U.S. Forest Service Research Note

UNITED STATES DEPARTMENT OF AGRICULTURE . FOREST SERVICE . FOREST PRODUCTS LABORATORY . MADISON, WIS

In Cooperation with the University of Wisconsin

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

September 1963

FPL-011

This Report is One of a Series
Issued in Cooperation with the
MIL-HDBK-23 WORKING GROUP ON COMPOSITE
CONSTRUCTION FOR FLIGHT VEHICLES
of the Departments of the
AIR FORCE, NAVY, AND COMMERCE

DETERMINATION OF MECHANICAL PROPERTIES OF ADHESIVES FOR USE IN THE DESIGN OF BONDED JOINTS[1,2]

By

EDWARD W. KUENZI, Engineer
and
GORDON H. STEVENS, Engineer

Forest Products Laboratory,[3] Forest Service
U.S. Department of Agriculture

- - - -

Summary

This report describes methods for determining the basic mechanical properties of adhesives subjected to shear or tension in bonds betweem relatively rigid adherends. The use of the adhesive 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 lightweight aircraft parts. Suitable design criteria for various types of joints and loading conditions are

---

[1]This research note replaces a report by the same title, published as Forest Products Laboratory Report No. 1851 in 1956. It is another progress report in the series (ANC-23, Item 54-1) prepared and distributed by the Forest Products Laboratory under U.S. Navy, Bureau of Naval Weapons Nos. 19-61-8041 WEPS and 19-63-8022 WEPS and U.S. Air Force Nos. DO 33(616)61-06 and 33(657)63-358. Results here reported are preliminary and may be revised as additional data become available.

[2]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.

[3]Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

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.

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 as when bonding metals, it was decided to evaluate 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.

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. Where more than one glue line was used, "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 several adhesive bonds that had a total deformation several times that of a single bond, and a more accurate determination of bond deformation was possible.

Each end of the tubular specimen was threaded or slotted for mounting in the torsion machine. Specimens with the threaded ends could also be evaluated in tension. Specimens of Metlbond 408 and FM 1000 adhesive had the ends of the specimens slotted and were loaded in compression, since they were not suitable for tension loading, to determine the modulus of elasticity. In figure 3 a slotted specimen is shown partially in place in the torsion machine.

Bonding of Test Specimens[4]

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 acrylo-nitrile-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.

---

[4]Bonding procedures were devised and carried out under the supervision of H. W. Eickner of the U.S. Forest Products Laboratory.

Metlbond 4021, a high-temperature-setting formulation of nitrile rubber and phenol resin in the form of an unsupported film.

FM 47 Tape, a high-temperature-setting formulation of vinyl-phenolic type supported on woven glass fabric.

Metlbond 408, a high-temperature-setting modified epoxy resin in an unsupported film.

FM 1000, a high-temperature-setting unsupported epoxy polyamide film.

Epon 422J Tape, a high-temperature-setting formulation of the epoxy-phenol type supported on woven glass fabric.

Epon VIII, a formulation of epoxy resins.

Tube and washer ends that were to be bonded with the first seven 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 bichromate, and 30 parts of water. Specimen ends that were to be bonded with Epon VIII and Epon 422J adhesives 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 bichromate, 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.

After the parts were ready for bonding, they were carefully assembled without adhesive, and 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.

The specimens were then assembled with the adhesives. The parts were alined 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 four 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 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.

Metlbond 4021.--A single coat of the priming component was sprayed on each of the surfaces to be bonded and air dried for 18 hours. The specimen was then assembled with a single film of adhesive, in the form of an oversized washer, at each joint. The assembly was then clamped with a pressure of 100 pounds per square inch and cured for 1 hour at 350° F.

FM 47 Tape.--A single coat of the priming component was sprayed on each of the surfaces to be bonded and precured for 1 hour at 220° F. The specimen was then assembled with a single film of the tape adhesive, in the form of an oversized washer, at each joint. The adhesive was cured at a pressure of 200 pounds per square inch for 30 minutes at a temperature of 300° F.

Epon 422J Tape.--A specimen was assembled with a single film of the tape adhesive, in the form of an oversized washer, at each joint. The adhesive was then cured at a pressure of 15 pounds per square inch for 30 minutes at a temperature of 330° F.

Metlbond 408.--A specimen was assembled with a single film of the tape adhesive, in the form of an oversized washer, at

each joint. The adhesive was then cured at a pressure of 15 pounds per square inch for 60 minutes at a temperature of 350° F.

FM 1000.--A specimen was assembled with a single film of the tape adhesive, in the form of an oversized washer, at each joint. The adhesive was then cured at a pressure of 15 pounds per square inch for 60 minutes at a temperature of 350° 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 or tension at a load within the elastic range, to obtain modulus of elasticity values and then tested in torsion.

Torsion Tests

Loading bars of the torsion testing machine with threaded studs were screwed into the test specimens with threaded ends. Difficulty in unscrewing tested specimens with threaded ends prompted design of specimens with slotted ends. Collars with crossed bars were fitted to the torsion machine for twisting specimens with slotted ends. Figure 3 shows a specimen with slotted ends partially in place in the torsion machine. The test specimen was fitted with a detrusion gage to measure the total twist over a 1-1/2 inch length of the specimen that included the adhesive 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 autocollimater. For a specimen with an outside diameter of 2 inches the detrusion readings were directly in radians. After the threaded specimens with the detrusion gage were mounted in the torsion machine, an initial load, not exceeding the elastic range of the adhesive, was applied and then removed from the specimen. This first application of load tightened the threaded specimens onto the threaded studs of the torsion machine and brought the specimen ends into firm contact with a shoulder at the base of the threaded stud.

When the load was reapplied to the specimen, detrusion values were read at various loads to determine the data for the stress-strain curve. Figure 4 shows the effect of the preloading on the stress-strain curve for a specimen. After the initial loading, the stress-strain curve was about the same shape for a second and third loading even after waiting for 1 hour before application of the third loading. The same test procedure was used for the specimens with slotted specimens to be consistent on loads applied to specimens. The data from the second loading were used in determining the adhesive properties.

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:[5]

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

where: τ -- shear stress
d -- outside diameter of the tube
d_i -- inside diameter of the tube
T -- applied torque.

---

[5]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.

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

$$G = \frac{\tau a}{\phi} \tag{2}$$

where: G -- shear modulus of aluminum
τ -- shear stress
a -- length of the tube between measuring points of the detrusion gage
ϕ -- 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:

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

where: ϕ_g -- adhesive bond detrusion
ϕ -- detrusion measured by gage
τ -- 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 γ_g:

$$\gamma_g = \frac{\phi_g}{t_g} \tag{4}$$

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:

$$G_g = \frac{\tau}{\gamma_g} \tag{5}$$

Tension or Compression Tests

Tension tests were made only on the threaded specimens. The torsion loading bars were screwed into the ends of the specimen and suspended by bolts in spherical bearings in the testing machine. The specimens with the slotted ends were loaded in compression to determine a measured modulus of elasticity. These specimens were loaded while supported on a base block having a spherical seat. 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 load-deformation 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:[6]

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

where: σ -- tensile stress or compressive 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:

$$E = \frac{\sigma a}{e} \tag{7}$$

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

---

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

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:

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

where: e_g -- adhesive bond deformation

e -- deformation measured by the gage

σ -- tensile stress or compressive 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 ϵ_g:

$$\epsilon_g = \frac{e_g}{t_g} \tag{9}$$

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

$$E_g' = \frac{\sigma}{\epsilon_g} \tag{10}$$

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, σ_x, and the resultant strains for an isotropic material is given by the formula.[7]

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

where: σ_x --stress in direction x

ϵ_x, ϵ_y, ϵ_z --strains in directions x, y, and z

E --modulus of elasticity

ν --Poisson's ratio.

Rewriting this formula for the adhesive bond gives:

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

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

$$\epsilon_{yg} = \epsilon_{zg} = -\nu\epsilon_x \tag{13}$$

where: ν -- Poisson's ratio for adherend

ϵ_x -- adherend strain in direction x.

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

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

or

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

---

[7] Timoshenko, S. Theory of Elasticity. McGraw-Hill. New York, N. Y. p. 11. 1934.

But $\frac{\sigma_{xg}}{\epsilon_{xg}} = E_g'$, 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 $\frac{\epsilon_x}{\epsilon_{xg}} = \frac{E_g'}{E}$, where E is the modulus of elasticity of the adherend. Substituting these expressions into equation (15) gives:

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

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

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

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

Substituting equation (17) in equation (16) and solving for ν_g gives:

$$\nu_g = \frac{2G_g - E_g'}{2\left(G_g - E_g' + 2G_g\nu\frac{E_g'}{E}\right)} \tag{18}$$

Then with a shear modulus, G_g, , from a torsion test, formula (18) can be used to find the Poisson' s ratio, ν_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:

$$E_g = 2(1 + \nu_g)G_g \tag{19}$$

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

Test Results

The results of tests to determine the adhesive bond properties are given in table 1 and summarized in table 2. Complete information was not obtained for all the adhesives and the data should not be construed as representing average property values.

The Poisson's ratio varied from 0.294 for the Epon 422J to 0.498 for the Metlbond MN3C. Scotchweld AF-6, Metlbond MN3C, and Metlbond 4021 were the least rigid of the adhesives tested. The shear strength of these adhesives was about 2,500 pounds per square inch for the Metlbond MN3C, about 3,900 pounds per square inch for the Scotchweld AF-6, and about 4,600 pounds per square inch for the Metlbond 4021. The shear strength values for the remaining, more rigid, adhesives ranged from about 3,700 to 8,200 pounds per square inch. A summary of the average values for the properties of the adhesives is presented in table 2.

Shear stress-strain curves for the adhesive bonds are given in figure 5. These curves were drawn from data for the specimen within a group that had property values near the group average. 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:

$$W_{PL} = \frac{\tau^2}{2G_g} \tag{20}$$

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:

Adhesive	Work to proportional limit	Work to failure
	In. -lb. per cu. in.	In. -lb. per cu. in.
Redux K-6	75	9,100
FM 47	35	130
Epon 422J	35	210
Epon VIII	55	670

Adhesive	Work to proportional limit	Work to failure
	In. -lb. per cu. in.	In. -lb. per cu. in.
FM 1000	120	16,000+
Metlbond 408	35	12,000
Scotchweld AF-6	1,500	1,800
Metlbond 4021	5,200	5,200
Metlbond MN3C	2,200	2,200

Thus the less rigid adhesives (Scotchweld AF-6, Metlbond 4021, and Metlbond MN3C) had much greater resilience in elastic behavior than the more rigid ones, but the work to failure was greatest for FM 1000, a rigid adhesive, and least for FM 47, another rigid adhesive.

Desire of Lap Joints

A joint commonly used for sheet materials is the adhesive-bonded lap joint. Theoretical analyses[8] 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.

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:[8]

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

[8] Goland, M. and Reissner, E. Stresses in Cemented Joints. Journal of Applied Mechanics. 1944.

where: τ_x -- shear stress at point $\underline{x}$

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

$$\beta = \sqrt{\frac{8G_g t}{Et_g}}$$

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

G_g -- shear modulus of the adhesive bond

t_g -- thickness of the adhesive bond

E -- modulus of elasticity of the bonded sheets

λ -- $1 - \nu^2$

ν -- Poisson's ratio for the bonded sheets.

The tearing (tensile) stress at any point a distance $\underline{x}$ from the center of a lap joint that is free to bend is given by the formula:–[8]

$$\sigma_x = \frac{2\kappa\gamma T}{\Delta L}\left\{\left[\frac{\gamma L}{2t} R2 - 2\sqrt{2}\,\alpha\,\mathrm{Cosh}\,\frac{\gamma L}{2t}\cos\frac{\gamma L}{2t}\right]\mathrm{Cosh}\,\frac{\gamma x}{t}\cos\frac{\gamma x}{t} + \left[\frac{\gamma L}{2t} R_1 - 2\sqrt{2}\,\alpha\,\mathrm{Sinh}\,\frac{\gamma L}{2t}\sin\frac{\gamma L}{2t}\right]\mathrm{Sinh}\,\frac{\gamma x}{t}\sin\frac{\gamma x}{t}\right\} \tag{22}$$

where: σ_x -- tensile stress at point $\underline{x}$

$$\gamma = \sqrt[4]{\frac{6E_g t}{Et_g}}$$

E_g -- modulus of elasticity of the adhesive bond

$$\Delta = \mathrm{Sinh}\,\frac{\gamma L}{t} + \sin\frac{\gamma L}{t}$$

$$R_1 = \text{Cosh}\,\frac{\gamma L}{2t}\,\sin\,\frac{\gamma L}{2t} + \text{Sinh}\,\frac{\gamma L}{2t}\,\cos\,\frac{\gamma L}{2t}$$

$$R_2 = \text{Sinh}\,\frac{\gamma L}{2t}\,\cos\,\frac{\gamma L}{2t} - \text{Cosh}\,\frac{\gamma L}{2t}\,\sin\,\frac{\gamma L}{2t}$$

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

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 ν = 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 6. 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 six 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 a tension of about 4,400 pounds per square inch at the end of the lap.

Stresses produced in the resilient bond of Metlbond MN3C tape adhesive are shown in figure 7. 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 a tension of about 260 pounds per square inch 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 8. 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:

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

and

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

These formulas ((23) and (24)) were used to determine the loads at which the maximum shear and tensile stresses, τ_{max} and σ_{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 9. The curves show that for the resilient adhesive Metlbond MN3C shearing stress is the controlling stress in the design of a lap joint for all lengths. The controlling stress in lap joints bonded with Redux K-6, a rigid adhesive, may be either shearing or tensile stresses. Shearing stress is the controlling stress for very short overlap, tension stress is controlling for the overlap of moderate length as usually used, and shearing stress is again the controlling stress for very long overlaps,

The design curves 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 concentration at the end of the lap. The curves in figures 6 and 7 show the stress distribution over the length of a lap joint. 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 (fig. 8). The effects of joint deformation on the structure must be considered and may be more important than load-carrying capacity.

The analysis and application of adhesive properties to the design of bonded lap joints is theoretical. Design curves presented in figure 9 are based on the adhesive properties only within the elastic range. If even a small portion of these curves could be checked by actual test there would be some basis for using these formulas in the design of lap joints.

Table 1.--Adhesive properties determined from tests of end-bonded aluminum tubing[1]

Specimen No.	Number of bonds	Total bond thickness	Shear: Modulus G_g	Shear: Proportional limit stress τ_{PL}	Shear: Shear strength τ_{max}	Compression: Modulus E_g	Compression: Poisson's ratio ν	Tension: Modulus E_g	Tension: Proportional limit stress σ_{PL}	Tension: Tensile strength σ_{max}	Tension: Poisson's ratio ν
		In.	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	
Average			184,000	5,000	8,200	490,000	.36	516,000	5,450	8,300	
TUBES BONDED WITH SCOTCHWELD AF-6 ADHESIVE[2]											
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						
Average			2,300	3,600	3,840	2,940	.498				
6	1	.002	5,330	3,330	3,890	15,900	.495				
7	1	.002	5,850	3,110	3,350	17,500	.495				
8	1	.002	5,720	3,820	3,920	17,100	.495				
9	1	.002	5,290	3,970	4,010	15,800	.496				
10	1	.002	8,340	4,370	4,490	24,800	.491				
11	1	.002	6,100	3,660	3,780	18,200	.495				
Average			6,100	3,710	3,910	18,200	.494				
12	1	.0021	4,370					13,100	1,600	2,170	0.494
13	1	.0020	4,300					12,900	2,110	2,710	.495
14	1	.0026	3,370					10,100	1,670	2,590	.494
15	1	.0019	1,540					4,600	2,040	2,960	.499
16	1	.0018	2,650					7,900	1,960	2,440	.494
17	1	.0020	2,870					8,400	730	1,520	.466
Average			3,200					9,500	1,680	2,400	.490

Table 1.--Adhesive properties determined from tests of end-bonded aluminum tubing[1]--continued

Specimen No.	Number of bonds	Total bond thickness	Shear: Modulus G_g	Shear: Proportional limit stress τ_{PL}	Shear: Shear strength τ_{max}	Compression: Modulus E_g	Compression: Poisson's ratio ν	Tension: Modulus E_g	Tension: Proportional limit stress σ_{PL}	Tension: Tensile strength σ_{max}	Tension: Poisson's ratio ν
		In.	P.s.i.	P.s.i.	P.s.i.	P.s.i.		P.s.i.	P.s.i.	P.s.i.	
TUBES BONDED WITH METLBOND MN3C TAPE ADHESIVE											
MT1	10	0.068	.....	.....	.....	5,620	.....	5,370	800	1,200	.....
MT2	10	.068	1,680	2,440	2,440	5,040	0.499	.....	.....	.....	.....
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	.....	.....	.....	.....
Average			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	.....	.....	.....	.....	.....	.....
Average			180,000	4,750	6,050	508,000	.412				
TUBES BONDED WITH METLBOND 4021 FILM ADHESIVE[2]											
M-1	1	.0030	7,900	970	.....	.....	.....	22,500	1,160	2,420	0.425
M-2	1	.0021	2,020	1,090	.....	.....	.....	6,000	950	2,690	.473
M-3	1	.0020	3,240	1,300	.....	.....	.....	9,500	1,020	3,000	.464
M-4	1	.0043	7,580	1,040	.....	.....	.....	22,600	1,530	2,730	.493
M-5	1	.0044	8,540	860	.....	.....	.....	25,400	870	2,510	.484
M-6	1	.0023	3,860	1,560	.....	.....	.....	11,500	2,260	2,920	.490
Average			5,520	1,140				16,200	1,300	2,710	.472
M-7	4	.0167	3,660	.....	4,780	10,920	.493	.....	.....	.....	.....
M-8	4	.0142	2,000	.....	4,480	5,990	.497	.....	.....	.....	.....
M-9	4	.0151	2,040	.....	4,580	6,120	.499	.....	.....	.....	.....
M-10	4	.0150	1,620	.....	.....	4,860	.499	.....	.....	.....	.....
M-11	4	.0140	1,690	.....	4,480	5,060	.498	.....	.....	.....	.....
M-12	4	.0130	1,740	.....	4,510	5,210	.498	.....	.....	.....	.....
Average			2,120		4,560	6,360	.497				

Table 1.--Adhesive properties determined from tests of end-bonded aluminum tubing[1]--continued

Specimen No.	Number of bonds	Total bond thickness	Shear: Modulus G_g	Shear: Proportional limit stress τ_{PL}	Shear: Shear strength τ_{max}	Compression: Modulus E_g	Compression: Poisson's ratio ν	Tension: Modulus E_g	Tension: Proportional limit stress σ_{PL}	Tension: Tensile strength σ_{max}	Tension: Poisson's ratio ν
		In.	P.s.i.	P.s.i.	P.s.i.	P.s.i.		P.s.i.	P.s.i.	P.s.i.	
TUBES BONDED WITH FM 47 TAPE ADHESIVE											
1	10	0.094			3,360						
2	1	.005			5,390						
3	1	.004			3,280						
4	1	.006			3,370						
5	1	.004			4,060						
6	10	.033	92,000	2,460	3,320	256,000	0.390				
7	10	.040	123,000	2,930	3,470	344,000	.400				
8	10	.037	112,000	2,250	2,530	310,000	.388				
9	10	.037	116,000	3,220	3,820	326,000	.410				
10	10	.037	115,000	1,580		314,000	.370				
11	10	.046	147,000	1,520		398,000	.352				
12	1	.003			3,890						
13	1	.003			4,010						
14	1	.003			4,150						
15	1	.003							3,350	4,070	
16	1	.003							3,640	4,070	
17	1	.003								4,770	
18	1	.003								4,510	
19	1	.003							3,060	4,190	
20	1	.003							3,640	4,510	
Average:			117,000	2,330	3,720	325,000	.385		3,420	4,350	
TUBES BONDED WITH EPON 422J TAPE ADHESIVE											
1	1	0.0145	202,000	3,470	5,480						
2	1	.0115	165,000		6,920						
3	5	.0471	180,000	3,470	5,280			485,000			0.347
4	5	.0503	224,000	2,740	5,270			592,000			.320
5	5	.0418	140,000	3,230	4,650			375,000			.336
6	5	.0407	239,000					573,000		2,750	.198
7	5	.0281	106,000					276,000		2,070	.302
8	1	.008	71,000					203,000		3,460	.420
9	1	.0089	114,000					260,000		1,980	.137
Average:			160,000	3,230	5,520			395,000		2,560	.294

Table 1.--Adhesive properties determined from tests of end-bonded aluminum tubing[1]--continued

Specimen No.	Number of bonds	Total bond thickness	Shear: Modulus G_g	Shear: Proportional limit stress τ_{PL}	Shear: Shear strength τ_{max}	Compression: Modulus E_g	Compression: Poisson's ratio ν	Tension: Modulus E_g	Tension: Proportional limit stress σ_{PL}	Tension: Tensile strength σ_{max}	Tension: Poisson's ratio ν
		In.	P.s.i.	P.s.i.	P.s.i.	P.s.i.		P.s.i.	P.s.i.	P.s.i.	
TUBES BONDED WITH METLBOND 408 FILM ADHESIVE											
M2	5	0.0147	54,000	1,900	5,640	152,000	0.406				
M3	5	.0345	38,100	920	2,530	109,000	.431				
M4	5	.0430	52,700	1,240	1,920	139,000	.317				
M5	5	.0110	55,500	2,820	6,550	160,000	.447				
M6	5	.0114	46,000	2,750	5,470	134,000	.450				
M7	1	.0073			6,420						
M8	1	.0045			6,750						
M9	1	.0077			6,730						
MD1	1	.0013			7,930						
MT1	1	.0039								8,000	
Average			49,300	1,870	5,550	139,000	.410			8,000	
TUBES BONDED WITH FM 1000 FILM ADHESIVE											
F1	1	.0015			10,550						
F2	5	.0355	84,600	2,970	7,450	240,000	.419				
F3	5	.0175	65,900	4,020	9,100	188,000	.422				
F4	5	.0285	73,500	3,950		207,000	.407				
F5	5	.0400	52,700	3,000	6,280	152,000	.439				
F6	5	.0200	63,300	3,000	6,400	174,000	.376				
F7	5	.0125	44,500	3,480	7,810	123,000	.383				
FA1	1	.0025								6,990	
Average			64,100	3,400	7,930	180,000	.408			6,990	

[1]The tubing tested was 61S aluminum tubing with 2 inches outside diameter, 1-1/2 inches inside diameter.

[2]Specimens within each group were made at the same time from the same supply of adhesive.

Table 2.--Summary of adhesive properties

Adhesive	Modulus of elasticity E_g	Modulus of rigidity G_g	Poisson's ratio ν	Shear strength τ	Tensile strength σ
	P.s.i.	P.s.i.		P.s.i.	P.s.i.
Redux K-6	500,000	184,000	0.36	8,200	8,300
AF-6[1]	18,200	6,100	.494	3,910	.....
	9,500	3,200	.490	.....	2,400
MN3C	5,200	1,530	.498	2,480	1,220
Epon VIII	508,000	180,000	.412	6,050	.....
Metlbond 4021[1]	16,200	5,520	.472	.....	2,710
	6,360	2,120	.497	4,560	.....
FM 47	325,000	117,000	.385	3,720	4,350
Epon 422J	395,000	160,000	.294	5,520	2,560
Metlbond 408	139,000	49,300	.410	5,550	8,000
FM 1000	180,000	64,100	.408	7,930	6,990

[1]These values represent two different batches of the adhesive, obtained at different dates.

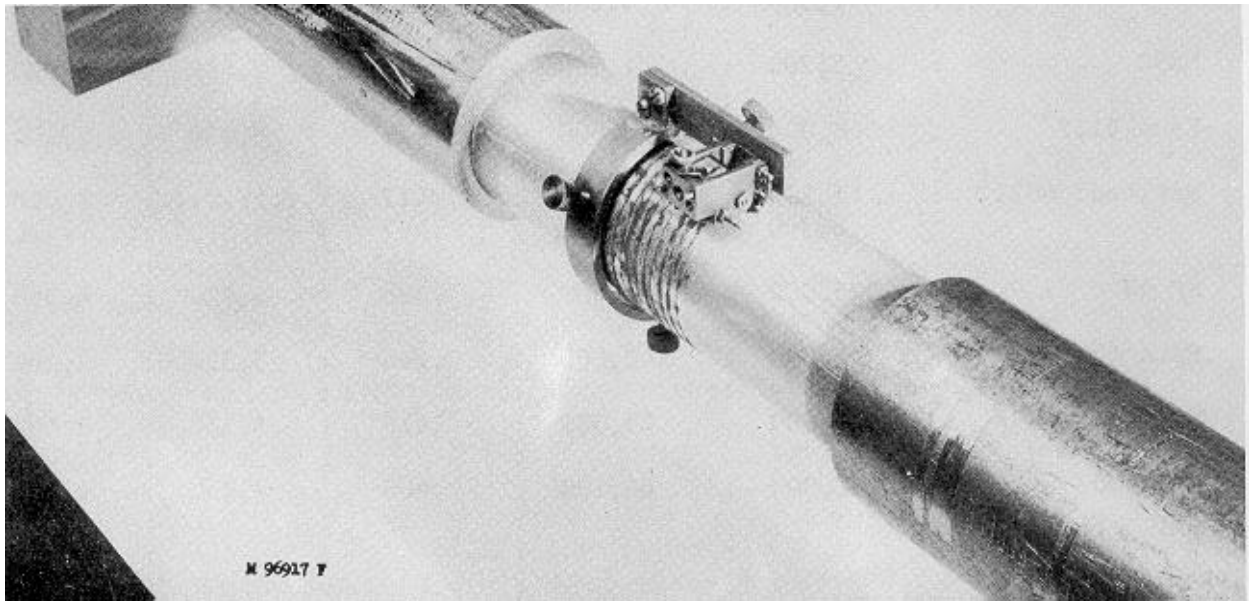

Figure 1. -- Torsion test specimen with Tuckerman gage and holder for measuring total detrusion across bonds.

ZM 96917 F

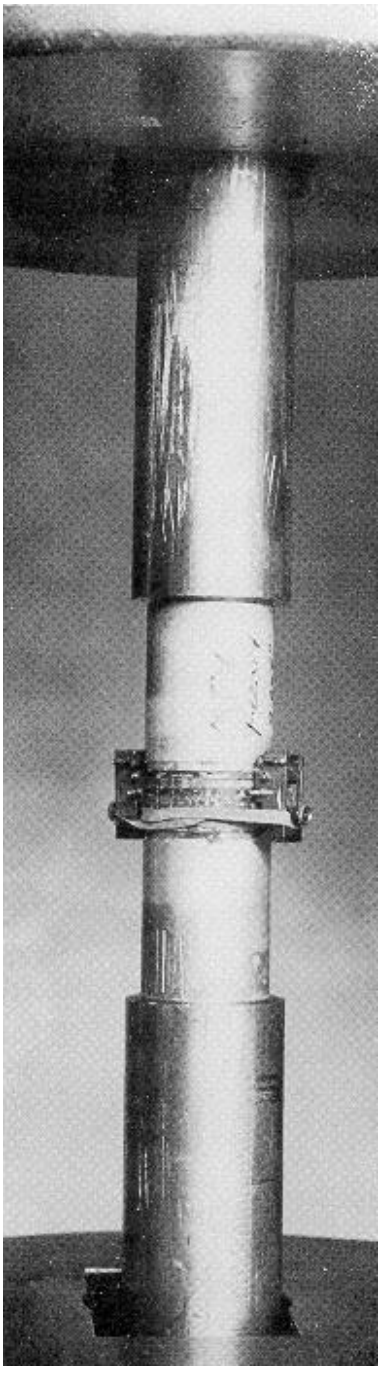

Figure 2. --Tension test specimen with Tuckerman gages for measuring total detrusion across bonds.

ZM 96918 F

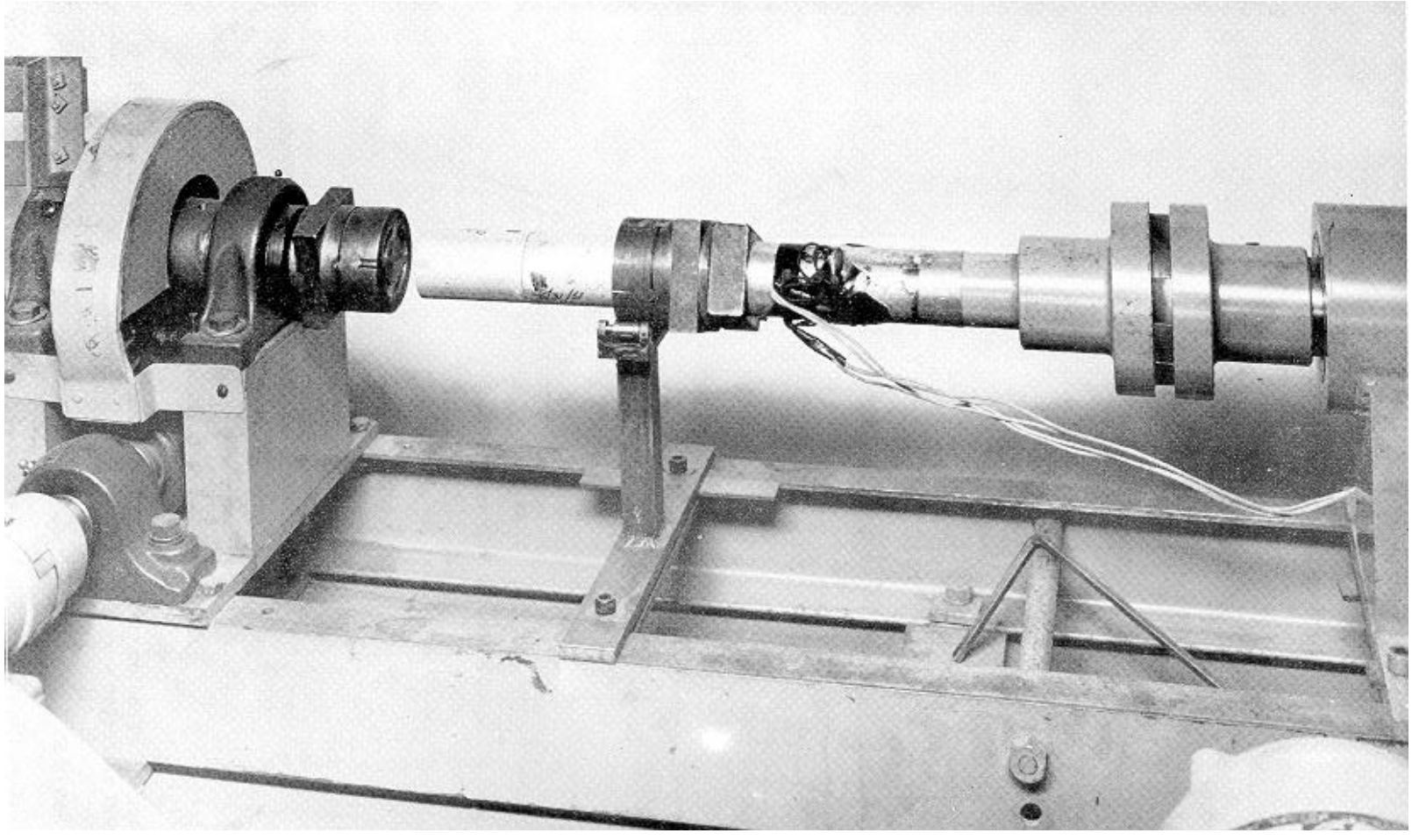

Figure 3.--Slotted specimen with adhesive bonds partially in place in the torsion machine.

ZM 123 422

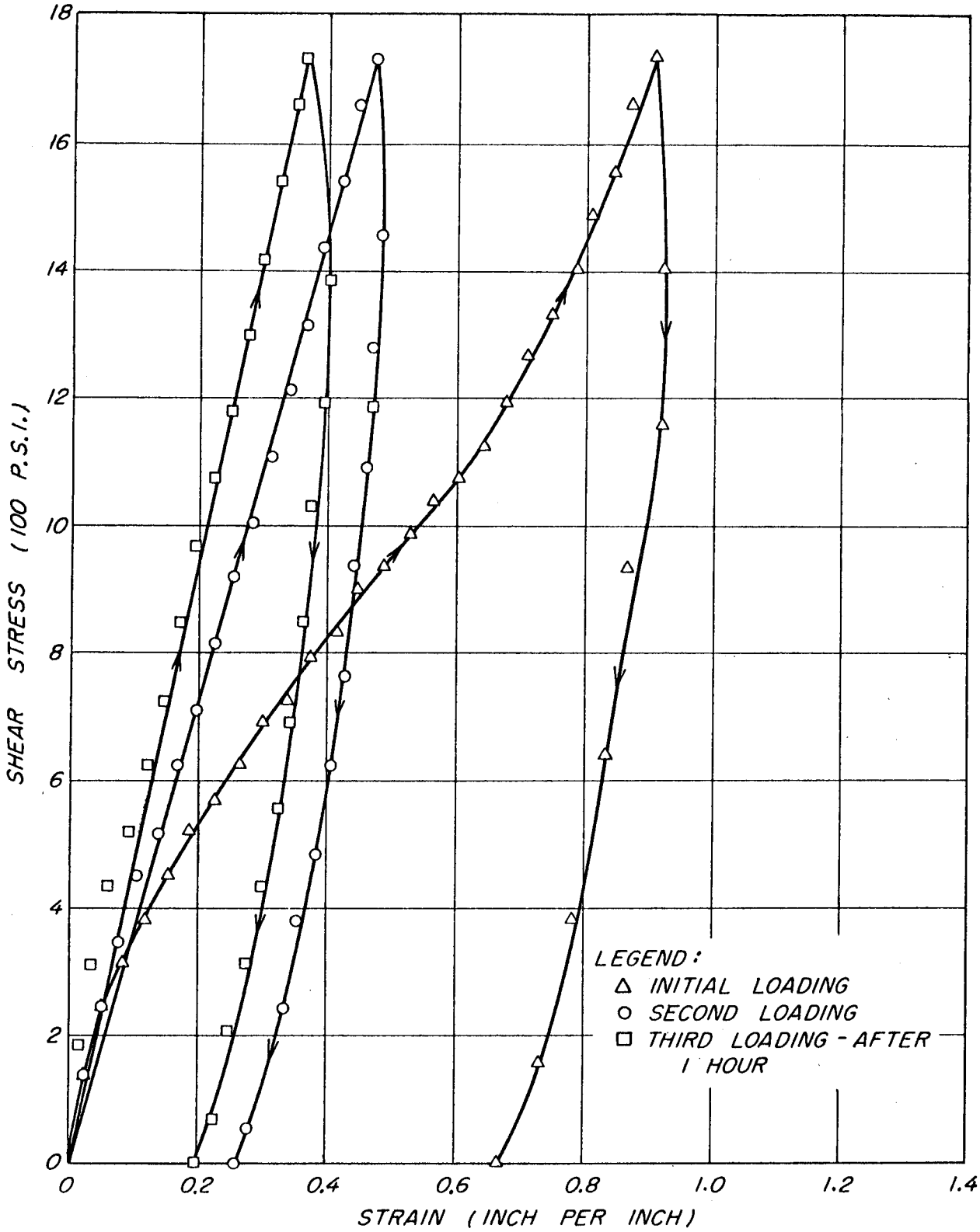

Figure 4. --Three stress strain curves made in succession on specimen bonded with Scotchweld AF-6 adhesive.

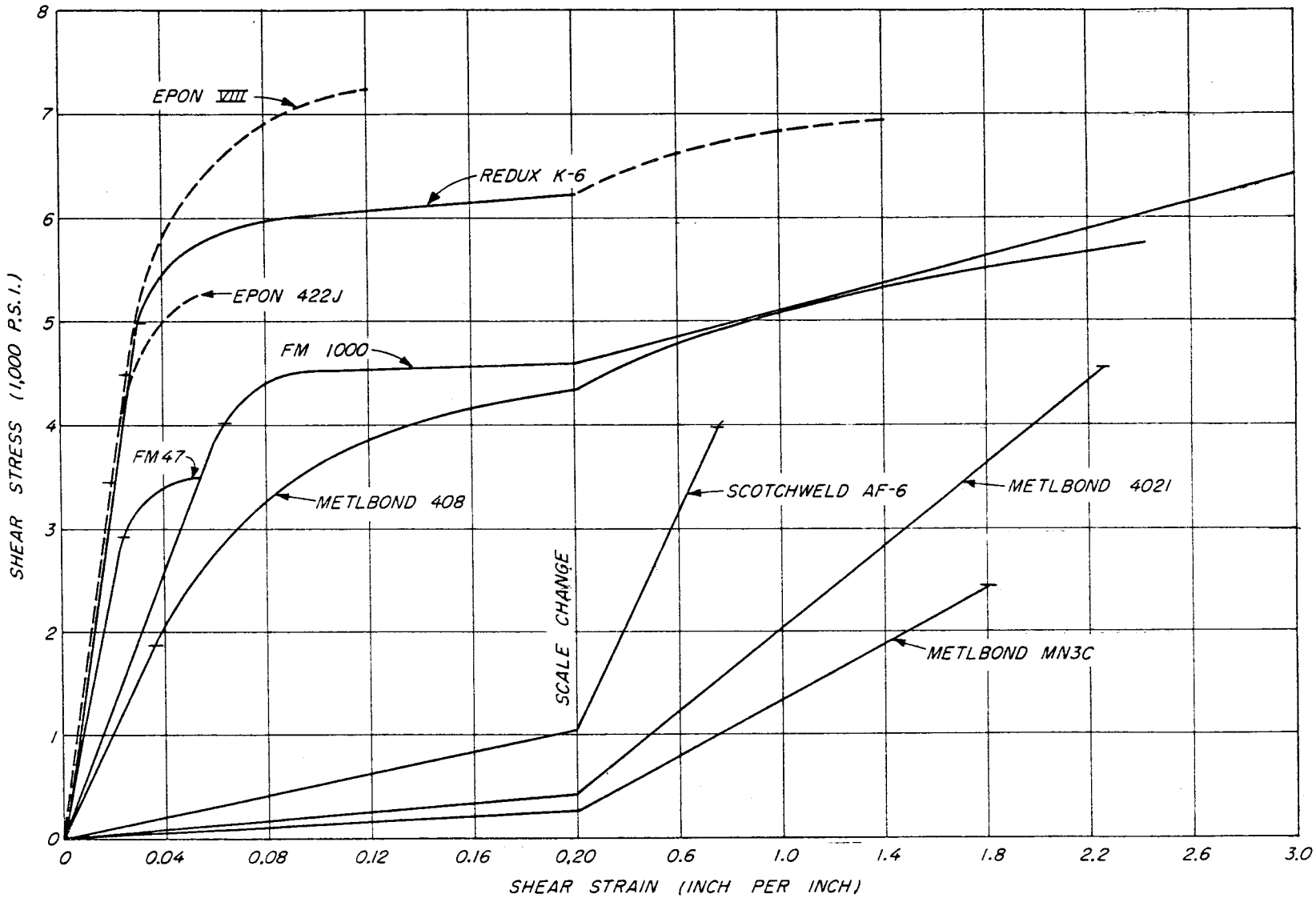

Figure 5.--Shear stress strain curves of adhesive bonds. Each curve represents a specimen near the average for each adhesive.

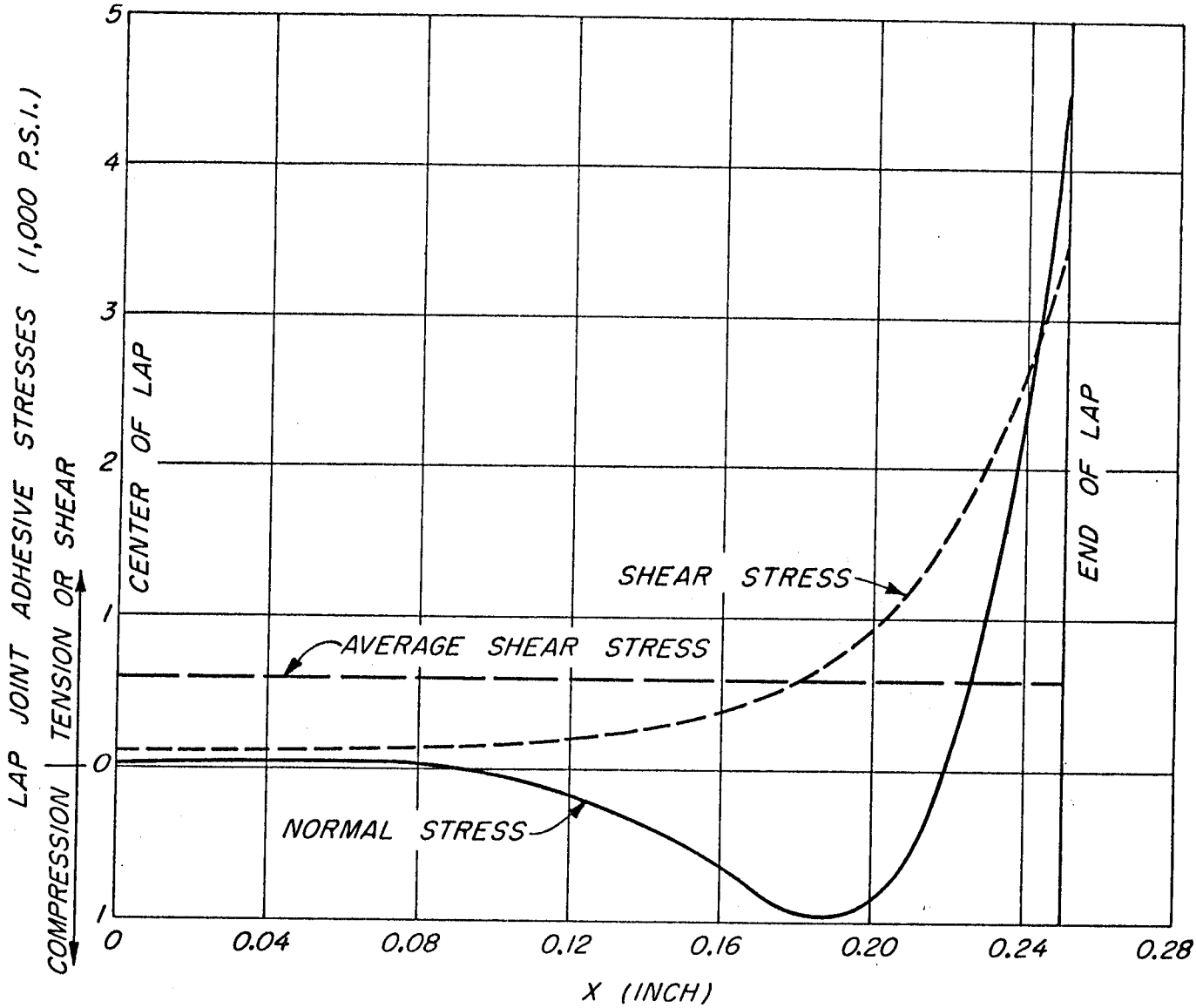

Figure 6.--Stresses in lap joint bonded with Redux K-6 adhesive (0.003-inch thick, Ga = 180,000 p.s.i.). One-half-inch lap of 0.064-inch aluminum loaded to 300 pounds per inch of width.

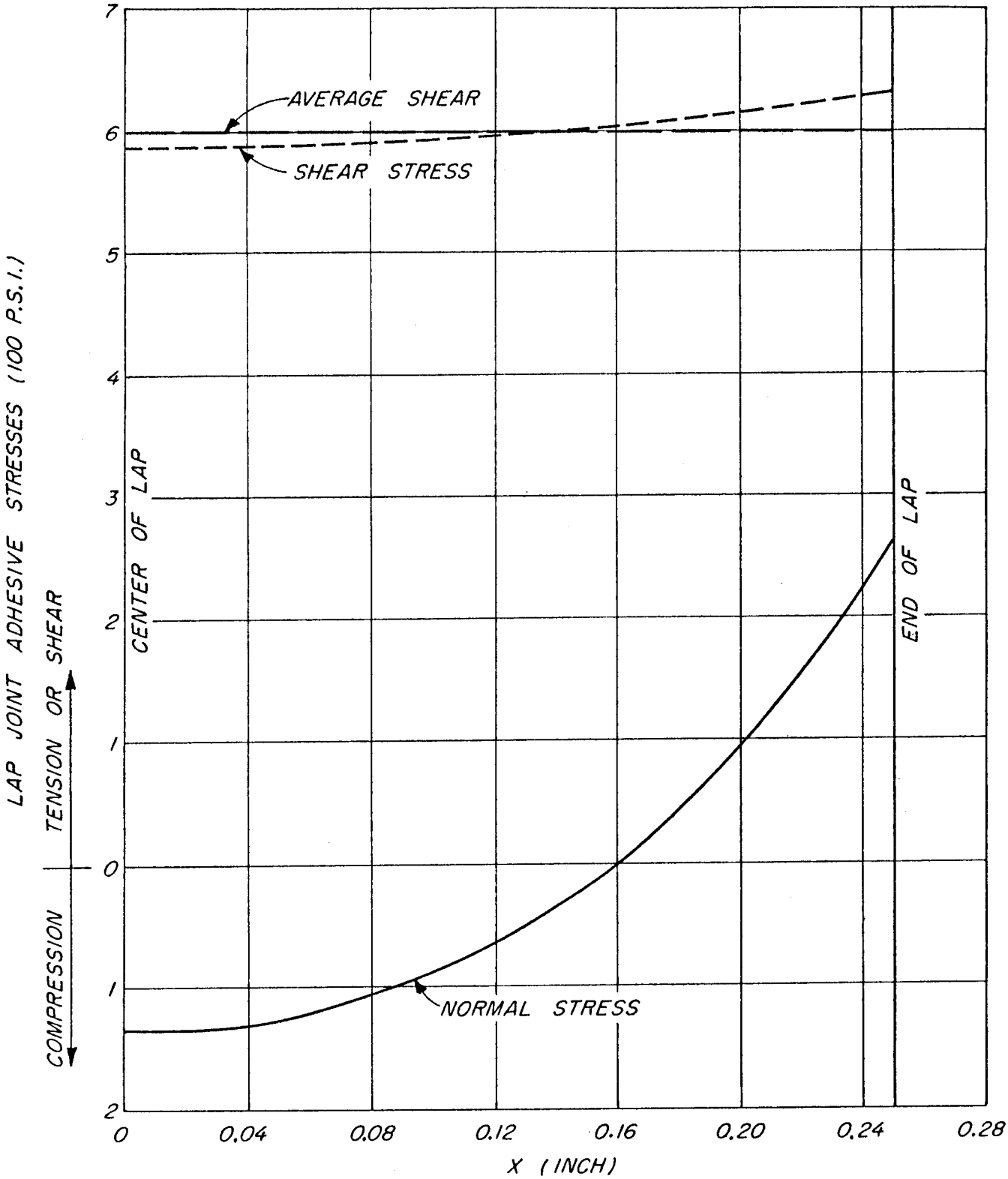

Figure 7.--Stresses in lap joint bonded with Metlbond MN3C tape adhesive (0.007-inch thick, Ga = 1,530 p.s.i.). One half-inch lap of 0.064-inch aluminum loaded to 300 pounds per inch of width.

FPL-011

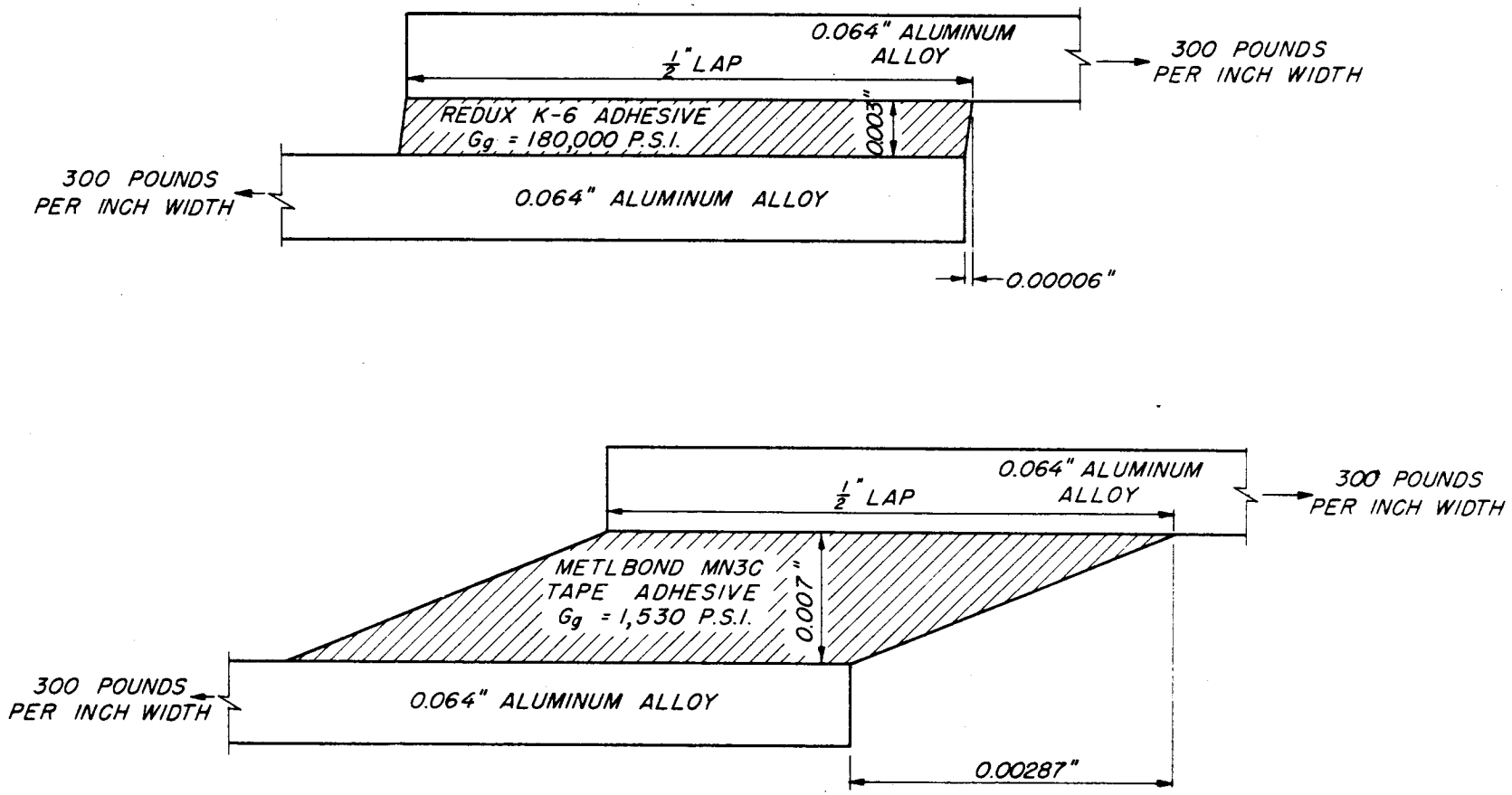

Figure 8.--Shear deformation of adhesives in lap joints between aluminum alloy sheets.

Z M 107 372

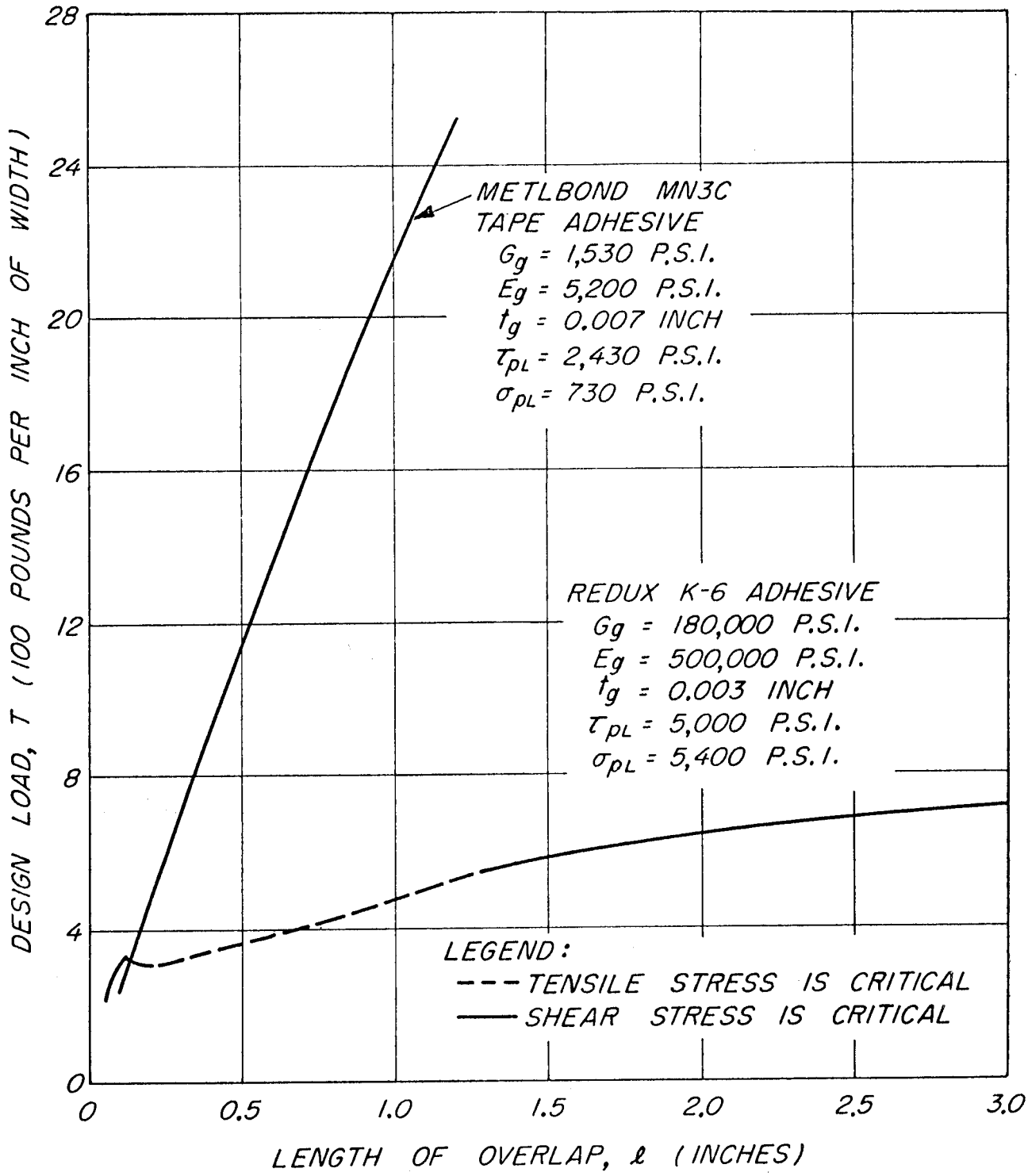

Figure 9.--Design loads for lap joints of 0.064-inch 7075 clad aluminum (E = 10,000 p.s.i. λ = 0.91).

WOOD · WATER · FORAGE · WILDLIFE · RECREATION

FOREST SERVICE

U S

DEPARTMENT OF AGRICULTURE