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Effect of Bonding Defects on Shear Strength in Tension of Lap Joints Having Brittle Adhesives

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Synopsis

In this paper we examine how the joint strength of lap joints containing a brittle adhesive may be affected by partial removal of adhesive from the bonded area. It is found that the shear strength in tension of a lap joint specimen is governed essentially by the leading edges of the joint and not by the bonded area.

INTRODUCTION

In a previous paper,[1] we considered the joint strength of lap shear joints bonded with ductile adhesives and examined how the shear strength in tension of these joints was affected by the bonding defects. It was shown that the joint strength is not governed by the bond edges but rather by the total bonded area. The lap joints containing a brittle adhesive were not included in the former study[1] because the stress distributions and the nature of the brittle failure in the adhesive layer required a different analysis.

While the ductile adhesive fails by a slow process of yielding,[1] brittle adhesives are known to fail by formation and propagation of cracks, in rapid succession. In addition, Goland and Reissner[2] have shown that the stress concentrations at the bond edges of lap joints are much more severe in the case of a brittle adhesive than in a ductile adhesive. For these reasons, the tensile shear strength of lap joints employing a brittle adhesive may be expected to be extremely sensitive to edge effects. In addition, if the tensile shear strength of a lap joint with a brittle adhesive is governed mainly by the leading edges of the joint, then partial removal of adhesive from the bonded area, remote from the leading edges, should have little or no effect on the joint strength.

In this paper, we consider lap joints containing a brittle adhesive and carefully examine the edge effects and their influence on the joint strength. The stress analysis is carried out by using the series approximation method of Goland and Reissner[2] for a relatively inflexible joint.

EXPERIMENTAL

Tensile shear specimens were constructed of 2024-T3 aluminum (Aluminum Co. of America). The dimensions of the pieces were 5 in. × 1 in. × $^1/_{16}$ in. The surface of the aluminum was treated by first vapor degreasing in trichloroethylene and then etching for 7 min at 65°C in a sodium dichromate–sulfuric acid bath. After etching, the specimens were rinsed in distilled water and dried in a forced-air oven at 60°C. Specimens were stored in desiccators over Ascarite and removed just prior to use. The epoxy adhesive consisted of a diglycidyl ether of bisphenol A having an epoxy equivalent weight of 179 (DER 332LC, Dow Chemical Co., Midland, Michigan) and diethylaminopropylamine mixed in a ratio of 100:7 parts, respectively.

The tensile shear specimens were prepared in a special device designed to produce an overlap ranging up to 3 in. Sections of an adhesive-backed 2.5-mil polypropylene were cut to correspond to the area of epoxy adhesive removed. The lap shear adhesive joints were then cured in a 70°C forced-air over for 16 hr under a 10-lb load. The polypropylene simply acts as the unbonded area or void. Specimens were removed from the oven and cooled to room temperature slowly under the 10-lb load. Five specimens were tested for each point recorded on the figures. The specimens were tested in tensile shear in accordance with ASTM D1002-53, except that the strain rate was 0.015 in./in.-min. Except where indicated, we are dealing with tensile shear specimens having an overlap of 1 in.

To measure the mechanical properties of epoxy used in the lap joints, a few dumbbell-shaped samples with a cross section of 0.185 in. × 0.09 in. were tested in simple tension. The results obtained at the strain rate of 0.2 in./in.-min are listed in Table I.

TABLE I
Mechanical Properties of Aluminum and Epoxy

	Young's modulus, psi	Poisson's ratio	Yield or fracture strength, psi	Strain at failure, %
Aluminum	10×10^6	0.33	48,000	20
Epoxy	2.3×10^5	0.33	9,200	5

RESULTS

In Figure 1, data are shown for a variation in overlap and its effect on the joint strength. Beyond a 1.5-in. overlap, little change is noted in the joint strength.

In the joints having an overlap of 2 in. or more, the aluminum yielded locally near the leading edges during the tests. The permanent set increases with the increase in the overlap length. It is apparent that for joints with an overlap of 1.5 in. or more, additional bending moments are at

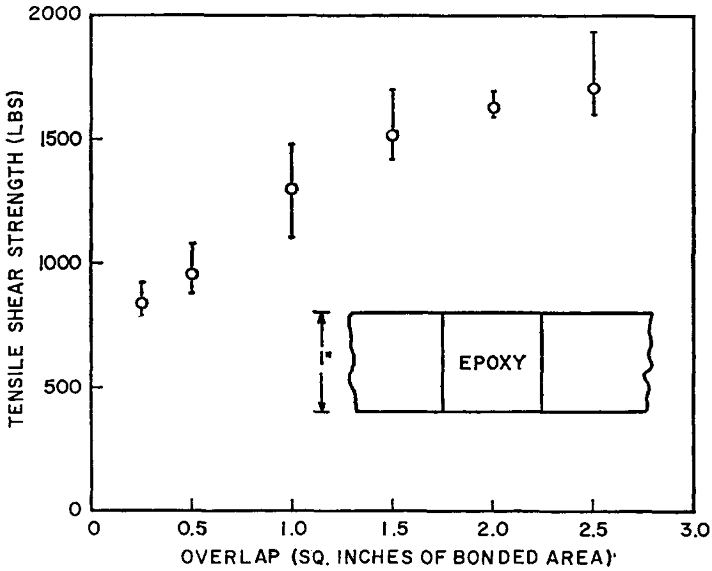

Fig. 1. Tensile shear strength (in lb) of lap specimens with variable overlap.

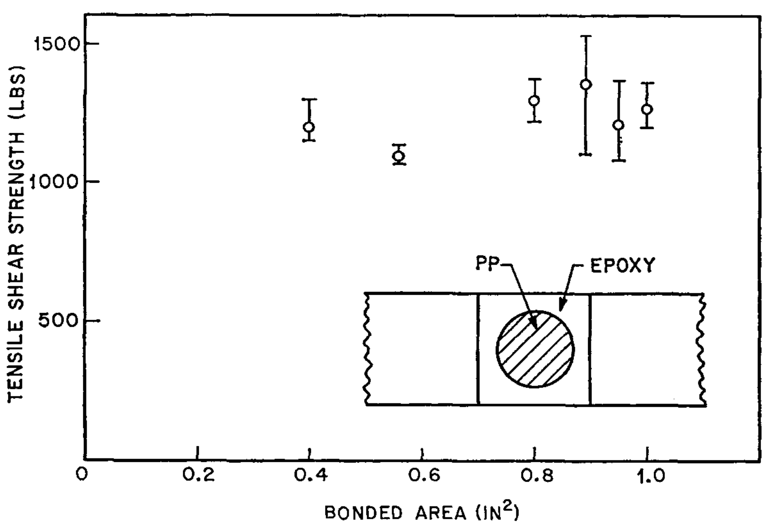

Fig. 2. Tensile shear strength (in lb) of lap specimens having circular defects.

work as a result of yielding in the aluminum. Since the remainder of the data in this report is confined to a 1-in. overlap, it is unlikely that spurious effects from unusual stresses will have occurred.

Two possible defects are considered. The effect due to circular defects is shown in Figure 2. Although the bonded area varies, the joint strength is essentially constant. Apparently, edges associated with the defects are not important.

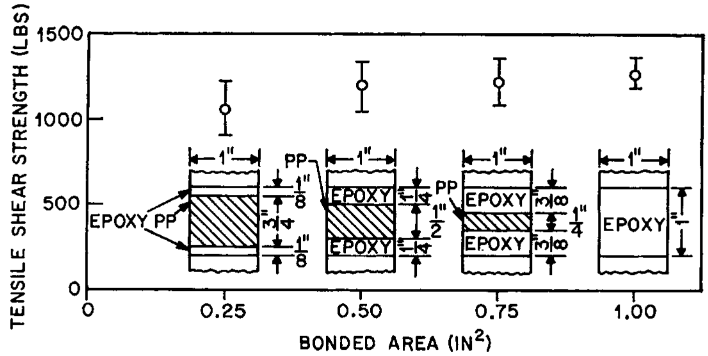

Fig. 3. Tensile shear strength (in lb) of lap specimens with horizontal rectangular-shaped defects.

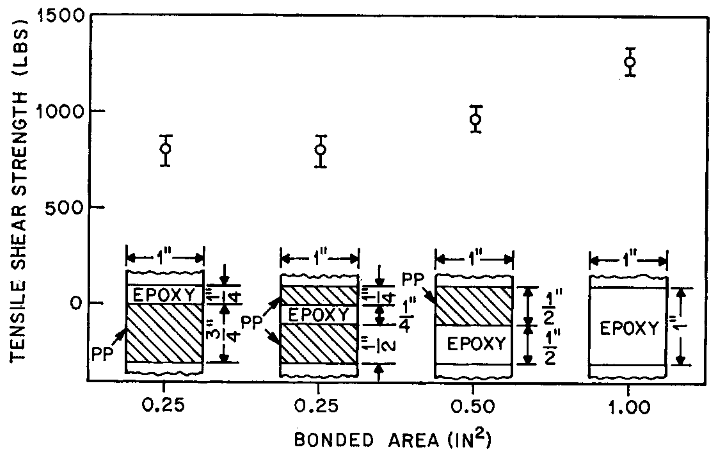

Fig. 4. Tensile shear strength (in lb) of lap specimens with horizontal rectangular-shaped defects.

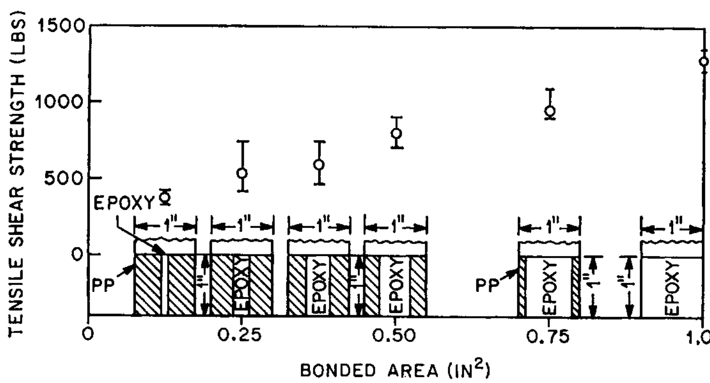

Fig. 5. Tensile shear strength (in lb) of lap specimens with symmetrically positioned rectangular-shaped defects, arranged vertically.

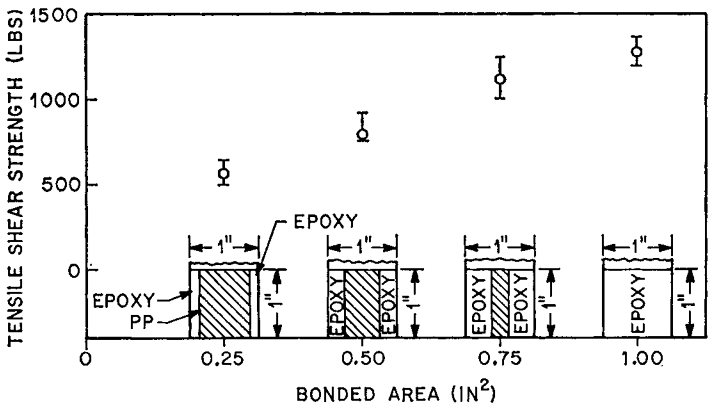

Fig. 6. Tensile shear strength (in lb) of lap specimens with symmetrically positioned rectangular-shaped defects, arranged vertically.

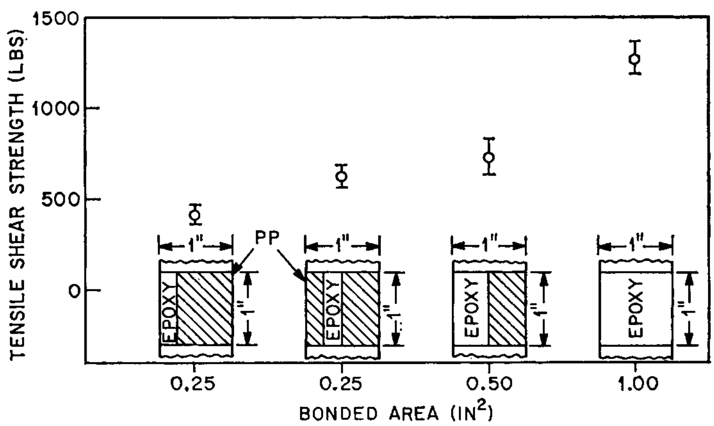

Fig. 7. Tensile shear strength (in lb) of lap specimens with nonsymmetrically positioned rectangular-shaped defects, arranged vertically.

Both Figures 3 and 4 show similar results for rectangular-shaped defects with the major axis of the defect oriented normal to the applied load. In Figures 5 and 6, the rectangular-shaped defects are arranged with the long dimension of the film parallel to the long dimension of the aluminum. In Figure 7, we prepared configurations similar to those in Figure 5 but offset to observe the effect of eccentric bonding.

STRESS ANALYSIS AND DISCUSSION

Earlier[1] we demonstrated by using a ductile adhesive (e.g., polyethylene) in a lap shear joint that the joint fails when the yield zones in the adhesive spread over the entire bonded area. The tensile shear strength of the flexible joint is then determined by the ultimate yield strength of the adhesive and is proportional to the total bonded area. In the case of a brittle adhesive in a lap shear joint, we observed that the joint failure originates at the bond edges by forming small cracks in the adhesive. The cracks appear to propagate quickly inward along the bond line, and the joint fails almost instantaneously without further increase in the applied load. Failure of the adhesive joint by propagation of an unstable crack[3] appears to be similar to the brittle fracture of a bulk material. Since an unstable crack can propagate easily without need for a further increase in the applied load, we may expect the tensile shear strength of an inflexible joint to depend primarily on the strength of the adhesive near the bond edges rather than on the strength of the adhesive in the entire bonded area.[1]

In the following, we calculate the stress distributions in a brittle adhesive by the method of Goland and Reissner,[2] assuming that the joint undergoes a cylindrical bending while the joint is under a tensile load. We note from the dimensions of the joint and the material properties in Table I that the joint satisfies the conditions for a relatively inflexible joint, namely,

$$\frac{\eta}{E_c} \leq \frac{1}{10}\frac{t}{E} \qquad \frac{\eta}{G_c} \leq \frac{1}{10}\frac{t}{G} \tag{1}$$

where E and G are, respectively, Young's modulus and the shear modulus of the adherend having a thickness t. The subscript c denotes the corresponding properties of the adhesive which has a thickness η. Thus, using the series solution method described by Goland and Reissner,[2] we find, for a joint with a 1-in. bond line and a tensile load of 1300 lb, the distributions of tearing stress σ and shearing stress τ in the brittle adhesive as plotted in Figure 8. Details of the calculation are listed in the Appendix. Figure 8 displays the curves for only one half the length of the overlap, since the stresses are symmetric about the midpoint of the overlap.

From Figure 8 the stress distributions in the brittle adhesive are seen to differ from those in the ductile adhesive[1] in two respects, namely, (1) the stress concentrations in σ and τ occur over much smaller regions near the bond edges, and (2) in the brittle adhesive the maximum tearing stress is much higher than the maximum shearing stress. The shearing stress increases rapidly from zero at the bond edge to a maximum value of 14,000 psi at a point 2×10^{-4} in. away from the bond edge. Consequently, for practical purposes, we may regard the largest stress concentrations to be at the two bond edges.

Since the applied load is transmitted through the adhesive by the shearing stress along the interface, we estimate from the shearing stress curve in Figure 8 that about 80% of the applied load is transmitted through the two $^1/_8$-in.-long bond lines adjoining the two bond edges. A reexamination of the shearing stress distribution in the joint with a ductile adhesive[1] reveals that the same bonded area near the bond edges transmits only about 40% of the applied load. Clearly, unlike the case of the flexible joint, the bond edges are very critical in an inflexible joint containing a brittle adhesive.

Before we examine the experimental results, it is interesting to see how the stress distributions in the adhesive are affected by the cylindrical bending

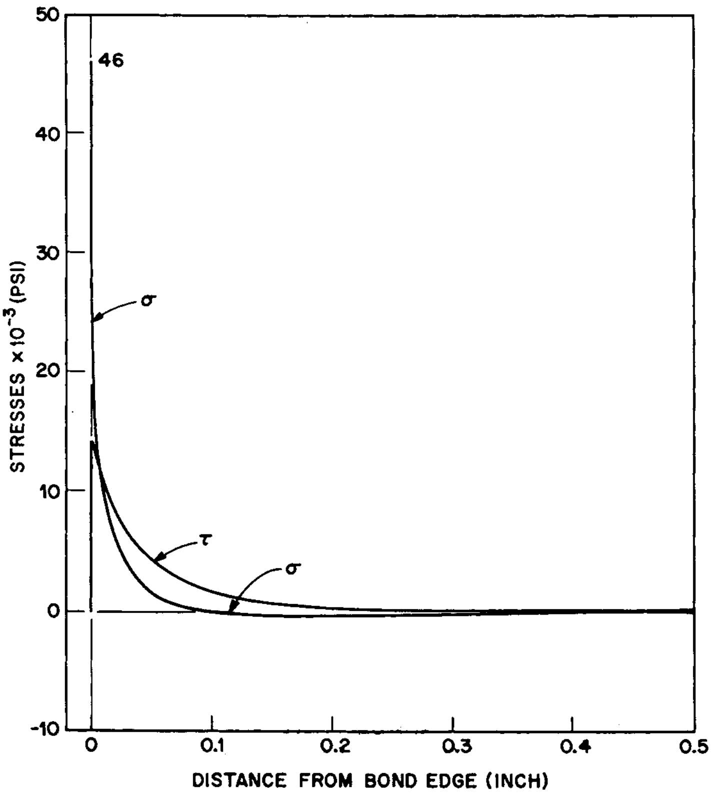

Fig. 8. Distributions of stresses along the bond line in the adhesive joint.

in the lap joint. Goodier and Hsu[4] showed that in the direct lap-joined plates having the same Poisson's ratio, the in-plane load applied to the thin plates is transmitted entirely as a line load through the periphery of the bonded area, if one excludes the bending that may accompany such a loading. Except for the bending, Goodier and Hsu's problem is essentially similar to that of the inflexible joint considered here since the thickness of the brittle adhesive is also neglected in Goland and Reissner's treatment. When the stress distributions in Figure 8 and the result of Goodier and Hsu's analysis are compared, we find that as a result of the cylindrical bending, the applied tensile load is transmitted through a wider bonded area in the joint. However, the bending also induces a very high concentration of tearing stress at the bond edges (Fig. 8). The large tearing stress is particularly undesirable in a joint containing a brittle adhesive, which fails usually by a cohesive mode under a tensile stress.

On the basis of the foregoing discussion, it is reasonable to expect that there will be little effect on the tensile shear strength of an inflexible joint due to circular defects (Fig. 2) or rectangular shaped/defects (Fig. 3), since in both types of joints the primary load-bearing area responsible for the joint strength is not significantly affected by the defects. The slightly reduced tensile shear strength in the joints (Figs. 2 and 3) with a smaller net bonded area is apparently due to the decrease in the bond length since, according to Figure 8, the middle portion of the bond line still transmits a fraction of the applied load. This fraction of the applied load will now have to be carried by the other bonded area in the joint. For the same reason, the lower tensile shear strength found in the joint (Figs. 1 and 4) having a single narrow bonded area may be attributed partly to the reduction in the bonded area. In addition, because of the proximity of the two bond edges, the interaction between the two stress fields at the bond edges may also be responsible for some reduction in the tensile shear strength. In the stress analysis of Goland and Reissner,[2] the interaction between the stress fields was avoided by assuming the bond length ($2c$) to be much larger than the thickness t of the adherend, say, $2c \geq 10t$.

In Figure 1, we observe that the tensile shear strength approaches a finite value of about 700 lb when the bonded area is reduced to zero. The same trend is also observed in other figures. This is perhaps the most striking evidence that the two bond edges are carrying the major portion of the applied load as predicted by the stress analysis. For the relatively flexible joints,[1] as the bonded area is decreased, the tensile shear strength approaches zero.

At larger bonded lengths (Fig. 1), the joint strength is seen to level off near 1.5 in. As mentioned earlier, this is apparently due to the additional bending moment caused by yielding in the adherend. Although the yield strength of the adherend is about 48,000 psi, it is found from Goland and Reissner's results[2] that the adherend will start to yield in a small region near the bond edges when the tensile load reaches about 800 lb. However, the effect due to yielding in the adherend will not become significant until the yield zone spreads over a large portion of the cross section. When this happens, the lap shear joint may be subjected to a highly localized bending near the bond edges, and the assumption that the lap joint bends cylindrically is no longer valid. The localized bending causes the overlap to rotate farther away from the loading axis and, as a result, induces a still larger tearing stress at the bond edges.

The linear dependence of the tensile shear strength on the bond width observed in Figures 5 and 6 also lends support to the viewpoint that the tensile shear strength of the inflexible joint is controlled primarily by the narrow bonded area near the bond edges.

Figure 7 shows how the joint strength can be affected by the bonding defects as well as by the eccentricity of their positions with respect to the loading axis. With the same bonded area of 0.25 in.^{2} it is seen that the joint strength decreases with the increase in the eccentricity of loading.

The above studies also suggest that it is perhaps more appropriate to express the tensile shear strength of a relatively inflexible joint in pounds or pounds per unit width of the bond edges which carry the major portion of the tensile load. In the relatively flexible joint, on the other hand, it may be more suitable to express the tensile shear strength in pounds or pounds per unit area of the bond, since in this case each unit area of the bond contributes in some proportion to the ultimate strength of the joint.[1]

Appendix

In the following we give a brief description of the stress analysis given by Goland and Reissner[2] for a relatively inflexible joint. The joint is assumed to undergo cylindrical bending when subjected to a tensile force T per unit joint width. In addition, the overlap section of the joint is assumed to consist of a homogeneous slab of length $2c$ and thickness $2t$ (neglecting the thickness of the adhesive) and with the same physical properties throughout as those of the adherend. The rectangular x–y coordinate system is fixed to the slab in such a way that the length of the slab runs from $y = -c$ to $y = c$ and the thickness runs from $x = 0$ to $x = t$.

Using the plane strain theory, Goland and Reissner first expressed the stress field in the slab as

$$\begin{aligned}
\sigma_x &= \sum_{n=1}^{\infty} b_n e^{\alpha(y-c)}[\alpha(y-c)+1]\cos \alpha x \\
\sigma_y &= \frac{p}{2} + \sum_{n=1}^{\infty} b_n e^{\alpha(y-c)}[\alpha(c-y)+1]\cos \alpha x \qquad \text{(A-1)} \\
\tau_{xy} &= \sum_{n=1}^{\infty} b_n \alpha(y-c) e^{\alpha(y-c)} \sin \alpha x
\end{aligned}$$

where

$$\alpha = \frac{n\pi}{2t}$$

$$b_n = \frac{2T}{n\pi t}\left\{\frac{12k}{n\pi}\left(\cos\frac{n\pi}{2} - \cos n\pi\right) - (3k+1)\sin\frac{n\pi}{2}\right\}$$

$$k = \frac{\cosh u}{\cosh u + 2\sqrt{2}\sinh u}$$

$$u = \sqrt{\frac{3(1-\nu^2)}{2}}\,\frac{c}{t}\sqrt{\frac{T}{Et}}$$

and ν is Poisson's ratio of the adherend. The stress field in (A-1) satisfies the boundary conditions at $y = \pm c(0 \le x \le 2t)$, but it also creates nonzero tractions ($\sigma_x \neq 0$, $\tau_{xy} = 0$) along the boundaries $x = 0$ and $x = t\,(-c \le y \le c)$. To eliminate the tractions there, Goland and Reissner chose two sets of forces acting along the edge lines $y = \pm c$ at several locations. The stress fields created by these forces are then superposed onto the stresses in (A-1) to yield an approximate solution to the problem.

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