DARCOM PAMPHLET DARCOM-P 706-316

ENGINEERING DESIGN HANDBOOK

JOINING OF ADVANCED COMPOSITES

US ARMY MATERIEL DEVELOPMENT AND READINESS COMMAND MARCH 1979

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PREFACE

This handbook should serve as a guide to designers concerned with the technology associated with the joining of advanced composites. It deals with basic joint design practice as well as with those practices specific to composite joining. Tabulated and graphical representations of joint property data obtained on both bonded and mechanically fastened composites are presented. These data can be used by designers to test the degree of conservatism in calculated joint properties for their composite joint designs and hopefully will impart the necessary degree of confidence or wariness in the early design stages where alterations can be made most economically.

It is hoped that the diversity of joint possibilities and the magnitude of the joint strength properties reported will prompt cautious designers of Army materiel to make use of the strength-to-weight advantages offered by advanced composites and also to recognize that the technology is available for practical implementation of these valuable engineering materials.

The handbook was prepared by Mr. Andrew Devine, Plastics Technical Evaluation Center (PLASTEC), the Defense Department's specialized information center on plastics located at the US Army Armament Research and Development Command, Dover, NJ.

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CHAPTER 1
INTRODUCTION

Advanced composites are defined. A broad overview of joining advanced composites is presented — the efficiency of load bearing joints, advantages and disadvantages of mechanical versus adhesive bonded joints, factors affecting choice of joints, bonded joint properties, and surface preparation.

1-0 List of Symbols

E = overall joint efficiency, dimensionless
E_L = load bearing efficiency, dimensionless
E_W = joint weight efficiency, dimensionless
L_c = load continuous member can support, lb
L_j = load joint can support, lb
W_c = weight of continuous member, lb
W_j = weight of joined member, lb

1-1 ADVANCED COMPOSITES DEFINED

Advanced composites is a term that has come into use in recent years, suggesting composite materials which possess characteristics so superior to earlier composites as to warrant the term "advanced". It is a poor term from the standpoint of knowing what exactly is referred to when the term is used. The term "composite" taken by itself is a compound structure or material comprised of a number of parts. It must be prefixed by other terms to clarify its meaning. Terms such as glass-resin composites, graphite-resin composites, carbon-resin composites, and boron-resin composites comprise a class often referred to as "fiber reinforced composites". These fibers can be long and oriented, or short and random within the resin matrix. Composite materials can be made up of metal layers and ceramic layers, or as constructions of metal or fiber reinforced composite skins bonded to metal or paper honeycomb, or wood or foam cores. Thus the term "composite" is a loosely defined term taken by itself. When it is prefixed by "advanced", it only becomes more nebulous.

For the purpose of this handbook, and in deference to its increased use in industry, the term "advanced composite" is employed. The scope of this handbook is limited only to the class of composites known as fiber-reinforced resin composites. These include glass, boron, and carbon or graphite reinforcing fibers. The term "advanced composite" refers to those composite materials employing high modulus reinforcing fibers in the resin matrix. In fact, the fibers serve less to reinforce the matrix than the resin serves to bind the fibers together. As a term, advanced composite is best understood when the composites described are compared with other composites employing lower modulus fibers. Advanced composites, by virtue of their high modulus fibers help make possible the strong, stiff, lightweight capability so vital to aircraft and munitions construction.

1-2 PRELIMINARY COMMENTS ON JOINT DESIGN

As a prelude to a discussion of joint design some comments should be made regarding the purpose of a joint. Very simply, the function of a joint is to unite two or more members together in order to transfer loads from one member or members to the other(s). How well a joint accomplishes this task is judged best by its overall joint efficiency E which is the product of its load bearing efficiency E_L and its weight efficiency E_W.

The load bearing efficiency E_L of a joint is defined as

$$E_L = \frac{L_j}{L_c}, \text{ dimensionless} \quad (1\text{-}1)$$

where:

L_j = load joint can support, lb
L_c = load continuous member can support, lb.

The weight efficiency E_W of a joint is

$$E_W = \frac{W_c}{W_j}, \text{dimensionless} \quad (1\text{-}2)$$

where

W_c = weight of continuous member, lb
W_j = weight of joined member, lb

therefore

$$E = E_L \times E_W, \text{dimensionless}. \quad (1\text{-}3)$$

The joint efficiency concept is easily understood by considering the example that follows. If one takes a length of material, weighs it, tests it for strength in a particular mode, and then cuts the material in two, joins it in one manner or other, weighs the entire assembly, and tests the assembly for strength in the same mode, one can employ the given equations to measure the success of the joint design chosen in matching the structural integrity and weight of the original unjoined material. The more closely E_L, E_W, and E approach unity, the better is the joint design from a performance standpoint.

Without belaboring the obvious, an E_L as close to 1 as possible is the condition to strive for because if E_L exceeds 1 then it can be assumed that a weight penalty is being imposed and E_W will decrease — an undesirable trait in most designs. This situation implies that the entire structure is being reinforced, since loads cannot be transferred between members which exceed the strength of the weakest member. Such a condition would arise in the cocooning of a joint by filament winding an entire area. However, this is essentially a rebuilding or remanufacturing process to correct a major design flaw and is not solely a joining process. Where joining two dissimilar members, the joint efficiencies must, of course, be arrived at based on the weaker of the two members being continuous.

Another factor which should be taken into account is a processing factor or cost of the joint, but this is a more difficult contribution to quantify. This factor is best considered as a comparison of the cost of making one joint design versus another, rather than between the cost of making a joint or leaving the member continuous. The latter comparison is unrealistic since joints are certainly not employed where it would be more feasible to omit them.

1-3 MECHANICAL VS ADHESIVE BONDED JOINTS

1-3.1 GENERAL

The adversary tone of this paragraph is justified because each joining technique produces a joint with significant differences in the manner in which they function. Mechanically fastened joints (bolts, rivets, screws, etc.) derive their strength from the strength of the fastener and the strength of members being joined such as in cases where the members are threaded and screwed together. In mechanical joints, loads are transferred by two locked surfaces bearing against each other. Bonded joints, on the other hand, derive their load bearing capabilities via a surface attachment which is a function of the surface energies of the adhesive and substrate as well as the polymer chemistry of the adhesive. Loads are transferred from one member to another across a common interface or boundary created by interfacial molecular attractions. The paragraphs that follow comment on the merits and disadvantages of each type of joint.

1-3.2 MECHANICAL JOINTS

On the positive side, mechanical joints:

1. Require no surface preparation of the substrate or white glove operations to assure cleanliness.
2. Are not as adversely or irreversibly affected by thermal cycling and high humidity as are bonded joints.
3. Present no unusual inspection problems for joint quality.
4. Permit disassembly without destruction of the substrate.

Mechanical joints are less favorable from the following standpoints:

1. They require machining of holes in the members to accommodate the mechanical attachments and thereby weaken the members.

2. They concentrate stress at the bearing surfaces, thereby creating stress risers which can induce failure in the joined member.

3. They are not generally as strong as are bonded joints unless they are heavy.

4. They add weight to the joint which reduces overall joint efficiency.

1-3.3 ADHESIVE BONDED JOINTS

Adhesive bonded joints have the following positive attributes:

1. They distribute load over a larger area than mechanical joints, thereby eliminating stress risers.

2. They can be designed so as not to weaken the joined members by machining operations in the joint area.

3. They are difficult to inspect for bond quality and voids.

4. They add a minimum of weight to the structure.

The drawbacks to bonded joints are:

1. They require adherend surface preparation and cleaning.

2. They are subject to degradation due to the effects of temperature and humidity cycling.

3. They are difficult to inspect for bond quality and voids.

4. Disassembly cannot be effected in most cases without destruction of the joined members.

1-4 BASIC JOINT DESIGN

1-4.1 GENERAL

Before a joint can be designed, the designer must possess some basic information. He must know the nature of the materials to be joined — physical yield strength, modulus of elasticity, thermal expansion and contraction behavior, and very often their chemistry. He must also know the stresses which the joint is expected to withstand in service, the environment in which the joint is to function, and its expected service time.

Knowing the nature of the materials to be joined and the service the joint is to provide, the designer can proceed to his next step — the selection of the type of joint to be employed. This requires a consideration of the limitations imposed by the materials on the processing or manufacture of the joint as well as special requirements such as disassembly capability for maintenance and quality control requirements. For example, a structural joint requiring disassembly capability would probably exclude the selection of a structural bonded joint. Similarly, if the joint is to be fabricated in a facility in which a manufacturer has no proper surface preparation facility, processing considerations would preclude use of a bonded joint. If on the other hand very thin members are to be joined which cannot be machined or weakened with holes in the joint area, then a bonded joint would be in order or strength-to-weight requirements might mandate a bonded joint.

The decision whether to use a mechanical or bonded joint requires careful consideration of all variables which will effect the final outcome and requires a systems approach with the relationship between the joint and the entire structure kept in mind at all times. Once this decision has been made, then the process of configuring the joint and selecting or altering materials to meet the performance requirements of the end item can proceed. This last process is considered to be the actual design step but often it is embarked upon without proper preparation and guidance.

1-4.2 IMPORTANT BONDED JOINT PROPERTIES

Although specific test specimens have been devised to test specific end items, the basic properties to test in an adhesive joint remain the same — tensile strength, tensile and compressive shear strengths, and peel. Other forms of tests include bending which actually creates peel and cleavage forces. Few of the tests used can isolate stress modes but merely attempt to do so as nearly as possible. Some tests accomplish this better than others but the basic reason for testing joint properties is to compare one adhesive/adherend combination with another under similar loading modes and to extrapolate these data to specific configurations. No doubt a variety of tests could be devised to ascertain the behavior of a specific bonded joint under a specific test mode and this type of final design testing should indeed be done. However, the basic design properties must be determined by standard, widely accepted and used test methods so a wide range of data from many sources can be continually generated.

1-4.3 IMPORTANT LAMINATE AND ADHESIVE PROPERTIES

The strength properties of laminates and adhesives are very much time and temperature dependent so it is important to know the conditions of service of bonded composite joints. The environmental effects — temperature, humidity; and exposure to fuels, chemicals, and sunlight — on the properties of adhesives and composites are not fully known or quantified but can and do have detrimental effects in many instances. For these reasons data presented should be viewed as typical of the particular situation, and subject to verification and prototype testing under the actual use conditions anticipated. In addition, factors such as cure cycle, cure pressure, surface preparation, machining, and fabrication will further alter properties. It is therefore advisable to adequately characterize the specific material design properties and their statistical accuracy before using them for design purposes. The tables and figures presented in this handbook are for guidance and comparison, and show trends. Absolute values given should be judged for their pertinence to a specific application and, if not entirely pertinent, then used with caution and with a sufficient safety factor for design purposes.

1-4.4 ADVANCED COMPOSITE JOINT CONSIDERATIONS

What has been said up to now has been general in nature and applies to composite and noncomposite alike. It should be remembered, however, that unlike isotropic materials such as metals, orthotropic materials — like advanced composites — undergo severe damage and weakening when they are cut or machined and thus become more susceptible to interlaminar shear within the substrate. For this reason bonded rather than mechanically fastened joints are most frequently employed in advanced composite joint design. More specifically, bonded joint configurations such as single and double laps or single and double strap type joints are preferred where feasible to avoid machining of the composites even though a weight penalty may be imposed. Exceptions to this practice would be beveling or tapering of the ends of a lap or strap to alleviate stress concentrations at the lap or strap ends. This practice does not damage any fibers in the bond area.

Along the same line, basic design practice for adhesive bonded composite joints should include making certain the surface fibers in a joint are parallel to the direction of pull in order to minimize interlaminar shear or failure of the bonded substrate layer. On composites whose joint areas have been machined — to a step lap configuration, for example — it is possible to have a joint interface comprised of fibers at other than the optimum 0-deg orientation to the load direction. This would tend to induce substrate failure easier than otherwise would be possible.

1-5 SURFACE PREPARATION OF ADVANCED COMPOSITES PRIOR TO BONDING

As with any bonding operation, the proper surface preparation is essential for obtaining quality bonds which fail cohesively rather than adhesively. Surface preparation for advanced composite substrates prior to bonding is accomplished best by solvent wiping to remove loose surface dirt and grime and, then abrading the surface by hand or machine. The first step removes loosely adhered weak boundary layers, and the second increases the surface energy of the faying surface as well as increasing the bond area by surface roughening. The abrading operation should be conducted with care, however, to avoid damaging surface fibers. The purpose is to roughen the resin matrix and expose, but not rupture, the reinforcing fibers. A surface roughening method having gained wide acceptance is the use of peel ply. This technique simply involves incorporating a nylon cloth in the outer layer of the composite during lay-up. The peel ply is torn or peeled away prior to bonding, fracturing the resin matrix and exposing a clean roughened surface for bonding. Surface roughness can to some extent be determined by the weave of the peel ply. The peel-ply method is fast and eliminates the need for solvent cleaning and removal of abraded resin dust. All abrasion treatments should have the same principles in common. These are (1) to thoroughly clean the surface prior to the abrasion step in order not to force dirt into the surface, (2) abrade, (3) remove abrasion dust, (4) clean again, and (5) Dry. One such method is outlined in Table 1-1.

TABLE 1-1. METHOD FOR PREPARING SURFACE

1. With a stiff brush and 2% aqueous solution of detergent at 104° to 122°F, scrub entire surface of panels.
2. Thoroughly rinse in tap water followed by immersion in distilled water.
3. Dry in forced air oven at 150°F for 30 min.
4. With 240 grit sandpaper, abrade bonding area plus 0.5 in. margin.
5. Dust abraded area with vacuum.
6. Swab off abraded area with acetone wet clean gauze.
7. Rinse generously in distilled water (entire panel).
8. Dry in forced air oven at 212°F for 60 min, then bond parts immediately.

CHAPTER 2
COMPOSITE JOINT DESIGN

The anisotropic nature of composites — a factor that must be reckoned with in joint design — is emphasized. The analysis of stress distributions of bonded joints, and pinned and bolted joints — as a function of distance along the joint — is presented in graphical form. Tables of tensile and shear strengths for mechanical and bolted joints are given for various composite fiber patterns and laminates.

2-0 LIST OF SYMBOLS

A = load area, in^2

D = diameter of bolt, in.

e = distance from edge of bolted joint to center of bolt hole, in.

E = elastic modulus, psi

E_x = elastic modulus of composite with fibers oriented parallel (longitudinally) to direction of applied stress, i.e., $\phi = 0$ deg, psi

E_y = elastic modulus of composite with fibers oriented perpendicularly (transversely) to direction of applied stress, i.e., $\phi = 90$ deg, psi

G = shear modulus, psi

G_{xy} = shear modulus in xy-plane, psi

K = principal stress factor, dimensionless

L = joint length, in.

P = applied load, lb

s = distance from side of bolted joint to center of bolt hole, in.

t_1, t_2 = thickness of adherends

t = thickness of adhesive layer, in.

W = width of bolted joint, in.

x = longitudinal distance parallel to applied load, in.

y = transverse distance perpendicular to applied load, in.

μ_{xy} = Poisson's ratio of composite, relating contraction in y-direction to extension in x-direction, dimensionless

μ_{yx} = Poisson's ratio of composite, relating contraction in x-direction to extension in y-direction, dimensionless

σ = laminate stress = P/A, psi

σ_{ave} = average compressive stress based on projected area of pin, psi

σ_{L_T} = tensile strength of composite with fibers oriented parallel (longitudinally) to direction of applied load, i.e., $\phi = 0$ deg, psi

σ_G = gross section stress level, psi

σ_{T_T} = tensile strength of composite with fibers oriented perpendicularly (transversely) to direction of applied load, i.e., $\phi = 90$ deg, psi

σ_{ox} = applied longitudinal tensile stress, psi

σ_x = tensile stress at point x inches from doubler edge, psi

σ_x/σ_{ox} = stress concentration factor at point x inches from doubler edge, dimensionless

σ_1 = principal stress on matrix, psi

τ = shear stress in adhesive, psi

τ_{mean} = mean shear stress, psi

ϕ = angle between fiber laminate direction and direction of load, deg

ϕ_c = angle between longitudinal tangent to bolt hole and line drawn from corner of composite to bolt hole at tangent point of contact, deg

2-1 DESIGN PHILOSOPHY

Most design techniques for joining composites are extensions of techniques used for isotropic materials. This approach is acceptable provided the designer remains attuned to the anisotropic nature of composites and how this can alter bulk composite properties and failure modes, depending on the working direction of the composite. By combining joint stress anlayses with material properties and failure criteria, the strength and deflection characteristics of a joint are, to some extent, predictable. For bonded joints, measurements of the strength and modulus of the composite members and cured films of the adhesive are required.

The lack of composite and adhesive property data as well as inadequate stress analyses available suggest that the best design procedure for bonded composite joints is to treat each joint as an individual structure, and test it and modify it as indicated. As more composite and adhesive data become available this process can be refined.

There are several stress analysis methods other than that discussed here. Each method, regardless of simplifying assumptions made, requires knowledge of the shear and tensile properties of the adhesive and adherend. These properties should reflect the pertinent joint environments of temperature and humidity for the special cure and lay-up characteristics of the composite as well as adhesive cure conditions and bond line thickness. It is unlikely, in the near future, that these data will be readily available in handbook form for quick reference—the variable combinations are too great. However, the data presented in this handbook have been assembled from several sources and do show some of the important work done as well as point out areas which require further study. Although the data available will grow with increased advanced composite and adhesive usage, it is unlikely to become available from a single source or data book.

A system needs to be established to deal with material property data generation. Ideally, all new data should be reported in a standardized format and placed in a centralized accessable data bank for computer-aided design and engineering purposes. The success of such a system requires the cooperation of all industry, university, and Government research and design programs to insure that the design data generated for specific purposes are reported in standard format for inclusion in the data bank and availability to all. The difficulty in compiling a handbook such as this within fiscal and time constraints is that of searching for, finding, and screening data, and then putting the data on a uniform basis for comparison. It is a task requiring many man-years of effort, as a minimum, to assemble useful design data and continuous updating to keep the information complete and current.

The reliability of static test data for design purposes depends a great deal on the nature of the end product being designed. The requirements of the automotive, sporting, and aircraft industries for example, differ both for performance and safety, and therefore the consequence of a functional failure in a product will determine how tightly or reliably various components need be designed. Failure of a graphite composite tennis racket frame during competition in no way approaches a failure in a glass composite helicopter rotor blade during flight. It is with the consequences of component failure then that the designer concerns himself when he decides what design data will be required and what testing need be done to supplement that available from manufacturers and the literature.

2-2 BONDED JOINT ANALYSIS AND DESIGN

Discrete element idealizations can be established for bonded and bolted composite joints, using digital computer methods for stress and deflection analysis. Photoelastic and computer calculated stress distributions can be compared for joints of given geometry. Once a satisfactory joint idealization is established, joint member materials and adhesives can be altered to evaluate how they effect stresses and deflections under a given load. Figs. 2-1 and 2-2 compare photoelastic and computer calculated stresses for a single strap joint (Fig. 2-3) at the centerline and edge of the strap (doubler). Figs. 2-4 and 2-5 show the results of an analysis of S-994 glass/Narmco 5505 resin composite sheet bonded to an aluminum strap (doubler) using FM-47 adhesive in which tensile stresses σ_{ox} in the main member and shear stresses τ in the adhesive are depicted. The spike in tensile stress will have a marked influence on fatigue life. A similar analysis using the gross and layer properties of S-994 glass/Narmco 5505 composite bonded with MB-408 adhesive is shown in Figs. 2-6 and 2-7.

Because discrete element analysis of joints consumes a good deal of time, even with the computer, a faster analytic solution using the computer was developed by McDonnell-Douglass Corp. based on an analytic solution for stresses in a symmetrical, double lap joint by Hahn.

Using this computer program to solve for stress in a symmetrical double-lap joint (Fig. 2-8), one obtained the stress distribution shown in Fig. 2-9. The assumptions made in generating this stess distribution were:

1. Only longitudinal stresses cause adherend deformation.
2. Shear stress is constant throughout the thickness of the glueline.
3. Adhesive tensile stress parallel to the glueline is negligible.
4. The adhesive stress-strain curve is constant.

It can be seen that good agreement exists between discrete element analyses and the analytical method (Hahn) except at the strap ends. Fig. 2-10 is a plot of predicted failing load vs overlap for a boron/5505 composite bonded to aluminum using MB-408. The curve obtained is typical of such plots. Fig. 2-11 indicates that varying the metal adherends from steel to titanium to aluminum has little impact on adhesive shear stress distribution. Increased doubler modulus increases stress at one end of strap but decreases it at the other.

2-3 BOLTED JOINT ANALYSIS AND DESIGN

Computer analysis of bolted joints yields the stress distributions seen in Fig. 2-12 for pin-loaded holes along with photoelastic test results. Computer predicted stress distributions in an S-994 glass/Narmco 5505 resin pin-loaded tension strip is shown in Fig. 2-13 where the elastic properties were calculated for a fiber volume content of 65% with zero voids.

The strength of composite bolted joints is dependent on the geometrical parameters edge-distance bolt-diameter ratio e/D, side-distance bolt-diameter ratio s/D, and laminate-thickness bolt-diameter ratio t/D; and orientation of reinforcing fibers in the composite layup, and fabrication and processing methods. Even when fabrication processes are closely controlled, specimens can show large scatter.

Bearing failures account for very few bolted composite joint failing modes. Unless edge and side distance ratios are very large, full bearing stress limit is rarely achieved. Laminates comprised primarily of $\pm\phi$ layers generally fail along filament lines — indicating that the interfilament strength of the matrix is the limiting factor. Laminates with 50% of the fibers oriented at 0° and 50° at $\pm\phi$ usually fail along 0-deg and 90-deg lines. When ϕ approaches 0, failure is usually by cleavage. This does not occur in a wide joint with side-by-side bolts. Generally, the tensile strengths of bolted specimens are somewhat lower than the strength of laminates without holes, which is attributable to the effect of stress concentrations at the holes.

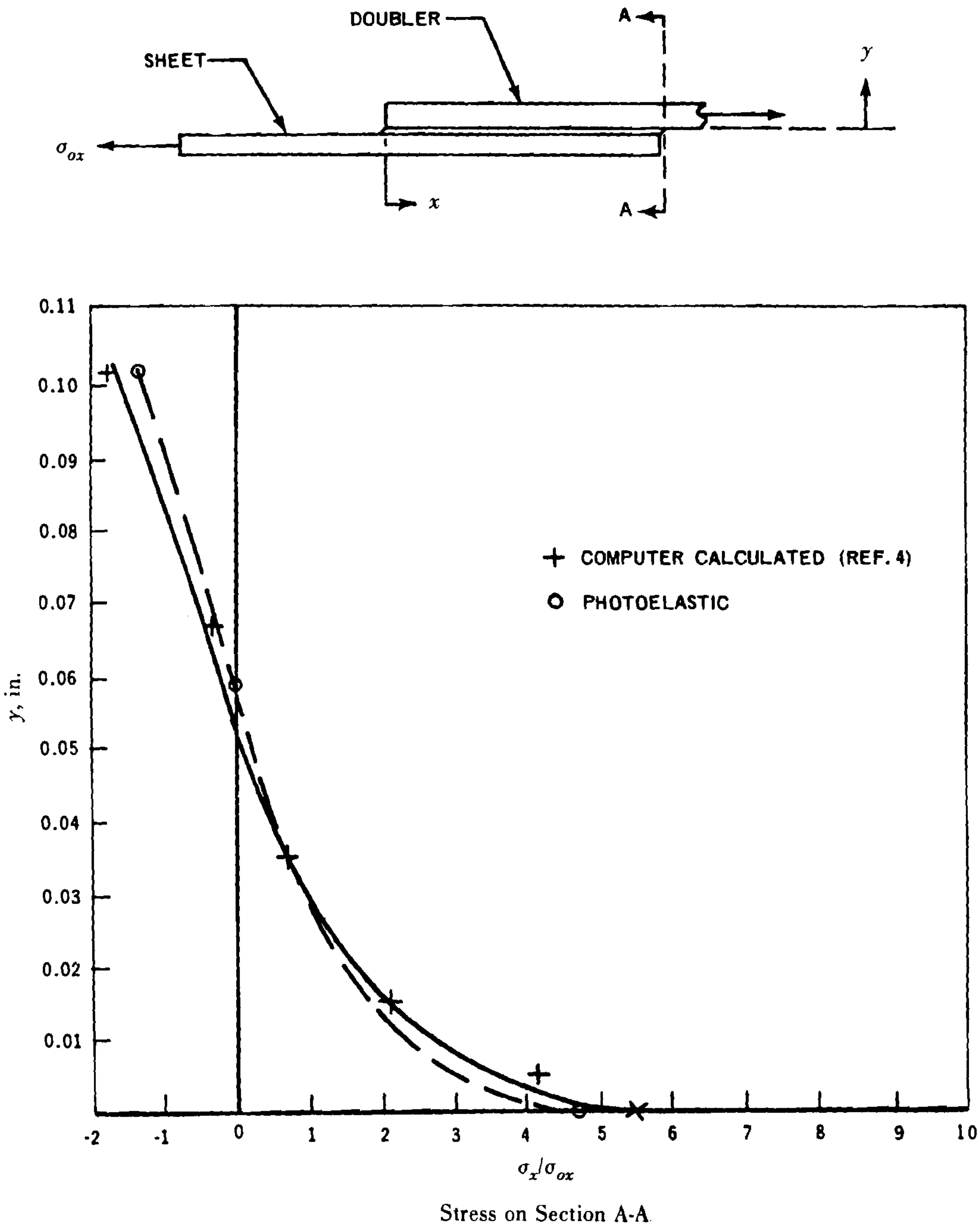

Figure 2-1. Comparison of Photoelastic and Computer Calculated Normal Stress on Centerline of Doubler[3]

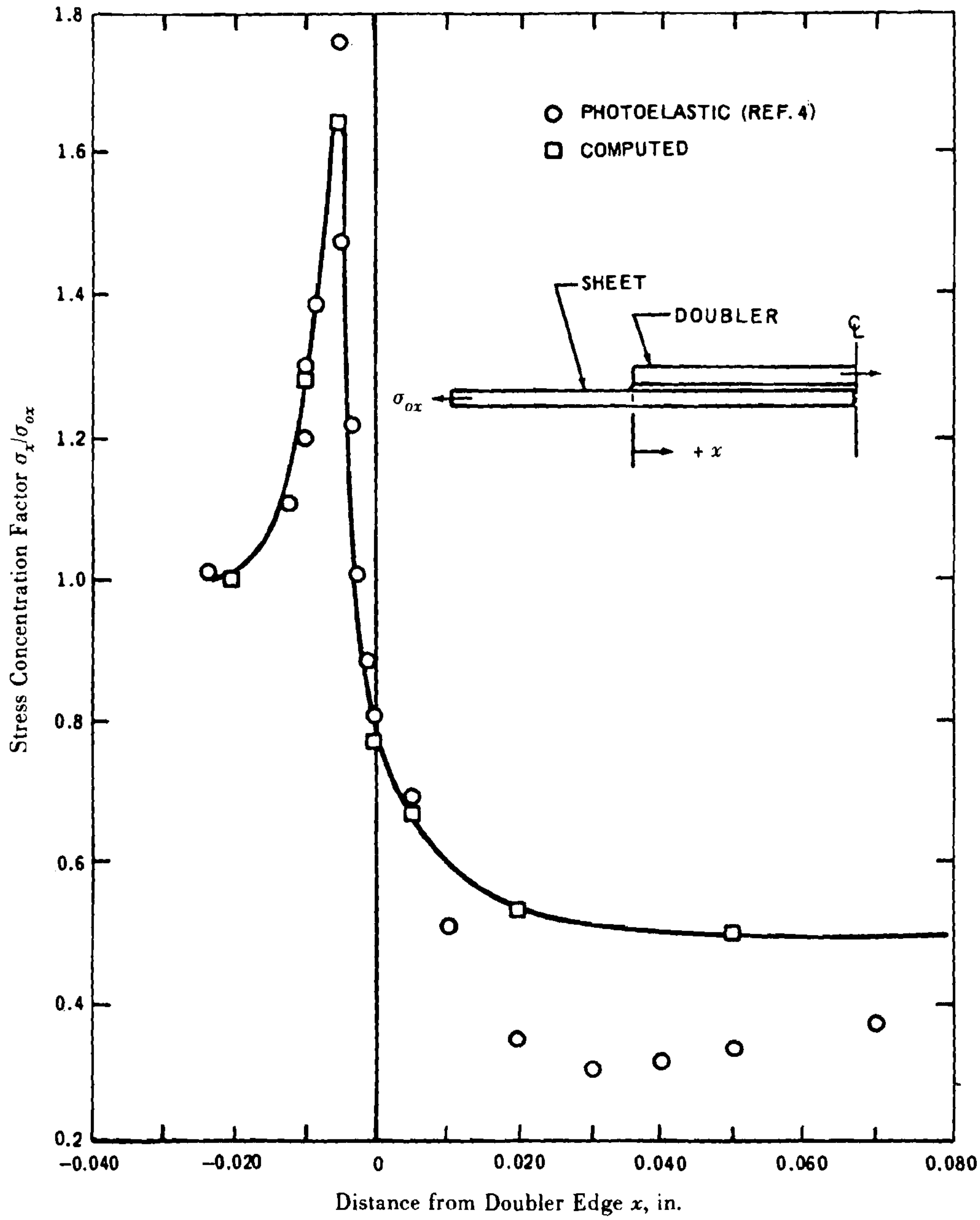

Figure 2-2. Comparison of Photoelastic and Computer Calculated Stresses at Edge of Doubler[3]

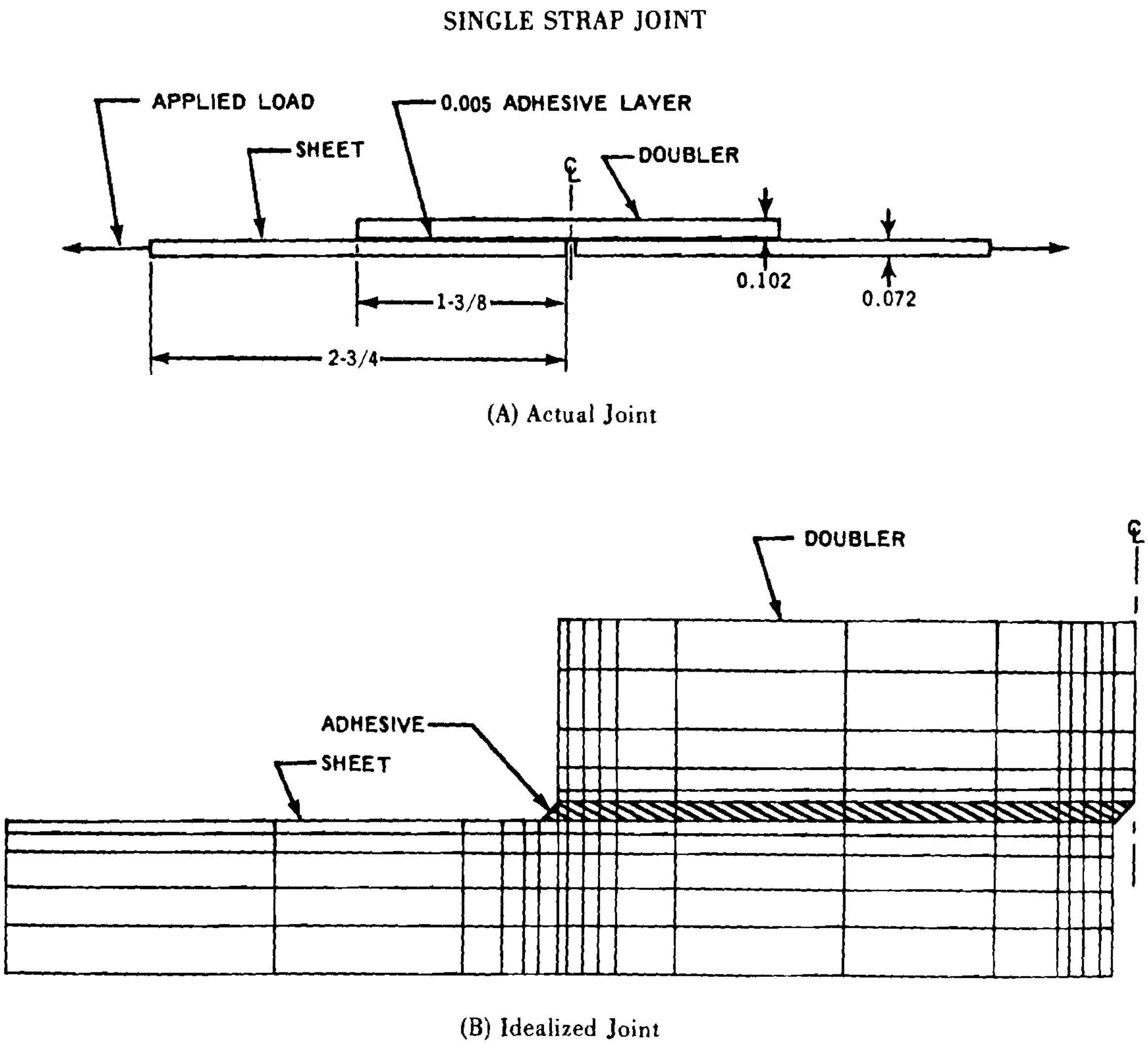

Figure 2-3. Actual and Idealized Joints[3]

Failure in a bolted joint depends on the interfilament strength of the matrix. In the plain laminate illustrated in Fig. 2-14, the interfilament line AB intersects the edges of the specimen. The load components of S and T introduce shear and tensile stresses on AB. Combined, these stresses produce a principal tensile stress on the matrix

$$\sigma_1 = \sigma K \quad (2\text{-}1)$$

where

σ = laminate stress = P/A, psi

K = principal stress factor, dimensionless
= $(1/2)\sin^2\phi(1 + \sqrt{1 + 4\cot^2\phi})$.

When ϕ = 90 deg, K = 1 and the strength of the laminate becomes the ultimate tensile strength of the resin matrix. Test results indicate that laminate transverse tensile strength exhibits large scatter due most likely to varying void content and cure cycles. When ϕ approaches 0 deg, the laminate strength is limited by the combined filament strength. Fig. 2-15 shows this effect clearly

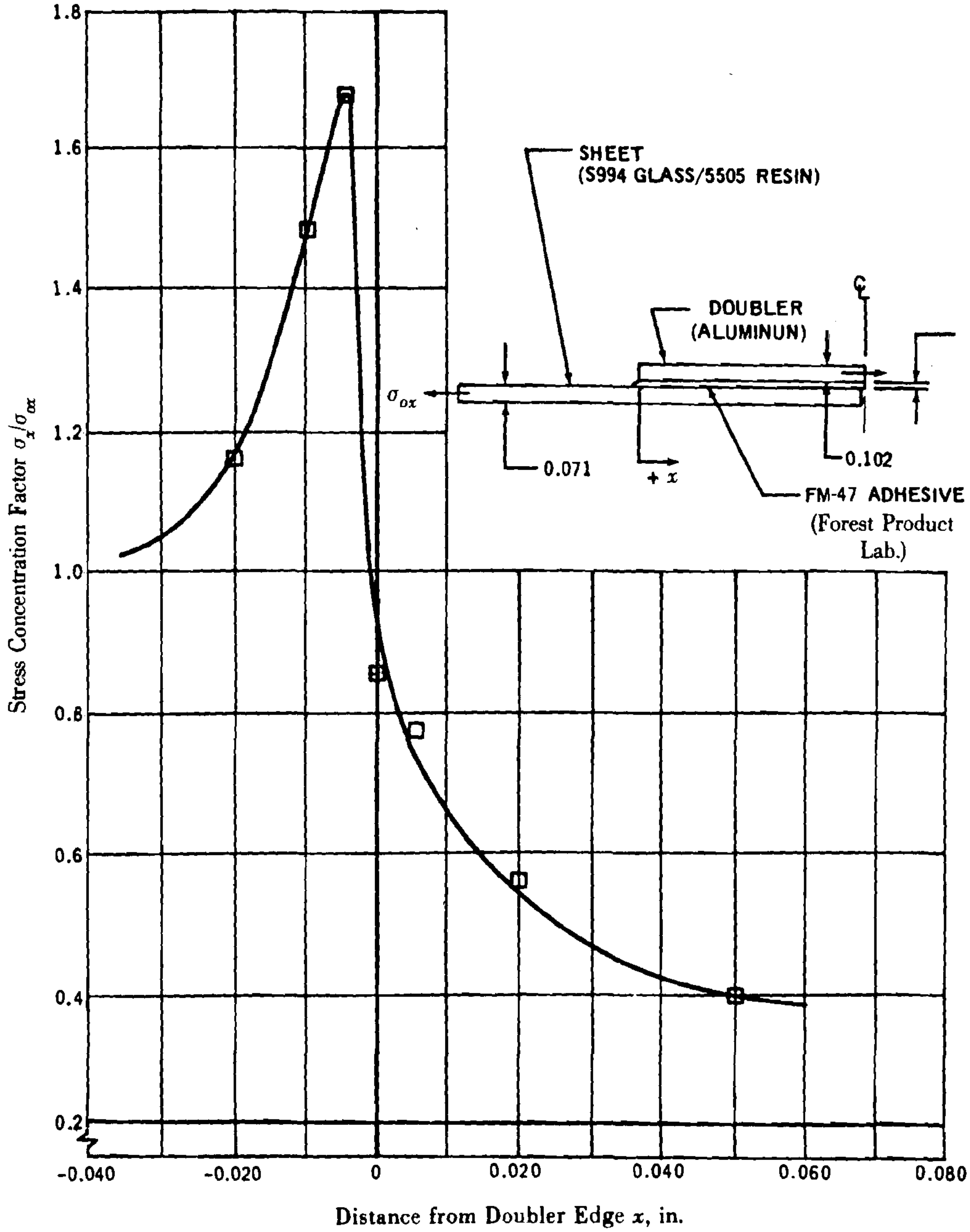

Figure 2-4. Tensile Stress Along Inner Face of Sheet at Edge of Doubler (Computer Calculated)[3]

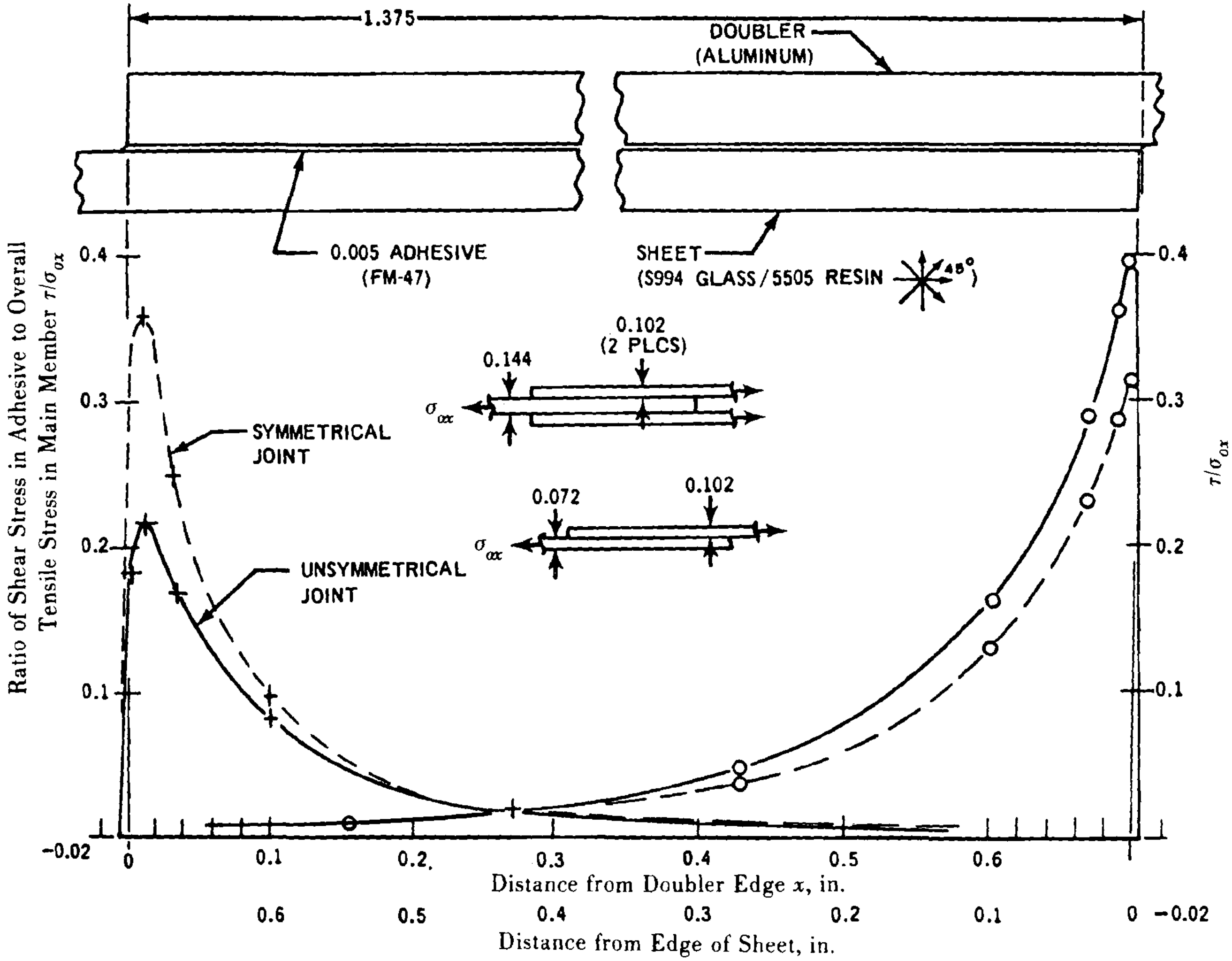

Figure 2-5. Shear Stress Distribution Adhesive (Computer Calculated)[3]

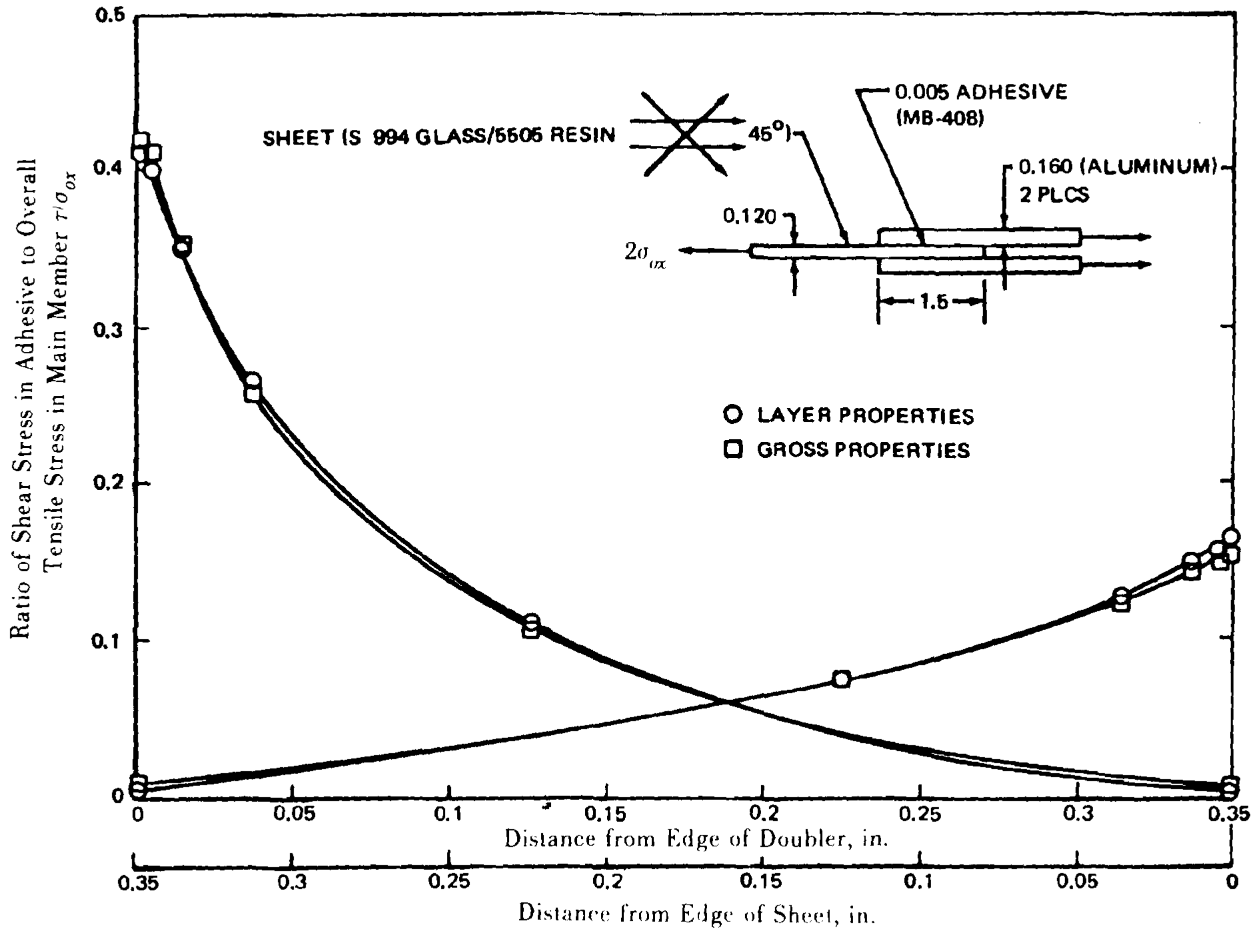

Figure 2-6. Shear Stress Distribution in Adhesive Using Layer Properties and Gross Properties of Composite[3]

as well as tests for $\pm\phi$-fiber orientations. Although both ϕ- and $\pm\phi$-patterns should yield identical monolayer matrix stresses, the $\pm\phi$-pattern cannot fail along a ϕ-interfilament line in one direction without shearing filaments in another. This is a synergistic advantage of crossing filaments.

Fig. 2-16 illustrates the case of the bolted laminate. The filament line AB running from the side of the hole to the edge of the specimen is a maximum when B coincides with C, the corner of the laminate; and $\phi = \phi_c$. Test results show peak strengths at this condition[2] Fig. 2-17 plots the principal tensile stresses in bolted and pinned composite joints against $\pm\phi$ from a number of referenced sources. The envelope of test results shows a fall off as ϕ approaches 0 deg or 90 deg. This is thought to result from the bolt applying load locally as filaments become unidirectional, causing shear or tension failures originating adjacent to the bolt. When 0-deg layers are used in conjunction with $\pm\phi$-layers, failures will usually be along 0-deg or 90-deg lines—the 90-deg failures thought to be secondary failure.

Tensile and shear-out stress limits for boron laminates using 0-deg and $\pm\phi$-layers are shown in Figs. 2-18 and 2-19. Table 2-1 summarizes some bolted boron composite joint strengths from referenced data sources. Table 2-2 shows

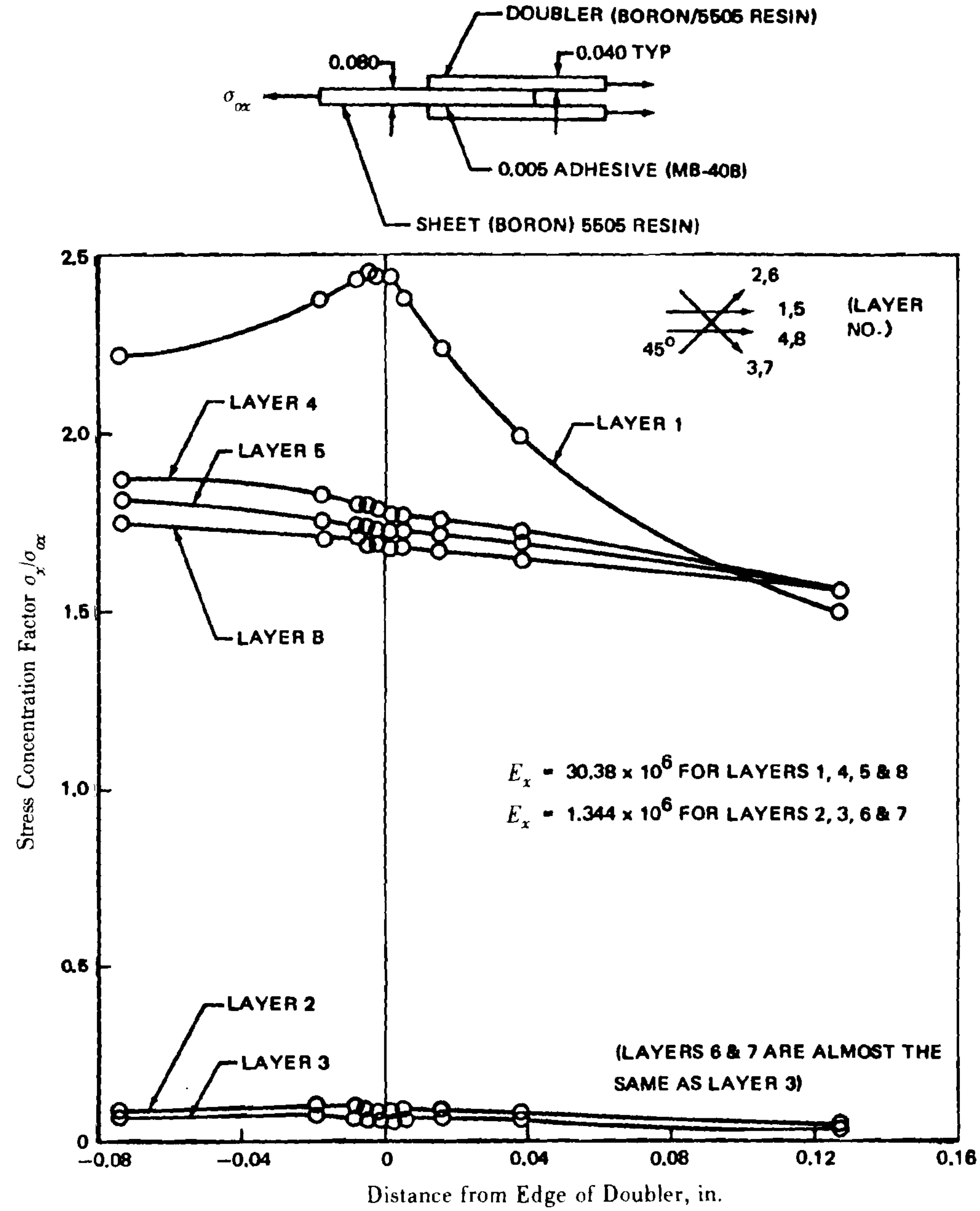

Figure 2-7. Tensile Stresses in Various Layers of Composite at Edge of Doubler[3]

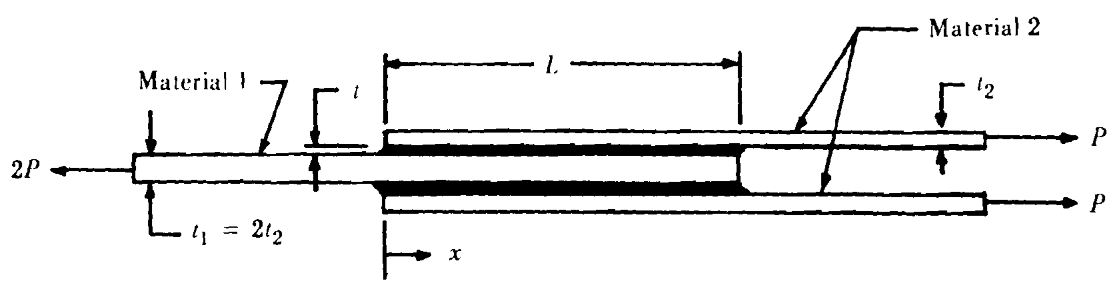

Figure 2-8. Symmetrical Double-Lap Joint[3]

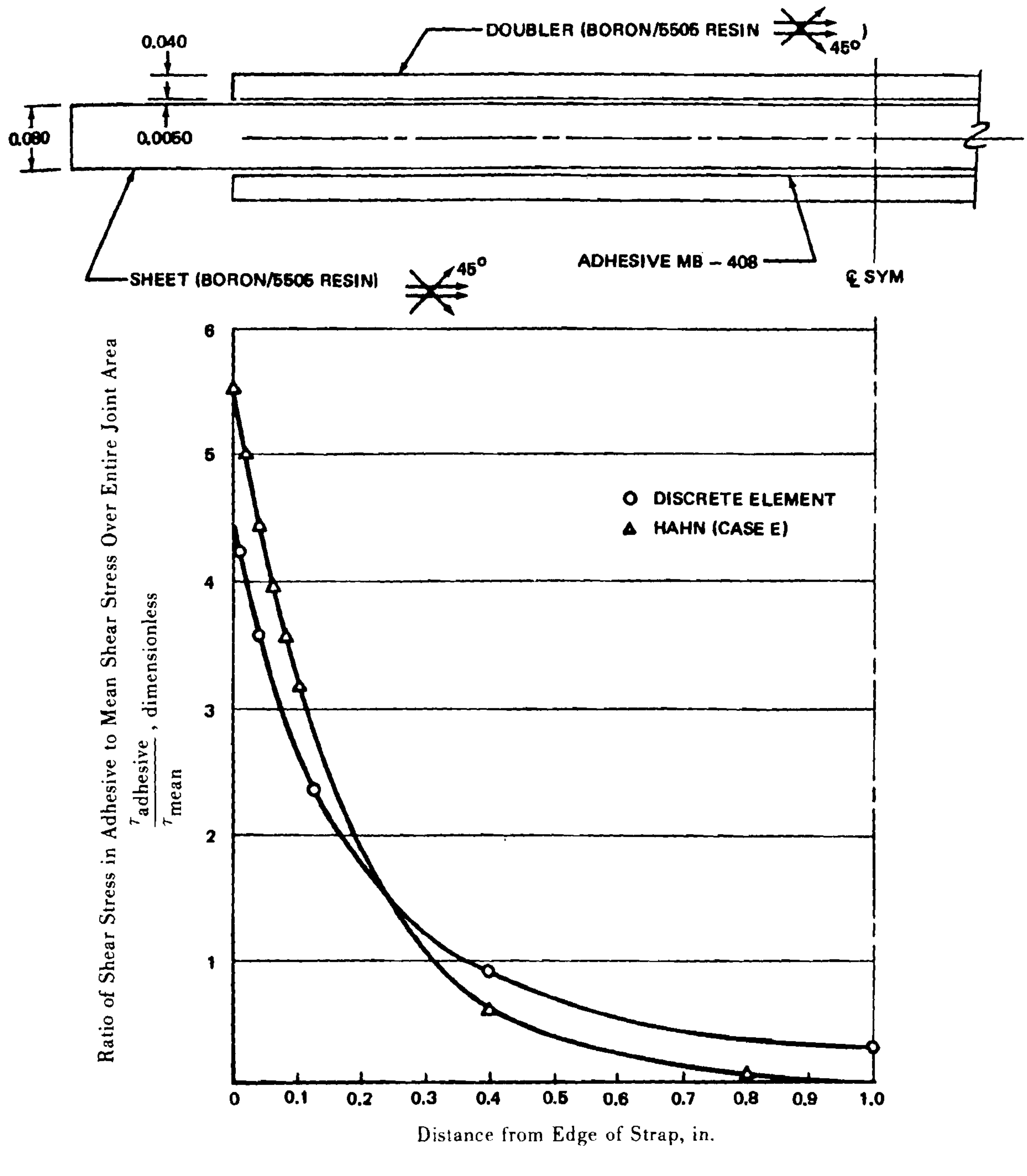

Figure 2-9. Comparative Discrete Element and Analytic Analyses of a Bonded Joint[3]

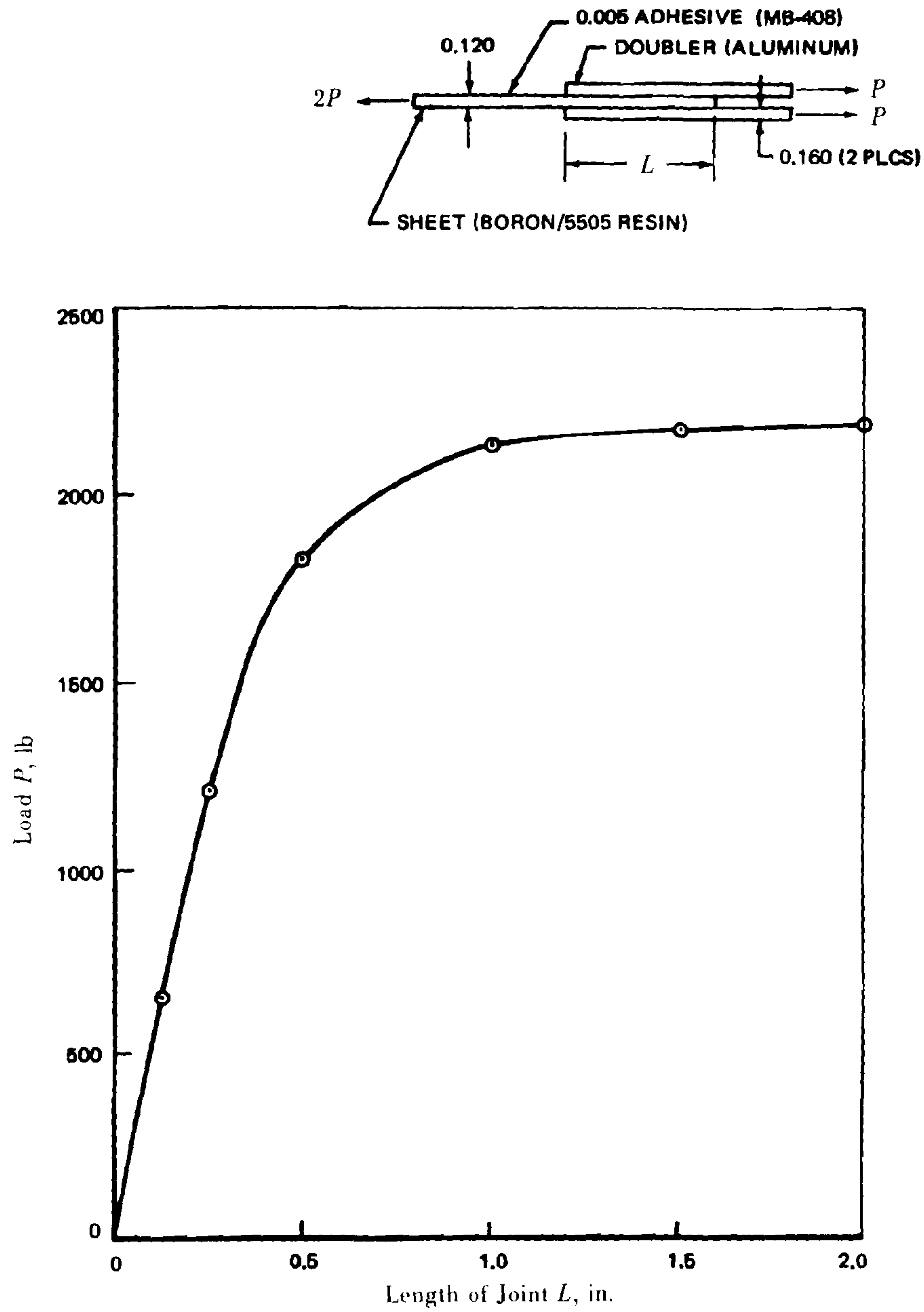

Figure 2-10. Predicted Joint Strength as a Function of Joint Length (Analytic Solution)[3]

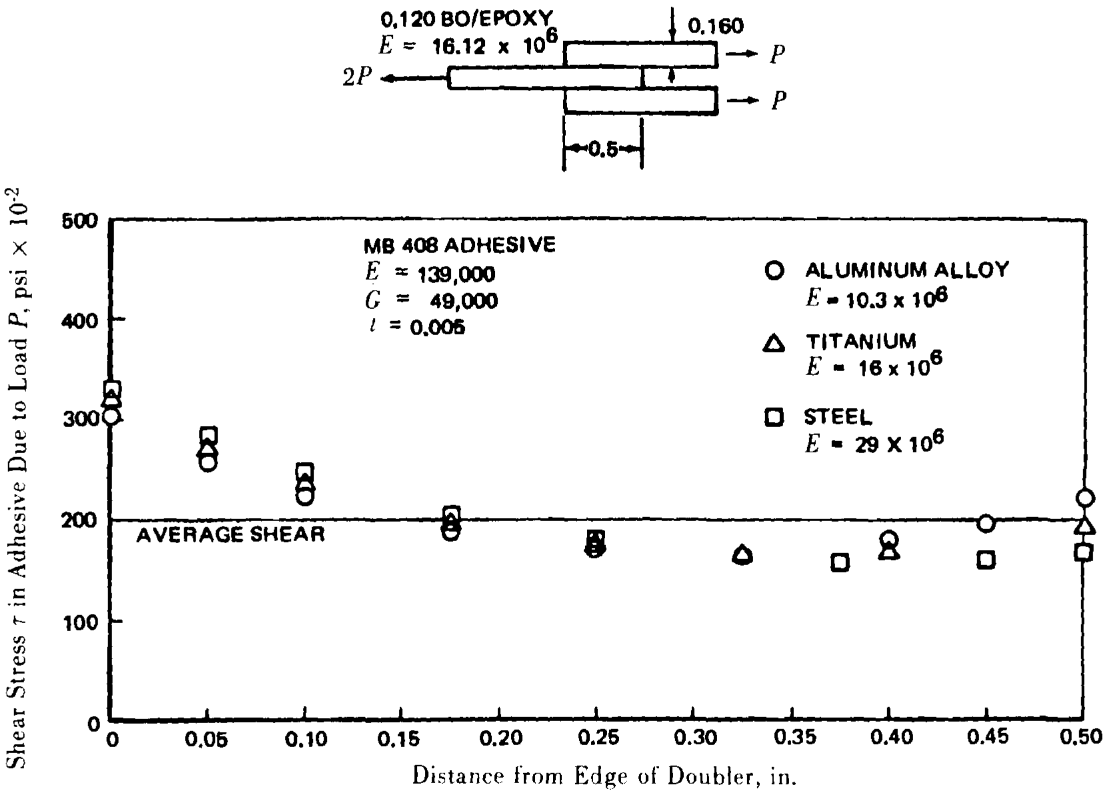

Figure 2-11. Shear Stress Distribution in Adhesive for Various Adherends[3]

predicted strengths for various bolted specimens.

2-4 FIBER ORIENTATION

As stated in par. 1-4.4, composites must not be stressed in a manner likely to induce delamination. This is why it is desirable in bonded joints to have surface fibers oriented parallel to the load direction, and to employ lap and strap joints when this is the case. The use of lap and strap joints precludes machining the bond area. When this is not the case, i.e., when surface fibers are oriented at other than 0 deg to the load direction, then joints such as scarf and landed scarf joints are useful even though machining is required to produce this configuration. Figs. 2-20 through 2-22 show some acceptable and unacceptable bonded composite joints as related to fiber orientation. As can be seen, machining of bond-line areas can result in disadvantageous load to fiber orientation which ultimately would result in failure by delamination of the composite. The proper orientation of the surface fibers in a bonded composite joint should not be an accident but should be included in the design. Even if a stepped lap joint is contemplated, very often it may be easier and less costly to lay up the step configuration prior to cure. This would eliminate the machining process and prevent damage to composite fibers.

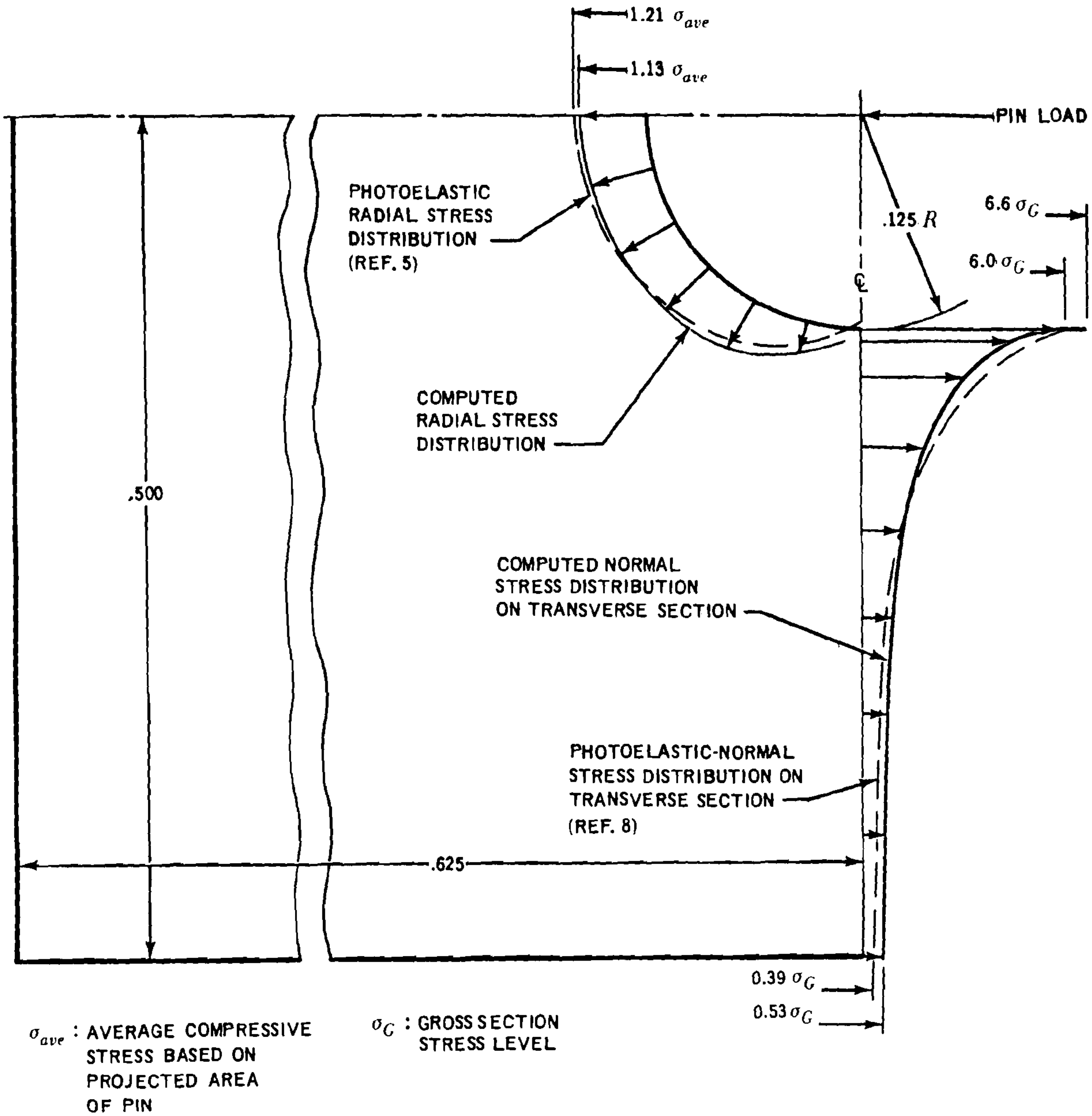

Figure 2-12. Comparison of Photoelastic and Computed Stress Distributions for Pin-Loaded Tension Strip[3]

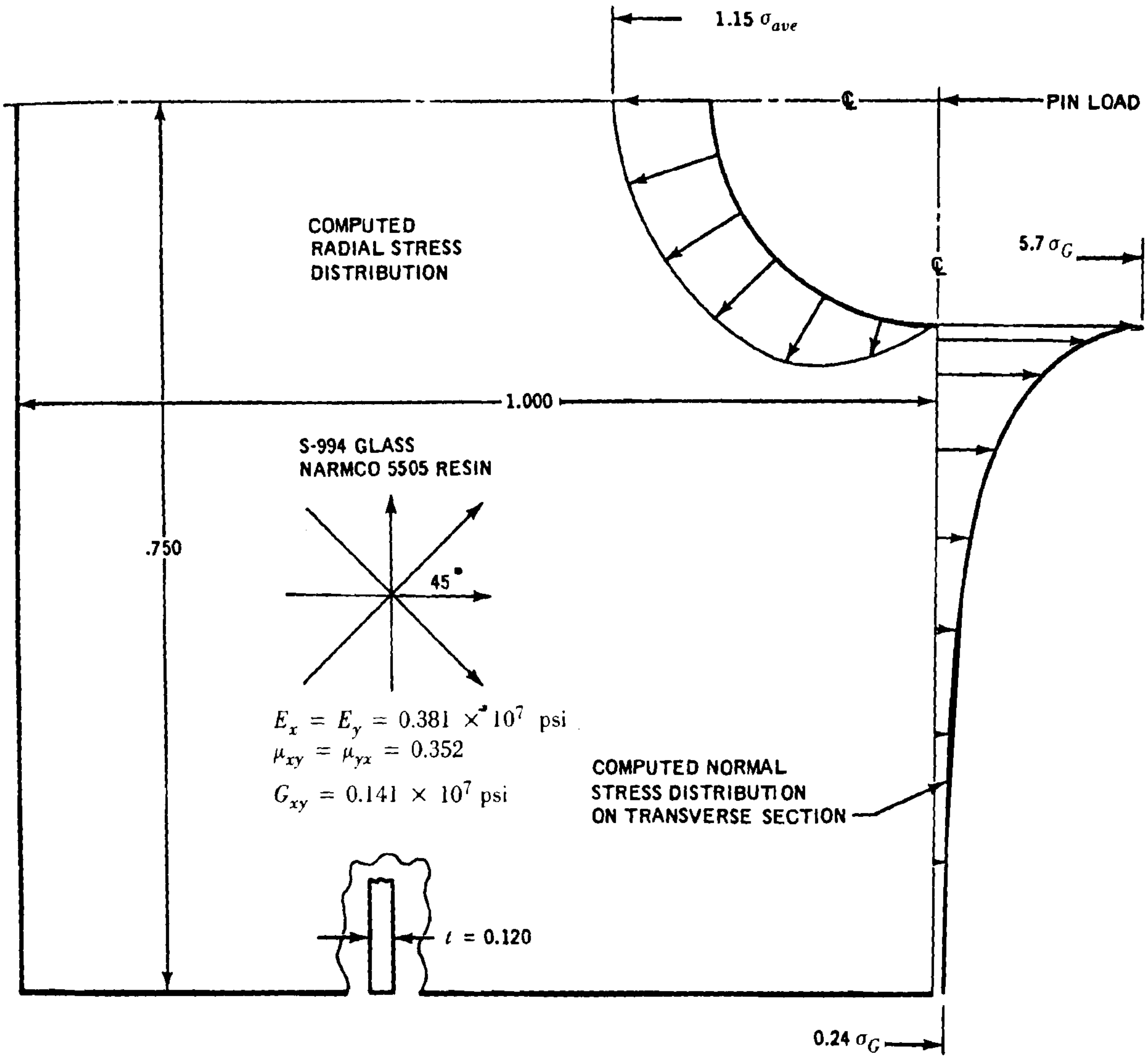

Figure 2-13. Local Stresses in Pin-Loaded Tension Strip[3]

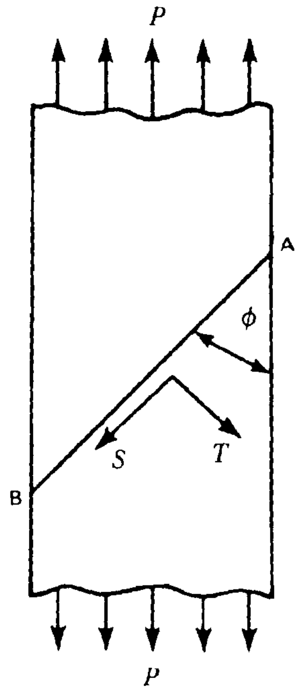

Figure 2-14. Stresses on Plain Laminate

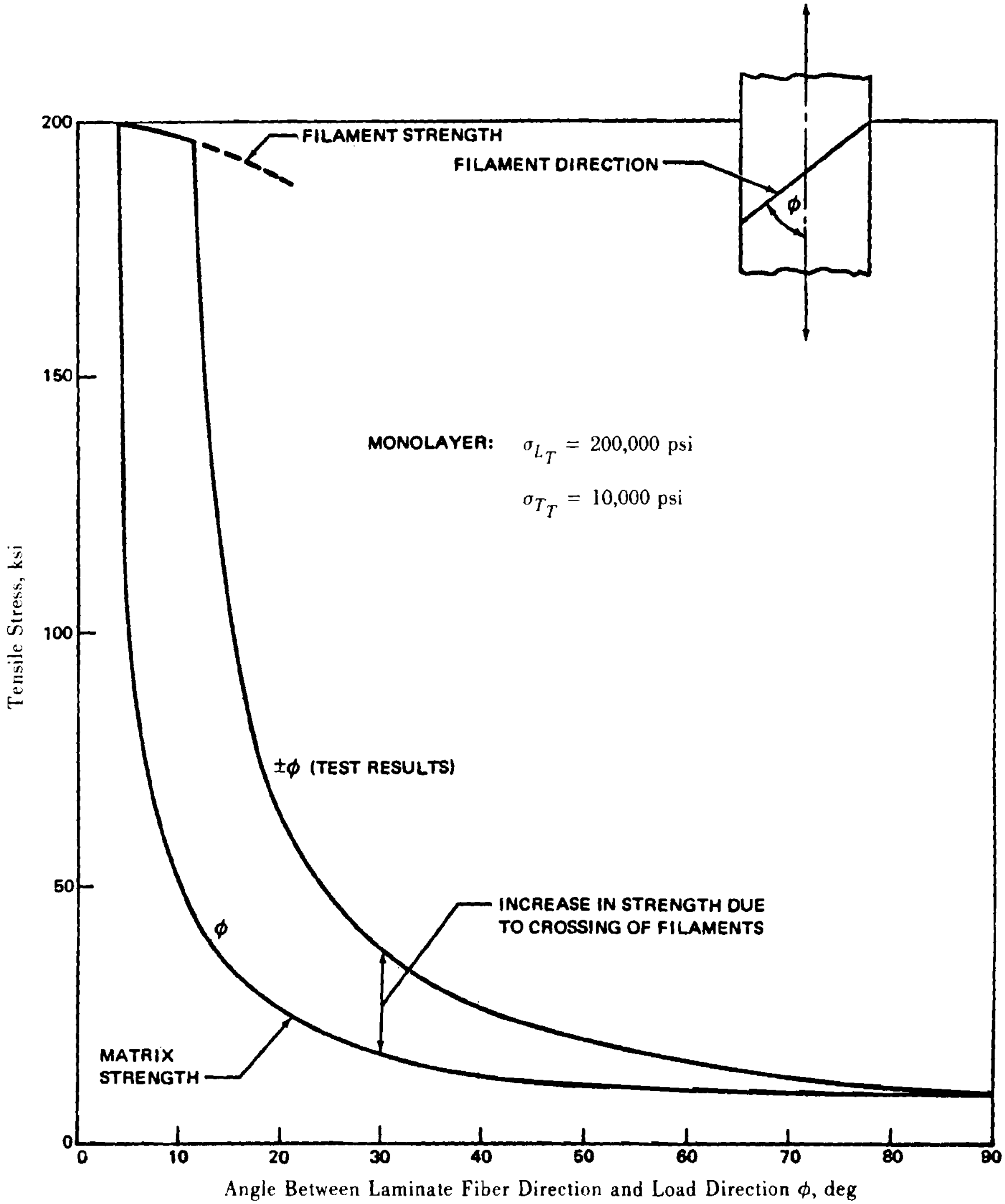

Figure 2-15. Tensile Strength of Boron Laminates[3]

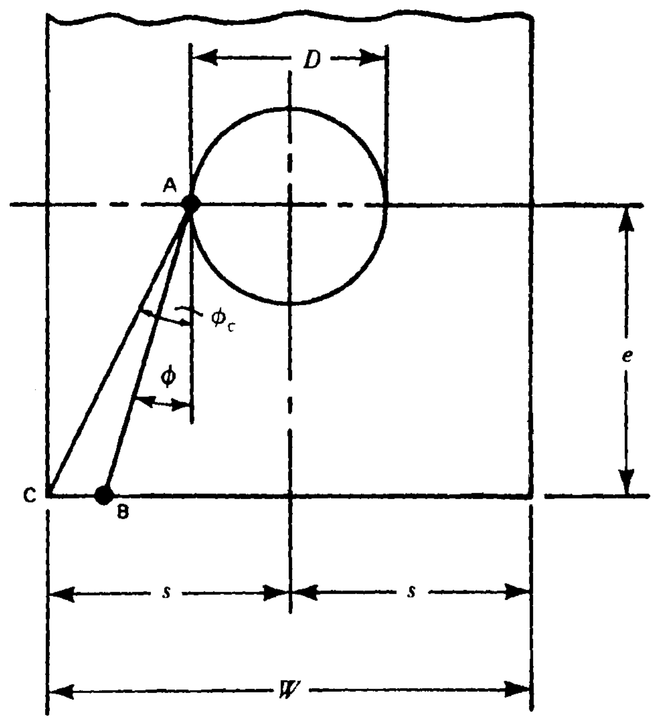

Figure 2-16. Stresses in Bolted Laminates[8]

SYMBOL	REF	TEST	$\frac{e}{D}$	$\frac{s}{D}$	$\frac{D}{t}$	REMARKS
×	2	1ST SERIES	2.67	3.33	1.88	PINNED
+	2	2ND SERIES	3.00	2.67	2.24	PINNED
⊙	2	2ND SERIES	3.00	2.67	2.24	BOLTED
⊡	3	3RD SERIES	3.00	2.67	1.12	PINS AND BOLTS
✳	3	4TH SERIES	3.00	2.67	1.12	CSK BOLTS
●	4	TABLES XLIX AND L	4.80	3.00	2.50	PINNED
▽	4	TABLE L	2.00	3.00	2.50	PINNED
△	5		2.00	2.38	4.80	PINNED

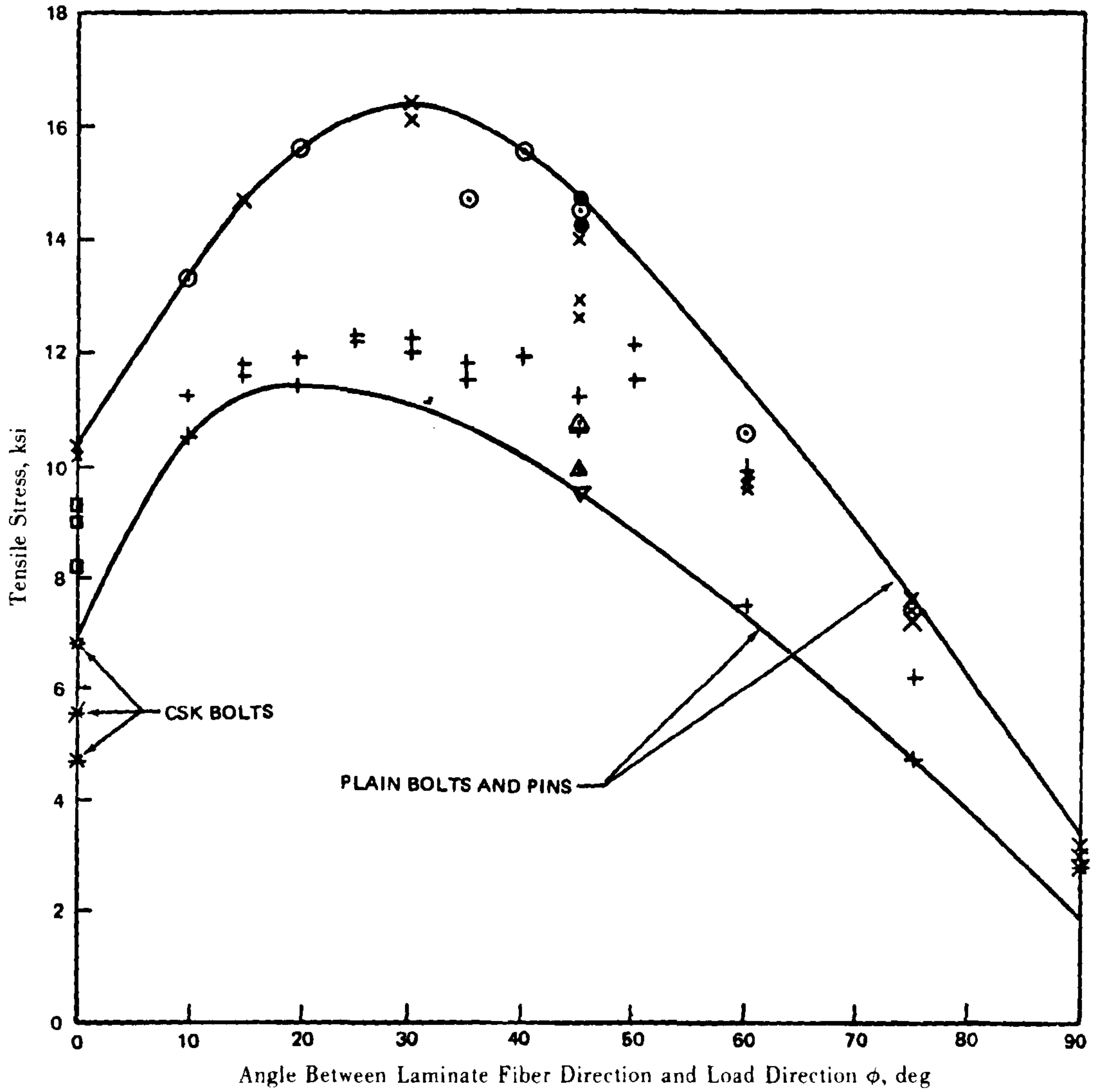

Figure 2-17. Principal Tensile Stresses in Bolted and Pinned Composite Joints — $\pm\phi$-Patterns[3]

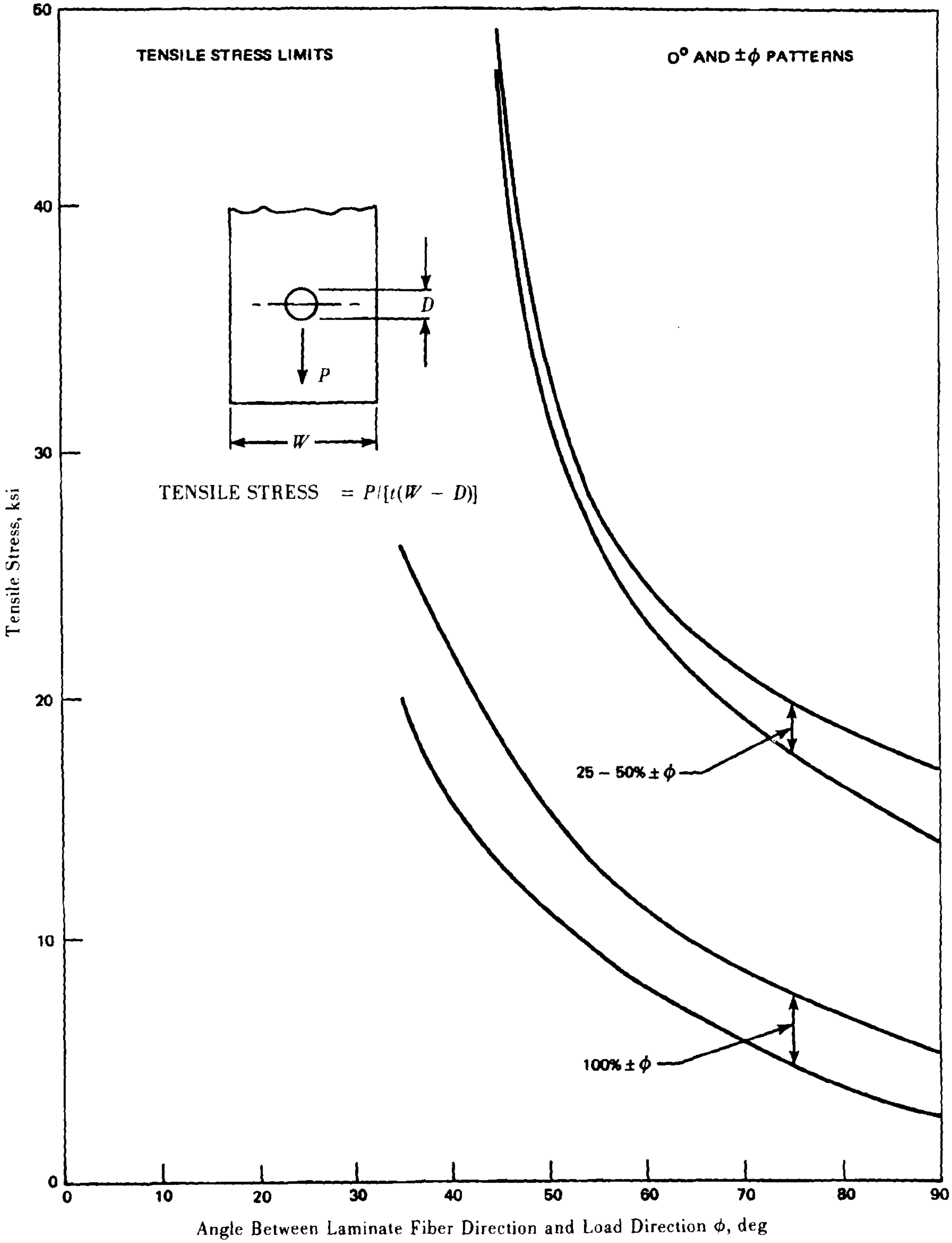

Figure 2-18. Tensile Stress Limits for Bolted Joints[3]

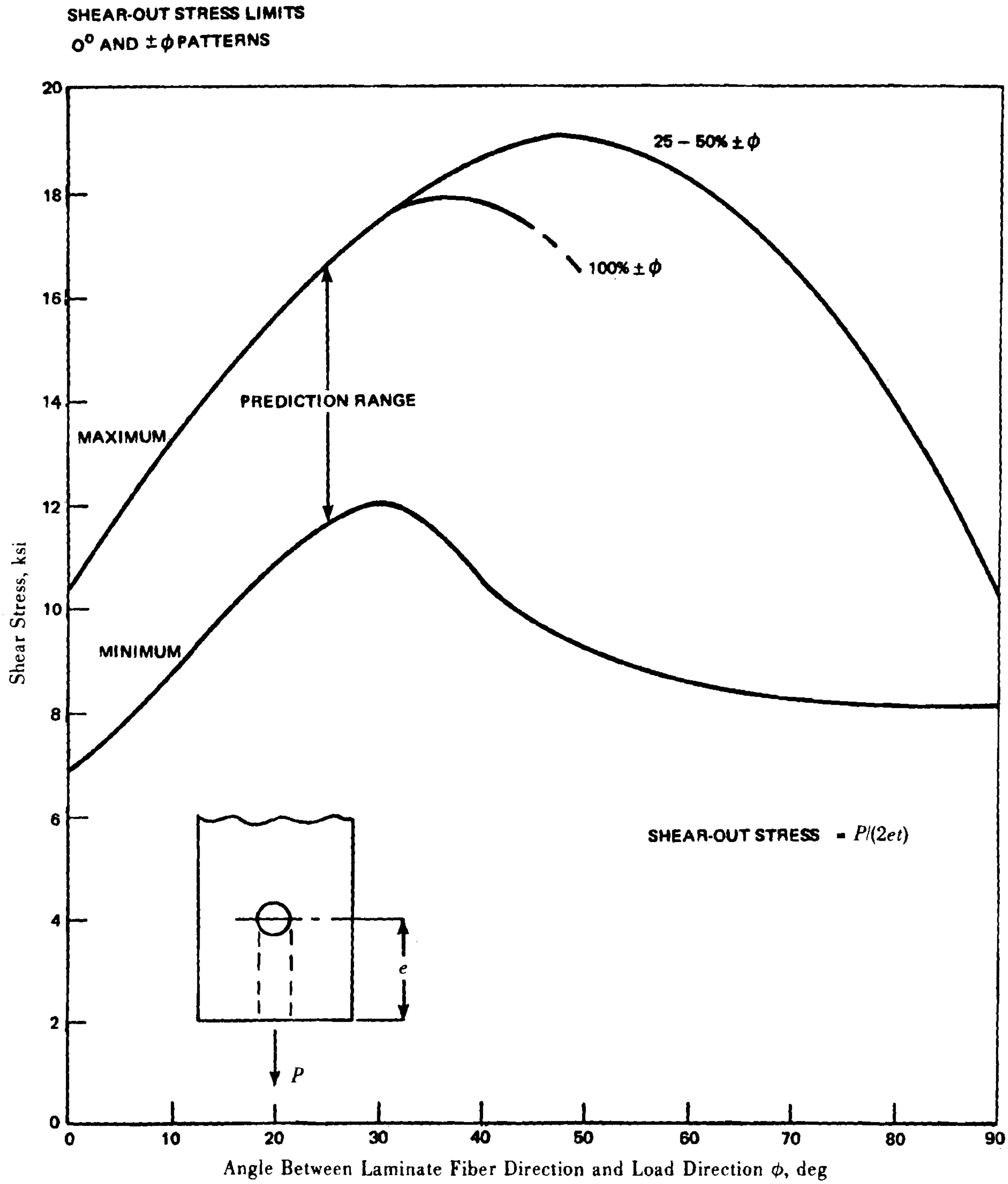

Figure 2-19. Shear-Out Stress Limits for Bolted Joints[3]

TABLE 2-1
SUMMARY OF COMPOSITE JOINT STRENGTH TESTS—MECHANICAL FASTENERS[2]

DATA SOURCE	PATTERN	CALCULATED STRENGTH LIMITS, lb				TEST LOAD, lb	FAILURE MODE
		MINIMUM		MAXIMUM			
REF. 2 FIRST SERIES (PINNED)	0	704	S	1056	S	1040	SHEAR (CLEAVAGE)
		697	S	1045	S	1045	
	±15	1000	S	1480	S	1410	ALONG FILAMENT LINES
		1010	S	1493	S	1420	
	±30	1260	S	1833	S	1730	
		1283	S	1870	S	1730	
		1213	S	1762	S	1660	
	±45	950	S	1694	S	1565	
		960	S	1712	S	1545	
		970	S	1730	S	1730	
	±60	878	T	1240	T	1130	
		878	T	1240	T	1150	
		878	T	1240	T	1165	
	±75	494	T	815	T	815	
		485	T	799	T	780	
		474	T	783	T	750	
	±90	2171	T	542	T	300	TENSION
		293	T	586	T	317	
		284	T	568	T	284	
REF. 2 SECOND SERIES (PINNED)	0	712	S	1070	S	715	CLEAVAGE
	±10	910	S	1370	S	1025	ALONG FILAMENT LINES
		920	S	1380	S	1110	
	±15	1010	S	1498	S	1120	
		1010	S	1498	S	1140	
	±20	1040	S	1643	S	1140	
		1027	S	1626	S	1170	
	±25	1107	S	1583	S	1130	
		1120	S	1600	S	1140	
	±30	1227	S	1780	S	1255	
		1240	S	1800	S	1240	
	±35	1226	S	1903	S	1320	
		1226	S	1903	S	1290	
	±40	1083	S	1614	T	1180	
		1096	S	1631	T	1200	
	±45	988	T	1391	T	990	
		999	T	1407	T	1060	
	±50	835	T	1198	T	1040	
(cont'd)		844	T	1210	T	1102	

S AND T INDICATE WHETHER SHEAR (S) OR TENSION (T) LIMITS ARE CRITICAL.

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TABLE 2-1 (cont'd)

DATA SOURCE	PATTERN	CALCULATED STRENGTH LIMITS, lb MINIMUM		CALCULATED STRENGTH LIMITS, lb MAXIMUM		TEST LOAD, lb	FAILURE MODE
REF. 2 SECOND SERIES (PINNED) (cont'd)	±60	577	T	820	T	580	
		570	T	812	T	748	
	±75	314	T	518	T	315	
		317	T	524	T	424	
	±90	201	T	401	T	217	TENSION
REF. 2 SECOND SERIES (BOLTED)	±10	910	S	1360	S	1300	ALONG FILAMENT LINES
	±15	990	S	1463	S	1390	
	±20	1120	S	1620	S	1520	
	±35	1227	S	1902	S	1655	
	±40	1180	T	1613	T	1555	
	±45	980	T	1390	T	1355	
	±60	583	T	830	T	820	
	±75	318	T	524	T	510	
REF. 2 THIRD SERIES (PINNED & NOTED)	0	1364	S	2024	S	1620	SHEAR (CLEAVAGE)
		1333	S	2000	S	2000	
		1341	S	2010	S	2010	
	0/15/-15/0 (BOLTED)	1980	S	2930	S	2410	ALONG 0° AND 90° LINES
		1923	S	2845	S	2270	
		1970	S	2910	S	2530	
	0/30/-30/0	2480	S	3600	S	2960	
		2425	S	3520	S	3190	
	0/45/-45/0	1980	S	3882	S	3310	
		1926	S	3775	S	3715	
		1938	S	3796	S	3550	
	0/60/-60/0 (BOLTED)	1756	S	3660	T	3615	
		1710	S	3560	T	3560	
		1727	S	3600	T	3400	
	0/90	2046	T	2480	T	2050	
		2036	T	2470	T	2050	
REF. 4 (PINNED)	±45	1748	T	2456	T	2453	ALONG FILAMENT LINES
		1763	T	2480	T	2456	
		1715	T	2412	T	2346	
	0/60/-60	2855	S	4290	T	4250	BEARING
		2630	S	3950	T	3935	
		2815	S	4225	T	3850	
	0/90	2520	T	3060	T	2915	TENSION
		1960	T	2380	T	2352	
		2030	T	2460	T	2347	
	0/60/-60/0	2550	S	3825	T	3685	TENSION
		3640	S	5470	T	5170	TENSION
		2280	S	4890	S	4550	SHEAR
		1520	S	3260	S	3255	TENSION
	0/90	1990	T	2416	T	2334	TENSION
(cont'd)		1363	S	2416	T	1450	TENSION

S AND T INDICATE WHETHER SHEAR (S) OR TENSION (T) LIMITS ARE CRITICAL.

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TABLE 2-1 (cont'd)

DATA SOURCE	PATTERN	CALCULATED STRENGTH LIMITS, lb MINIMUM		CALCULATED STRENGTH LIMITS, lb MAXIMUM		TEST LOAD, lb	FAILURE MODE
REF. 4 (PINNED) (cont'd)	0/45/-45	3640	S	7125	S	5190	TENSION
		2273	S	4450	S	4370	SHEAR
		1515	S	2970	S	2970	SHEAR
	±45	1760	T	2474	T	2445	TENSION
		1053	S	1882	S	1277	SHEAR
	0/15/-15	5700	S	8460	S	5700	BEARING
		3910	S	5800	S	4000	SHEAR
		2443	S	3624	S	2540	SHEAR
		1630	S	2416	S	1960	SHEAR
REF. 5 (PINNED) 0/45/-45 PATTERN	$\frac{e}{D} = 2$, $\frac{s}{D} = 1$	303	S	367	T	310	
	2	303	S	593	S	303	
	3	303	S	593	S	383	
	4	303	S	593	S	445	
	$\frac{e}{D} = 3$, 1	356	T	367	T	360	
	2	394	S	772	S	556	
	3	394	S	772	S	489	
	4	394	S	772	S	535	
	$\frac{e}{D} = 4$, 1	356	T	367	T	367	
	2	606	S	1148	T	712	
	3	606	S	1187	S	820	
	4	606	S	1187	S	711	
	$\frac{e}{D} = 5$, 2	757	S	1148	T	820	
	3	757	S	1484	S	835	
	4	757	S	1484	S	871	
REF. 5 (PINNED)	0/90	672	S	857	S	702/813	
	0/90	504	S	643	S	505/550	
	±45	504	S	887	T	600/644	
Z3824815 (1/4 in. DIA PIN)	(-1) 0/45/-45/0	2620	S	5130	S	4440	SHEAR
		2620	S	5130	S	3620	
		2615	S	5120	S	4230	
	(-503) 0/45/-45/90					3590	BEARING
						3640	
						3800	
	(-507) 0/45/-45/0	2650	S	5190	S	2960	SHEAR
	2%SiC/Al_2O_3	2646	S	5180	S	4500	NOT FAILED
	WHISKERS	2646	S	5180	S	3620	SHEAR/TENSION
	(-509) 0/45/-45/0	2585	S	5060	S	3710	BEARING
	1%SiC/Al_2O_2	2594	S	5080	S	3910	SHEAR
	WHISKERS	2580	S	5050	S	3670	SHEAR
	(-511) 0/45/-45/0	2620	S	5130	S	4200	BEARING
	Al_2O_3/AIN	2620	S	5130	S	4050	BEARING
	WHISKERS	2620	S	5130	S	3660	NOT FAILED

S AND T INDICATE WHETHER SHEAR (S) OR TENSION (T) LIMITS ARE CRITICAL.

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TABLE 2-1 (cont'd)

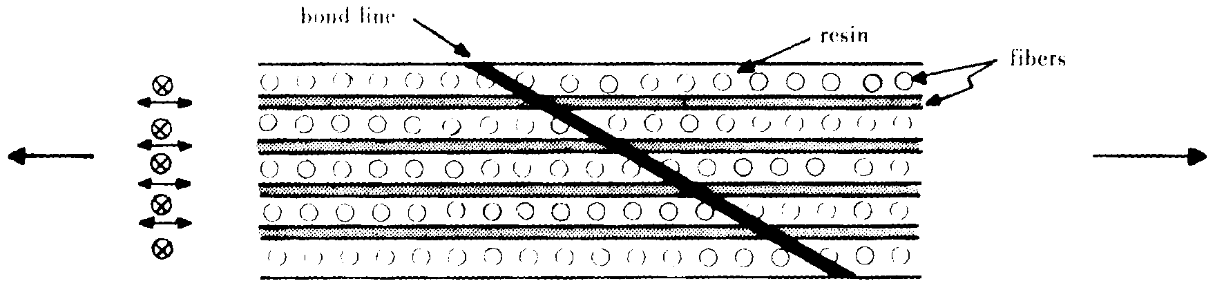
DATA SOURCE	PATTERN	CALCULATED STRENGTH LIMITS, lb MINIMUM		CALCULATED STRENGTH LIMITS, lb MAXIMUM		TEST LOAD, lb	FAILURE MODE
OTHER END (1/2 in. HOLE)							
Z3824815 (1/2 in. DIA PIN)	(-1) 0/45/-45/0	2910	S	5700	S	4440	NOT FAILED
		2910	S	5700	S	3620	
		2900	S	5700	S	4230	
	(-503) 0/45/-45/90					3590	
						3640	
						3800	
	(-507) 2%SiC/Al_2O_3 WHISKERS	2944	S	5780	S	2960	NOT FAILED
		2940	S	5760	S	4500	BEARING
		2940	S	5760	S	3620	NOT FAILED
	(-509) 0/45/-45/0 1%SiC/Al_2O_3 WHISKERS	2873	S	5630	S	3710	
		2880	S	5650	S	3910	
		2865	S	5620	S	3670	
	(-511) 0/45/-45/0 2%Al_2O_3/AlN WHISKERS	2910	S	5700	S	4200	
		2910	S	5700	S	4050	NOT FAILED
		2910	S	5700	S	3660	SHEAR

S AND T INDICATE WHETHER SHEAR (S) OR TENSION (T) LIMITS ARE CRITICAL.

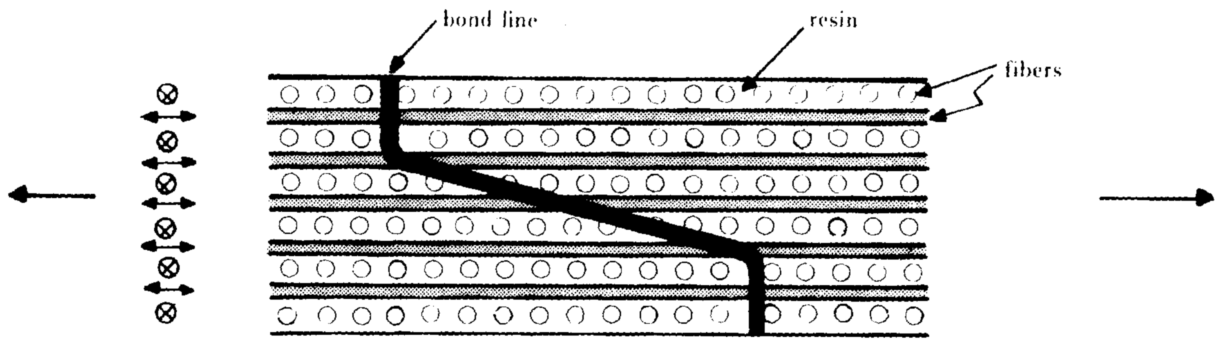
TABLE 2-2
PREDICTED STRENGTH RANGES FOR BOLTED JOINT SPECIMENS[8]

DRAWING NO.	PATTERN A*	e, in.	t, in.	PREDICTED LOAD, lb		BEARING LIMIT, lb**
				MINIMUM	MAXIMUM	
Z 3824831	50	0.75	0.12	1745 S	3420 S	3375
	33 1/3					4500
Z 3824832	50	0.50	0.12	1163 S	2280 S	3375
	50		0.16	1552 S	3040 S	4500
	33 1/3		0.12	1163 S	2280 S	4500
	25		0.16	1552 S	3040 S	6750
Z 3824833	50	0.75	0.12	1745 S	3420 S	3375
	50		0.16	2328 S	4560 S	4500
	33 1/3		0.12	1745 S	3420 S	4500
	25		0.16	2328 S	4560 S	6750
Z 3824834	50	1.25	0.12	2910 S	4580 T	3375
	50		0.16	3880 S	6110 T	4500
	33 1/3		0.12	2910 S	4580 T	4500
	25		0.16	3880 S	6110 T	6750
WITH 5/16 IN. BUSHINGS						
	50	0.50	0.12	1163 S	2280 S	5625
	50		0.16	1552 S	3040 S	7500
	33 1/3		0.12	1163 S	2280 S	7500
	25		0.16	1552 S	3040 S	11250
	50	0.75	0.12	1745 S	3420 S	5625
	50		0.16	2328 S	4560 S	7500
	33 1/3		0.12	1745 S	4320 S	7500
	25		0.16	2328 S	4560 S	11250
	50	1.25	0.12	2910 S	3880 T	5625
	50		0.16	3880 S	5170 T	7500
	33 1/3		0.12	2910 S	3880 T	7500
	25		0.16	3880 S	5170 T	11250

*A INDICATES % FIBERS AT ±45°. BALANCE OF FIBERS AT 0°.
**ASSUMED BEARING STRESSES: 150,000 PSI FOR 50% AT ±45°
200,000 PSI FOR 33 1/3% AT ±45°
225,000 PSI FOR 25% AT ±45°.
S AND T INDICATE WHETHER SHEAR (S) OR TENSION (T) LIMITS ARE CRITICAL.

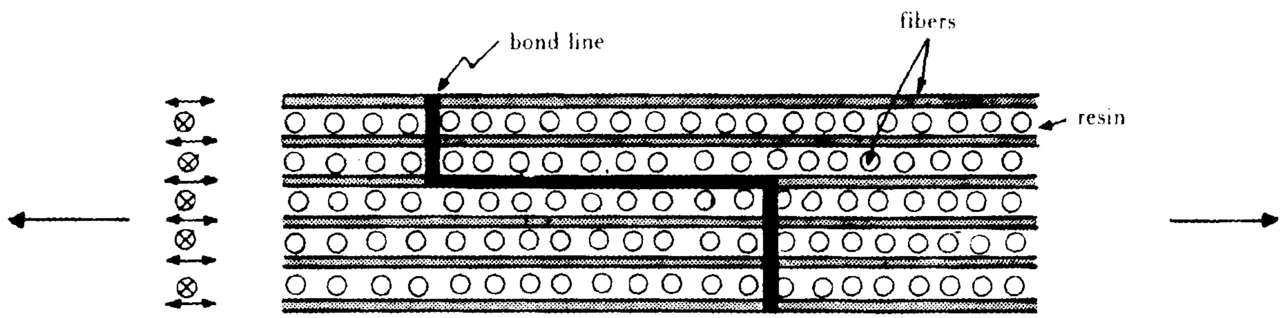


(A) Scarf



(B) Landed Scarf

Acceptable machined joint configurations with compromising load direction to fiber orientation.



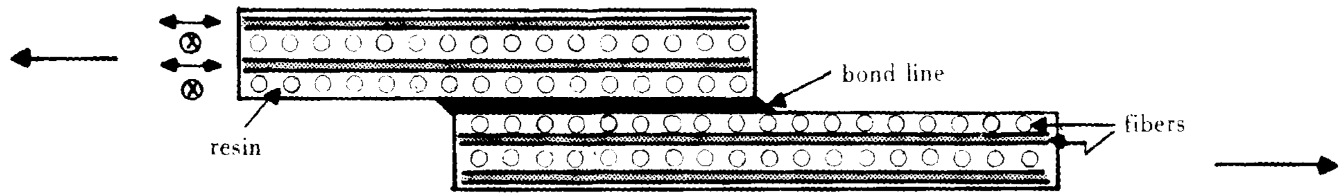
(C) Stepped Lap

Unacceptable because of possibility of having load bearing surface fibers perpendicular to load.

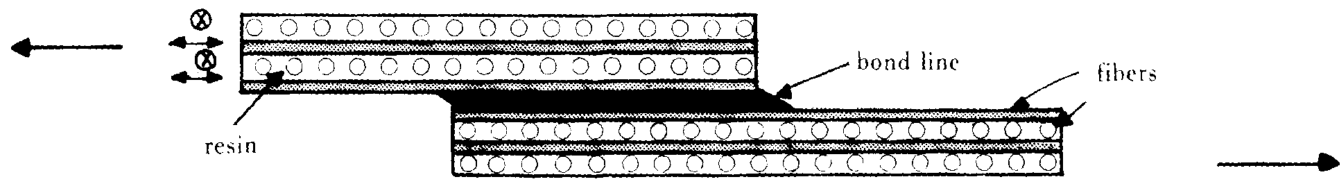
⊗ — fiber orientation normal to page

↔ — fiber orientation parallel to page

Figure 2-20. Machined Joints

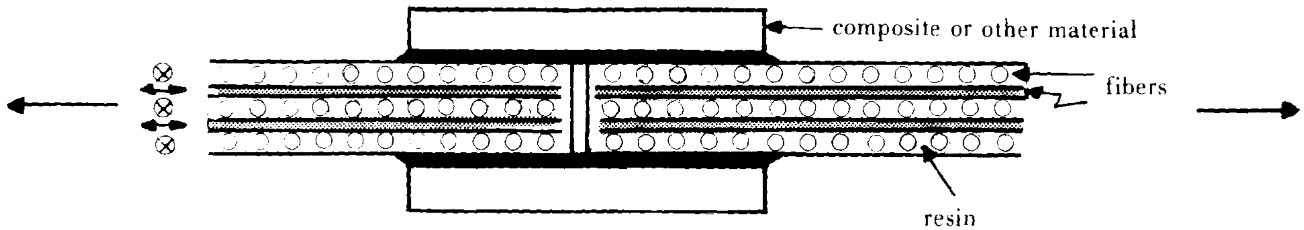


(A) *Poor*--surface fibers normal to load

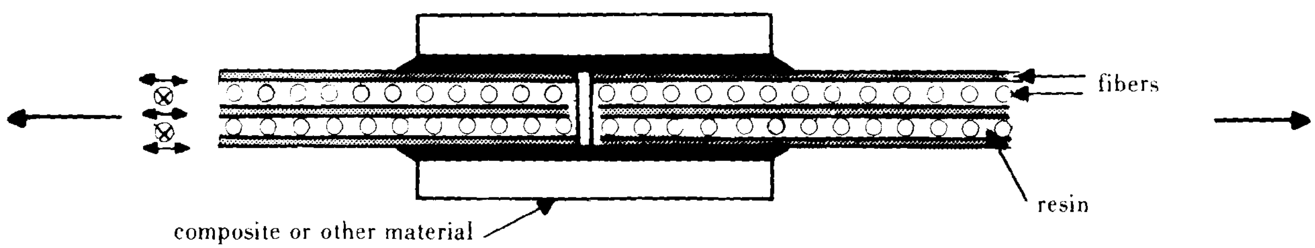


(B) *Good*--surface fibers parallel to load

Figure 2-21. Single-Lap Joints (no machining)



(A) *Poor*--surface fibers normal to load



(B) *Good*--surface fibers parallel to load

Figure 2-22. Double-Strap Joints (no machining)

REFERENCES

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4. F. Wilson, *Research on Resin-Impregnated, Collimated Boron Filaments and Improved High-Modulus, High-Strength Filaments and Compositions,* Whittaker Corp., AFML-TR-67-20, Wright-Patterson Air Force Base, OH, January 1967.
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CHAPTER 3

DESIGN DATA REQUIREMENTS

Graphs and tables of values of the ultimate strength and stress/strain behavior of composite joints in tension, compression, shear, and bearing are presented as a function of various fiber orientations and fibers. Graphs of bond strength as a function of temperature are presented. Properties of various adhesives also are presented.

3-0 LIST OF SYMBOLS

A = area of joint, in.^{2}
E = elastic modulus, psi
E_L = elastic modulus of composite with fibers parallel (longitudinal) to direction of applied stress, i.e., ϕ = 0 deg, psi
E_{L_c} = compressive elastic modulus of composite with fibers parallel (longitudinal) to direction of applied stress, i.e., ϕ = 0 deg, psi
E_{L_t} = tensile elastic modulus of composite with fibers parallel (longitudinal) to direction of applied stress, i.e., ϕ = 0 deg, psi
E_T = elastic modulus of composite with fibers perpendicular (transverse) to direction of applied stress, i.e., ϕ = 90 deg, psi
E_{T_c} = compressive elastic modulus of composite with fibers perpendicular (transverse) to direction of applied stress, i.e., ϕ = 90 deg, psi
E_{T_t} = tensile elastic modulus of composite with fibers perpendicular (transverse) to direction of applied stress, i.e., ϕ = 90 deg, psi
E_x = elastic modulus in direction of applied load, psi
F_{L_c} = compressive strength of composite with fibers parallel (longitudinal) to direction of applied load, i.e., ϕ = 0 deg, psi
F_{L_t} = tensile strength of composite with fibers parallel (longitudinal) to direction of applied load, i.e., ϕ = 0 deg, psi
F_s = in-plane shear strength, psi
F_{T_c} = compressive strength of composite with fibers perpendicular (transverse) to direction of applied load, i.e., ϕ = 90 deg, psi
F_{T_t} = tensile strength of composite with fibers perpendicular (transverse) to direction of applied load, i.e., ϕ = 90 deg, psi
f^{bru} = ultimate bearing strength, psi
f^{cu} = ultimate compressive strength, psi
f^{ils} = interlaminar shear strength, psi
f^{isu} = ultimate interlaminar shear strength, psi
f^s = shear stress, psi
f^{su} = ultimate shear strength, psi
f_a^{su} = ultimate shear strength of adhesive joint, psi
f^{tu} = ultimate tensile strength, psi
G = modulus of rigidity (shear) of adhesive, psi
G_{LT} = shear modulus with fibers parallel (longitudinal) to direction of applied shear, psi
G_{xy} = shear modulus in xy-plane, psi
ℓ = length of specimen, in.
= distance between fulcrum and load, in.
L_a = length of adhesive joint, in.
P = loads (as indicated in text), lb
S = distance, in.
t = thicknesses—i.e., of ply, adherend, specimen as indicated in text—in.
W = width, in.
γ = shear strain, in./in.
γ_{xy} = shear strain in xy plane, in./in.
ϵ = strain, in./in.

μ_{LT} = Poisson's ratio with stress applied parallel (longitudinally) to fiber orientation of composite, dimensionless

μ_{TL} = Poisson's ratio with stress applied perpendicularly (transversely) to fiber orientation of composite, dimensionless

σ = pure tensile strength of adhesive, psi

τ = pure shear strength of adhesive, psi

ϕ = angle between fiber laminate direction and direction of load, deg

3-1 BASELINE DATA

An essential part of joint design is to characterize the properties of the members to be joined. This means that the ultimate strength and stress-strain behavior should be ascertained in tension, compression, shear, and bearing. Similarly, when a bonded joint is contemplated, the important adhesive properties to characterize are those in shear and tension. This information will characterize adherend stiffness and adhesive strength adequately.

3-2 LAMINATE MECHANICAL PROPERTIES

The laminate properties of interest can be obtained from the results of tension tests, compression tests, in-plane (edgewise) shear tests, interlaminar shear tests, and pin bearing tests.

For a specific glass and boron composite, the elastic moduli in tension and compression are given in Tables 3-1 through 3-3. Table 3-4 reports the shear moduli for the same glass and boron composite obtained from in-plane shear tests. Some interlaminar shear test data can be found in Table 3-5 and pin bearing strengths in Table 3-6. The pin bearing results are for both boron and glass composites with a nominal pin diameter of 0.25 in., an edge-distance bolt-diameter ratio e/D = 4.5, and a side-distance bolt-diameter ratio s/D = 3.

For Type AS/3002 graphite composite the tensile and compressive strengths and moduli are presented in Figs. 3-1 through 3-4. In-plane shear stress strain data are given in Fig. 3-5 and interlaminar shear strengths are given in Fig. 3-6.

TABLE 3-1. UNIDIRECTIONAL LAMINATE PROPERTIES[1]

	S-994 FIBERGLASS		BORON	
	NARMCO 5505 RESIN	828-1031 BDMA-MNA RESIN	NARMCO 5505 RESIN	
	EXPERIMENT	LITERATURE*	EXPERIMENT	LITERATURE*
ELASTIC PROPERTIES				
E_L, 10^6 psi	5.85-9.30	7.65 (1)	24.8-29.6	30.00 (2)
E_T, 10^6 psi	1.59-2.25	2.24 (1)	1.90-2.21	3.00 (2)
G_{LT}, 10^6 psi	0.84-1.43	0.78 (1)	0.73-0.88	1.10 (2)
μ_{LT}	0.248-0.308	0.270 (1)	0.163-0.266	0.380 (2)
μ_{TL}	0.027-0.075	0.079 (1)	0.018-0.029	0.038 (2)
STRENGTH PROPERTIES				
F_{L_t}, 10^3 psi	175.3-242.0	264.0 (1)	152-190.7	200.0 (2)
F_{L_c}, 10^3 psi	—	173.0 (1)	—	250.0 (2)
F_{T_t}, 10^3 psi	7.96-9.60	7.5 (3)	6.80-8.37	7.0 (3)
F_{T_c}, 10^3 psi	—	29.0 (1)	—	20.0 (3)
F_s, 10^3 psi	9.62-13.58	8.5 (1)	11.04-15.00	12.0 (3)

(1) Data from Ref. 4, page 239. Fiberglass/828-1031 BDMA-MNA Laminate.
(2) Data from Ref. 5.
(3) Data estimated from Ref. 6.

*Data from literature were used in analysis. These gave better correlation of predicted properties with test results for multidirectional laminates used in specimens.

TABLE 3-2
SUMMARY OF THEORETICAL AND EXPERIMENTAL TENSION PROPERTIES[1]

			ELASTIC CONSTANTS				STRENGTH PROPERTIES			VOLUME FRACTIONS		
			PREDICTED		ACTUAL		PREDICTED		ACTUAL			
	LAMINATE PATTERN	LAMINATE THICKNESS in.	E_x, 10^6 psi	μ_{xy}	E_x, 10^6 psi	μ_{xy}	FIRST FAILURE STRESS, ksi	ULTIMATE STRESS, ksi	ULTIMATE STRESS, ksi	FILAMENT	RESIN	VOIDS
Boron/Narmco 5505	ALL 0°	0.030			25.50 24.80 27.20 25.80 27.60 29.60	0.250 0.241 0.266 0.164 0.167 0.163			158.5 158.5 171.0 190.7 180.0 152.0	0.595	0.381	0.024
					AVG 26.75	AVG 0.209			AVG 168.5			
	ALL 90°	0.050			2.21 2.03 1.90	0.018 0.029 0.021			7.15 6.80 8.37	0.621	0.324	0.055
					AVG 2.05	AVG 0.023			AVG 7.44			
	0°/45°/-45°/0°	0.040			16.80 16.50 17.40	0.722 0.714 0.745			95.0 99.5 88.0	0.636	0.332	0.032
			17.13	0.688	AVG 16.90	AVG 0.727	94.0	101.5	AVG 94.2			
	0°/45°/-45°/0°	0.040			14.8 15.7	0.704 0.706			100.0 95.0	0.545	0.412	0.043
			17.13	0.688	AVG 15.3	AVG 0.705	94.0	101.5	AVG 97.5			
	0°/45°/-45°/0°	0.080			15.1 14.7	0.710 0.616			98.2 102.5	0.537	0.436	0.027
	45°/0°/0°/-45°		17.13	0.688	AVG 14.9	AVG 0.663	94.0	101.5	AVG 100.4			
	0°/45°/-45°/0°	0.120			17.0 16.7	0.687 0.720			102.0 104.3	0.612	0.342	0.046
			17.13	0.688	AVG 16.9	AVG 0.704	94.0	101.5	AVG 103.2			
	0°/45°/-45°/0°	0.160			17.2 17.0	0.777 0.700			93.3 98.5	0.597	0.330	0.073
			17.13	0.688	AVG 17.1	AVG 0.738	94.0	101.5	AVG 95.9			
	0°/45°/-45°/90°	0.040			11.5 11.5 11.2	0.331 0.312 0.329			60.0 43.8 53.8	0.602	0.342	0.056
			11.87	0.336	AVG 11.4	AVG 0.324	31.1	66.4	AVG 52.5			
	0°/45°/-45°/90°	0.120			10.8 9.7	0.394 0.200			66.0 57.4	0.609	0.346	0.045
			11.87	0.336	AVG 10.3	AVG 0.298	31.1	66.4	AVG 61.7			

(cont'd on next page)

TABLE 3-2 (cont'd)

			ELASTIC CONSTANTS				STRENGTH PROPERTIES			VOLUME FRACTIONS		
			PREDICTED		ACTUAL		PREDICTED		ACTUAL			
	LAMINATE PATTERN	LAMINATE THICKNESS in.	E_x, 10^6 psi	μ_{xy}	E_x, 10^6 psi	μ_{xy}	FIRST FAILURE STRESS, ksi	ULTIMATE STRESS, ksi	ULTIMATE STRESS, ksi	FILAMENT	RESIN	VOIDS
S-994 Glass/Narmco 5505	ALL 0°	0.060			7.70 7.80 9.30	0.308 0.248 0.263				0.548	0.411	0.005
		0.030			5.85 6.56 6.40	0.266 0.288 0.260			175.3 203.3 242.0			
					AVG 7.27	AVG 0.272			AVG 206.8			
	ALL 90°	0.060			2.20 2.19	0.075 0.068			7.48 8.00	0.548	0.411	0.005
		0.050			2.25 1.84 1.59	0.063 0.027 0.071			8.17 7.96 9.60	0.594	0.401	0.005
					AVG 2.01	AVG 0.061			AVG 8.24			
	0°/45°/-45°/0°	0.080			4.55 4.06 5.77	0.591 0.575 0.577			120.0 143.4 137.0			
			5.10	0.453	AVG 4.79	AVG 0.581	19.6	115.3	AVG 133.4			
	0°/45°/-45°/90°	0.080			3.66 3.80 3.75				62.6 55.4 57.3			
			3.92	0.308	AVG 3.74		6.6	65.3	AVG 58.4			

TABLE 3-3. SUMMARY OF THEORETICAL AND EXPERIMENTAL COMPRESSION PROPERTIES[1]

		ELASTIC CONSTANTS				STRENGTH PROPERTIES			
		ELASTIC MODULUS E		POISSON'S RATIO μ_{xy}		PREDICTED		ACTUAL	
CONFIGURATION Z3824818	SPECIMEN NUMBER	PREDICTED 10^6 psi	ACTUAL 10^6 psi	PREDICTED	ACTUAL	FIRST FAILURE STRESS, ksi	ULTIMATE STRESS, ksi	ULTIMATE STRESS, ksi	REMARKS
−1	1	17.1	17.0	0.688	0.638	95.2	134.8	94.4	
0°/45°/-45°/0°	2	17.1	16.1	0.688	0.950	95.2	134.8	—	
t = 0.120 in.	2	16.4	13.3	0.688	0.135	95.2	134.8	105.6	SECOND LOADING
BORON/NARMCO 5505	3	17.1	17.4	0.688	0.169	95.2	134.8	100.9	
−501 0°/45°/-45°/0°	1	5.1	5.0	0.453	0.130	37.4	86.5	86.0	
t = 0.120 in.	2	5.1	5.0	0.453	0.095	37.4	86.5	89.3	
S-994/NARMCO 5505	3	5.1	4.12	0.453	0.119	37.4	86.5	89.5	
−503 PATTERN NOTED	1	19.7	14.3	0.439	0.063	150.0	176.0	166.8	PATTERN CONSISTED OF 20% CIRCULAR, 20% AT
t = 0.100 in. BORON/NARMCO 5505	2	19.7	18.8	0.439	0.093	150.0	176.0	165.0	±45°, AND 60% LONGITUDINAL—CIRCU-
AND NOTED	3	19.7	24.7	0.439	0.055	150.0	176.0	171.4	LAR WRAPS WERE S-994
−505 PATTERN NOTED	1	5.65	6.5	0.247	0.065	46.5	110.7	99.0	PATTERN CONSISTED OF 20% CIRCULAR, 20% AT
t = 0.100	2	5.65	5.0	0.247	0.065	46.5	110.7	99.5	±45°, AND 60%
S-994/NARMCO 5505	3	5.65	4.76	0.247	0.051	46.5	110.7	71.3	LONGITUDINAL
−507 0°/45°/-45°/0°	1	17.1	20.0	0.688	0.173	96.2	134.8	154.8	
t = 0.120 in. BORON/NARMCO 5505	2	17.1	15.14	0.688	0.100	96.2	134.8	135.7	SiC—AlN WHISKERS ADDED TO LAMINATE AT 2% OF RESIN WEIGHT
+ NOTED WHISKERS	3	17.1	17.24	0.688	0.160	96.2	134.8	137.7	
−509 0°/45°/-45°/0°	1*	17.1	11.10	0.688	0.111	95.2	134.8	137.3*	
t = 0.120 in. BORON/NARMCO 5505	2	17.1	14.10	0.688	0.138	95.2	134.8	161.6	SiC—AlN WHISKERS ADDED TO LAMINATE AT 1% OF RESIN WEIGHT
+ NOTED WHISKERS	3	17.1	12.20	0.688	0.171	95.2	134.8	159.9	
−511 0°/45°/-45°/0°	1	17.1	16.2	0.688	0.155	95.2	134.8	170.3	
t = 0.120 in. BORON/NARMCO 5505	2	17.1	18.8	0.688	0.188	95.2	134.8	124.2	Al_2O_3—AlN WHISKERS ADDED TO LAMINATE AT 2% OF RESIN WEIGHT
+ NOTED WHISKERS	3	17.1	13.2	0.688	0.139	95.2	134.8	165.3	

*Retaining ring failed

TABLE 3-4
SUMMARY OF THEORETICAL AND EXPERIMENTAL IN-PLANE SHEAR PROPERTIES[1]

			ELASTIC CONSTANTS		STRENGTH PROPERTIES						
			SHEAR MODULUS, G		PREDICTED		ACTUAL		VOLUME FRACTIONS		
MATERIALS	PATTERN	THICKNESS, in.	PREDICTED, 10^6 psi	ACTUAL, 10^6 psi	FIRST FAILURE STRESS, ksi	ULTIMATE STRESS, ksi	FIRST FAILURE STRESS, ksi	ULTIMATE STRESS, ksi	FILAMENTS	RESIN	VOIDS
S-994/NARMCO 5505	ALL 0°	0.100	—	1.43 0.91 0.84	—	—	8.3 7.1 6.0	13.58 11.0 9.62	0.627	0.365	0.008
				AVE 1.06			AVE 7.1	AVE 11.40			
	0°/±45°/0°		1.52	2.03 1.79 1.50	10.7	46.6	—	34.5 42.1 34.9			
				AVE 1.77				AVE 37.2			
	0°/±45°/90°		1.52	2.08 2.24 1.93	10.7	46.6	—	34.8 34.2 33.7			
				AVE 2.08				AVE 34.2			
BORON/NARMCO 5505	ALL 0°	0.100	—	0.88 0.77 0.73	—	—	NONE 6.9 7.3	15.00 12.50 11.04	0.589	0.367	0.044
				AVE 0.79			AVE 7.1	AVE 12.84			
	0°/±45°/0°		4.45	6.22 6.17 6.05	20.4	52.0		46.0 41.3 41.0			
				AVE 6.15				AVE 42.7			
	0°/±45°/90°		4.45	5.48 6.23 5.80	20.4	52.0		31.7 33.8 33.7			
				AVE 5.84				AVE 33.1			

TABLE 3-5. INTERLAMINAR SHEAR TEST RESULTS[1]

CONFIGURATION	SPECIMEN MATERIALS AND FIBER PATTERN	GAGE, in.	WIDTH, in.	AREA, A, in.^{2}	FAILURE LOAD, P, lb	INTERLAMINAR SHEAR STRENGTH = $3P/(4A)$, psi
−1	BORON/NARMCO 5505	0.1203	0.4248	0.0511	715	10,480
	0°/45°/-45°/0°	0.1194	0.4156	0.0496	657	9,940
		0.1158	0.4323	0.0501	683	10,200
−501	S-994 GLASS/NARMCO 5505	0.1364	0.3625	0.0494	790	12,000
	0°/45°/-45°/0°	0.1283	0.3720	0.0477	795	12,500
		0.1384	0.3690	0.0511	845	12,400
−503	BORON/NARMCO 5505	0.1179	0.3988	0.0470	488	7,780
	0°/45°/-45°/90°	0.1280	0.3950	0.0477	518	8,150
		0.1217	0.3906	0.0475	570	9,000
−505	S-994 GLASS/NARMCO 5505	0.1370	0.4007	0.0549	501	6,850
	0°/45°/-45°/90°	0.1373	0.3648	0.0501	526	7,875
		0.1278	0.3900	0.0498	519	7,805
−507	BORON/NARMCO 5505	0.1152	0.3422	0.0394	705	13,425
	SiC-Al_2O_3 WHISKERS AT 2%	0.1201	0.3620	0.0435	712	12,250
	OF RESIN WEIGHT	0.1189	0.3651	0.0434	721	12,450
	0°/45°/-45°/0°					
−509	BORON/NARMCO 5505	0.1181	0.3509	0.0414	680	12,300
	SiC-Al_2O_3 WHISKERS AT 1%	0.1173	0.3548	0.0416	669	12,040
	OF RESIN WEIGHT	0.1162	0.3532	0.0410	671	12,250
	0°/45°/-45°/0°					
−511	BORON/NARMCO 5505	0.1190	0.3689	0.0439	629	10,720
	AlN-Al_2O_3 WHISKERS AT 2%	0.1242	0.3681	0.0457	661	10,830
	OF RESIN WEIGHT	0.1233	0.3678	0.0453	640	10,600
	0°/45°/-45°/0°					

TABLE 3-6. PIN-BEARING TEST RESULTS[1]

SPECIMEN MATERIALS AND FIBER PATTERNS	GAGE, in.	HOLE DIA, in.	PIN DIA, in.	BEARING AREA, in²	ULTIMATE LOAD, lb	AVERAGE STRESS AT FAILURE: BEARING, psi	AVERAGE STRESS AT FAILURE: SHEAR-OUT, psi	BEARING STRESS AT 4% OFFSET, psi	FAILURE MODE	TEST DATE
BORON/NARMCO 5505 0°/45°/-45°/0°	0.1200	0.258	0.257	0.0308	4,440	144,000	14,800	121,000	COMBINED SHEAR AND BEARING	
	0.1200	0.260	0.257	0.0308	3,620	117,500	12,100	72,700	SHEAR-OUT	7/67
	0.1198	0.2569	0.257	0.0308	4,230	137,500	14,100	136,500	COMBINED SHEAR AND TENSION	
	0.1295	0.2557	0.255	0.0330	3,562	108,000	11,000	98,000	SHEAR-OUT	
	0.1286	0.2554	0.255	0.0328	3,723	113,500	11,500	82,400		12/68
	0.1286	0.2565	0.256	0.0329	3,590	109,000	11,100	97,200		
	0.1260	0.2552	0.2540	0.0320	3,585	112,000	11,400	—	SHEAR-OUT	
	0.1293	0.2565	0.2560	0.0331	3,665	110,800	11,300	—		12/68
	0.1254	0.2563	0.2550	0.0320	3,570	111,500	11,300	—		
S-994 GLASS/NARMCO 5505 0°/45°/-45°/0°	0.1368	0.255	0.2550	0.0349	1,800	53,100	5,300	48,000	BEARING	
	0.1260	0.255	0.2550	0.0321	1,950	60,700	6,200	29,000		10/67
	0.1320	0.254	0.2530	0.0334	1,990	59,600	6,040	41,400		
BORON/NARMCO 5505 0°/45°/-45°/90°	0.1200	0.260	0.2570	0.0308	3,590	116,500	12,000	95,500	BEARING	
	0.1200	0.260	0.2570	0.0308	3,640	118,100	12,100	76,000		7/67
	0.1200	0.264	0.2630	0.0316	3,800	120,000	12,700	49,500		
	0.1150	0.2555	0.2550	0.0293	4,145	141,300	14,400	119,400	BEARING	
	0.1150	0.2546	0.2540	0.0292	4,255	145,700	14,800	113,000		12/68
	0.1190	0.2550	0.2540	0.0302	4,055	134,300	13,600	—		
	0.1182	0.2552	0.2540	0.0300	3,718	123,900	12,600	—	BEARING	
	0.1171	0.2550	0.2540	0.0298	4,115	138,000	14,000	—		12/68
	0.1192	0.2551	0.2540	0.0302	3,780	125,000	12,700	—		
S-994 GLASS/NARMCO 5505 0°/45°/-45°/90°	0.1250	0.255	0.2550	0.0319	1,965	61,600	6,300	25,200	BEARING	
	0.1390	0.255	0.2550	0.0354	2,210	62,500	6,350	46,200		10/67
	0.1360	0.256	0.2550	0.0347	2,185	63,000	6,430	57,000		
BORON/NARMCO 5505 SiC-Al_2O_3 WHISKERS AT 2% OF RESIN WEIGHT 0°/45°/-45°/0°	0.1215	0.2569	0.2570	0.0313	2,960	96,600	9,770	56,600	COMBINED SHEAR AND BEARING	
	0.1212	0.2569	0.2570	0.0312	4,500	144,200	14,800	135,800	BEARING (AT ½ DIAMETER LOADING PIN)	12/67
	0.1212	0.2580	0.2580	0.0313	3,620	115,900	11,900	81,000	COMBINED SHEAR AND TENSION	
BORON/NARMCO 5505 SiC-Al_2O_3 WHISKERS AT 1% OF RESIN WEIGHT 0°/45°/-45°/0°	0.1185	0.2569	0.2570	0.0305	3,710	121,800	12,500	90,600	BEARING	
	0.1189	0.2559	0.2560	0.0304	3,910	128,600	13,200	39,700	COMBINED SHEAR AND BEARING	12/67
	0.1182	0.2559	0.2560	0.0302	3,670	121,300	12,400	118,600	COMBINED SHEAR AND BEARING	
BORON/NARMCO 5505 AlN-Al_2O_3 WHISKERS AT 2% OF RESIN WEIGHT 0°/45°/-45°/0°	0.1200	0.2610	0.2610	0.0313	4,200	134,100	14,000	79,500	BEARING	
	0.1200	0.2610	0.2570	0.0308	4,050	131,500	13,500	98,800	BEARING	7/67
	0.1200	0.2630	0.2630	0.0315	3,660	—	—	85,000	SHEAR (AT ½ DIAMETER LOADING PIN)	
	0.1163	0.2570	0.2560	0.0298	3,860	129,500	13,300	124,000	SHEAR-OUT	
	0.1163	0.2564	0.2560	0.0298	3,775	126,600	13,000	117,200		12/68
	0.1170	0.2560	0.2550	0.0298	4,040	135,500	13,800	115,400		

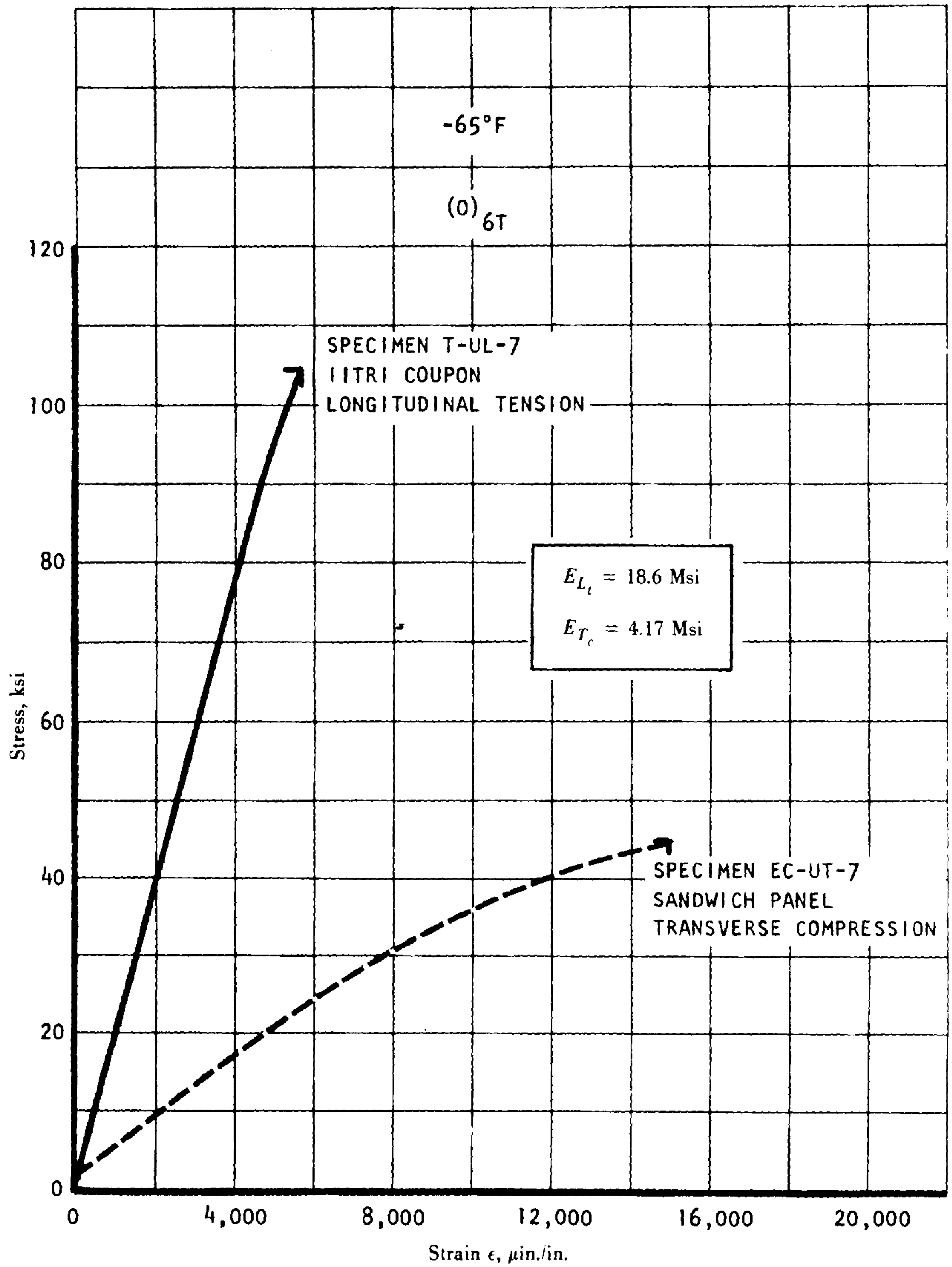


Figure 3-1. Unidirectional Graphite/Epoxy (Type AS/3002-Batch) Longitudinal Tension and Transverse Compression Stress—Strain Curves at -65°F (Ref. 2)

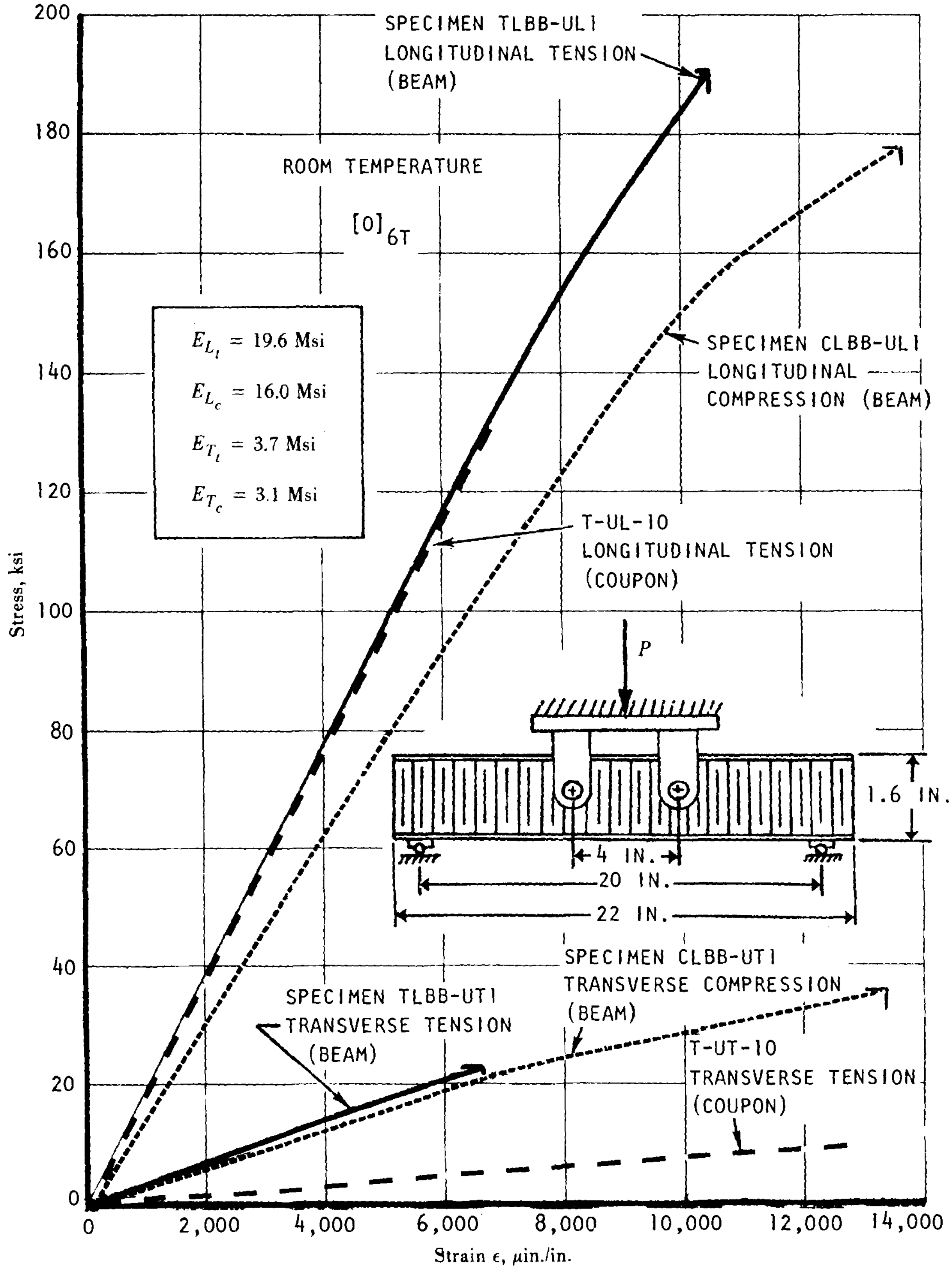


Figure 3-2. Unidirectional Graphite/Epoxy (Type AS/3002-Batch) Longitudinal and Transverse Tension and Compression Stress—Strain Curves at Room Temperature[2]

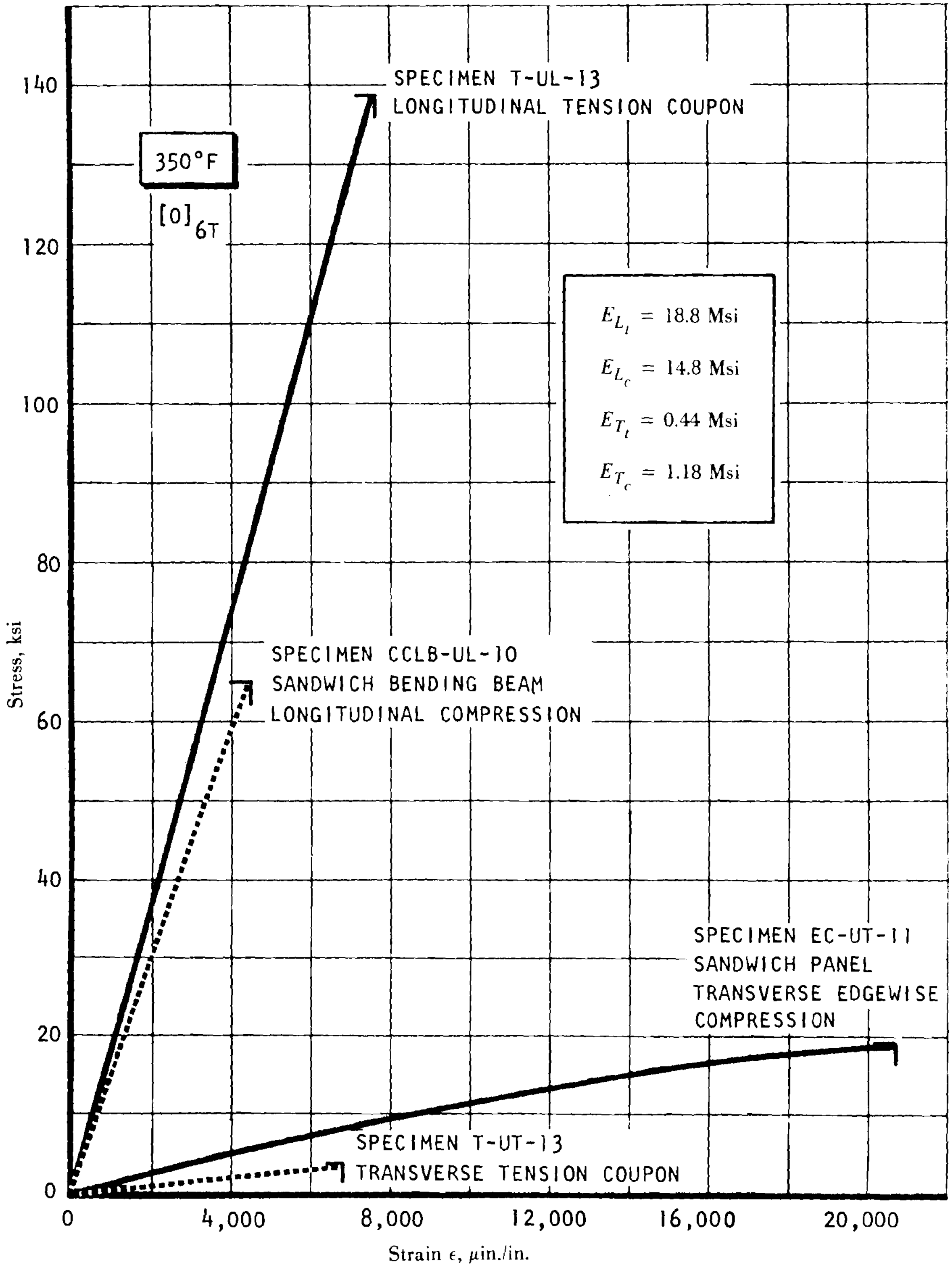
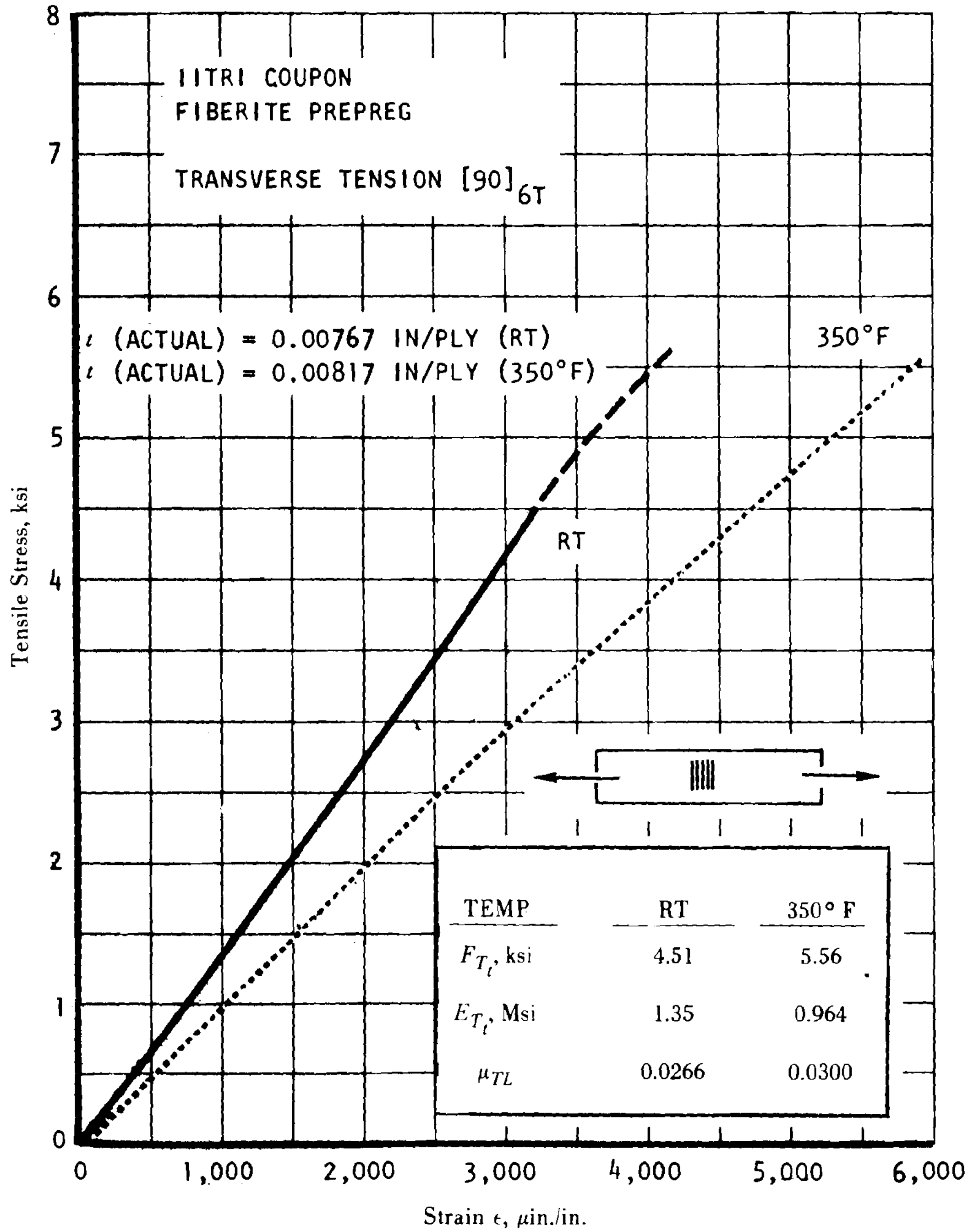


Figure 3-3. Unidirectional Graphite/Epoxy (Type AS/3002-Batch) Longitudinal and Transverse Tension and Compression Stress—Strain Curves at 350°F (Ref. 2)



TEMP	RT	350° F
F_{T_t}, ksi	4.51	5.56
E_{T_t}, Msi	1.35	0.964
μ_{TL}	0.0266	0.0300

Figure 3-4. Graphite/Epoxy Typical Transverse Unidirectional Tension Stress—Strain Properties (Type AS/3002 Continuous-Treated Fiber)[2]

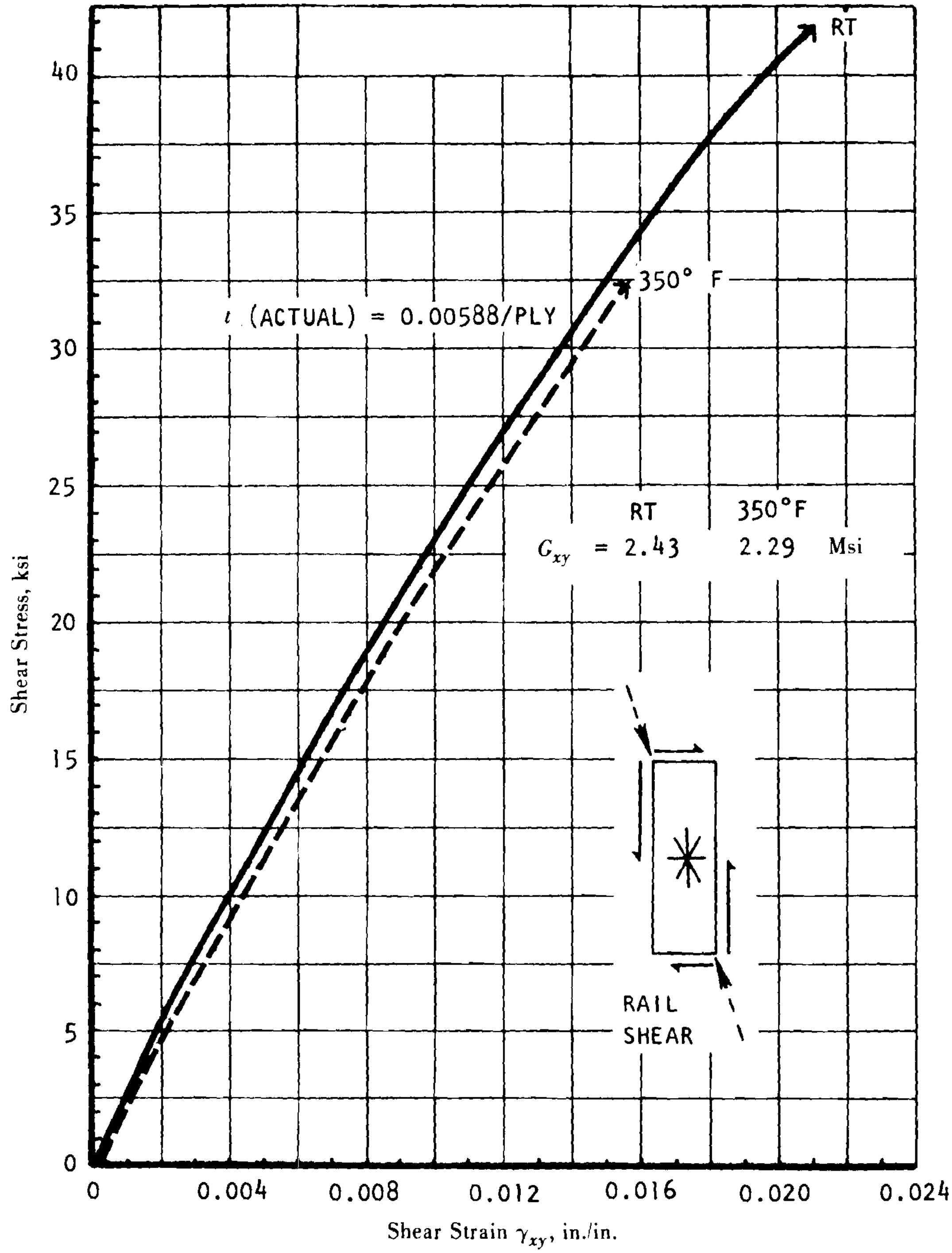


Figure 3-5. Graphite/Epoxy—In-Plane Shear Stress-Strain Properties—Crossply | 0/±45/90|s (Type A/3002 Batch—Untreated Fiber)[2]

3-3 MECHANICAL PROPERTIES OF ADHESIVES

The important mechanical properties to identify for an adhesive are Young's tensile modulus, shear modulus, precision elastic limit, and fracture stress in a joint. With regard to Young's modulus for an adhesive there needs to be resolved the difference between the tensile modulus of an adhesive in free bulk, free film, and constrained film (joint) form. Kutsha and Hofer[8] assumed that the tensile modulus obtained from

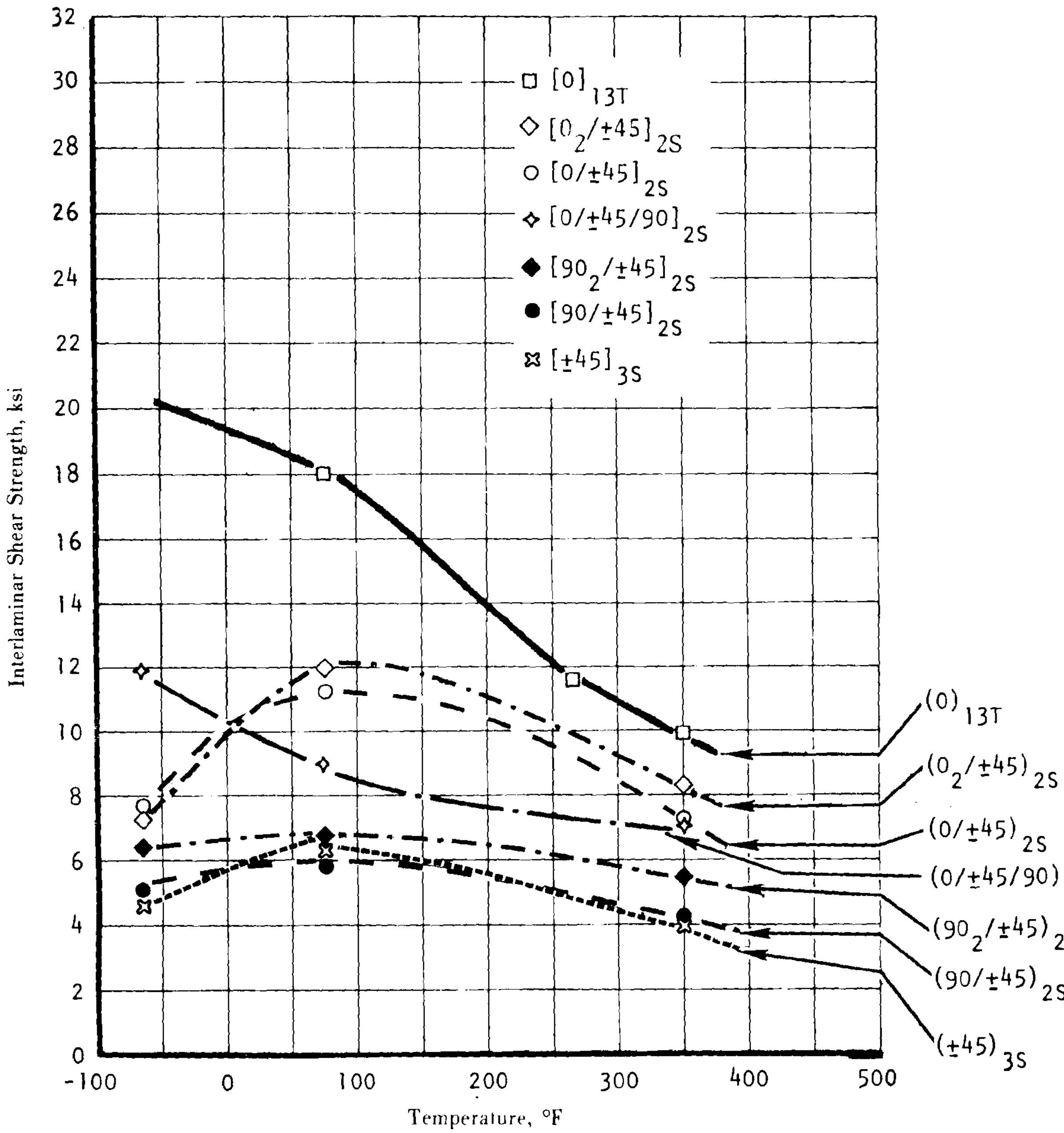


Figure 3-6. Interlaminar Shear Strength vs Temperature for Various Orientations—Type AS/3002, Batch, Graphite/Epoxy[2]

the behavior of adhesives in free film form could be used to characterize their general behavior. Table 3-7 summarizes the mechanical properties of several adhesives determined from tensile tests performed on adhesive films. Rutherford and Hughes[4] maintain that the important tensile modulus to determine is the effective tensile modulus E^*—the modulus of the adhesive in thin film form constrained between two adherends. In such a constrained state the adhesive cannot deform according to its own Poisson's ratio but conforms to that of the adherend which is generally lower. Such restriction effectively increases the tensile modulus. Tables 3-8 and 3-9, and Figs. 3-7 through 3-18 show the results of their work on several adhesives. In the case of Epon

TABLE 3-7
SUMMARY OF MECHANICAL PROPERTIES OF ADHESIVE FILMS[3]

Adhesive	Chemical Type Manufacturer	Tensile Strength, psi	Maximum Strain, %	Modulus, 10^5 psi	Deflection Rate, in./min
FM 1000	Polyamide Epoxy American Cyanamid, Bloomingdale Division	3400	>300	1.60	0.05
Metlbond 400	Nylon Epoxy Whittaker Corp. Narmco Materials Div.	7310	200	2.92	2.0*
AF 131	Modified Epoxy 3 M Co.	5300	1.15	4.82	0.05
FM 47	Vinyl Phenolic American Cyanamid, Bloomingdale Division	8300	1.50	6.21	0.5*

*No strain rate effect on modulus.

TABLE 3-8. AVERAGE SHEAR MICROSTRAIN PROPERTIES[4]

	EC-2214			ADX-41.2		
	−65°F	74°F	200°F	−67°F	74°F	350°F
Virgin Modulus, psi	301,300	280,000	137,900	267,000	189,000	29,500
Modulus After Stress, psi	296,300	216,300	125,000	201,600	140,500	25,700
Precision Elastic Limit, psi	434	115	<57	433	110	<38
Microyield Stress, psi	1250	390	<57	1734	290	<38
Fracture Stress, psi	12,904	7600	3996	4150	7400	3130
Fracture Strain	221.8×10^{-3}	206.5×10^{-3}	344.79×10^{-3}	28.64×10^{-3}	94.48×10^{-3}	525.0×10^{-3}

TABLE 3-9. AVERAGE TENSILE MICROSTRAIN PROPERTIES[4]

	EC-2214			ADX-41.2		
	−67°F	74°F	200°F	−67°F	74°F	300°F
Virgin Modulus, psi	1,623,300	1,120,000	416,900	963,300	800,800* 707,800**	332,400*
Modulus After Stress, psi	1,402,200	1,115,000	398,800	955,700	707,800**	261,400*
Precision Elastic Limit, psi	—	3750	102	3210	2790	78
Microyield Stress, psi	—	5360	153	3210	5870	118
Fracture Stress, psi	12,550	11,140	4060	15,826	9260	6300
Fracture Strain	12.63×10^{-3}	22.80×10^{-3}	90.5×10^{-3}	20.4×10^{-3}	17.54×10^{-3}	82.11×10^{-3}

*0.003 in. bond line
**0.012 in. bond line

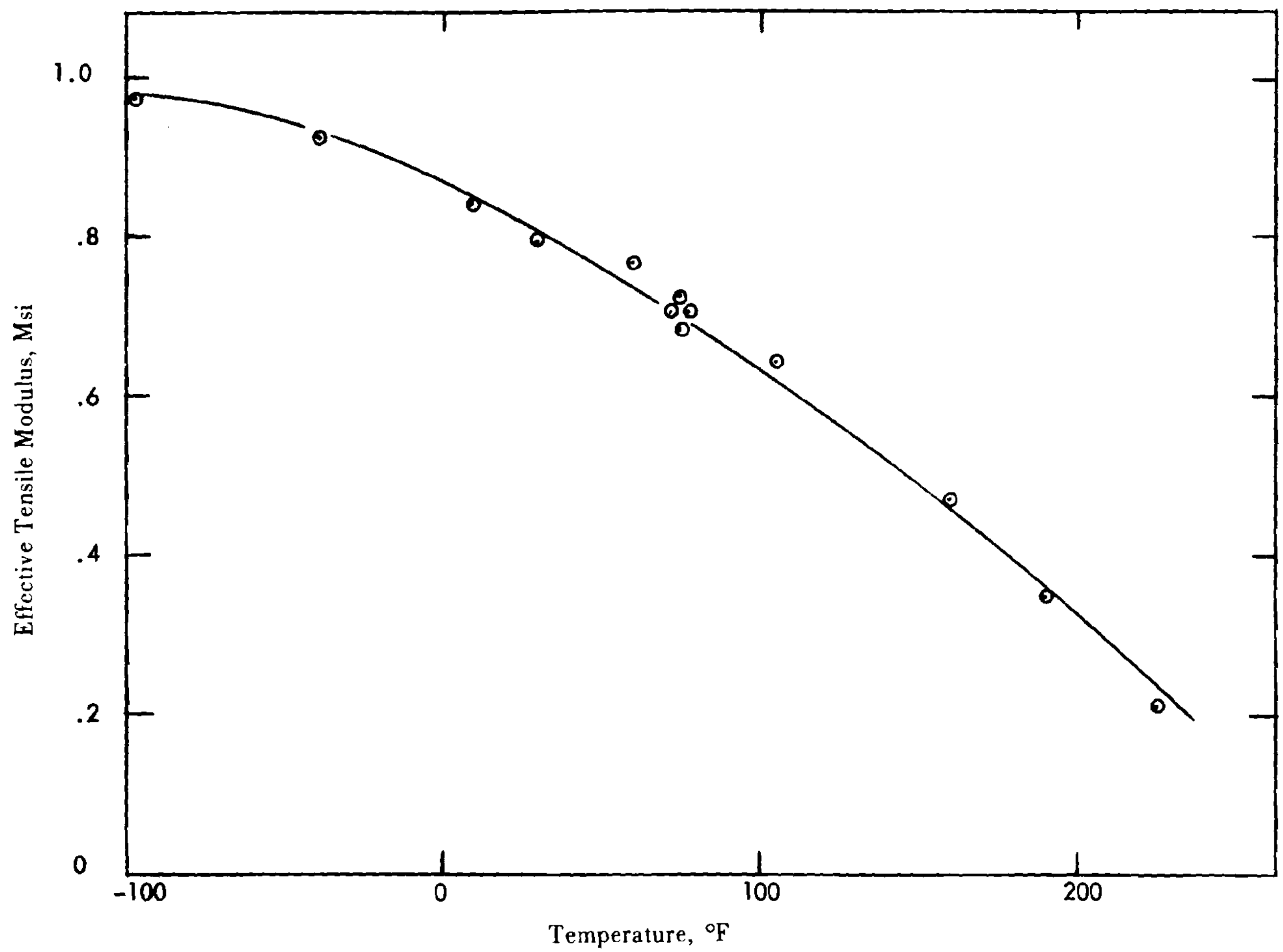


Figure 3-7. Tensile Tests, Epon 828/V40, Stainless Steel Adherends as a Function of Temperature[4]

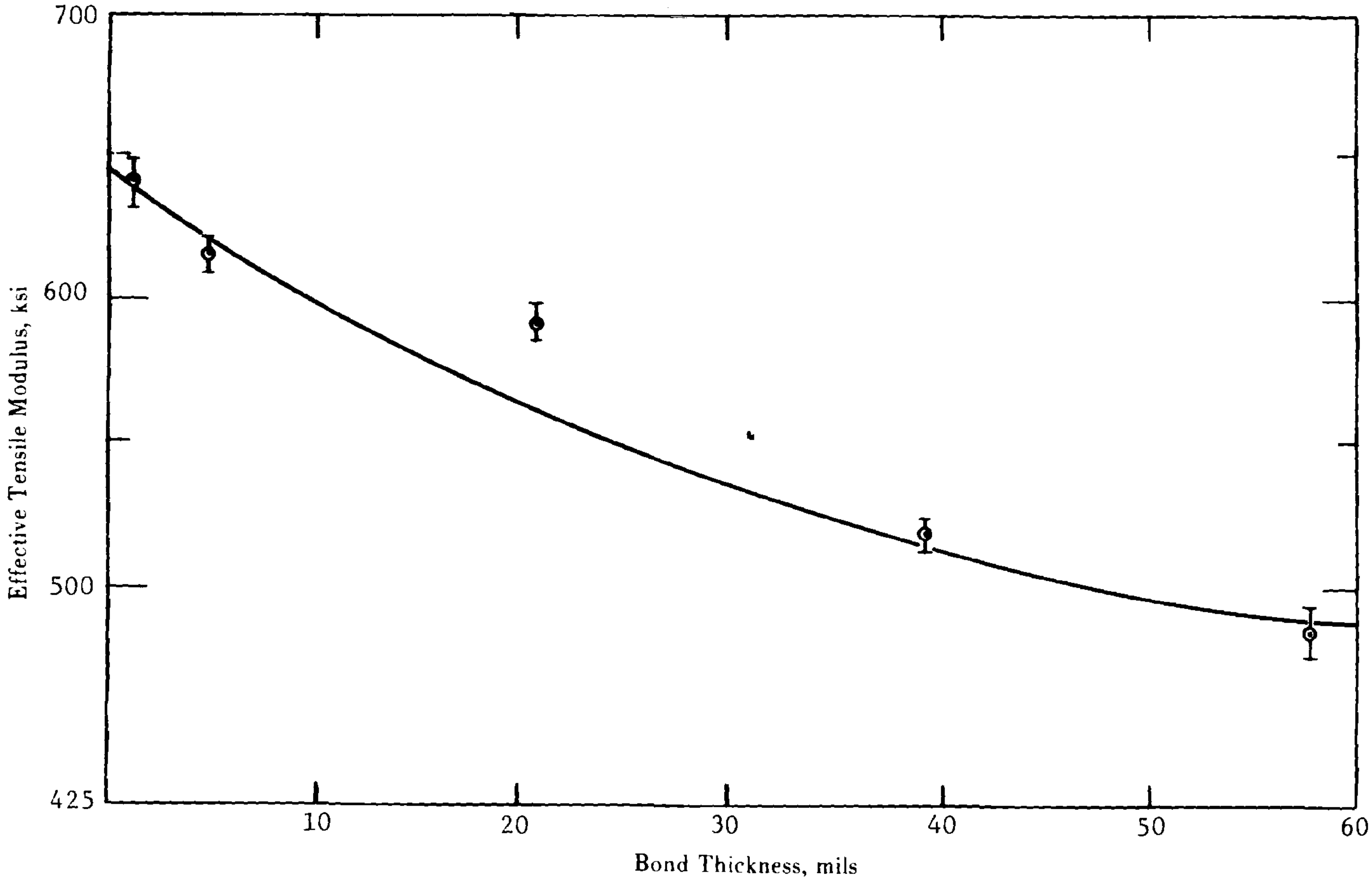


Figure 3-8. Tensile Tests, Epon 828/V40, Stainless Steel Adherends as a Function of Bond Thickness[4]

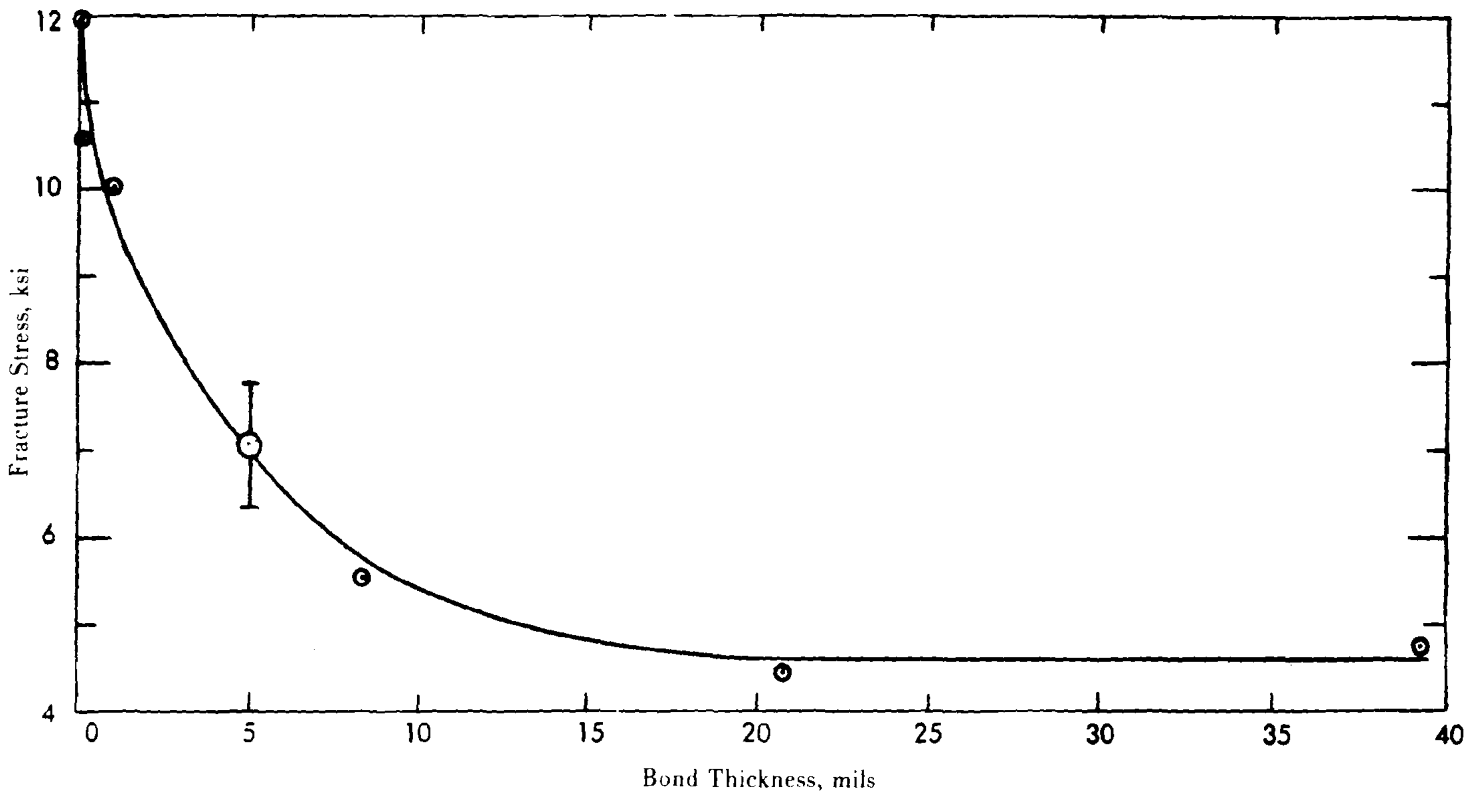


Figure 3-9. Tensile Tests, Epon 828/V40, Stainless Steel Adherends[4]

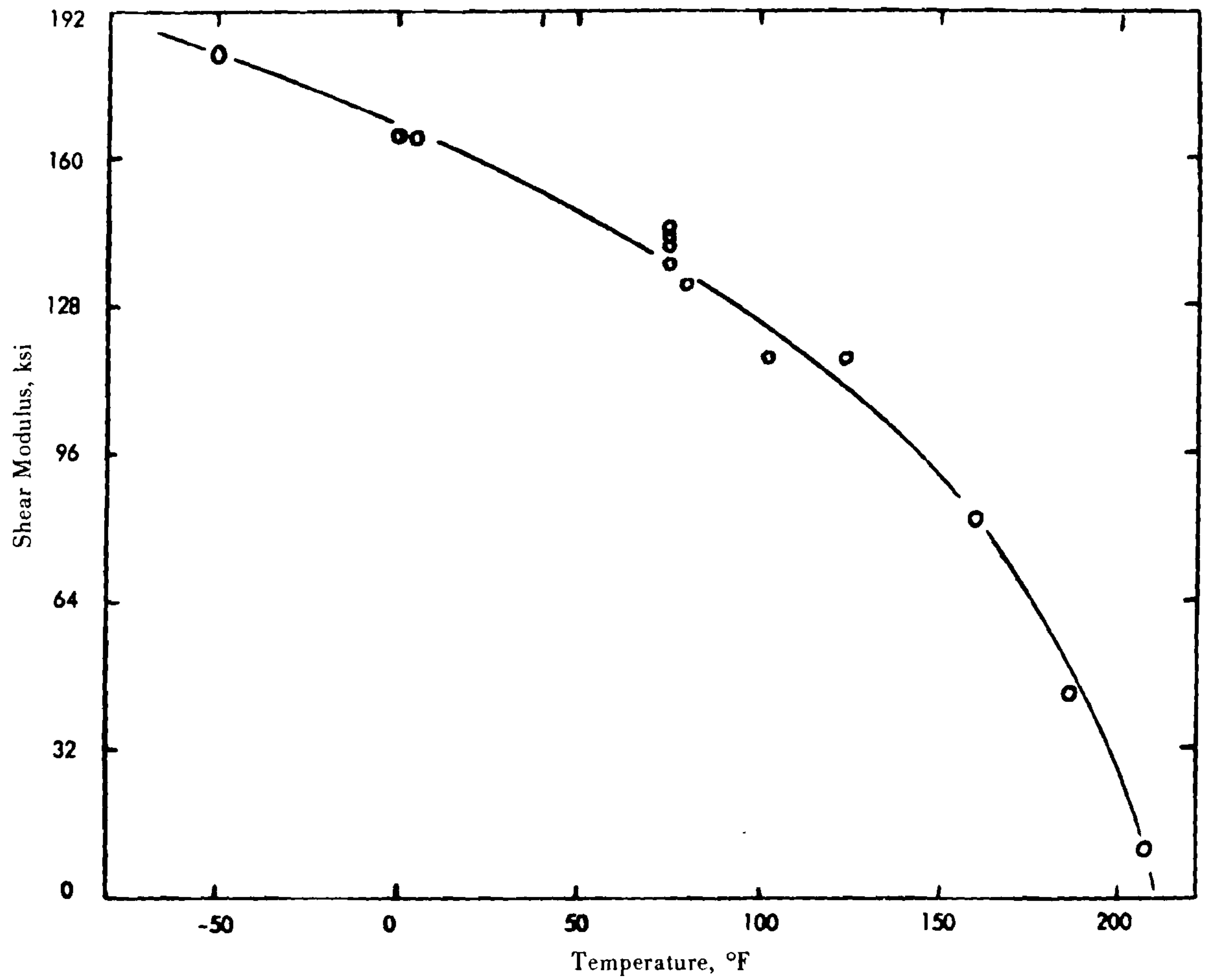


Figure 3-10. Shear Tests, Epon 828/V40, Stainless Steel Adherends[4]

828/V40 epoxy adhesive the effective tensile modulus in a stainless steel joint is nearly twice the bulk tensile modulus. Generation of this type of effective mechanical data is essential to reliable joint design data input. Table 3-10 presents data on some additional adhesives.

The tensile property data are obtained by the tensile testing of films or cast coupons of adhesive. The effective tensile property data are yielded by circular butt tensile bonded joint specimens. The shear modulus G is obtained from napkin or torsion ring tests which provide the stress-strain behavior of the adhesive in pure shear. The shear properties of several adhesives are presented in Tables 3-8 and 3-10 and Figs. 3-10, 3-15, and 3-17. Hughes concludes the following regarding the tensile modulus of the adhesives tested:

1. E^* increases as bond line thickness decreases.
2. E^* generally decreases with rising temperature.
3. Permanent adhesive strain lowers E^*.
4. Increasing the strain rate for viscoelastic adhesives raises E^*.
5. Tensile and compressive moduli are the same.

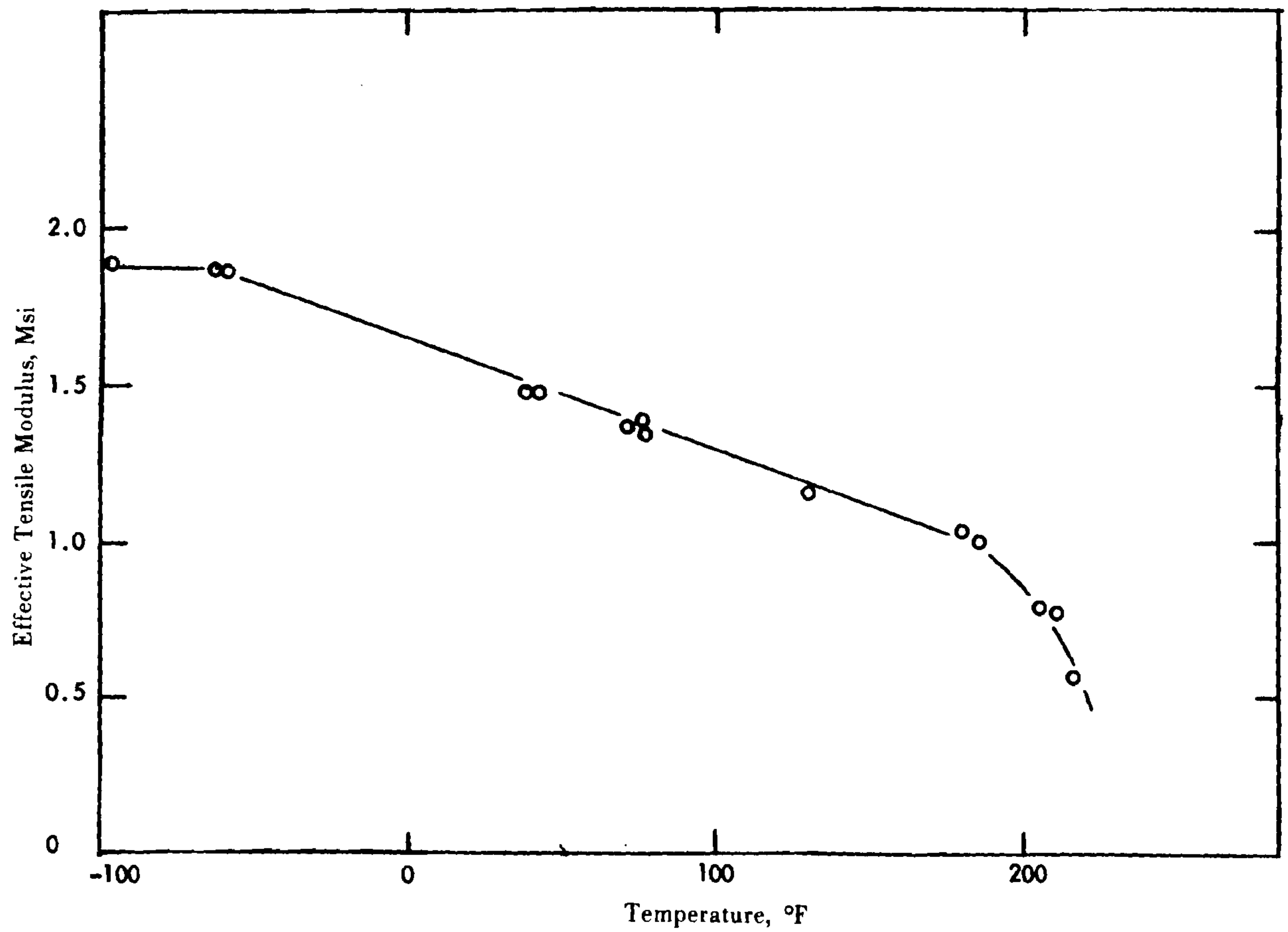


Figure 3-11. Tensile Tests, EC2214, Stainless Steel Adherends as a Function of Temperature[4]

Hughes concludes the following regarding the shear modulus G of the adhesive tested:

1. G decreases with rising temperature.
2. Permanent adhesive strain lowers G.
3. Increasing the strain rate increases G.
4. G is independent of adhesive thickness between 4 and 40 mils.

It is clear therefore that the conditions under which shear and tensile modulus are obtained for a given adhesive adherend system can alter their values and must be taken into consideration.

3-4 DESIGN DATA GENERATION

Although there are much published data on the mechanical properties of composites and adhesives, it will always be necessary to conduct tests on specific composite fiber orientations and on adhesives under the special environmental conditions in which a design is to provide service. Published graphical or tabulated data representations are useful primarily as a starting point for the designer but the data represented and the manner of generation may not be directly applicable to a given design. Testing for materials acceptance is also a requirement. The data obtained for a given property are a function of the test specimen configuration and the test method employed. The paragraphs that follow discuss some test methods and the type of data they yield.

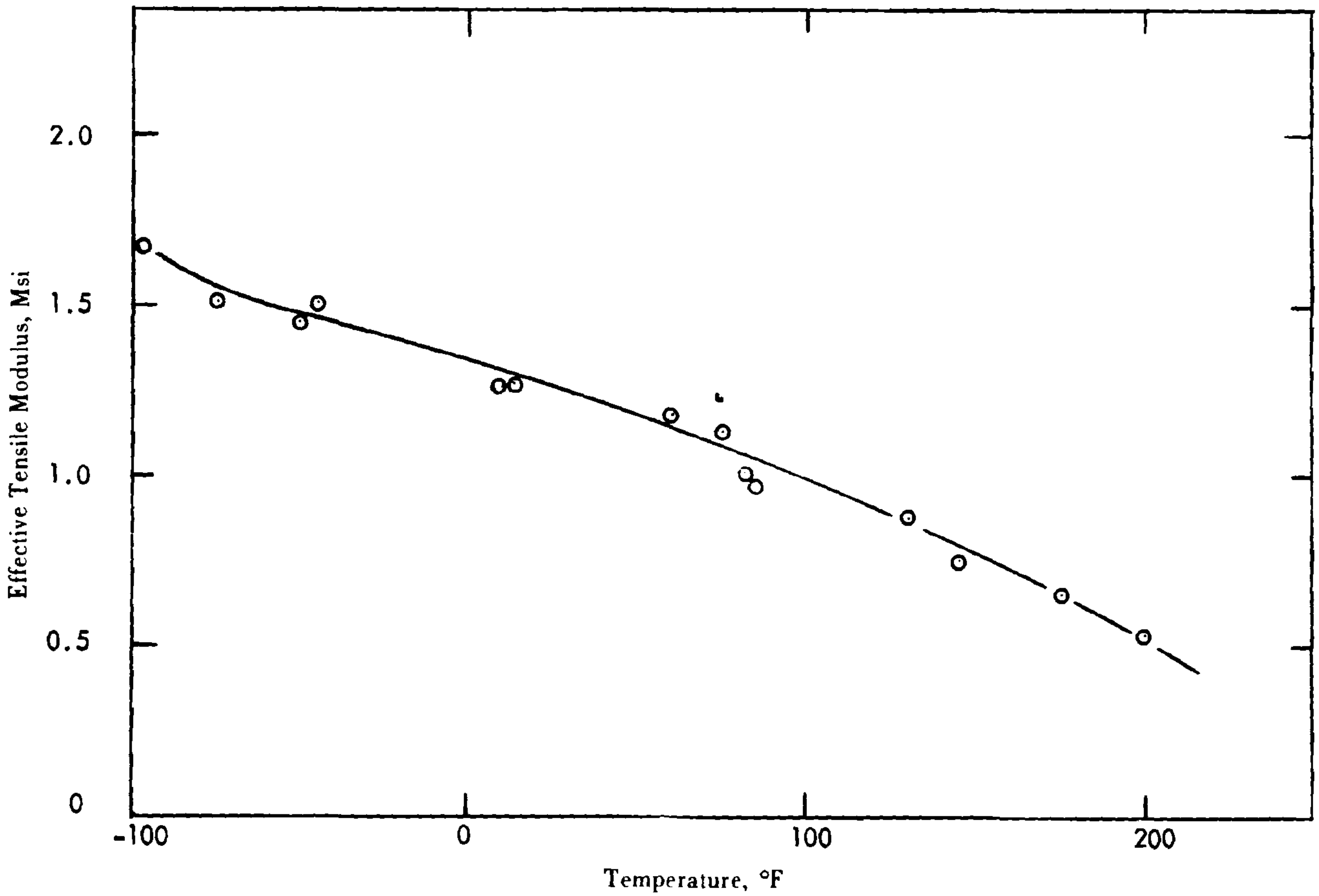


Figure 3-12. Tensile Tests, EC2214, Aluminum Adherends[4]

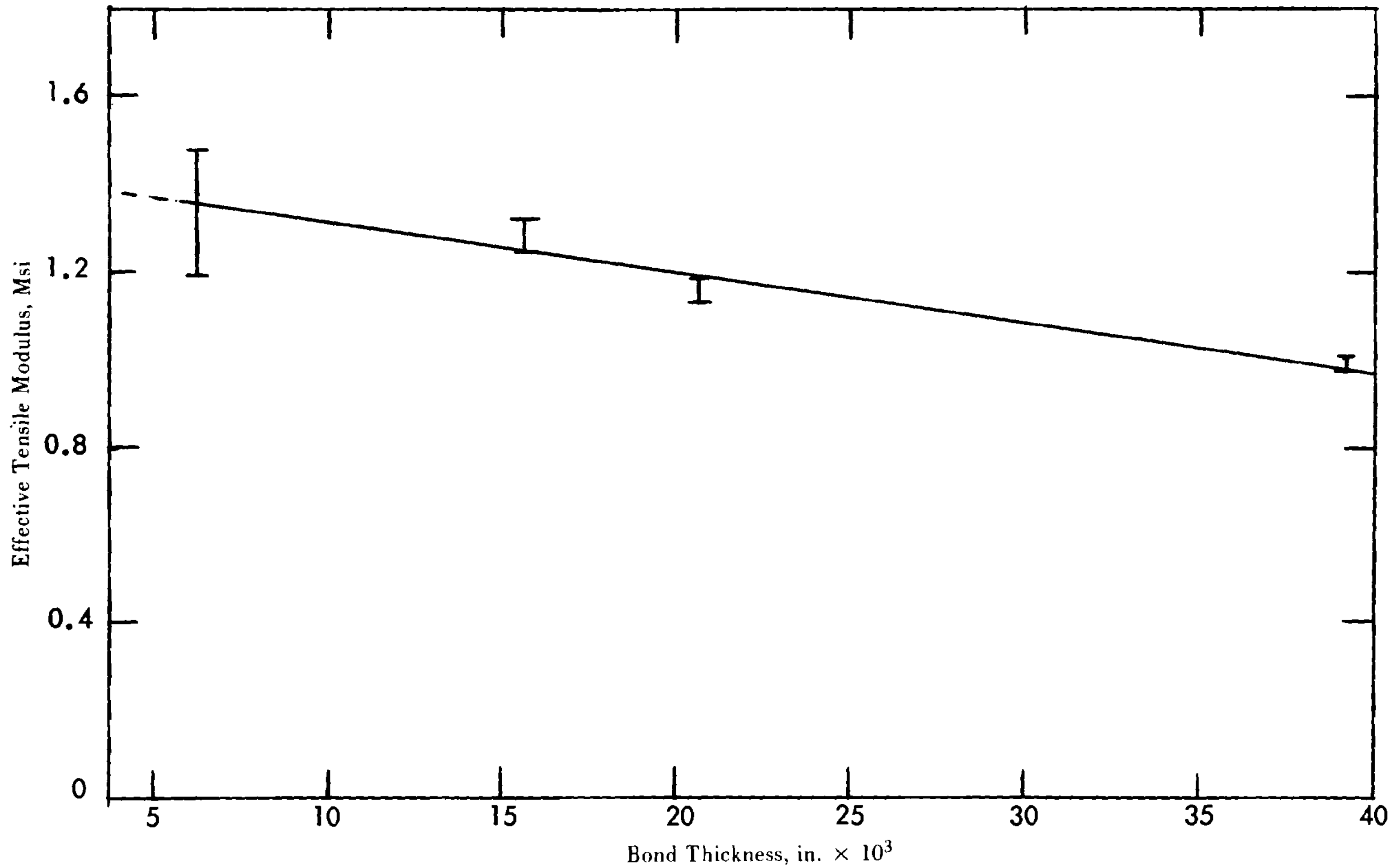


Figure 3-13. Tensile Tests, EC2214, Stainless Steel Adherends as a Function of Bond Thickness[4]

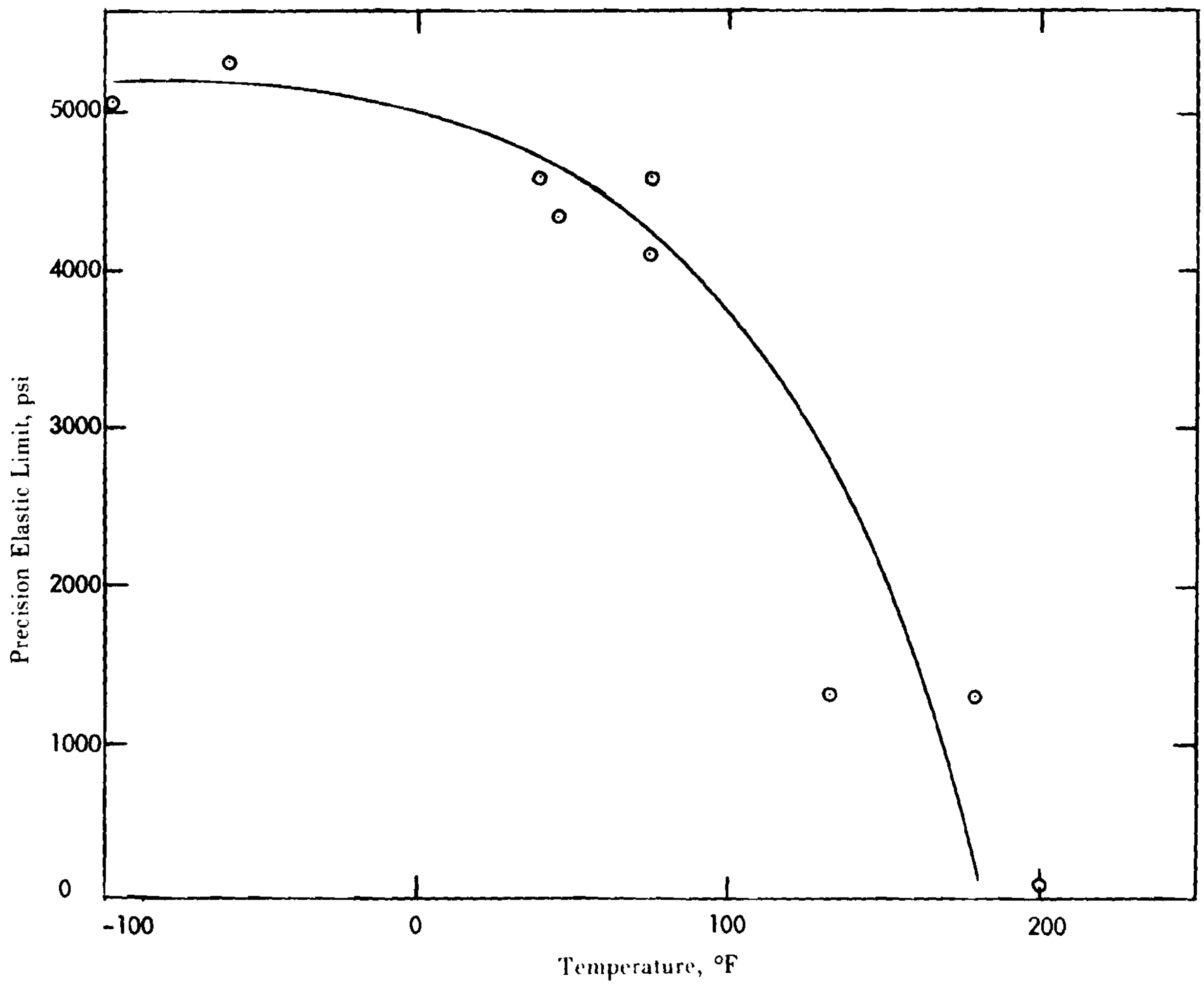


Figure 3-14. Tensile Tests, EC2214, Stainless Steel Adherends[4]

3-4.1 COMPOSITE MECHANICAL PROPERTY TESTS

3-4.1.1 Tension Properties

The properties of laminates in tension are usually determined either from tension coupons or sandwich bending beams. The tension coupons are either the dog bone type used in ASTM D638 Type 1, or a tab-ended, straight-sided specimen or a modified bow tie (long-necked) specimen. For military applications a modified ASTM D638 *Tensile Properties of Plastics* is to be employed (Ref. 5) for woven fabric (bi-directional) laminates. For nonwoven (directional) laminates ASTM D-3039 *Tensile Properties of Oriented Fiber Composites* is the method called for with modifications (Ref. 5). The specimen employed is commonly referred to as the IITRI (Illinois Institute of Technology Research Institute) coupon.

Another means of obtaining tension property data employs the sandwich bending beam (Fig. 3-19). The sandwich bending beam method is a more expensive method because of the nature of the specimen but the higher strengths obtained with the sandwich beam indicate that the localized stress concentrations inherent in the IITRI coupon serve to yield lower strength data. Figs. 3-1 through 3-3 present tension stress-strain data for Type AS/3002 from both IITRI coupon and sandwich bending beam tests.

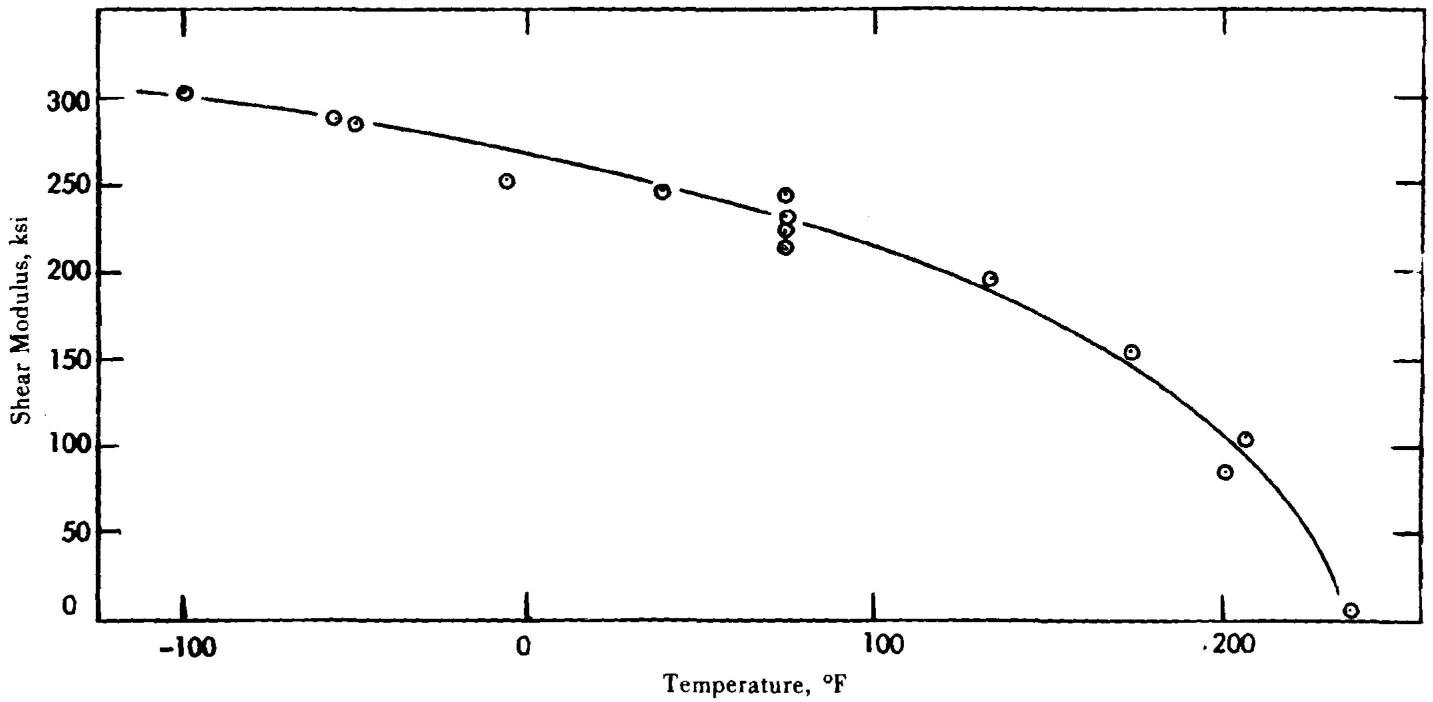


Figure 3-15. Shear Tests, EC2214, Aluminum Adherends[4]

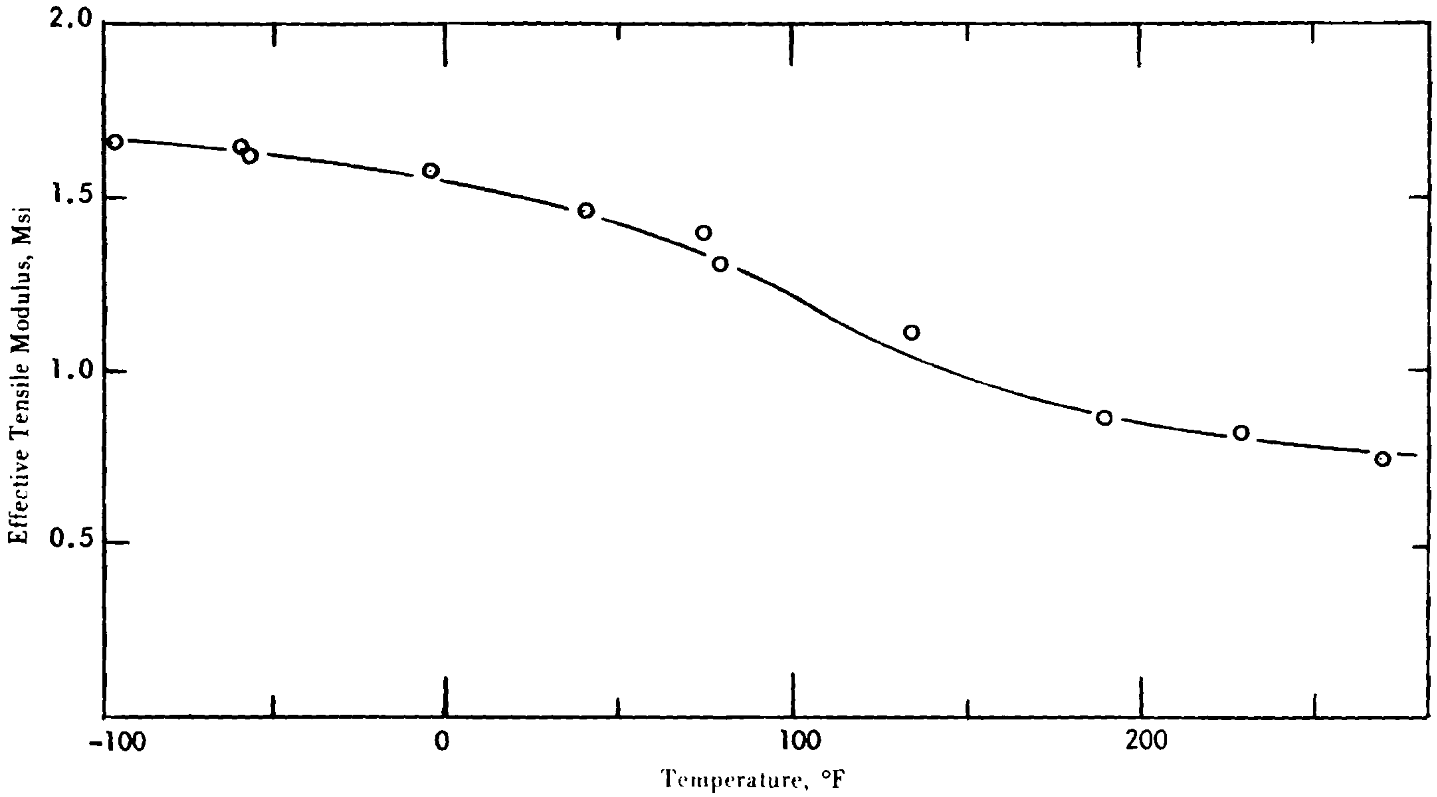


Figure 3-16. Tensile Tests, Metlbond 329, Aluminum Adherends[4]

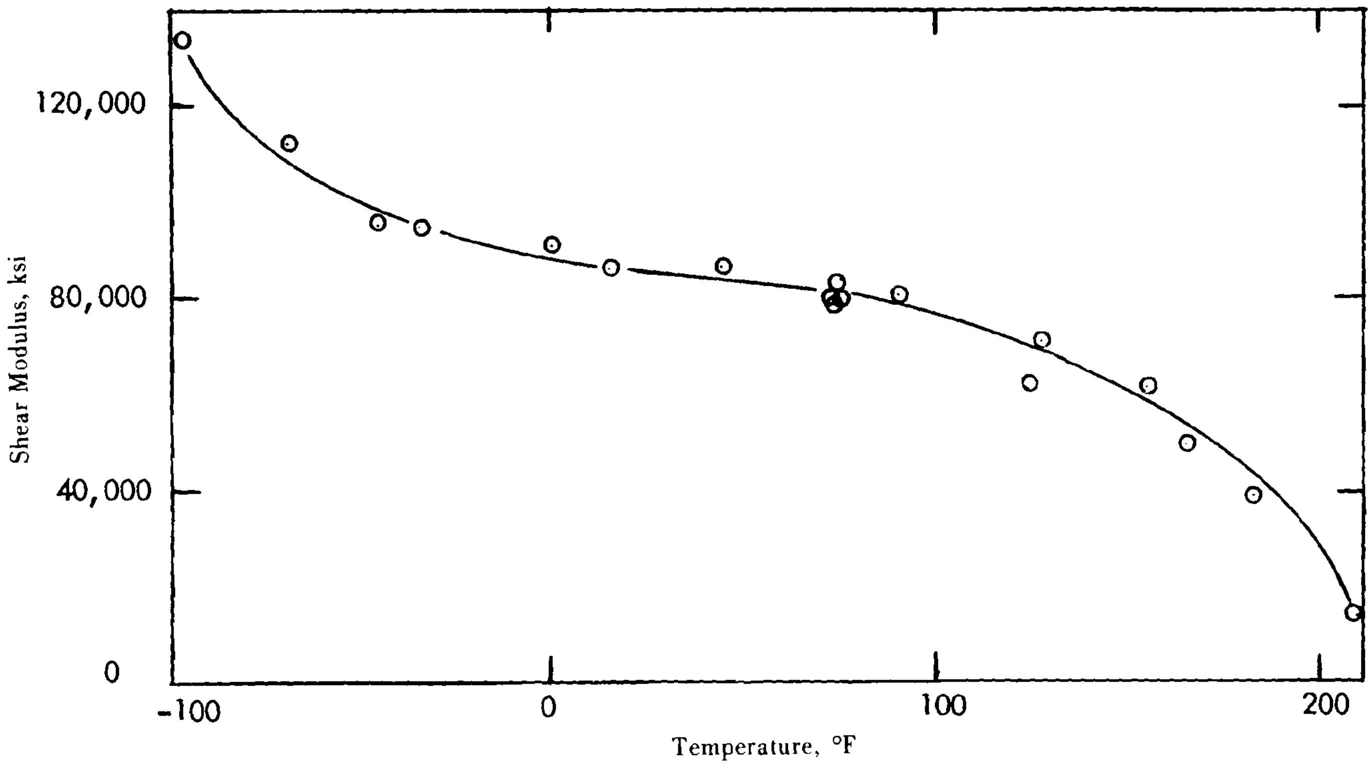


Figure 3-17. Shear Tests, Epon 9601, Aluminum Adherends[4]

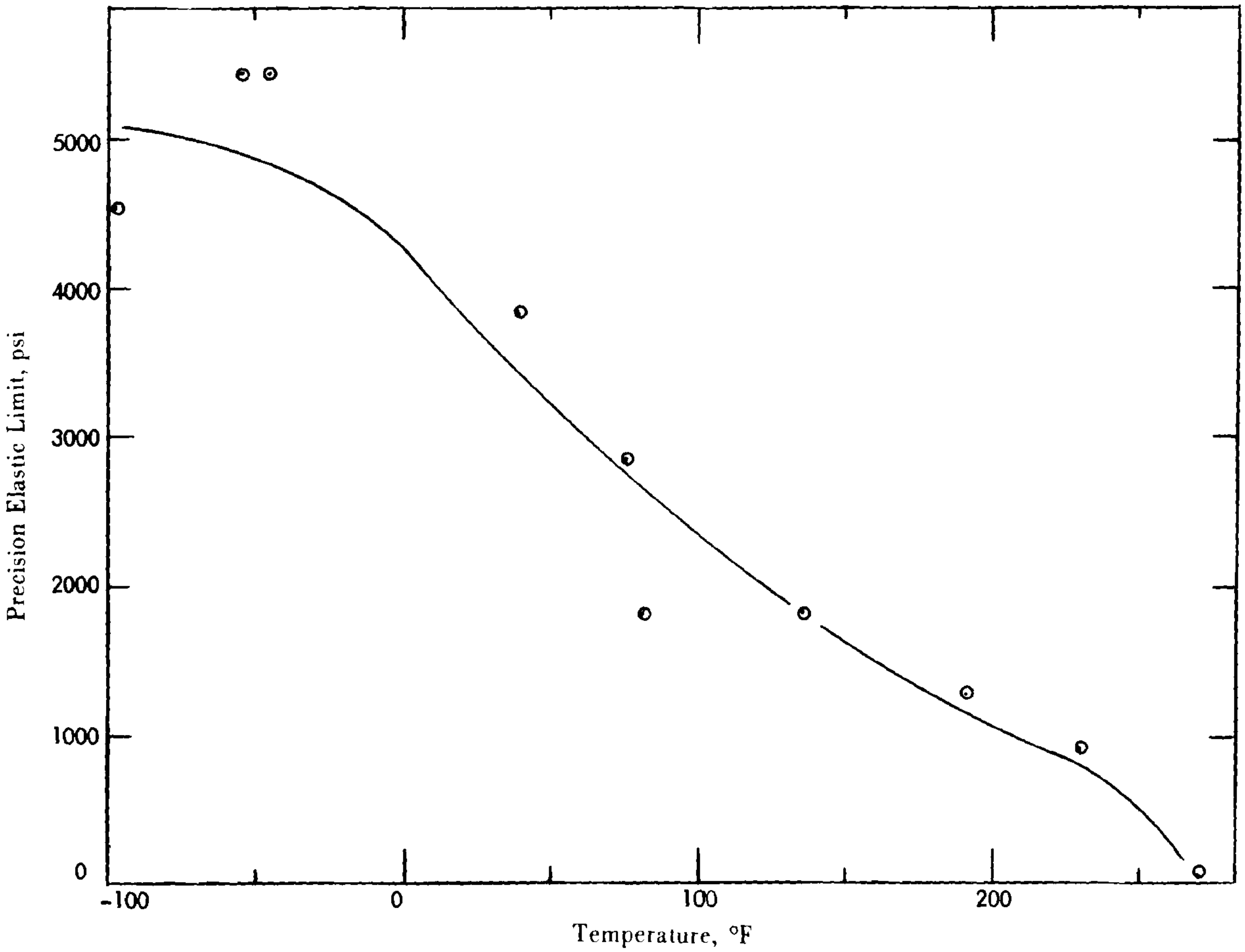


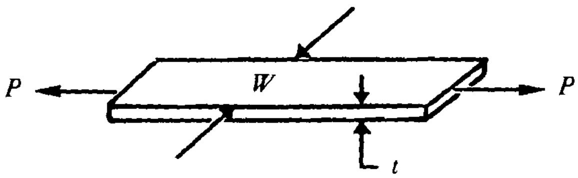
Figure 3-18. Tensile Tests, Metlbond 329, Aluminum Adherends[4]

TABLE 3-10. ELASTIC PROPERTIES OF ADHESIVES[1]

MATERIAL	E, psi	G, psi	μ	τ, psi	σ, psi	SOURCE
AF-110 (MOD-EP)	123,478	—	—	--	9258	3M COMPANY
REDUX K-6 (MOD-PH)	500,000	184,000	0.360	8200	8300	FPL-011
FM-47 (VINYL-PH)	325,000	117,000	0.385	3720	4350	FPL-011
MB-408 (NY-EP)	139,000	49,300	0.410	5550	8000	FPL-011
FM-1000 (NY-EP)	180,000	64,100	0.408	7930	6990	FPL-011
EPON 422J (EP-PH)	395,000	160,000	0.294	5520	2560	FPL-011
EPON VIII (EP-PA)	508,000	180,000	0.412	6050	—	FPL-011

MOD-EP = MODIFIED EPOXY
MOD-PH = MODIFIED PHENOLIC
PH = PHENOLIC
NY = NYLON
EP = EPOXY
PA = PASTE

FPL = FOREST PRODUCTS LAB
E = MODULUS OF ELASTICITY
G = MODULUS OF RIGIDITY
μ = POISSON'S RATIO
τ = PURE SHEAR STRENGTH
σ = PURE TENSILE STRENGTH



E = tensile stress/tensile strain = f/ϵ, psi

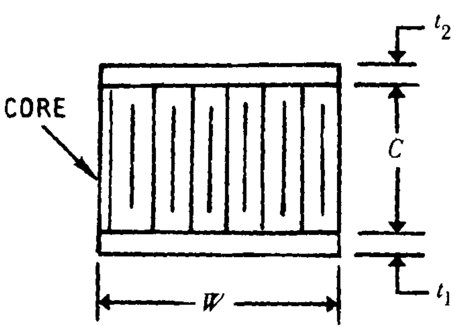
$f^{tu} = P/(Wt)$, psi

where

f^{tu} = ultimate tensile strength, psi
P = failure load, lb
W = coupon width, in.
E = elastic modulus, psi
f = tensile stress, psi
ϵ = tensile strain, in./in.

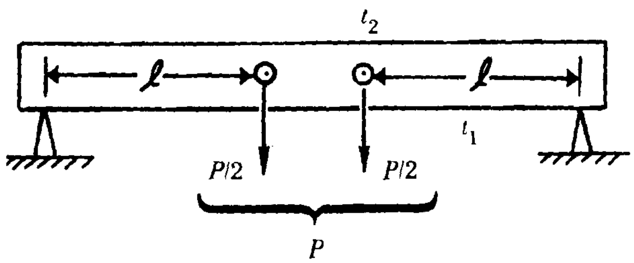
(A) Tension Coupons

(1) Tension Test:



$$f^{tu} = \frac{P\ell}{2t_1 W\left(C + \frac{t_1}{2} + \frac{t_2}{2}\right)}, \text{ psi}$$

(2) Compression Test:



$$f^{cu} = \frac{P\ell}{2t_2 W\left(C + \frac{t_1}{2} + \frac{t_2}{2}\right)}, \text{ psi}$$

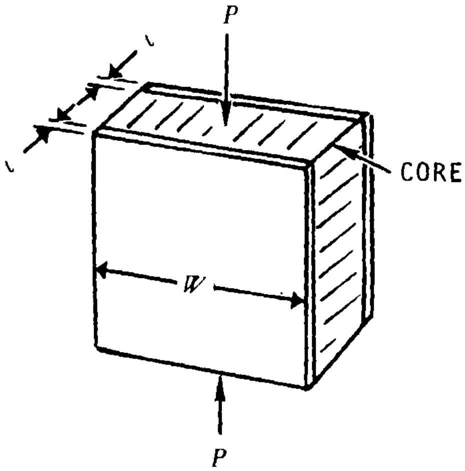
where

f^{tu} = ultimate tensile strength, psi
f^{cu} = ultimate compressive strength, psi
t_1, t_2 = laminate thickness, in.
C = core thickness, in.
W = width, in.
P = failure load, lb
ℓ = length between fulcrum and load, in.

(B) Sandwich Bending Beams

(cont'd on next page)

Figure 3-19. Reduction of Equations for Different Types of Specimens Tested



G = shear stress/shear strain = f^s/γ = psi

f^{cu} = $P/(Wt)$, psi

where

G = shear modulus, psi

f^{cu} = ultimate shear strength, psi

P = failure load, lb

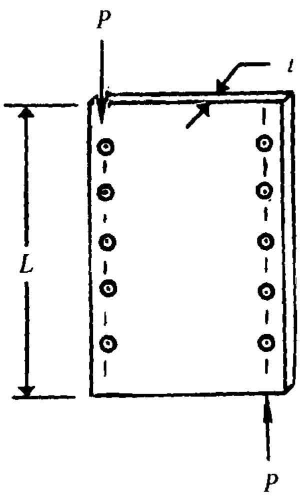
W = width, in.

t = laminate, thickness

f^s = shear stress, psi

γ = shear strain, in./in.

(C) Edgewise Compression Specimens



G = shear stress/shear strain = f^s/γ = psi

f^{su} = $P/(Lt)$, psi

where

G = shear modulus, psi

f^{su} = ultimate shear strength, psi

f^s = shear stress, psi

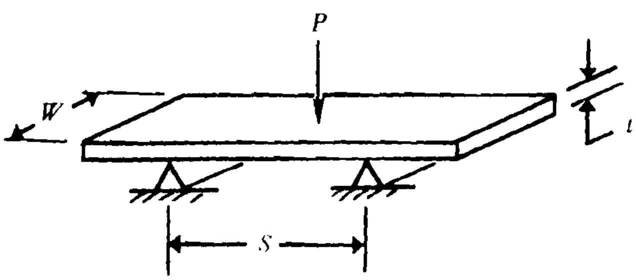
γ = shear strain, in./in.

P = failure load, lb

L = length, in.

t = laminate thickness, in.

(D) Rail Shear Specimens



f^{isu} = $3P/(4Wt)$, psi

where

f^{isu} = interlaminar shear strength, psi

P = failure load, lb

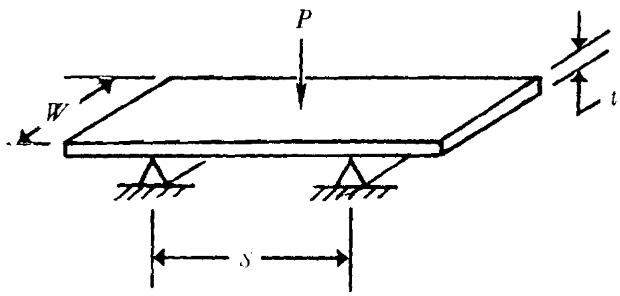
W = width, in.

t = laminate thickness, in.

(E) Interlaminar Shear Specimens

(cont'd on next page)

Figure 3-19. (cont'd)



$$f^{flex\ ult} = 3PS/(2Wt^2),\ \text{psi}$$

where

$f^{flex\ ult}$ = ultimate flexural strength, psi
P = failure load, lb
S = distance between fulcrums, in.
W = width, in.
t = laminate thickness, in.

(F) Flexure Specimens

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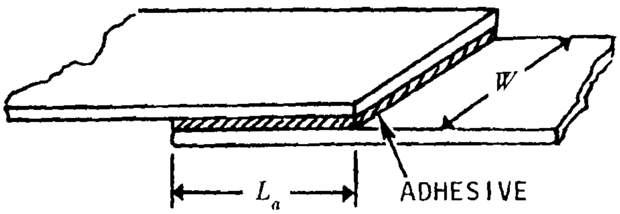
(1) Single-Lap Joints:

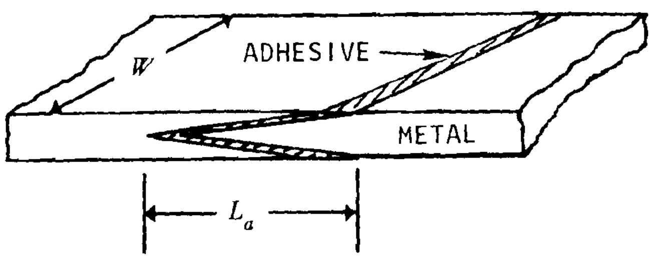


$$f_a^{su} = P/(WL_a),\ \text{psi}$$

NOTE: For compression sandwich specimens, there were two face sheets (one per face joint) and, hence, the equation must be divided by 2, i.e.,

$$f_a^{su} = P/(2WL_a),\ \text{psi}$$

(2) Symmetric Double Scarf Joint:



$$f_a^{su} = P/(2WL_a),\ \text{psi}$$

NOTE: For compression sandwich specimens, there were two face sheets (one joint per face sheet) and, hence, the equation must be divided by 2, i.e.,

$$f_a^{su} = P/(4WL_a),\ \text{psi}$$

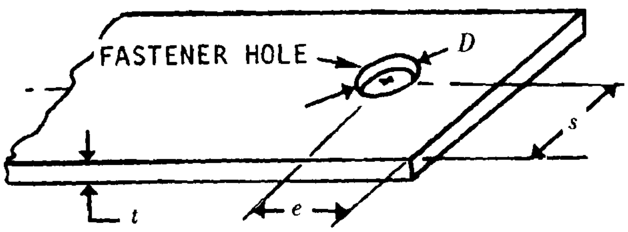
(cont'd on next page)

Figure 3-19. (cont'd)

where

f_a^{su} = ultimate shear strength of adhesive joint, psi
P = failure load, lb
W = width, in.
L_a = length of adhesive joint, in.

(G) Bonded Joints (Adhesive Shear Strength)



(1) Bearing Strength:

$$f^{bru} = P/(Dt), \text{ psi}$$

(2) Net Tension Strength:

$$f^{tu} = \frac{P}{2Dt\left(\frac{s}{D} - 0.5\right)}, \text{ psi}$$

(3) Shear-Out Strength:

$$f^{su} = \frac{P}{2Dt\left(\frac{e}{D} - 0.5\right)}, \text{ psi}$$

NOTE: Compression mechanical joints all failed in bearing; hence, bearing strength is defined as

$$f^{bru} = P/(DtN), \text{ psi}$$

(cont'd on next page)

Figure 3-19. (cont'd)

where

f^{bru} = ultimate bearing strength, psi
f^{tu} = ultimate tensile strength, psi
f^{su} = shear-out strength, psi
P = load for appropriate failure mode, lb
t = laminate thickness, in.
D = bolt hole diameter, in.
e = distance from edge of bolted joint to center of bolt hole, in.
s = distance from side of bolted joint to center of bolt hole, in.
N = number of fasteners, dimensionless

(H) Mechanical Joint

Figure 3-19. (cont'd)

3-4.1.2 Compression Properties

Compression data should be obtained by the sandwich bending beam method (Ref. 5) for nonwoven laminates tested in the direction of the fibers (0-deg orientation). Woven fabric laminates tested in the 0-deg or 90-deg direction, and nonwoven laminates tested in the 90-deg direction should be tested in accordance with ASTM D695 *Compressive Properties of Rigid Plastics* with modifications as outlined in Ref. 5.

Another method uses a tubular specimen, as described in Ref. 1, to generate the compression data on glass and boron composites presented in Table 3-3.

3-4.1.3 Intralaminar Shear Properties (In-Plane Shear)

These properties are obtained by the use of the "rail shear test" (Ref. 5) for any angle for which shear characteristics are desired. Ultimate shear stress f^{su} is determined as follows:

$$f^{su} = \frac{P}{\ell t}, \text{psi} \qquad (3\text{-}1)$$

where

P = load on the rails, lb
ℓ = length of specimen, in.
t = thickness of specimen, in.

The shear modulus is obtained as follows:

$$G = \frac{\text{shear stress}}{\text{shear strain}} = \frac{f^s}{\gamma}, \text{psi} \qquad (3\text{-}2)$$

3-4.1.4 Interlaminar Shear Properties

These properties have been determined according to the method prescribed in ASTM D2733 *Interlaminar Shear Strength of Structural Reinforced Plastics at Elevated Temperatures*, Method A. However, for other reinforcements such as boron, graphite, and Kevlar, ASTM D2344 *Apparent Horizontal Shear Strength of Reinforced Plastic by the Short Beam Method* is recommended. It is suggested that the fiberglass reinforced composites be tested this way as well.

3-4.1.5 Flexural Properties of Laminates

These properties should be determined according to ASTM D790 *Flexural Properties of Plastics*. Like interlaminar shear, a simple beam specimen is used but the calculations differ as shown in Fig. 3-19.

3-4.1.6 Bearing Strength of Laminates

Bearing strength determinations should be conducted according to ASTM D953 *Bearing Strength of Plastics*.

3-4.1.7 Test Specimen Schematics and Data Reduction Equations

Fig. 3-19 depicts the specimens and equations to be used to obtain the materials property data needed for design.

3-4.2 SUMMARY

Variations on some of the tests discussed here have been used and the data they yield may be more representative of the material than the tests recommended. What is important is that the test method used be known and that the limitations and inherent imperfections in the test and resultant data be recognized. No single data source should be regarded as infallible or absolute. Tables 3-11 and 3-12 summarize the tests used and data yielded for both laminates and adhesives.

TABLE 3-11
LAMINATE PROPERTY DETERMINATION

Test Method	Data Yielded
Sandwich Beam	Tensile and Compressive Properties f^{tu}, f^{cu}, E_L, E_T
ASTM D3039 (IITRI Coupon)	Tensile Properties (nonwoven) F^{tu}, E_L, E_T
ASTM D638 (Long Bow Tie Coupon)	Tensile Properties (woven) f^{tu}, E_L, E_T
Tubular Compression	Compression Properties f^{cu}, E
Rail Shear	Intralaminar (in-plane) Shear f^{su}, G
ASTM D2733	Interlaminar Shear (fiberglass only) f^{ils}
ASTM D2344 (Short Beam)	Interlaminar Shear (fiberglass, boron, graphite, Kevlar) f^{isu}
ASTM D953 (Pin Bearing)	Bearing Strength f^{br}

TABLE 3-12
ADHESIVE PROPERTY DETERMINATION

Test Method	Data Yielded
Napkin Torsion Ring Test	Shear Properties f^{su}, G
Thick Adherend Lap Shear	Shear Properties f^{su}, G
Circular Butt Joint	Tensile Properties f^{tu}, E

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3. D. Kutscha and K. E. Hafer, *Feasibility of Joining Advance Composite Flight Vehicle Structures*, Tech Report AFML-TR-68-391, USAF Contract No. AF33 (615)-3962, Wright-Patterson Air Force Base, OH, January 1969.
4. E. J. Hughes and J. L. Rutherford, *Study of Micromechanical Properties of Adhesive Bonded Joints*, Picatinny Arsenal Tech Report 3744, Performed under contract DAAA 21-67-C-0500 by Aerospace Research Center, General Precision Systems, Inc., Little Falls, NJ, August 1968.
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CHAPTER 4
BASIC BONDED AND BOLTED LAP JOINT CONFIGURATIONS AND DESIGN VARIATIONS

The design and strength of basic type joints — single lap, double lap, scarf, stepped, bolted, and combinations — are presented as functions of adhesives, fiber orientation, and fibers. Comparisons of joint strengths and weights are made. Methods of reducing stress concentration in joints are presented. The response of various bonds to fatigue are presented.

4-0 List of Symbols

D = bolt hole diameter, in.
e = distance from edge of bolted joint to center of bolt hole, in.
E = joint efficiency, dimensionless
= elastic modulus of adhesive, psi
E_L = elastic modulus of composite with fibers parallel (longitudinal) to direction of applied stress, psi
E_T = elastic modulus of composite with fibers perpendicular (transverse) to direction of applied stress, psi
E_1 = elastic modulus of composite, psi
E_2 = elastic modulus of joined material, psi
f^{br} = bearing strength, psi
f^{bru} = ultimate bearing strength, psi
f_a^s = shear strength of joint, psi
f_{max}^s = maximum shear strength of adhesive, assuming plastic shear stress distribution, psi
f^{su} = ultimate shear strength, psi
f^{tu} = ultimate tensile strength, psi
F_s = average stress, psi
G = shear modulus, psi
L_a = length of adhesive joint, in.
N = cycles to failure
P = applied load, lb
R = radius, in.
s = distance from side of bolted joint to center of bolt hole, in.
t_i = thickness of materials, i = 1, 2, ..., in.
W_c = maximum width of plastic zone of joint, in.
σ_A = tensile stress in region A, psi
σ_B = tensile stress in region B, psi
τ = shear stress in adhesive, psi
= shear stress at bond line, psi

4-1 GENERAL

Designing composite joints generally can follow the same priorities established for mechanical and bonded joints using isotropic materials. The relatively low shear strength of epoxy resin composites, however, make this property limiting in many composite joint designs — mechanical and bonded.

4-2 BONDED JOINTS

When designing a bonded joint, composite or otherwise, the bonded area should be as large as possible and as much of the bond area as possible should be working, i.e., transferring loads. This implies good strain compatibility between joint members and good stress distribution in the adhesive. The joint design should be stressed in the maximum strength mode which, for adhesives, is shear or tensile. Peel and cleavage stresses should be minimized. Good bonded joint design requires that the adherend materials, joint configuration, and load directions work toward the aforementioned aims. This serves to distribute stress and avoid stress concentrations, particularly at edges, which create peel and cleavage forces.

In selecting adhesives it is important to consider the rate at which the load is to be applied to the joint. When loads are applied suddenly, as impulse or impact loads are, the adhesive must be elastic enough to take shock loading without failing. Often there can be conflict in this area. Thermosetting adhesives, usually rigid and of high tensile and shear strength under static and dynamic loads, are often impact sensitive and exhibit poor impact strength. Elastomeric adhesives generally possess poor shear and tensile strength but have good peel and cleavage strength and can withstand shock loads. Sustained dead loading of bonded joints can cause creep of some adhesives, and this behavior must be ascertained to avoid creep weakening of and dimensional changes in the structure.

Bonded joint strength depends greatly on the properties of the adhesive but maximum strength is achieved when the relative stiffness of the adherends is the same. This situation provides a symmetric stress distribution and the best joint efficiency. For highly loaded joints, however, the ultimate shear strength of the adhesive alone (determined from torsional ring tests) is not a good criterion for adhesive selection. Where strain incompatibility exists in the adherends, a more ductile adhesive can improve joint strength.

To achieve strain compatibility in a joint comprised of two adherends of the same material, the thicknesses of both adherends must be equal. When bonding different adherend materials it is important to match adherend stiffness by matching the products of the elastic modulus E and thickness t, i.e., Et*, of the joined materials.

When large loads are required and length L to thickness t (L/t) ratios approach 25, the interlaminar shear strength of the laminate is limiting. For improved bonded joint capability, interlaminar shear strength improvements in the laminate must go hand in hand with improved adhesive shear strength.

4-2.1 BONDED SINGLE-LAP JOINTS

This type joint is the simplest of bonded joint configurations. In joints of this type the offset loading characteristics produce the highest stress concentration factor (SCF) and carry the least load at the center of the joint. Stiffness mismatch in the adherends will serve to further aggravate an already poor stress distribution situation in the joint. Fig. 4-1 shows this effect for several combinations of boron, glass, and aluminum joints using Shell 951 adhesive (shear stress in adhesive τ = 6000 psi). When the results fall along the τ = 6000-psi line, the adhesive is equalizing the shear stress over the entire area. As lap length increases, stress concentrations are set up at the lap ends causing failure at lower loads. Fig. 4-2 illustrates how increased Et ratio improves the average adhesive stress in the joint. (Pattern configurations are shown in Table 4-1.) The improvement is even more pronounced for larger L/t ratios. In addition, as lap length increases, peel stresses are introduced due to bending. The ability of the adhesive to equalize stresses over the joint area also becomes less as adherend materials are mixed ($E_1t_1 \neq E_2t_2$). When adherends are not of the same material, unfavorable thermal stresses can also be set up between adherends during adhesive cure which adversely affect joint strength. Table 4-2 summarizes some single-lap test results, using Shell 951 adhesive on boron/aluminum and fiberglass/aluminum joints.

4-2.2 BONDED DOUBLE-LAP JOINTS

The double-lap joint configuration eliminates much of the bending and peel stresses present in the single-lap joint. Fig. 4-3 and Table 4-3 show the results of boron/aluminum and glass/aluminum joints. It can be seen that for the boron/aluminum joints a higher average bond stress was realized probably due to the lower bending and peel forces. The same was not true for the glass/aluminum double-lap specimens.

The effect of stiffness matching in double-lap joints is clearly illustrated in Figs. 4-4 and 4-5. It is easily observed that as the Et ratio (smaller Et divided by larger Et) approaches unity, there was a general increase in joint strength. Table 4-4 summarizes test results for some composite/metal double-lap joints of varying Et ratios.

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*In subsequent discussions we will refer to "Et ratio" for convenience. The correct interpretation is "a ratio of Et's", i.e., $E_1t_1/(E_2t_2)$.

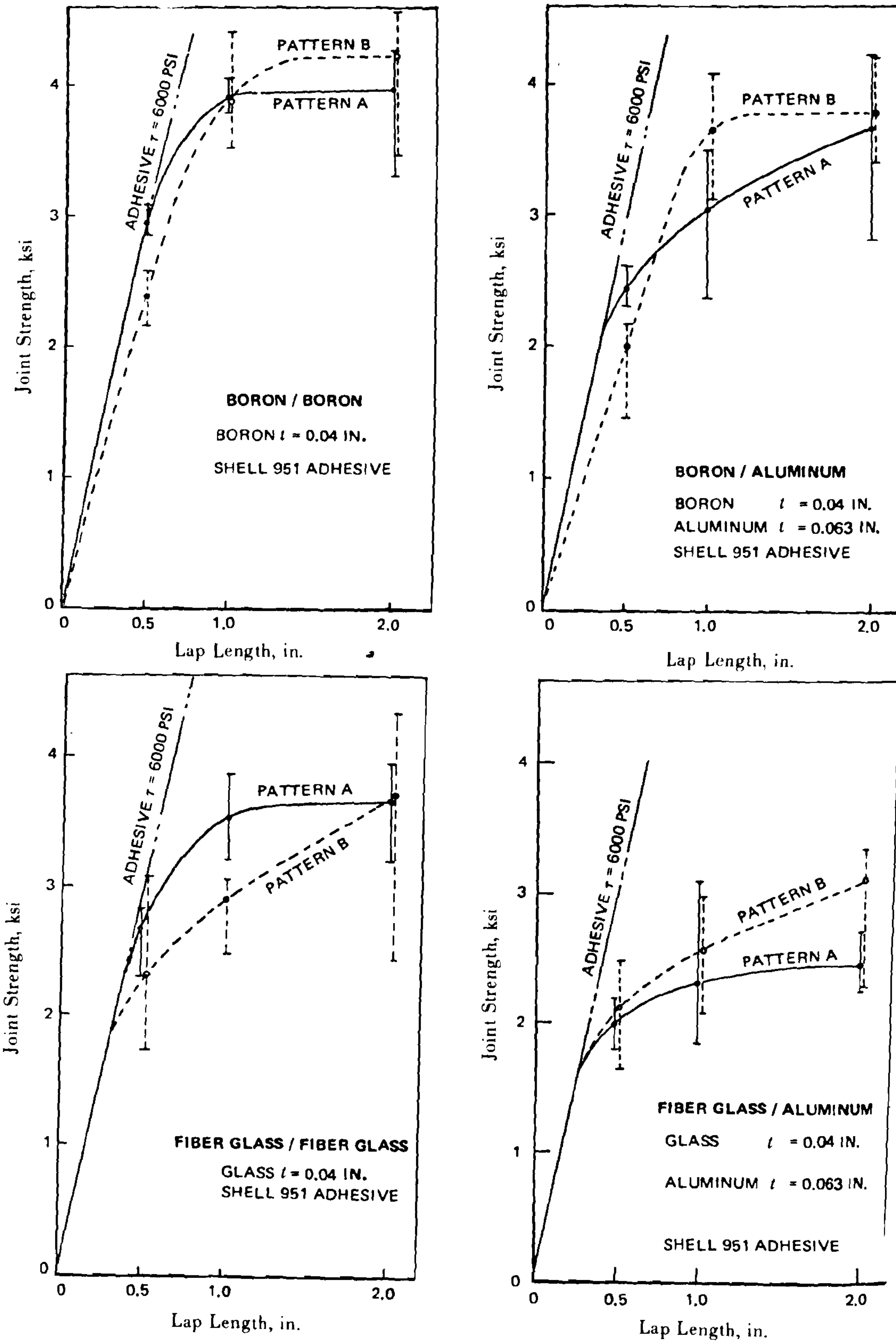


Figure 4-1. Single-Lap Bonded Joint Strength[2]

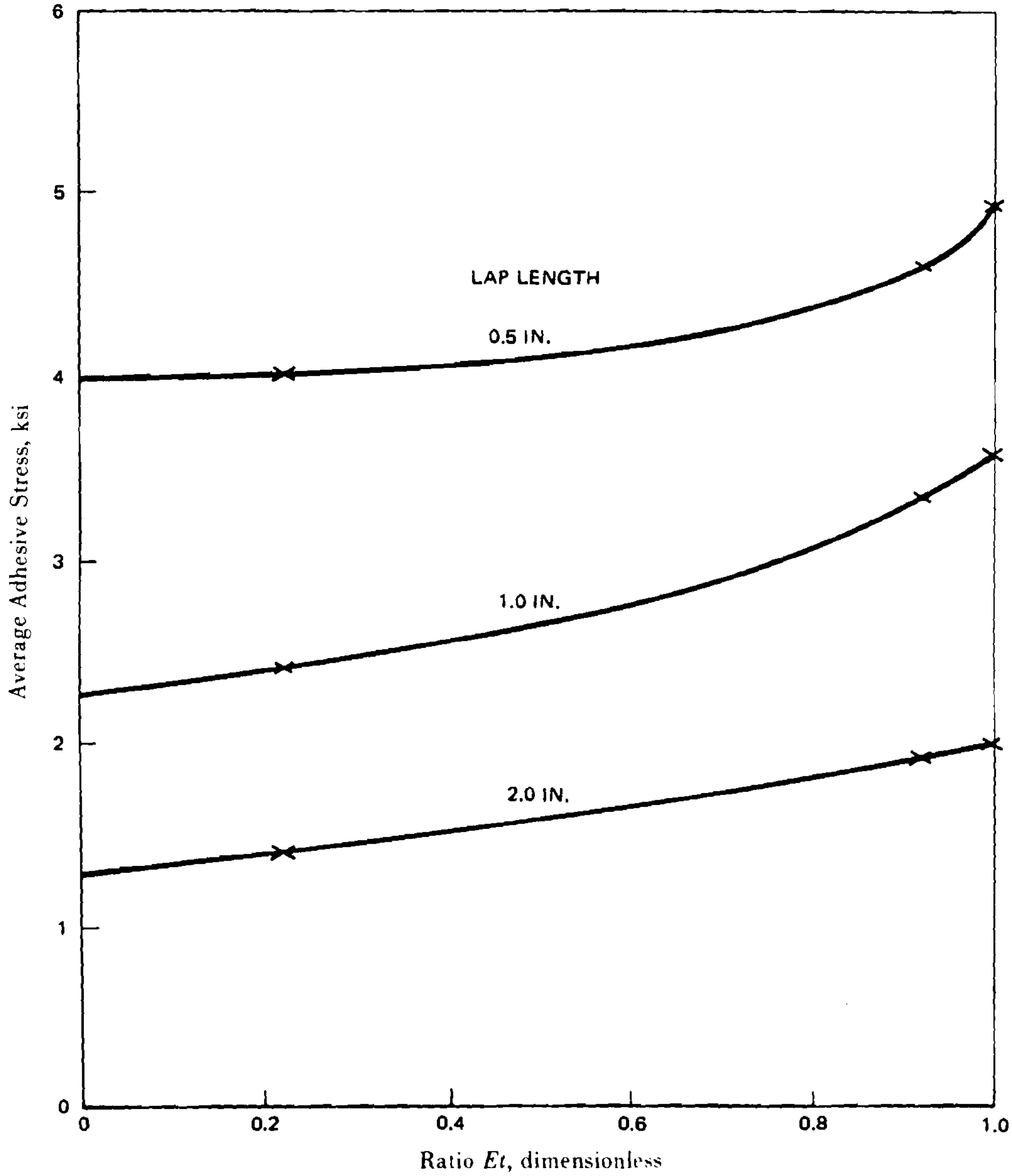


Figure 4-2. Effect of *Et* Ratio on Single-Lap Adhesive Joint Strength[1]

Comparing the test data of Table 4-5 with the predicted adhesive stress at failures for corresponding L/t in Fig. 4-6 indicates that the test results generally fall below the predicted failing stress for an *Et* ratio of 1.00 for boron/aluminum and 0.31 for glass/aluminum. Theoreticaly, for joint lengths of less than 2/3 in. ($L/t \approx 8$), the ultimate average adhesive shear stress of 6650 psi (Shell 951) should be achieved with either glass or boron composite. The double-lap test results do not achieve the maximum design ultimate of 6650 psi but are within the range of experimentally determined results obtained on the torsion ring shear tests for Shell 951 (4640 — 7220 psi). Several variables can account for this including bond line thicknesses which were only about 1/3

TABLE 4-1
JOINT SPECIMEN LAMINATE PATTERNS

LAMINATE PATTERN	PATTERN DESIGNATION	PERCENT OF PLIES AT ±45°
0°/±45°/0°	A	50
+45°/0°/0°/-45°	B	50
±15°	C	0
±45°/±45°/0°(16 LAYERS)/±45°/±45°	D	33-1/3
±45°/±45°/0°(24 LAYERS)/±45°/±45°	E	25
±45°/0°(8 LAYERS)/±45°	F	33-1/3
±45°/0°(12 LAYERS)/±45°	G	25

those for which the torsion ring data were obtained as well as differences in curing rates and pressures, surface condition, voids in bond line, etc. This necessitates the inclusion of a safety factor in the design to allow for such variables.

The curves developed in Fig. 4-7 are based on the assumption that the adhesive is an elastic/perfectly plastic material that becomes plastic at the joint extremities under high load. In this plastic zone the stress reaches the ultimate shear strength of the adhesive. The Width W_c of this zone is assumed constant for a given joint type and adhesive, and for any one-lap distance. Fig. 4-8 depicts the elastic and assumed stress distributions in the adhesive. The ultimate shear stress is determinable either from very short lap joints or, as in this case, by torsion shear tests. W_c is determined by testing a joint of long L/t ratio and determining the elastic stress distribution in the adhesive. Fig. 4-8 shows the elastic stress distribution which gives the same average stress F_s as in the test joint. f^{su} was determined to be 6650 psi. Since the stress cannot exceed f^{su}, the elastic stress distribution is truncated at this value and the area of the elastic distribution above f^{su}, areas A and C, are added below as areas B and D. W_c then is the maximum width of the plastic zone. For identical adherends, the plastic zone would be the same at both extremities. For different adherends and/or thicknesses, only one end achieves maximum. Other joints can then be analysed to determine the shape of the elastic distribution and, with f^{su} and W_c known, the average stress F_s can be determined. This is the manner in which Fig. 4-8 was prepared.

For boron and glass composites whose outer layers are oriented at 0 deg, adhesive failure is anticipated and the curves should be valid. At a 45-deg outer layer fiber orientation, there are some data to indicate failure in the laminate resin at lower stress levels.

4-2.3 BONDED SCARF JOINTS

In theory, a bonded scarf joint approaches the ideals of strain compatibility in the adherends and uniform stress distribution in the adhesive. In practice, however, one may find it difficult to realize the full potential of a scarf joint due to the peculiar processing and fabrication problems encountered in machining steep scarf angles, handling the frangible scarf ends, and applying uniform pressure to the angled bond line to control bond line thickness.

Fig 4-9 shows a finite element stress analysis for an idealized scarf joint, and Fig. 4-10 shows the adherend normalized stress distributions in a

TABLE 4-2
SUMMARY OF SINGLE-LAP BONDED JOINT TEST RESULTS USING SHELL 951 ADHESIVE[2]

JOINT DESCRIPTION, MATERIALS, AND GAGES in.	PATTERN@	NOMINAL LAP LENGTH, in.	AVERAGE ADHESIVE THICKNESS, in.	ULTIMATE STATIC LOAD, lb	AVERAGE ADHESIVE SHEAR STRESS AT FAILURE*, psi	AVERAGE ADHEREND TENSILE STRESS AT FAILURE		
						COMPOSITE, psi	ALUMINUM, psi	FAILURE MODES**
SINGLE LAP BORON (0.040)/ BORON (0.040)	A	0.50	0.0029	2905	5722	72,500	NOT APPLICABLE	(1)
	A	1.00†	0.0010	3908	3875	97,700		(2)
	A	1.00††	0.0034	3385	3336	84,000		(2)
	A	2.00	0.0024	3959	1957	99,000		(2)
	B	0.50	0.0019	2362	4678	59,000		(2)
	B	1.00	0.0020	3898	3868	97,500		(2)
	B	2.00	0.0019	4209	2155	105,000		(3)
SINGLE LAP FIBERGLASS (0.040)/ FIBERGLASS (0.040)	A	0.50	0.0017	2648	5087	66,300	NOT APPLICABLE	(1)
	A	1.00	0.0014	3538	3424	88,500		(1)
	A	2.00	0.0020	3650	1794	91,300		(1)
	B	0.50	0.0010	2496	5056	62,400		(1), (2)
	B	1.00	0.0010	2719	2665	68,000		(1), (2)
	B	2.00	0.0021	3708	1839	92,700		(1), (2)
SINGLE LAP BORON (0.040)/ 7075-T6 (0.063)	A	0.50	0.0019	2416	4738	60,400	39,300	(1), (2)
	A	1.00†	0.0019	2514	2480	62,700	39,900	(1), (2)
	A	1.00††	0.0030	3040	3016	75,800	48,300	(1), (2)
	A	2.00	0.0020	3670	1832	91,600	58,300	(1), (2)
	B	0.50	0.0013	2009	3570	50,200	31,900	(2)
	B	1.00	0.0022	3645	3630	91,200	58,000	(2)
	B	2.00	0.0019	3780	1928	94,500	60,000	(2), (3)
SINGLE LAP FIBERGLASS (0.040)/ 7075-T6 (0.063)	A	0.50	0.0016	2006	3958	50,100	31,800	(1)
	A	1.00	0.0030	2318	2229	58,000	36,800	(1)
	A	2.00	0.0026	2463	1226	61,500	39,100	(1)
	B	0.50	0.0034	2121	4100	53,000	33,700	(1)
	B	1.00	0.0030	2553	2589	64,800	41,000	(1)
	B	2.00	0.0022	3094	1560	77,300	49,000	(1)
SINGLE LAP BORON (0.040)/ 7075-T6 (0.063) EXTERNAL SCARF	A	1.00	0.0054	2781	2677	69,500	44,200	
SINGLE LAP FIBERGLASS (0.040)/ 7075-T6 (0.063) EXTERNAL SCARF	A	1.00	0.0035	2383	2306	59,500	37,900	

*AVERAGE OF FIVE TESTS
**(1) ADHESIVE
(2) INTERLAMINAR SHEAR
(3) TENSION IN BASIC LAMINATE SECTION

†TESTED IN JANUARY 1968
††TESTED IN DECEMBER 1968
@SEE TABLE 4-1

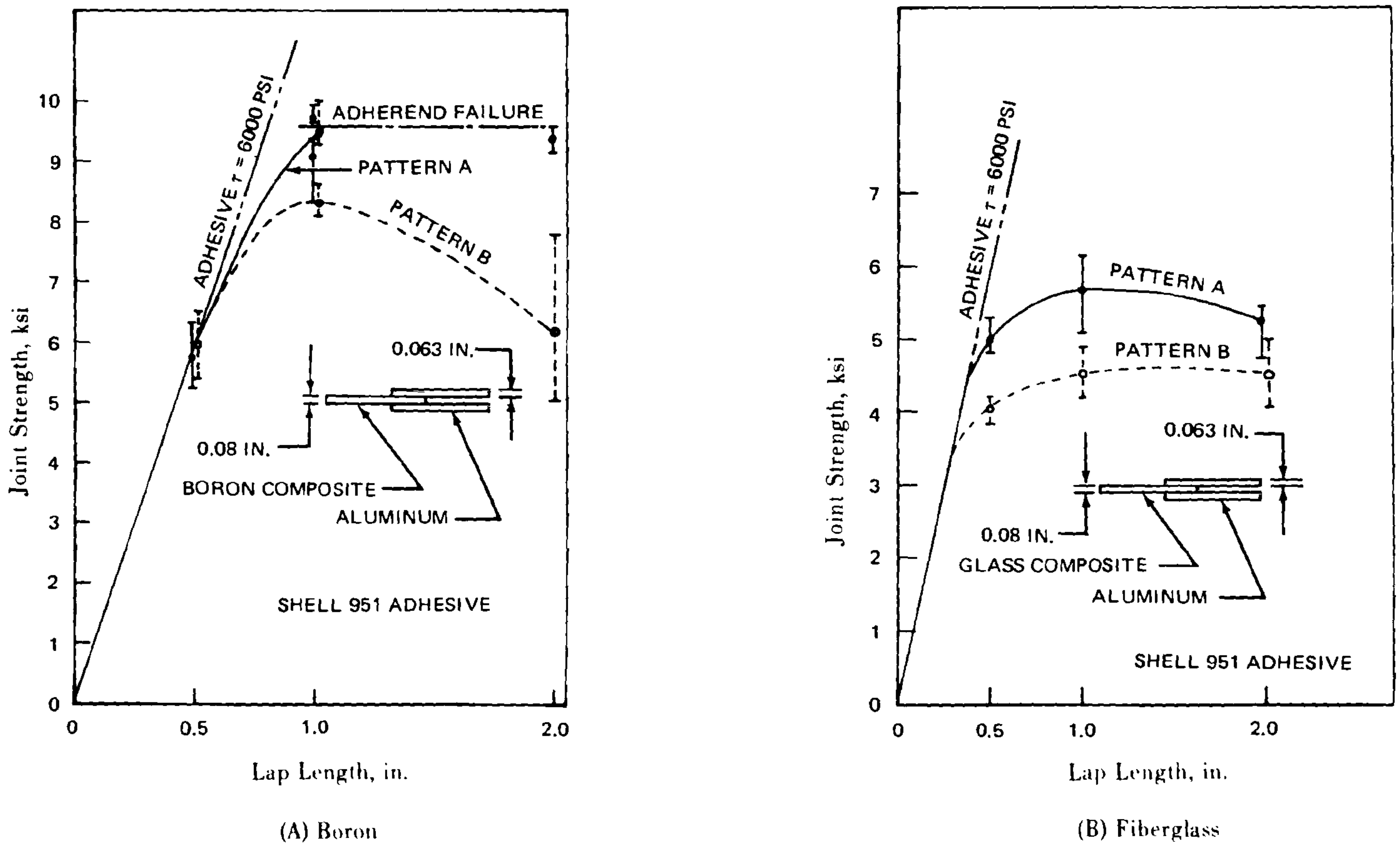


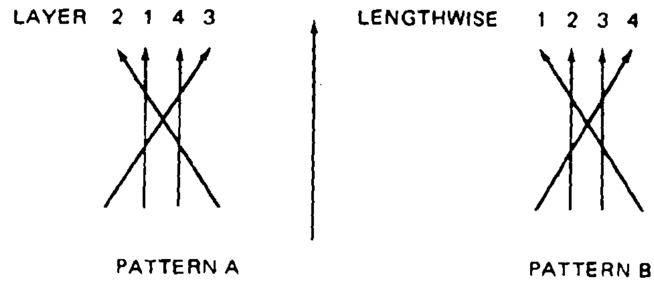
Figure 4-3. Double-Lap Bonded Joint Strength[2]

TABLE 4-3
SUMMARY OF DOUBLE-LAP BONDED JOINT TEST RESULTS (1-IN. SPECIMEN WIDTH) USING SHELL 951 ADHESIVE[2]

JOINT DESCRIPTION, MATERIALS, AND GAGES in.	PATTERN@	NOMINAL LAP LENGTH, in.	AVERAGE ADHESIVE THICKNESS, in.	ULTIMATE STATIC LOAD, lb	AVERAGE ADHESIVE SHEAR STRESS AT FAILURE,* psi	AVERAGE ADHEREND TENSILE STRESSES AT FAILURE		FAILURE MODES**
						COMPOSITE, psi	ALUMINUM, psi	
DOUBLE LAP BORON (0.080)/ 7075-T6 (0.126)	A	0.50	0.0011	5769	5625	72,000	45,700	(1), (2)
	A	1.00†	0.0012	9104	4406	113,600	72,200	(2), (3)
	A	1.00††	0.0020	9746	4482	122,000	77,300	(3)
	A	2.00	0.0010	9378	2340	117,000	74,500	(1), (4)
	B	0.50	0.0015	5982	5793	74,700	47,500	(1), (2)
	B	1.00†	0.0012	8327	4160	104,000	66,000	(3)
	B	1.00††	0.0026	9502	4751	118,700	75,400	(3)
	B	2.00	0.0014	6180	1540	77,200	49,000	(2), (3)
DOUBLE LAP FIBERGLASS (0.080)/ 7075-T6 (0.126)	A	0.50	0.0023	5038	4986	63,000	40,000	(1)
	A	1.00	0.0033	5713	2743	71,500	45,400	(1), (2)
	A	2.00	0.0034	5297	1347	66,200	42,000	(1), (2)
	B	0.50	0.0019	4059	4008	50,900	32,200	(2)
	B	1.00	0.0023	4530	2257	56,600	36,000	(2)
	B	2.00	0.0025	4561	1110	57,100	36,200	(2)

*AVERAGE OF FIVE TESTS
**(1) ADHESIVE
(2) INTERLAMINAR SHEAR
(3) TENSION IN BASIC LAMINATE SECTION
(4) TENSION IN BASIC ALUMINUM SECTION

†TESTED IN FEBRUARY 1968
††TESTED IN DECEMBER 1968
@SEE TABLE 4-1



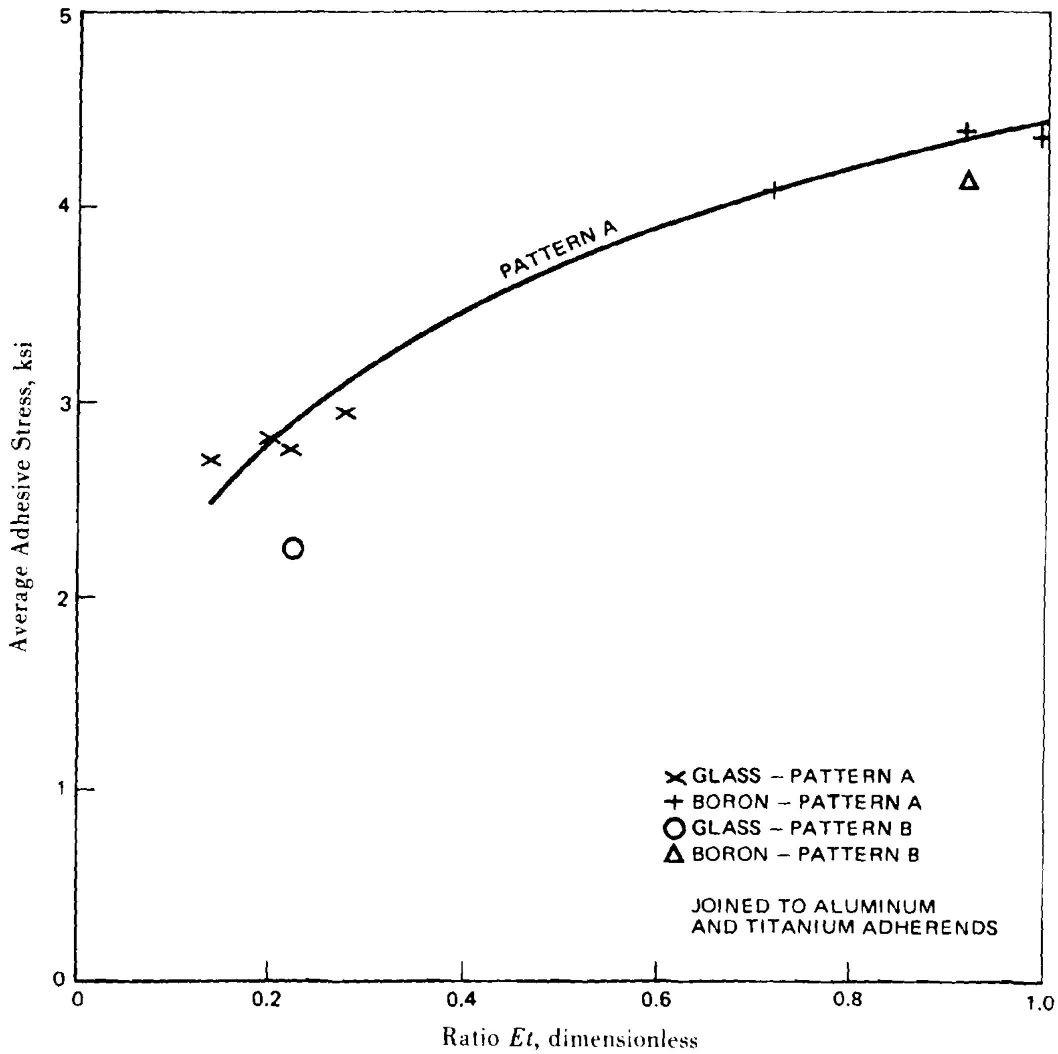


Figure 4-4. Effect of *Et* Ratio on Double-Lap Adhesive Joint Strength for Glass, Boron/Aluminum, Titanium Adherends[1]

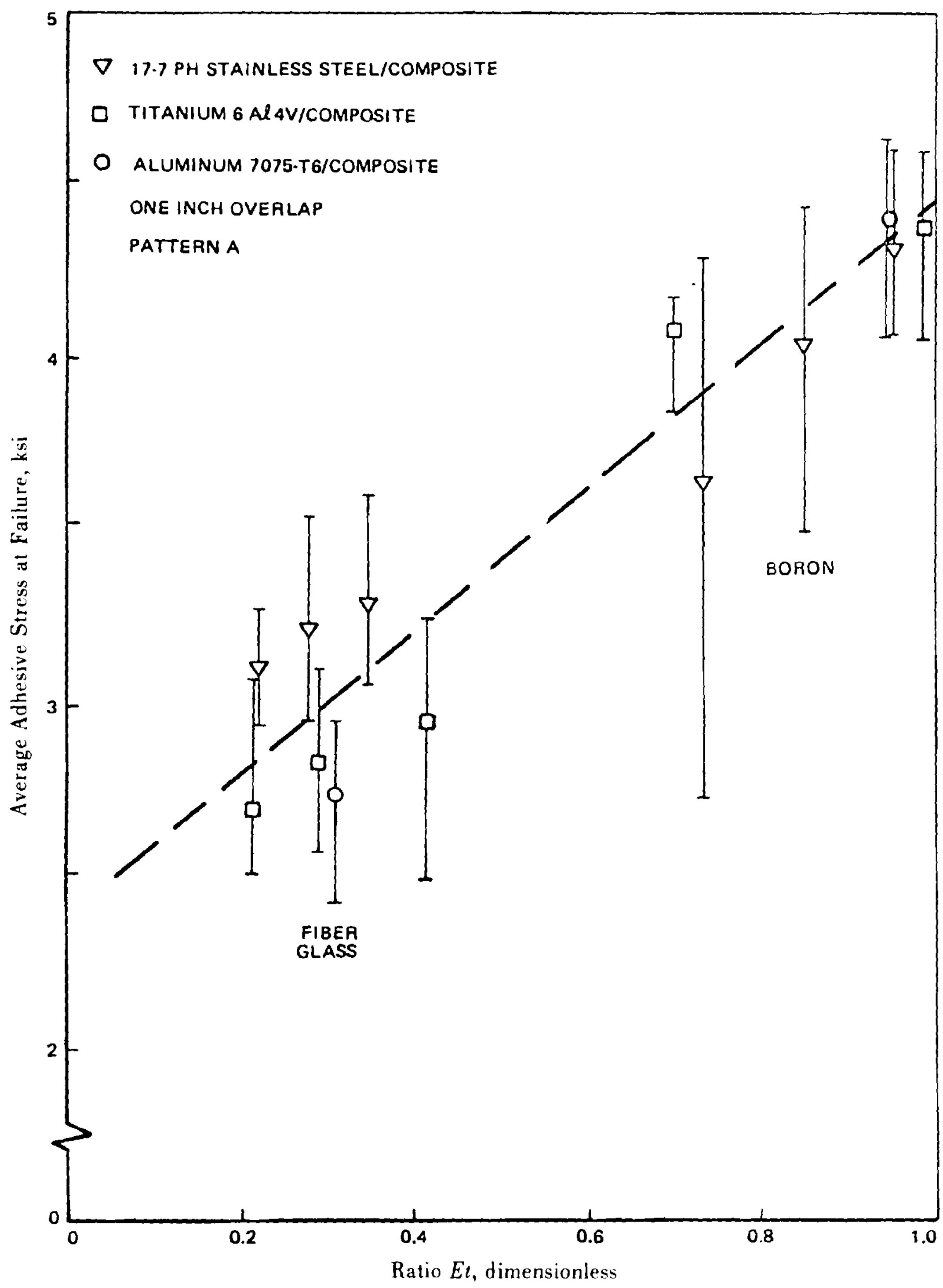


Figure 4-5. Effect of *Et* Ratio on Double-Lap Adhesive Joint Strength for Stainless Steel, Titanium, Aluminum/Composite Adherends[2]

TABLE 4-4
SUMMARY OF DOUBLE-LAP BONDED JOINT TEST RESULTS FOR VARIOUS *Et* RATIOS USING SHELL 951 ADHESIVE[2]

JOINT MATERIALS, AND GAGES, in.	PATTERN@	NOMINAL LAP LENGTH, in.	AVERAGE ADHESIVE THICKNESS, in.	ULTIMATE STATIC LOAD, lb	AVERAGE ADHESIVE SHEAR STRESS AT FAILURE,* psi	AVERAGE ADHEREND TENSILE STRESSES AT FAILURE		FAILURE MODES**
						COMPOSITE, psi	METAL, psi	
BORON (0.080)/ S STL△ (0.040)	A	1.00	0.0016	8065	4040	101,000	202,000	(1), (2), (3)
BORON (0.080)/ S STL (0.050)	A	1.00	0.0020	8650	4325	108,000	173,000	(1), (2), (3)
BORON (0.080)/ S STL (0.064)	A	1.00	0.0045	7290	3645	91,200	114,000	(1), (3)
BORON (0.080)/ Ti (0.064)	A	1.00	0.0042 0.0036	6600† 9530††	3148 4746	82,500 119,000	103,000 149,000	(1), (2), (3)
BORON (0.080)/ Ti (0.090)	A	1.00	0.0032 0.0030	8760†† 8812†	4380 4375	110,000 109,500	98,000 97,300	(2), (3)
BORON (0.080)/ Ti (0.126)	A	1.00	0.0040	8100	4088	101,500	64,300	(3)
FIBERGLASS (0.080)/ S STL (0.040)	A	1.00	0.0012	6575	3287	82,300	164,500	(1), (2)
FIBERGLASS (0.080)/ S STL (0.050)	A	1.00	0.0016	6460	3230	80,750	129,000	(1), (2)
FIBERGLASS (0.080)/ S STL (0.064)	A	1.00	0.0010	6235	3115	78,000	97,500	(1), (2)
FIBERGLASS (0.080)/ Ti (0.064)	A	1.00	0.0042	5957	2952	74,500	93,000	(1)
FIBERGLASS (0.080)/ Ti (0.090)	A	1.00	0.0027	5815	2838	72,600	64,500	(1), (2)
FIBERLGASS (0.080)/ Ti (0.126)	A	1.00	0.0045	5608	2691	70,200	44,500	(1), (2)

*AVERAGE OF FIVE TESTS
**(1) ADHESIVE
(2) INTERLAMINAR SHEAR
(3) TENSION IN BASIC LAMINATE SECTION
(4) TENSION IN BASIC METAL SECTION
△S STL = STAINLESS STEEL
GAGES NOTED FOR METALS INCLUDE THOSE FOR BOTH METAL ADHERENDS.

†TESTED IN MAY 1968
††TESTED IN JANUARY 1969
@ SEE TABLE 4-1

TABLE 4-5
SUMMARY OF DOUBLE-LAP BONDED JOINT TEST RESULTS (1-IN. SPECIMEN WIDTH)[2]

JOINT DESCRIPTION, MATERIALS, AND GAGES, in.	PATTERN@	NOMINAL LAP LENGTH, in.	AVERAGE ADHESIVE THICKNESS, in.	ULTIMATE STATIC LOAD, lb	AVERAGE ADHESIVE SHEAR STRESS AT FAILURE*, psi	AVERAGE ADHEREND TENSILE STRESSES AT FAILURE		FAILURE MODES**
						COMPOSITE, psi	ALUMINUM, psi	
DOUBLE LAP BORON (0.080)/ 7075-T6 (0.126)	A	0.50	0.0011	5769	5625	72,000	45,700	(1), (2)
	A	1.00†	0.0012	9104	4406	113,600	72,200	(2), (3)
	A	1.00††	0.0020	9746	4482	122,000	77,300	(3)
	A	2.00	0.0010	9378	2340	117,000	74,500	(1), (4)
	B	0.50	0.0015	5982	5793	74,700	47,500	(1), (2)
	B	1.00†	0.0012	8327	4160	104,000	66,000	(3)
	B	1.00††	0.0026	9502	4751	118,700	75,400	(3)
	B	2.00	0.0014	6180	1540	77,200	49,000	(2), (3)
DOUBLE LAP FIBERGLASS (0.080)/ 7075-T6 (0.126)	A	0.50	0.0023	5038	4986	63,000	40,000	(1)
	A	1.00	0.0033	5713	2743	71,500	45,400	(1), (2)
	A	2.00	0.0034	5297	1347	66,200	42,000	(1), (2)
	B	0.50	0.0019	4059	4008	50,900	32,200	(2)
	B	1.00	0.0023	4530	2257	56,600	36,000	(2)
	B	2.00	0.0025	4561	1110	57,100	36,200	(2)

*AVERAGE OF FIVE TESTS
**(1) ADHESIVE
(2) INTERLAMINAR SHEAR
(3) TENSION IN BASIC LAMINATE SECTION
(4) TENSION IN BASIC ALUMINUM SECTION

†TESTED IN FEBRUARY 1968
††TESTED IN DECEMBER 1968
@SEE TABLE 4-1

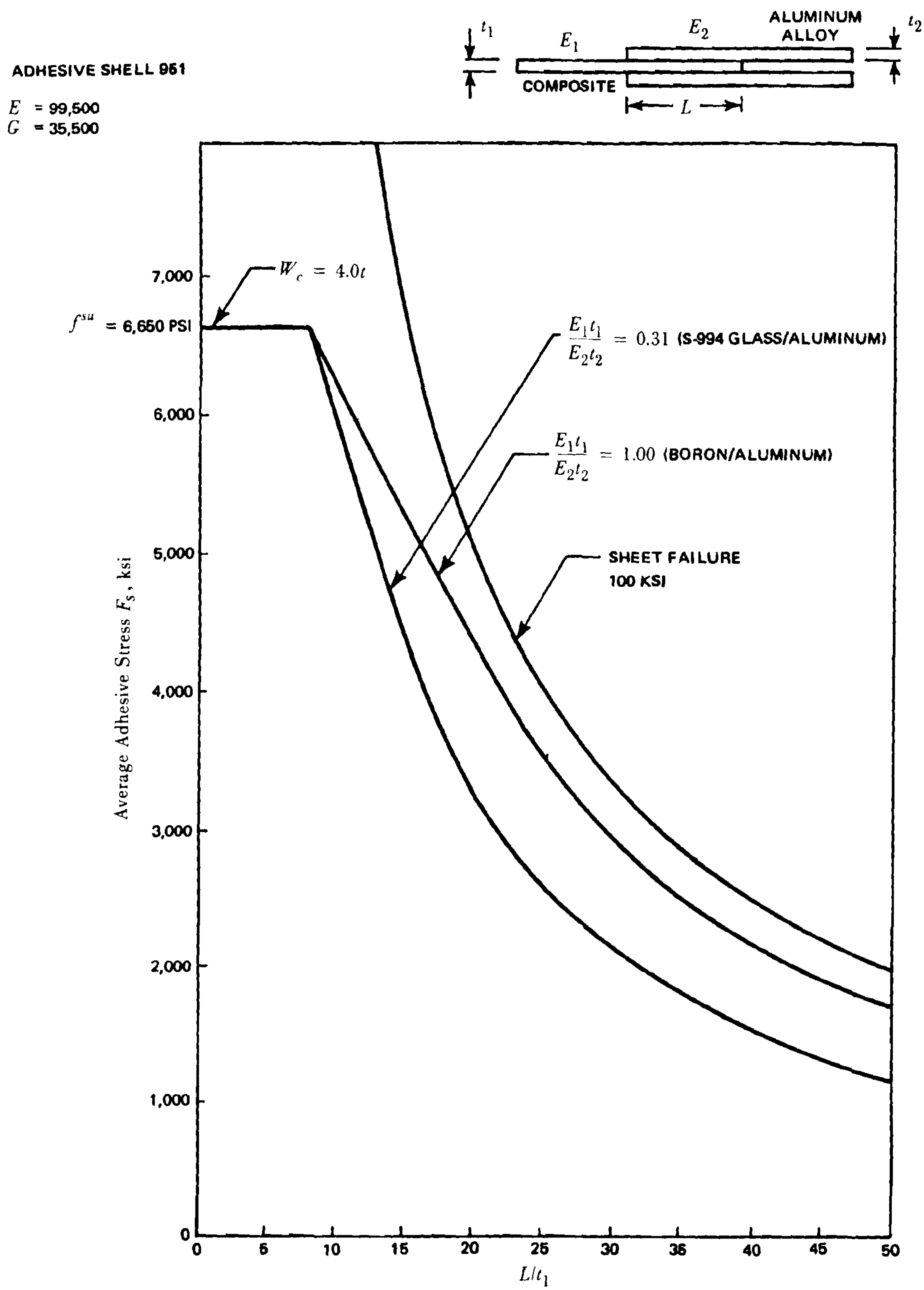


Figure 4-6. Predicted Joint Strength for Double-Lap Bonded Joints Using Shell 951 Adhesive[3]

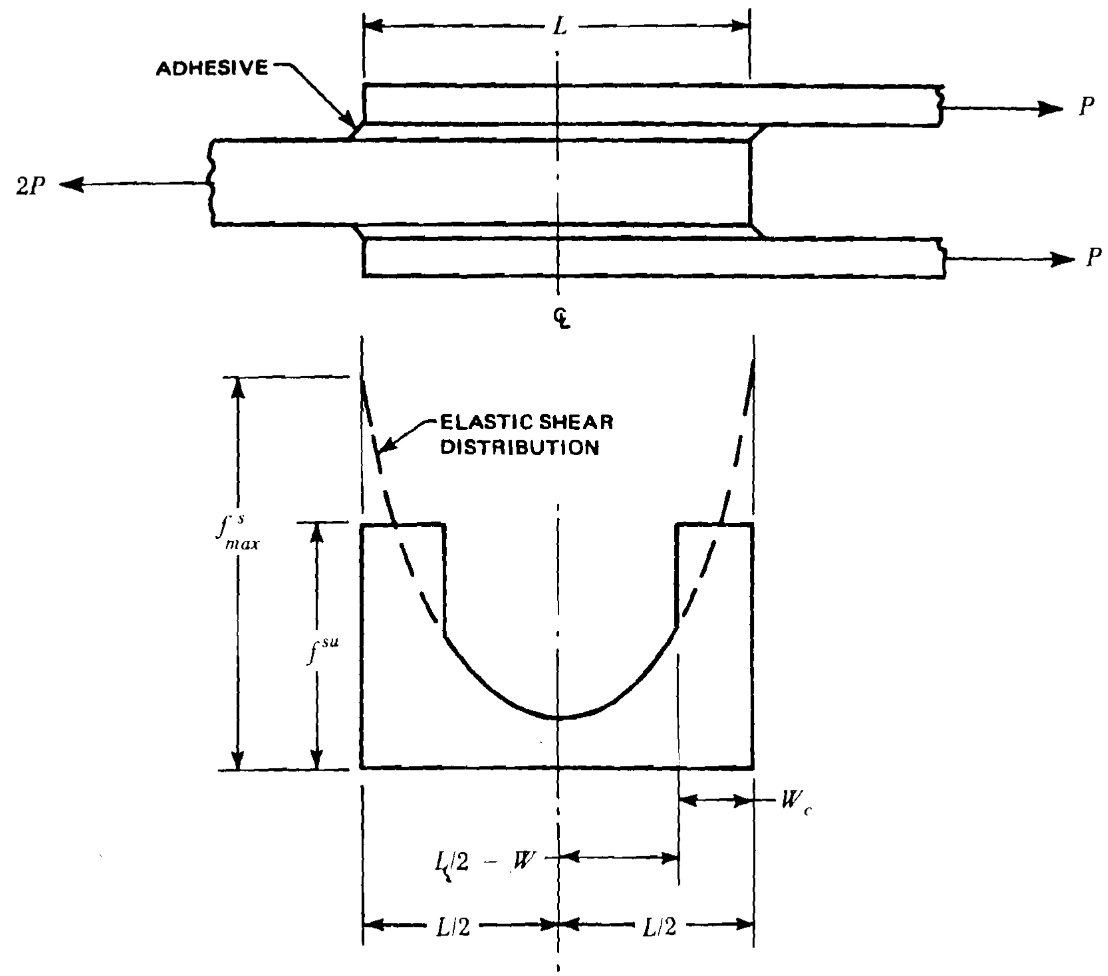


Figure 4-7. Double-Lap Joint Showing Plastic Shear Distribution in Adhesive[1]

boron/boron composite scarf joint. Figs. 4-11 and 4-12, respectively, show shear and tensile stress distributions in the adhesive of a scarf joint. For the variable *Et* ratios of a boron composite/aluminum scarf joint due to different fiber orientations present in the bond line, the adhesive stress distribution would look like that shown in Fig. 4-13.

Actual test results on boron/boron and boron/aluminum scarf joints using Shell 951 adhesive were found not to be as strong as expected and achieved just over 75% of the adhesive shear stress design value. As stated earlier it is suspected (1) that, because of the nonflat configuration, it is difficult to maintain bond line pressure during cure; and (2) that bond quality, especially on small overlaps with steep scarf angles, is not optimum. In addition, bond line thicknesses ($\approx$0.014 in.) tended to be larger by several-fold over flat lap type joints. This is probably due to the inability to control bond line pressure. Figs. 4-14 and 4-15, respectively, plot the joint strength of composite/aluminum and composite/composite joints versus overlap length and scarf angle.

An alternative to the scarf joint, which avoids some of the processing difficulties of scarf joint manufacture, is the external scarf or beveled single-lap joint. This joint retains the strain compatibility of the adherends but introduces the offset loading characteristics of the single-lap joint. However, improved processing ease and

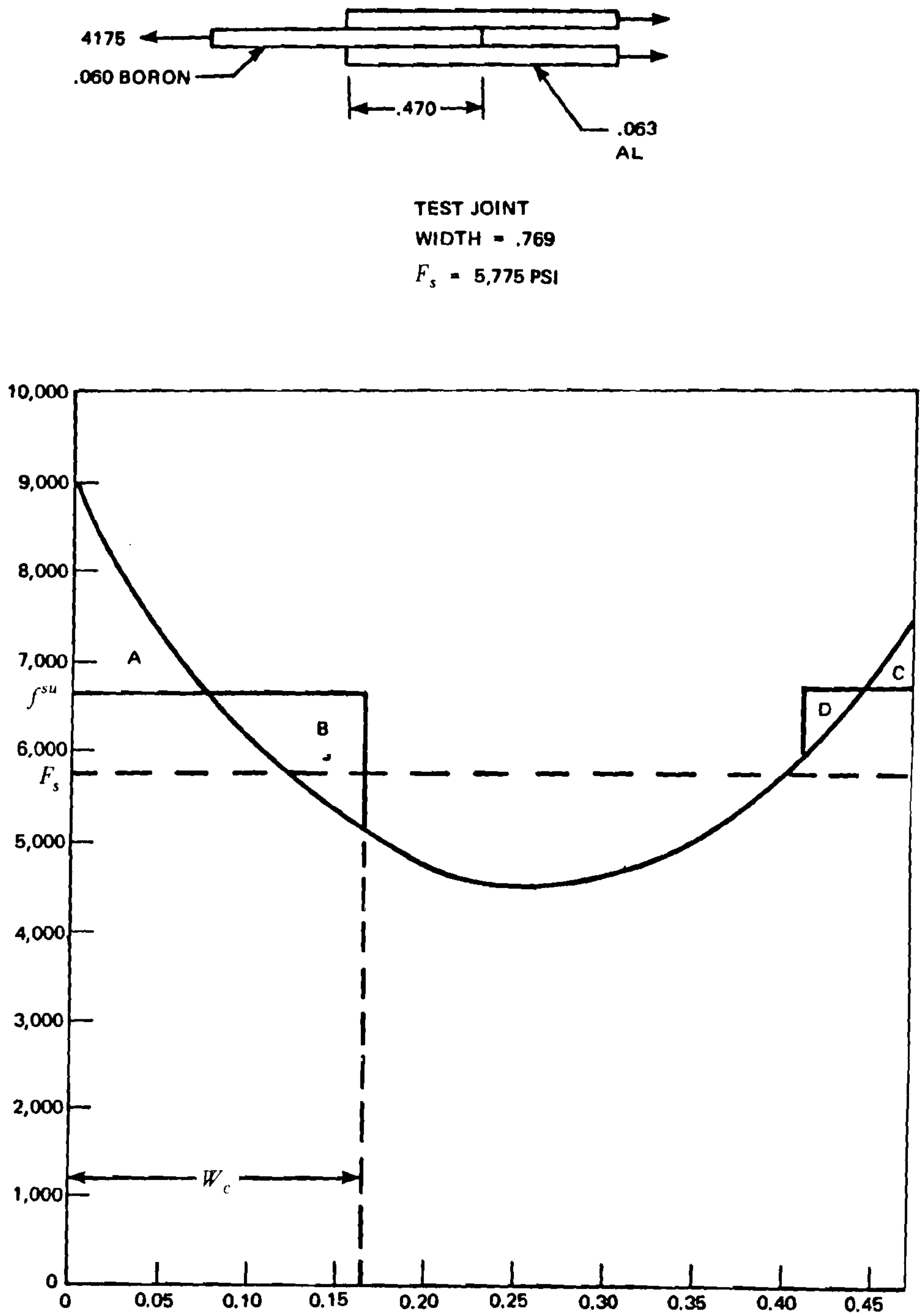


Figure 4-8. Stress Distribution in Actual Test Joint Based on Computer Analysis[1]

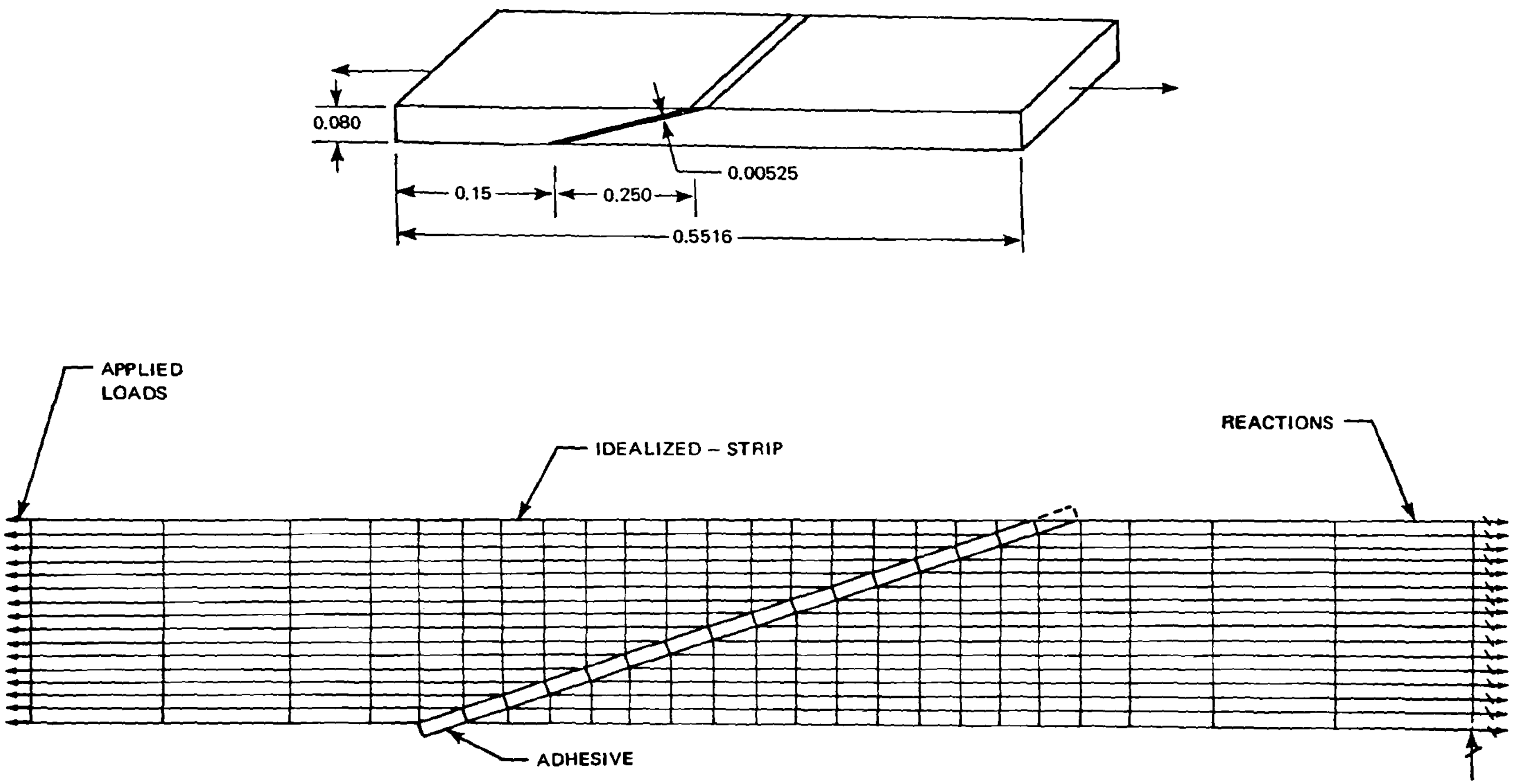


Figure 4-9. Idealized Scarf Joint[3]

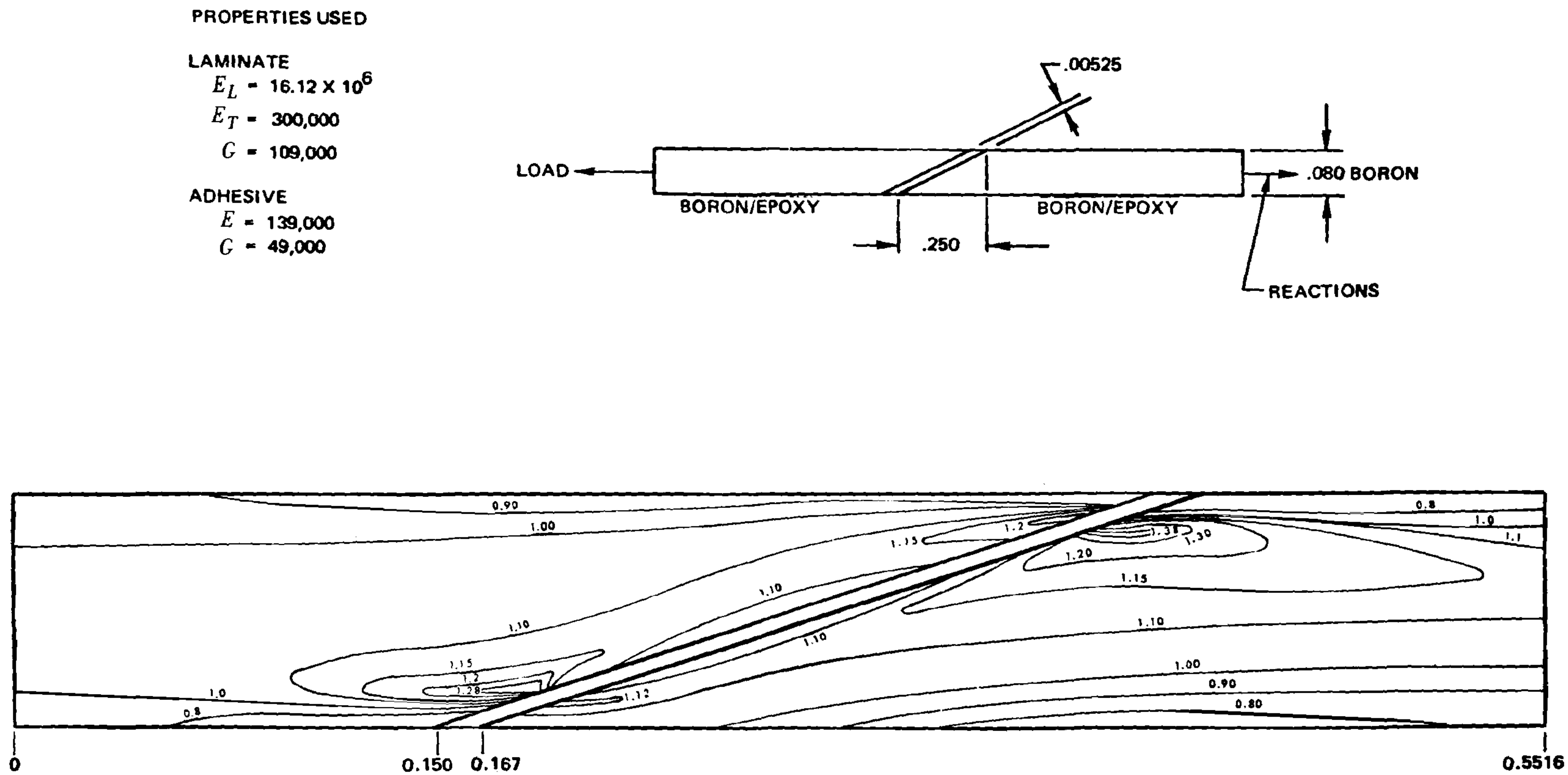


Figure 4-10. Adherend Normalized Stress Distributions in a Scarf Joint[3]

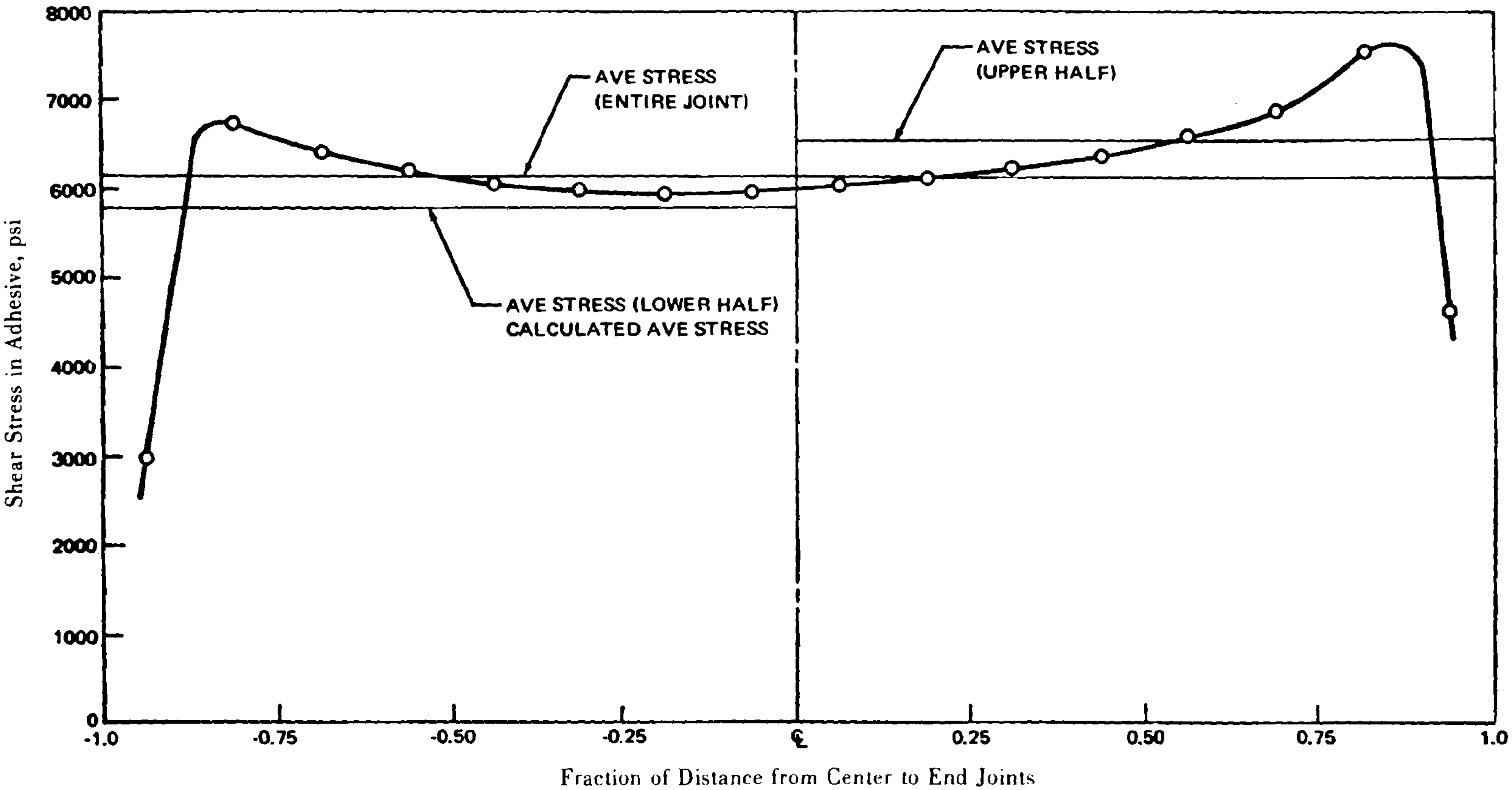


Figure 4-11. Shear Stress Distribution in the Adhesive of a Scarf Joint[3]

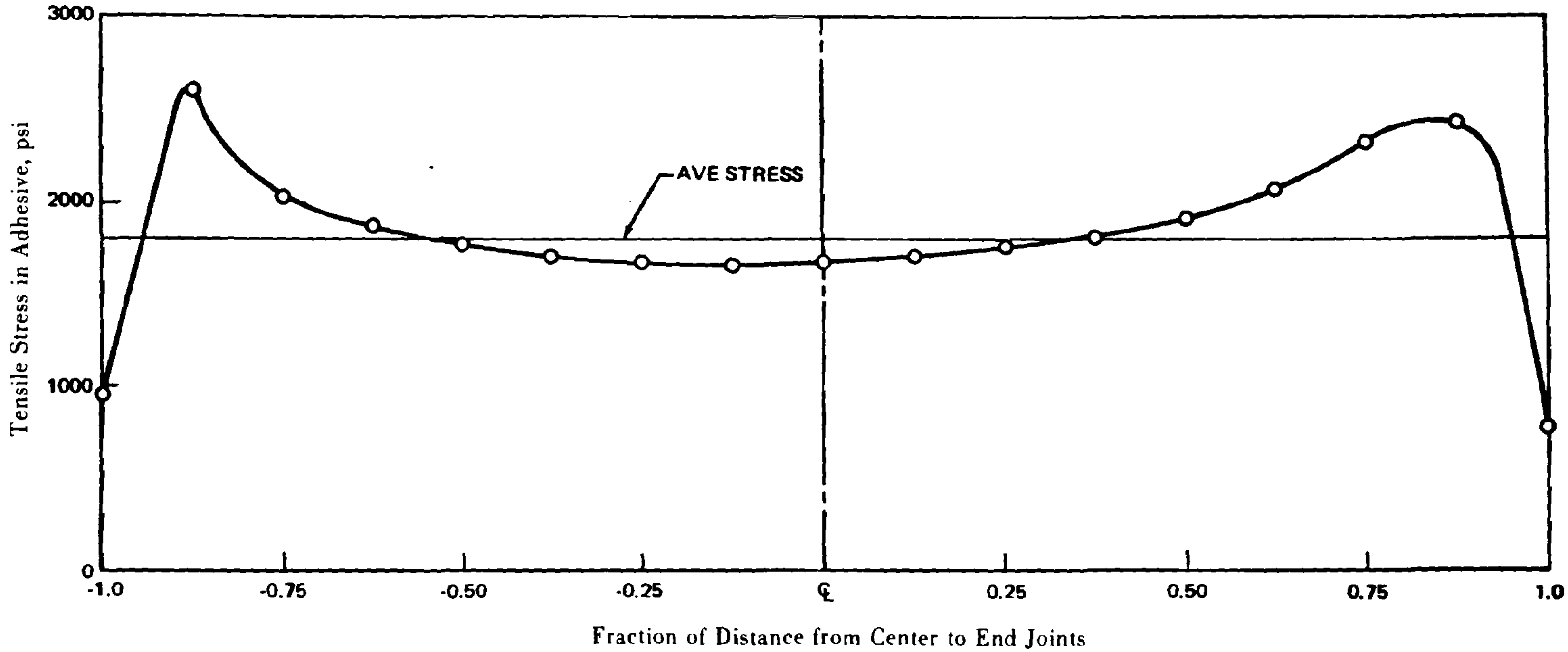


Figure 4-12. Tensile Stress Distribution in the Adhesive of a Scarf Joint[3]

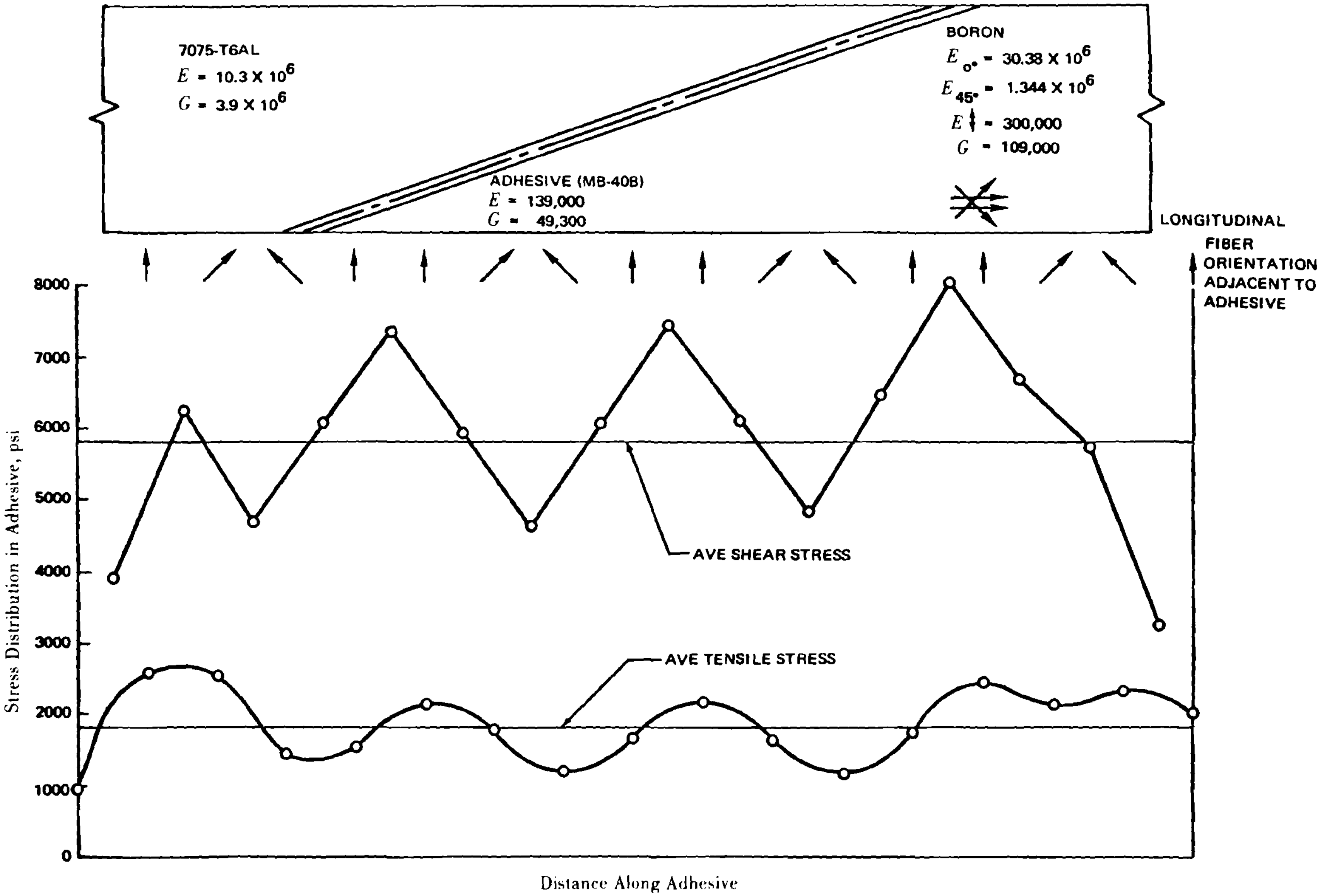


Figure 4-13. Stress Distribution in the Adhesive of an Aluminum/Boron Scarf Joint[3]

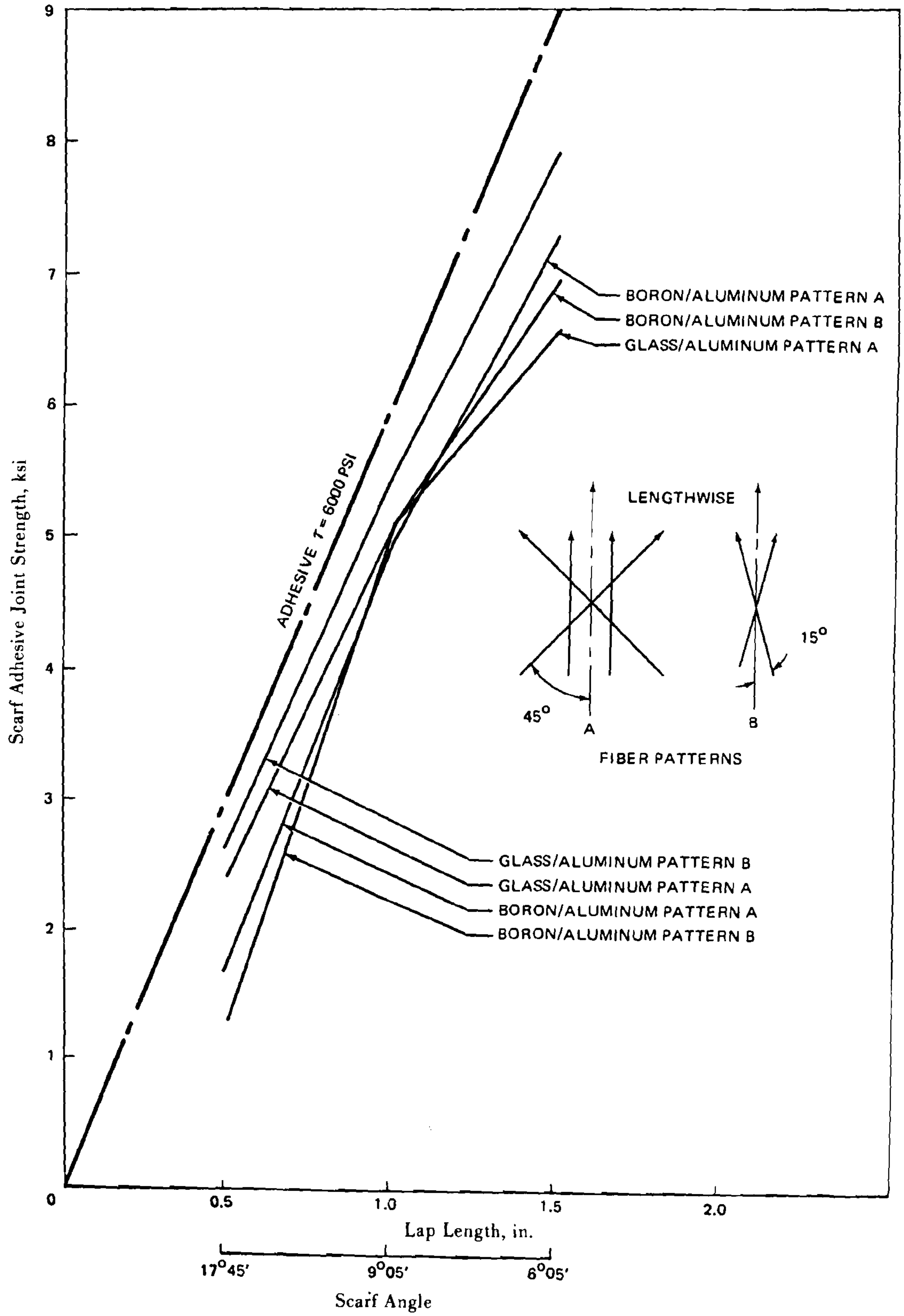


Figure 4-14. Scarf Adhesive Joint Strength — Composite-to-Aluminum[1]

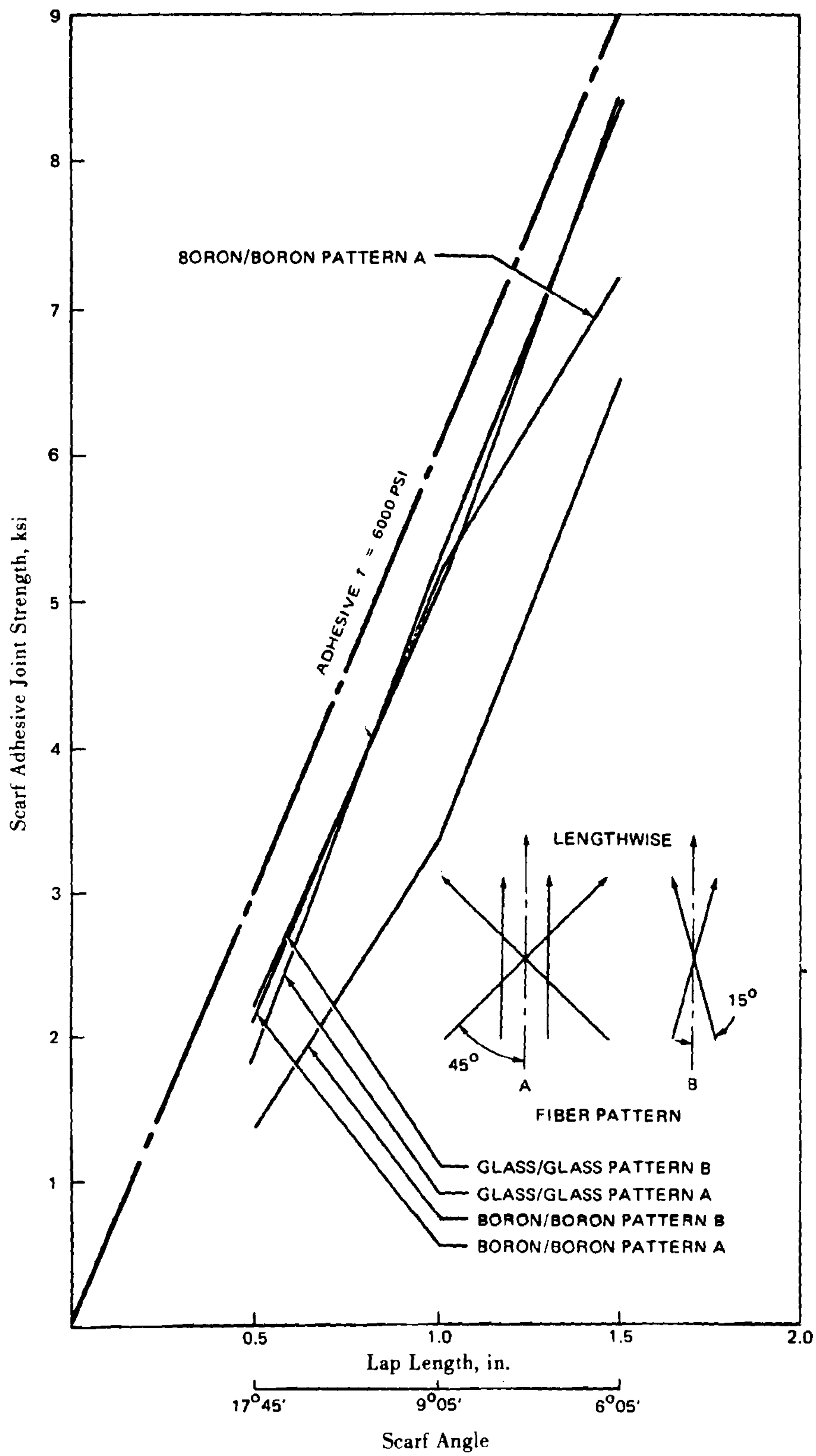


Figure 4-15. Scarf Adhesive Joint Strength — Composite-to-Composite[1]

resultant bond quality improvements can result due to the flat nonmachined bonding surfaces whose fibers can be oriented parallel to load direction.

4-2.4 STEPPED LAP JOINTS

Fig. 4-16 depicts an idealized two-step lap joint whose adhesive stress distribution is presented in Fig. 4-17. The results of tests on boron and glass composites bonded to aluminum using Shell 951 adhesive reveal, rather surprisingly, that joint strength was independent of the number of steps employed in Fig. 4-18. These results were for a joint overlap of 2 in. Joint efficiency of a two-step lap joint is improved over the single-lap joint. The center of the two-step lap is seen to carry some stress but stresses at the end seem to spike higher. The percentage of adhesive working is about the same for a two-step lap as for a single lap. If more steps and shorter L/t ratios are employed, this configuration should prove very worthwhile. Since a scarf joint can be considered to be a multistepped lap joint in which the number of steps approach infinity, a scarf joint is considered the limiting case for a multistepped lap joint. However, due to the processing difficulties discussed for a scarf joint, it achieved only 75% of the design limit compared with about 95% for boron/aluminum stepped lap joints. For glass/aluminum stepped lap joints, only about 65% of the design limit was achieved.

4-2.5 BONDED JOINT PERFORMANCE COMPARED.

Fig. 4-19 compares the test results of single, double, and stepped lap joints with a scarf joint on boron/aluminum bonded with Shell 951. It can be seen that the single lap joint is quite efficient for low L/t ratios but rapidly yields diminishing returns on increased lap length. In contrast, the double-lap joint is more than twice as strong as the single lap which has the highest stress concentration at lap ends and carries the least load at the center of the joint. Stepped lap and scarf joints can potentially achieve the highest average adhesive shear strength.

4-2.6 FIBER ORIENTATION VS JOINT STRENGTH — IN-BONDED JOINTS

The fiber orientation patterns used in bonded joints are extremely important since the layers adjacent to the bond carry an increasing share of the stress as shown in Fig. 2-7. It is known that laminate modulus is a significant factor, so the nature of the substrate member is important. However, since the gross modulus is the same for a given laminate—regardless of fiber orientation— and the modulus ratio of 0-deg to 45-deg layers is approximately 10 to 1, then bond strength differences can be expected depending on outer layer fiber orientation. Since surface fiber orientation has no effect on gross laminate strength or stiffness, it is a variable which effects bond strength only. Bonded composite joint data must always present composite lay up patterns where possible since fiber orientation, particularly in the surface layers, has a profound effect on bonded composite joint strengths.

4-3 BOLTED COMPOSITE JOINTS

Generally only 25-50% of the basic laminate strength is achieved with mechanical fasteners. The use of metal interlayers (shims) are sometimes employed to bring joint efficiency over 50% but this results in reduced weight efficiency. Mechanical joints usually are designed to fail in bearing rather than shear-out or tension. This requires that edge-distance bolt-diameter e/D and side-distance bolt-diameter s/D ratios higher than for metals are required to avoid shear-out or tension failures in composites. In unsymmetrical joints, such as single laps, multiple rows of fasteners are suggested to minimize bending. Generally, in order to achieve full bearing strength, D/t ratios < 2 are recommended.

Design variations for bolted composite joint specimens can include different edge distance e, side distance s, fastener diameter D, laminate

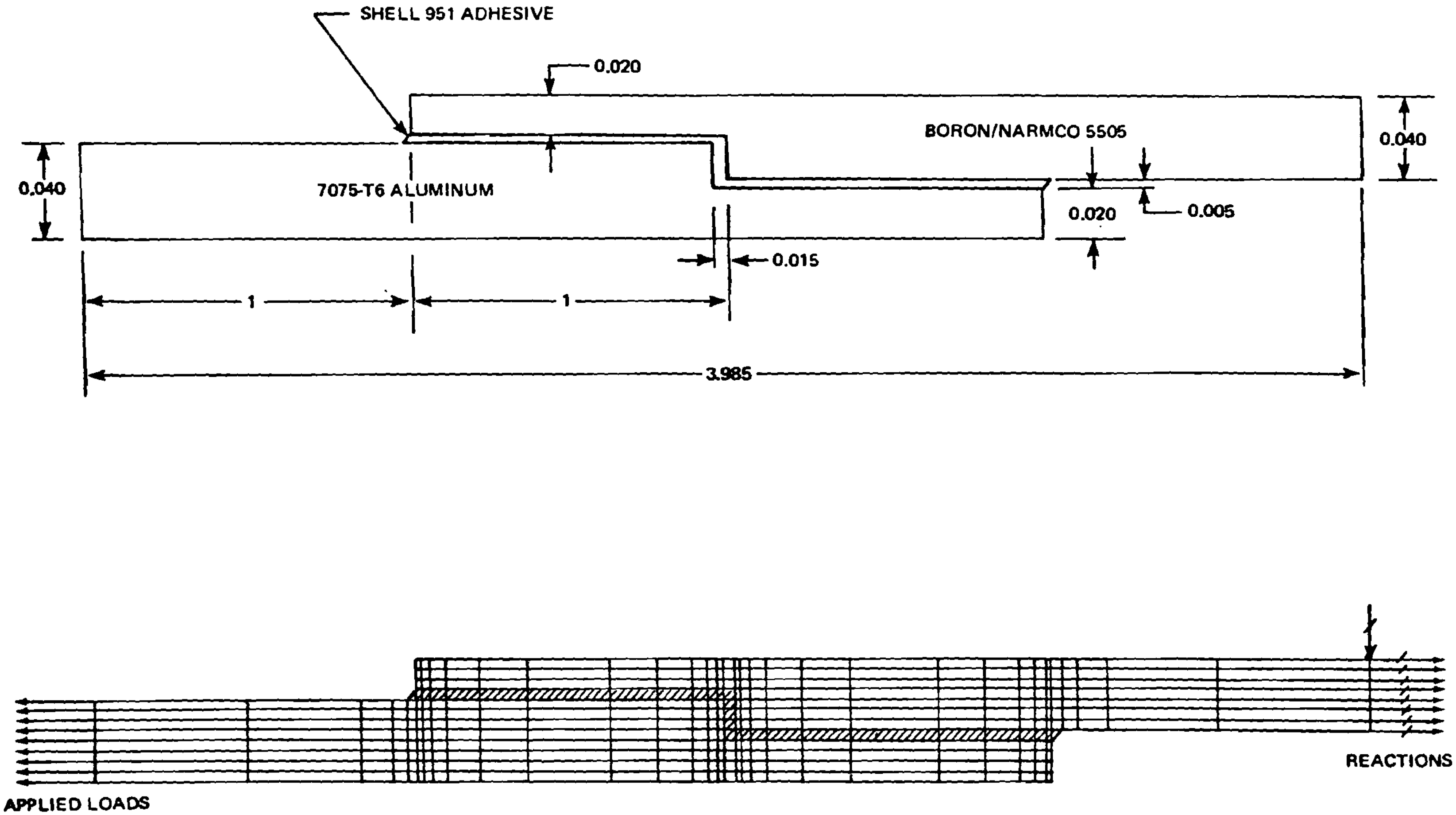


Figure 4-16. Idealized Two-Step Lap Joint[2]

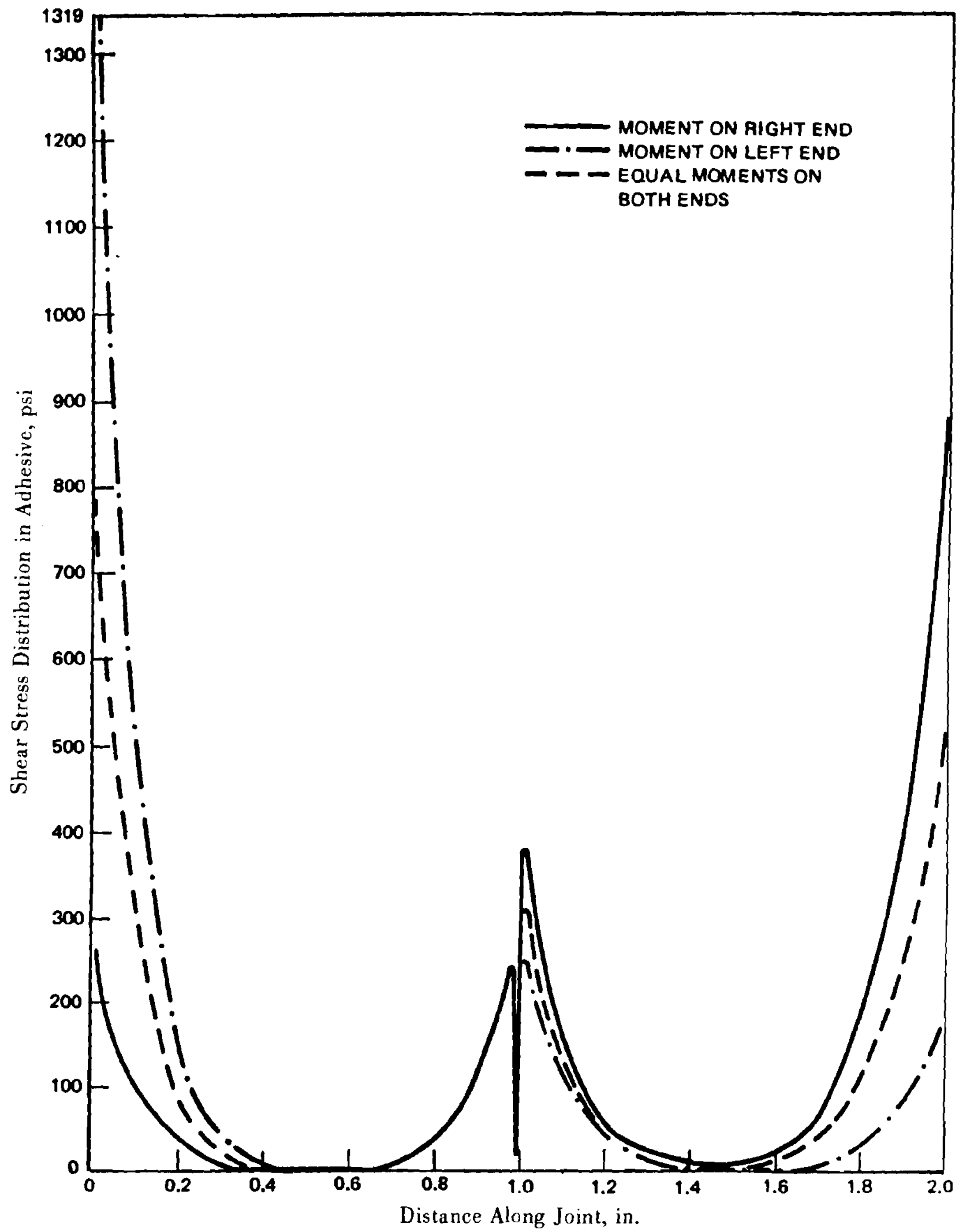


Figure 4-17. Stress Distribution in the Adhesive of a Two-Step Lap Joint[2]

thickness *t*, laminate lay-up patterns, and bolt arrangements. Bolt strength should be chosen to preclude bolt failure. When properly chosen, these parameters provide a balanced joint design in shear, tension, and bearing strengths, respectively. Because lay-up patterns can alter the shear, tension, and bearing properties of the laminate, the optimization of joint proportions must be geared to these laminate patterns. A bolted joint differs from a pinned joint in that clamping friction is an added factor in contributing to joint strength. With friction a factor

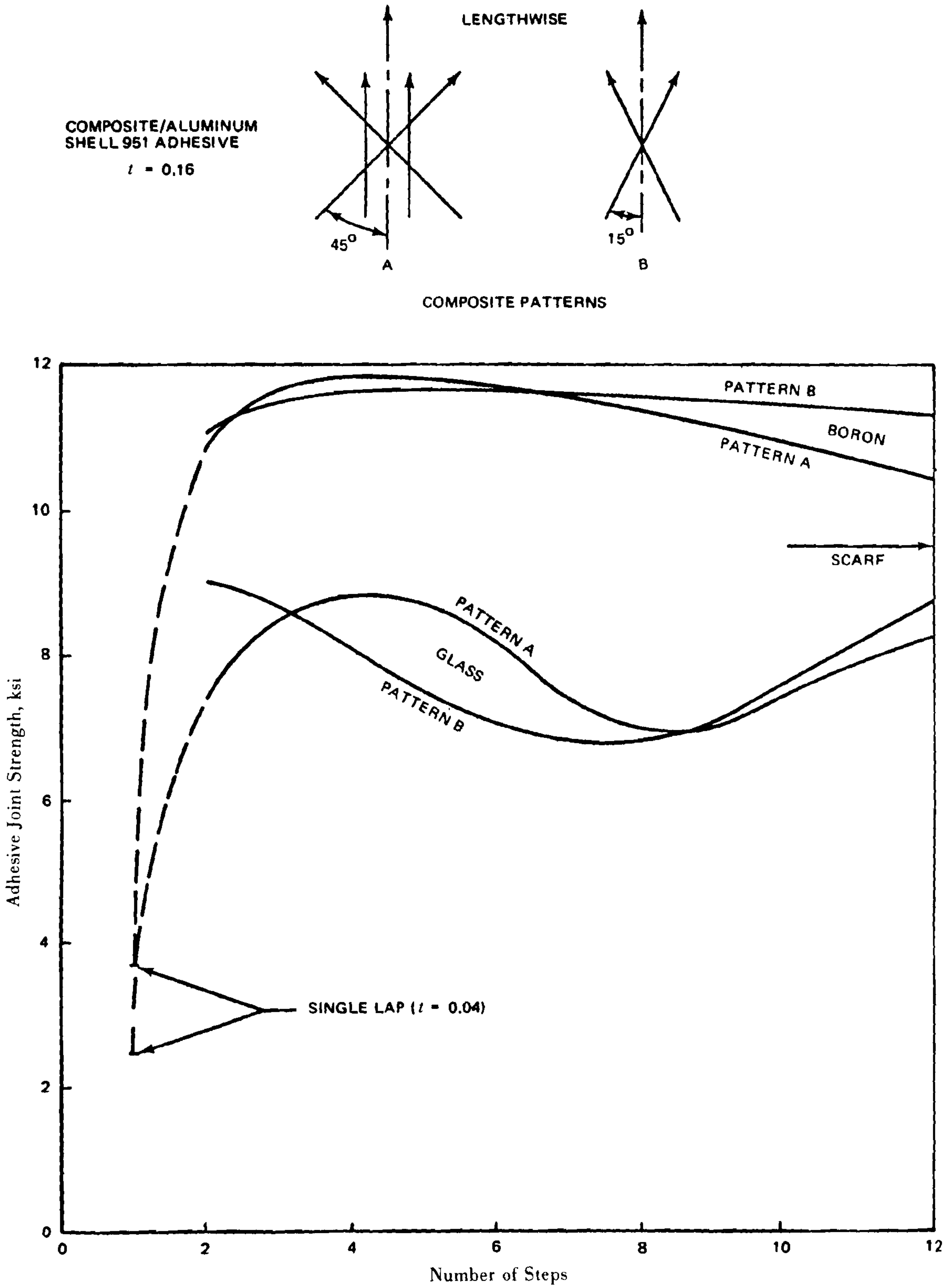


Figure 4-18. Stepped Lap Adhesive Joint Strength[4]

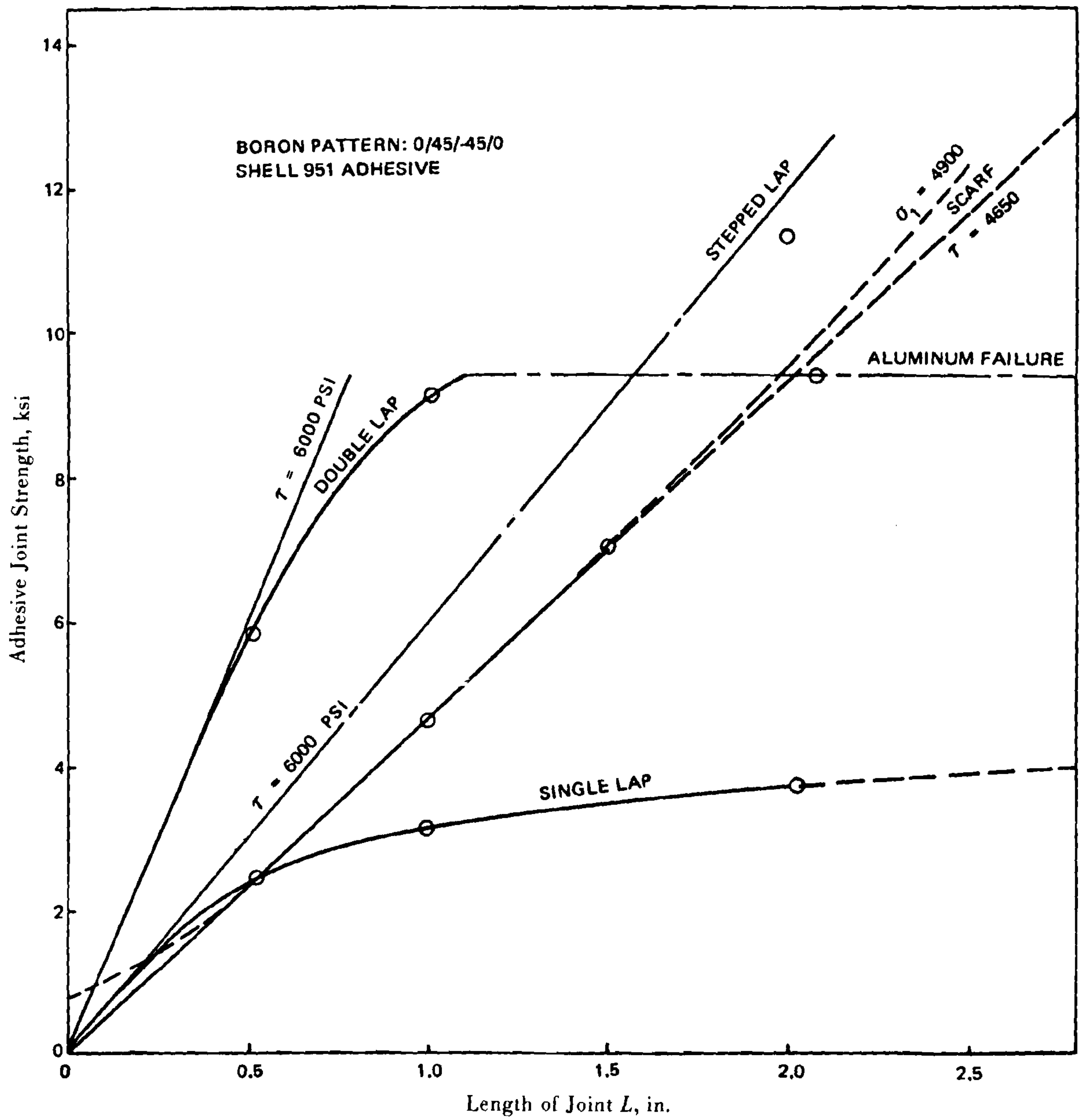


Figure 4-19. Boron-to-Aluminum Joint Strength[4]

in bolted joint strength, the surface condition and roughness as well as bolt torques must be specified in a bolted joint.

Specimen width should be chosen to allow sufficient side-distance bolt-diameter ratios s/D to preclude failure in tension through the bolt holes. Test results indicate that to achieve full bearing stress, t/D ratios should not be less than about 0.5. Similarly published test results suggest that the edge distance be great enough to yield an e/D ratio $\approx$ 5. Beyond this, bearing stress did not increase. Thus, to achieve full bearing stress, an $e/D > 5$ and $t/D > 0.5$ are suggested.

4-3.1 SINGLE- AND DOUBLE-LAP BOLTED JOINTS

4-3.1.1 Plain Holes

Tables 4-6 and 4-7, respectively, show the strengths of single- and double-lap joints of boron and glass composites bonded to themselves and to aluminum. These results indicate only slight improvement in strength for the double-lap composite/aluminum joints over the single lap. Failing modes in both cases were predominatly shear-out of the composite with some interlaminar shear and tension failures in the composite for the double-lap joints. The added weight considerations may not justify the small gain in strengths obtained.

4-3.1.2 Bushed Holes

Table 4-8 summarizes the test results obtained on double-lap joints with bushed holes. Since joint dimensions differ from the plain hole joint results in Tables 4-6 and 4-7, direct comparison cannot be made. However, from examining the average laminate stresses at failure, the bushed hole joints exhibit significantly lower laminate stress bearing capability for all their excess weight; for this reason they are not efficient joints.

4-3.1.3 Bolted Joints With Reinforced Edges

Reinforcing the edges of bolted joints can be employed to reduce the edge distances needed to develop full bolt strength and reduce shear-out failures. The reinforcement can be in the form of laminate buildup at the edge, or the inclusion of a shim of metal or other reinforcement. Tables 4-9 and 4-10 show the results of tests on composite and steel shim-reinforced laminates, respectively. It can be seen that the steel shim-reinforced joints failed primarily by tension in the laminate at the base of the shim and by shim delamination and laminate shear-out, but occasional bolt shear did occur — indicating that reinforcement can help the joint approach full bolt strength.

4-4 BOLTED AND BONDED JOINTS

Bolted and bonded joints yield strengths which are superior to either bolted or bonded joints of similar configuration when used alone. Table 4-11 shows that the bolted and bonded glass/aluminum joints were three times as strong as their bolted-only counterparts, and bolted and bonded boron/aluminum joints were five times

**TABLE 4-6
SUMMARY OF SINGLE-LAP BOLTED JOINT TEST RESULTS
(1-IN. SPECIMEN WIDTH)***

JOINT DESCRIPTION AND MATERIALS	LAMINATE THICKNESS, in.	ULTIMATE STATIC LOAD**, lb	AVERAGE LAMINATE STRESSES AT FAILURE			FAILURE MODE
			SHEAR-OUT psi	TENSION, psi	BEARING, psi	
SINGLE LAP FIBERGLASS/7075-T6	0.112	2523	15,200	28,030	119,920	SHEAR-OUT
SINGLE LAP BORON/7075-T6	0.116	2823	16,160	29,640	127,740	SHEAR-OUT
SINGLE LAP FIBERGLASS/ FIBERGLASS	0.114	2087	12,430	23,580	98,120	SHEAR-OUT
SINGLE LAP BORON/BORON	0.116	2560	14,720	27,210	115,240	SHEAR-OUT

*0.190-IN. BOLT DIAMETER, 0.750-IN. EDGE DISTANCE, PATTERN A, TABLE 4-1.
**AVERAGE OF FIVE TESTS

TABLE 4-7
SUMMARY OF DOUBLE-LAP BOLTED JOINT TEST RESULTS (1-IN. SPECIMEN WIDTH)[2]

JOINT AND MATERIALS	LAMINATE THICKNESS, in.	EDGE DISTANCE, in.	PATTERN †	ULTIMATE STATIC LOAD, AVERAGE OF 5 TESTS, lb	AVERAGE LAMINATE STRESSES AT FAILURE			
					SHEAR-OUT, psi	TENSION, psi	BEARING psi	FAILURE MODE*
DOUBLE-LAP FIBERGLASS/7075-T6	0.100	0.50	A	1862	18,600	23,000	98,000	(1), (4)
	0.102	0.75	A	2359	15,400	28,600	122,000	(1), (4)
	0.104	1.25	A	2583	9,900	30,700	131,000	(3), (4)
	0.110	0.50	F	1133	10,300	12,800	54,200	(1), (4)
	0.102	0.75	F	1630	10,600	19,700	84,000	(1), (4)
	0.108	1.25	F	2226	8,200	25,400	108,500	(1), (4)
	0.148	0.50	A	2559	17,300	21,300	91,000	(1), (4)
	0.138	0.75	A	3244	15,700	29,000	123,000	(1), (4)
	0.146	1.25	A	3782	10,400	32,000	136,500	(3), (4)
	0.138	0.50	G	1340	9,700	12,000	51,100	(1), (4)
	0.151	0.75	G	2302	10,200	18,900	80,000	(1), (4)
	0.143	1.25	G	2600	7,300	22,400	95,500	(1), (4)
DOUBLE-LAP BORON/7075-T6	0.128	0.50	A	2189	17,100	21,200	90,000	(1)
	0.117	0.75	A	3028	17,200	32,000	136,000	(1)
	0.120	1.25	A	3420	11,400	35,200	150,000	(1), (2), (4)
	0.133	0.50	D	1524	11,500	14,200	60,600	(1)
	0.115	0.75	D	2059	11,900	22,100	94,500	(1)
	0.116	1.25	D	3107	10,700	33,000	141,000	(1)
	0.168	0.50	A	2621	15,600	19,200	82,000	(1)
	0.160	0.75	A	4214	17,500	32,500	138,700	(1), (2)
	0.163	1.25	A	4756	11,700	36,000	154,000	(1), (2), (4)
	0.166	0.50	E	1648	9,900	12,300	52,100	(1)
	0.157	0.75	E	2604	11,000	20,500	87,500	(1)
	0.165	1.25	E	4317	10,500	32,300	138,000	(1)

*(1) SHEAR-OUT
(2) TENSION AT SECTION THROUGH BOLT HOLE
(3) BEARING
(4) INTERLAMINAR SHEAR
**THESE STRESSES COMPUTED AS THOUGH ADHESIVE WAS NOT INCLUDED.

†SEE TABLE 4-1

TABLE 4-8
SUMMARY OF DOUBLE-LAP BOLTED JOINT TEST RESULTS — BUSHED HOLES[2]

JOINT DESCRIPTION, MATERIALS, AND SPECIMEN WIDTH	LAMINATE THICKNESS, in.	BOLT DIAMETER, in.	EDGE DISTANCE, in.	PATTERN*	FIBER AT ±45°, %	ULTIMATE STATIC LOAD AVERAGE OF 5 TESTS, lb	AVERAGE LAMINATE STRESSES AT FAILURE			FAILURE MODES†
							SHEAR-OUT, psi	TENSION, psi	BEARING, psi	
DOUBLE LAP	0.171	0.3125	1.0	A	50	4773	11,690	24,670	74,800	(1)
BORON-ALUMINUM	0.171	0.3125	1.5	A	50	4524	8,820	27,930	84,640	(2)
	0.176	0.3125	2.0	A	50	4565	6,480	27,360	83,020	(1), (2)
1.250-IN.	0.127	0.3125	1.0	A	50	3595	13,460	28,820	86,100	(1), (2)
SPECIMEN	0.126	0.3125	1.5	A	50	3865	10,220	32,340	98,000	(1), (2)
WIDTH	0.127	0.3125	2.0	A	50	4683	9,230	39,240	118,240	(1), (2)
DOUBLE LAP	0.167	0.3125	1.0	A	50	4253	12,710	26,860	81,380	(1)
FIBER-	0.166	0.3125	1.5	A	50	4889	9,820	31,490	94,260	(3)
GLASS/ALUMINUM	0.146	0.3125	2.0	A	50	5001	8,590	37,210	110,000	(3)
1.250-IN.	0.128	0.3125	1.0	A	50	3487	13,660	29,190	87,480	(1)
SPECIMEN	0.122	0.3125	1.5	A	50	3825	10,480	33,740	100,540	(3)
WIDTH	0.121	0.3125	2.0	A	50	4174	8,810	37,120	110,200	(3)

†(1) SHEAR-OUT
(2) TENSION AT SECTION THROUGH BOLT HOLE
(3) BEARING FAILURE

*SEE TABLE 4-1

TABLE 4-9
SUMMARY OF COMPOSITE-REINFORCED BOLTED JOINT TEST RESULTS[2]

JOINT DESCRIPTION, MATERIALS, AND SPECIMEN WIDTH	LAMINATE THICKNESS, in.	BOLT DIAMETER, in.	EDGE DISTANCE, in.	PATTERN†	FIBER AT ±45°, %	ULTIMATE STATIC LOAD AVERAGE OF 5 TESTS, lb	AVERAGE LAMINATE STRESSES AT FAILURE			FAILURE MODES*
							SHEAR-OUT, psi	TENSION, psi	BEARING, psi	
DOUBLE-LAP BORON/STEEL** 0.750-IN. SPECIMEN WIDTH	0.278	0.190	0.50	A	50	4,602	16,500	28,600	87,300	(1)
	0.279	0.190	0.75	A	50	6,910	16,600	44,300	130,000	(1), (3)
	0.279	0.190	1.25	A	50	7,215	10,400	45,900	137,000	(1), (3)
	0.292	0.190	0.50	D	43	3,885	13,300	23,500	70,000	(1)
	0.301	0.190	0.75	D	43	6,785	15,000	39,700	118,500	(1)
	0.289	0.190	1.25	D	43	7,140	9,900	43,600	130,000	(1)
DOUBLE-LAP FIBERGLASS/ STEEL** 0.750-IN. SPECIMEN WIDTH	0.283	0.190	0.50	A	50	5,975	21,100	37,500	111,000	(1), (2)
	0.268	0.190	0.75	A	50	6,390	15,800	42,400	125,500	(1), (2)
	0.275	0.190	1.25	A	50	6,725	9,800	42,900	129,000	(1), (2)
	0.257	0.190	0.50	F	43	4,763	18,500	33,300	97,500	(1), (2)
	0.274	0.190	0.75	F	43	6,470	15,700	41,800	124,000	(1), (2)
	0.257	0.190	1.25	F	43	6,420	10,000	44,500	131,000	(1), (2)
DOUBLE-LAP BORON/STEEL** 1-IN. SPECIMEN WIDTH	0.366	0.250	0.75	A	50	9,179	16,700	33,500	100,000	(1)
	0.378	0.250	1.00	A	50	11,914	15,800	42,000	126,000	(1), (3)
	0.361	0.250	1.50	A	50	12,021	11,100	44,400	133,000	(1), (3)
	0.346	0.250	0.75	E	39	6,284	12,100	24,200	72,500	(1)
	0.373	0.250	1.00	E	39	10,715	14,400	38,300	115,000	(1)
	0.343	0.250	1.50	E	39	10,300	10,000	40,000	120,000	(1)
DOUBLE-LAP FIBERGLASS/ STEEL** 1-IN. SPECIMEN WIDTH	0.381	0.250	0.75	A	50	10,796	18,900	37,700	113,000	(1), (2)
	0.351	0.250	1.00	A	50	11,200	15,900	42,500	127,700	(1), (2)
	0.324	0.250	0.75	G	39	7,463	15,300	30,700	92,000	(1), (2)
	0.342	0.250	1.00	G	39	8,742	12,800	34,100	102,000	(1), (2)
	0.353	0.250	1.50	G	39	10,430	9,800	39,500	118,000	(1), (2)

*(1) SHEAR-OUT
(2) INTERLAMINAR SHEAR
(3) TENSION AT SECTION THROUGH BOLT HOLE
**RIGID TEST FIXTURE

†SEE TABLE 4-1

TABLE 4-10
SUMMARY OF SHIM-REINFORCED BOLTED JOINT TEST RESULTS[2]

JOINT DESCRIPTION, MATERIALS, AND SPECIMEN WIDTH	LAMINATE THICKNESS, in.	BOLT DIAMETER, in.	EDGE DISTANCE, in.	PATTERN†	ULTIMATE STATIC LOAD AND NO. TESTS, lb	AVERAGE LAMINATE STRESSES AT FAILURE			FAILURE MODES*
						SHEAR-OUT, psi	TENSION, psi	BEARING, psi	
DOUBLE-LAP	0.192	0.190	0.375	A	6,938 (5)	49,100	64,500	191,000	(2), (3), (4)
BORON/STEEL**	0.192	0.190	0.500	A	6,670 (4)	34,700	62,000	184,000	(2), (3), (4)
0.750-IN.	0.192	0.190	1.000	A	7,813 (5)	20,400	72,600	215,000	(2), (7)
SPECIMEN WIDTH	0.192	0.190	0.375	D	6,893 (5)	47,800	64,000	189,500	(2), (3)
	0.192	0.190	0.500	D	7,690 (5)	40,000	71,500	212,000	(2), (3)
	0.192	0.190	1.000	D	8,360 (4)	21,800	77,800	130,000	(1), (3)
DOUBLE-LAP	0.192	0.190	0.375	A	4,550 (4)	31,600	42,400	125,000	(2), (3)
FIBERGLASS/	0.192	0.190	0.500	A	5,300 (5)	27,600	49,400	146,000	(2), (3)
STEEL*	0.192	0.190	1.000	A	5,006 (5)	13,000	46,500	137,500	(2), (3)
0.750-IN.	0.192	0.190	0.375	F	4,070 (5)	28,200	37,900	112,000	(2), (3), (4)
SPECIMEN WIDTH	0.192	0.190	0.500	F	5,354 (5)	27,900	49,800	147,400	(2)
	0.192	0.190	1.000	F	5,316 (5)	13,800	49,400	146,000	(2), (3)
DOUBLE-LAP	0.260	0.250	0.4375	A	11,905 (5)	52,500	61,300	184,000	(4)
BORON/STEEL**	0.260	0.250	0.500	A	12,820 (5)	49,400	65,800	197,000	(4), (5)
1-IN.	0.260	0.250	0.750	A	12,800 (4)	32,800	65,700	197,100	(4)
SPECIMEN WIDTH	0.260	0.250	0.4375	E	10,800 (3)	47,500	55,500	166,000	(6)
	0.260	0.250	0.500	E	11,815 (5)	45,500	60,600	184,000	(3), (4)
	0.260	0.250	0.750	E	14,900 (5)	38,200	76,500	229,000	(2), (3), (4)
	0.260	0.250	1.250	E	14,850 (2)	22,800	76,200	228,000	(1)
DOUBLE-LAP	0.260	0.250	0.500	A	7,172 (5)	27,600	36,800	110,000	(3), (4)
FIBERGLASS/	0.260	0.250	0.750	A	8,888 (5)	22,800	45,500	137,000	(3)
STEEL**	0.260	0.250	0.500	G	7,100 (5)	27,400	36,500	109,400	(3)
1-IN.	0.260	0.250	0.750	G	7,392 (5)	18,900	37,900	113,700	(3)
SPECIMEN WIDTH	0.260	0.260	1.250	G	8,142 (5)	12,500	41,700	125,000	(3), (4)

*1. BOLT SHEAR
2. TENSION IN LAMINATE AT BASE OF SHIMS
3. SHIM DELAMINATION AND LAMINATE SHEAR-OUT
4. TENSION IN LAMINATE AND SHIM OF SECTION THROUGH FASTENER HOLE
5. TENSION IN LAMINATE AND ONE SHIM, TENSION AND SHEAR-OUT IN SECOND SHIM
6. SHEAR-OUT OF LAMINATE AND ONE SHIM, TENSION IN SECOND SHIM
7. TENSION IN OUTER PLIES OF LAMINATE AT BASE OF SHIMS AND AT SECTION THROUGH FASTENER HOLE IN PLIES BETWEEN SHIMS; PARTIAL DELAMINATION OF SHIMS.

**RIGID TEST FIXTURE

†SEE TABLE 4-1

TABLE 4-11
SUMMARY OF DOUBLE-LAP BOLTED AND BONDED JOINT TEST RESULTS[2]

JOINT AND MATERIALS	LAMINATE THICKNESS, in.	EDGE DISTANCE, in.	PATTERN †	ULTIMATE STATIC LOAD, AVERAGE OF 5 TESTS, lb	AVERAGE LAMINATE STRESSES AT FAILURE			FAILURE MODE*
					SHEAR-OUT, psi	TENSION, psi	BEARING, psi	
DOUBLE-LAP FIBERGLASS/7075-T6 BOLTED AND BONDED	0.120	0.75	A	7470	41,500**	77,000**	328,000**	(1), (2)
DOUBLE-LAP BORON/7075-T6 BOLTED AND BONDED	0.120	0.75	A	12,875	71,500**	132,000**	564,000**	(1), (2)

*(1) TENSION AT SECTION THROUGH BOLT HOLE
(2) INTERLAMINAR SHEAR
**THESE STRESSES COMPUTED AS THOUGH ADHESIVE WAS NOT INCLUDED.
†SEE TABLE 4-1

as strong as bolted only. The presence of a bolt in a bonded double-lap joint of 3-in^2 area is seen to increase average bond shear stress in glass from 1800 psi to 2717 psi, and in boron from 3300 psi to 4300 psi. There is, therefore, a synergistic effect of the bolt and adhesive on one another.

4-5 REDUCING STRESS CONCENTRATIONS IN JOINTS

4-5.1 Model

The double-strap joint pictured in Fig. 4-20 will be used to illustrate some of the things which can be done to reduce stress concentrations due to stress risers resulting from abrupt configurational changes in bonded joints.

Assume undirectional composites with fibers parallel to load direction, then three types of failure are likely:

1. Tensile failure of main member of region A
2. Tensile failure of strap through region B.
3. Bond failure and shear-out originating at points C.

The stress diagrams in Fig. 4-20 show the stress concentrations in the main members, straps, and bond line as σ_A, σ_B, and τ, respectively.

4-5.2 STRAP MODIFICATIONS

Strap and main member failures can be minimized by proper sizing of members — e.g., making straps the same thickness as the main member (if the strap and main member are the same materials) to reduce strap failures, and increasing strap length to eliminate bond failure and shear-out. Main member failures at region B can be alleviated by reducing the stress concentrations in this area due to the abrupt load transfer between strap and main member. This can be done in several ways — by reducing strap thickness at the strap ends or by increasing adhesive thickness at the strap ends. Fig. 4-21 shows a number of ways to reduce strap thickness locally.

The stepped strap configuration (Fig. 4-21 (A)) affords greater flexibility and reduced stress concentration at the strap/main member boundary. While this reduces the probability of main member failure in the aforementioned location, the steps create stress risers in the strap thus introducing a new possible mode of failure — strap delamination originating at the step corners. Fig. 4-21 (B) shows a tapered strap which accomplishes the same stress concentration reduction as the stepped strap but in a continuous fashion. Finite element analysis by Sage[5] showed that stress concentration factors as low as about 1.1 were possible for a taper angle of under 5 deg with no step at the strap end. However, the end produced by machining to this angle is so frangible as to cause problems in machining, handling, and bonding. This led Sage to a radiused strap

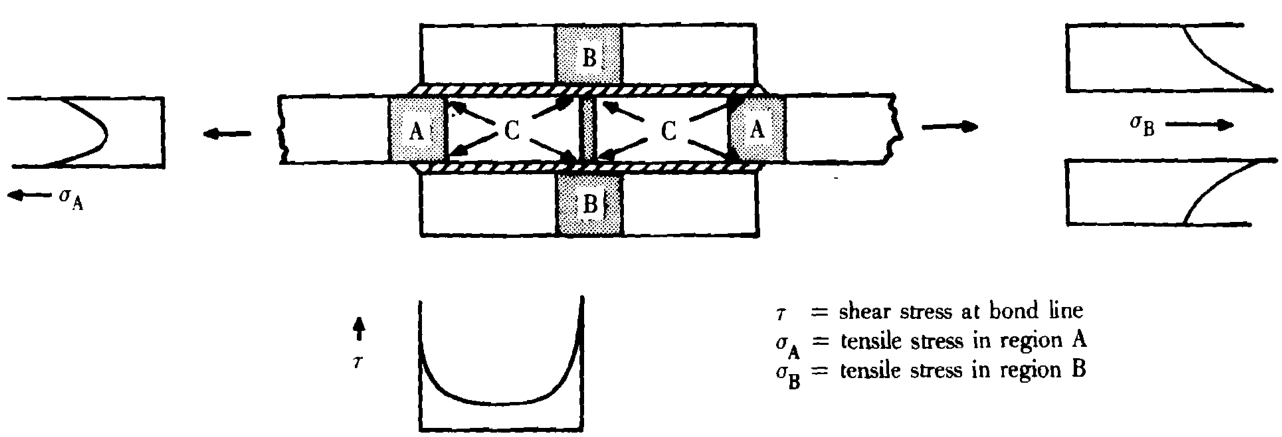
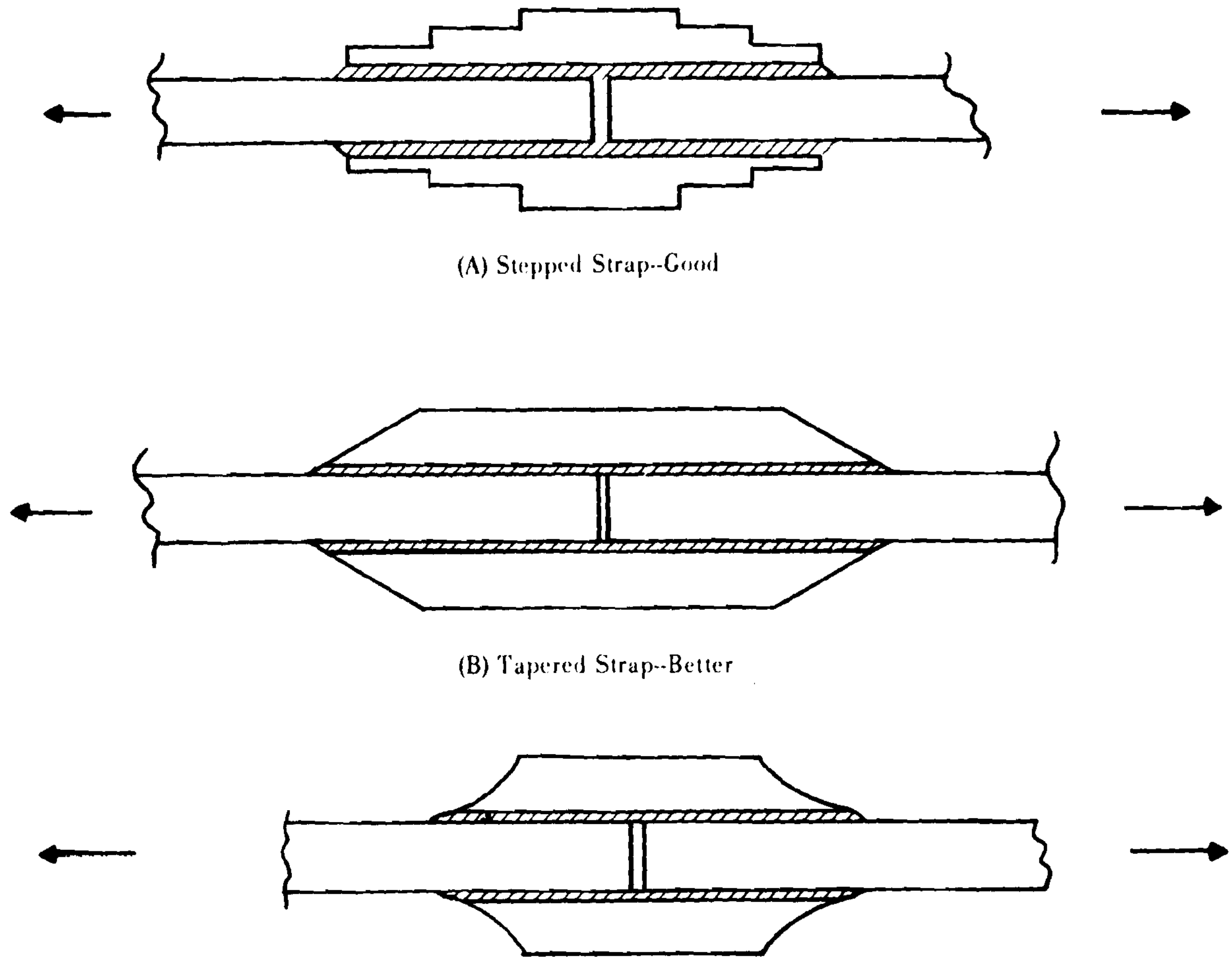


Figure 4-20. Model of a Double-Strap Joint



(A) Stepped Strap--Good

(B) Tapered Strap--Better

(C) Radiused Strap--Best

Figure 4-21. Ways to Reduce Strap Thickness Locally

configuration (Fig. 4-21 (C)) which solved a number of problems. First, the tangent to a large enough radius can easily approximate the 5-deg taper at the strap end and thereby meet the reduced stress concentration requirement. Second, a straight taper of this angle would require the removal of a large mass of strap and is not necessary after a modest distance from the strap end. Third, a flat strap can be bonded on and the radius machined afterward, allowing for uniform pressure application during cure and eliminating the handling problems. Small radii were found to cause interlaminar shear failure in the strap skin similar to that cautioned against in the stepped strap configuration. Larger radii circumvented this failure mode. The following equation suggests the minimum radius R to avoid this failure mode:

$$R = \left(\frac{f^{tu}}{f^{su}}\right) \times \frac{t}{2}\text{, in.} \qquad (4\text{-}1)$$

f^{tu} = ultimate tensile strength of the composite, psi

f^{su} = ultimate shear strength of the composite, psi

t = thickness of the joined composite members, in.

A factor of 2 was built into this equation in an effort to make R large enough to eliminate tensile failure as well. Fig. 4-22 shows us that a key advantage of the radiused strap is that, even for a short strap length, the favorable 5 deg angle at the strap end can be achieved for lowered stress. A modified straight taper is also shown which might offer a further advantage over the radiused strap yet avoid the difficulties of a straight taper.

4-5.3 INCREASED ADHESIVE THICKNESS

Another way to overcome the stress concentration at the ends of a strap is to increase the adhesive thickness at the main member/strap end interface. This avoids the abrupt load transfer in a manner much the same as reducing strap thickness or reducing stiffness in the region, thereby relieving rather than restraining stresses and distributing them more efficiently over the whole joint area. Fig. 4-23 is the configuration suggested by Sage to accomplish this in a double-strap joint.

Machining of the straps depicted in Fig. 4-23 would be rather tedious so a stepped strap configuration (Fig. 4-24) is suggested.

By forming the steps in the strap using prepreg, the machining of steps can be eliminated; however, filling the steps with adhesive is required. The performance of these joints is illustrated in Table 4-12. Load bearing efficiencies of greater than 100% have been achieved. This means that failure occurred outside the joint area in the main member. Thus, the joint could be considered too efficient from a load bearing standpoint and perhaps weight could be saved by design refinements.

4-5.4 INFLUENCE OF STRAP AND ADHESIVE THICKNESS ALTERATIONS ON JOINT EFFICIENCY

Tables 4-12 and 4-13 summarize the results of tests on type I and II carbon fiber reinforced plastic double-strap joints conducted by Sage. The load bearing efficiencies can be observed to respond to strap length, strap composition, strap radius, or step filler; and failure modes reflect the stress concentrations which result from the different configurations.

4-5.5 VARIABLE ADHESIVE STIFFNESS

Another means of reducing stress concentration at joint extremities is by the use of two adhesives of varying stiffness (Fig. 4-25) in the bond line. A lower stiffness adhesive at the joint ends will provide better stress distribution by relieving itself of the higher stresses at the joint ends and transferring the load into the center of the joint where a higher stiffness adhesive can carry a larger share of the load.

4-6 TYPICAL BOLTED JOINT CONFIGURATIONS

Several examples of bolted joint configurations are presented in Fig. 4-26. Variations on these basic joints can involve varying bolt placement on large joints but little else.

4-7 BOLTED FAILURE MODES

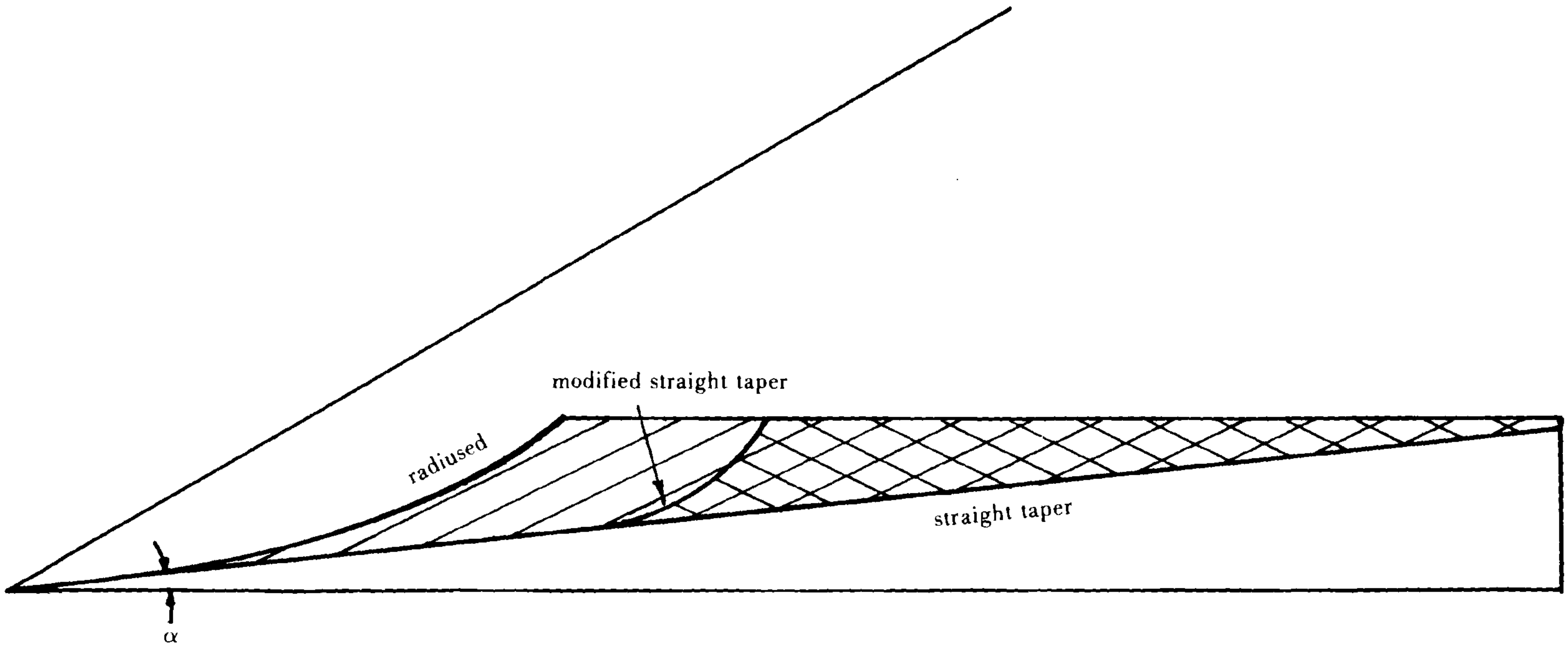
The types of failures which can occur in bolted joints are shown in Fig. 4-27. Bolted joints usually are designed to fail in bearing rather than tension or shear-out but all types of failure are encountered — usually a mixture of several modes. Another possibility, though rarely encountered, is bolt failure. Bolt strength should always be chosen to preclude this type of failure.

4-8 TYPICAL BONDED JOINT CONFIGURATIONS

Bonded joint design alternatives are more numerous than for bolted joints and are depicted in Fig. 4-28. Included are single and double laps; single and double straps; scarfs; and pinned, keyed, and variable stiffness and thickness adhesive types.

4-9 BONDED FAILURE MODES

Bonded joints should ideally fail cohesively since that indicates the adhesive has been stressed to its ultimate in load transfer



All can provide for an $\alpha = 5$ deg at strap end but a radiused or modified straight taper permits a shorter more practical strap length.

Figure 4-22. Methods of Reducing Stress Concentration at Strap Ends

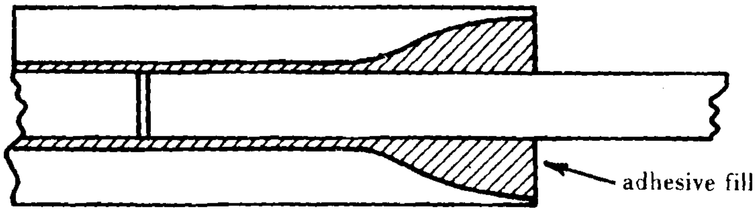


Figure 4-23. Idealized Shape for Variable Adhesive Thickness

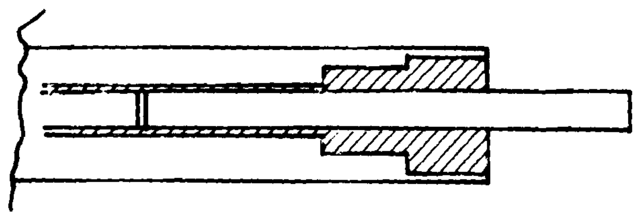


Figure 4-24. Filled Step Strap Joint

capability. Adhesive failure indicates that poor adhesion is present due usually to poor processing or to adverse environmental effects such as moisture displacing the adhesive at the adhesive/adherend interface. Interlaminar shear failure in the composite is encountered frequently due to the anisotropic nature of laminates and the many processing parameters which can induce flaws in the composite. Fig. 4-29 depicts possible failure modes.

4-10 WEIGHT OF JOINTS

As discussed in Chapter 1 the weight of the joint is critical to its overall efficiency and ultimate usefulness. Load carrying efficiencies of 100% or more are possible but excessive weight is the price paid. A load carrying efficiency of 100% accompanied by a weight efficiency of 50% yields an overall joint efficiency E of just 50% as defined by Eq. 1-3. High joint efficiencies are achieved by keeping the load carrying capability of the joint design as close to that of the continuous unjoined member while keeping the weight increment added as small as one can.

A weight study conducted on different boron composite and aluminum joints (bonded and bolted)[1] yielded data on weight added to achieve different joint strengths. The results (Fig. 4-30) show that a weight increment of about 0.04 lb/in. of bonded joint width was required to obtain a single-lap joint strength of about 3500 lb/in.; double-lap joint strength, of about 5500 lb/in.; and a scarf joint strength, of about 20,000 lb/in. Just 0.01 lb/in. of joint width yields a strength of 20,000 lb/in. for a four-step lap joint. Thus a stepped lap or scarf joint is seen to be much more efficient than a double- or single-lap joint. Data from the bolted joint study (Fig. 4-31) show an almost linear relationship between strength, and weight, i.e., those bolted configurations which were the strongest were also the heaviest. It is significant to note that the incorporation of adhesive into a bolted lap joint raised joint strength approximately threefold with no weight penalty as shown in Fig. 4-31. Fig. 4-32 compares the weight added by different joint designs to achieve the same load. The bonded scarf and stepped lap joint are shown to add little or

TABLE 4-12
PERFORMANCE OF RADIUSED DOUBLE-STRAP JOINTS EMPLOYING CARBON FIBER REINFORCED PLASTICS[5]

FIBER TYPE		STRAP DIMENSIONS, mm			RADIUS R,	FAILURE MODE UNDER STATIC	JOINT	
MAIN MEMBER	STRAP	LENGTH	WIDTH	THICKNESS	mm	AXIAL TENSION	EFFICIENCY	COMMENT
I	I	76	24	1.27	200	Tension in main member away from joint area	1	Failure outside joint indicates over design and excess weight. Shorter strap length is possible.
I	I	76	24	1.27	76	Tension in main member away from joint area	1	Same as above.
I	grp*	76	24	1.27	76	Interlaminar shear in grp strap close to bond	0.7	Strap strength is too low. Lower stiffness grp chases stress to joint center.
I	grp	76	24	1.27	200	Interlaminar shear in grp strap close to bond	0.7	Same as above.
I	I	50	24	1.27	76	Tension in strap at center	0.7	Increased stress concentrations due to shorter strap length
II	II	76	24	1.27	76	Shear in strap	1	Radius is insufficient to alleviate stress concentration in the stiffer Type II crfp.†
II	II	76	24	1.27	200	Tension in main member away from joint area	1	Shorter strap length is possible. Larger radius chased failure back to main member outside of joint.
II	II	76	24	1.27	200	Tension in main member and strap at strap end	1	AF-130 adhesive used. More brittle than BSL 312/3 used on others

*grp — glass reinforced plastic

†crfp — carbon reinforced plastic

TABLE 4-13
PERFORMANCE OF INVERSED STEPPED STRAP JOINTS EMPLOYING CARBON FIBER REINFORCED PLASTICS[5]

FIBER TYPE		STRAP DIMENSIONS, mm			FILLING	FAILURE MODE	LOAD BEARING	
MAIN MEMBER	STRAP	LENGTH	WIDTH	THICKNESS	IN STEPS	UNDER STATIC AXIAL TENSION	EFFICIENCY *E*	COMMENT
I	I	127	24	1.00	crfp*	Tension in main member	1	Joint overdesigned. Shorter strap could cut weight.
I	I	90	24	1.00	crfp	Tension and shear at strap end	0.7	crfp fibers transverse to load unable to withstand increased stress at this strap length.
I	I	127	24	1.00	Adhesive BSL 312/3	Tension in main member outside joint area	1	Larger strap length with adhesive step filler yields same result as with crfp filler. Some strap length between 127 mm and 90 mm seems optimum.
I	I	90	24	1.00	Adhesive BSL 312/3	Tension and shear at strap end	0.9	Failure mode similar to crfp filler at this strap length but higher failing load and shear location indicate isotrophic adhesive filler cohesively stronger than transverse crfp.
II	II	90	24	1.00	crfp	Tension and shear at strap end	0.7	Same as configuration 2.
II	II	90	24	1.00	Adhesive BSL 312/3		1	Same as configuration 4 but higher strength main member fails at higher load.

*carbon reinforced plastic

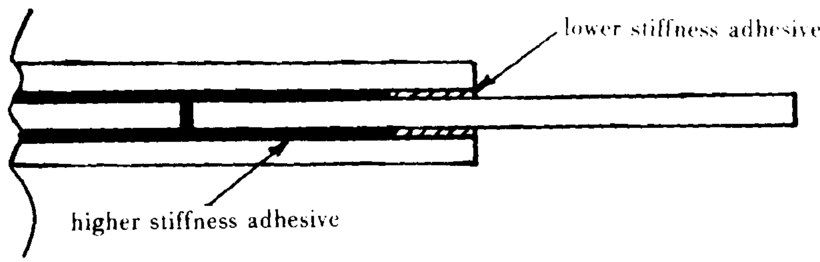
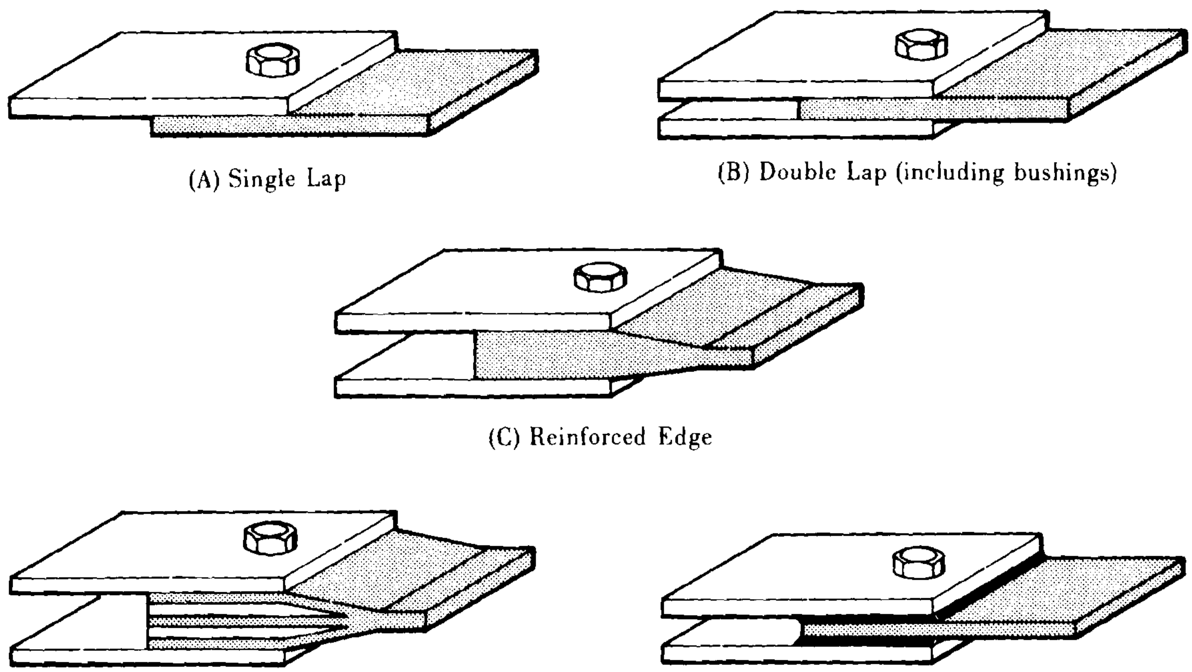


Figure 4-25. Variable Stiffness Adhesive Joint



(A) Single Lap

(B) Double Lap (including bushings)

(C) Reinforced Edge

(D) Shim Joint

(E) Bolted-Bonded

Figure 4-26. Bolted Joint Designs[2]

no weight whereas the bonded double-lap and bolted double-lap joints added in excess of 30% to the basic panel weight.

4-11 FATIGUE

4-11.1 BONDED JOINTS

The fatigue behavior of several types of glass/aluminum and boron/aluminum bonded joints is shown in Table 4-14. Clearly, although the scarf joints had among the highest average adhesive shear stress by comparison with the other joint types, the low stress concentration factor (SCF) in the scarfed configuration resulted in less severe stressing of the joint. This is graphically depicted in Fig. 4-33. S-N (Stress-Number of Cycles to Failure) curves for boron/aluminum bonded scarf and double-lap joints are shown in Figs. 4-34 and 4-35. Similar curves for a graphite/graphite single-lap and graphite/titanium scarf joints are shown in Figs. 4-36 through 4-40 for both room temperature and 350°F. Elevated temperature is seen to reduce fatigue endurance substantially.

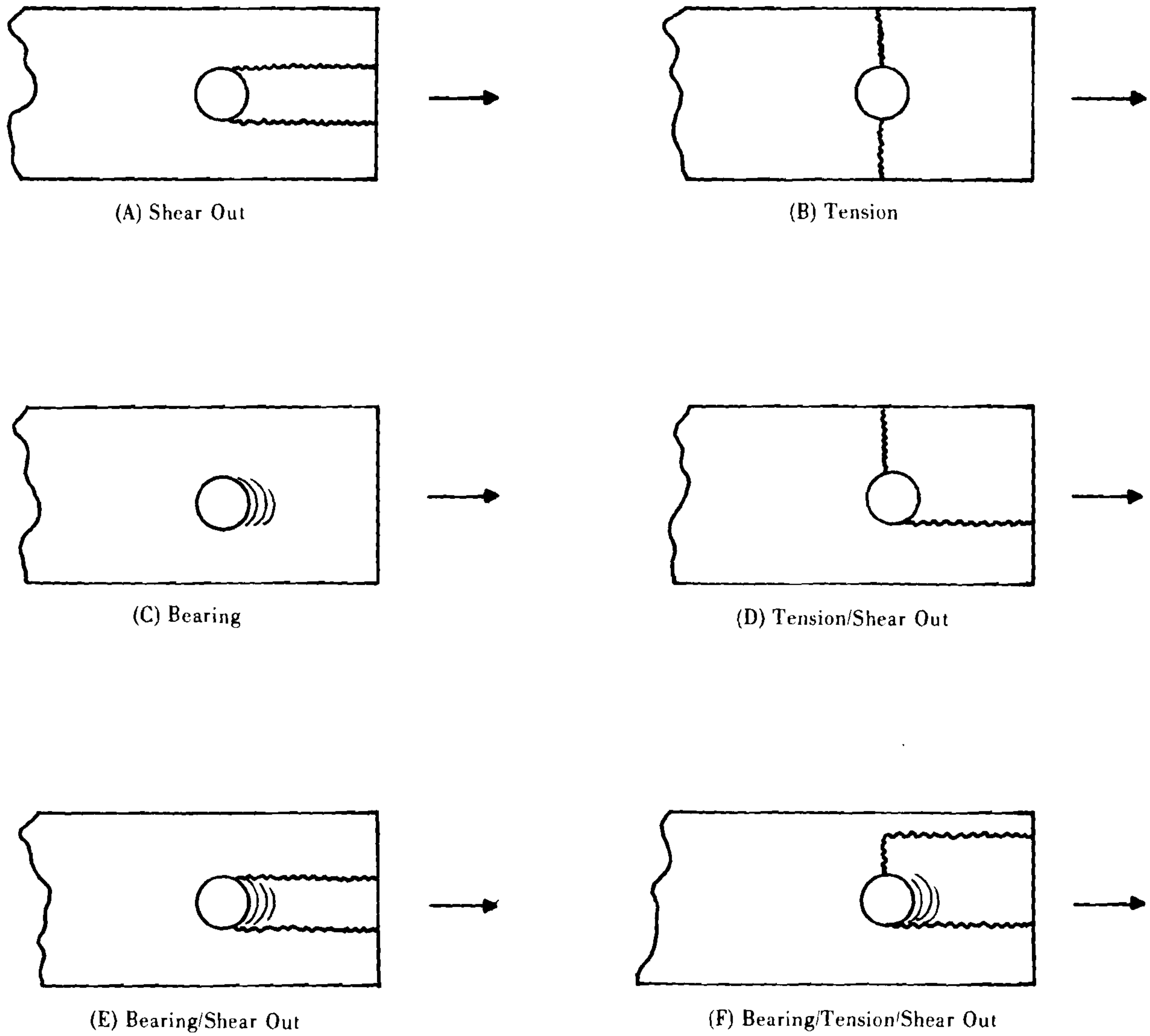
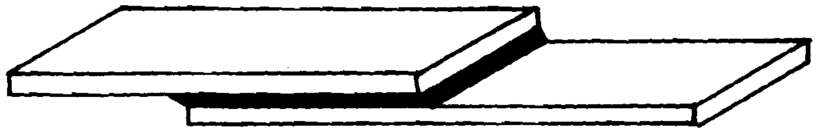


Figure 4-27. Bolted Failure Modes

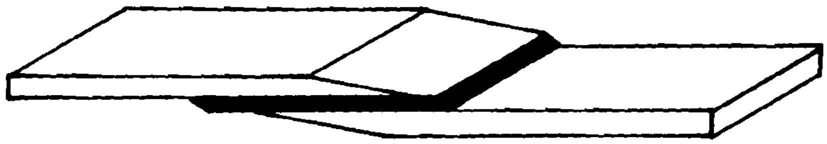
4-11.2 BOLTED JOINTS AND BOLTED-BONDED JOINTS

A tabulation of single- and double-lap boron and glass bolted joint fatigue results is presented in Table 4-15 as well as data on bolted and bonded glass/aluminum and boron/aluminum joints. Double-lap bolted joint fatigue endurance was greater than for the single lap. Failure was through the aluminum bolt hole not the boron bolt hole. Direct comparisons between the bolted and the bonded joints are not possible because of the different configurations but, generally, the maximum loads on the bolted joints were less than those on the bonded joints.

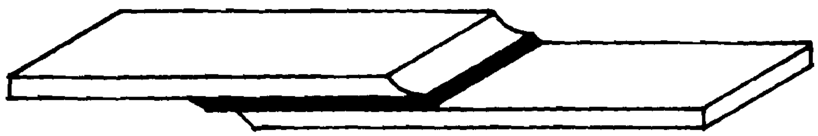
Adding adhesive to the bolted joint permitted the maximum and minimum load on the joint to be increased 250% with good results. Failures in the configuration were a mixture of laminate and aluminum through the bolt hole, and aluminum through the basic section.



simple

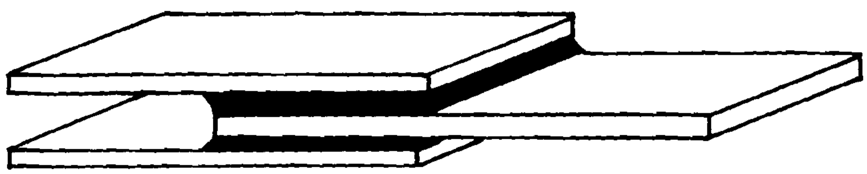


beveled (external scarf)

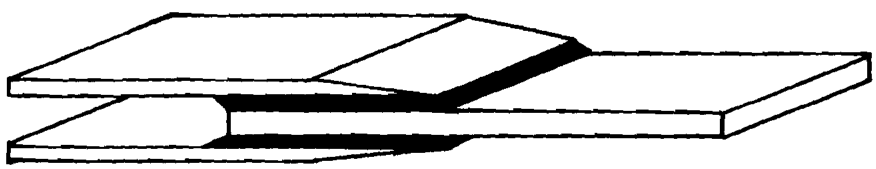


radiused

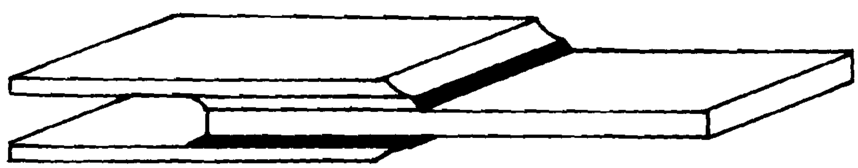
(A) Single-Lap Joints



simple



beveled



radiused

(B) Double-Lap Designs

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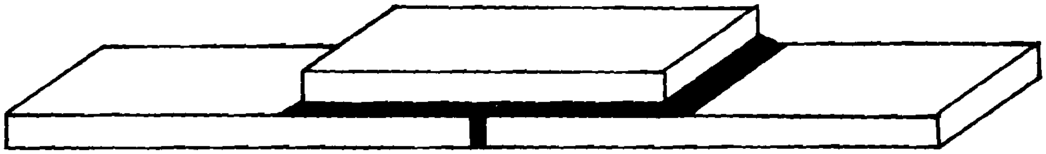
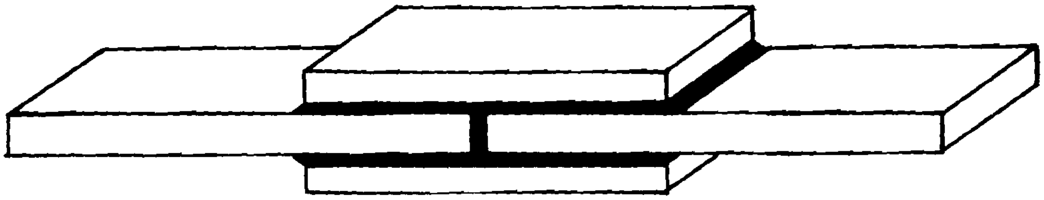
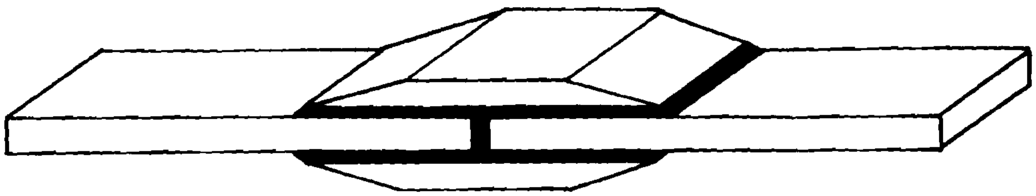
Figure 4-28. Bonded Joint Designs



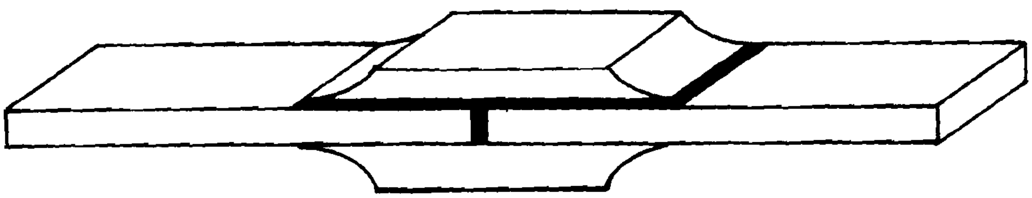
single strap



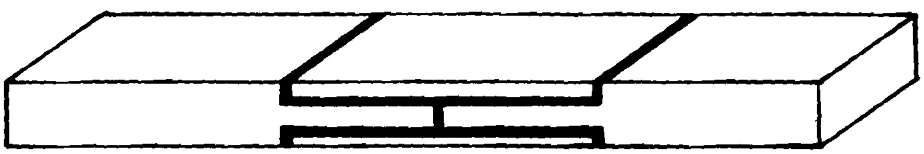
double strap



beveled straps



radiused straps



recessed double strap

(C) Strapped Joints

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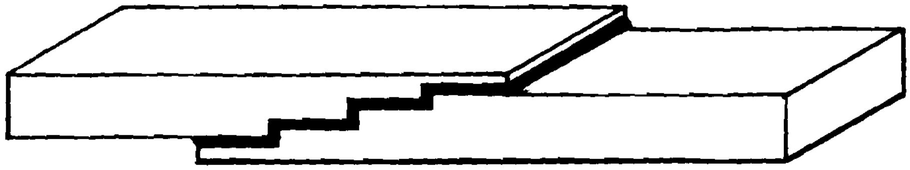
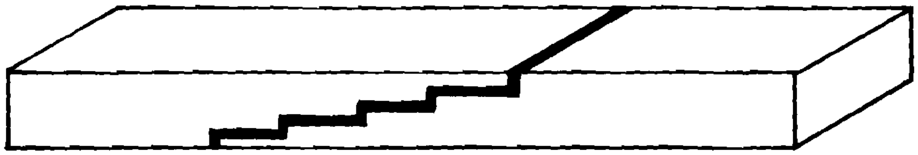
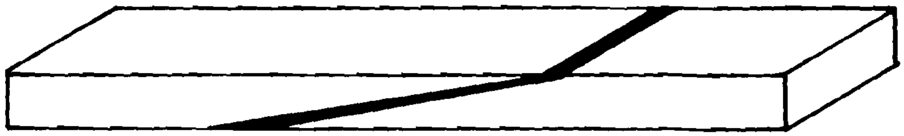
Figure 4-28. (cont'd)



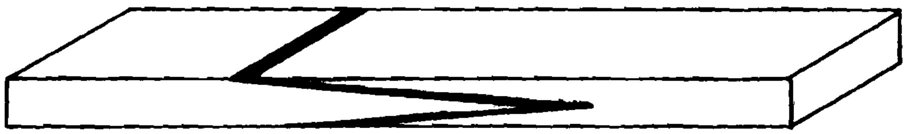
simple stepped lap



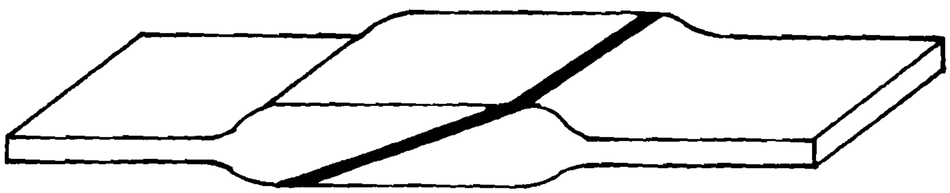
recessed stepped lap



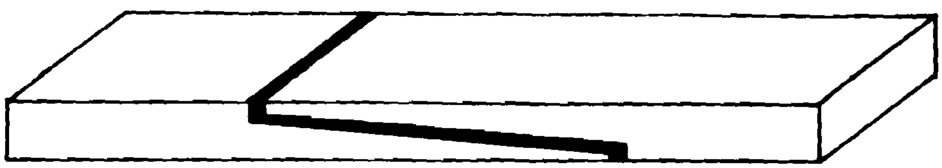
scarf (single taper)



scarf (double taper)



increased thickness scarf joint

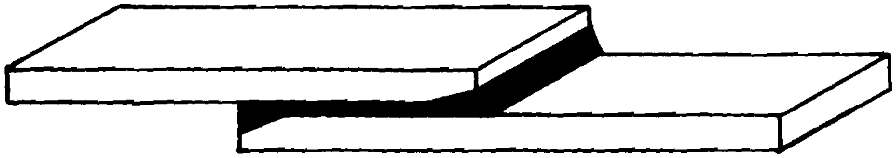


landed scarf

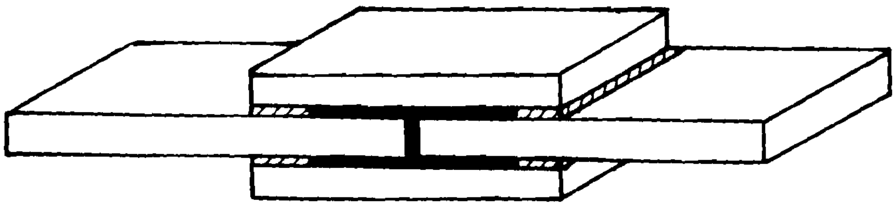
(D) Stepped Lap and Scarf Joints

(cont'd on next page)

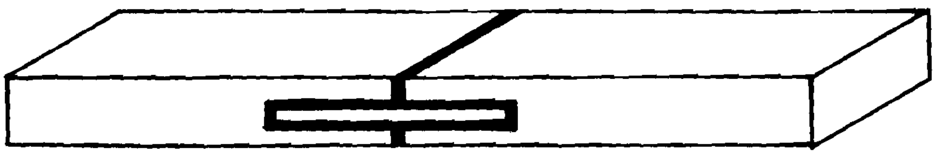
Figure 4-28. (cont'd)



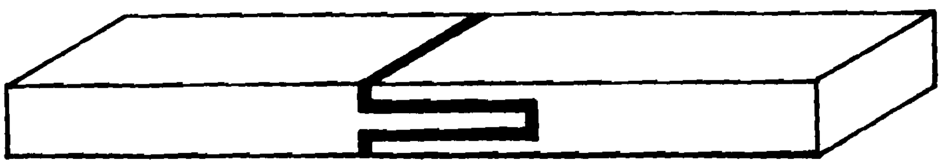
variable adhesive thickness



variable stiffness adhesive



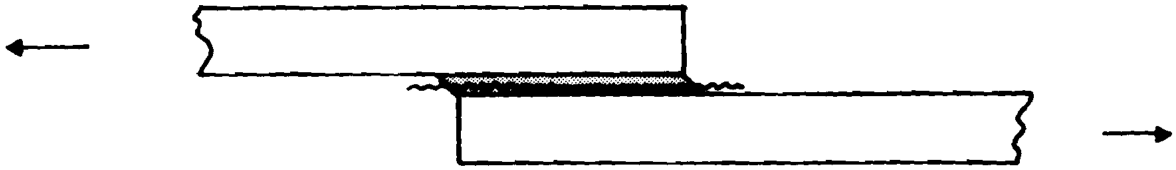
pin



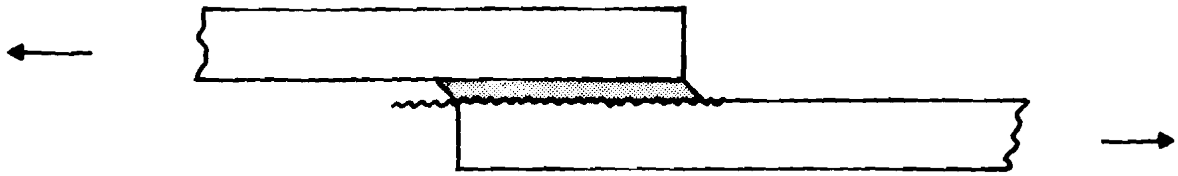
key

(E) Adhesives

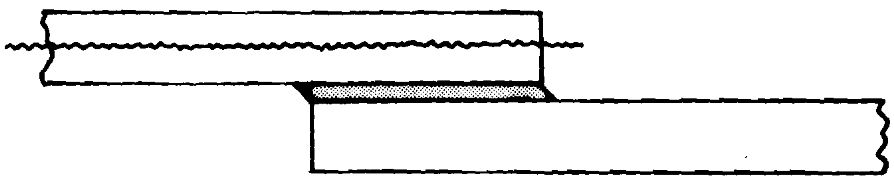
Figure 4-28. (cont'd)



(A) Cohesive

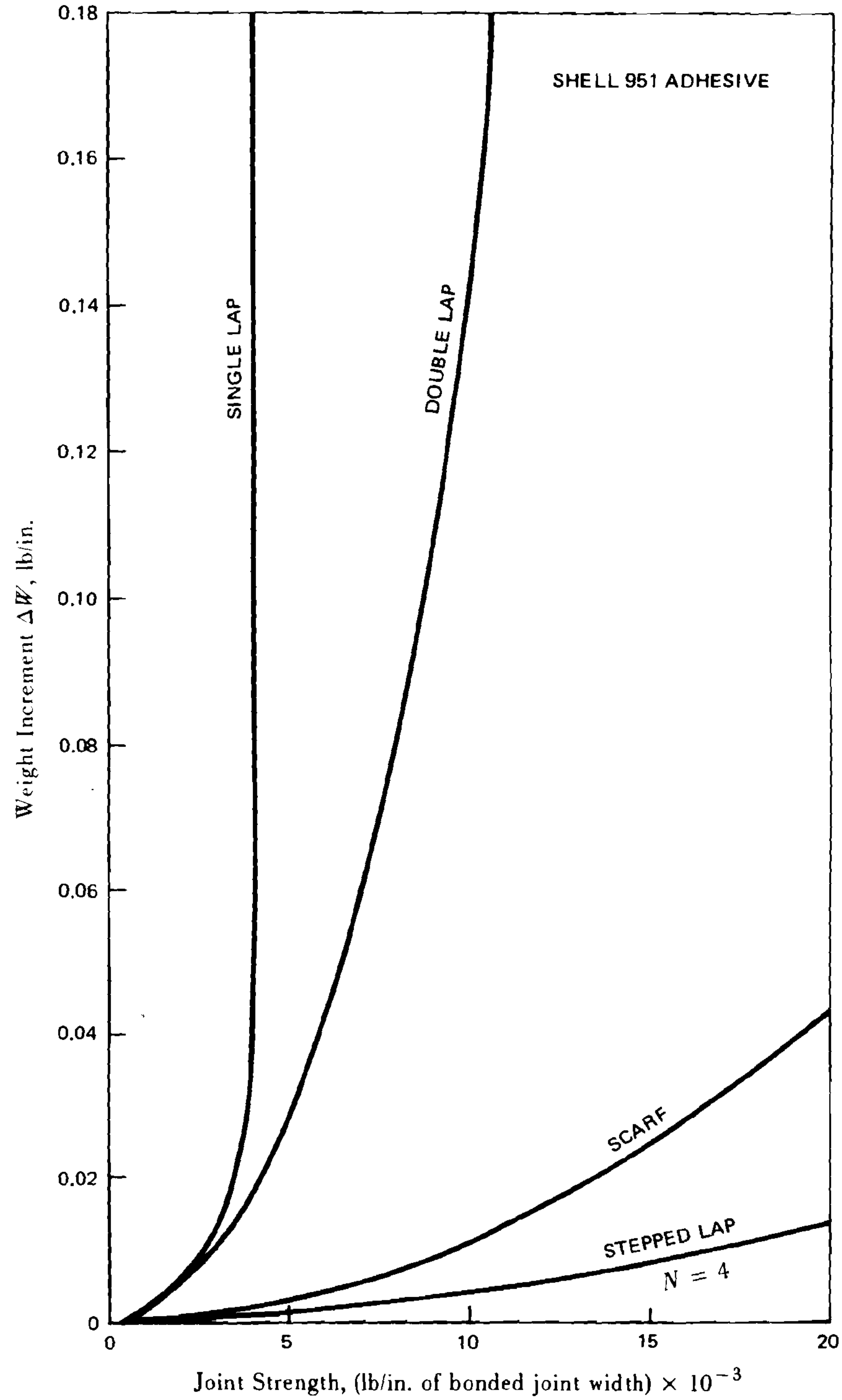


(B) Adhesive



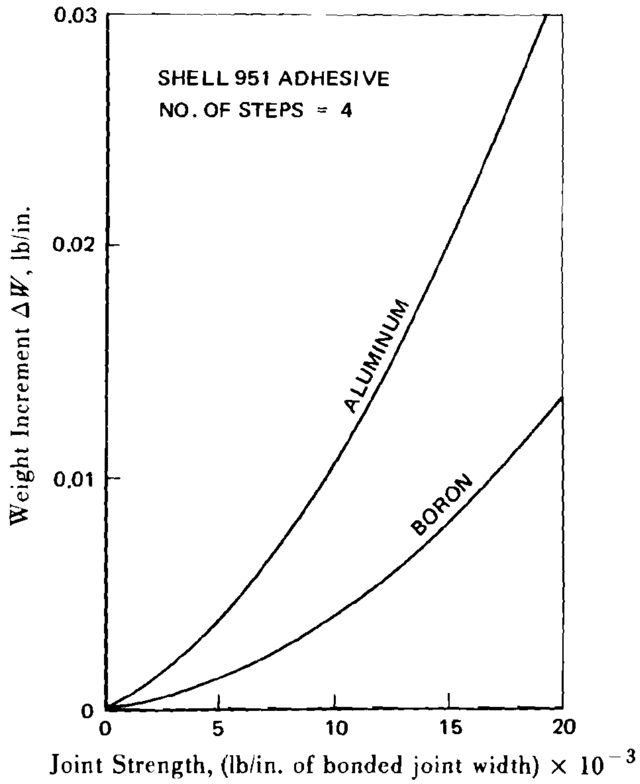
(C) Interlaminar Shear

Figure 4-29. Bonded Failure Modes



(A) Weight Increments for Bonded Joints in Boron Panels

Figure 4-30. Weight Increments vs Strength of Joints[2]



(B) Comparison of Weight Increments for Stepped Lap Joints

Figure 4-30. (cont'd)

S-N curves for flush head and protruding head bolted graphite joint configurations are shown in Figs. 4-41 and 4-42, respectively. Fatigue behavior is not predictable at present based on mechanical property data. Factors which affect fatigue life are numerous. They include joint type and configuration, fiber orientation, adhesive type, processing variables for laminate manufacture, surface preparation of laminate if it is to be bonded, adhesive cure schedule, and environmental effects of temperature and humidity. These factors make prediction of static strength of joints difficult and the introduction of dynamic cyclic loads compounds the difficulty. For this reason S-N curves must be developed for a joint design representative of the end item.

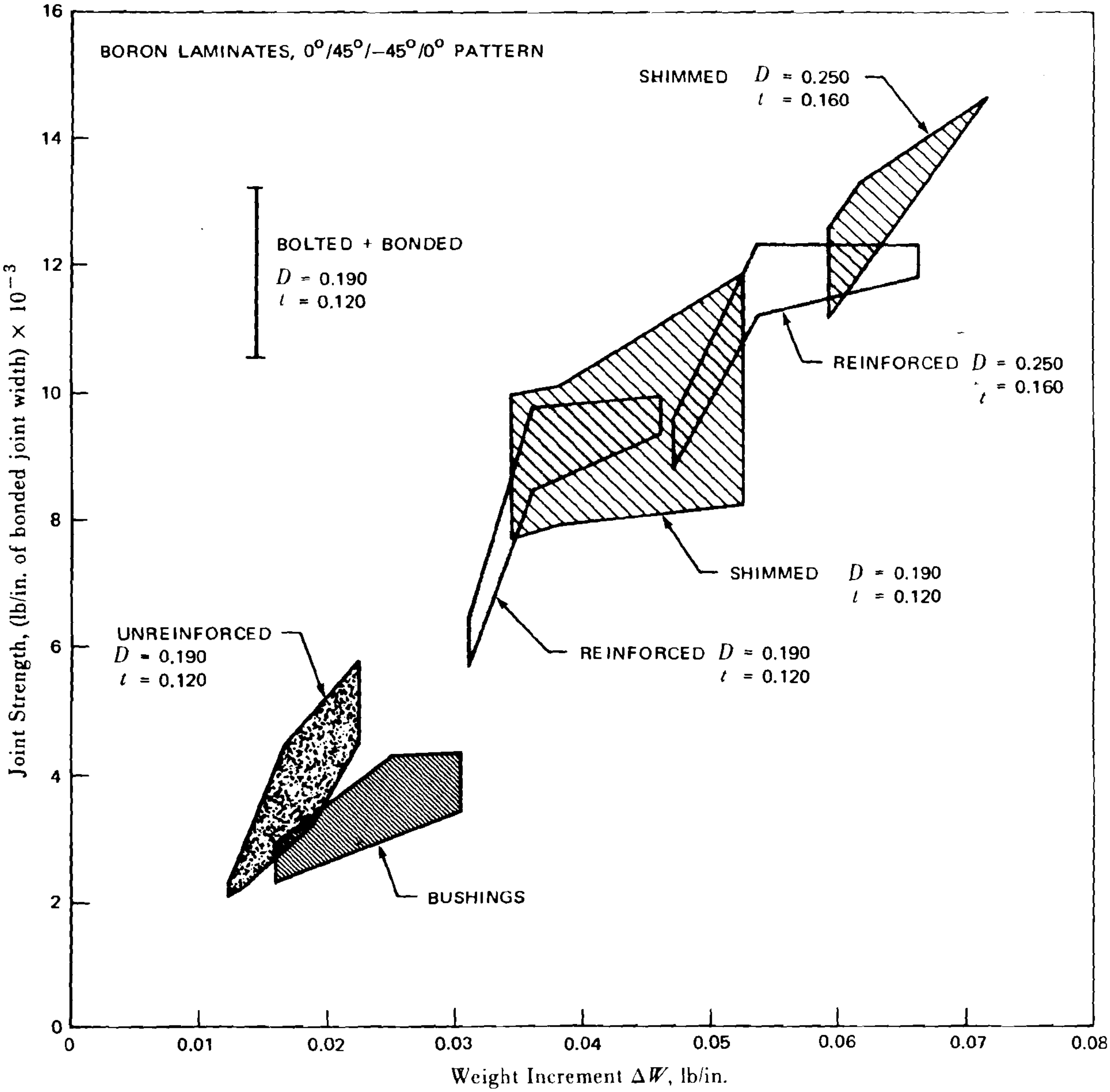


Figure 4-31. Strength — Weight Relationships for Bolted Joints[2]

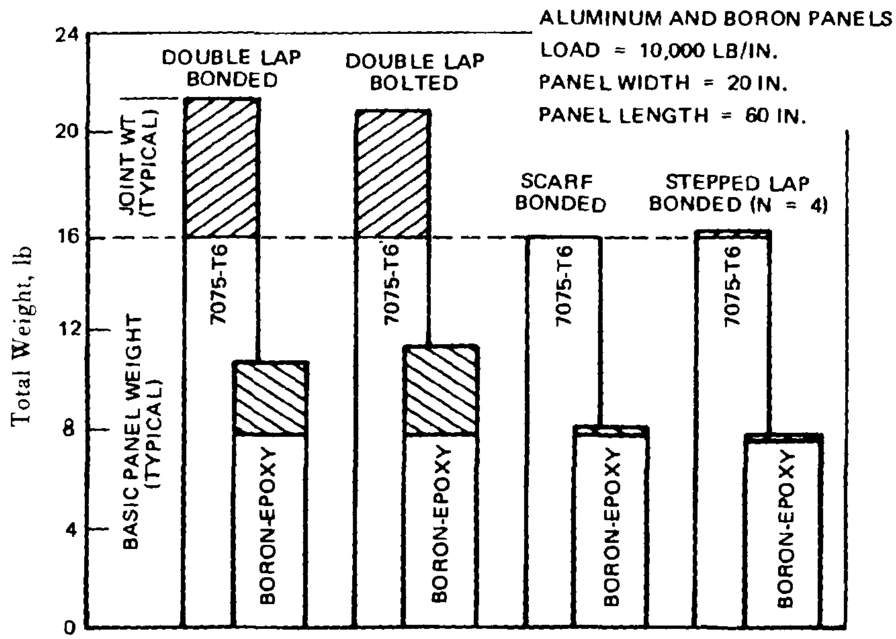


Figure 4-32. Total Weight Comparisons for Panels and Joints[2]

TABLE 4-14
SUMMARY OF BONDED JOINT FATIGUE TEST RESULTS*2

JOINT TYPE	MATERIALS AND GAGES, in.	OVERLAP LENGTH, in.	MAXIMUM LOAD / MINIMUM LOAD lb/lb	MAXIMUM LOAD % OF STATIC ULTIMATE	TESTS	ADHESIVE STRESS AT MAXIMUM LOAD, psi	APPROXIMATE SCF IN ADHESIVE	(SCF) × AVERAGE STRESS AT MAXIMUM LOAD, psi	RANGE OF CYCLES TO FAILURE	FAILURE MODE
SINGLE LAP	BORON/ALUMINUM (0.040)/(0.063)	1	1800/90	72	5	1,800	4.8	8,600	8,000 TO 35,000	ADHESIVE
	FIBERGLASS/ALUMINUM (0.040)/(0.063)	1	1600/80	69	5	—	—	--	10,700 TO 19,400	ADHESIVE
DOUBLE LAP	BORON/ALUMINUM (0.080)/(0.126)	1	6400/260	70	5	3,200	3.4	10,900	480 TO 1,860	ADHESIVE
	FIBERGLASS/ALUMINUM (0.080)/(0.126)	1	4200/200	73	2	—	—	—	1,700 TO 2,300	ADHESIVE
		1	3400/170	60	3	—	—	—	1,600 TO 8,500	ADHESIVE
	BORON/ALUMINUM (0.160)/(0.160)	2	6600/330	56	3	3,300	3.6	11,900	1,000 TO 5,000	ADHESIVE
FOUR-STEP LAP	BORON/ALUMINUM (0.160)/(0.160) PATTERN C	2	8200/410	70	2	4,100	3.6	14,700	750 TO 2,000	ADHESIVE
		2	6600/330	57	2	3,300	3.6	11,900	7,500 TO 12,720	ADHESIVE
	FIBERGLASS/ALUMINUM (0.160)/(0.160)	2	6600/330	75	5	—	—	—	200 TO 300	ADHESIVE
SCARF	BORON/ALUMINUM (0.160)/(0.160)	1	3300/165	70	5	3,300	1.4	4,600	15,000 TO 119,000	ADHESIVE
	FIBERGLASS/ALUMINUM (0.160)/(0.160)	1	3800/190	70	5	—	—	–	1,400 TO 20,000	ADHESIVE

R = ,0.05 — 1-IN. SPECIMEN WIDTH.
VE — LAMINATE PATTERN A, SEE TABLE 4-1.

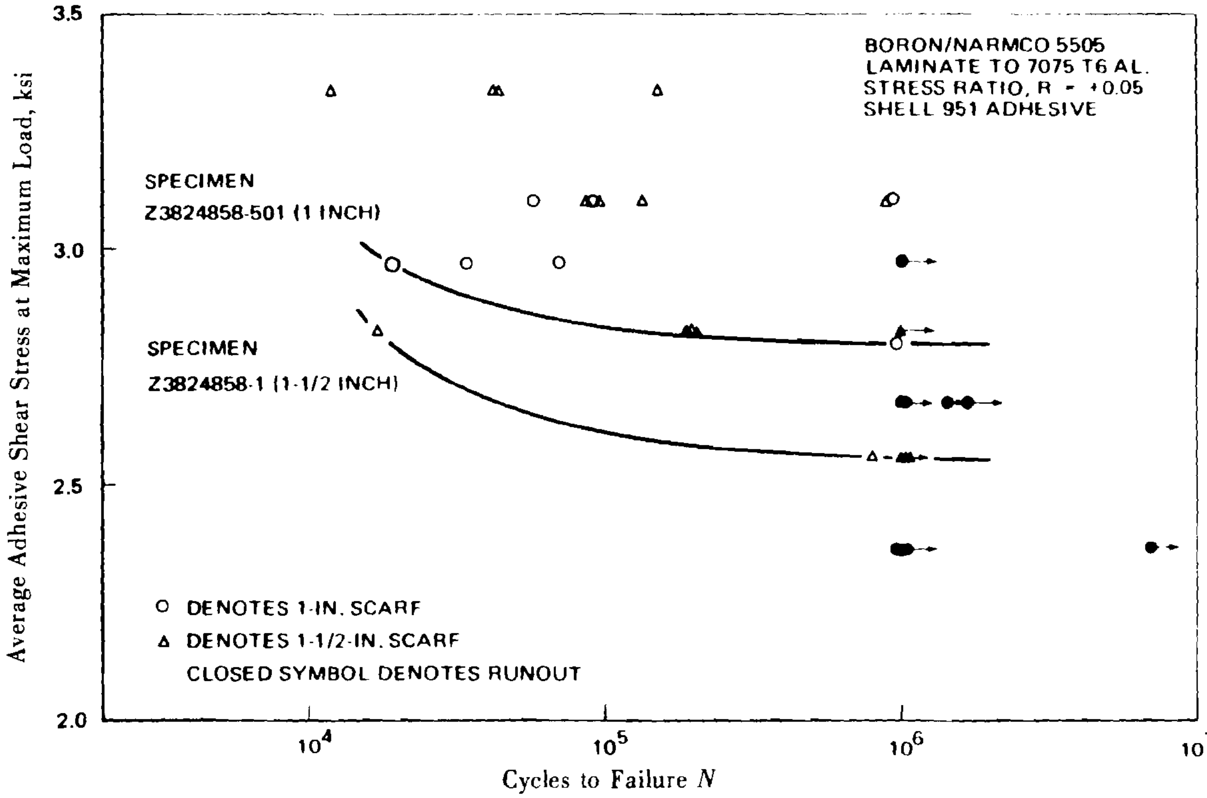


Figure 4-33. Fatigue Data for Adhesive Scarf Joints[1]

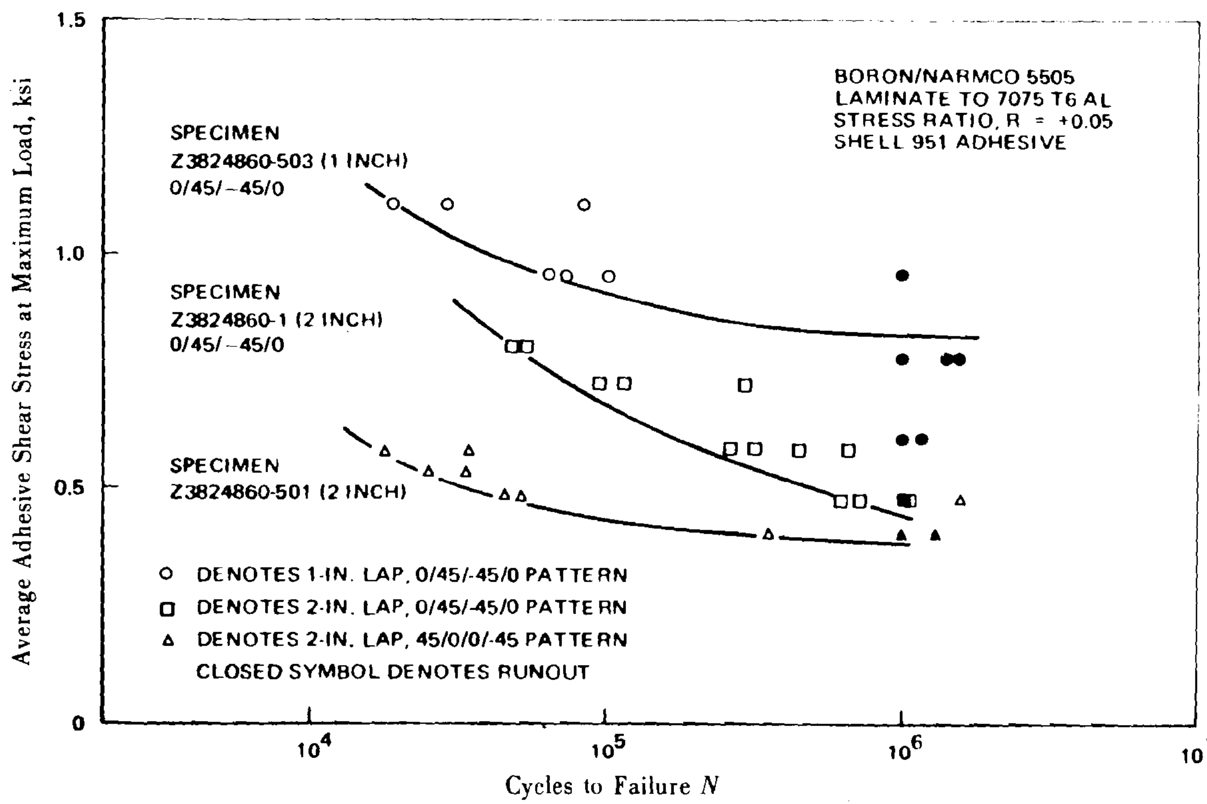


Figure 4-34. Fatigue Data for Adhesive Double-Lap Joints[1]

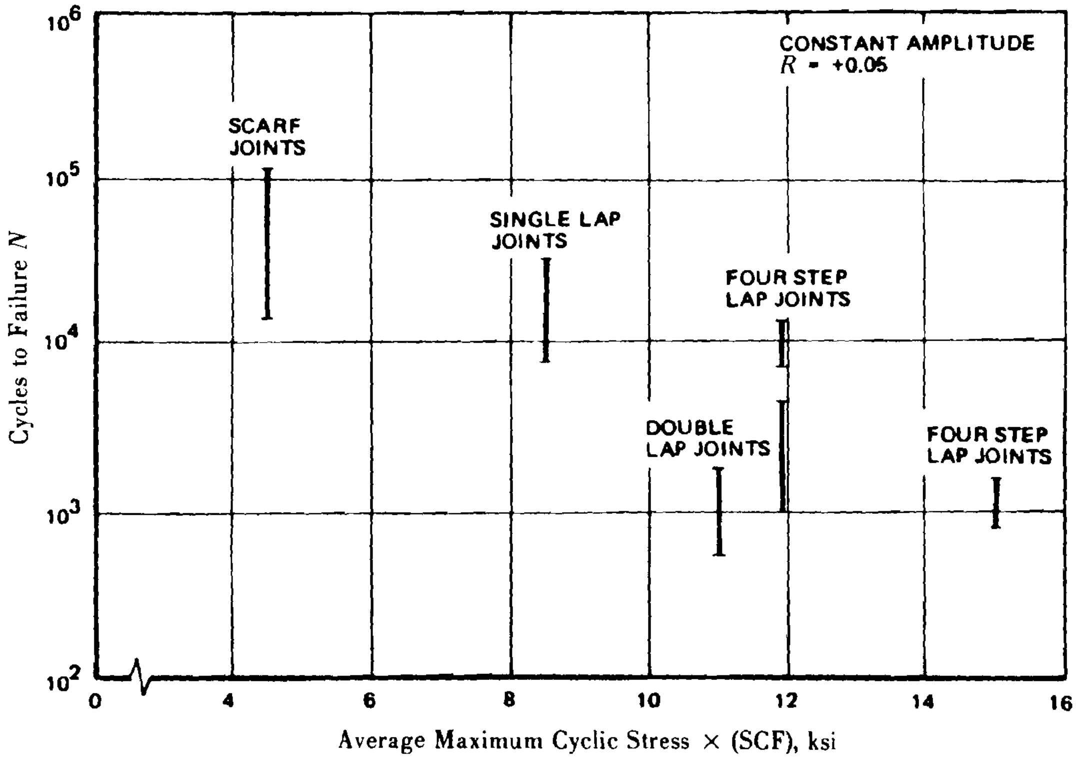


Figure 4-35. Fatigue Life of Boron Composite-to-Aluminum Alloy Bonded Joints[6]

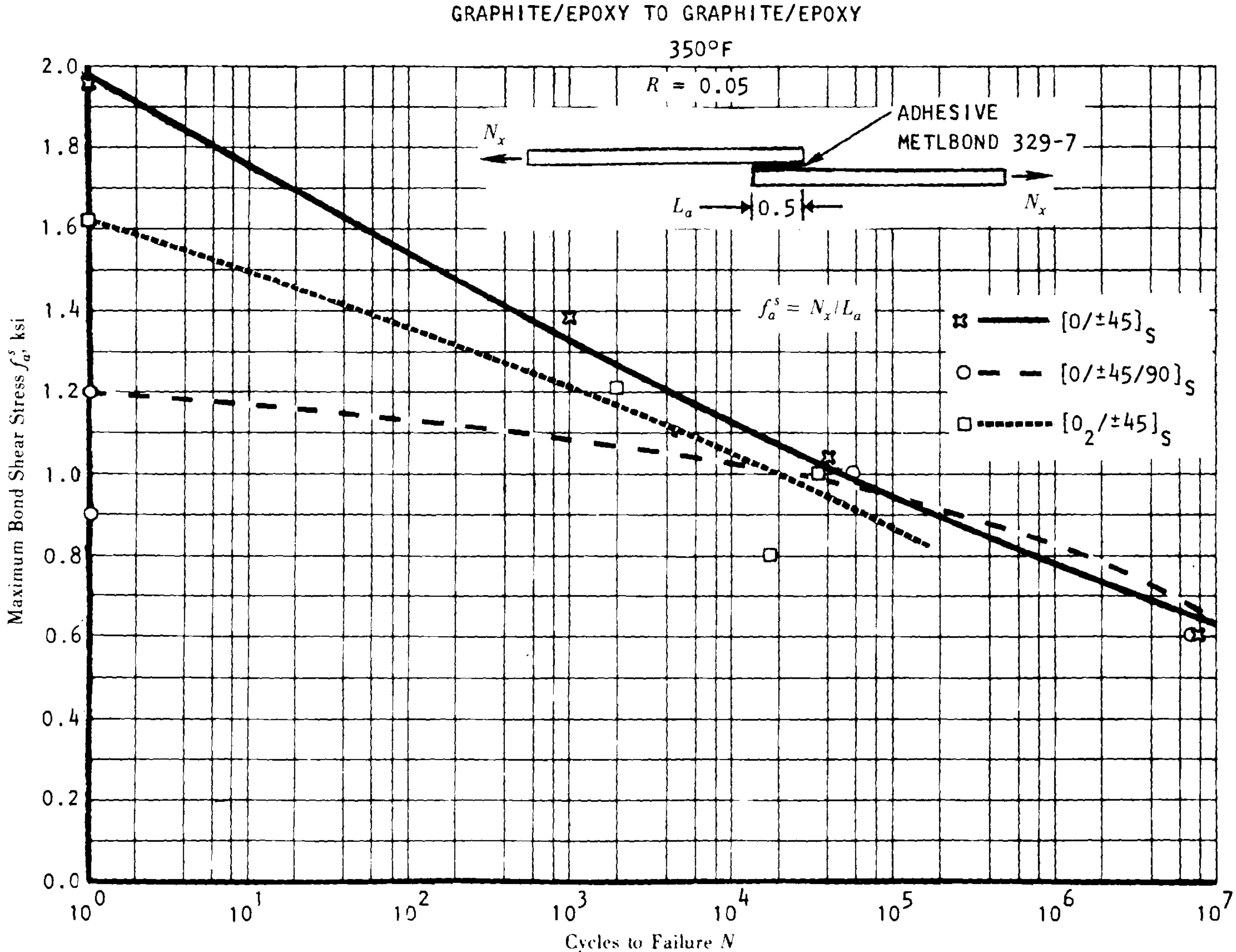


Figure 4-36. Single-Lap Bonded Joint Tension Fatigue S-N Curve — Type AS/3002-Batch, Graphite/Epoxy, 350°F (Ref. 7)

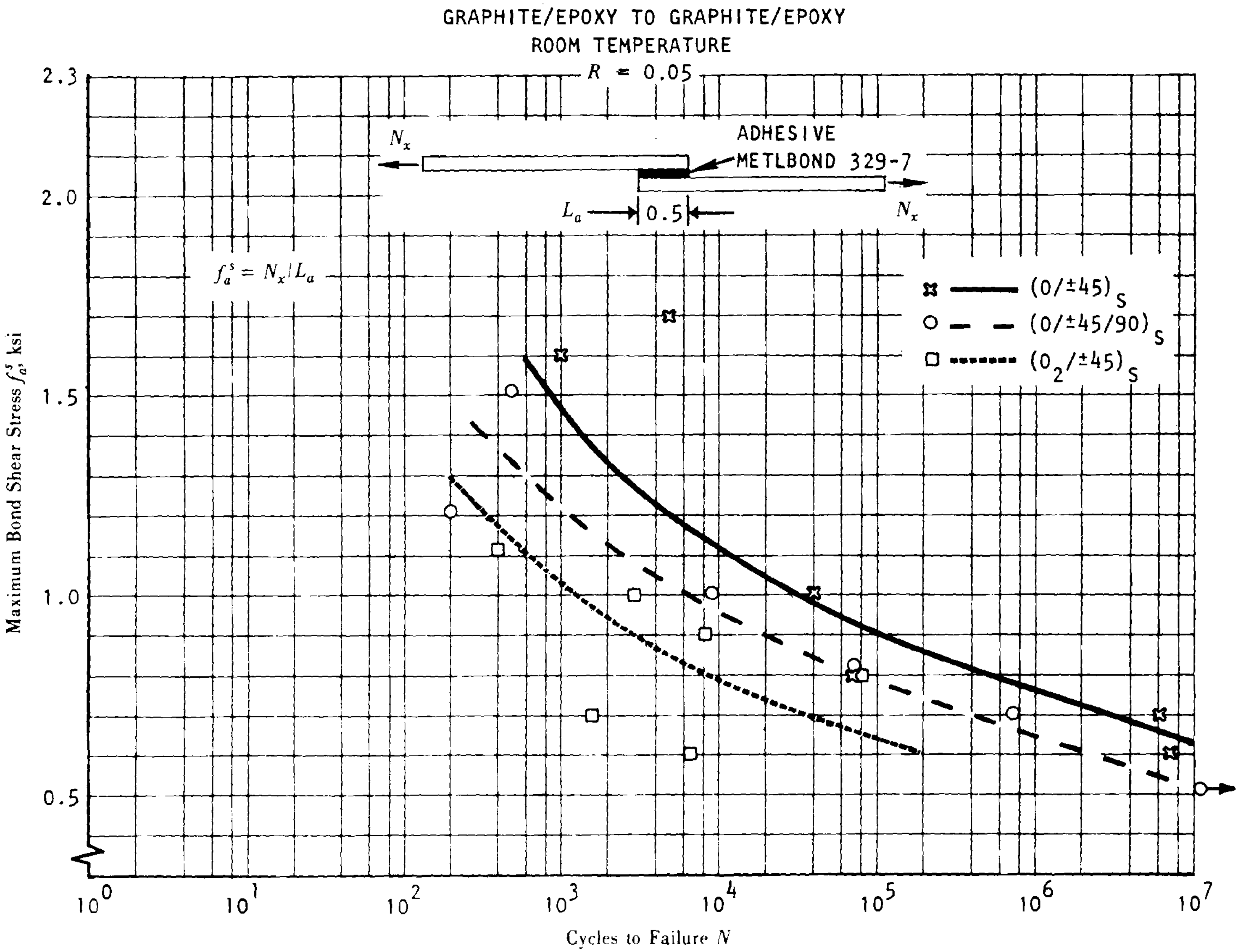


Figure 4-37. Single-Lap Bonded Joint Tension Fatigue S-N Curve—Type AS/3002-Batch, Graphite/Epoxy, Room Temperature[7]

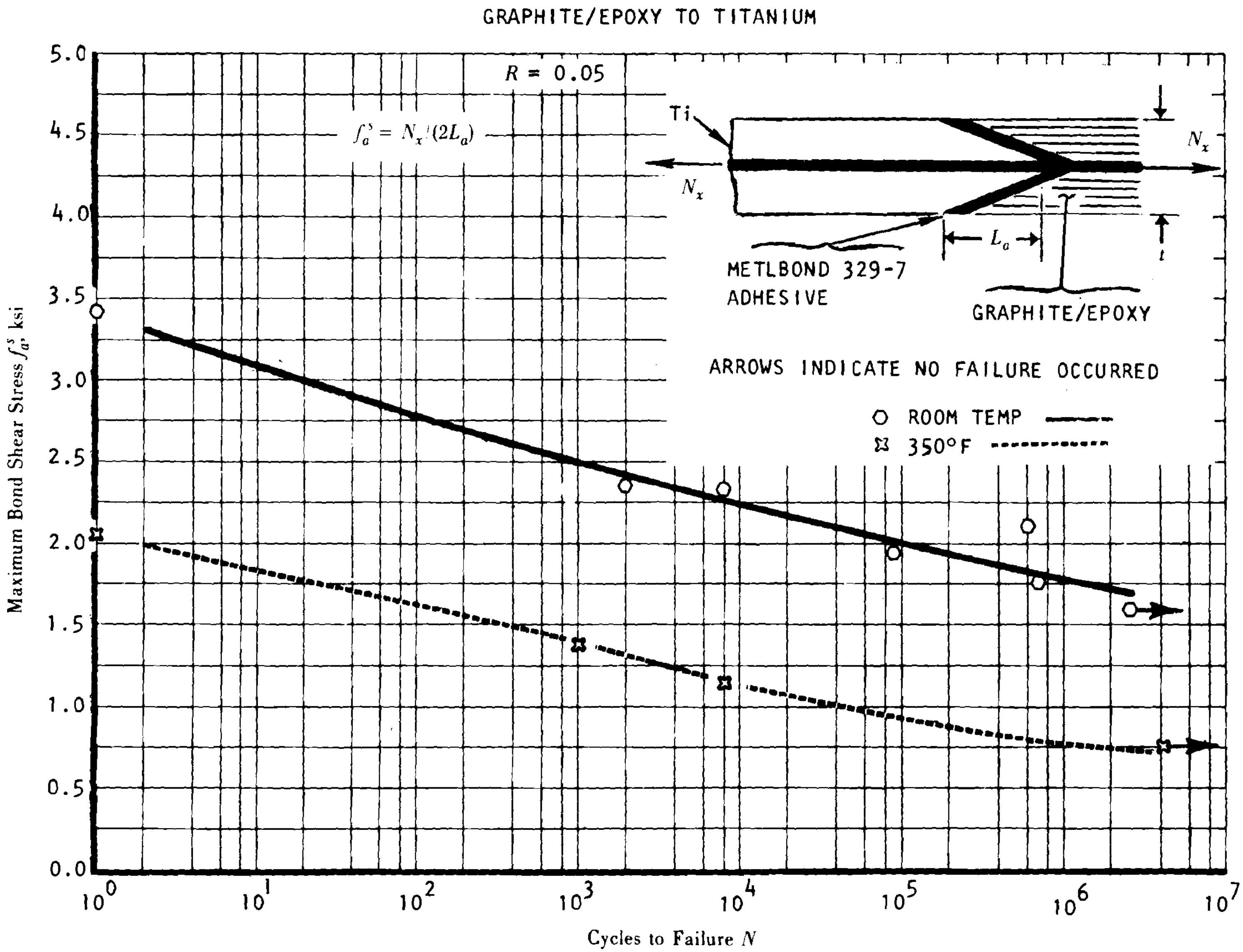


Figure 4-38. Bonded Symmetrical Scarf Joint Tension Fatigue S-N Curves — Type AS/3002-Batch, Graphite/Epoxy — Room Temperature and 350°F, $[0/^{\pm}45]_{2S}$ (Ref. 7)

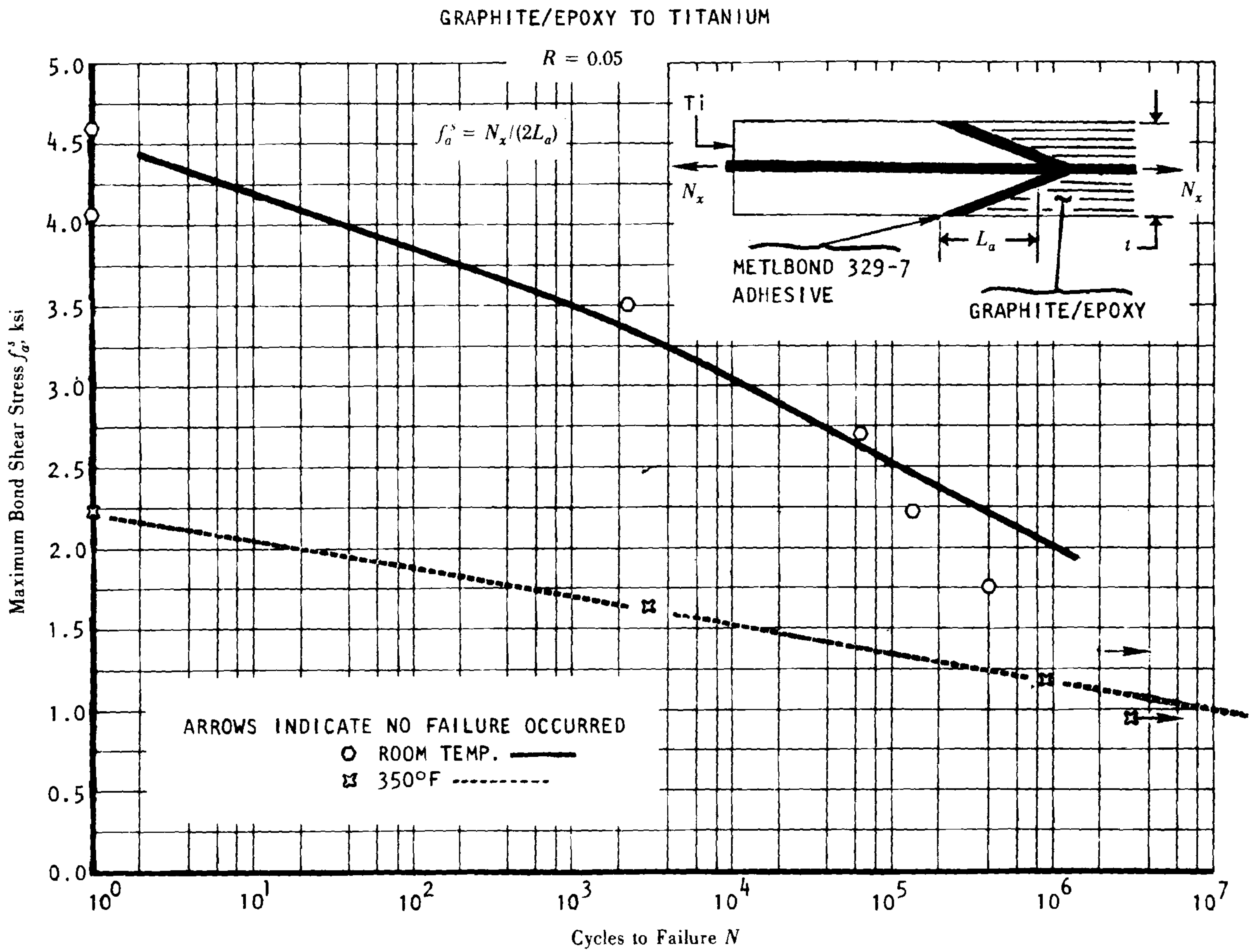


Figure 4-39. Bonded Symmetrical Scarf Joint Tension Fatigue S-N Curves — Type AS/3002-Batch, Graphite/Epoxy — Room Temperature and 350°F, $[0/\pm45/90]_{2S}$ (Ref. 7)

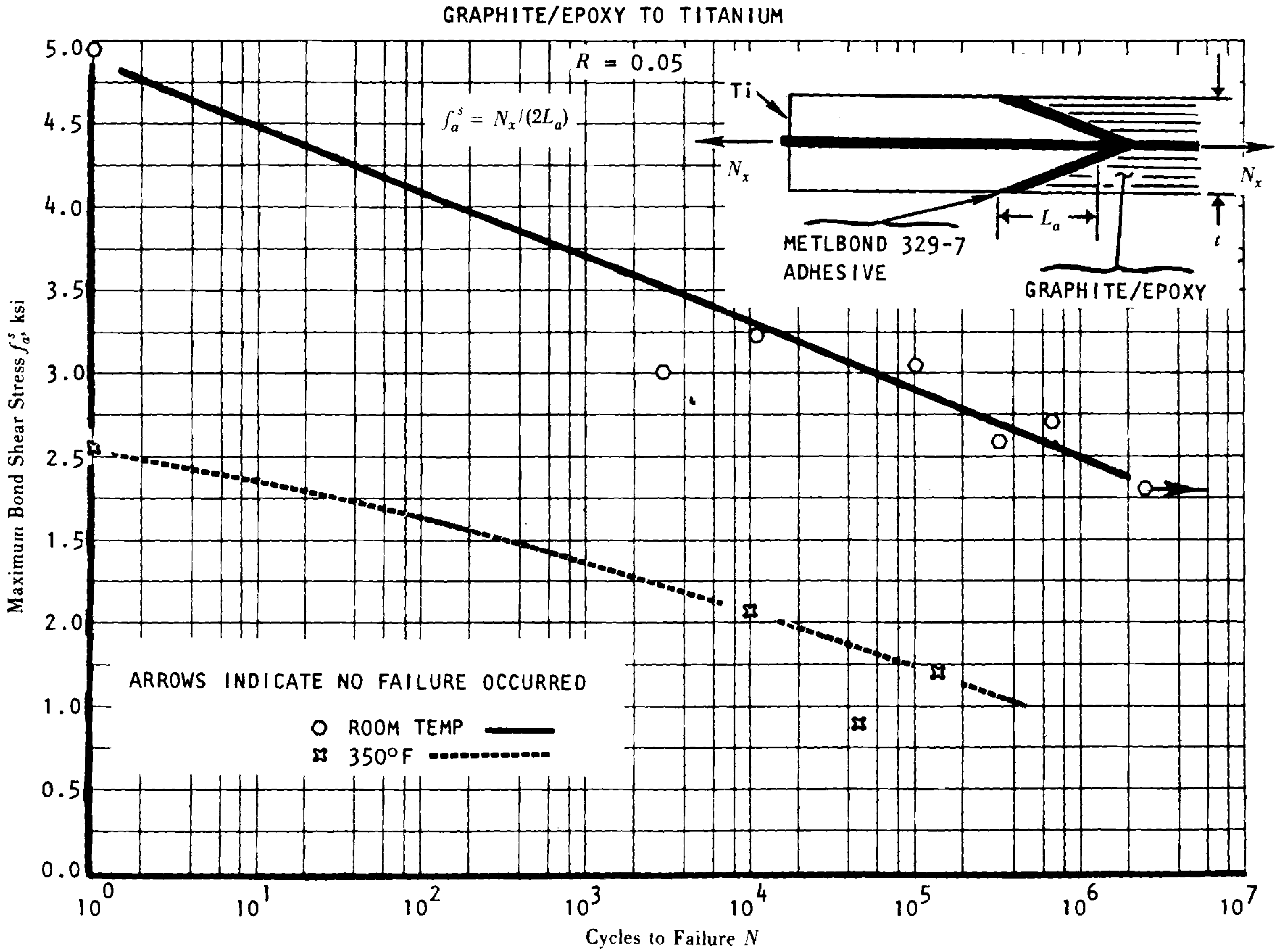


Figure 4-40. Bonded Symmetrical Scarf Joint Tension Fatigue S-N Curves — Type AS/3002-Batch, Graphite/Epoxy — Room Temperature and 350°F, $[0_2/\pm 45]_{2S}$ (Ref. 7)

TABLE 4-15
SUMMARY OF BOLTED JOINT FATIGUE TEST RESULTS*[2]

JOINT TYPE	MATERIALS AND GAGES, in.	EDGE DISTANCE, in.	MAXIMUM LOAD / MINIMUM LOAD lb/lb	MAXIMUM LOAD % OF STATIC ULTIMATE	TESTS	RANGES OF CYCLES TO FAILURE	FAILURE MODES
SINGLE LAP	BORON/BORON (0.120)/(0.120)	0.750	1800/90	70	5	4,000 TO 13,000	BEARING AND SHEAR-OUT
	BORON/7075-T6 (0.120)/(0.160)		1960/98	70	5	1,000 TO 24,000	BORON-BEARING ALUMINUM THROUGH FASTENER HOLE
	FIBERGLASS/FIBERGLASS (0.120)/(0.120)		1460/73	70	5	1,700 TO 7,000	DELAMINATION AND SHEAR-OUT
	FIBERGLASS/7075-T6 (0.120)/(0.160)		1765/88	70	5	1,100 TO 62,700	DELAMINATION AND SHEAR-OUT
DOUBLE LAP	BORON/7075-T6 (0.120)/(0.200)		2100/105	70	5	130,000 TO 2,677,000	ALUMINUM THROUGH FASTENER HOLE NONE (RUNOUTS)
	FIBERGLASS/7075-T6 (0.120)/(0.200)		1650/83	70	3	1,000,000 TO 7,591,000	NONE (RUNOUTS)
			1890/95	80	2	1,247,000 TO 1,731,000	NONE (RUNOUTS) ALUMINUM THROUGH FASTENER HOLE
DOUBLE LAP BOLTED AND BONDED	BORON/7075-T6 (0.120)/(0.200)	0.750	4950/248	38	5	101,000 TO 176,000	LAMINATE AND ALUMINUM THROUGH HOLE ALUMINUM THROUGH BASIC SECTION
	FIBERGLASS/7075-T6 (0.120)/(0.200)		4950/248	66	5	11,400 TO 49,200	DELAMINATION AND ADHESIVE

*STRESS RATIO, $R = ,0.05$
BOLT DIAMETER, $D = 0.190$ IN.

1-IN. SPECIMEN WIDTH
LAMINATE PATTERN A,
SEE TABLE 4-1.

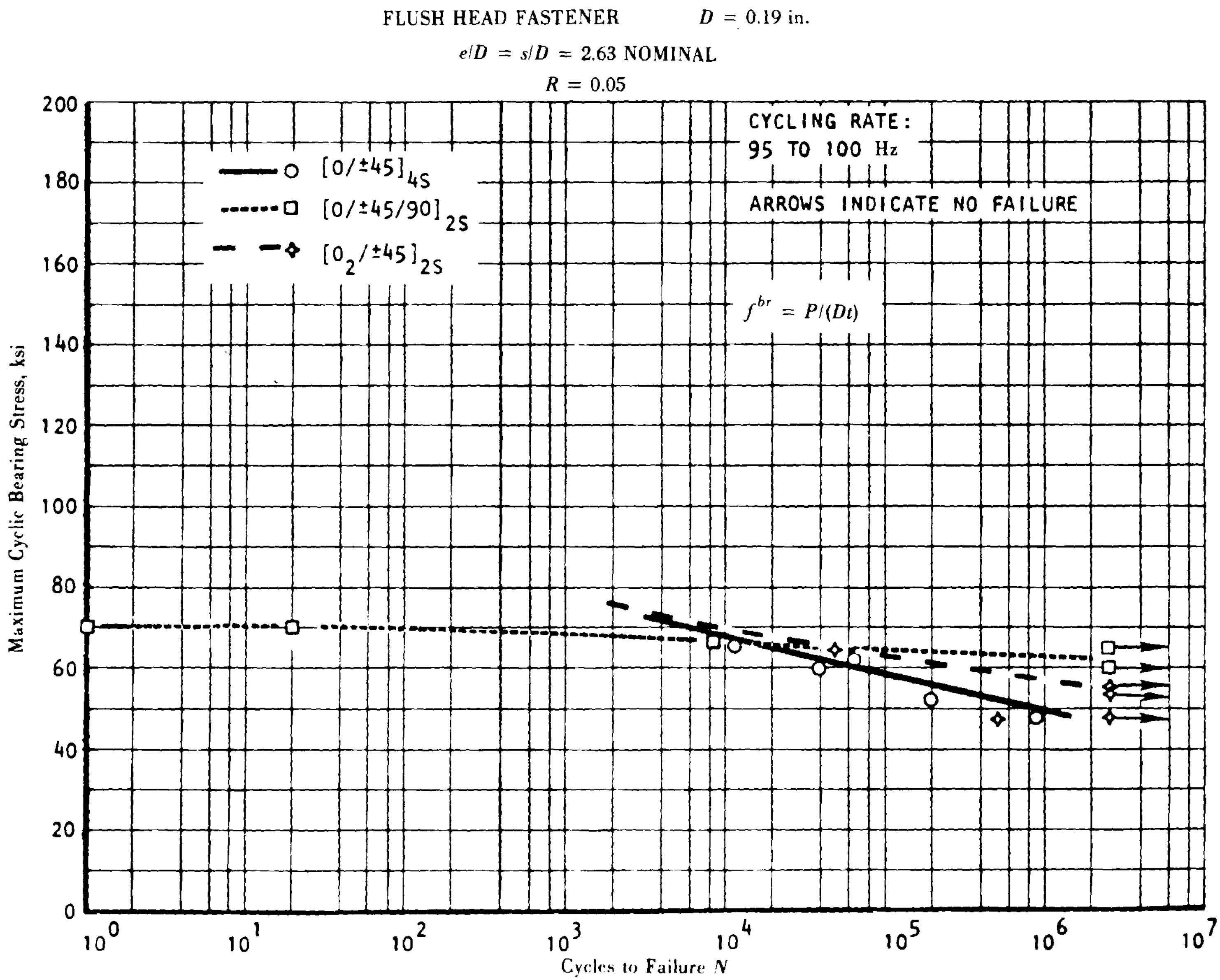


Figure 4-41. Room Temperature Fatigue S-N Curves for Various Crossplied Graphite/Epoxy to Steel Single-Lap Flush Head Mechanical Joints — Type AS/3002-Batch, Graphite/Epoxy[7]

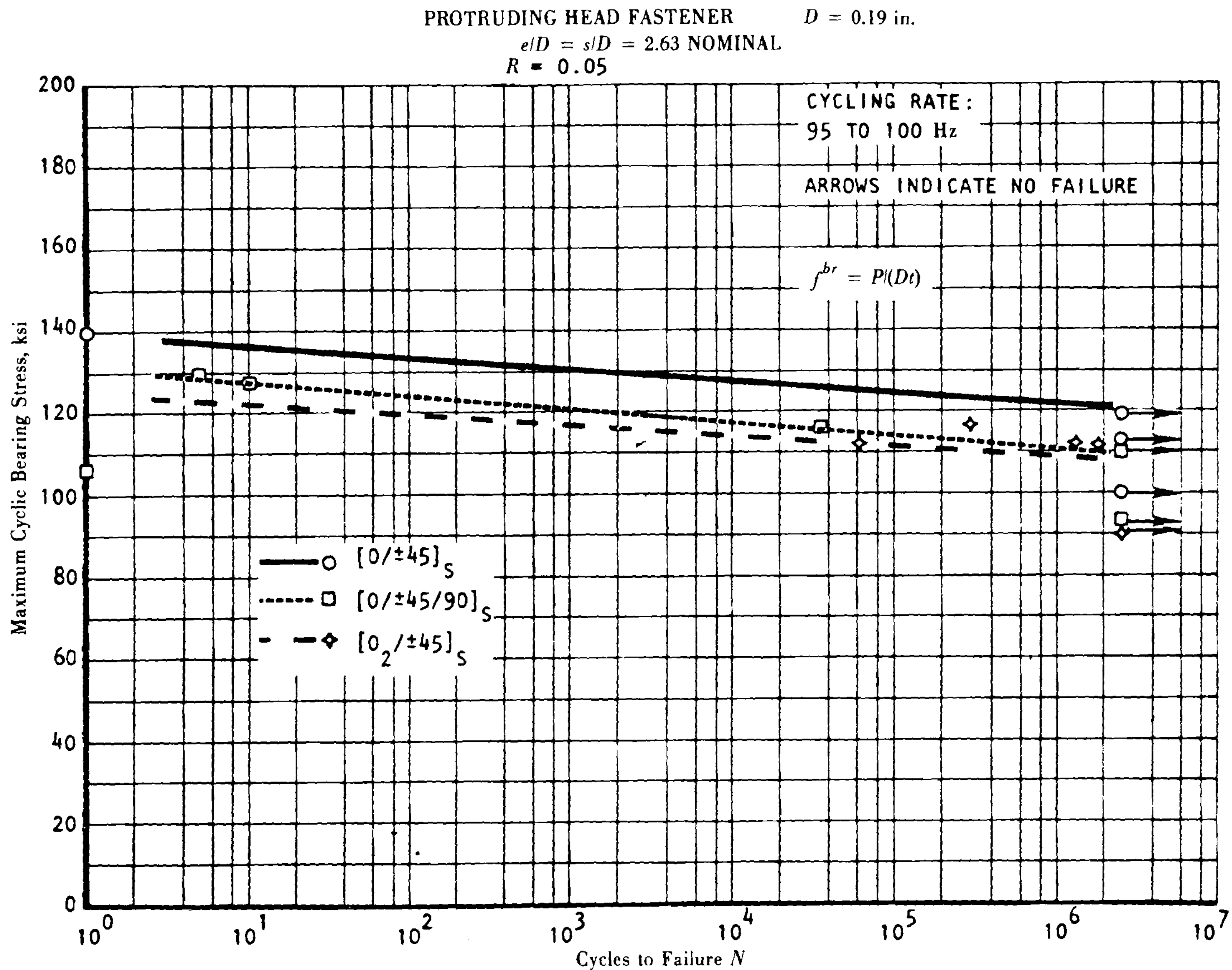


Figure 4-42. Room Temperature Fatigue S-N Curves for Various Crossplied Graphite/Epoxy to Steel Single-Lap Protruding Head Mechanical Joints — Type AS/3002-Batch, Graphite/Epoxy[7]

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1. A. V. Hawley, et al., *Investigations of Joints and Cutouts in Advanced Fibrous Composites for Aircraft Structures*, Fifth Quarterly Progress Report, Contract No. F 33615-67-C-1582, Wright-Patterson Air Force Base, OH, July 1968.
2. G. M. Lehman and A. V. Hawley, *Investigations of Joints in Advanced Fibrous Composites for Aircraft Structures, Vol. 1, Technical Discussion and Summary*, Technical Report AFFDL-TR-69-43, Vol. 1, Wright-Patterson Air Force Base, OH, June 1969.
3. A. V. Hawley, et al., *Investigations of Joints and Cutouts in Advanced Fibrous Composites for Aircraft Structures*, Third Quarterly Progress Report, Contract No. F33615-67-C-1582, Wright-Patterson Air Force Base, OH, January 1968.
4. A. V. Hawley, et al., *Investigations of Joints and Cutouts in Advanced Fibrous Composites for Aircraft Structures*, Fourth Quarterly Progress Report, Contract No. F33615-67-C-1582, Wright-Patterson Air Force Base, OH, April 1968.
5. G. N. Sage, "Some Aspects of Bonded Joint Design in CPFP", Composites 7, No. 4, IPC Science and Technology Press Ltd., Guildford, Surry, England (October 1976).

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