

# **DETERMINATION OF MECHANICAL PROPERTIES OF ADHESIVES FOR USE IN THE DESIGN OF BONDED JOINTS**

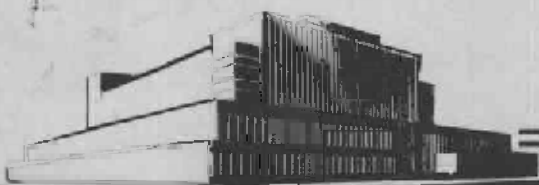
**January 1956**

INFORMATION REVIEWED  
AND REAFFIRMED

1962

**No. 1851**

**This Report Is One of a Series  
Issued in Cooperation with the  
ANC-23 PANEL ON COMPOSITE CONSTRUCTION  
FOR FLIGHT VEHICLES  
of the Departments of the  
AIR FORCE, NAVY, AND COMMERCE**



**FOREST PRODUCTS LABORATORY**

**MADISON 5, WISCONSIN**

**UNITED STATES DEPARTMENT OF AGRICULTURE  
FOREST SERVICE**

**In Cooperation with the University of Wisconsin**

DETERMINATION OF MECHANICAL PROPERTIES OF ADHESIVES FOR

USE IN THE DESIGN OF BONDED JOINTS<sup>1,2</sup>

By

EDWARD W. KUENZI, Engineer

Forest Products Laboratory,<sup>3</sup> Forest Service  
U. S. Department of Agriculture

-----  
Summary

This report describes test methods for determining the basic mechanical properties of adhesives subjected to shear or tension in bonds between relatively rigid adherents. The use of the properties for designing lap joints is also discussed.

Introduction

The development of adhesives for the bonding of metals has made possible the design of efficient structural assemblies, and these adhesives are particularly suitable for joining thin sheet materials to produce light-weight aircraft parts. Suitable design criteria for various types of joints and loading conditions are lacking, largely because the behavior of the joints under various loads depends on the mechanical properties of the adhesives in the joints, and such properties have not been determined.

---

<sup>1</sup>This progress report is one of a series (ANC-23, Item 54-1) prepared and distributed by the Forest Products Laboratory under U. S. Navy, Bureau of Aeronautics Nos. NAer 01628 and NAer 01593 and U. S. Air Force Nos. D0(33-616) 53-20 and AF 18(600)102, Amendment A6 (55-286). Results here reported are preliminary and may be revised as additional data become available.

<sup>2</sup>Trade names are used in this report at the request of the ANC-23 Panel, and their use implies no endorsement of the products named by the U. S. Forest Products Laboratory or any other government agency.

<sup>3</sup>Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

Considerable work has been and is being done to determine the suitability of adhesives for bonding systems by conducting strength tests of lap joints. Analyses of the strength data have been extended to determine "effective" elastic properties as well as the shear strength of various adhesives, and because of this, property values determined vary with the number of different analyses employed. The "effective" elastic properties and strength values obtained are useful primarily for predicting the strength of lap-joint specimens. It would seem unlikely that design criteria based on a joint with considerable flexibility at failure (such flexibility as results from stressing the adhesive far beyond the elastic range of behavior) would predict proper behavior at lower stresses, or for more rigid joints such as would be required to bond skins to spars, edgings on sandwich, laps in sandwich facings, or doublers on sandwich facings.

It is the purpose of the work reported here to establish, if possible, methods of test to determine the properties of adhesives when used in actual bonded joints. Adhesive films or cast adhesives could have been evaluated, but since the surfaces, bonding conditions, and other factors could not be duplicated when bonding metals, it was decided to test actual bonded specimens. The adhesive-bond properties that were to be determined were the shear modulus, modulus of elasticity, Poisson's ratio, shear and tensile stress-strain curves, and shear and tensile strength. These properties could then be used in theoretical or empirical design criteria for any particular joint to be designed. This report includes an illustration of the application of available design criteria for determining the behavior of lap joints.

Although there are few theoretical design criteria available for many types of bonded joints, the continued use of these joints will require such criteria, incorporating proper parameters, so that elastic behavior and deformations, as well as impact and creep effects, can eventually be considered. Thus, ultimately, a joint could be designed by using actual adhesive properties rather than purely by rule-of-thumb procedure.

### Test Specimens

For the accurate determination of the shear properties of most materials, the torsion test of circular cylinders is unexcelled. For a solid cylinder, however, the shear stress varies radially from zero at the center to a maximum at the perimeter. Thus, when loaded above the proportional limit stress at the perimeter, the material is no longer homogeneous in a radial direction, and failing torque cannot be converted into shearing strength, just as failing bending moment in a beam cannot readily be converted into actual tensile or compressive stresses. Most of this difficulty can be overcome by twisting a tubular section. The thinner the tube wall, the more nearly the perimeter shear stress approaches the stress at the inner diameter, and nearly pure shear strength, as well as the entire shear stress-strain curve, can be obtained.

Specimens for the determination of the shear and tensile properties of adhesives were made by bonding together the ends of 61S aluminum alloy tubing 1-1/2 inches in inside diameter and 2 inches in outside diameter. For determinations of shear or tensile strength only, 2 pieces of tubing about 2-1/2 inches long were bonded together. For determinations of elastic properties and stress-strain curves, 9 "washers" of the tubing, each 1/8 inch thick, were bonded to each other and between two 2-1/2-inch-long tubes (figs. 1 and 2). This resulted in a specimen with 10 adhesive bonds that had a total deformation 10 times that of a single bond, and a more accurate determination of bond deformation was then possible. The ends of the tubular specimens were threaded for attachment to the testing machine's loading fixtures.

#### Bonding of Test Specimens<sup>4</sup>

The ends of the tubes and "washers" were smoothly surfaced in a lathe and then etched and bonded with the following adhesives:

Redux K-6, a high-temperature-setting, two-component formulation of phenol resin solution and a vinyl polymer powder.

Scotchweld AF-6, a high-temperature-setting adhesive formulation of acrylonitrile-butadiene rubber and phenol resin in the form of an unsupported tape.

Metlbond MN3C Nylon Tape, a high-temperature-setting formulation of neoprene, nylon, and phenol resins supported as a film on nylon-fabric tape.

Epon VIII, a formulation of epoxy resins.

Specimen ends that were to be bonded with the first 3 of the above adhesives were etched for 10 minutes at 140° to 160° F. in a solution consisting of 10 parts by weight of concentrated sulfuric acid, 1 part of sodium dichromate, and 30 parts of water. Specimen ends that were to be bonded with Epon VIII adhesive were etched for 20 minutes at 140° to 160° F. in a solution consisting of 12.5 parts of concentrated sulfuric acid, 3.5 parts of sodium dichromate, and 30 parts of water. The etching solution was rinsed from all specimen parts with running cold and hot water. The parts were then dried in a current of air.

When the parts were ready for bonding, each specimen was carefully assembled without adhesive, and its total length was measured with a micrometer reading to 0.001 inch. This was done so that the total adhesive thickness could be obtained by subtracting the original length from the length of the bonded specimen.

---

<sup>4</sup>Bonding procedures were devised and carried out under the supervision of H. W. Eickner of the U. S. Forest Products Laboratory.

The specimens were then assembled with the adhesives. The parts were aligned in a straight piece of angle-iron trough, and pressure was applied with a calibrated spring compressed by a bolt that passed through the tubes. Pressure was controlled by tightening the bolt until the spring was compressed to the deflection necessary to produce the desired pressure. The bonds were then cured by placing the entire assembly in an oven at the proper curing temperature. The particular procedure and curing temperature and pressure for each adhesive are given as follows:

Redux K-6.--One medium coat of the liquid component of the adhesive was brushed on the surfaces that were to be bonded, and the powdered component was sprinkled immediately onto the wet coating. Excess powder was brushed from the surface. The adhesive was air dried overnight, and the specimen was then cured for 15 minutes at a temperature of 300° F. and a pressure of 100 pounds per square inch.

Scotchweld AF-6.--A single film of this tape adhesive was used at each joint in a specimen. The film was cut into washers slightly larger in outside diameter and smaller in inside diameter than the tubular specimen. After the specimen was assembled, the adhesive was cured for 45 minutes at a temperature of 325° F. and a pressure of 150 pounds per square inch.

Metlbond MN3C Nylon Tape.--The surfaces that were to be bonded were sprayed with 4 coats of a priming component to a total thickness of 0.001 to 0.002 inch. Each coat was air dried for 30 minutes, and the final coat was dried for 3 to 5 hours. The specimen was assembled with a single film of the tape adhesive, in the form of oversize washers, at each joint. The curing was completed at a pressure of 50 pounds per square inch for 12 minutes at 300° F. and 30 minutes at 335° F.

Epon VIII.--One medium coat of adhesive was applied to each surface that was to be bonded. The adhesive was cured for 90 minutes at a temperature of 200° F. and a pressure of 10 pounds per square inch.

After the bonded specimens cooled, excess adhesive was carefully removed from their exterior and interior surfaces.

### Testing Procedures

The bonded specimens were tested either in torsion to determine shear stress-strain curves, shear modulus, proportional limit stress, and shear strength, or in tension to determine modulus of elasticity, proportional limit stress, and tensile strength. In several instances, torsion specimens were first tested in compression to obtain modulus of elasticity values and then tested in torsion.

Torsion Tests.--Loading bars for the jaws of a torsion testing machine were screwed into the ends of the test specimen. The test specimen was fitted with a detrusion gage to measure total twist across the bonds. The gage, shown on the specimen in figure 1, consisted of a ring held to the specimen with three pointed set screws and a Tuckerman optical strain gage fastened to a bar rigidly attached to the ring. The position of the ring was adjusted so that the ring was concentric with the tubular test specimen, and the movable knife edge of the gage was just in contact with the specimen surface. This arrangement made it possible to read total detrusions to 0.000001 inch by reading the vernier scale in the Tuckerman autocollimator. Detrusion readings were taken at various applied loads to determine data for stress-strain curves.

To determine the detrusion in the adhesive bonds, it was necessary to subtract the detrusion in the aluminum tube from the total measured detrusion. The amount of detrusion in the aluminum was determined by testing a tube without bonds and obtaining a shear modulus. This shear modulus was then used to calculate aluminum detrusions for the bonded specimens. Before they were tested, these specimens without bonds were subjected to the heating schedule used to cure the bonded specimens.

Shear stresses were calculated from the formula:<sup>2</sup>

$$\tau = \frac{16dT}{\pi(d^4 - d_1^4)} \quad (1)$$

where:  $\tau$  -- shear stress  
 $d$  -- outside diameter of the tube  
 $d_1$  -- inside diameter of the tube  
 $T$  -- applied torque.

For the specimen without bonds, the shear modulus was calculated from the formula:

$$G = \frac{\tau a}{\phi} \quad (2)$$

where:  $G$  -- shear modulus of aluminum  
 $\tau$  -- shear stress  
 $a$  -- length of the tube between measuring points of the detrusion gage  
 $\phi$  -- detrusion measured by the gage.

The test of the tube without bonds gave a shear modulus value of 3,700,000 pounds per square inch. This value was used in calculating the total adhesive bond detrusion from the formula:

---

<sup>2</sup>This formula gives a surface shear stress of  $0.933T$  for a tube of the size tested (2-inch outside diameter, 1-1/2-inch inside diameter). The stress at the inner diameter is  $0.699T$ .

$$\phi_g = \phi - \frac{\tau}{G} (a - t_g) \quad (3)$$

where:  $\phi_g$  -- adhesive bond detrusion  
 $\phi$  -- detrusion measured by gage  
 $\tau$  -- shear stress  
 $G$  -- shear modulus of aluminum  
 $a$  -- length of tube between measuring points of the detrusion gage  
 $t_g$  -- total thickness of adhesive between measuring points of the detrusion gage.

The shear strain in the adhesive was obtained by calculating the value of  $\gamma_g$ :

$$\gamma_g = \frac{\phi_g}{t_g} \quad (4)$$

Stress-strain curves were then drawn and the shear modulus,  $G_g$ , the initial slope of the stress-strain curve, was given by the formula:

$$G_g = \frac{\tau}{\gamma_g} \quad (5)$$

Tension tests.--Tension tests were made on the same type of specimen used for the torsion tests. The torsion loading bars were screwed into the ends of the specimen and suspended by bolts in spherical bearings in the testing machine. Two Tuckerman optical strain gages of 1-1/4-inch gage length were used to measure the total deformation across the bonded parts. The testing apparatus is shown in figure 2. Deformation readings were taken at various applied loads to determine data for stress-strain curves.

In order to determine deformation in the adhesive bonds, it was necessary to subtract the deformation in the aluminum tube from the total measured deformation. The amount of deformation in the aluminum was determined by testing a tube without bonds to obtain a modulus of elasticity, which was then used to calculate aluminum deformations for the bonded specimens.

Tensile stresses were calculated from the formula:<sup>6</sup>

$$\sigma = \frac{4P}{\pi(d^2 - d_i^2)} \quad (6)$$

---

<sup>6</sup>This formula gives a stress of 0.726P for the size of tube tested (2-inch outside diameter, 1-1/2-inch inside diameter).

where:  $\sigma$  -- tensile stress  
 $d$  -- outside diameter of tube  
 $d_i$  -- inside diameter of tube  
 $P$  -- applied tensile load.

For the specimen without bonds, the modulus of elasticity was calculated from the formula:

$$E = \frac{\sigma a}{e} \quad (7)$$

where:  $E$  -- modulus of elasticity of aluminum  
 $\sigma$  -- tensile stress  
 $a$  -- length of the tube between measuring points of the deformation gage  
 $e$  -- total deformation measured by the gage.

The test of the tube without bonds gave a modulus of elasticity value of 10,500,000 pounds per square inch. This value was used to calculate the total adhesive deformation from the formula:

$$e_g = e - \frac{\sigma}{E} (a - t_g) \quad (8)$$

where:  $e_g$  -- adhesive bond deformation  
 $e$  -- deformation measured by the gage  
 $\sigma$  -- tensile stress  
 $E$  -- modulus of elasticity of aluminum  
 $a$  -- length of the tube between measuring points of the deformation gage  
 $t_g$  -- total thickness of adhesive between measuring points of the deformation gage.

The tensile (or compressive) strain in the adhesive was obtained by calculating the value of  $\epsilon_g$ :

$$\epsilon_g = \frac{e_g}{t_g} \quad (9)$$

A "measured" modulus of elasticity of the adhesive,  $E_g'$ , the initial slope of the stress-strain curve, was calculated by:

$$E_g' = \frac{\sigma}{\epsilon_g} \quad (10)$$

Because the adhesive bonds are very thin and less rigid than the adherends, these bonds must be restrained. Formula 10, therefore, does not give a correct modulus of elasticity for the adhesive bond. Normally, in most tests of materials, the specimens are proportioned so that natural lateral contraction (Poisson's ratio effects) can occur in tension, or lateral



expansion can occur in compression. The following analysis is presented as a method of obtaining the correct modulus of elasticity,  $E_g$ . It is assumed in the analysis that the bond is isotropic and that the lateral contractions or expansions of the bond must be the same as those of the adherends under the same tensile stress.

The relation between a stress,  $\sigma_x$ , and the resultant strains for an isotropic material is given by the formula:<sup>7</sup>

$$\sigma_x = \frac{E}{1 + \nu} \left[ \epsilon_x + \frac{\nu(\epsilon_x + \epsilon_y + \epsilon_z)}{1 - 2\nu} \right] \quad (11)$$

where:  $\sigma_x$  -- stress in direction x

$\epsilon_x, \epsilon_y, \epsilon_z$  -- strains in directions x, y, and z

$E$  -- modulus of elasticity

$\nu$  -- Poisson's ratio.

Rewriting this formula for the adhesive bond gives:

$$\sigma_{xg} = \frac{E_g}{1 + \nu_g} \left[ \epsilon_{xg} + \frac{\nu_g}{1 - 2\nu_g} (\epsilon_{xg} + \epsilon_{yg} + \epsilon_{zg}) \right] \quad (12)$$

Assuming that the lateral strains in the adhesive are the same as those in the adherends, then:

$$\epsilon_{yg} = \epsilon_{zg} = -\nu\epsilon_x \quad (13)$$

where:  $\nu$  -- Poisson's ratio for adherend

$\epsilon_x$  -- adherend strain in direction x.

Substituting equation (13) into equation (12) gives:

$$\sigma_{xg} = \frac{E_g}{1 + \nu_g} \left[ \epsilon_{xg} + \frac{\nu_g}{1 - 2\nu_g} (\epsilon_{xg} - 2\nu\epsilon_x) \right] \quad (14)$$

or

$$\frac{\sigma_{xg}}{\epsilon_{xg}} = \frac{E_g}{1 + \nu_g} \left[ 1 + \frac{\nu_g}{1 - 2\nu_g} (1 - 2\nu \frac{\epsilon_x}{\epsilon_{xg}}) \right] \quad (15)$$

---

<sup>7</sup>Timoshenko, S. Theory of Elasticity, p. 11, McGraw Hill, New York, N. Y. 1934.

But  $\sigma_{xg}/\epsilon_{xg} = E_g'$ , the "measured" modulus of elasticity, and since the stress in the adhesive is the same as that in the adherend ( $\sigma_{xg} = \sigma_x$ ), then  $\epsilon_x/\epsilon_{xg} = E_g'/E$ , where  $E$  is the modulus of elasticity of the adherend. Substituting these expressions into equation 15 gives:

$$E_g' = \frac{E_g}{1 + \nu_g} \left[ 1 + \frac{\nu_g}{1 - 2\nu_g} (1 - 2\nu) \frac{E_g'}{E} \right] \quad (16)$$

Thus equation (16) relates  $E_g$  and  $E_g'$ , but contains an unknown Poisson's ratio  $\nu_g$ . For isotropic materials it is known that:

$$G_g = \frac{E_g}{2(1 + \nu_g)} \quad (17)$$

where:  $G_g$  -- shear modulus of the adhesive bond.

Substituting equation (17) in equation (16) and solving for  $\nu_g$  gives:

$$\nu_g = \frac{2G_g - E_g'}{2(G_g - E_g' + 2G_g \frac{E_g'}{E})} \quad (18)$$

Then with a shear modulus,  $G_g$ , from a torsion test, formula 18 can be used to find the Poisson's ratio,  $\nu_g$ , of the adhesive bond. Finally, this value of Poisson's ratio can then be used along with the shear modulus to find the modulus of elasticity,  $E_g$ , from the formula:

$$E_g = 2(1 + \nu_g)G_g \quad (19)$$

For the computations in this report, the values of the adherend properties were  $E = 10,500,000$  pounds per square inch and  $\nu = 0.42$ . Actually, formula 18 is relatively insensitive to the values of  $E$  and  $\nu$  because they appear as small terms in part of the denominator.

### Test Results

The results of tests to determine adhesive bond properties are given in table 1. Complete information was not obtained for all adhesives, and the data should not be construed as representing average property values, because only a few tests have actually been made. The data do show that a reasonable consistency of results was obtained. Of the 4 adhesives tested,

2 were rigid adhesives and 2 nearly plastic adhesives. Plasticity is indicated by a Poisson's ratio of 0.50. Redux K-6 and Epon VIII were nearly 100 times more rigid than Scotchweld AF-6 or Metlbond MN3C, but the strength values varied only by a factor between 2 and 3.

Typical shear stress-strain curves for the adhesive bonds are given in figure 3. The big difference in initial slope of these curves demonstrates the difference in rigidity. The area under the stress-strain curves represents work done in shearing the specimens. This work can be used as an indication of behavior under impact: the larger the amount of work, the greater the impact resistance. The work to proportional limit stress, or modulus of resilience, can be calculated from the formula:

$$W_{PL} = \frac{\tau^2}{2G_g} \quad (20)$$

The work to failure,  $W$ , was obtained by measuring the entire area under the curve with a planimeter. Values of work to proportional limit and work to failure for the adhesives are:

<u>Adhesive</u>	<u>Work to proportional</u>	<u>Work to failure</u>
	<u>limit</u>	
	<u>In.-lb. per cu. in.</u>	<u>In.-lb. per cu. in.</u>
Redux K-6	74	9,100
Epon VIII	56	670
Scotchweld AF-6	5,700	7,400
Metlbond MN3C	2,200	2,200

Thus the less rigid adhesives (Scotchweld AF-6 and Metlbond MN3C) had much greater resilience in elastic behavior than the more rigid ones (Redux K-6 and Epon VIII), but the work to failure was greatest for Redux K-6, a rigid adhesive, and least for Epon VIII, another rigid adhesive.

#### Design of Lap Joints

A joint commonly used for sheet materials is the adhesive-bonded lap joint. Theoretical analyses have been developed for the stresses that occur in the adhesive bond in lap joints between thin members subjected to tension. The property values determined for a rigid and a resilient adhesive were used in the following design of lap joints between 0.064-inch aluminum sheets.

Since the theories developed are based on elastic behavior of materials, the analysis performed here does not apply to stresses exceeding proportional limit values.

Since the most complete data were obtained for Redux K-6 and Metlbond MN3C tape, these adhesives are considered in the following design calculations.

It is of interest to examine the stress variation in a lap joint. The shear stress at any point a distance  $x$  from the center of a lap joint that is free to bend is given by the formula:<sup>8</sup>

$$\tau_x = \frac{T}{4L} \left[ \frac{\beta L}{2t} (1 + 3\kappa) \frac{\cosh \frac{\beta x}{t}}{\sinh \frac{\beta L}{2t}} + 3(1 - \kappa) \right] \quad (21)$$

where:  $\tau_x$  -- shear stress at point  $x$   
 $T$  -- load on the lap joint, per unit width  
 $L$  -- length of the overlap  
 $t$  -- thickness of each bonded sheet  
 $x$  -- distance from the center of the overlap, measured in the direction of lap

$$\beta = \sqrt{\frac{\beta G_g t}{Et_g}}$$

$$\kappa = \frac{1}{1 + 2\sqrt{2} \tanh \left( \frac{L}{2t} \sqrt{\frac{3\lambda T}{2Et}} \right)}$$

$G_g$  -- shear modulus of the adhesive bond  
 $t_g$  -- thickness of the adhesive bond  
 $E$  -- modulus of elasticity of the bonded sheets  
 $\lambda = 1 - \nu^2$   
 $\nu$  -- Poisson's ratio for the bonded sheets.

The tearing (tensile) stress at any point a distance  $x$  from the center of a lap joint that is free to bend is given by the formula:<sup>8</sup>

$$\sigma_x = \frac{2\kappa\gamma T}{\Delta L} \left\{ \left[ \frac{\gamma L}{2t} R_2 + 2\alpha \cosh \frac{\gamma L}{2t} \cos \frac{\gamma L}{2t} \right] \cosh \frac{\gamma x}{t} \cos \frac{\gamma x}{t} + \left[ \frac{\gamma L}{2t} R_1 + 2\alpha \sinh \frac{\gamma L}{2t} \sin \frac{\gamma L}{2t} \right] \sinh \frac{\gamma x}{t} \sin \frac{\gamma x}{t} \right\} \quad (22)$$

---

<sup>8</sup>Goland, M. and Reissner, E. Stresses in Cemented Joints. Journal of Applied Mechanics. 1944.

where:  $\sigma_x$  -- tensile stress at point  $x$

$$\gamma = \sqrt{\frac{6E_g t}{Et_g}}$$

$E_g$  -- modulus of elasticity of the adhesive bond

$$\Delta = \sinh \frac{\gamma L}{t} + \sin \frac{\gamma L}{t}$$

$$R_1 = \cosh \frac{\gamma L}{2t} \sin \frac{\gamma L}{2t} + \sinh \frac{\gamma L}{2t} \cos \frac{\gamma L}{2t}$$

$$R_2 = \sinh \frac{\gamma L}{2t} \cos \frac{\gamma L}{2t} - \cosh \frac{\gamma L}{2t} \sin \frac{\gamma L}{2t}$$

$$\alpha = \frac{L}{2t} \sqrt{\frac{3\lambda T}{2Et}}$$

Shear and tensile stresses were computed by using formulas (21) and (22) for Redux K-6 (for which  $G_g = 180,000$  pounds per square inch,  $t_g = 0.003$  inch, and  $E_g = 500,000$  pounds per square inch) and Metlbond MN3C tape (for which  $G_g = 1,530$  pounds per square inch,  $t_g = 0.007$  inch, and  $E_g = 5,200$  pounds per square inch). The bonds were 1/2-inch lap joints of 0.064-inch-thick sheets of aluminum (for which  $E = 10,000,000$  pounds per square inch and  $\nu = 0.3$ ) under a load of 300 pounds per inch of width.

Stresses produced in the rigid bond of Redux K-6 adhesive are shown in figure 4. The shear stress is rather low throughout the central portion of the lap and rises quite sharply to a maximum at the end of the lap. This maximum shear stress is 3,520 pounds per square inch, which is about 6 times the average shear stress of 600 pounds per square inch. The normal stress is also low, even compressive in nature throughout the central portion of the lap, and rises sharply to tension at the end of the lap.

Stresses produced in the resilient bond of Metlbond MN3C tape adhesive are shown in figure 5. The shear stress is nearly constant throughout the lap; it rises gradually to a maximum value of 630 pounds per square inch at the end of the lap, which is only 5 percent greater than the average shear stress. The normal stress varies from compression at the center of the lap to tension at the end of the lap, but the rise to maximum tension is much more gradual than that for the rigid Redux K-6 adhesive.

A comparison of the shear deformation in the bonds of Redux K-6 and Metlbond MN3C at a load of 300 pounds on a 1/2-inch lap of 0.064-inch aluminum sheets is shown in figure 6. In this figure, the deformations shown are drawn to the same scale for each adhesive. The more resilient Metlbond MN3C bond deforms about 48 times as much as the rigid Redux K-6 bond. The Metlbond MN3C adhesive bond was 2-1/3 times as thick as the Redux K-6 adhesive bond. The deformation of the Metlbond was therefore

2-1/3 times greater than if it had been of the same thickness as the Redux bond.

Formulas (21) and (22) give shear and normal stresses as functions of the distance  $x$ . These formulas, when written for the maximum shear and tearing stresses, become:

$$\tau_{\max} = \frac{T}{4L} \left[ \frac{\beta L}{2t} (1 + 3\kappa) \coth \frac{\beta L}{2t} + 3(1 - \kappa) \right] \quad (23)$$

and

$$\sigma_{\max} = \frac{\kappa \gamma T}{2t \left( \sinh \frac{\gamma L}{t} + \sin \frac{\gamma L}{t} \right)} \left[ \gamma \left( \sinh \frac{\gamma L}{t} - \sin \frac{\gamma L}{t} \right) + 4 \sqrt{2} \alpha \frac{t}{L} \left( \cosh \frac{\gamma L}{t} + \cos \frac{\gamma L}{t} \right) \right] \quad (24)$$

These formulas (23 and 24) were used to determine the loads at which the maximum shear and tensile stresses,  $\tau_{\max}$  and  $\sigma_{\max}$ , reached proportional limit values for various amounts of overlap of 0.064-inch aluminum alloy sheets. Loads were calculated for Redux K-6, a rigid adhesive, and for Metlbond MN3C tape, a more resilient adhesive. The calculated loads could be considered as design loads for the particular amount of overlap, because greater loads would probably produce permanent deformations. The resultant loads are plotted against the overlap length in figure 7. The curves show that shearing stress is the controlling factor for very short overlaps, while for moderate overlaps, such as are commonly used, tearing stresses control design. For long overlaps, shear stresses are again critical. The data also show that the more resilient Metlbond MN3C tape can have considerably higher design loads than can the more rigid adhesive, Redux K-6. This, of course, would be expected, because the more rigid the adhesive, the greater the stress concentrations at the end of the lap. It should be recalled, however, that the deformation occurring in joints made with the resilient adhesive, Metlbond MN3C, would be much greater than that in joints made with Redux K-6. The effects of joint deformation on the structure must be considered and may be more important than load-carrying capacity.

The foregoing analysis and application of properties to the design of bonded joints is entirely theoretical. Actual behavior should be checked by careful experiment. Even if only portions of the analysis could be checked experimentally, there would be a good basis for using the analysis in the design of bonded joints.

Table 1.--Adhesive properties determined from tests of end-bonded aluminum tubing<sup>1</sup>

Specimen No.	Number of bonds	Total thickness	Shear			Compression		Tension		
			Modulus	Proportional limit stress	Shear strength	Modulus	Poisson's ratio	Modulus	Proportional limit stress	Tensile strength
			$E_g$	$\tau_{PL}$	$\tau_{max}$	$E_g$	$\nu$	$E_g$	$\sigma_{PL}$	$\sigma_{max}$
		Inch	P.s.i.	P.s.i.	P.s.i.	P.s.i.		P.s.i.	P.s.i.	P.s.i.
Tubes Bonded with Redux K-6 Adhesive										
A1	10	0.028	190,000			525,000	0.37			
1	10	.024	170,000	5,000	6,960	460,000	.34			
2	1	.005			9,050					
R4	10	.032	193,000	5,000	8,350					
R5	10	.030						516,000	5,450	6,620
R6	1	.003			8,400					
R7	1	.005			8,320					
R8	1	.006								6,620
R9	1	.0035								11,680
Ave.			184,000	5,000	8,200	490,000	.36	516,000	5,450	8,300
Tubes Bonded with Scotchweld AF-6 Adhesive										
1	10	.012	980	2,920	2,920	2,940	.498			
2	1				4,490					
3	5	.017	1,500	3,130	3,130					
4	2	.003	1,640	4,330	4,710					
5	1	.002	5,100	3,950	4,060					
Ave.			2,300	3,600	3,840	2,940	.498			
Tubes Bonded with Metlbond MN3C Tape Adhesive										
MT1	10	.068				5,620		5,370	800	1,200
MT2	10	.068	1,680	2,440	2,440	5,040	.499			
MT3	10	.073				5,250		5,620	660	1,150
MT4	10	.075	1,350	2,440	2,440	4,040	.498			
MT5	1	.004								1,300
MT7	10	.063	1,570	2,400	2,550	4,700	.498			
Ave.			1,530	2,430	2,480	4,940	.498	5,500	730	1,220
Tubes Bonded with Epon VIII Adhesive										
E1	10	.008			6,000					
E2	10	.006	180,000	5,000	6,000	512,000	.423			
E3	10	.009	180,000	4,500	7,250	505,000	.401			
E4	10	.017			5,480					
E5	9				5,490					
Ave.			180,000	4,750	6,050	508,000	.412			

<sup>1</sup>The tubing tested was 61S aluminum tubing, with 2 inches outside diameter, 1-1/2 inches inside diameter.

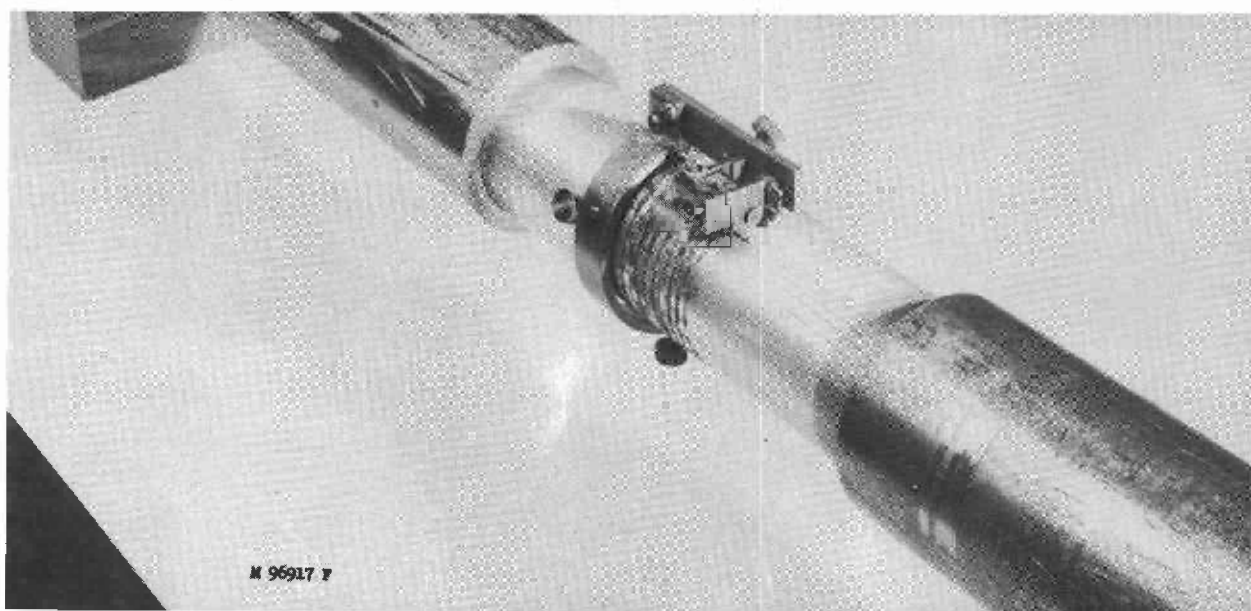


Figure 1. --Torsion test specimen with Tuckerman gage and holder for measuring total detrusion across bonds.

ZM 96917 F



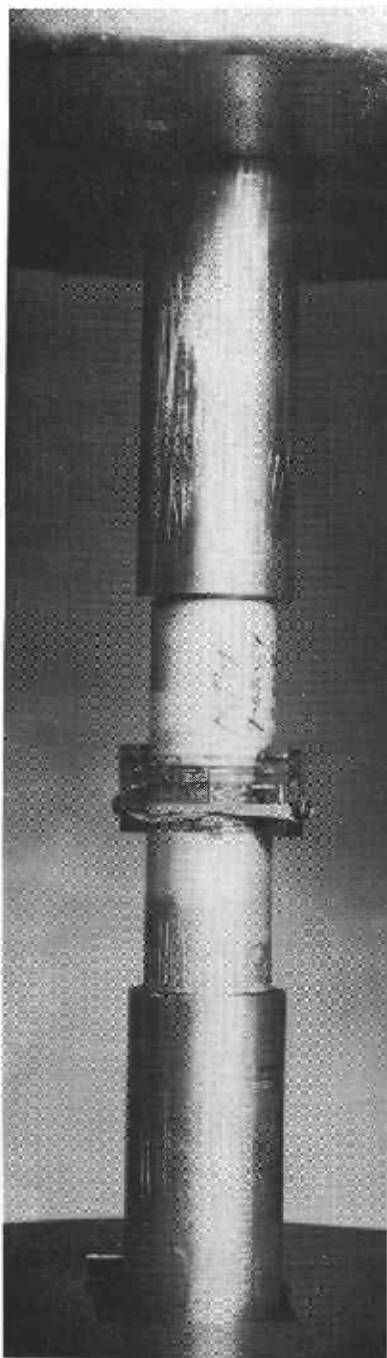


Figure 2. -- Tension test specimen with Tuckerman gages for measuring total detrusion across bonds.

ZM 96918 F

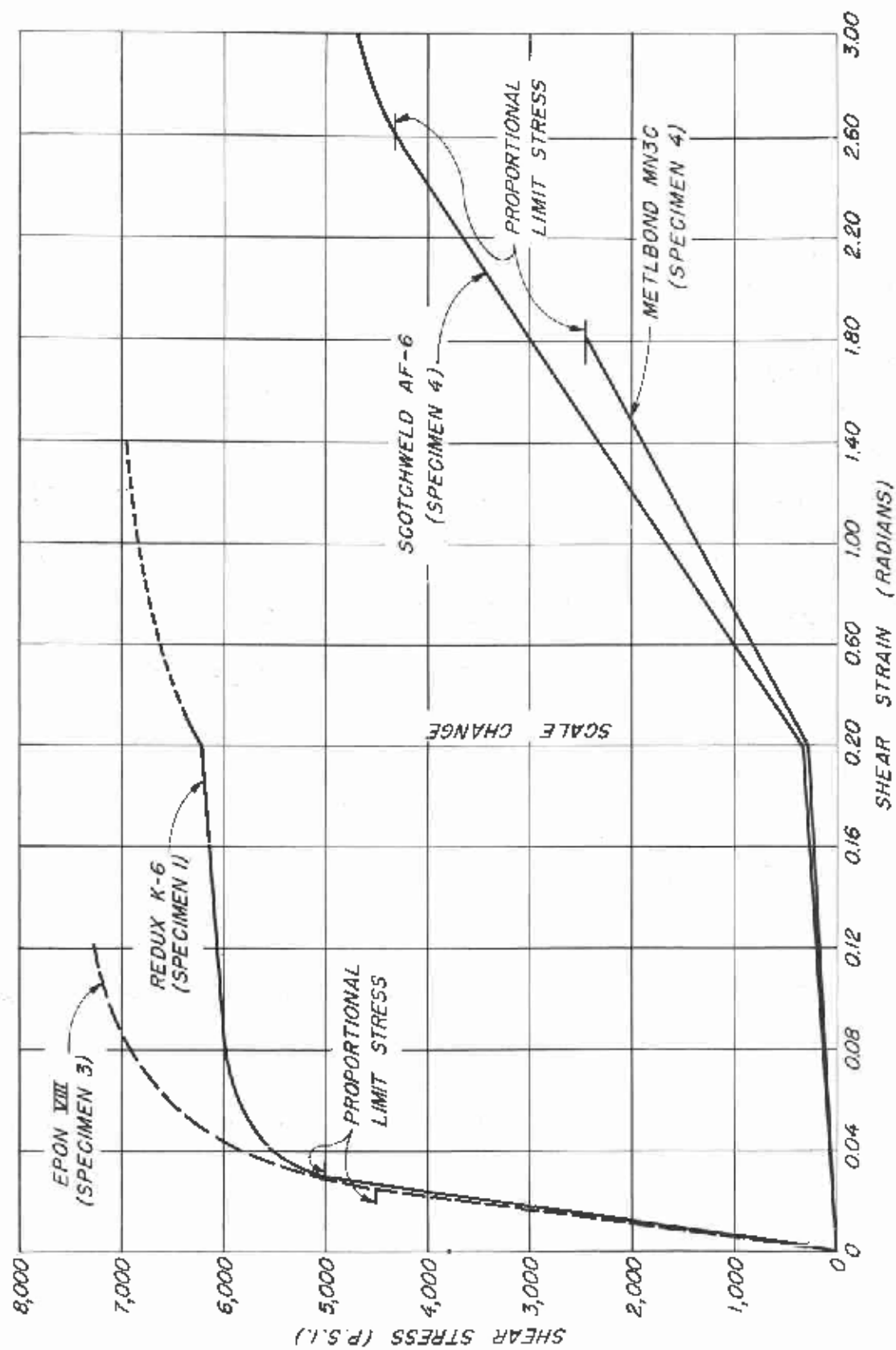


Figure 3.--Shear stress-strain curves for 4 adhesive bonds.

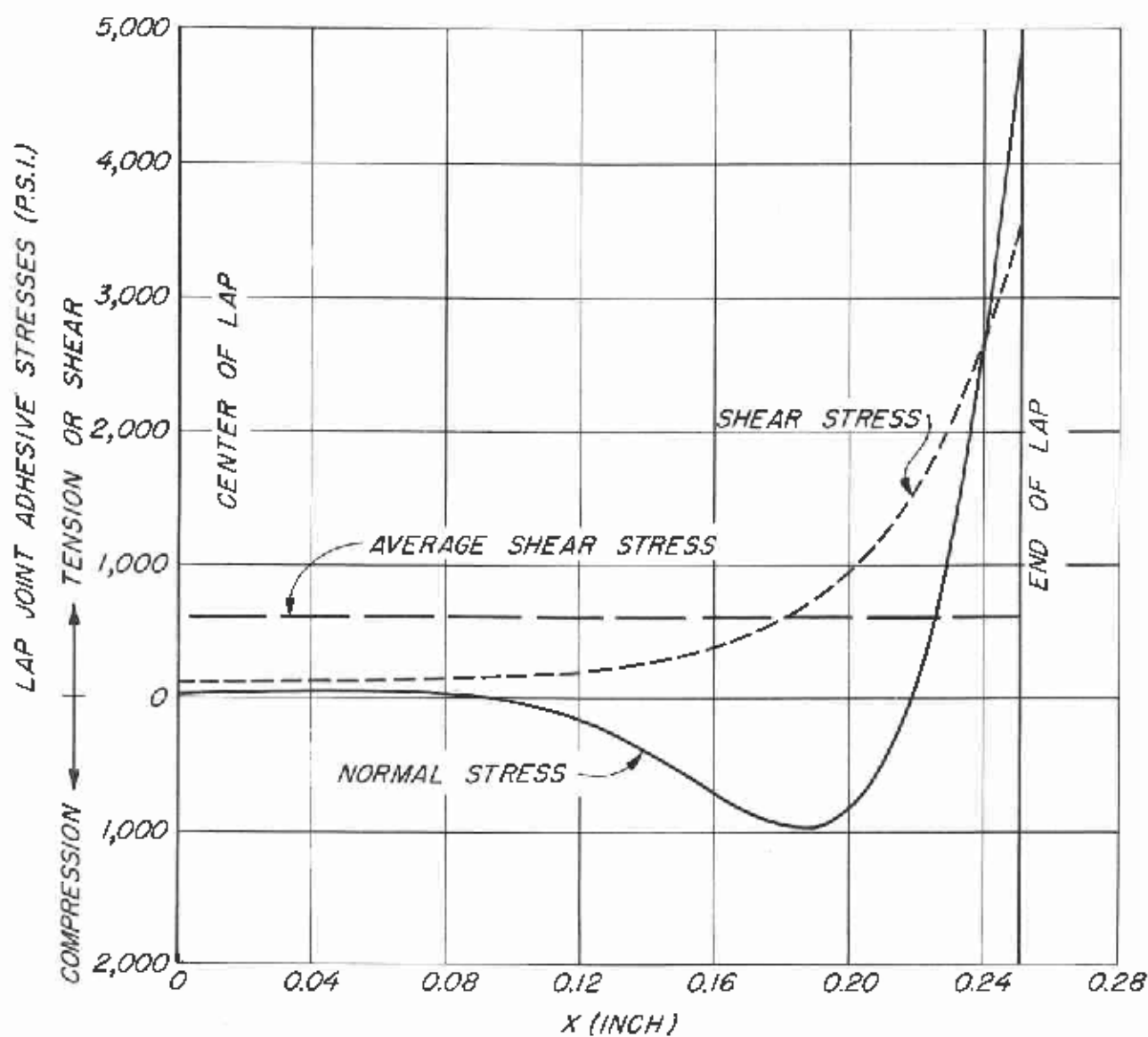


Figure 4. --Stresses in lap joint bonded with Redux K-6 adhesive (0.003-inch thick,  $G_a = 180,000$  P. s. i.). One-half-inch lap of 0.064-inch aluminum loaded to 300 pounds per inch of width.

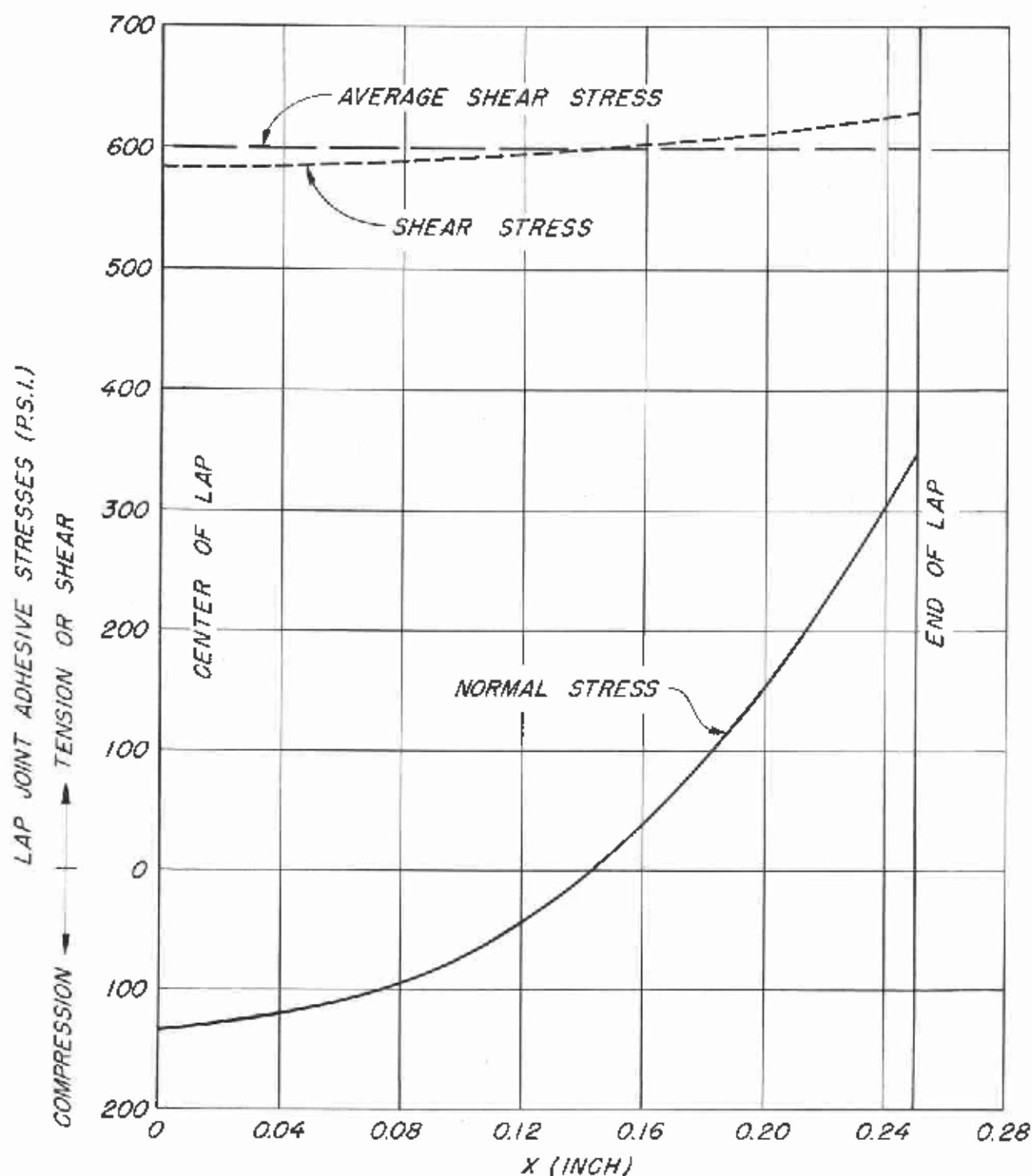


Figure 5. --Stresses in lap joint bonded with Metlbond MN3C tape adhesive (0.007-inch thick,  $G_a = 1,530$  P. s. i.). One-half-inch lap of 0.064-inch aluminum loaded to 300 pounds per inch of width.

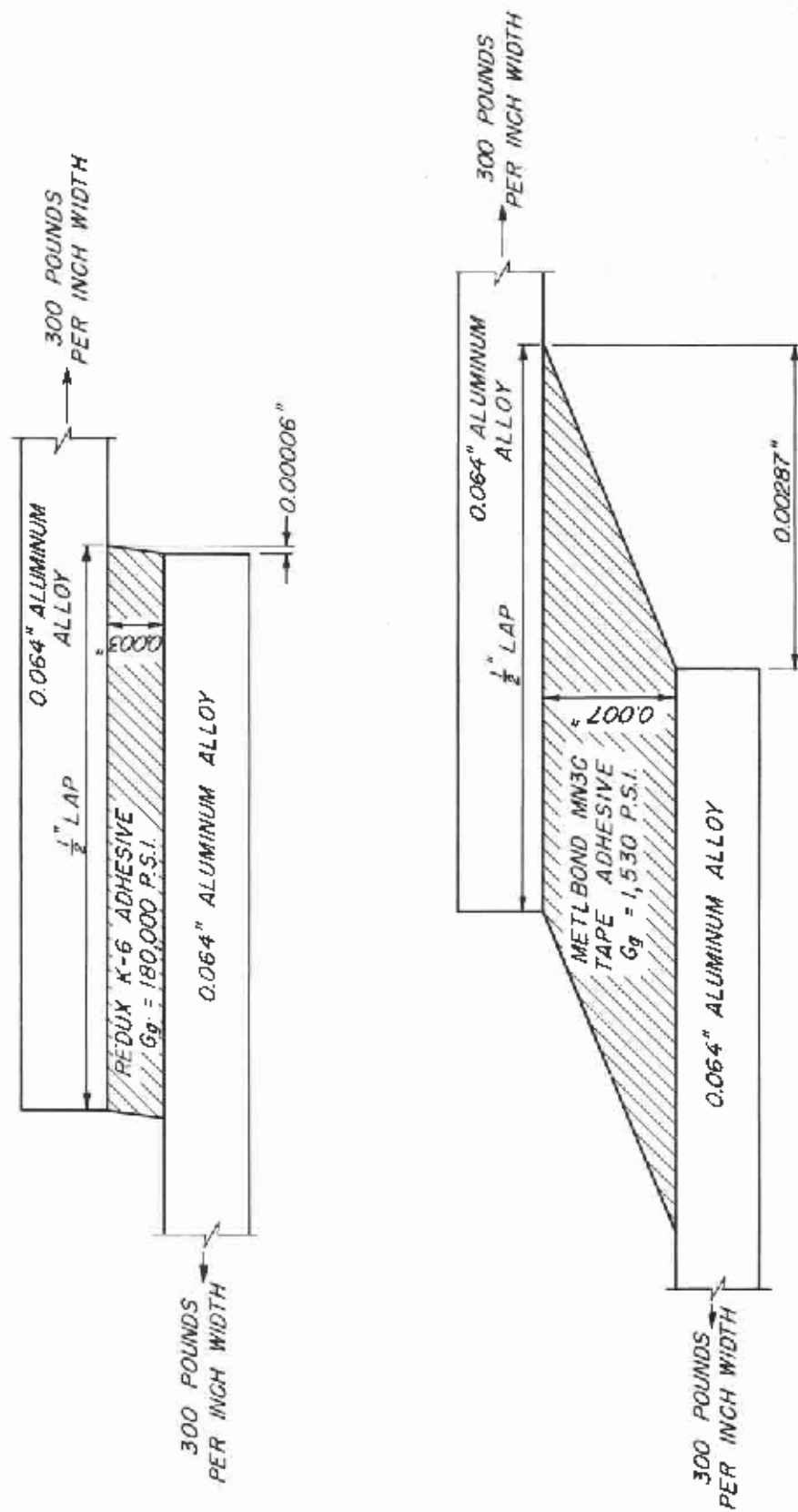


Figure 6. -- Shear deformation of adhesives in lap joints between aluminum alloy sheets.

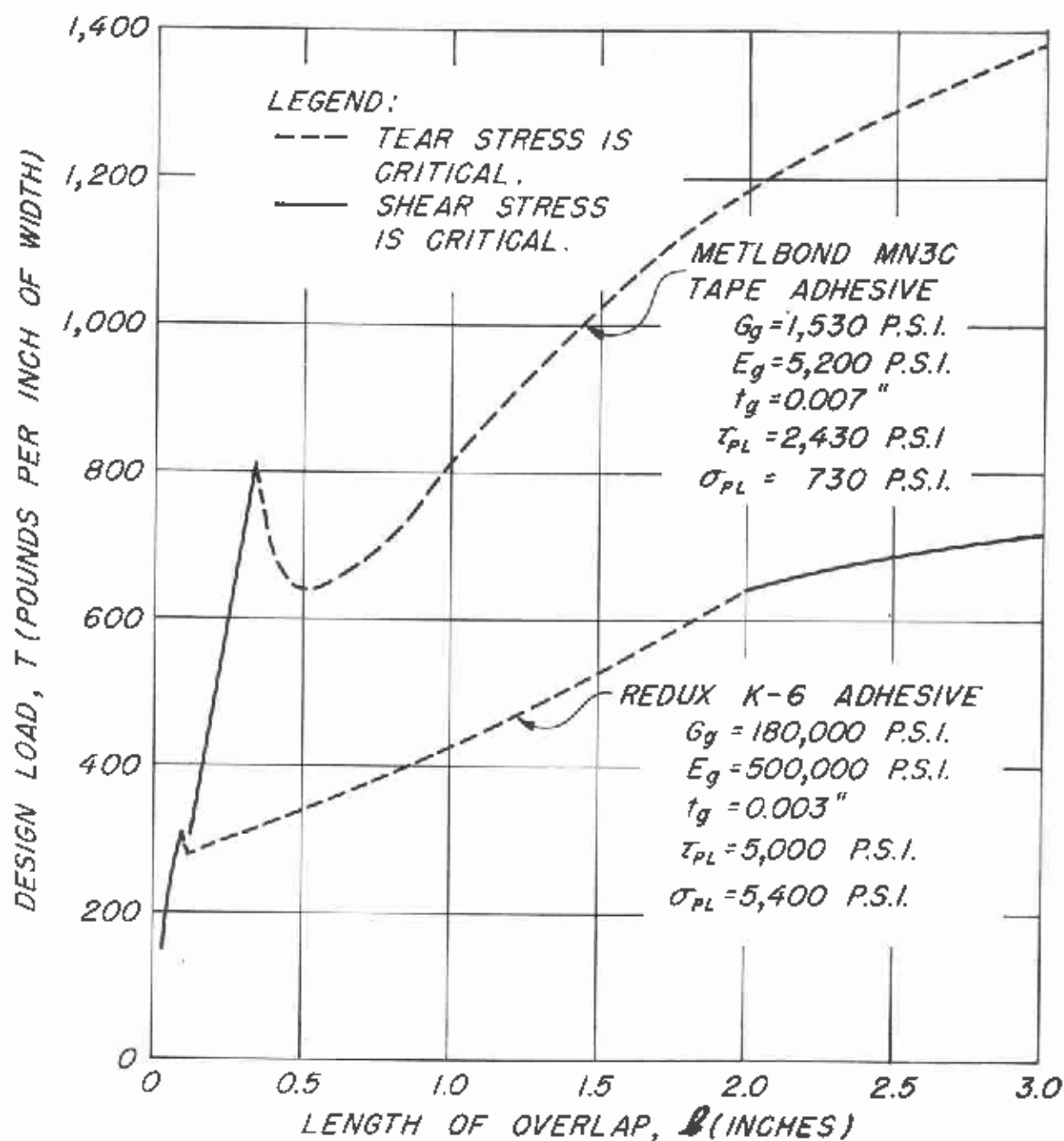


Figure 7. --Design loads for lap joints of 0.064-inch 75ST clad aluminum.  
 $E = 10,000,000$  P. s. i.,  $\lambda = 0.91$ .

SUBJECT LISTS OF PUBLICATIONS ISSUED BY THE

FOREST PRODUCTS LABORATORY

The following are obtainable free on request from the Director, Forest Products Laboratory, Madison 5, Wisconsin:

List of publications on  
Box and Crate Construction  
and Packaging Data

List of publications on  
Chemistry of Wood and  
Derived Products

List of publications on  
Fungus Defects in Forest  
Products and Decay in Trees

List of publications on  
Glue, Glued Products,  
and Veneer

List of publications on  
Growth, Structure, and  
Identification of Wood

List of publications on  
Mechanical Properties and  
Structural Uses of Wood  
and Wood Products

Partial list of publications for  
Architects, Builders,  
Engineers, and Retail  
Lumbermen

List of publications on  
Fire Protection

List of publications on  
Logging, Milling, and  
Utilization of Timber  
Products

List of publications on  
Pulp and Paper

List of publications on  
Seasoning of Wood

List of publications on  
Structural Sandwich, Plastic  
Laminates, and Wood-Base  
Aircraft Components

List of publications on  
Wood Finishing

List of publications on  
Wood Preservation

Partial list of publications for  
Furniture Manufacturers,  
Woodworkers and Teachers of  
Woodshop Practice

Note: Since Forest Products Laboratory publications are so varied in subject no single list is issued. Instead a list is made up for each Laboratory division. Twice a year, December 31 and June 30, a list is made up showing new reports for the previous six months. This is the only item sent regularly to the Laboratory's mailing list. Anyone who has asked for and received the proper subject lists and who has had his name placed on the mailing list can keep up to date on Forest Products Laboratory publications. Each subject list carries descriptions of all other subject lists.