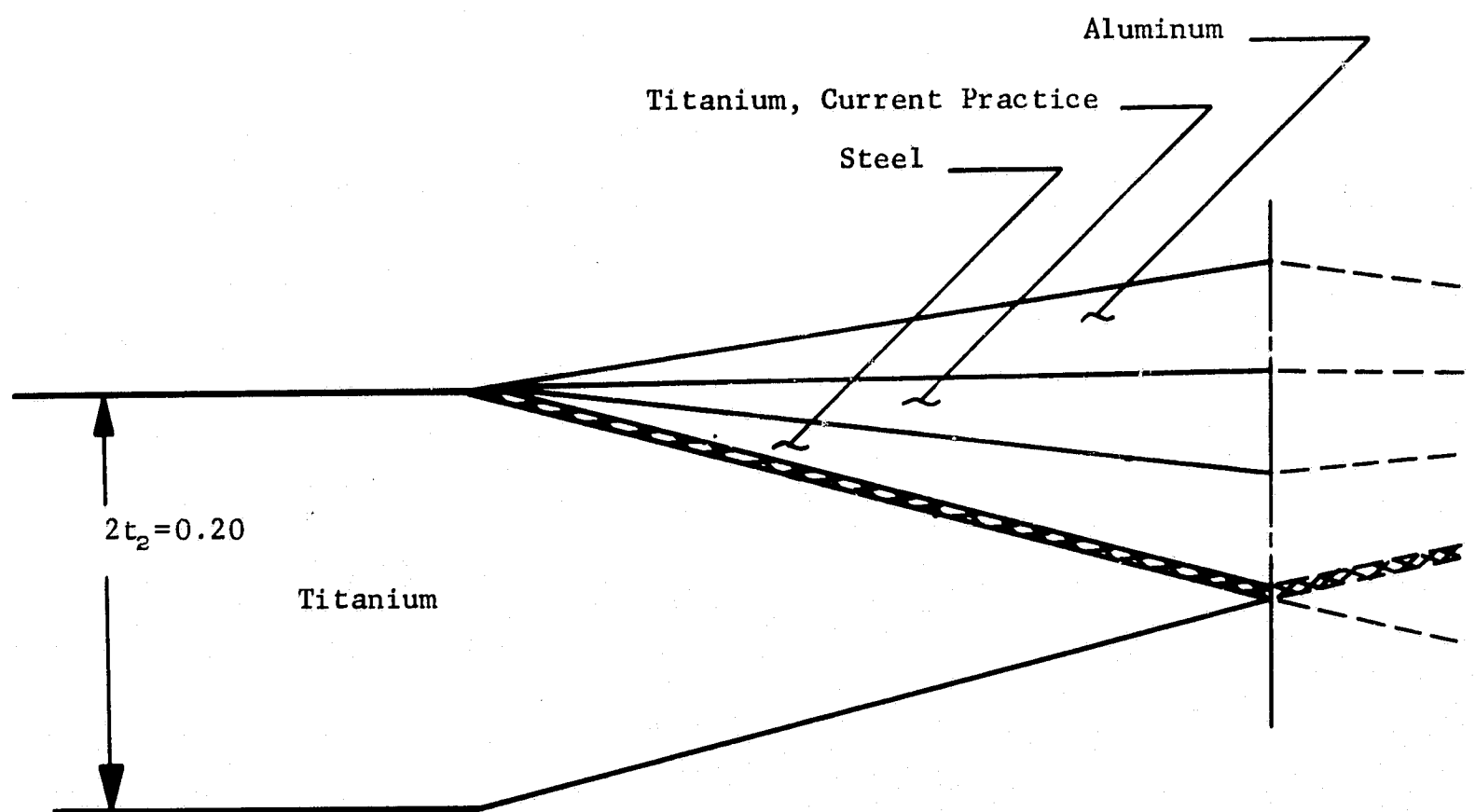
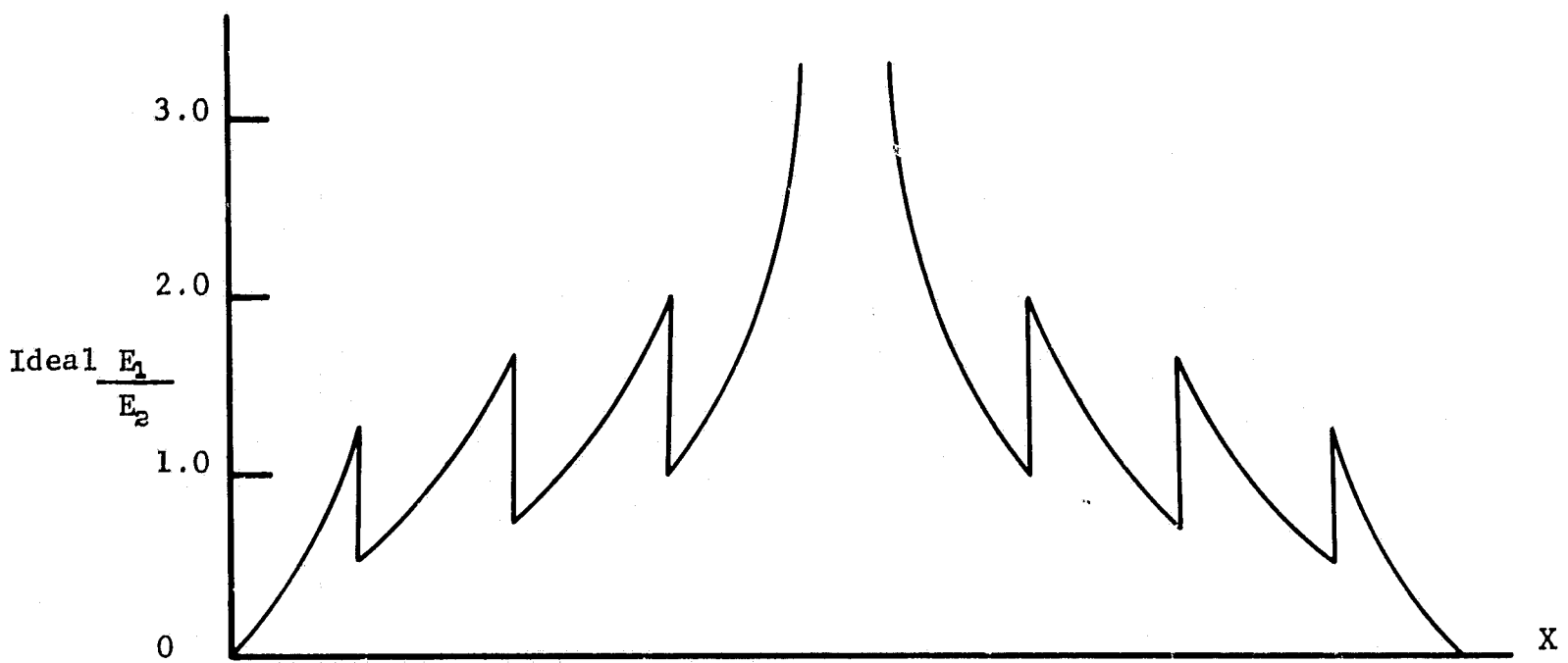
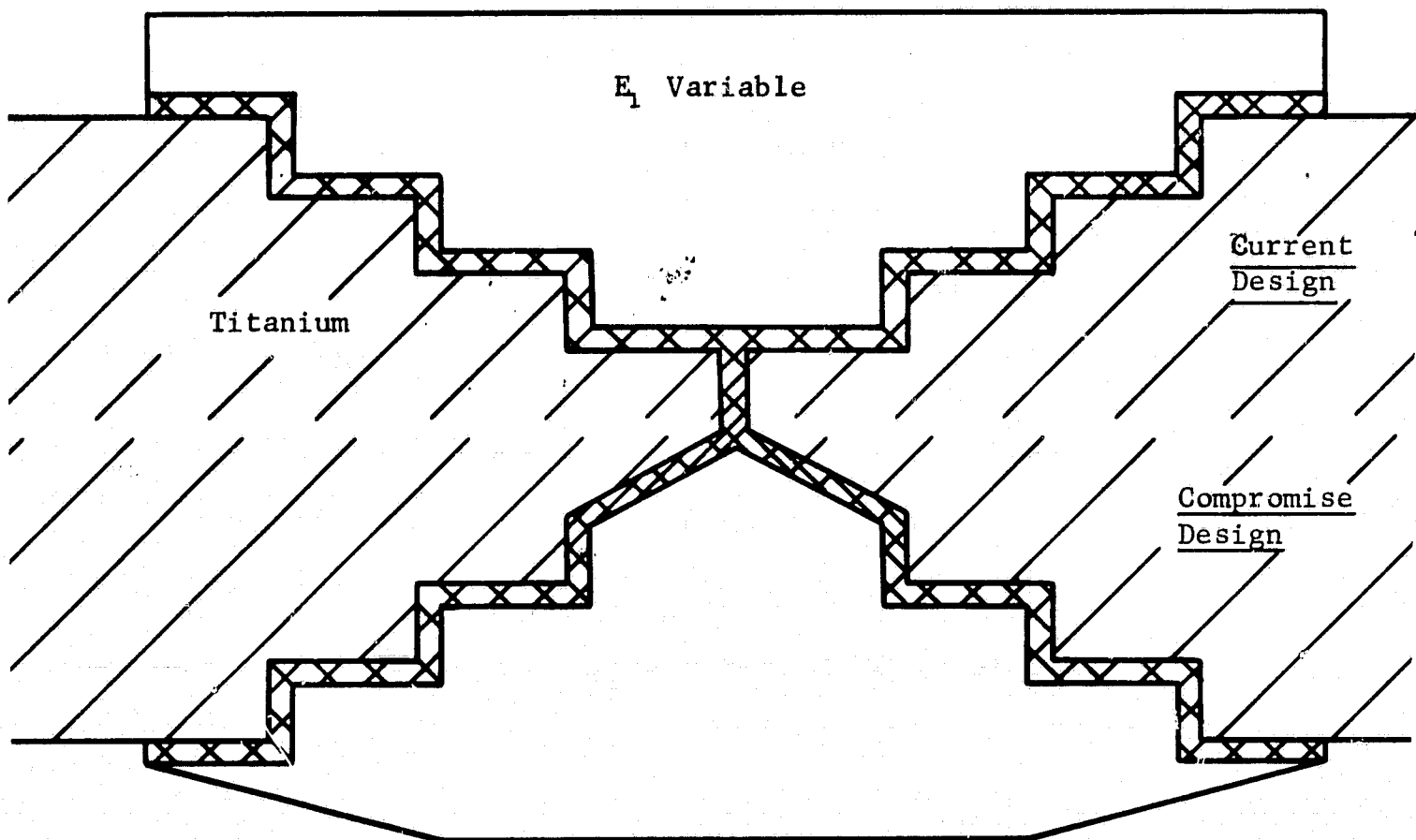


Figure 3-30. Optimum Doubler Configuration for Double-Scarf Joint, Compared with Current Practice.



(a) Optimum Modulus



(b) Stepped-Lap Doubler Configurations

Figure 3-31. Current and Compromise Stepped-Lap Joint Designs.

at the steps is not considered here. If some freedom is allowed in doubler geometry, the compromise design shown in the bottom half of Figure 3-31b is a definite improvement over the current-practice design shown in the top half of Figure 3-31b. However, if the current-design geometric configuration is a requirement, the only way to achieve the criterion is to alter the tensile modulus continuously along the bondline. This, obviously, is impossible for a metallic doubler, but can be approached, at least, if the doubler is of composite construction. This possibility will be considered in the next example.

(d) Double-Lap Butt Joint, Stepped Bondline, Standard Doubler Geometry

In this case, no restriction is imposed on the adherend moduli, and the curve of Figure 3-31a can be applied to the tailoring of these moduli. A means of approximating this criterion is represented in Figure 3-32. This joint design more fully utilizes the tailoring capabilities of composite materials by "grading" the adherend tensile moduli through their thicknesses. In this case, the criterion (8) would be considered a guideline; verification of the improvement would be a job for the finite-element computer program.

The means for selection of the moduli in example (d) would logically be a practical implementation of (8). Instead of matching strains, point-for-point, it would be practical to require that the total elongations be equal over each selected sublength, i.e.,

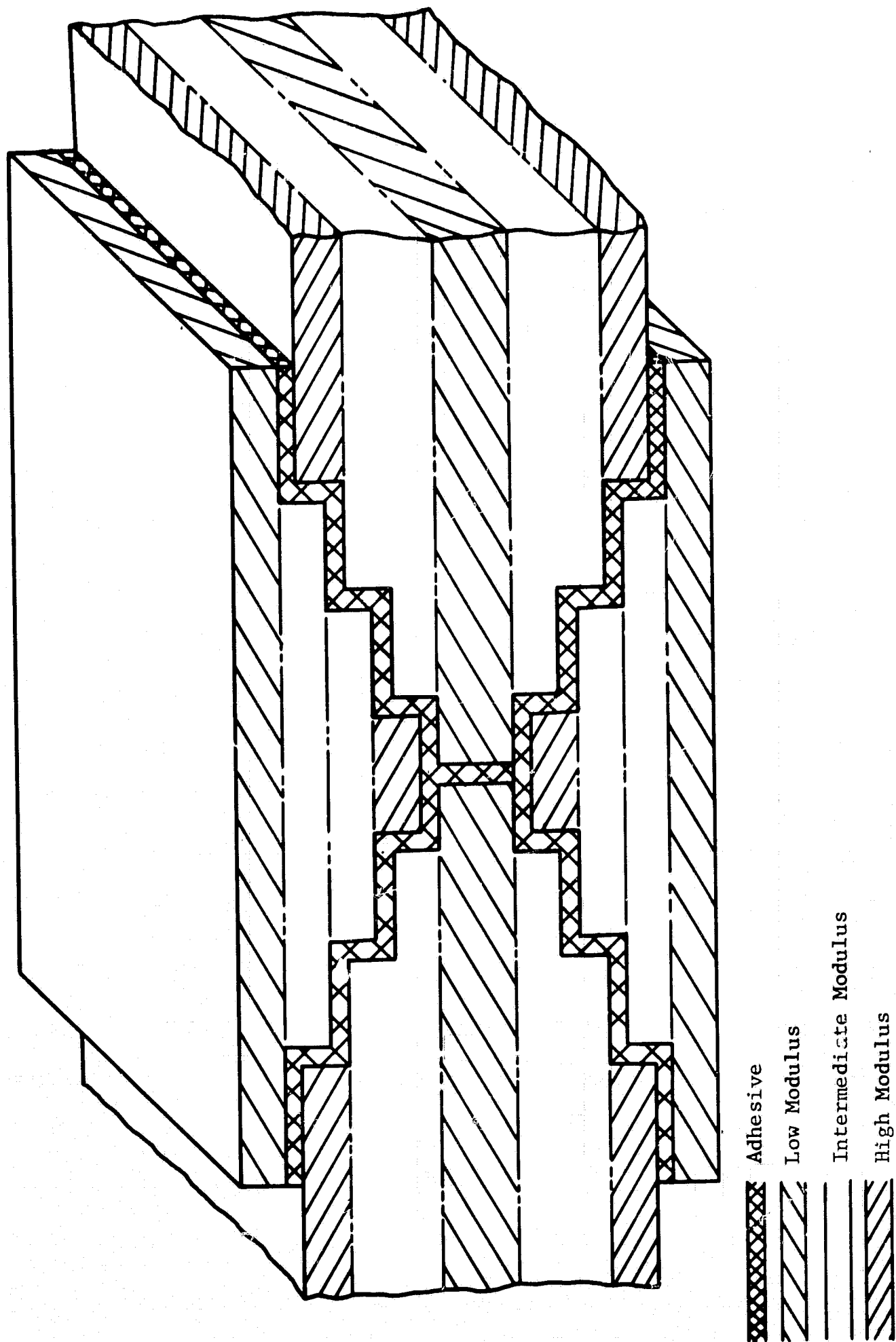


Figure 3-32. Schematic of "Optimized" Composite Stepped-Lap Joint.

$$\int_{S_i}^{S_{i+1}} \epsilon_{ss1} ds = \int_{S_i}^{S_{i+1}} \epsilon_{ss2} ds \quad (9)$$

or, equivalently, that the average tensile strains be equal over these sublengths. The moduli corresponding to (9) could then be obtained by judicious choice of layup patterns, if laminated filamentary composite materials are to be used to fabricate the adherends.

The following sections describe results of a study to implement the unique properties of filamentary composite materials in designing optimum joints. A four-step bondline has been adopted, and the effects of varying cross-sectional modulus and/or step depth according to (8) have been considered.

## SECTION 4

### DESIGN OF STEPPED-LAP BONDED JOINTS USING THE SIMPLIFIED CRITERION

#### Basic Configuration

The basic joint configuration shown in Figure 4-33 was chosen for the initial study. Though this design was chosen for its fabricability and demonstration potential, rather than economy, it has practical merit in the joining of dissimilar materials such as titanium and boron-epoxy composites. The adhesive was, in all cases studied, a .005-inch layer of Metlbond 328. The bonding area was maintained constant at 1-inch x 1-inch in all configurations. A brittle adhesive was used in order that the joints would fail catastrophically when peak adhesive shear stresses reached the ultimate adhesive shear strength. Using the brittle adhesive, the magnitude of the applied load at failure would then provide a reliable measure of the degree to which stress concentrations are reduced in the refined designs.

#### Average-Strain Design Criterion for Stepped-Lap Joints

The design criterion (8) reduces to the form (10) for the stepped-lap design of Figure 4-33:

$$\frac{x}{t_1 E_1} = \frac{(L-x)}{t_2 E_2} \quad (10)$$

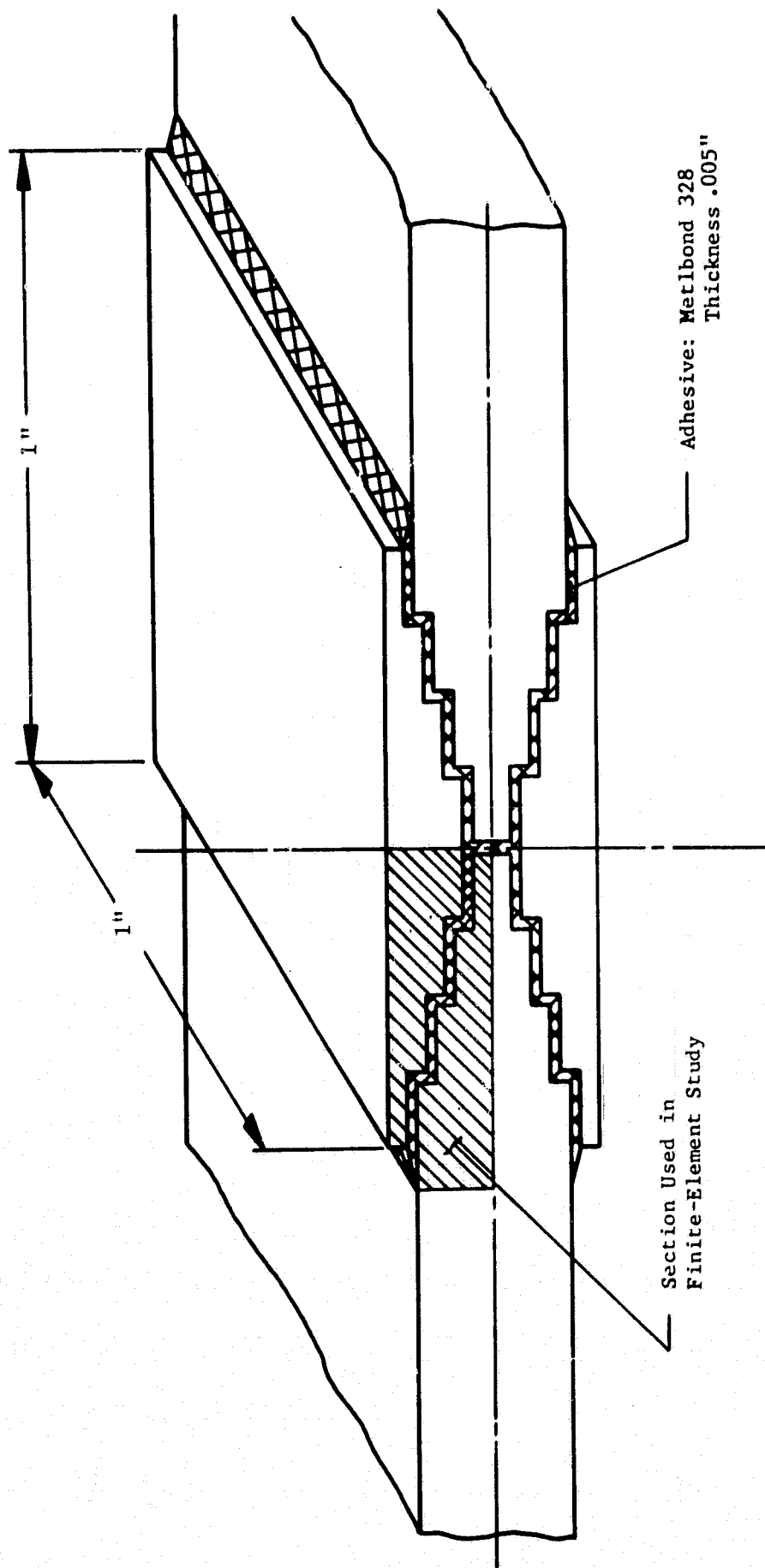


Figure 4-33. Basic Four-Stepped-Lap Joint Considered in Design Study.

When constructed of fiber composite materials with plies parallel to the joint midplane, the thicknesses  $t_{1i}, t_{2i}$  and moduli  $E_{1i}, E_{2i}$  are constant over each step interval  $(x_{i-1} < x < x_i)$ . In order to apply the optimization procedure with these constraints it is necessary to require equal elongations over the step lengths, as in (9), rather than point wise satisfaction of (10). Other reduction schemes could be applied, obviously, but the scheme described here and formulated in Equation (9) is the simplest. By use of (9), the average-strain criterion becomes

$$\left( \frac{x_i + x_{i-1}}{2L} \right) \left( 1 + \frac{t_{2i} E_{2i}}{t_{1i} E_{1i}} \right) = 1 \quad (11)$$

in each subinterval  $(x_{i-1} < x < x_i)$ .

When the straight-lap joint is employed, only one subinterval can be practically considered  $(0 < x < L)$ , and the criterion (11) reduces to the well-known criterion for straight-lap joints:

$$\frac{t_2 E_2}{t_1 E_1} = 1 \quad (12)$$

When departures from (12) exist, the adhesive shear stress distribution loses its symmetry; and the resulting maximum stress concentration will always exceed that obtained through criterion (12).

Two hypothetical four-step-lap joint designs will be considered:

- (a) The four steps are equal in length and depth, both in the doubler and the main plate, but adherend moduli may vary; and

- (b) The material moduli are fixed throughout each adherend, and the four steps have equal length, but the step depths may vary.

When the four steps are equal, the relations

$$\begin{aligned} x_i &= \frac{L}{4} \cdot i \\ t_{1i} &= \frac{t}{5} \cdot i \\ t_{2i} &= \frac{t}{5} \cdot (5-i) \end{aligned} \quad (13)$$

hold, and the cross-sectional moduli must, ideally, satisfy the relations

$$\begin{aligned} \frac{E_{2i}}{E_{1i}} &= \left( \frac{i}{5-i} \right) \left( \frac{8}{2i-1} - 1 \right) = 1.75 \quad (0 < x < \frac{L}{4}) \\ &= 1.11 \quad (\frac{L}{4} < x < \frac{L}{2}) \\ &= 0.90 \quad (\frac{L}{2} < x < \frac{3L}{4}) \\ &= 0.57 \quad (\frac{3L}{4} < x < L) \end{aligned} \quad (14)$$

The ratios of tensile moduli are most readily accomplished, using composite materials in the manner illustrated in Figure 3-32.

When the moduli are equal in each adherend, and the steps are equal in length only, the relations

$$\begin{aligned} E_{2i} &= E_2 ; E_{1i} = E_1 \\ x_i &= \frac{L}{4} \cdot i \end{aligned} \quad (15)$$

hold. The step depths  $t_{1i}$ ,  $t_{2i}$  must satisfy the relations

$$\begin{aligned} \frac{t_{2i}}{t_{1i}} &= \frac{E_1}{E_2} \left( \frac{8}{2i-1} - 1 \right) = 7.00 \quad (0 < x < \frac{L}{4}) \\ &= 1.67 \quad (\frac{L}{4} < x < \frac{L}{2}) \\ &= 0.60 \quad (\frac{L}{2} < x < \frac{3L}{4}) \\ &= 0.14 \quad (\frac{3L}{4} < x < L) \end{aligned} \quad (16)$$

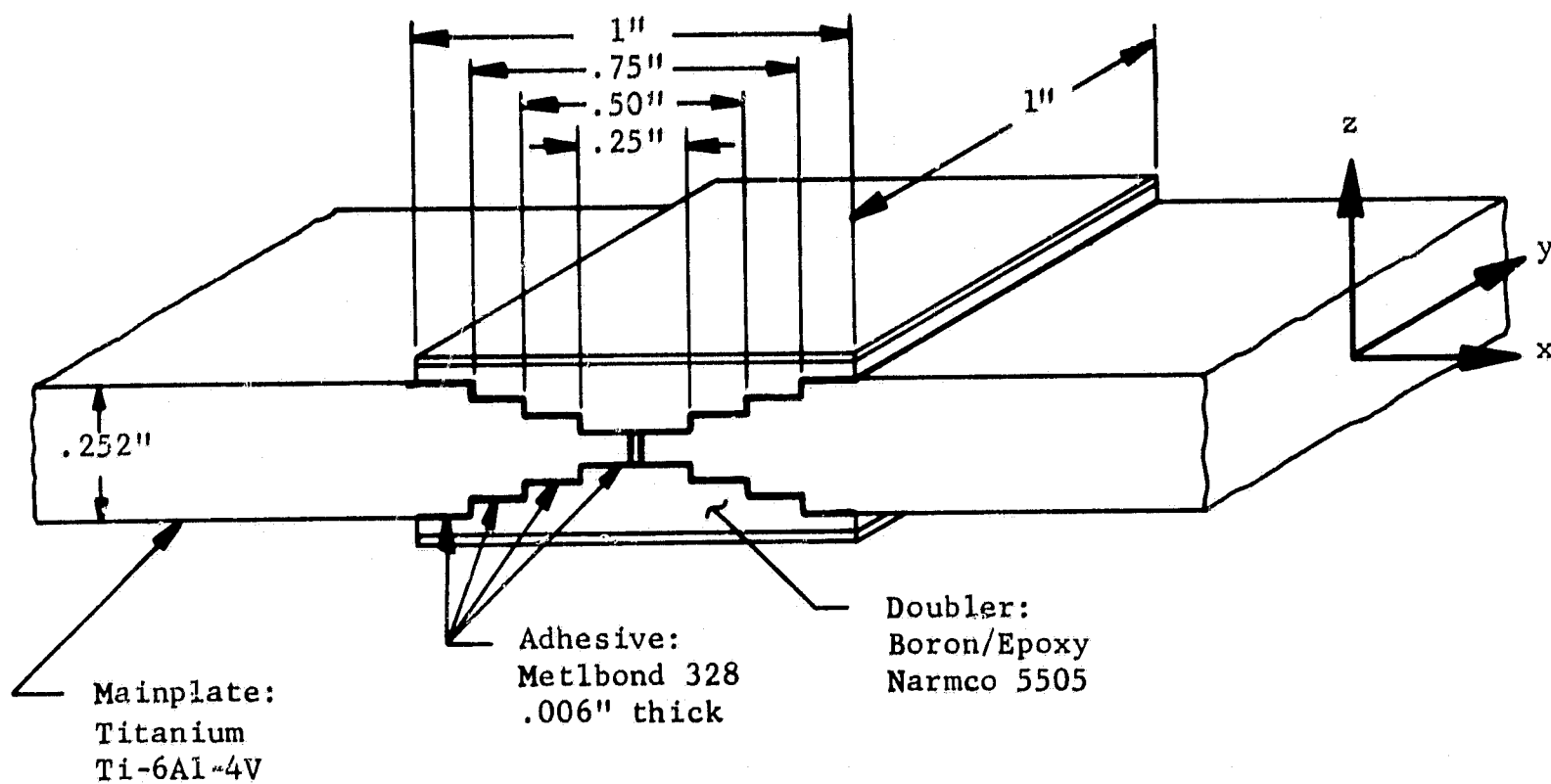
Equations(16) apply even when homogeneous metallic adherends are used.

Like any such failure criterion, the effects of departure from (14) or (16) cannot be directly evaluated from the statement of the criterion (10) itself. Joints designed by these simple criteria can be compared, however, with similar conventional designs by using the finite-element program developed earlier, and by comparing failure loads obtained from actual tests using brittle adhesives. Both approaches have been employed under this program, and sufficient verification of the simplified criterion has been achieved.

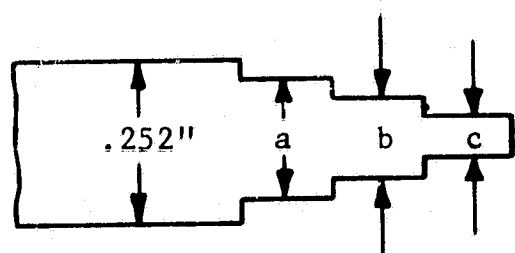
#### Joining of Titanium and Boron/Epoxy

Stepped-lap joints were designed using the average strain criterion (11) for bondlines with four steps. In view of current interest in the joining of titanium and boron-epoxy composite material, the basic design consisted of titanium main plates and boron-epoxy doublers. The bonding agent was Metlbond 328.

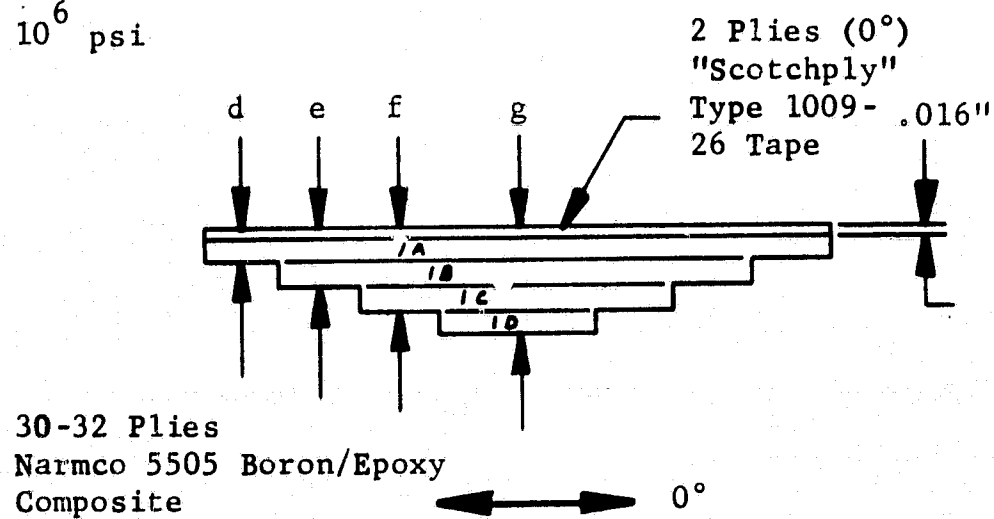
The five design configurations considered in this study are summarized in Figure 4-34 and in the accompanying Table 4-V. Two plies of SCOTCHPLY type 1009-26 tape constitute the outer plies of the doublers while 30 to 32 plies of NMD-5505 boron-epoxy composite material constitute the inner plies. The two SCOTCHPLY plies not only serve as a "finish" to the joint, but they provide backup material for the machining of the



(a) Basic Geometry



(b) Titanium Mainplate,  
 $E = 16 \times 10^6$  psi



(c) Boron-Epoxy Doubler

Figure 4-34. Titanium-Boron/Epoxy Stepped-Lap Joint Configurations and Properties.

TABLE 4-V

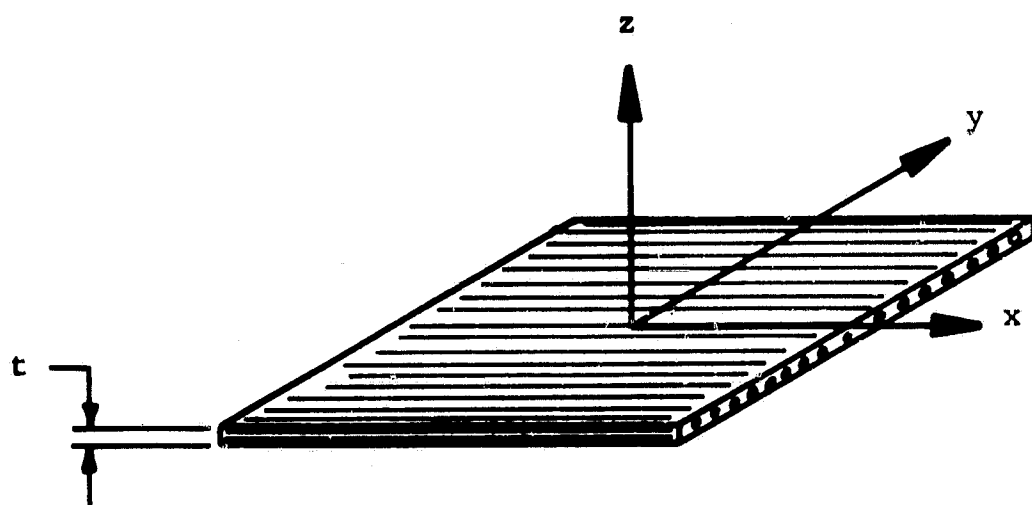
## TITANIUM-BORON/EPOXY STEPPED-LAP JOINT CONFIGURATIONS AND PROPERTIES

| CONFIGURATION<br>NUMBER | MAINPLATE<br>DIMENSIONS, INCHES |      |      | DOUBLER<br>DIMENSIONS, INCHES |      |      |      | TENSILE MODULI, $\text{psi} \times 10^{-6}$ |          |          |          |
|-------------------------|---------------------------------|------|------|-------------------------------|------|------|------|---------------------------------------------|----------|----------|----------|
|                         | a                               | b    | c    | d                             | e    | f    | g    | $E_{1A}$                                    | $E_{1B}$ | $E_{1C}$ | $E_{1D}$ |
| 1                       | .189                            | .126 | .063 | .048                          | .079 | .110 | .142 | 13.1                                        | 16.7     | 16.7     | 16.7     |
| 2                       | .189                            | .126 | .063 | .048                          | .079 | .110 | .142 | 8.3                                         | 13.1     | 27.3     | 30.5     |
| 3                       | .189                            | .126 | .063 | .048                          | .079 | .110 | .142 | 22.5                                        | 27.3     | 20.3     | 13.1     |
| 4                       | .182                            | .108 | .046 | .039                          | .073 | .110 | .142 | 12.3                                        | 16.7     | 16.7     | 16.7     |
| 5                       | .162                            | .090 | .030 | .029                          | .073 | .109 | .141 | 10.8                                        | 16.7     | 16.7     | 16.7     |

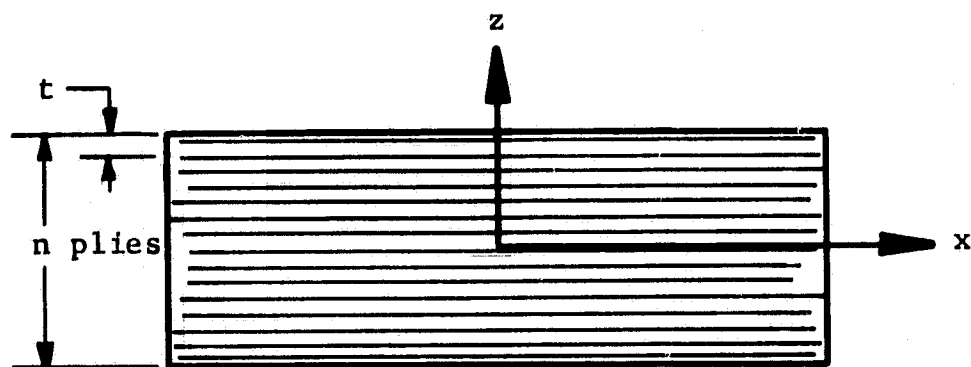
stepped doublers. The moduli  $E_{1A}, E_{1B}, E_{1C}, E_{1D}$  of the sections indicated in Figure 4-34c are determined from the properties of the NMD-5505 boron-epoxy and SCOTCHPLY 1009-26 plies, and from the prescribed  $0^\circ$  and  $90^\circ$  layup pattern for each configuration. The ply properties are summarized in Figure 4-35 and Table 4-VI. The interlaminar shear modulus is unknown for layup patterns which are not unidirectional, i.e., for a  $0^\circ - 90^\circ$  combination. For computation purposes, the moduli for unidirectional ( $0^\circ$ ) patterns were used. Since the order of magnitude of  $G_{zx}$  is more important than an "exact" number, this assumed value will lead to essentially the same conclusions that could be obtained from a more exact value.

Configurations 1, 2 and 3 have identical geometries, but have differing moduli at each doubler cross-section. The mainplate and doubler step depths are equal in these configurations. A comparison of net cross-sectional moduli with the optimum moduli determined from the criterion (11) are shown in Figure 4-36. From this figure, it can be seen that Configuration 2 conforms best to the optimum criterion, Configuration 3 conforms least, and Configuration 1 is an intermediate case. On the basis of this comparison, the strengths of these configurations could be ordered OPTIMUM-2-1-3, in descending order. It was not practical to design a configuration that conformed exactly to the optimum because the specified doubler thickness limits the number of  $0^\circ$  and  $90^\circ$  plies available for modulus-tailoring in each step. The values shown in Table 4-V can be attained, using  $0^\circ$  and  $90^\circ$  orientations only. More refined tailoring of tensile moduli could be achieved by using other orientations, but serious difficulties with torsional coupling effects and nonlinear stress-strain properties would obscure the intended demonstration.

Configurations 4 and 5 are joints with near-identical modulus ratios at the different cross-sections, but with differing step depths. A comparison of step-depth ratios for Configurations 3, 4, 5 with the optimum ratios determined from (11) are shown in Figure 4-37. Conformity



(a) Ply Configuration



(b) Laminate Configuration

Figure 4-35. Geometry of Composite Ply Laminate

TABLE 4-VI

PROPERTIES OF COMPOSITE PLIES

| BORON/EPOXY (NMD-5505)                               | GLASS/EPOXY (SCOTCHPLY 1009-26)                      |
|------------------------------------------------------|------------------------------------------------------|
| $E_x = 30.0 \times 10^6$ psi [4]                     | $6 \times 10^6$ psi from [4]                         |
| $E_y = 3.2 \times 10^6$ psi [4]                      | $3.2 \times 10^6$ psi from [6]                       |
| $\nu_{xy} = .040$ [4]                                |                                                      |
| $\nu_{yx} = .370$ [4]                                |                                                      |
| $G_{xy} = 1.05 \times 10^6$ psi [4]                  |                                                      |
| $G_{zx} = 1.5 \times 10^6$ psi [4]                   | $1.25 \times 10^6$ psi [5]                           |
| $E_z = 3.2 \times 10^6$ psi from [6]                 | $3.2 \times 10^6$ psi from [6]                       |
| Average thickness, $t = .004$ -inch<br>in Lamination | Average thickness, $t = .007$ -inch<br>in Lamination |

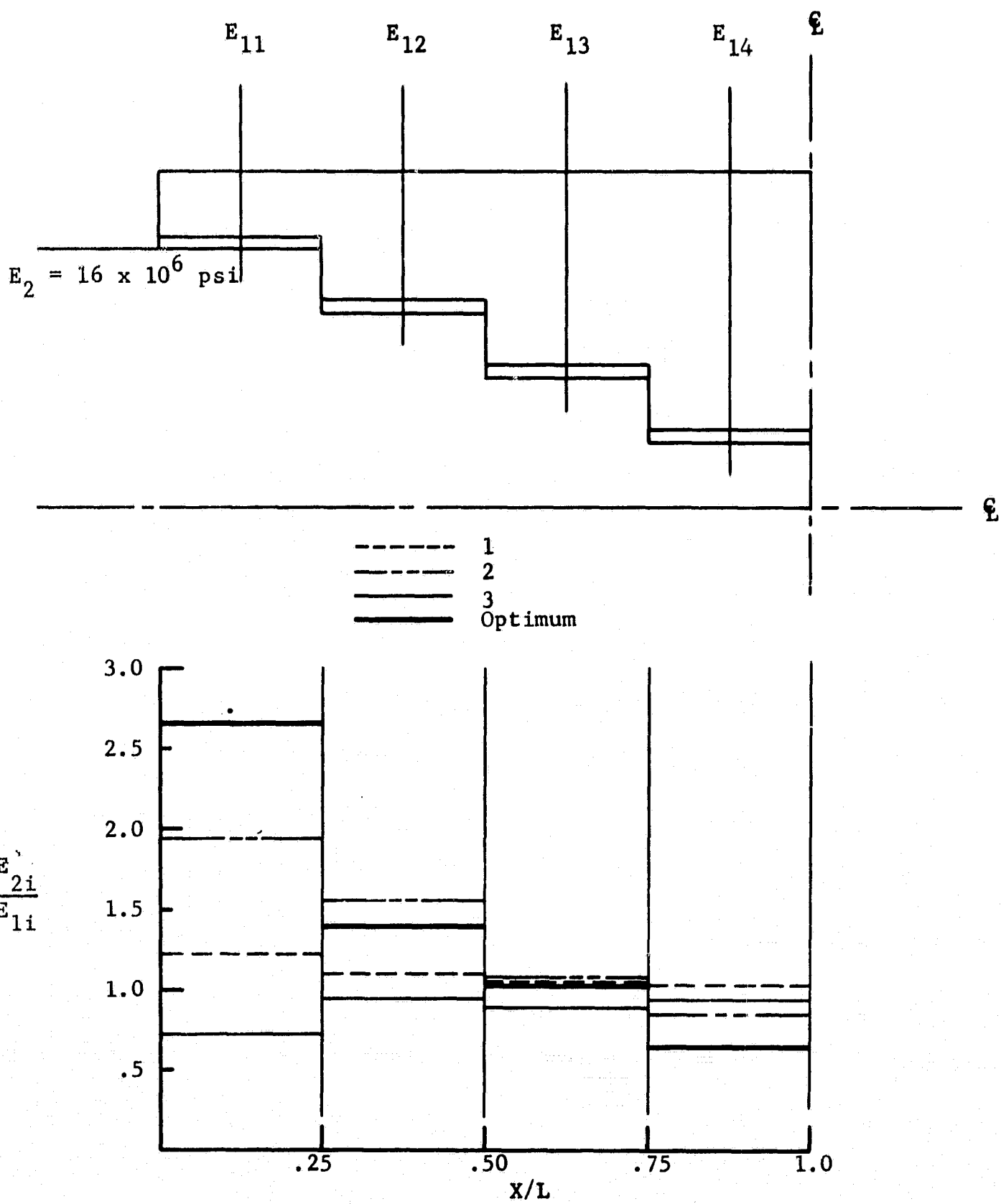
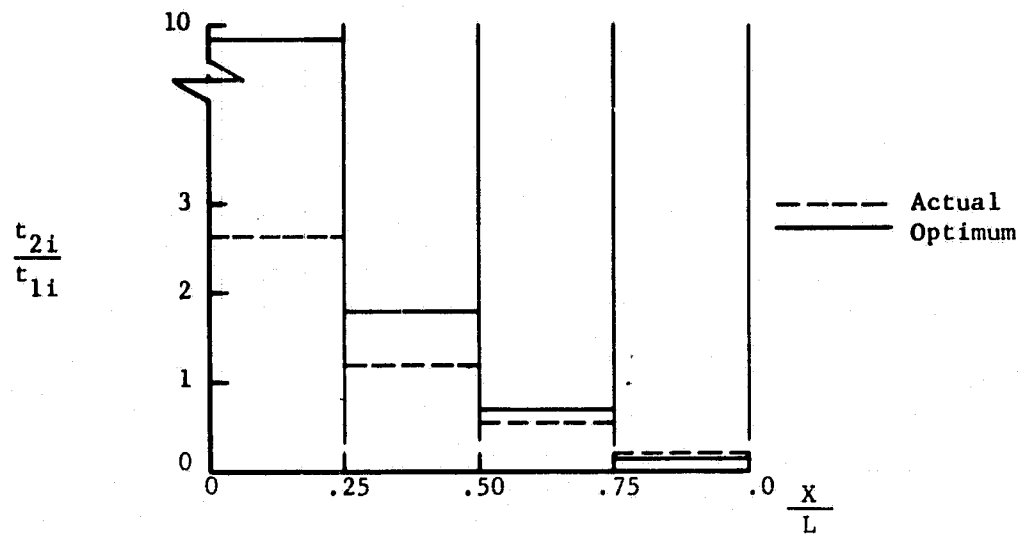
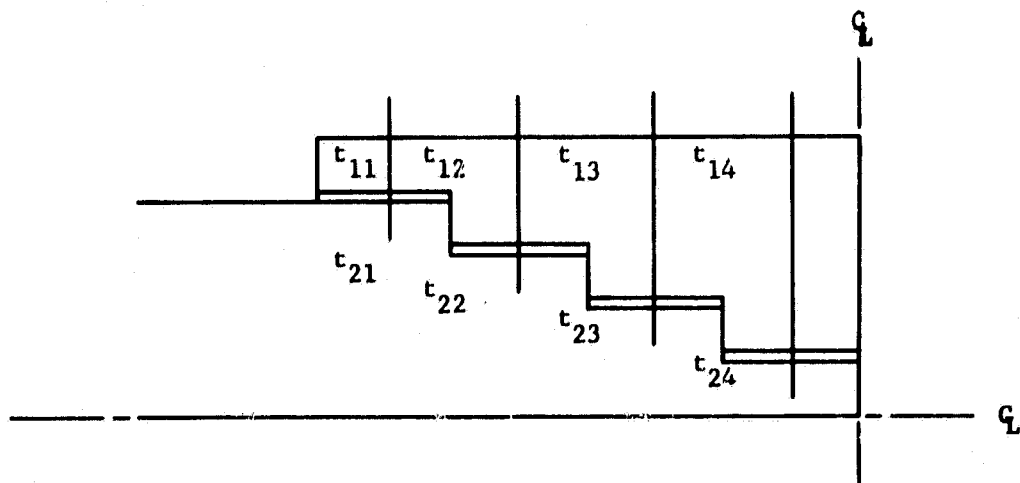
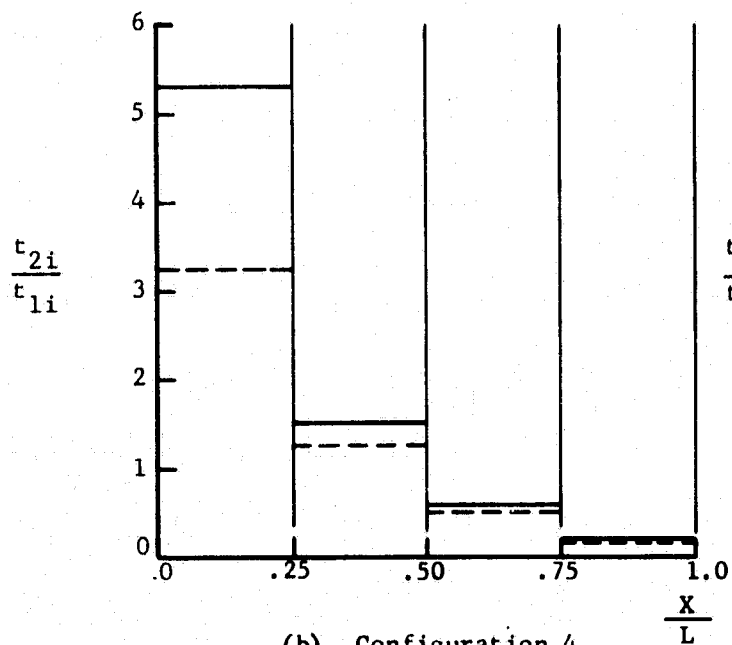


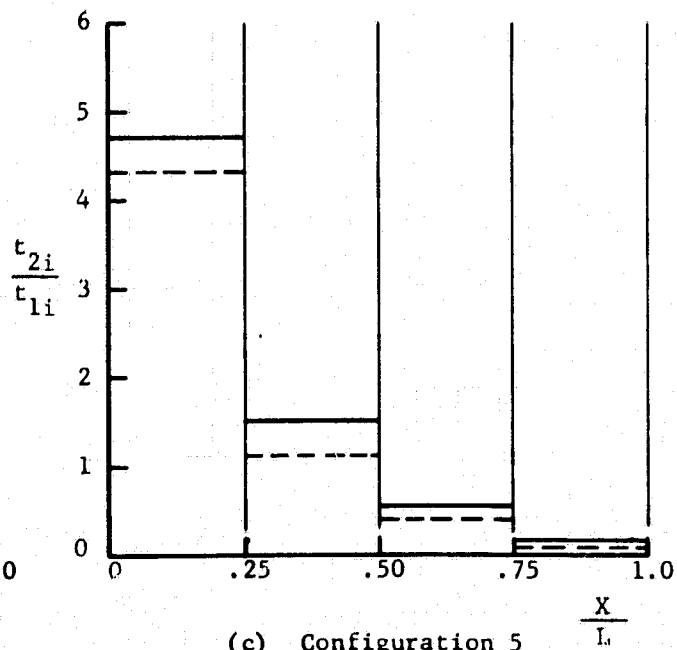
Figure 4-36. Comparisons of Average-Strain Modulus Ratios  $E_{2i}/E_{1i}$  for Stepped-Lap Configurations 1,2,3.



(a) Configuration 3



(b) Configuration 4



(c) Configuration 5

Figure 4-37. Comparisons of Average-Strain Thickness Ratio  $t_{2i}/t_{1i}$  for Stepped-Lap Configurations 3,4,5.

to the optimum configuration is, in each case, excellent except in the region  $(0 < x < \frac{L}{4})$ . In this range, Configurations 3 and 4 depart from the optimum. On the basis of this comparison, Configuration 5 should provide the strongest joint, while Configuration 3 should be significantly lower in strength than either of the other two. In descending order, the relative strengths are expected to be OPTIMUM-5-4-3.

The qualitative evaluation obtained from the simplified design criterion (11) is corroborated in Figures 4-38 and 4-39, in which the five adhesive shear stress distributions are determined from the finite-element program. In Figure 4-38, the lowest peak stresses and, consequently, the highest strength occurs with Configuration 2. Configuration 3 exhibits the highest peak stresses, while Configuration 1 has intermediate peak levels. In Figure 4-39, the lowest peak stresses occur in Configuration 5, while Configuration 3 exhibits the highest peak levels. These evaluations, obtained from a rather involved finite-element procedure, agree qualitatively with the predictions obtained from the simplified average-strain design criterion (11). With the aid of the criterion (11), it appears feasible to develop initial optimum designs of joints in composite materials without employing lengthy, expensive, finite-element parameter studies. Once the basic geometry and properties have been established by this procedure, the finite-element program could then be used, if necessary, to numerically evaluate the developed joint stresses.

#### Fabrication and Testing of Stepped-Lap Titanium-Boron/Epoxy Joints

The five configurations specified in Table 4-V and Figure 4-34 were fabricated and tested to evaluate the simplified failure criterion. The adherend layup patterns are summarized in Appendix C, Table C-1. The construction, before bonding, is illustrated in Figure 4-40. The holes in the titanium mainplates accommodate the loading apparatus. The five completed configurations are shown in Figure 4-41, with four specimens per configuration. Close-ups of the bondlines for one specimen of each configuration are shown

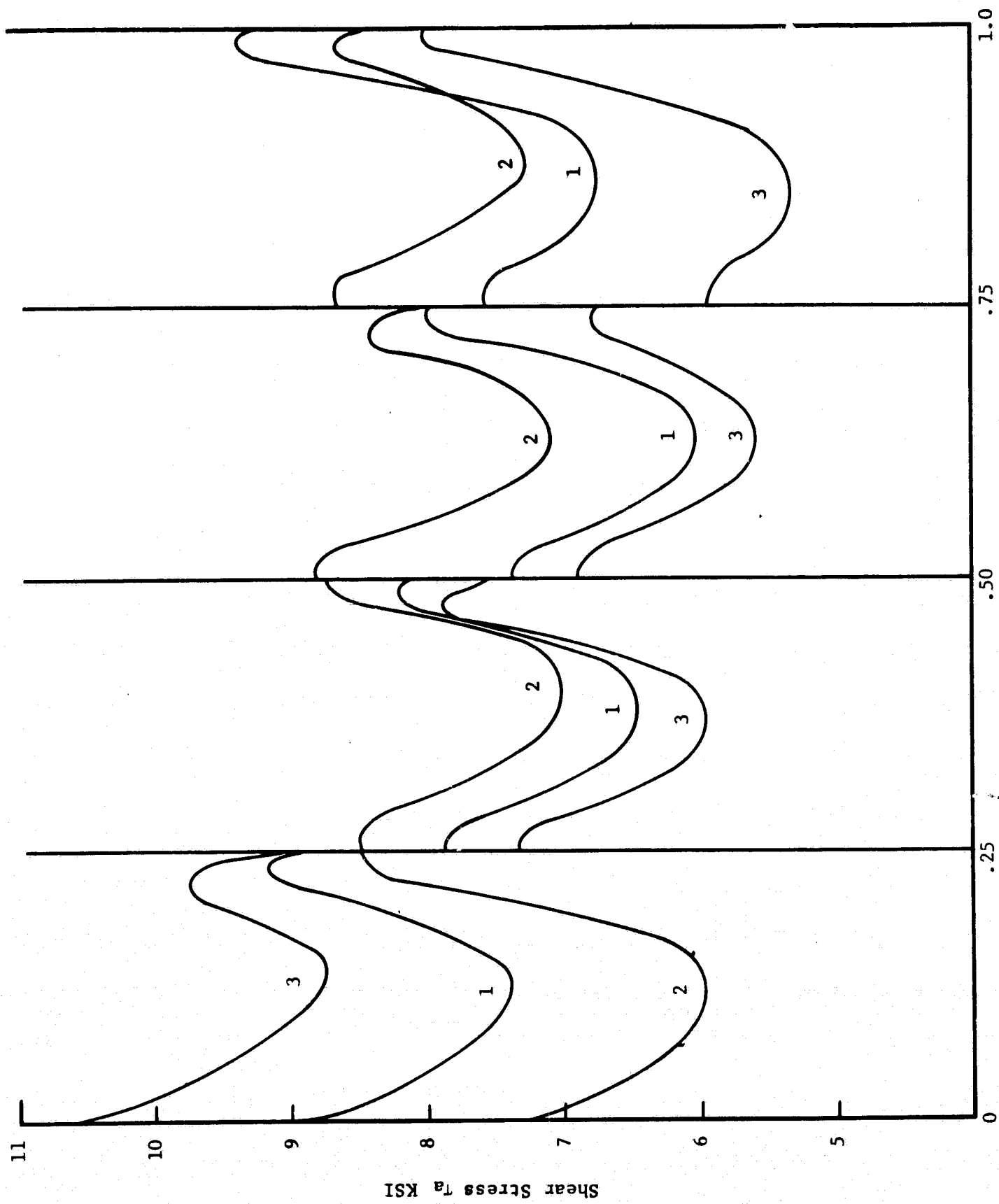


Figure 4-38. Finite-Element Adhesive Shear Stress Distributions for Stepped-Lap Configurations 1, 2, 3.

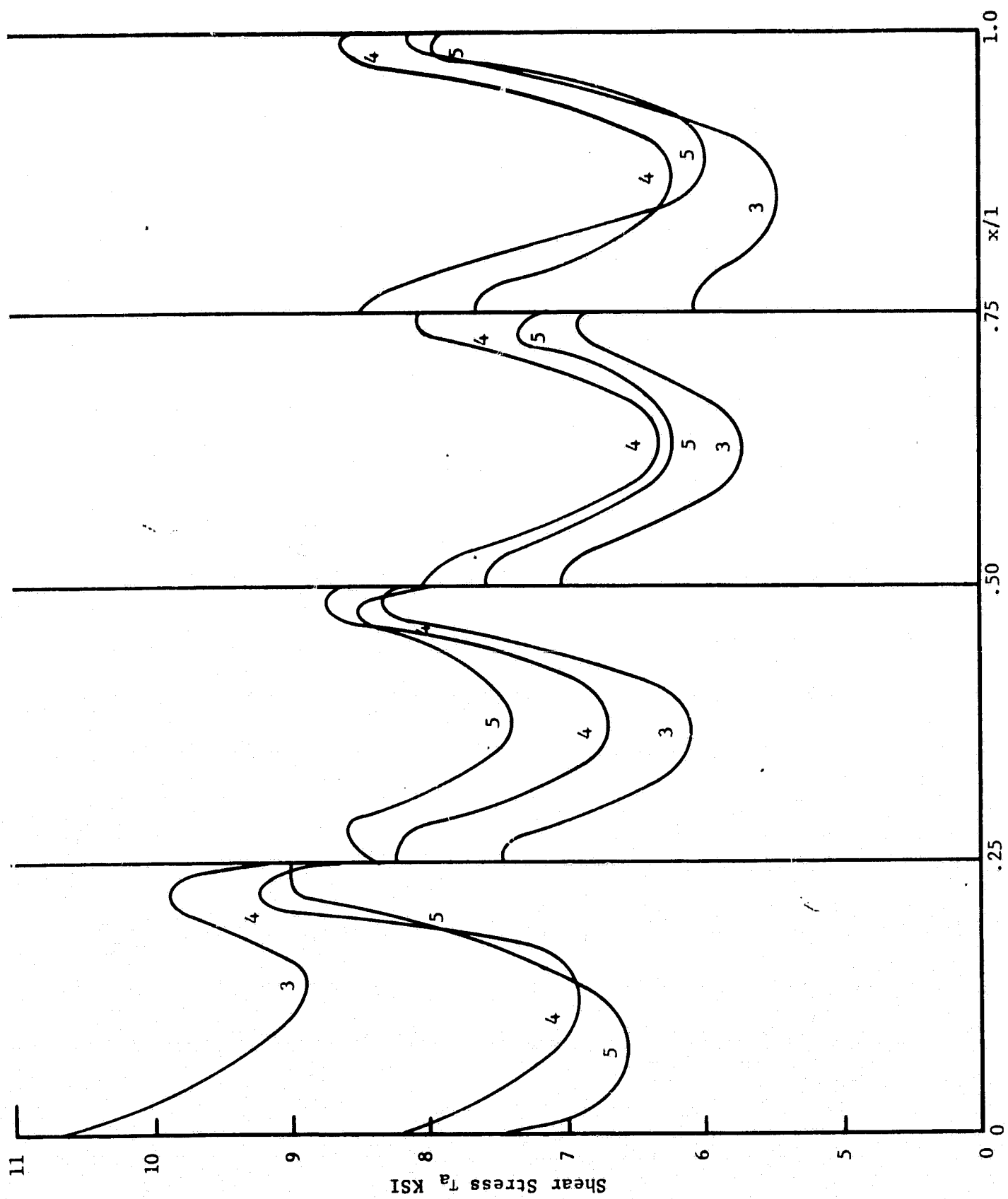


Figure 4-39. Finite-Element Adhesive Shear-Stress Distributions for Stepped-Lap Configurations 3, 4, 5.

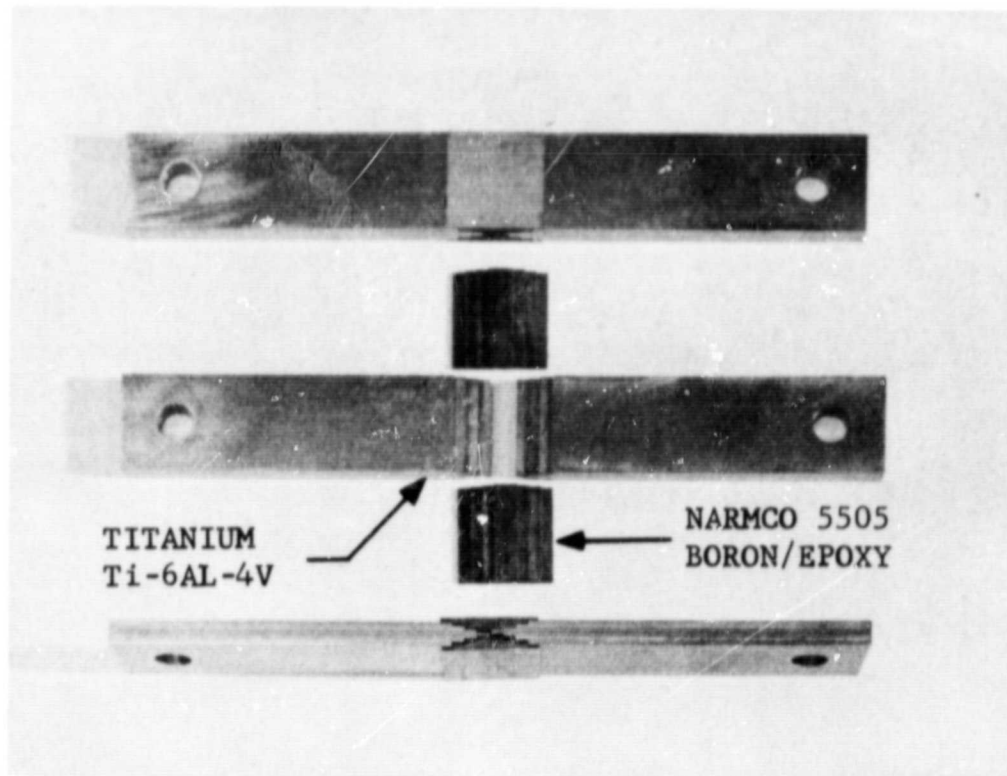


Figure 4-40. Titanium-Boron/Epoxy Stepped-Lap Joint; Before Bonding.

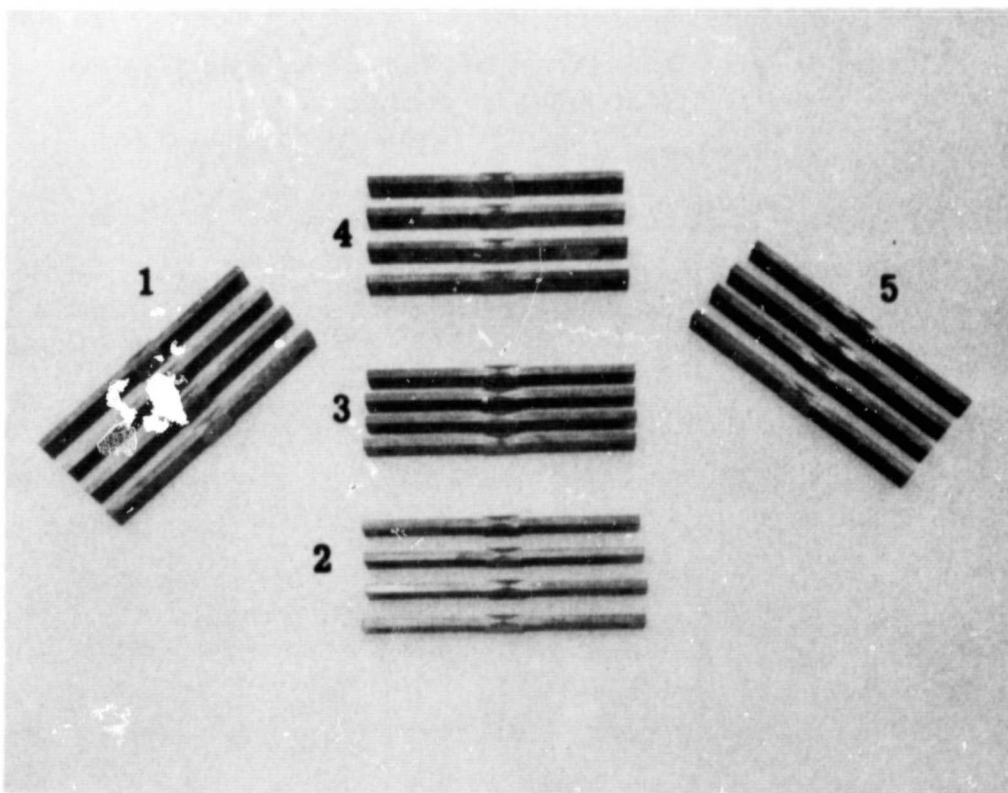


Figure 4-41. Titanium-Boron/Epoxy Stepped-Lap Joint; Five Configurations Completed.

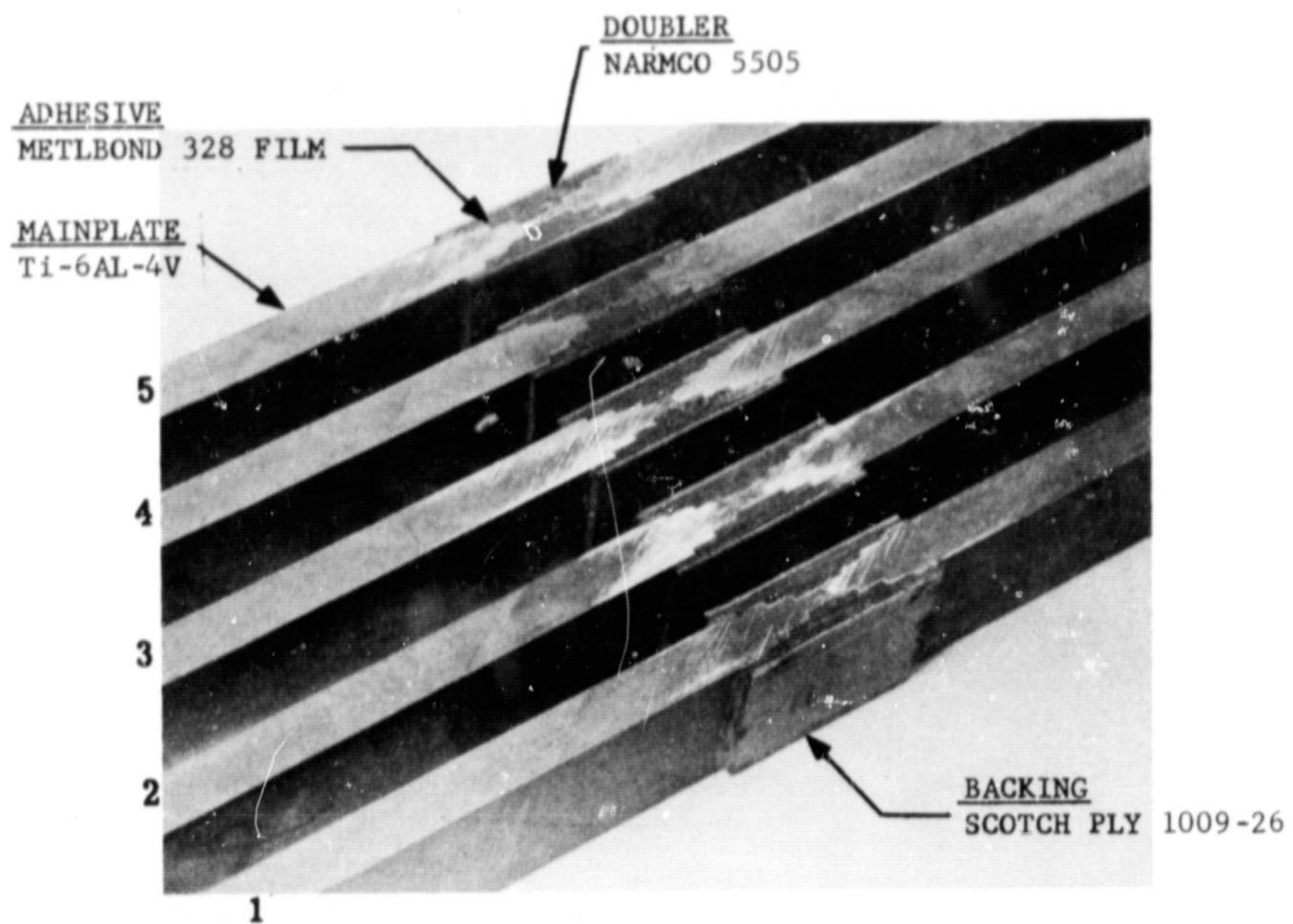


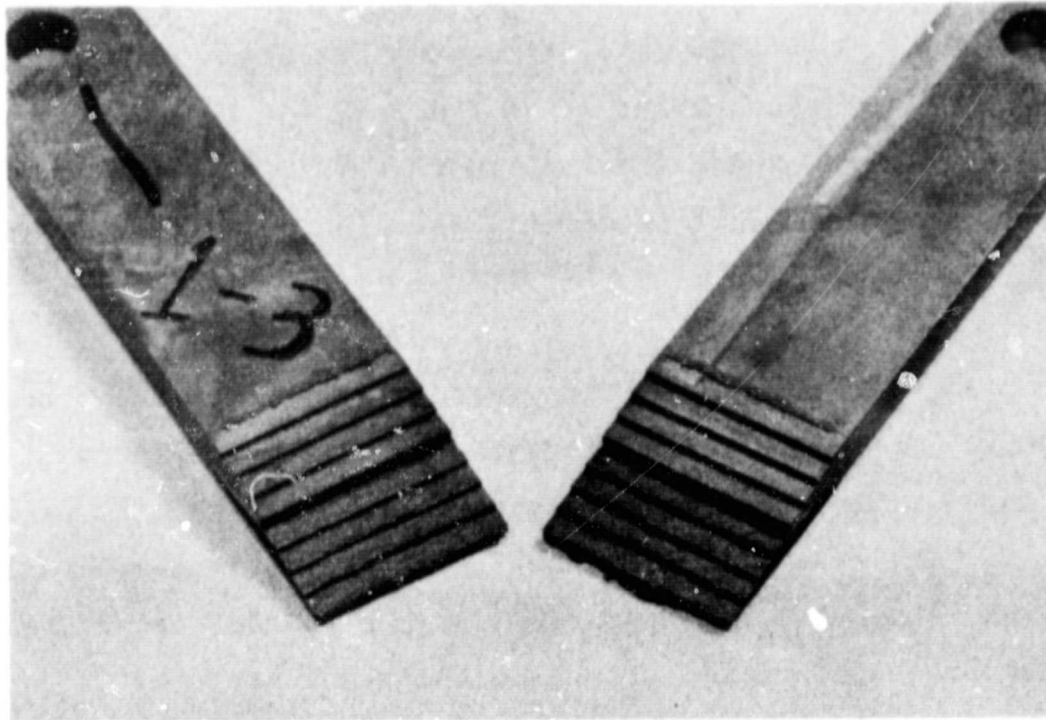
Figure 4-42. Bondlines of Titanium-Boron/Epoxy Stepped-Lap Joints.

in Figure 4-42. Note that the step depths for Configurations 1, 2 and 3 are the same, while those of 4 and 5 are varied. The glass backing can be clearly seen on the doublers in this figure. The marks on the titanium mainplates result from a light filing that was done to break corners prior to bonding.

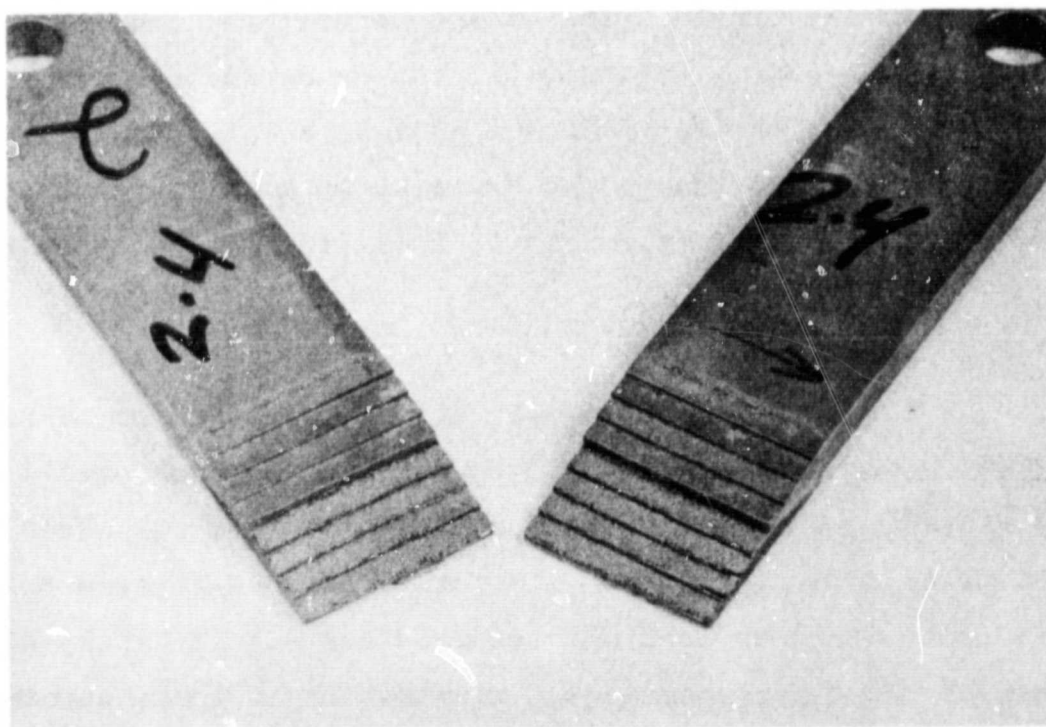
The titanium mainplates were etched, using the procedure outlined in both Appendix B and Reference [8]. The mainplates of Configurations 1 and 2 were subjected to a single cycle of the etch procedure in Appendix B. The remaining three configurations were subjected to two etching cycles. The boron/epoxy doublers were prepared, using the simple MEK degreasing procedure of [9], omitting the sandblast step.

The failures for Configurations 1 and 2 are shown in Figure 4-43. Note that the failure occurs in the adhesive-to-titanium interface. The failures for Configuration 3, 4 and 5 are shown in Figure 4-44. In these cases, the failure occurs nearly equally in the adhesive-to-titanium interface and in the first layers of the boron-epoxy doublers. Since the composite shear stress is directly related to bondline shear stress in joints of this type, the optimization procedure will lead to likewise reduced peak shear stresses in the boron/epoxy doublers. Thus, the average shear stresses at failure will still follow the order established by the optimization criterion.

The results of the tensile failure tests are summarized in Table 4-VII. Two data points were rejected, using Chauvenet's criterion outlined in [10]. This criterion provides a statistical basis for evaluation of data that appears extraneous, i.e., that appears to come from specimens whose fabrication and/or loading histories are significantly different from those of the other specimens. Examination of these specimens after their rejection revealed doubler misalignment during bonding, and it can be concluded that their rejection was justified. A strong correlation exists between the percent standard deviation ( $\sigma, \%$ ) of the joint strengths and the number of etch cycles applied to the titanium doublers. Not only

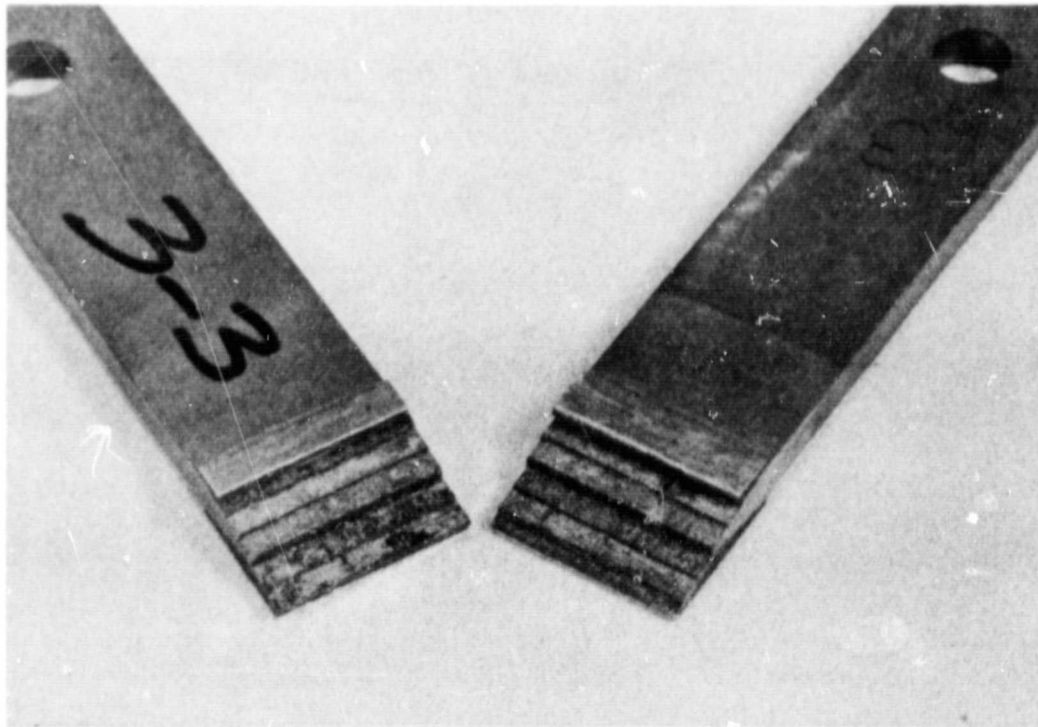


(a) Configuration 1. Failure at Average Stress  
= 2890 psi, Standard Deviation = 15.0%.

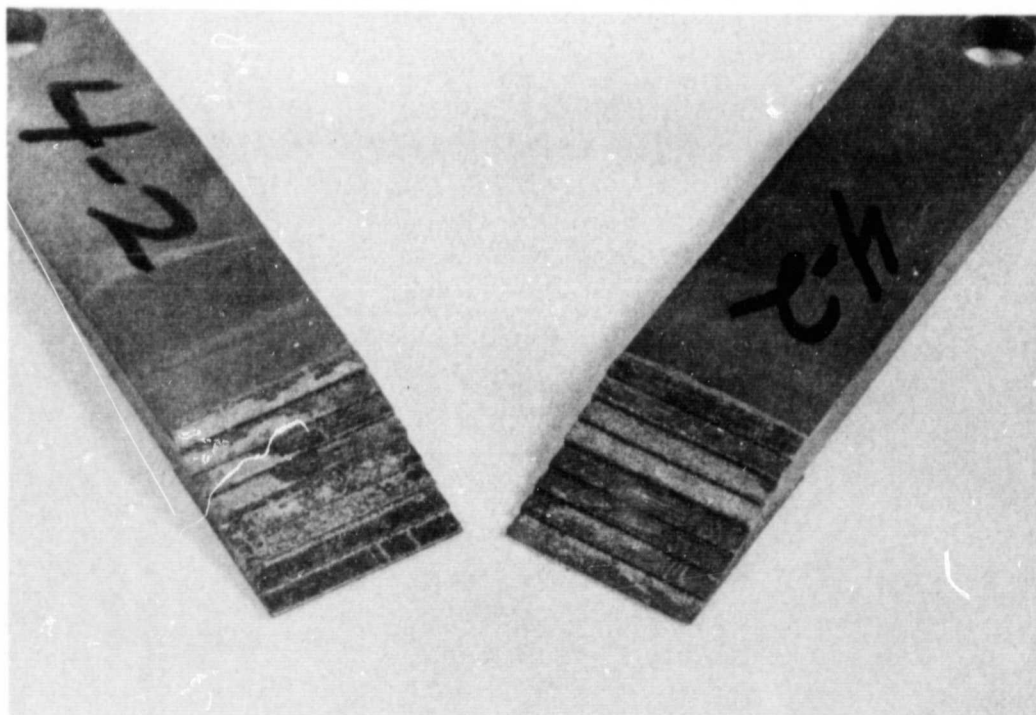


(b) Configuration 2. Failure at Average Stress  
= 3370 psi, Standard Deviation = 12.2%

Figure 4-43. Failure in Configurations 1 and 2. Mainplates  
Subjected to Single Etch Cycle.

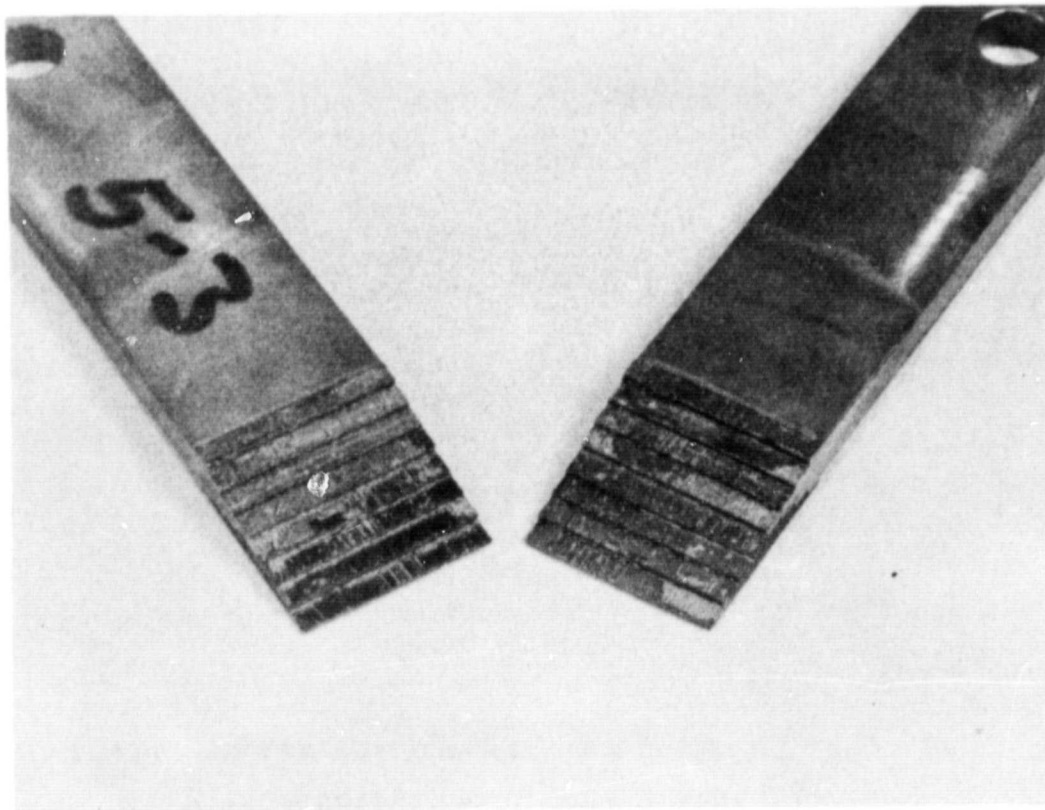


(a) Configuration 3. Failure at Average Stress  
= 2823 psi, Standard Deviation = 1.1%.



(b) Configuration 4. Failure at Average Stress  
= 4667 psi, Standard Deviation - 2.0%.

Figure 4-44. Failure in Configurations 3, 4, and 5. Mainplates  
Subjected to Two Etch Cycles.



(c) Configuration 5. Failure at Average Stress = 5038 psi, Standard Deviation = 3.7%.

Figure 4-44. Failure in Configurations 3, 4, and 5. Mainplates Subjected to Two Etch Cycles.

TABLE 4-VII

## SUMMARY OF TENSILE SHEAR FAILURE TESTS FOR TITANIUM-BORON/EPOXY STEPPED-LAP JOINTS

| CONFIGURATION | SPECIMEN | FAILURE<br>LOAD, LB | AVERAGE<br>STRESS, psi | JOINT STRENGTH<br>psi AVERAGE | STANDARD<br>$\sigma$ , psi | DEVIATION<br>$\sigma$ , % | REMARKS              |
|---------------|----------|---------------------|------------------------|-------------------------------|----------------------------|---------------------------|----------------------|
| 1             | 1        | 3000                | 3000                   | 2890                          | 400                        | 15.0                      | Single<br>Etch Cycle |
|               | 2        | 2720                | 2720                   |                               |                            |                           |                      |
|               | 3        | 2950                | 2950                   |                               |                            |                           |                      |
|               | 4        | *                   | —                      |                               |                            |                           |                      |
| 2             | 1        | 3400                | 3400                   | 3370                          | 385                        | 12.2                      | Single<br>Etch Cycle |
|               | 2        | 3560                | 3560                   |                               |                            |                           |                      |
|               | 3        | **                  | —                      |                               |                            |                           |                      |
|               | 4        | 3150                | 3150                   |                               |                            |                           |                      |
| 3             | 1        | 2810                | 2810                   | 2823                          | 31                         | 1.1                       | Double<br>Etch Cycle |
|               | 2        | 2800                | 2800                   |                               |                            |                           |                      |
|               | 3        | 2870                | 2870                   |                               |                            |                           |                      |
|               | 4        | Saved               | —                      |                               |                            |                           |                      |
| 4             | 1        | 4760                | 4760                   | 4667                          | 93                         | 2.0                       | Double<br>Etch Cycle |
|               | 2        | 4700                | 4700                   |                               |                            |                           |                      |
|               | 3        | 4540                | 4540                   |                               |                            |                           |                      |
|               | 4        | Saved               | —                      |                               |                            |                           |                      |
| 5             | 1        | 4830                | 4830                   | 5038                          | 190                        | 3.7                       | Double<br>Etch Cycle |
|               | 2        | 5200                | 5200                   |                               |                            |                           |                      |
|               | 3        | 5250                | 5250                   |                               |                            |                           |                      |
|               | 4        | 4870                | 4870                   |                               |                            |                           |                      |

\* Failure Load 2000 Lb. Data rejected using Chauvenet's criterion for sample rejection, see [10].

\*\* Failure Load 2550 Lb. Data rejected using Chauvenet's criterion for sample rejection, see [10].

are the joint strengths, on the whole, increased by the second etching, but the scatter in the observed joint strengths is reduced by an order of magnitude. Even with the improvement of strength, Configuration 3 is still the weakest joint, as predicted from the simplified criterion. Moreover, the strength ordering OPTIMUM-2-1-3 for equal step, variable modulus joints and OPTIMUM-5-4-3 for variable step joints is in agreement with the order determined from the simplified criterion.

#### Joining of Boron/Epoxy Composite Materials

A stepped-lap joint configuration was designed for joining boron/epoxy sections, using the stepped-lap criterion (11). The bonding agent was Metlbond 328, as employed in the titanium-boron/epoxy joints. The design configuration is summarized in Figure 4-45 and accompanying Table 4-VIII. Since four equal steps were adopted for the design, the minimum section thicknesses were found to be thick enough that the SCOTCHPLY reinforcing layers were not necessary. A comparison between the optimum and actual modulus ratio  $\frac{E_2}{E_1}$  at each cross-section is shown in Figure 4-46. Note the close agreement, implying a near-optimum utilization of the adhesive in this four-step configuration. Failure would be expected to occur in the laminate, rather than in the adhesive itself, since the inter-laminar shear stress concentrations may be higher than those in the adhesive bondline.

#### Fabrication and Testing of Boron/Epoxy Stepped-Lap Joint

The configuration described in Table 4-VIII and Figure 4-45 was fabricated and tested, and the tentative conclusions drawn from the simplified failure criterion were evaluated. The required layup patterns are summarized in Appendix C, Table C-2. The construction, before bonding, is shown in Figure 4-47. Note that each joint is made up of four boron/epoxy mainplate sections and two boron/epoxy doublers. The four completed specimens, built to the specification of Table 4-VIII, are shown in Figure 4-48.

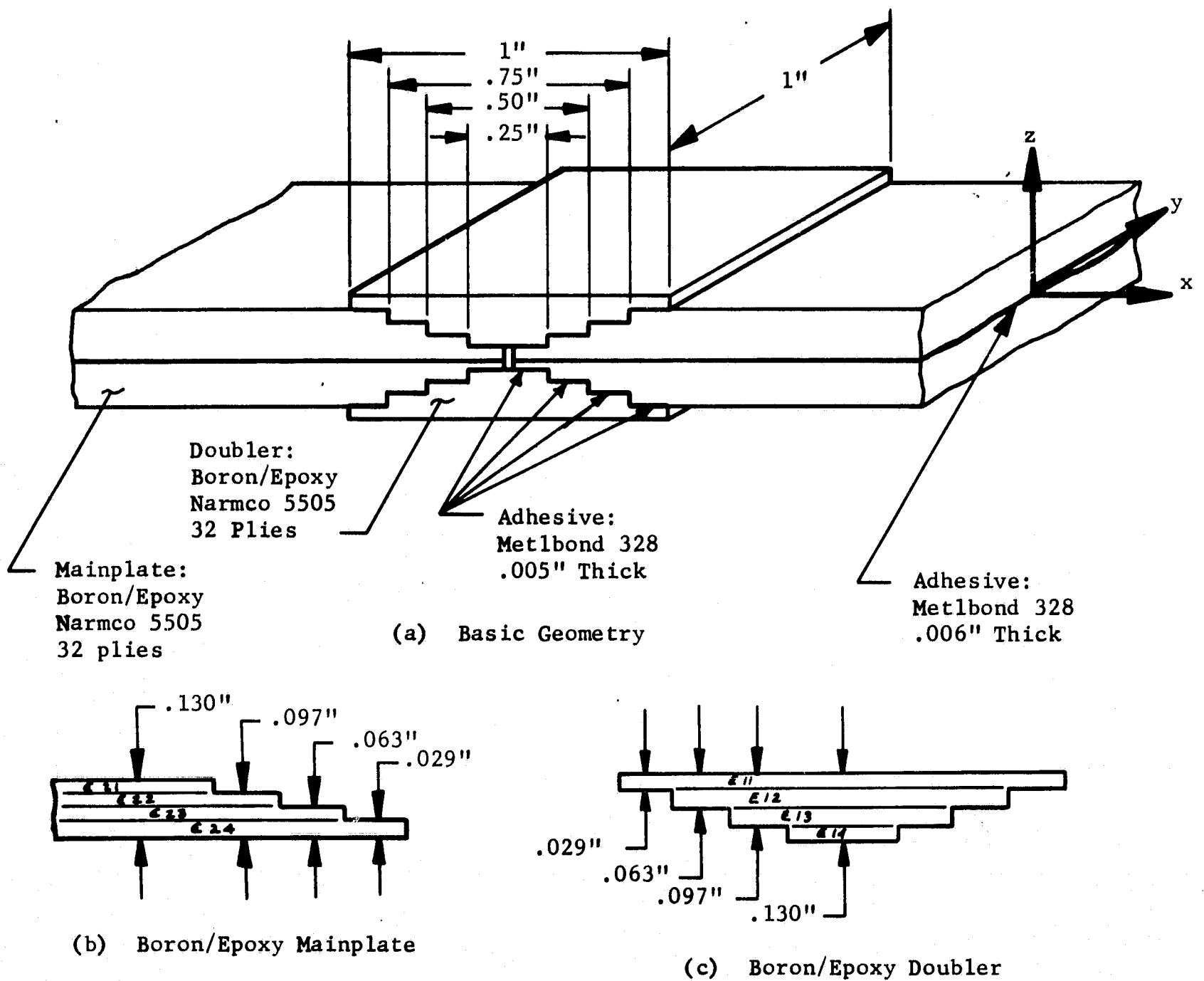


Figure 4-45. Properties of Boron/Epoxy-Boron/Epoxy Stepped-Lap Joint.

TABLE 4-VIII

PROPERTIES OF BORON/EPOXY-BORON/EPOXY STEPPED-LAP JOINT  
TENSILE MODULI  $\text{psi} \times 10^{-6}$

| MAINPLATE       |                 |                 |                 | DOUBLER         |                 |                 |                 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| E <sub>21</sub> | E <sub>22</sub> | E <sub>23</sub> | E <sub>24</sub> | E <sub>11</sub> | E <sub>12</sub> | E <sub>13</sub> | E <sub>14</sub> |
| 23.3            | 15.1            | 16.6            | 10.85           | 10.85           | 16.6            | 15.1            | 23.3            |

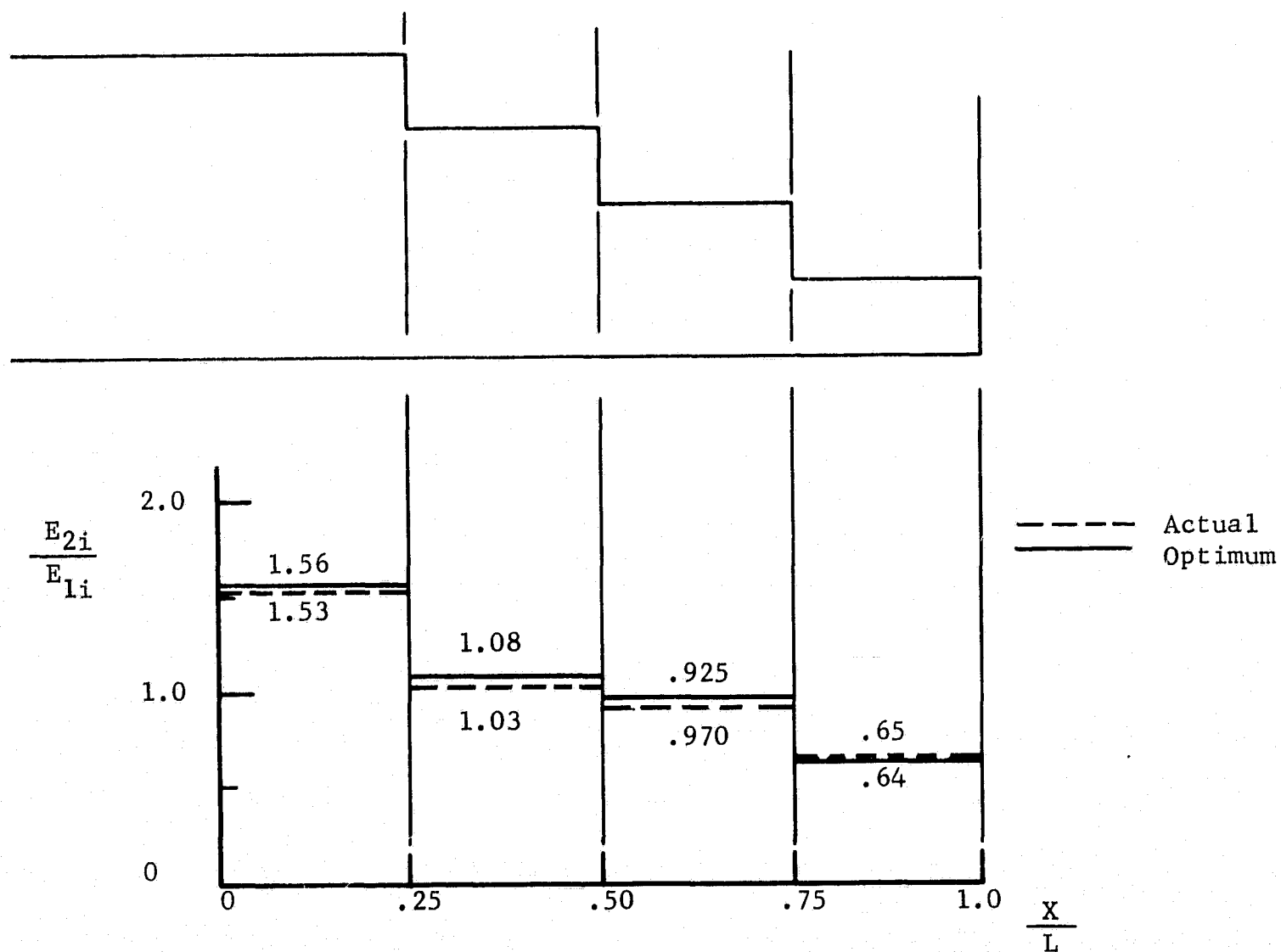


Figure 4-46. Comparison of Average-Strain Modulus Ratios  $\frac{E_{2i}}{E_{1i}}$  for Boron/Epoxy-Boron/Epoxy Stepped-Lap Joint.

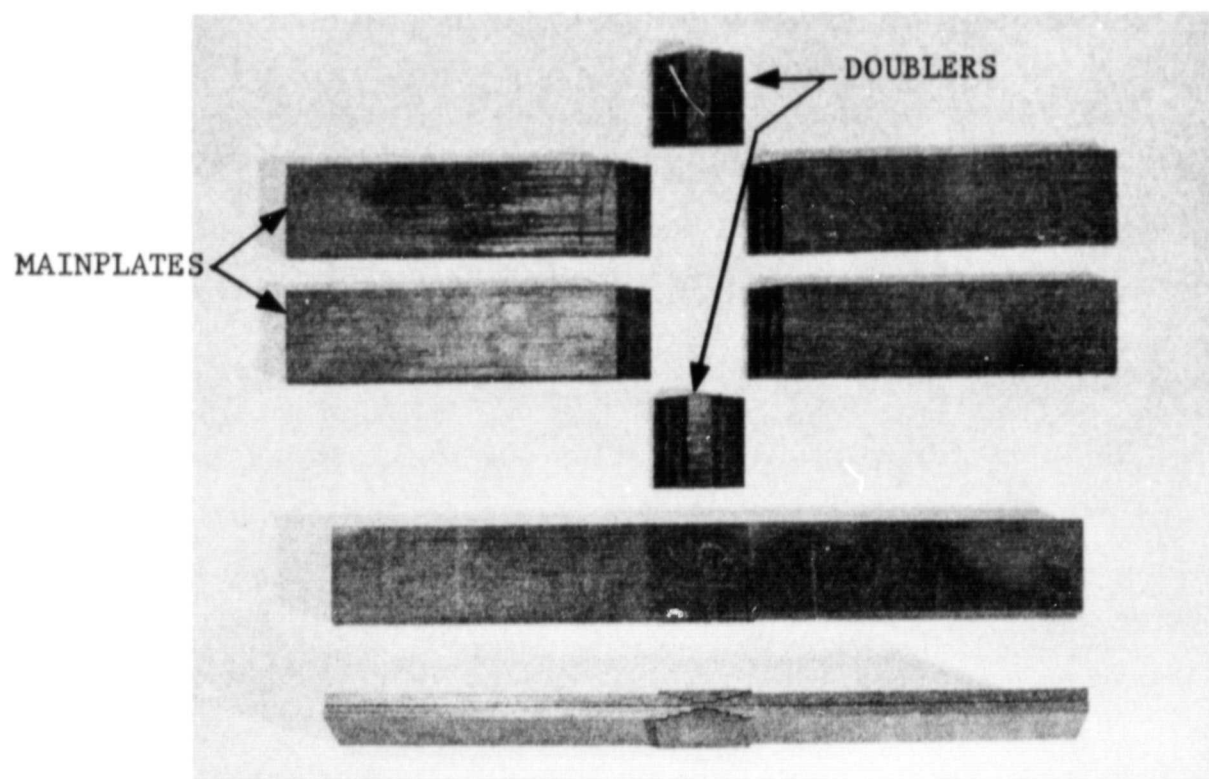


Figure 4-47. Boron/Epoxy Stepped-Lap Joint;  
Before Bonding.

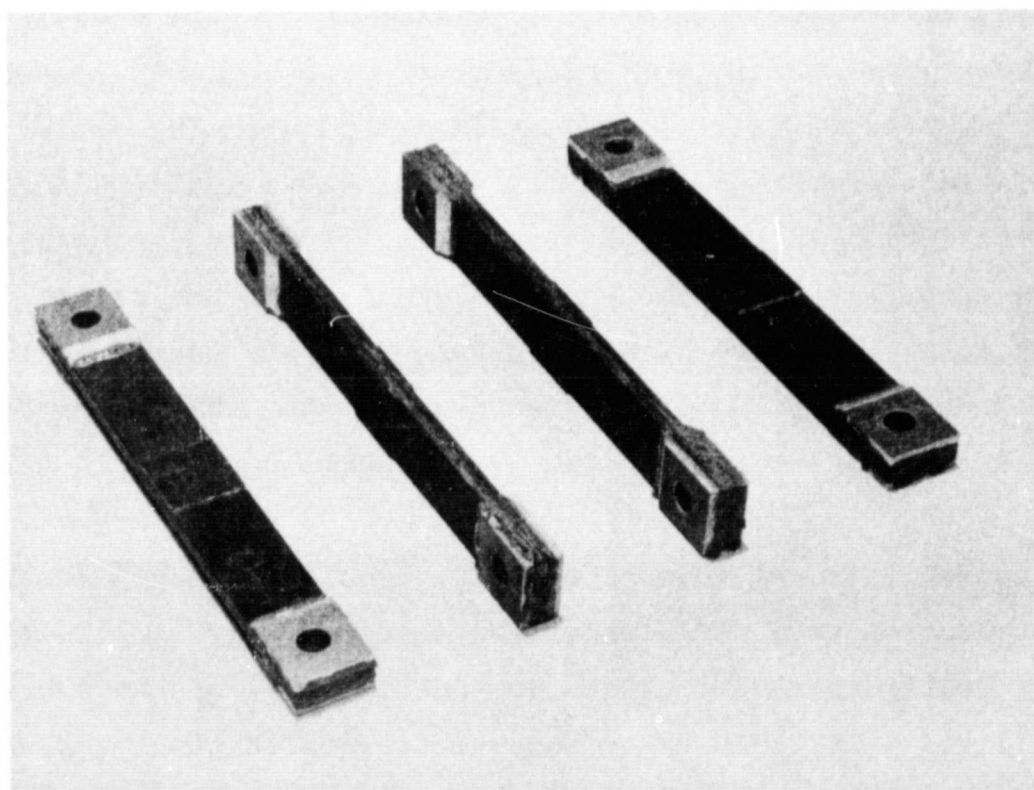


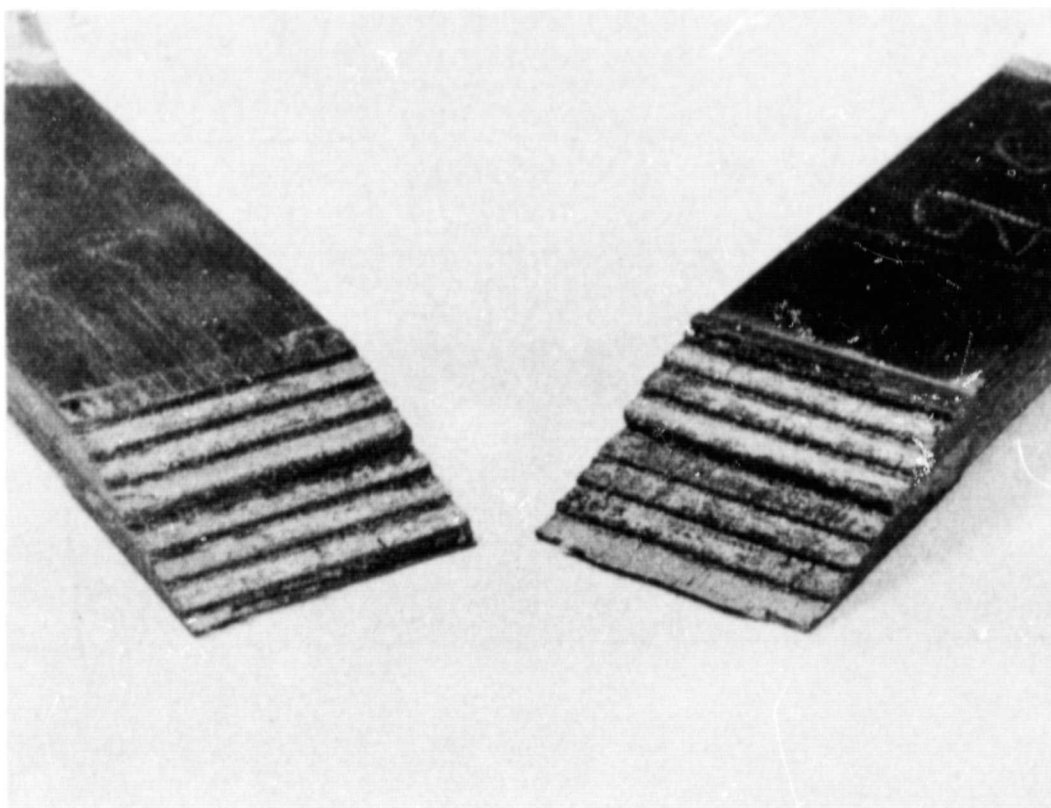
Figure 4-48. Boron/Epoxy Stepped-Lap Joint;  
Configuration Completed.

The holes were bored in the composite material before the four aluminum end-doublers were bonded in place. The relative positions of these doublers were maintained by placing pins in the holes during the adhesive cure. The external flashing that is seen in Figure 4-48 was not removed prior to testing, since it was desired to reduce the possibility of damage to the bondline.

The failures for this configuration are represented in Figure 4-49. The failure occurs primarily in the layers of the composite adjacent to the bondline. As indicated qualitatively by the simplified analysis, the joint shear strength is developed to its full potential for this four-step composite configuration.

Results of the tensile failure tests are summarized in Table 4-IX. As in the previous tests on titanium-boron/epoxy joints, the scatter of data is very small, and the tensile strength (3877 psi) compares very favorably with results obtained by others [11, 12]. The strength would improve considerably, of course, if a ductile bonding agent were used, rather than the brittle one that was intentionally used here. Further evidence that full potential strength is attained can be gained from the analysis in [5] and experimental data in [12]. In [5], it is shown that the shear stress concentration factor in the boron/epoxy laminate is approximately 2.8. The adhesive shear stress at the adhesive-adherend interface is magnified by this factor in the boron/epoxy plies adjacent to the bondline, implying an average shear stress of 10,850 psi in these plies. This value compares closely with average interlaminar shear strengths reported in [12].

It is important to note that the tensile strength of this boron/epoxy configuration exceeds those of the geometrically similar titanium-boron/epoxy Configurations 1, 2 and 3. On the basis of the comparisons in Figures 4-36 and 4-46, this is to be expected qualitatively, since agreement with the optimum configuration is more nearly achieved in the boron/epoxy joint. However, since the failure modes of Configurations 1 and 2 were related to the titanium-to-adhesive interface strength rather than to



Average Failure Stress =  $3877 \text{ psi} \pm 2.3\%$

Figure 4-49. Failure in Boron/Epoxy Stepped-Lap Joint.

TABLE 4-IX

SUMMARY OF TENSILE-SHEAR FAILURE TESTS FOR  
BORON/EPOXY-BORON/EPOXY STEPPED-LAP JOINT

| SPECIMEN | FAILURE<br>LOAD, LB | AVERAGE FAILURE<br>STRESS, psi | JOINT STRENGTH<br>psi | STANDARD DEVIATION<br>$\sigma$ , psi | STANDARD DEVIATION<br>$\sigma$ , psi | REMARKS                                              |
|----------|---------------------|--------------------------------|-----------------------|--------------------------------------|--------------------------------------|------------------------------------------------------|
| 1        | 4000                | 4000                           |                       |                                      |                                      |                                                      |
| 2        | 3800                | 3800                           | 3877                  | 88                                   | 2.3                                  | Degreasing<br>Preparation<br>as described<br>in [9]. |
| 3        | 3830                | 3830                           |                       |                                      |                                      |                                                      |
| 4        | Saved               | —                              |                       |                                      |                                      |                                                      |

the adherent interlaminar shear strength, more definite conclusions must await results of detailed testing programs beyond the intended scope of this investigation. The test results do indicate the feasibility of this simplified design approach, since the two are in excellent qualitative agreement.

## SECTION 5

### THE EFFECTS OF ADHEREND SHEAR MODULI AND ADHESIVE NONLINEARITIES ON THE STRENGTH OF LAP JOINTS

The joint design analyses existing in the literature have two serious shortcomings: First, the adherends are assumed to have infinite shear moduli, when in reality, these are relatively low finite values. Second, the adhesives are assumed to have linear shear stress-strain properties, although nonlinearity in the properties of these organic materials is the rule rather than the exception. With increasing application of composite materials in joints, it is no longer safe to ignore these two facts. The low interlaminar shear moduli of composite materials, along with their relatively low shear strengths, makes knowledge of adherend shear deformations and stresses of great practical value to the designer, who must strive to fully utilize the limited shear capabilities of these materials. Using modern adhesives, in fact, the shear stiffness of the adherends and adhesive may be nearly the same; conventional linear design techniques are incapable of dealing with this problem. Moreover, since adhesive flow in regions of high shear stress has been recognized to produce a strengthening effect on the joint, an evaluation of the extent of this effect is essential to a more complete understanding of composite joint behavior.

In the brief analysis to follow, the adherend shear properties and adhesive nonlinearities are included in a study of the double-lap joint. Linear adherend properties are assumed, and the adhesive is assumed

nonlinear but elastic. The resulting stress distributions more closely describe the response of practical double-lap joints in composite materials.

### Analysis of Practical Straight-Lap Joints

Referring to Figure 5-50, the equations of equilibrium (1) can be seen to be unaffected by the small adherend deformations:

$$\frac{dP_1}{dx} = \frac{b\tau_a}{\cos^2 \theta} = b\tau_a \quad (1), \text{ repeated}$$

$$\frac{dP_2}{dx} = \frac{b\tau_a}{\cos^2 \theta} = b\tau_a$$

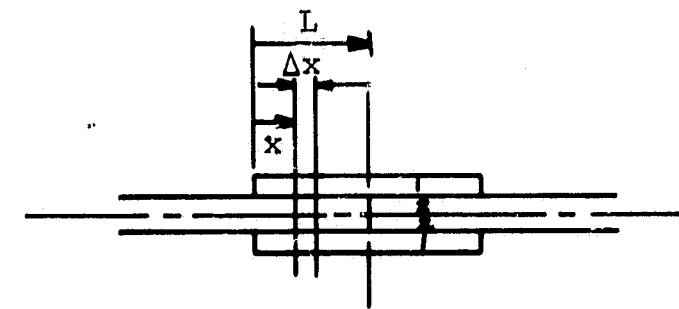
In allowing adherend shear deformations, however, the loads  $P_1, P_2$  can no longer be assumed to be uniformly distributed over the cross-sections. Instead, the stresses  $\sigma_1, \sigma_2$  must be integrated over each cross-sectional area to obtain  $P_1, P_2$ .

$$\begin{aligned} P_1(x) &= b \int_0^{t_1} \sigma_1(\xi, x) d\xi = bE_1 \int_0^{t_1} \epsilon_1(\xi, x) d\xi \\ P_2(x) &= b \int_{-t_2}^0 \sigma_2(\beta, x) d\beta = bE_2 \int_{-t_2}^0 \epsilon_2(\beta, x) d\beta \end{aligned} \quad (17)$$

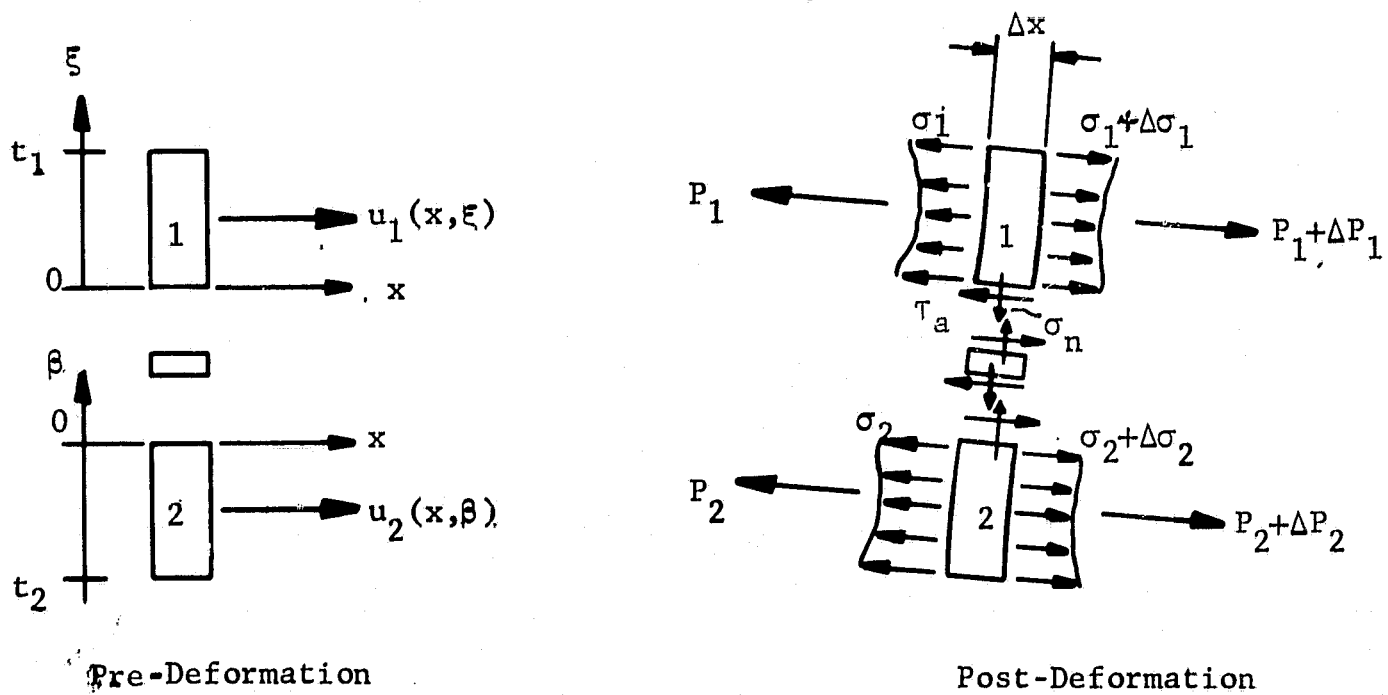
where  $\beta$  and  $\xi$  are defined in Figure 5-50b. The stresses  $\sigma_1$  and  $\sigma_2$  are linear functions of the adherend strains  $\epsilon_1(\xi, x), \epsilon_2(\beta, x)$  which are, in turn, functions of the adherend displacements  $u_1(\xi, x), u_2(\beta, x)$ .

The adherend shear stresses have two important boundary conditions:

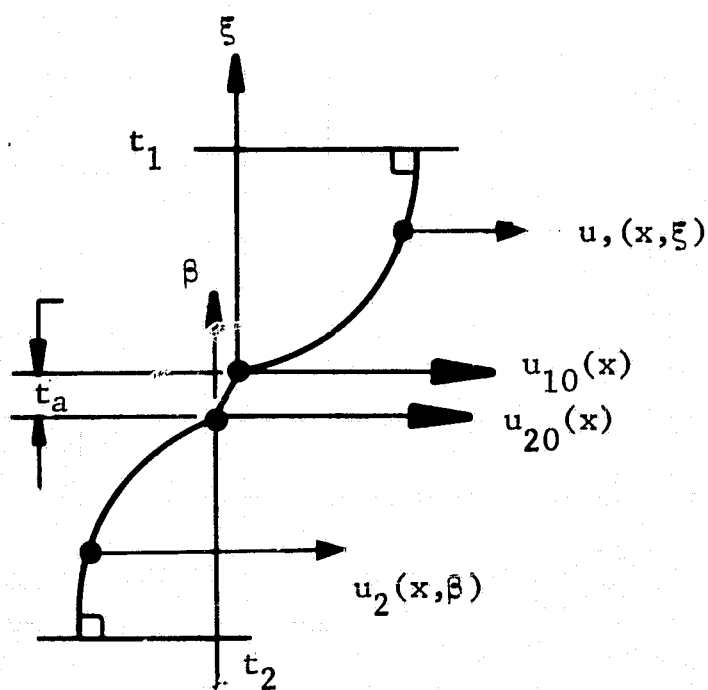
- (a) they must reduce to zero at  $\xi = t$ , and  $\beta = -t_2$ , and (b) they must equal



(a) Straight-Lap Joint Geometry



(b) Adherend Elements with Shear Deformation



(c) Adherend Displacement Distribution

Figure 5-50. Double Straight-Lap Joint with Shear Effects Included.

the adhesive shear stress  $\tau_a$  at  $\xi=0$  and  $\beta=0$ . . Due to the adherend linearity assumption, these conditions may be stated in terms of the displacements  $u_1(\xi, x)$ ,  $u_2(\beta, x)$  in the following form:

$$\begin{aligned}\tau_1 = G_1 \gamma_1 = G_1 \frac{\partial u_1}{\partial \xi} &= 0 \text{ at } \xi = t_1 \\ \tau_1 = G_1 \gamma_1 = G_1 \frac{\partial u_1}{\partial \xi} &= \tau_a \text{ at } \xi = 0\end{aligned}\quad (18)$$

$$\begin{aligned}\tau_2 = G_2 \gamma_2 = G_2 \frac{\partial u_2}{\partial \beta} &= 0 \text{ at } \beta = -t_2 \\ \tau_2 = G_2 \gamma_2 = G_2 \frac{\partial u_2}{\partial \beta} &= \tau_a \text{ at } \beta = 0\end{aligned}\quad (19)$$

Figure 5-50c depicts displacements  $u_1, u_2$  which satisfy these requirements. The simplest functions which would provide compatible adherend displacements are

$$\begin{aligned}u_1(\xi, x) &= u_{10}(x) + \left( \frac{\partial u_1}{\partial \xi} \right)_{\xi=0} \left( \xi - \frac{\xi^2}{2t_1} \right) \\ u_2(\beta, x) &= u_{20}(x) + \left( \frac{\partial u_2}{\partial \beta} \right)_{\beta=0} \left( \beta + \frac{\beta^2}{2t_2} \right)\end{aligned}\quad (20)$$

where  $u_{10}$  and  $u_{20}$  are displacements at the respective interfaces. In terms of the adhesive shear stress  $\tau_a$  these displacements become

$$\begin{aligned}u_1(\xi, x) &= u_{10}(x) + \frac{\tau_a}{G_1} \left( \xi - \frac{\xi^2}{2t_1} \right) \\ u_2(\beta, x) &= u_{20}(x) + \frac{\tau_a}{G_2} \left( \beta + \frac{\beta^2}{2t_2} \right)\end{aligned}\quad (21)$$

These assumed displacement functions reduce to the classical form when the moduli  $G_1$  and  $G_2$  are increased to infinity. Further examination reveals that (21) is equivalent to assuming linear shear stress distributions through the adherends. Although not strictly true for composite adherends, the linear variation is an improved approximation to the actual distribution, particularly when the adherends are homogeneous. Refined distributions would provide greater detail, but the essential features of the shear effects will be contained in this simplified analysis.

Substituting the derivatives of (21) into (17) yields the following expressions for  $P_1(x)$  and  $P_2(x)$ :

$$\begin{aligned} P_1(x) &= bE_1 \left( \frac{du_{10}}{dx} t_1 + \frac{1}{G_1} \frac{d\tau_a}{dx} \frac{t_1^2}{3} \right) \\ P_2(x) &= bE_2 \left( \frac{du_{20}}{dx} t_2 - \frac{1}{G_2} \frac{d\tau_a}{dx} \frac{t_2^2}{3} \right) \end{aligned} \quad (22)$$

From Figure 5-50c the adhesive shear strain  $\gamma_a$  is, by definition, equal to

$$\gamma_a(x) = \frac{u_{10}(x) - u_{20}(x)}{t_a} \quad (23)$$

and its derivative, in terms of  $\tau_a$ , is

$$\frac{d\gamma_a}{dx} = \frac{d\gamma_a}{d\tau_a} \cdot \frac{d\tau_a}{dx} = \frac{1}{t_a} \left( \frac{du_{10}}{dx} - \frac{du_{20}}{dx} \right) \quad (24)$$

Combining (22) and (24), we obtain

$$\frac{d\gamma_a}{d\tau_a} \cdot \frac{d\tau_a}{dx} = \frac{1}{bt_a} \left( \frac{P_1}{E_1 t_1} - \frac{P_2}{E_2 t_2} \right) - \frac{1}{t_a} \left( \frac{t_1}{3G_1} + \frac{t_2}{3G_2} \right) \frac{d\tau_a}{dx} \quad (25)$$

Differentiating (25) and applying the equilibrium relation (1) yields the governing equation for the straight-lap joint:

$$\begin{aligned} \frac{d^2 \tau_a}{dx^2} \cdot \frac{d\gamma_a}{d\tau_a} + \frac{1}{t_a} \left( \frac{t_1}{3G_1} + \frac{t_2}{3G_2} \right) + \frac{d^2 \gamma_a}{d\tau_a^2} \left( \frac{d\tau_a}{dx} \right)^2 \\ = \frac{1}{t_a} \left( \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right) \tau_a \end{aligned} \quad (26)$$

Since the adherend forces are related to the applied load  $P$  by the relation  $P_1 + P_2 = P$ , the boundary conditions on the shear stress  $\tau_a$  can be obtained directly from (25):

$$\begin{aligned} \frac{d\tau_a}{dx} \cdot \frac{d\gamma_a}{d\tau_a} + \frac{1}{t_a} \left( \frac{t_1}{3G_1} + \frac{t_2}{3G_2} \right) &= \frac{1}{bt_a} \left( \frac{-P}{E_2 t_2} \right) \text{ at } x = 0 \\ &= \frac{1}{bt_a} \left( \frac{P}{E_1 t_1} \right) \text{ at } x = L \end{aligned} \quad (27)$$

Equation (26) along with boundary conditions (27) can be solved numerically, using a Runge-Kutta procedure in combination with a special extrapolation procedure. A Fortran I computer program is presented in Appendix D for the case  $E_1 t_1 = E_2 t_2$ . Nonsymmetric cases ( $E_1 t_1 \neq E_2 t_2$ ) are treated in Appendix E, but the specialized program in Appendix D is sufficient to illustrate the effects of adherend shear moduli and adhesive nonlinearities.

#### Straight-Lap Joints with Linear Adhesives

Before considering typical joint configurations with nonlinear adhesive properties, the effect of actual adherend shear moduli will be

evaluated, assuming a linear high modulus adhesive. Consider the joint of Cases 1 and 2 (Figure 2-5). Assuming the same linear adhesive and bondline thickness ( $G_a = 175,000 \text{ psi} = \frac{d\gamma_a}{d\tau_a}^{-1}$ ,  $t_a = .004''$ ), the adhesive shear stress distributions under load  $\bar{P}$  are shown in Figure 5-51 for the five adherend materials outlined in Table 5-X. The thicknesses are chosen, in each case, so that the cross-sectional stiffnesses  $E_1 t_1, E_2 t_2$  are all equal to  $6.25 \times 10^5 \text{ lb./inch}$ . A comparison of case (c) in Figure 5-51 and the solution for Cases 1 and 2 in Figure 2-5 reveals good agreement between the finite-element solution and the analytic solution of (26). Note in Figure 5-51 that reduction of the shear modulus can lead to considerable reduction of the stress concentration factor, from 5.86 for the "pseudo-aluminum" joint (e) with infinite shear modulus, to 3.96 for the boron/epoxy joint (d).

The classical analysis yields stress concentration factors that are more conservative than those obtained with the improved model presented in this paper. The improved analysis yields the shear stress distributions through the adherend thicknesses, an essential feature if composite materials are to be utilized more effectively in joint design.

#### The Effect of Adhesive Nonlinearity

Berg<sup>[1]</sup> has shown that many nonlinear adhesives may be characterized by the stress-strain relation.

$$\tau_a = \frac{G_a}{\gamma_a} \left( 1 - e^{-\Omega \gamma_a} \right) \quad (28)$$

As the sketch in Figure 5-52 demonstrates, the parameter  $G_a$  is the initial modulus at  $\tau_a = 0$ , while the parameter  $\frac{G_a}{\Omega}$  is equal to the ultimate stress,  $\tau_{ULT}$ . Two adhesives with the initial bondline

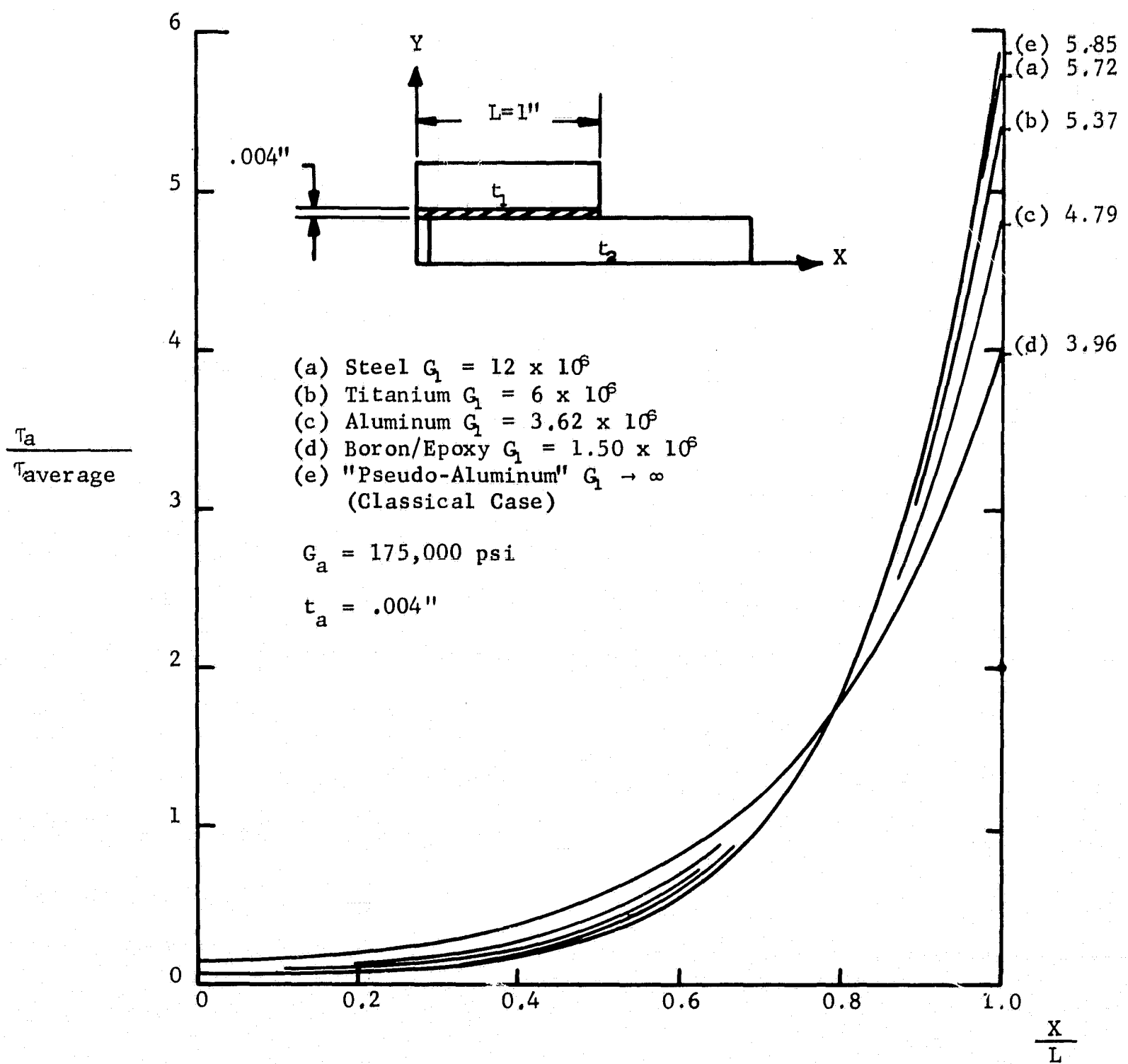


Figure 5-51. Shear Stress Distribution Along the Bondline of a Double-Lap Joint for Typical Adherends.  $E_1 t_1 = E_2 t_2 = \text{Constant}$

TABLE 5-X

COMPARISON OF STRESS CONCENTRATION FACTORS OF  
TYPICAL STRAIGHT-LAP JOINTS.  $E_1 t_1 = E_2 t_2 = \text{CONSTANT}$ ,

| ADHEREND AND<br>DOUBLER MATERIAL                                          | $E_1 = E_2$ psi  | $t_1 = t_2$ IN. | $G_1 = G_2$ psi    | STRESS CONCENTRATION<br>FACTOR SCF |
|---------------------------------------------------------------------------|------------------|-----------------|--------------------|------------------------------------|
| (a) Steel                                                                 | $30 \times 10^6$ | .0208           | $12. \times 10^6$  | 5.72                               |
| (b) Titanium                                                              | $16 \times 10^6$ | .0391           | $6.00 \times 10^6$ | 5.38                               |
| (c) Aluminum                                                              | $10 \times 10^6$ | .0625           | $3.62 \times 10^6$ | 4.79                               |
| (d) Boron/Epoxy                                                           | $10 \times 10^6$ | .0625           | $1.50 \times 10^6$ | 3.96                               |
| (e) "Pseudo-<br>Aluminum"*<br>( $G \approx \infty$ )                      | $10 \times 10^6$ | .0625           | $3.62 \times 10^6$ | 5.86                               |
| <u>Adhesive:</u> Metlbond 328 ( $G_a = 175,000$ psi), thickness = 0.004". |                  |                 |                    |                                    |

\* "Pseudo-Aluminum" has the same tensile properties as Aluminum, but is assumed to have a near-infinite shear modulus in accord with classical assumptions.

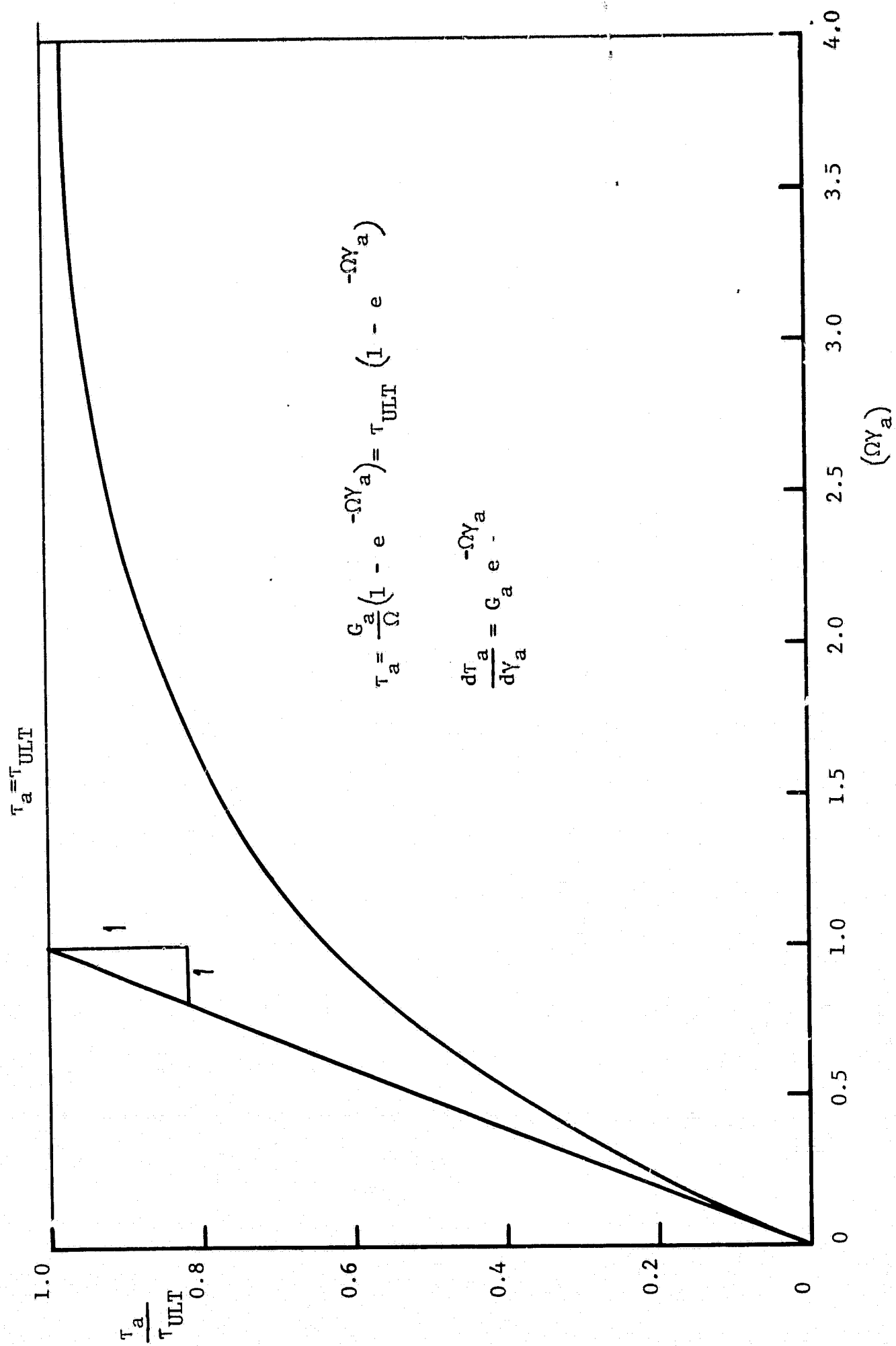


Figure 5-52. Typical Shear Stress-Strain Relation for Nonlinear Elastic Adhesives.

stiffness ( $G_a = 175,000$  psi,  $t_a = .004$ " ) considered earlier, but with ultimate stresses 2460 psi and 6900 psi respectively, will be considered in this example. The five adherend materials outlined in Table 5-X will be used. Solution of (26), using the stress-strain relation (28) and assuming a load  $P=1000$  lb yields the stress concentration factors shown in Table 5-XI. From the numbers presented in this table, it can be seen that the combination of adhesive nonlinearity and adherend shear deformations reduces the shear stress concentration factor from 5.86 for the "classical" (linear adhesive, infinite shear modulus) joint to the value 2.36 for a typical boron-epoxy joint. Figure 5-53 describes the effect of adhesive nonlinearity on the boron/epoxy joint configuration. Note the tendency toward uniform shear stress distribution. This intuitively-evident result can be evaluated numerically, using the programs in Appendix D and Appendix E.

#### Simplified Design Criterion for Adhesive Bonded Joints with Finite Adherend Shear Moduli and Nonlinear Adhesive Properties

The definition (23) of adhesive shear strain  $\gamma_a$  and the expressions (21) defining adherend deformations can be combined to form a simplified design criterion analogous to (8). From (5) the uniformity of bondline shear strain requires

$$\frac{d\gamma_a}{dx} = \frac{1}{t_a} \left( \frac{dU_{10}}{dx} - \frac{dU_{20}}{dx} \right) = 0 \quad (29)$$

or, using (22) and recognizing that  $\frac{d\tau_a}{dx} = 0$ :

$$\frac{P_1}{bt_1E_1} - \frac{P_2}{bt_2E_2} = 0 \quad (30)$$

TABLE 5-XI

EFFECTS OF ADHESIVE NONLINEARITY ON STRESS CONCENTRATION  
FACTORS OF TYPICAL STRAIGHT-LAP JOINTS.  $E_1 t_1 = E_2 t_2 = \text{CONSTANT}$ .

| MATERIAL                                                                                | THICKNESS<br>INCHES | STRESS CONCENTRATION FACTOR, P = 1000 LB. |                                 |                                 |
|-----------------------------------------------------------------------------------------|---------------------|-------------------------------------------|---------------------------------|---------------------------------|
|                                                                                         |                     | LINEAR                                    | NONLINEAR                       |                                 |
|                                                                                         |                     |                                           | $\tau_{ULT} = 2460 \text{ psi}$ | $\tau_{ULT} = 6900 \text{ psi}$ |
| (a) Steel                                                                               | .0208               | 5.72                                      | 2.40                            | 4.29                            |
| (b) Titanium                                                                            | .0391               | 5.38                                      | 2.40                            | 4.18                            |
| (c) Aluminum                                                                            | .0625               | 4.79                                      | 2.39                            | 3.96                            |
| (d) Boron/Epoxy                                                                         | .0625               | 3.96                                      | 2.36                            | 3.53                            |
| (e) "Pseudo-Aluminum<br>( $G = \infty$ )                                                | .0625               | 5.86                                      | 2.40                            | 4.33                            |
| <u>Adhesive:</u> Initial modulus $G_a = 175,000 \text{ psi}$ , thickness = .004-inches. |                     |                                           |                                 |                                 |

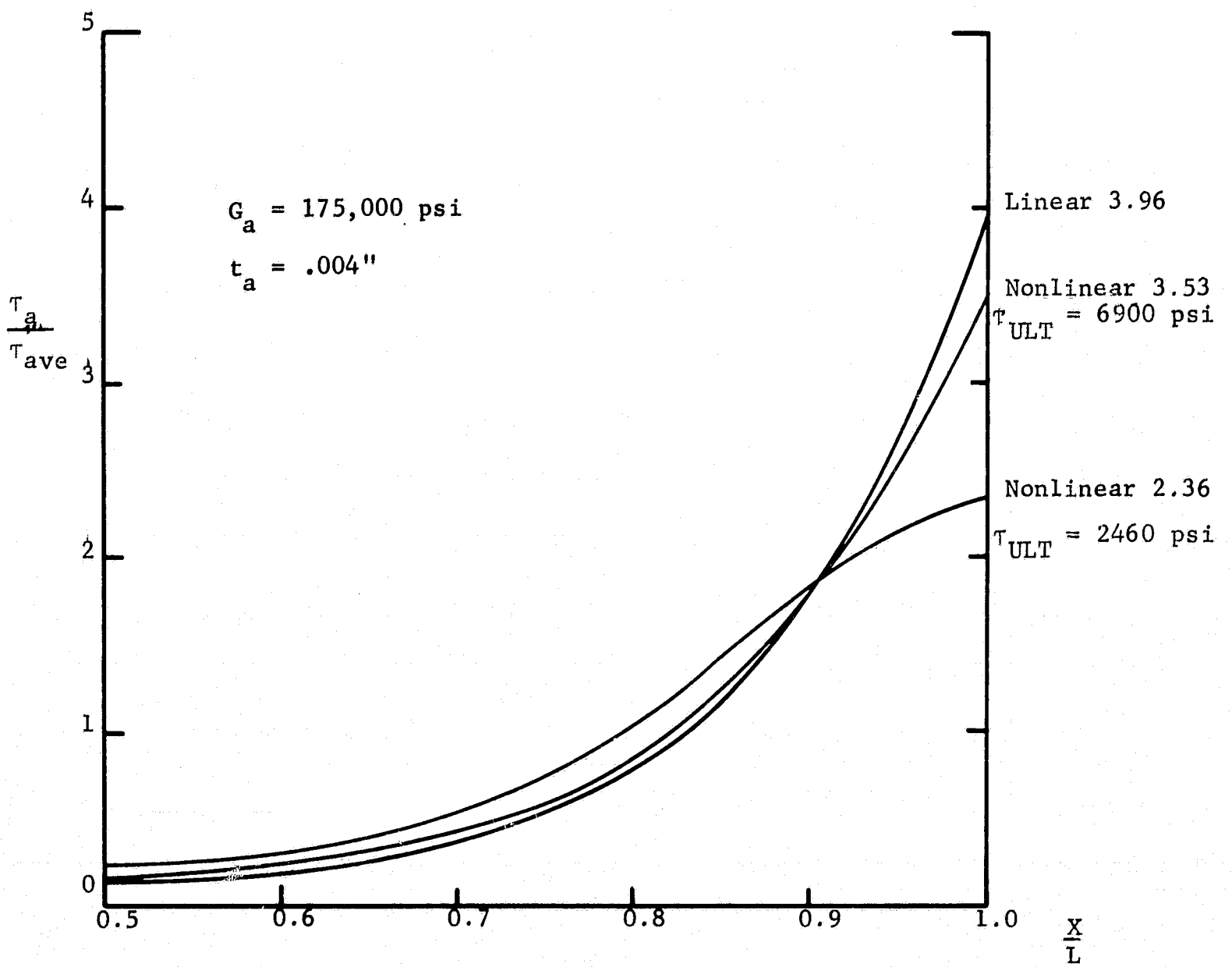


Figure 5-53. Shear Stress Distribution Along the Bondline of Double-Lap Joint. Effects of Adhesive Non-linearity on a Boron/Epoxy Joint.

Referring to (6) for the case  $\theta = 0$ , it is evident that the form of the criterion is unaffected by the adhesive nonlinearity and finite adherend shear moduli. The criterion (29) reduces identically to the criterion (10) for straight-lap joints, or criterion (11) for stepped-lap joints. Although these properties may greatly affect the shape of the adhesive shear stress distribution, from the designer's standpoint the criterion for uniform shear stress distribution is governed solely by the adherend tensile moduli and thicknesses. It can be shown that this conclusion also holds true for the scarf-type joint.

With a small additional effort, it is possible to design joints with strength properties improved over those designed by classical approaches. Moreover, inclusion of adherend shear properties and adhesive nonlinear properties present little difficulty in design of optimum configurations.

## SECTION 6

### DESIGN OF STRAIGHT-LAP COMPOSITE JOINTS

The results presented in the previous sections indicate a potential for improving the strength of titanium-boron/epoxy joints by altering adherend shear moduli. Only with composite materials is it possible to simultaneously tailor tensile stiffness  $E_1 t_1$  and the cross-sectional shear modulus  $G_1$  in the adherend. As Figure 5-51 and Table 5-X indicate, a reduction in the thickness shear modulus of the adherend would lead to reduction of stress concentrations in the adhesive. One technique for accomplishing this objective with boron/epoxy composite materials is the interleaving of glass scrim cloth with the boron/epoxy plies during layup. With proper control of this process, the stiffness  $E_1 t_1$  can be maintained constant while considerably increasing the ratio  $\frac{t_1}{G_1}$ . Since the glass scrim layers effectively increase boron/epoxy ply separation, the increase of  $t_1$  is accompanied by a decrease of thickness shear modulus  $G_1$ .

The adhesive Metlbond 328 was used in this study to eliminate adhesive nonlinearity effects of the type illustrated in Figure 5-53. Since the shear modulus resulting from the interleaving of scrim cloth is not readily determined, a qualitative study was performed. Strength of a "base" configuration, containing no scrim layers, was compared with strengths of three other configurations with varying amounts of scrim. The boron/

epoxy plies (NMD-5505) were all oriented in the same direction ( $0^\circ$ ) to eliminate the shear relieving effects of  $0^\circ$  -  $90^\circ$  layup combinations and the interaction between the adhesive and adjacent plies.\*

#### Design, Fabrication, and Testing of Titanium-Boron/Epoxy Straight-Lap Joints

Four straight-lap joint configurations were designed and fabricated with 1 x 1-inch boron/epoxy doublers and 1-inch wide by 0.252-inch thick titanium mainplates. The boron/epoxy doublers each consisted of sixteen plies of NMD-5505, oriented unidirectionally, and 0, 8, 16, or 32 plies of Type 104 glass scrim cloth, depending upon the desired configuration. The layup patterns are summarized in Appendix C, Table C-3. Due to the lower modulus and thickness of the scrim cloth fibers, the net section stiffness  $E_1 t_1$  of the adherend is unchanged by the addition of the scrim cloth, but the interlaminar shear stiffness will be decreased as the number of scrim plies increases. Table 6-XII defines the four configurations with respect to the number of scrim plies.

The bonded joints are shown in Figure 6-54. Four configurations are shown; each is represented by four specimens. Two titanium etch cycles were used to prepare the titanium mainplates. The adherend preparation and bonding procedures have been discussed previously and need not be repeated. On the basis of interlaminar shear modulus alone, the expected order of joint strengths is 4B - 3B - 2B - 1B in descending order.

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\* A useful technique proposed by Boyle [11] consists of placing  $90^\circ$  boron/epoxy plies on the adhesive-adherend interfaces. This method yields excellent joint strength improvements, but alters the effective adhesive properties in a yet-undetermined manner. The effect is believed to be a simultaneous reduction of adherend tensile and shear moduli and adhesive shear modulus near the bondline. Meaningful investigation of the adherend shear effects alone requires that only unidirectional boron plies be utilized in this study.

TABLE 6 -XII

BORON/EPOXY-BORON/EPOXY STRAIGHT-LAP JOINT CONFIGURATIONS

| CONFIGURATION | NUMBER OF<br>0° BORON PLIES | NUMBER OF<br>104 SCRIM PLIES | CURED DOUBLER<br>THICKNESS, IN. |
|---------------|-----------------------------|------------------------------|---------------------------------|
| 1B            | 16                          | 0                            | .072"                           |
| 2B            | 16                          | 8                            | .075"                           |
| 3B            | 16                          | 16                           | .067"                           |
| 4B            | 16                          | 32                           | .091"                           |

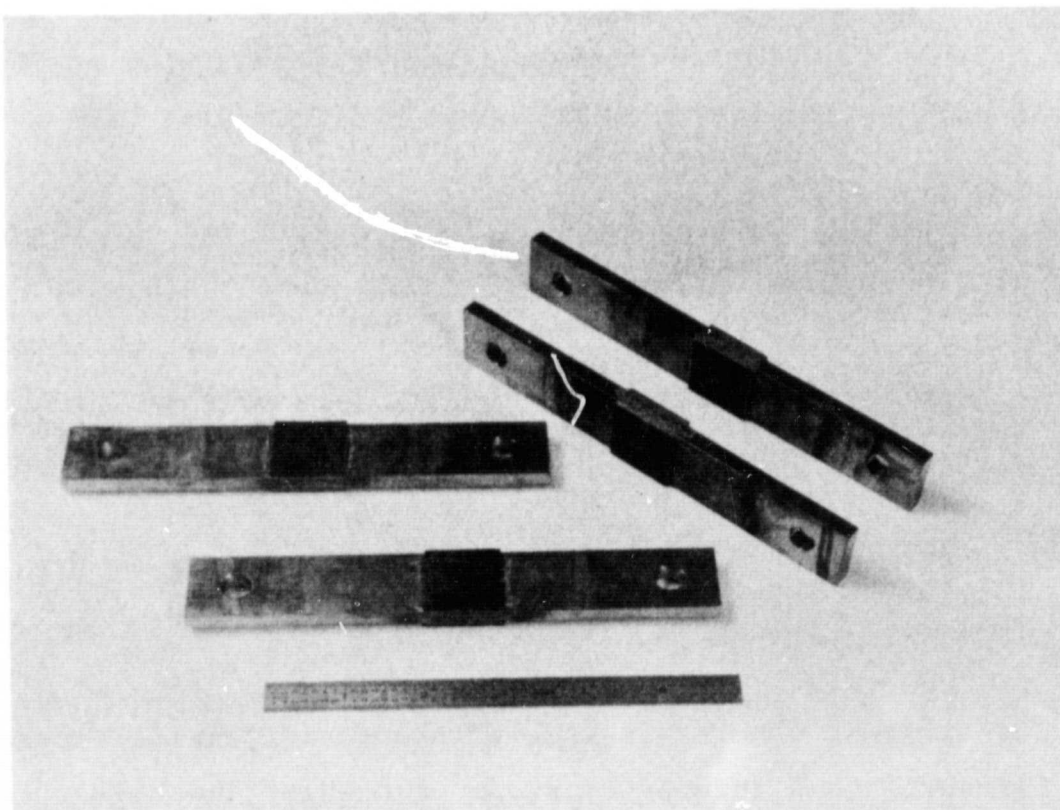


Figure 6-54. Titanium-Boron/Epoxy Straight-Lap Joints; Configurations Completed.

The results of destructive tensile-shear tests are listed in Table 6-XIII. The associated failure modes were identical, and are represented by the single failed configuration shown in Figure 6-55. As Table 6-XIII indicates, the joint configurations can be listed, in descending order of joint strength: 4B - 3B - 1B - 2B. Since the strengths of 1B and 2B are nearly the same, these two configurations actually belong in the same strength category. The joint failure mode, represented in Figure 6-55, is primarily an adhesive shear failure, but there is some evidence of doubler interlaminar shear failure in Configurations 1B and 2B. The double-etch procedure used to prepare the titanium surfaces has completely eliminated the titanium-to-adhesive interface failure noted in earlier tests.

On the basis of tests conducted in this study, it can be concluded that the strength of the straight-lap joint can be improved by reducing the doubler shear modulus through the thickness. This modulus-reduction can be effectively accomplished using glass scrim cloth, but as Table 6-XIII indicates, this cloth must separate each ply of boron. In Configuration 2B, for example, the scrim separates double plies of boron, with no discernible strength improvement over the all-boron Configuration 1B.

Comparison of the tests results in Table 6-VIII and the results for stepped-lap configurations in Table 4-VII reveal that the simple straight-lap configurations are stronger than the stepped-lap configurations, even though their bondline thicknesses are less. This increase can be attributed to two factors:

- (a) The addition of scrim cloth reduces adhesive shear stress,  
and
- (b) The straight doubler is free of shear and tensile stress concentrations induced by steps in doubler thickness.

TABLE 6 -XIII

## SUMMARY OF TENSILE-SHEAR FAILURE TESTS FOR TITANIUM-BORON/EPOXY STRAIGHT-LAP JOINTS

| CONFIGURATION | SPECIMEN | FAILURE<br>LOAD, LB. | AVERAGE FAILURE<br>STRESS, psi | JOINT STRENGTH<br>psi AVERAGE | STANDARD<br>$\sigma$ , psi | DEVIATION<br>$\sigma$ , psi | REMARKS |
|---------------|----------|----------------------|--------------------------------|-------------------------------|----------------------------|-----------------------------|---------|
| 1B            | 1        | 5325                 | 5325                           | 5233                          | 82.6                       | 1.6                         |         |
|               | 2        | Saved                | —                              |                               |                            |                             |         |
|               | 3        | 5125                 | 5125                           |                               |                            |                             |         |
|               | 4        | 5250                 | 5250                           |                               |                            |                             |         |
| 2B            | 1        | Saved                | —                              | 5167                          | 31.4                       | 0.6                         |         |
|               | 2        | 5175                 | 5175                           |                               |                            |                             |         |
|               | 3        | 5125                 | 5125                           |                               |                            |                             |         |
|               | 4        | 5200                 | 5200                           |                               |                            |                             |         |
| 3B            | 1        | 5000                 | 5000                           | 5375                          | 266                        | 5.0                         |         |
|               | 2        | Saved                | —                              |                               |                            |                             |         |
|               | 3        | 5550                 | 5550                           |                               |                            |                             |         |
|               | 4        | 5575                 | 5575                           |                               |                            |                             |         |
| 4B            | 1        | 5600                 | 5600                           | 5512                          | 357                        | 6.5                         |         |
|               | 2        | 5450                 | 5450                           |                               |                            |                             |         |
|               | 3        | 5000                 | 5000                           |                               |                            |                             |         |
|               | 4        | 6000                 | 6000                           |                               |                            |                             |         |

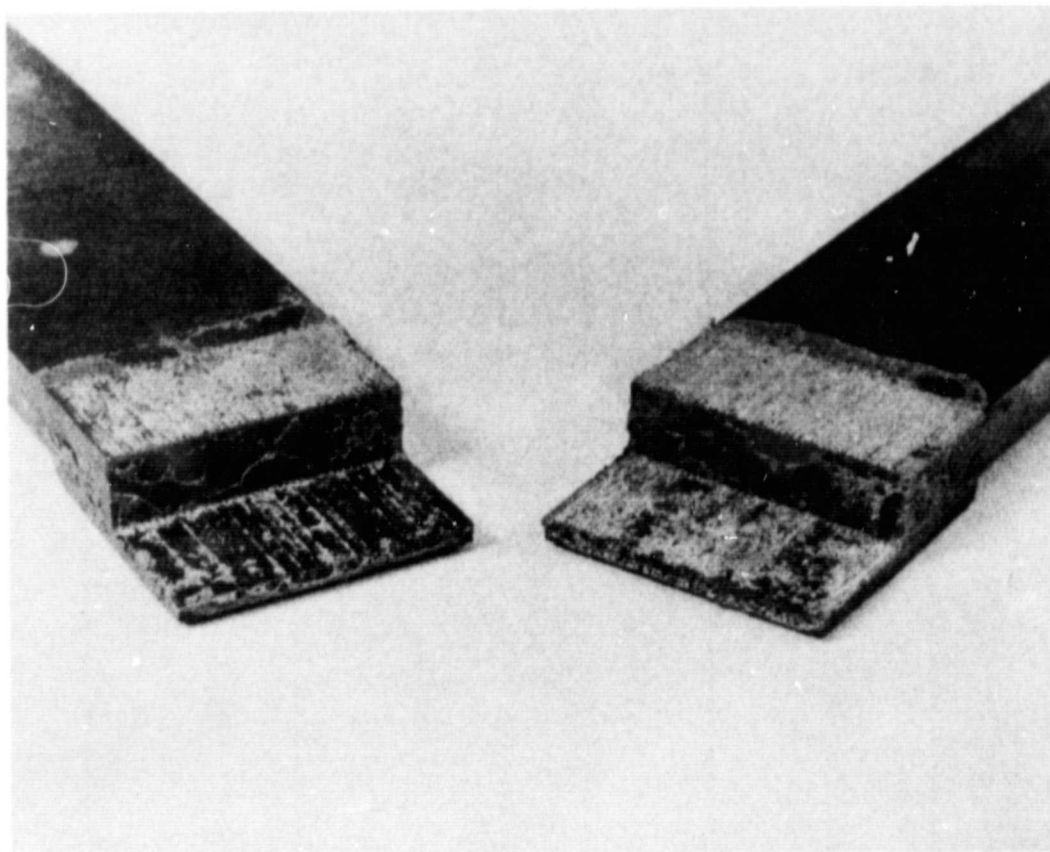


Figure 6-55. Failure in Titanium-Boron/Epoxy  
Straight-Lap Joints.

Because of the latter effect, the interlaminar shear stresses are reduced, permitting more complete development of adhesive shear strength in the straight-lap joint. The predominance of doubler interlaminar shear failure in the stepped-lap joint, compared with the adhesive shear mode which characterized the straight-lap joint failure, substantiates this argument.

While introduction of glass scrim increases the average joint strength, Table 6-VIII makes it evident that these strengths also become subject to a higher degree of scatter ( $\sigma, \%$ ). The correlation between the scatter of test results and the number of glass scrim plies is strong. This phenomenon is easily understood qualitatively, since the number of ply interfaces (regions of potential interlaminar shear failure) are increased by the addition of scrim. Moreover, the increased uncertainty in process and layup parameters should also be reflected in these figures.

The scope of this program precluded more detailed study of the doubler shear effect using more scrim plies and various orientation patterns. Additional correlation was obtained, however, from the study of straight-lap boron/epoxy-boron/epoxy and titanium-titanium joints. These results are discussed in the following paragraphs.

#### Design, Fabrication, and Testing of Boron/Epoxv-Boron/Epoxv Straight-Lap Joints

A straight-lap joint was designed and fabricated with 1 x 1-inch boron/epoxy doublers and 1-inch wide by 0.090-inch thick boron/epoxy main-plates. Since the construction technique was identical to that employed in Section 4 for the stepped-lap boron/epoxy joints, it will not be repeated here. The adherend material consisted of sixteen plies of NMD-5505 oriented unidirectionally, and 32 plies of Type 104 glass scrim cloth. The layup pattern is summarized in Appendix C, Table C-4. This pattern is identical to the pattern for the titanium-boron/epoxy Configuration 4B, outlined in Table C-3. On the basis of adhesive shear stress alone, the boron/epoxy-

boron/epoxy configuration should be a stronger joint than the titanium-boron/epoxy configuration, due to the reduced mainplate shear modulus.

The four bonded joint specimens in this configuration are shown in Figure 6-56. Results of destructive tensile shear tests are listed in Table 6-XIV, and the associated failure modes are shown in Figure 6-57.

The adherend-to-adhesive bondline failure shown in Figure 6-57a was the principal failure mode for this configuration, although the strongest specimen (#1) exhibited some adherend interlaminar shear failure (as shown in Figure 6-57b). Since the principal mode was not the same as the failure mode observed in the titanium-boron/epoxy specimens, a direct comparison of joint strengths could not be made. Further examination of the failure surfaces revealed that separation occurred in the doubler-to-adhesive interface. These doublers were subjected only to the MEK cleaning operation, while the thicker mainplates were also sandblasted. Even with the reduced interface strength, the strength of the joint is still high enough (4425 psi) to indicate the strengthening effect of the reduced adherend shear moduli.

If the adherend-to-adhesive interface strength can be improved, while somehow increasing the doubler interlaminar shear strength, a joint strength exceeding those observed to date can be achieved. In this event, the failure would occur only in the adhesive. Since currently available composite materials do not have sufficient interlaminar shear strength for this demonstration, the most promising joint for demonstrating this improvement seemed to be the titanium-titanium joint. With proper surface preparation, the interface strength should be high, while the relatively high shear strength of the titanium would preclude adherend shear failure. The titanium-titanium configuration of the following section was designed to demonstrate this potential strengthening effect.

#### Design, Fabrication, and Testing of Titanium-Titanium Straight-Lap Joints

A titanium-titanium straight-lap joint was fabricated and tested. The 1 x 1-inch doublers were 0.126-inch thick, while the 1-inch wide

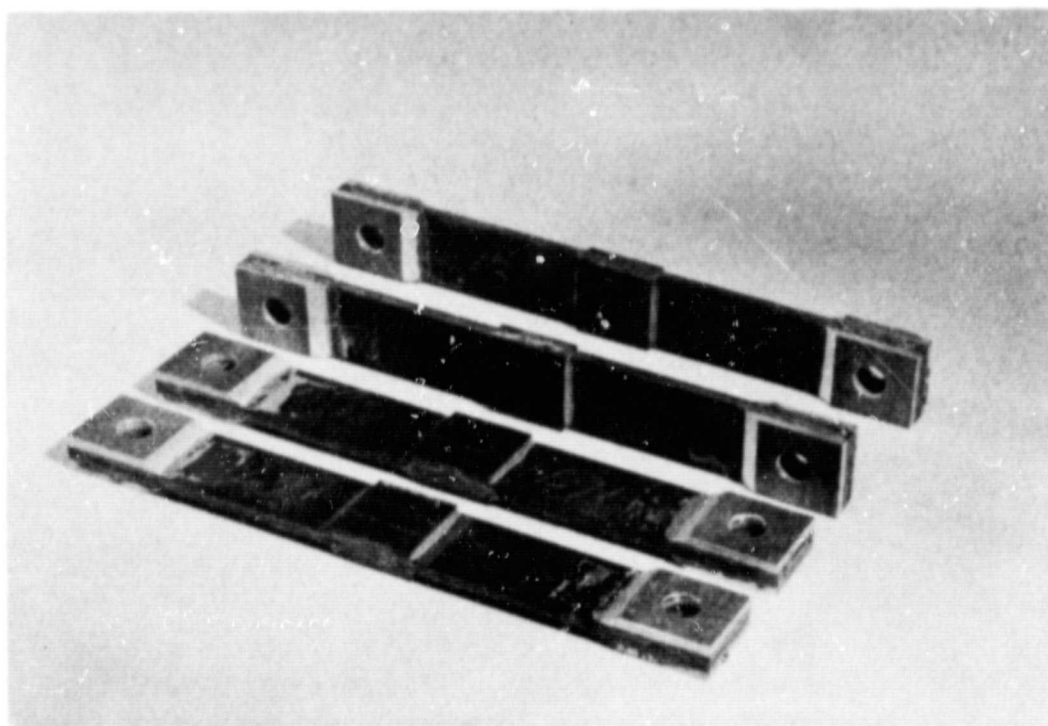
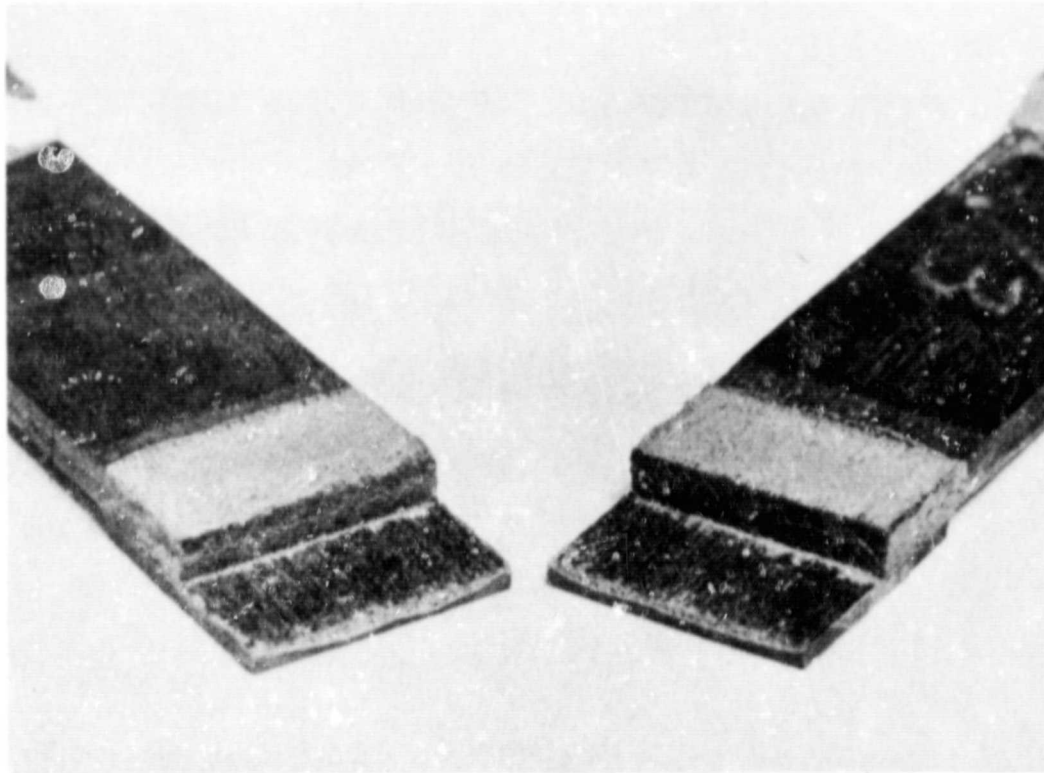


Figure 6-56. Straight-Lap Boron/Epoxy Joint Configuration;  
Configuration Completed.

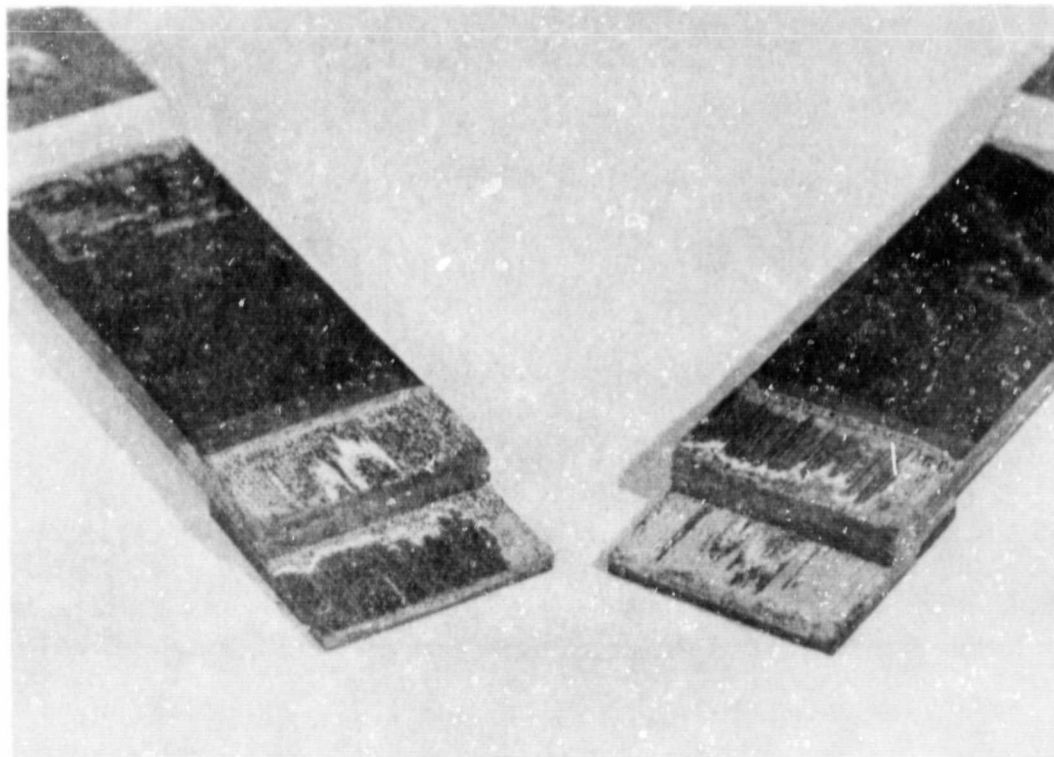
TABLE 6-XIV

SUMMARY OF TENSILE-SHEAR FAILURE TESTS FOR  
BORON/EPOXY-BORON/EPOXY STRAIGHT-LAP JOINTS

| SPECIMEN | FAILURE<br>LOAD, LB. | AVERAGE FAILURE<br>STRESS, psi | JOINT STRENGTH<br>psi | STANDARD DEVIATION |                | REMARKS |
|----------|----------------------|--------------------------------|-----------------------|--------------------|----------------|---------|
|          |                      |                                |                       | $\sigma$ , psi     | $\sigma$ , psi |         |
| 1        | 4900                 | 4900                           |                       |                    |                |         |
| 2        | 3875                 | 4300                           | 4425                  | 369                | 8.3            |         |
| 3        | 4600                 | 4600                           |                       |                    |                |         |
| 4        | 3900                 | 3900                           |                       |                    |                |         |



(a) Adherend-to-Adhesive Interface Failure.



(b) Adherend Interlaminar Shear Failure.

Figure 6-57. Failure in Boron/Epoxy-Boron/Epoxy Straight-Lap Joint.

mainplates were 0.252-inch thick. The Et products of this joint were the same as those of the earlier tests ( $E_t = 6.25 \times 10^6$  Lb/in). The four specimens of this configuration are shown in Figure 6-58. The results of destructive tensile-shear tests are listed in Table 6-XV, and the associated failure mode is represented in Figure 6-59.

Failure of this configuration was almost 100 percent adhesive; no evidence of titanium-to-adhesive interface failure was noted. Since this failure mode was different from those observed in the boron-epoxy adherends, a direct comparison of adhesive bondline strengths could not be made. It was apparent that the double-etch procedure used to prepare the titanium surface proved effective in eliminating failures in the titanium-to-adhesive interface, and resulted in more complete utilization of the adhesive strength. The strength-reducing effect of the high doubler shear modulus was more than offset by the effects of improved bond quality and doubler shear strength.

Full realization of composite (and metallic) joint strength requires that

- (a) Adherends possess high interlaminar shear strength,
- (b) adherend-to-adhesive interface strength be high (achieved by proper surface preparation), and
- (c) adherend stiffness properties be tailored to the joint design restrictions.

These three must be satisfied together if the strength of the adhesive is to be developed fully. With lapses in (a) or (b), failure will occur in the adherends or adherend-to-adhesive interface before the adhesive fails, although complete conformity to (c) would help to forestall these failures. With lapses in (c), failure will occur at point of stress concentration in the adhesive. These concentrations also increase shear stresses in the adherend and the interface, and may induce failure in these modes as well.

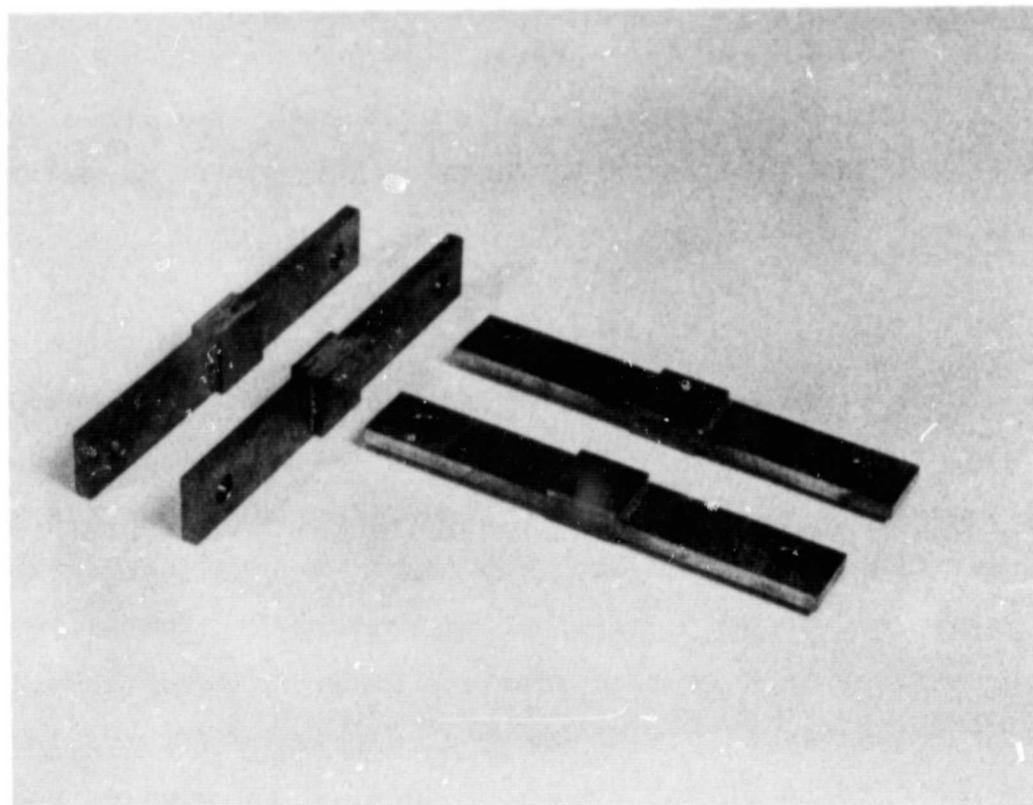


Figure 6-58. Straight-Lap Titanium-Titanium Joint;  
Configuration Completed.

TABLE 6-XV

SUMMARY OF TENSILE-SHEAR FAILURE TESTS FOR  
TITANIUM-TITANIUM STRAIGHT-LAP JOINTS

| SPECIMEN | FAILURE<br>LOAD, LB. | AVERAGE FAILURE<br>STRESS, psi | JOINT STRENGTH<br>psi | STANDARD DEVIATION<br>$\sigma$ , psi | STANDARD DEVIATION<br>$\sigma$ , psi |
|----------|----------------------|--------------------------------|-----------------------|--------------------------------------|--------------------------------------|
| 1        | 5000                 | 5000                           |                       |                                      |                                      |
| 2        | 5625                 | 5625                           | 5581                  | 619                                  | 11.1                                 |
| 3        | 6425                 | 6425                           |                       |                                      |                                      |
| 4        | 5275                 | 5275                           |                       |                                      |                                      |

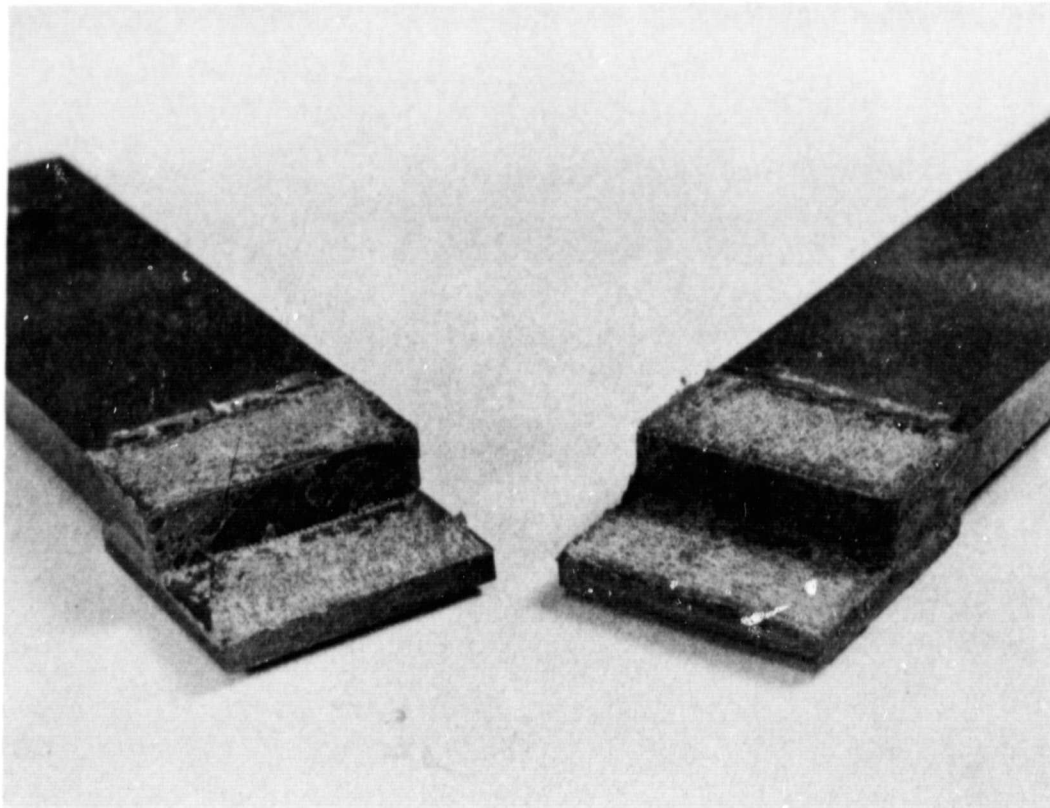


Figure 6-59. Failure in Straight-Lap Titanium-Titanium Joint.

## SECTION 7

### CONCLUSIONS AND RECOMMENDATIONS

All objectives of the contracted study have been achieved. A simplified joint design procedure has been developed for achieving uniform adhesive shear stress, and the effects of adhesive and adherend strengths and stiffnesses on the joint strength have been investigated. The photo-elastic technique for monitoring adhesive shear stresses has been re-evaluated, using a finite-element computer program adapted for this study. Conclusions and recommendations are enumerated in the following paragraphs.

#### The Simplified Design Criterion

A design criterion, based upon the matching of adherend strains along the bondline, has been developed and evaluated both analytically and experimentally. When all other production parameters are maintained constant, the changes of material and geometry suggested by this criterion have, in the cases tested, led to increased strength of symmetrical lap bonded joints. In the straight-lap configurations investigated, this criterion is shown to be applicable even when the adherends have low thickness-shear moduli and the adhesives have nonlinear properties.

#### Effect of Adherend Shear Modulus and Adhesive Nonlinearity

Analysis and test results demonstrate that reduced adherend shear moduli can lead to considerable reduction in adhesive peak shear stresses.

Further reductions can be achieved if the adhesive has greater ductility, given the same shear strength. A straight-forward procedure has been developed for determining adhesive shear stresses in typical straight-lap joints, accounting for finite adherend shear moduli and nonlinear adhesive shear properties. To the author's knowledge, these solutions are presented here for the first time.

#### Effect of Adhesive, Adherend and Interface Strengths

Failure of the joints tested in this study were of three types:

- (a) Shear failure in the boron/epoxy laminate,
- (b) shear failure in the adherend-to-adhesive interface, and
- (c) shear failure of the adhesive itself.

The first was related to the laminate shear strength and was of particular importance to strength of the boron/epoxy joints. The second was directly related to the adherend surface preparation. The third was governed by the degree to which the simplified design criterion was satisfied. Joints failing in mode (c) were always strongest; joints failing in mode (b) were always weakest. Improvement of the design by use of the simplified strain-matching criterion nearly always increased joint strength, regardless of mode of failure. This result indicates that a reduction of peak shear stresses has been accomplished, using this procedure. Reduction of adherend shear strength or degradation of the adherend-to-adhesive interface properties always reduced the joint strength and often affected the failure mode. Each of these factors had sufficient influence on the joint strength that the benefits gained from improvement of one could be negated by the degradation of another.

### The Photoelastic Method for Determining Adhesive Shear Stress

The photoelastic method has been shown to yield only a qualitative indication of adhesive shear stress, when used in the manner discussed herein. The technique is appropriate where visualization of the adhesive shear stress field is necessary, but it should not be used to determine the magnitudes of these stresses. The photoelastic display is in particularly large quantitative error in regions of high geometric or adhesive-strain gradients.

### Suggested Design Optimization Procedure

The optimization of a joint design, subject to given geometric and material requirements, can be accomplished by the following procedure:

1. Suitable adhesive materials are selected on the basis of critical environmental conditions such as temperature, humidity, corrosive atmosphere, etc.
2. Adherend geometric and/or material constraints are established from the overall structural requirements. Typical of these would be "--- to join titanium and boron/epoxy of a specified layup pattern ---" or, "--- to join two boron/epoxy panels in a specified bond-line configuration ---" or, "--- to join two materials with a specified exterior joint geometry ---".
3. Determine optimum joint design conditions, using the simplified design criterion (8), p. 3-7.
4. Design joints representing practical approximations to the optimum design, and compare their strengths qualitatively, using the optimum as a reference.

5. Select the designs best approximating the optimum.  
Make final selections on the basis of adherend shear and tensile strengths and the effectiveness of available bonding procedures.
6. Determine stress distributions in the selected design, using the finite-element computer program and assumed (or known) joint material properties. The material properties are, of course, given for the prescribed environmental conditions. In many applications, this last step is optional.

The procedure outlined above was employed in the design of the stepped-lap joints:

1. Metlbond 328 was the chosen adhesive, because it satisfied the requirements of high strength, low ductility and potential for bondline thickness control.
2. The bondline geometry (four step) and doubler geometry (flat external surface) constraints were established for fabricability and demonstration potential.
3. The constraints were employed in the design criterion (8) to obtain the stepped-lap joint criterion (10). Practical approximations to criterion (10), based on the matching of total strain in each step, led to the average-strain criterion (11), p. 4-3.
4. Five configurations were designed, and their strengths compared on the basis of (11).

5. Joints which conformed best to the criterion were tentatively judged superior in strength, and would have ordinarily been chosen for further study. The tests performed corroborated the choices made.
6. The finite-element computer analysis, assuming linear joint properties, produced qualitative agreement with the choices made. Joints which conformed best with the criterion were shown to be stronger in both the analytic and the test programs.

#### The Tailoring Capabilities of Composite Materials

The optimum design can often be achieved only by simultaneous change of adherend geometry and stiffness along the bondline. Limited adjustment can be performed using metallic materials, but the greatest freedom in design can be achieved with the aid of composite materials. By controlling layup patterns and ply properties, adherends have been fabricated which closely conform to the optimum property and geometric requirements.

An effective technique for simultaneously altering tensile and shear stiffnesses in composite adherends is the interleaving of glass scrim with the boron/epoxy plies. With slight effect on tensile stiffness, the interlaminar shear modulus can be reduced enough to realize significant improvements in joint strength. In practice, this method leads to greater scatter of failure strengths and may, in extreme cases, alter the failure mode by reducing the adherend interlaminar shear strength. Test results indicate a strong correlation between joint shear strength and the number of interleaved scrim plies.

## Recommendations

The analysis developed herein can be used to generate an almost unlimited range of parameter studies, demonstrating the effects of joint material and geometry parameters on the stress distributions in the joint. These distributions, in combination with appropriate shear failure criteria, can be used to determine the relations between the design parameters and joint strength. Actual generation of these studies was not the object of this investigation; the improved capability to generate them has been accomplished, and is summarized in the computer programs of Appendices D and E.

The experimental results indicate that the design procedure used in this study will definitely lead to improved joint strength. Control of fabrication parameters was maintained sufficiently that scatter of strength test results was less than 10 percent for specimens with improved surface preparation. With strict control, the scatter for titanium-boron/epoxy specimens was maintained at less than 6.5 percent. Without the improved surface preparation, however, this scatter increased to 12.2 and 15 percent. These scatters, and the associated strengths, are directly related to the fabrication procedures.

It is now necessary to evaluate the influence of fabrication parameters on joint strength. This information should be sufficient to determine how closely the joint design specification must be met in order to achieve the desired range of joint strengths. A experimental study, using carefully controlled fabrication procedures would accomplish this objective. Such parameters as joint alignment, bondline thickness control, geometry control, surface preparation technique, adhesive pressure, and adherend layup control must be investigated for a number of contemporary adhesives. A sufficient number of joint specimens must be produced under each fabrication condition to permit a statistical evaluation of its affect on joint strength.

Adhesive characterization is another important factor in joint design. With the aid of the procedures developed in this study, it is feasible to perform tests on standard joint configurations, invert the results of adherend surface strain measurements, and obtain descriptions of the adhesive shear stress-strain curve. Previous to this study, the adherend shear deformations were not considered, and such an inversion would not have led to correct shear properties. A study of this type would be both experimental and analytical, and would yield statistical descriptions of effective adhesive properties. These properties are particularly appropriate to applications in joint design.

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## APPENDIX A

### PRELIMINARY SURVEY OF BONDED JOINT DESIGN

#### ANALYTICAL BACKGROUND

The modern approach to bonded joint design appears to have begun with Volkersen<sup>(1)</sup> (1939) and Goland and Reissner<sup>(2)</sup> (1944), who studied the stress distributions in a single-lap joint, using plate theory and the theory of elasticity. Later elastic analyses were performed by Sherrer<sup>(3)</sup> (1957), Hahn and Fouser<sup>(4)</sup> (1962), and Lubkin<sup>(5)</sup> (1957), but it appears that the fundamental elastic formulation of the problem in most of the later analyses can be traced to the "classical" formulation of Goland and Reissner. In the Goland-Reissner study, the adherend materials away from the joint are treated as plates, bent into cylindrical shape by moments induced by the offset tensile loads applied to the joint. Due to the thinness of the adhesive layer, normal stresses parallel to the adherends are neglected and the remaining stresses are assumed constant through the adhesive thickness. On the basis of strain energy considerations, two extreme cases are defined: the joint with relatively inflexible cement layer, and the joint with relatively flexible cement layer. In the former case, the tension stress is assumed linearly distributed over each adherend, and adherend shear stresses are neglected; i.e., plane sections remain plane near the joint edge. With these assumptions, solution of the stress distribution in the adhesive becomes a plane-strain problem in the theory of elasticity, and is performed approximately.

g. 3

The relatively flexible cement layer is treated by assuming the adhesive strains large compared with the adherend transverse normal and shear strains. The strain differentials between the adherends are related to the adhesive shear strains, and a set of equations in the adhesive stresses is obtained. In this analysis, Goland and Reissner recognize that analytic rigor could still be maintained in their approach, even for nonlinear adhesive and adherend materials, but the matter is not pursued further. This latter analysis forms the basis from which most of the later modifications have sprung. Its value has been proven in the considerable body of experimentation which has followed, both destructive (Eickner<sup>(6)</sup> (1955), Anderson<sup>(7)</sup> (1967), Goodwin<sup>(11)</sup> (1963)) and photoelastic (Lobbett and Robb<sup>(8)</sup> (1962), Mylonas<sup>(15)</sup> (1955), Tuzi and Shimada<sup>(9)</sup> 1964-65, Hahn and Fouzer<sup>(4)</sup> (1962), Feher<sup>(10)</sup> (1967), and Anderson<sup>(7)</sup> (1967-68) . These experiments generally agree that, provided the responses remain linear and the cement relatively flexible, the Goland-Reissner analysis provides excellent insight into joint behavior. Most of the discrepancies have been correlated either with inelastic behavior in the joint or deficiencies in the bonding techniques. It was recognized, for example, that adhesive yield improved joint strength through redistribution of the resultant stresses.

In 1967, Berg<sup>(12)</sup> of Whittaker Research & Development extended the Goland-Reissner analysis to include the nonlinear stress-strain relation:

$$\tau_o(\gamma) = a[1 - e^{-b\gamma}]$$

where  $a$  and  $b$  are experimentally determined adhesive properties. For the first time, the effect of an adhesive nonlinearity on joint strength could be evaluated quantitatively, accounting for details of the material properties  $a$  and  $b$  . Berg's analysis constituted a rigorous extension of the Goland-Reissner elastic formulation, and required a straightforward numerical computation to obtain the solution. As such, the approach is readily adaptable to other forms of adhesive nonlinearity.

In addition to material nonlinearity, it was understood that shear lag in the adherends, particularly for stepped shapes, would prove important in determination of adhesive stresses. Since the Goland-Reissner results have generally proven conservative, the need to refine the analysis for weight-strength purposes has prompted development of various discrete-element modelling techniques that would consider adherend shear effects. Cornell<sup>(13)</sup> (1953), Lobbett and Robb<sup>(8)</sup> (1962), and Anderson<sup>(7)</sup> (1967) have generated discrete element models consisting of springs and beams, or shear webs and tensile rods that yielded much data valuable to the study of joints. Application of the computer to joints, using the plate element approach, has not been widely documented. Although a well-established technique, this form of the finite element approach seems to enjoy a proprietary status. Analyses of stepped-lap, simple-lap, and double-lap joints have been performed by Feher<sup>(10)</sup>, using a plate element program developed at Whittaker Research & Development in 1968. This program is now in use in a NASA-sponsored study being conducted by Whittaker.

Several adaptations of linear discrete element programs have been made to account for plastic effects in the adhesive (Goodwin<sup>(11)</sup> (1963), for example). These tend to be of an empirical nature. While the analytic approaches permit ready formulation, including nonlinear effects, for simple shapes, the discrete element approaches appear best adapted to include shear effects and a variety of joint geometries. A study of nonlinear joints with complex shapes will require exploitation of the positive features of each technique.

Determination of adhesive properties has been a problem which has developed parallel to the analysis of joints. Several studies have been performed for the purpose of evaluating adhesive properties suitable for joint study. These include both indirect methods (Kuenzi and Stevens<sup>(14)</sup> (1963), Feher<sup>(10)</sup> (1967)) and direct measurement techniques (Hughes, Rutherford<sup>(16)</sup> (1968), Berg<sup>(12)</sup> (1968)).

In these studies it has become apparent that observed properties of the adhesive are strongly correlated with the properties of the adherends. In the practical analysis of joints using these observed properties, it becomes necessary to do one of two things: either (a) translate these observed properties into fundamental properties, then analyze the joint accounting for the adherend-adhesive interaction of properties, or (b) translate the observed properties into "effective" properties, then analyze the joint, using a somewhat simpler analysis. Each technique requires much iteration between experimental and analytic study in order to verify that the fundamental or "effective" properties are appropriate to joint design.

Some tests, most notably the lap shear test, have been abused in their application to bonding studies. On the one hand, the joint properties are to be determined, assuming the adhesive properties; on the other hand, the adhesive properties are to be deduced from the joint behavior. In general, the same test cannot be employed to support the assumptions used both in joint idealization and in adhesive characterization - any more than one equation can lead to a complete solution for two unknowns! Either independent tests are necessary, or the basic test must be suitably modified to bring out important features of the adhesive and the stress distribution separately.

Simplified design methods have been presented by Szepe<sup>(18)</sup> (1957), by Tombach<sup>(17)</sup> (1957), and by McCombs, et.al.<sup>(19)</sup> (1968), wherein data from a relatively few tensile tests are used to develop empirical design curves for a particular joint configuration. The design techniques mentioned are best applicable to linearly elastic adherends and adhesives, using ultimate elastic stress failure criteria. The testing experience indicates, however, that linear joint behavior to failure is a relatively rare occurrence, and that departure from linearity has important consequences with respect to joint strengths.

Probably the most graphic description of nonlinear adhesive and adherend effects is contained in the recent paper by Wegman, Devine, Lacher, and Anderson<sup>(20)</sup>. In this work, striking experimental evidence is presented that strongly correlates joint strength with adherend ultimate strength. In double-lap joints of overlap  $L$  and adherend thickness  $t$ , the ultimate cohesive failure load  $P_{ult}$  is related to  $L/t$  as illustrated in Figure A-1. Segment I of this curve appears dependent solely upon the nonlinear adhesive shear properties, segment II upon nonlinear local adherend strains, and segment III upon the adherend strength itself. A transition from adhesive shear to adhesive peel failure occurs in portion II, accompanied by evidence of yield in the adherend material. This abrupt transition from adherend-elastic to adherend-inelastic behavior has also been observed by Duke and Stanbridge<sup>(21)</sup> (1968) in peel tests to determine cleavage strength of bonded thin adherends. It is evident from both studies that adherend yield has profound effects on the apparent strength of adhesive joints.

Application of composite materials in bonded joints has been seriously considered lately, in view of the potential weight savings in aerospace structural applications. In order to realize the potential weight savings, however, it is necessary to achieve greater confidence in the design technique; i.e., to reduce the safety factors currently used in designing metallic joints. Even with homogeneous isotropic adherends, the full consideration of material properties - so essential to full utilization of the joint - has not yet been accomplished. The urgent current interest in composite applications forces the analyst (and the technology) to make a giant step, in which he must not only analyze the effects of nonlinear material properties, but must also consider a variety of new failure modes associated with layered orthotropic adherends.

Several factors combine to make the Goland-Reissner analysis less applicable to composite joints than to metallic joints:

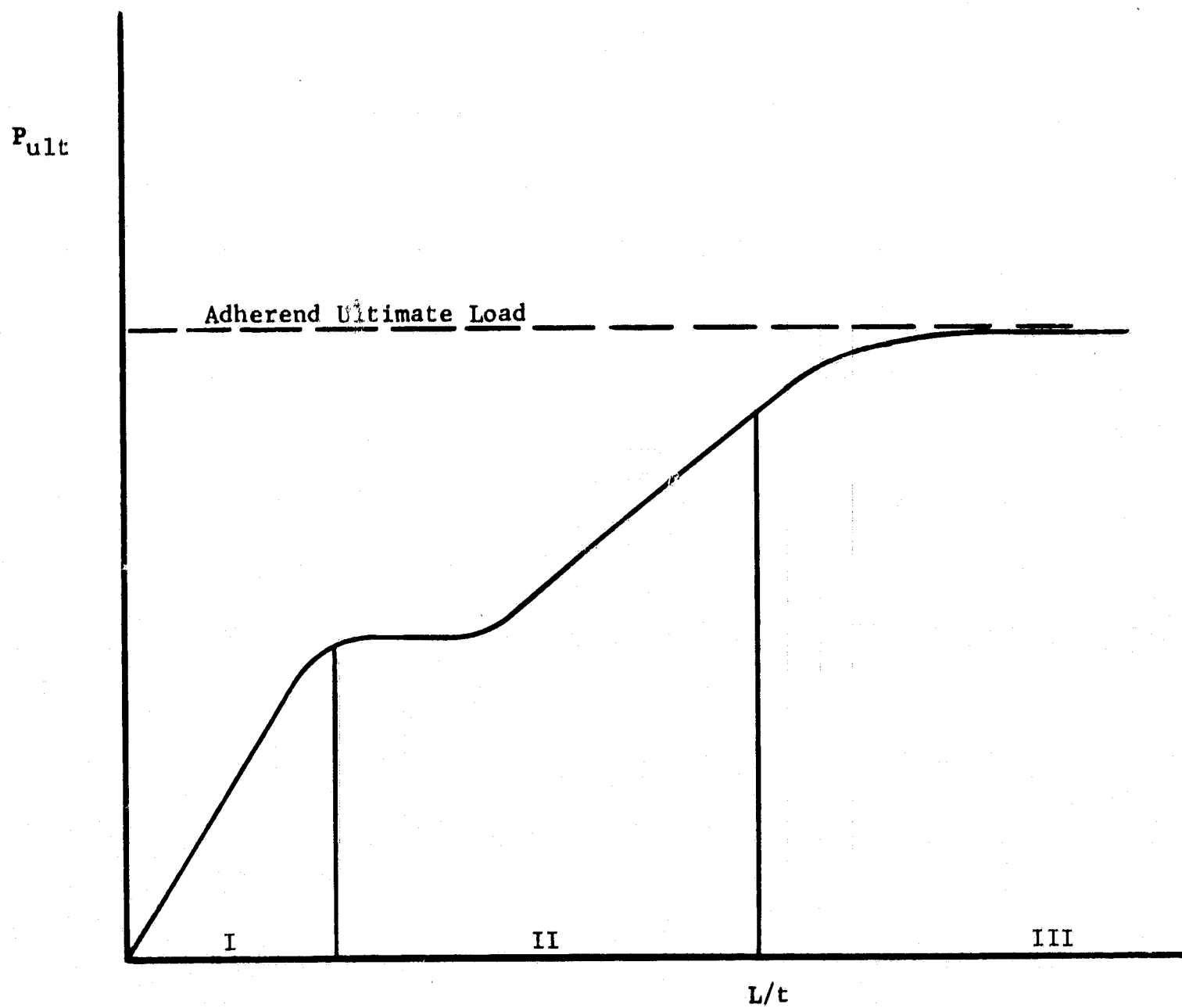


FIGURE A-1. SCHEMATIC REPRESENTATION OF  
OBSERVED ULTIMATE LOADS  $P_{ult}$  FOR A  
DOUBLE-LAP JOINT. ( $L$ =OVERLAP LENGTH,  $t$ =ADHEREND THICKNESS)

- a. The shear stiffness of the matrix material may be similar to (or even less than) the shear stiffness of the adhesive. This fact makes analysis of adherend shear lag essential to effective study of composites.
- b. The inhomogeneity and orthotropy of the adherends give rise to yet unknown interlaminar shear stress-strain relations.
- c. The properties of the resin and the fiber are not well understood, but there is evidence that resin properties are nonlinear even at low stress levels, affecting the manner in which shear forces are transferred across layers and through the adhesive.

#### The Current State of the Art

The study of bonded joints must now pass through the so-called "classical" development phase, where linear systems and simple analytic models are employed. Experience gained during this phase has indicated that these models are not adequate to explain the observed responses, even for homogeneous adherends.

Work is already being conducted in the study of composite joints by Whittaker Corporation<sup>(22, 26, 27)</sup> and others (i.e., Refs 7, 23). Most of the available literature presents results that are tentative and "subject to modification and correction," and is either test-oriented or involved with analysis of linear composite behavior. It is generally recognized, however, that composite interlaminar stress-strain behavior is nonlinear, particularly at low strain levels.

Essential to the prediction of failure in composite joints will be the understanding of the stress distribution in nonlinear layered orthotropic adherends, bonded by a nonlinear adhesive. Adequate treatment of this model of the composite joint has yet to be accomplished.

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## APPENDIX B

### PREPARATION OF TITANIUM-ALLOY SURFACES FOR ADHESIVE BONDING<sup>[8]</sup>

- (1) Wipe with methyl ethyl ketone
- (2) Degrease with trichloroethylene vapor
- (3) Pickle in the following water solution at room temperature for 30 seconds:  
  
Nitric acid (15 percent by volume of  
70 percent  $\text{HNO}_3$  solution)  
  
Hydrofluoric acid (3 percent by volume  
of 50 percent HF solution)
- (4) Rinse in tap water at room temperature
- (5) Immerse in the following water solution at room temperature for 2 minutes:  
  
Trisodium phosphate; 50 grams/liter  
of solution  
  
Potassium fluoride: 20 grams/liter of  
solution  
  
Hydrofluoric acid (50 percent solution)  
26 milliliters/liter of solution
- (6) Rinse in tap water at room temperature
- (7) Soak in 150°F tap water for 15 minutes
- (8) Spray with distilled water and air dry.

# APPENDIX C

## LAMINATION PATTERNS FOR BORON/EPOXY SPECIMENS

TABLE C-1

### TITANIUM-BORON/EPOXY STEPPED-LAP JOINTS

| CONFIGURATION | 1, 4, 5   |                        | 2         |                        | 3         |                        |
|---------------|-----------|------------------------|-----------|------------------------|-----------|------------------------|
| PLY NUMBER    | TYPE      | DEGREES<br>ORIENTATION | TYPE      | DEGREES<br>ORIENTATION | TYPE      | DEGREES<br>ORIENTATION |
| 1             | SCOTCHPLY | 0                      | SCOTCHPLY | 0                      | SCOTCHPLY | 0                      |
| 2             | SCOTCHPLY | 0                      | SCOTCHPLY | 0                      | SCOTCHPLY | 0                      |
| 3             | NMD-5505  | 0                      | NMD-5505  | 90                     | NMD-5505  | 0                      |
| 4             | NMD-5505  | 90                     | NMD-5505  | 90                     | NMD-5505  | 0                      |
| 5             | ↑         | 0                      | ↑         | 0                      | ↑         | 0                      |
| 6             |           | 90                     |           | 90                     |           | 0                      |
| 7             |           | 0                      |           | 90                     |           | 0                      |
| 8             |           | 90                     |           | 90                     |           | 0                      |
| 9             |           | 0                      |           | 0                      |           | 0                      |
| 10            |           | 90                     |           | 90                     |           | 0                      |
| 11            |           | 0                      |           | 90                     |           | 0                      |
| 12            |           | 90                     |           | 0                      |           | 0                      |
| 13            |           | 0                      |           | 90                     |           | 0                      |
| 14            |           | 90                     |           | 0                      |           | 0                      |
| 15            |           | 0                      |           | 90                     |           | 90                     |
| 16            |           | 90                     |           | 0                      |           | 0                      |
| 17            |           | 0                      |           | 90                     |           | 0                      |
| 18            |           | 90                     |           | 0                      |           | 0                      |
| 19            |           | 0                      |           | 0                      |           | 0                      |
| 20            |           | 90                     |           | 0                      |           | 90                     |
| 21            |           | 0                      |           | 0                      |           | 0                      |
| 22            | ↓         | 90                     | ↓         | 90                     | ↓         | 90                     |

TABLE C-1 (Continued)

| CONFIGURATION 1, 4, 5 |          |                     | 2        |                     | 3        |                     |
|-----------------------|----------|---------------------|----------|---------------------|----------|---------------------|
| PLY NUMBER            | TYPE     | DEGREES ORIENTATION | TYPE     | DEGREES ORIENTATION | TYPE     | DEGREES ORIENTATION |
| 23                    | NMD-5505 | 0                   | NMD-5505 | 0                   | NMD-5505 | 0                   |
| 24                    | ↑        | 90                  | ↑        | 0                   | ↑        | 90                  |
| 25                    |          | 0                   |          | 0                   |          | 0                   |
| 26                    |          | 90                  |          | 0                   |          | 90                  |
| 27                    |          | 0                   |          | 0                   |          | 90                  |
| 28                    |          | 90                  |          | 0                   |          | 0                   |
| 29                    | NMD-5505 | 0                   | ↓        | 0                   | ↓        | 90                  |
| 30                    | NMD-5505 | 90                  |          | 0                   |          | 90                  |
| 31                    | —        | —                   |          | 0                   |          | 0                   |
| 32                    | —        | —                   |          | 0                   |          | 90                  |
| FINISHED THICKNESS    |          | .142"               |          |                     | .142"    | .142"               |

TABLE C-2  
BORON/EPOXY STEPPED-LAP JOINT

| PLY NUMBER | TYPE     | DEGREES ORIENTATION |
|------------|----------|---------------------|
| 1          | NMD-5505 | 0                   |
| 2          | NMD-5505 | 0                   |
| 3          | ↑        | 90                  |
| 4          |          | 0                   |
| 5          |          | 0                   |
| 6          |          | 90                  |
| 7          |          | 0                   |
| 8          |          | 0                   |
| 9          |          | 90                  |
| 10         |          | 0                   |
| 11         |          | 90                  |
| 12         |          | 0                   |
| 13         |          | 90                  |
| 14         |          | 0                   |
| 15         |          | 90                  |
| 16         |          | 0                   |
| 17         |          | 90                  |

TABLE C-2 (Continued)

| PLY NUMBER            | TYPE               | DEGREES<br>ORIENTATION |
|-----------------------|--------------------|------------------------|
| 18                    | NMD-5505<br>↑<br>↓ | 0                      |
| 19                    |                    | 90                     |
| 20                    |                    | 0                      |
| 21                    |                    | 90                     |
| 22                    |                    | 0                      |
| 23                    |                    | 90                     |
| 24                    |                    | 0                      |
| 25                    |                    | 90                     |
| 26                    |                    | 90                     |
| 27                    |                    | 0                      |
| 28                    |                    | 90                     |
| 29                    |                    | 90                     |
| 30                    |                    | 0                      |
| 31                    | NMD-5505           | 90                     |
| 32                    | NMD-5505           | 90                     |
| FINISHED<br>THICKNESS |                    | .130"                  |

TABLE C-3

## TITANIUM-BORON/EPOXY STRAIGHT-LAP JOINTS

| CONFIGURATION                                                                                                                               | 1B       | 2B        | 3B        | 4B        |
|---------------------------------------------------------------------------------------------------------------------------------------------|----------|-----------|-----------|-----------|
| PLY NUMBER*                                                                                                                                 | TYPE**   | TYPE**    | TYPE**    | TYPE**    |
| 1                                                                                                                                           | NMD-5505 | NMD-5505  | 104 Scrim | NMD-5505  |
| 2                                                                                                                                           | NMD-5505 | 104 Scrim | NMD-5505  | 104 Scrim |
| 3                                                                                                                                           | —        | NMD-5505  | 104 Scrim | 104 Scrim |
| 4                                                                                                                                           | —        | —         | NMD-5505  | 104 Scrim |
| 5                                                                                                                                           | —        | —         | —         | NMD-5505  |
| 6                                                                                                                                           | —        | —         | —         | 104 Scrim |
| 7                                                                                                                                           | —        | —         | —         | 104 Scrim |
| 8                                                                                                                                           | —        | —         | —         | 104 Scrim |
| * Above patterns performed <u>eight</u> times to attain final laminates.<br>** All NMD-5505 Boron/Epoxy plies are laid with 0° orientation. |          |           |           |           |
| FINISHED<br>THICKNESS                                                                                                                       | .072"    | .075"     | .067"     | .091"     |

TABLE C-4

BORON/EPOXY STRAIGHT-LAP JOINTS

| PLY NUMBER*                                                                                                                                                 | TYPE**    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| 1                                                                                                                                                           | NMD-5505  |
| 2                                                                                                                                                           | 104 Scrim |
| 3                                                                                                                                                           | 104 Scrim |
| 4                                                                                                                                                           | 104 Scrim |
| 5                                                                                                                                                           | NMD-5505  |
| 6                                                                                                                                                           | 104 Scrim |
| 7                                                                                                                                                           | 104 Scrim |
| 8                                                                                                                                                           | 104 Scrim |
| <p>* Above patterns were performed <u>eight</u> times to attain final laminates.</p> <p>** All NMD-5505 Boron/Epoxy plies are laid with 0° orientation.</p> |           |
| FINISHED THICKNESS                                                                                                                                          | .090"     |

#### APPENDIX D

FORTRAN COMPUTER PROGRAM FOR STRAIGHT-LAP JOINTS WITH  
 $E_1 t_1 = E_2 t_2$  EFFECTS OF ADHESIVE NONLINEARITY AND ADHEREND  
SHEAR MODULUS INCLUDED.

#### ASSUMPTIONS:

- (a) Adhesive shear stress-strain relation

$$\tau_a = \frac{G_a}{\Omega} \left( 1 - e^{-\Omega \gamma_a} \right)$$

- (b) Adherend stress-strain relations

$$\left. \begin{array}{l} \tau_1 = G_1 \gamma_1 \\ \sigma_1 = E_1 \epsilon_1 \end{array} \right\} \text{ DOUBLER}$$

$$\left. \begin{array}{l} \tau_2 = G_2 \gamma_2 \\ \sigma_2 = E_2 \epsilon_2 \end{array} \right\} \text{ MAINPLATE}$$

- (c) Thickness =  $t_1$  (doubler),  $2t_2$  (mainplate) inches

- (d) Doubler length =  $2L$  inches

- (e) Doubler width =  $b$  inches

- (f) Load =  $2P$  lb.

INPUTS:

1040  $E_1, G_1, t_1$

1050  $E_2, G_2, t_2$

1060  $G_a, \Omega, t_a, b$

1070  $(\tau_a)_{x=0}$

1080  $P_o, \Delta P, P_f$

OUTPUTS:

(a)  $x, \tau_a(x) \quad x=0.5L(0.25L)L$

(b)  $P=2b \int_{0.5L}^L \tau_a(x) dx$

(c) Stress concentration factor  $SCF = \frac{\tau_a(L)}{(\tau_a)_{ave}}$

LISTING:

TNHARI 11:04 LA "L" 07/11/69

100 DIMENSION Q21(2), GS(21), CAY(4)

110 READ, E1, G1, T1

115 READ, E2, G2, T2

120 READ, G, OM, TA, B

130 READ, TAUO

135 READ, PO, DELP, PF

140 PRINT, " E1", " E2", " T1", " T2"

150 PRINT, E1, E2, T1, T2

160 PRINT, " "

170 PRINT, " G", " G1", " G2", " OMEGA"

180 PRINT, G, G1, G2, OM

190 PRINT, " "

200 PRINT, " B", " TA", " TAUO"

210 PRINT, B, TA, TAUO

220 PRINT, " "

240 DO 5 P=PO, PF, DELP

250 Q2=P/(TA\*B\*E1\*T1)

260 PRINT, "P =", P

270 GS(1) = TAUO

280 TAUPO=0.

290 EL = 1.

300 C1=(1./(E1\*T1)+1./(E2\*T2))/TA

310 C2=(T1/G1+T2/G2)/(3.\*TA)

320 IC=0

```

330 EPS=1.E-5
340 H=EL/40.
350 H2=H/2.
360 H8=H/8.
370 DO 300 I=1,20
380 DO 200 K=1,2
390 TAU=TAU0
400 TAUP=TAUP0
410 IF(IC) 10,10,20
420 10 CONTINUE
430 ELC2 = EL/2.
450 20 CONTINUE
460 DO 100 J=1,20
470 X=EL/2.+J*H
480 XTAU=TAU
490 XTAUP = TAUP
500 IJUMP = 1
510 GO TO 80
520 30 XTAU=TAU+H2*TAUP+H8*CAY(1)
530 XTAUP=TAUP+CAY(1)/2.
540 IJUMP=2
550 GO TO 80
560 40 XTAUP=TAUP+CAY(2)/2.
570 IJUMP=3
580 GO TO 80
590 50 XTAU=TAU+H*TAUP+H2*CAY(3)
600 XTAUP=TAUP+CAY(3)
610 IJUMP=4
620 GO TO 80
630 60 DTAU=H*(TAUP+(CAY(1)+CAY(2)+CAY(3))/6.)
640 DTAUP=(CAY(1)+CAY(4))/6.+(CAY(2)+CAY(3))/3.
650 TAU=TAU+DTAU
660 TAUP=TAUP+DTAUP
670 IF(IC) 100,100,70
680 GS(J+1) = TAU
690 PRINT,X,TAU
700 GO TO 100
710 80 TEMP=C1*XTAU-OM/(G-OM*XTAU)+2*XTAUP+2
715 TEMP=TEMP*H
720 CAY(IJUMP)=TEMP/(1./(G-OM*XTAU)+C2)
730 GO TO (30,40,50,60),IJUMP
740 100 CONTINUE
750 IF(IC) 110,110,400
760 110 Q21(K)=(C2+1./(G-OM*TAU))*TAUP
770 IF(K-2) 120,190,190
780 120 IF(ABS(Q21(1)-Q2)-EPS) 130,130,180
790 130 IC=1
800 PRINT" "
810 X=EL/2.
820 PRINT," X"," TAU"
830 PRINT,X,TAU0
840 GO TO 200

```

```

850 180 TAUO=TAUO*1.1
860 190 CONTINUE
870 200 CONTINUE
890 290 TAUO=TAUO/11.*(10.+(Q2-Q21(1))/(Q21(2)-Q21(1)))
900 300 CONTINUE
910 400 CONTINUE
920 SE=GS(1)+GS(21)
930 SI=0.
940 SP=0.
950 DO 410 J=3,19,2
960 410 SP=SP+GS(J)*2.
970 DO 420 J=2,20,2
980 420 SI=SI+4.*GS(J)
990 PS=H/1.5*(SE+SP+SI)
992 SCF=TAU*B*EL/P
1000 PRINT,"INTEGRAL OF TAU A =",PS
1002 PRINT,"STRESS CONCENTRATION FACTOR =",SCF
1010 5 CONTINUE
1020 END
1030 $DATA

```

SAMPLE RUN:

TITANIUM ADHERENDS,

$E_1 = E_2 = 16 \times 10^6 \text{ psi}$   
 $G_1 = G_2 = 6.15 \times 10^6 \text{ psi}$   
 $t_1 = t_2 = 0.125''$

HIGH MODULUS NONLINEAR ADHESIVE

$G_a = 2 \times 10^5 \text{ psi}$   
 $\Omega = 100$   
 $t_a = 0.008''$   
 $b = 1''$

STARTING ASSUMED STRESS  $\tau_a(0.5L) = \tau_o = 50 \text{ psi}$

INPUT LOAD  $P_o = P_f = 100 \text{ Lb.}, \Delta P = 0$

INPUTS:

1040 16.0 E6, 6.15 E6, 0.125  
1050 16.0 E6, 6.15 E6, 0.125  
1060 2.0 E5, 100., 0.008, 1.0  
1070 50.0  
1080 100., 100., 101.

COMPUTER RUN:

RUN

| E1          | E2          | T1   | T2   |
|-------------|-------------|------|------|
| 1.60000E+07 | 1.60000E+07 | .125 | .125 |

| G         | G1          | G2          | OMEGA  |
|-----------|-------------|-------------|--------|
| 200000.00 | 6.15000E+06 | 6.15000E+06 | 100.00 |

| B    | TA   | TAU0  |
|------|------|-------|
| 1.00 | .008 | 50.00 |

P = 100.00

| X    | TAU      |
|------|----------|
| .50  | 51.5873  |
| .525 | 51.8828  |
| .55  | 52.7724  |
| .575 | 54.2657  |
| .60  | 56.3787  |
| .625 | 59.1341  |
| .65  | 62.5611  |
| .675 | 66.6962  |
| .70  | 71.5829  |
| .725 | 77.2722  |
| .75  | 83.8232  |
| .775 | 91.303   |
| .80  | 99.7872  |
| .825 | 109.3606 |
| .85  | 120.1169 |
| .875 | 132.1599 |
| .90  | 145.603  |
| .925 | 160.5696 |
| .95  | 177.1932 |
| .975 | 195.6173 |
| 1.00 | 215.9949 |

INTEGRAL OF TAU A = 99.978

STRESS CONCENTRATION FACTOR = 2.1599

## APPENDIX E

FORTRAN COMPUTER PROGRAM FOR STRAIGHT-LAP JOINTS WITH  
 $E_1 t_1 \neq E_2 t_2$ . EFFECTS OF ADHESIVE NONLINEARITY AND ADHEREND  
SHEAR MODULUS INCLUDED.

### ASSUMPTIONS:

- (a) Adhesive shear stress-strain relation

$$\tau_a = \frac{G_a}{\Omega} \left( 1 - e^{-\Omega \gamma_a} \right)$$

- (b) Adherend stress-strain relations

$$\left. \begin{array}{l} \tau_1 = G_1 \gamma_1 \\ \sigma_1 = E_1 \epsilon_1 \end{array} \right\} \quad \text{DOUBLER}$$

$$\left. \begin{array}{l} \tau_2 = G_2 \gamma_2 \\ \sigma_2 = E_2 \epsilon_2 \end{array} \right\} \quad \text{MAINPLATE}$$

- (c) Thickness =  $t_1$  (doubler),  $2t_2$  (mainplate) inches

- (d) Doubler length =  $2L$  inches

- (e) Doubler width =  $b$  inches

- (f) Load =  $2P$  lb.

INPUTS:

1040  $E_1, G_1, t_1$   
1050  $E_2, G_2, t_2$   
1060  $G_a, \Omega, t_a, b$   
1070  $(\tau_a)_{x=0}$   
1080  $P_o, \Delta P, P_f$

OUTPUTS:

(a)  $x, \tau_a(x) \quad x=0.5L(0.25L)L$   
(b)  $P=2b \int_{0.5L}^L \tau_a(x) dx$   
(c) Stress concentration factor  $SCF = \frac{\tau_a(L)}{(\tau_a)_{ave}}$

LISTING:

```
100 DIMENSION Q21(2),G5(21,2),CAY(4)
110 DIMENSION Q2F(2),F1(2)
120 DELD=.05
130 DATA EPSTAU//.01//,EPS/1.E-4/
140 DATA E1/ //,G1/ //,T1/ /
150 DATA E2/ //,G2/ //,T2/ /
160 DATA G/ //,OM/ //,TA/ //,B/ /
170 DATA TAUO/ /
180 DATA PO/ //,DELP/ //,PF/ /
185
190 P=PO
200 PRINT,"          E1","          E2","          T1","          T2"
210 PRINT,E1,E2,T1,T2
220 PRINT," "
230 PRINT,"          G","          G1","          G2","          OMEGA"
240 PRINT,G,G1,G2,OM
250 PRINT," "
260 PRINT,"          B","          TA","          TAUO"
270 PRINT,B,TA,TAUO
280 PRINT," "
290
300
310 PRINT," "
320 TAUPO=0.
330 EL = 1.
340 C1=(1./(E1*T1)+1./(E2*T2))/TA
350 C2=(T1/G1+T2/G2)/(3.*TA)
360 1 IF(P-PF-1.E-5) 2,800,800
370 2 CONTINUE
```

```

380 02F(1)=P/(TA*B*T1*E1)
390 02F(2)=-P/(TA*B*T2*E2)
400 PRINT999,P
401 999 FORMAT(5X,3HP= ,F7.1,7H POUNDS)
410 PRINT," "
420 D0=EL/2.
430 DO 700 N=1,15
440 LO 600 M=1,2
450 D=D0
460
470 DO 500 L=1,2
480 GO TO (4,5),L
490 4 H=(EL-D)/20.
500 GO TO 6
510 5 H=-D/20.
520 6 CONTINUE
530 H2=H/2.
540 H8=H/8.
550 IC=0
560 DO 300 I=1,20
570 DO 200 K=1,2
580 GS(1,L)=TAU0
590 TAU=TAU0
600 TAUP=TAUP0
610 DO 100 J=1,20
620 X=D+J*H
630 XTAU=TAU
640 XTAUP = TAUP
650 IJUMP = 1
660 GO TO 80
670 30 XTAU=TAU+H2*TAUP+H8*CAY(1)
680 XTAUP=TAUP+CAY(1)/2>
690 IJUMP=2
700 GO TO 80
710 40 XTAUP=TAUP+CAY(2)/2.
720 IJUMP=3
730 GO TO 80
740 50 XTAU=TAU+H*TAUP+H2*CAY(3)
750 XTAUP=TAUP+CAY(3)
760 IJUMP=4
770 GO TO 80
780 60 DTAU=H*(TAUP+(CAY(1)+CAY(2)+CAY(3))/6.)
790 DTAUP=(CAY(1)+CAY(4))/6.+(CAY(2)+CAY(3))/3.
800 TAU=TAU+DTAU
810 TAUP=TAUP+DTAUP
820 IF(IC) 100,100,70
830 70 GS(J+1,L) TAU
840 GO TO 100
850 80 CONTINUE
860 TEMP =C1*XTAU-UM/(G-UM*XTAU)+2*XTAUP+2
870 TEMP=TEMP*H
880 CAY(IJUMP)=TEMP/(1./(G-UM*XTAU)+C2)
890 GO TO (30,40,50,60),IJUMP
900 100 CONTINUE
910 IF(IC) 110,110,400

```

```

920 110 Q21(K)=(C2+1./(G-QM*TAU))*TAUP
930 IF(K-2) 120,190,190
940 120 CONTINUE
950 IF(ABS(Q21(1)-Q2F(L))-EPS) 130,130,180
960 130 IC=1
970 GS(1,L)=TAU0
980 GO TO 200
990 180 TAU0=TAU0*1.1
1000 190 CONTINUE
1010 200 CONTINUE
1020 290 TAU0=TAU0/11.*(10.+(Q2F(L)-Q21(1))/(Q21(2)-Q21(1)))
1030 300 CONTINUE
1040 PRINT,"COULD NOT CONVERGE, L=",L
1050 STOP
1060 400 CONTINUE
1070 500 CONTINUE
1080 IF(ABS((GS(1,1)-GS(1,2))/GS(1,1))-EPS*TAU) 510,510,580
1090 510 PRINT,"          X","          TAU"
1100 HD/20.
1110 DO 525 J=1,21,4
1120 X=(J-1)*H
1130 PRINT998,X,GS(22-J,2)
1131 525 CONTINUE
1140 H=(EL-D)/20.
1150 DO 535 J=1,21,4
1160 X=D+(J-1)*H
1170 PRINT998,X,GS(J,1)
1171 998 FORMAT(10X,F5.3,5X,F10.3)
1172 535 CONTINUE
1180 PRINT," "
1190 PS=0.
1200 DO 575 I=1,2
1210 GO TO (545,550),I
1220 545 H=(EL-D)/20.
1230 GO TO 555
1240 550 H=D/20.
1250 555 CONTINUE
1260 SE=GS(1,1)+GS(21,1)
1270 SI=0.
1280 SP=0.
1290 DO 560 J=3,19,2
1300 560 SP=SP+GS(J,1)*2.
1310 DO 570 J=2,20,2
1320 570 SI=SI+4.*GS(J,1)
1330 PS=PS+H/3.*(SE+SP+SI)
1340 INTP=INTP+PS
1350 575 CONTINUE
1360 SCF1=GS(21,1)*B*EL/P
1361 SCF2=GS(21,2)*B*EL/P
1362 IF(SCF1-SCF2)801,801,802
1363 801 SCF=SCF2
1364 GO TO 803
1365 802 SCF=SCF1
1366 803 CONTINUE

```

```

1370 PRINT997,PS
1371 997 FORMAT(14H INTEGRAL P = ,F7.1,7H POUNDS)
1380 PRINT996,SCF
1381 996 FORMAT(31H STRESS CONCENTRATION FACTOR = ,F5.3)
1390 PRINT," "
1400 P=P+DELP
1410 GO TO 1
1420 580 DO=DO*(1.+DELD)
1430 F1(M)=GS(1,1)-GS(1,2)
1440 600 CONTINUE
1450 DO=DO/(1.+DELD)+2
1460 DD=F1(1)*D*DELD/(F1(1)-F1(2))
1470 DO=DO+DD
1480 700 CONTINUE
1490 PRINT,"COULD NOT CONVERGE IN TAU"
1500 800 STOP
1510 END

```

SAMPLE RUN:

TITANIUM ADHERENDS,

$E_1=E_2=16 \times 10^6$  psi  
 $G_1=G_2=6.15 \times 10^6$  psi  
 $t_1=t_2=0.125$ "

HIGH MODULUS NONLINEAR ADHESIVE

$G_a=2 \times 10^5$  psi  
 $\Omega = 100$   
 $t_a=0.008$ "  
 $b=1$ "

STARTING ASSUMED STRESS  $\tau_a(0.5L)=\tau_o=50$ psi

INPUT LOAD  $P_o=P_f=100$  Lb.,  $\Delta P=0$

INPUTS:

```

140 DATA E1/16.E+6/,G1/6.15E+6/,T1/.060/
150 DATA E2/16.E+6/,G2/6.15E+6/,T2/.125/
160 DATA G/2.E+5/,OM/200./,TA/.008/,B/1./
170 DATA TAU0/50./
180 DATA PO/100./,DELP/25./,PF/101./

```

COMPUTER RUN:

RUN

|               |               |               |               |
|---------------|---------------|---------------|---------------|
| E1            | E2            | T1            | T2            |
| 1.6000000E+07 | 1.6000000E+07 | 6.0000000E-02 | 1.2500000E-01 |
| G             | G1            | G2            | OMEGA         |
| 2.0000000E+05 | 6.1500000E+06 | 6.1500000E+06 | 2.0000000E+02 |
| B             | TA            | TAUO          |               |
| 1.0000000E+00 | 8.0000000E-03 | 5.0000000E+01 |               |

P= 100.0 POUNDS

| X     | TAU     |
|-------|---------|
| 0.    | 174.133 |
| 0.086 | 113.832 |
| 0.172 | 74.908  |
| 0.258 | 51.311  |
| 0.343 | 38.780  |
| 0.429 | 34.866  |
| 0.429 | 34.866  |
| 0.543 | 41.872  |
| 0.658 | 65.390  |
| 0.772 | 113.269 |
| 0.886 | 198.913 |
| 1.000 | 337.774 |

INTEGRAL P = 99.9 POUNDS  
STRESS CONCENTRATION FACTOR = 3.378