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Effects of Symmetrical Bonding Defects on Tensile Shear Strength of Lap Joints Having Ductile Adhesives

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Synopsis

In this paper we examine the effect on joint strength of depleting the bond line of a relatively flexible adhesive (polyethylene) while maintaining a constant adhesive film thickness. It is shown that the tensile shear strength of a lap specimen is not governed by edge effects but rather by the bonded area. By using limit analysis of the plasticity theory, we demonstrate why the tensile shear strength of the joint is insensitive to stress concentrations at the bonding defects.

INTRODUCTION

The earliest theoretical analysis of lap joints is due to Volkersen.[1] Volkersen ignored the tearing stresses resulting from the bending of the members and confined his attention to the determination of the distribution of the shearing stresses in the adhesive layer. He assumed that these stresses arise solely from differential straining in the lap joint. The theory of Volkersen is unsatisfactory, since no account is taken of the stresses set up in the adhesive as a result of the eccentricity of loading of the lap joint. Goland and Reissner[2] first formulated such a theory. These investigators determined the stress acting upon the edge of the joint by considering the lap joint and the neighboring sheet to act as a cylindrically bent plate of variable cross section and variable neutral plane. More recently, other investigations[3] have modified the approach of Goland and Reissner.

In this paper, we examine the effect on joint strength of depleting the bond line of a relatively flexible adhesive while maintaining a constant film thickness. If the tensile shear strength of a lap specimen is governed by edge effects, then creation of additional edges by the partial removal of adhesive from the bonded area should have an effect on the joint strength. On the other hand, there is reason to believe that the joint strength of a lap shear specimen is not significantly affected by edge effects if a ductile adhesive is used. In this report, we vary the geometry of the defect as well as the distribution of adhesive in the bond line to produce a variety of joint configurations. How large a defect can be tolerated before premature failure occurs? Does the geometry and location of the defect modify the joint strength? These are some of the questions we addressed ourselves to initially.

EXPERIMENTAL

The tensile shear specimens were constructed of unclad 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 polyethylene used was a low-density (0.92 g/cm^3) material, supplied in 0.005-in. sheets. The polyethylene was solvent wiped with acetone prior to use.

The tensile shear specimens were prepared in a special device designed to produce an overlap ranging up to 3.0 in. Sections of polyethylene of varying sizes and shapes were placed between the aluminum adherends. To maintain the bond line thickness and to act as the unbonded area, 0.003-in. FEP Teflon film was used. Sections of the FEP Teflon were cut to correspond to the area of polyethylene removed. The lap shear specimens were then placed into a 350°F forced-air oven for 2.5 hr under a 10-lb load. These conditions are sufficient for the spreading of the polyethylene onto the chemically etched aluminum. The FEP Teflon 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. Six 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. per min. Except where indicated, we are dealing with tensile shear specimens having an overlap of 1 in.

RESULTS

In Figure 1, data are shown for a variation in overlap and its effect on the joint strength. Beyond a 3-in. overlap, other factors are operative (bending), and a deviation from linearity is observed. 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 are likely to occur.

Two possible defects are considered. The effect due to circular defects is shown in Figure 2. Although the bonded area varies, the joint strength based on 1 in.^{2} of net bonded area is constant.

Both Figure 3 and Figure 4 show similar results for rectangular shaped defects with the major axis of the defect oriented normal to the applied load. Apparently, edge effects are minimized. Figure 5 summarizes these results. In Figure 6, the rectangular-shaped defects are arranged with the long dimension of the film parallel to the long dimension of the aluminum.

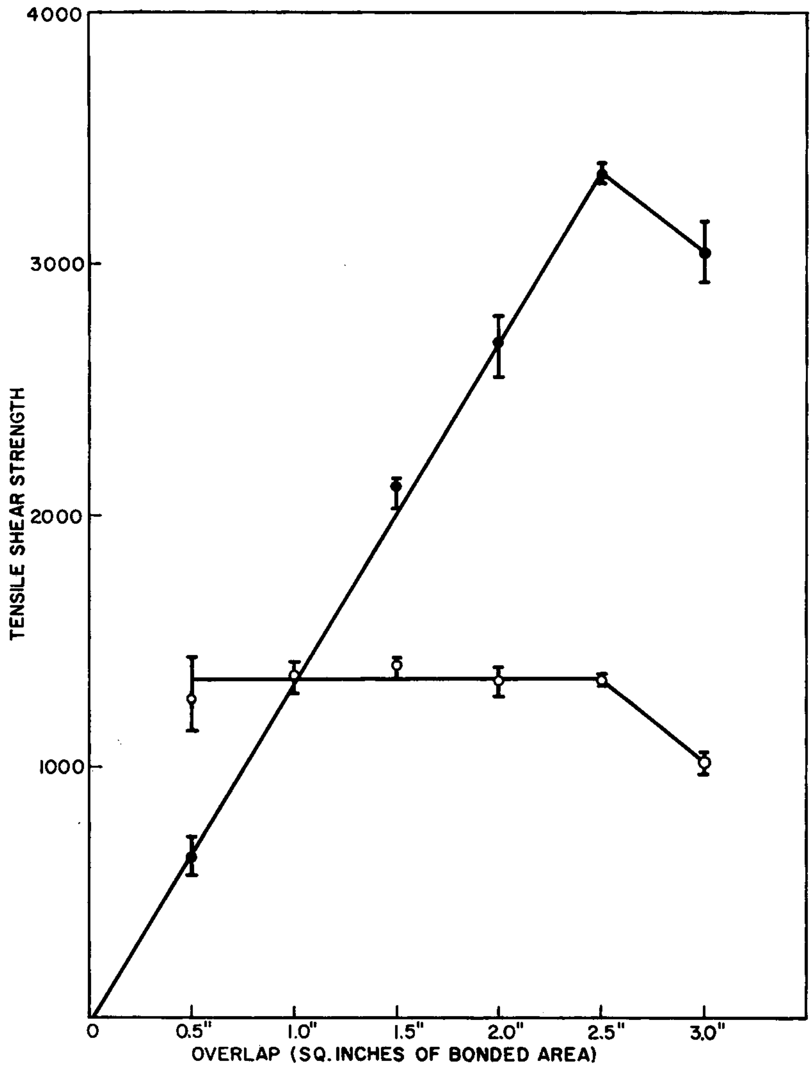

Fig. 1. Tensile shear strength of lap shear specimens with variable overlap: (●) measured joint strengths in lb; (○) joint strengths in lb/in.^{2} of bonded area.

ANALYSIS AND DISCUSSION

From the foregoing test results, it is seen that, as long as the loading is symmetrical with the center line of the joint plane, the tensile shear strength of the lap joint (defined as the applied load at the moment of failure divided by the net bonded area) is the same for all samples, regardless of the shape or position of the bonding defects. When dealing with a ductile adhesive, one which can redistribute the applied stress in an effective manner, the actual bond area and not the size or shape of the defect is of primary impor-

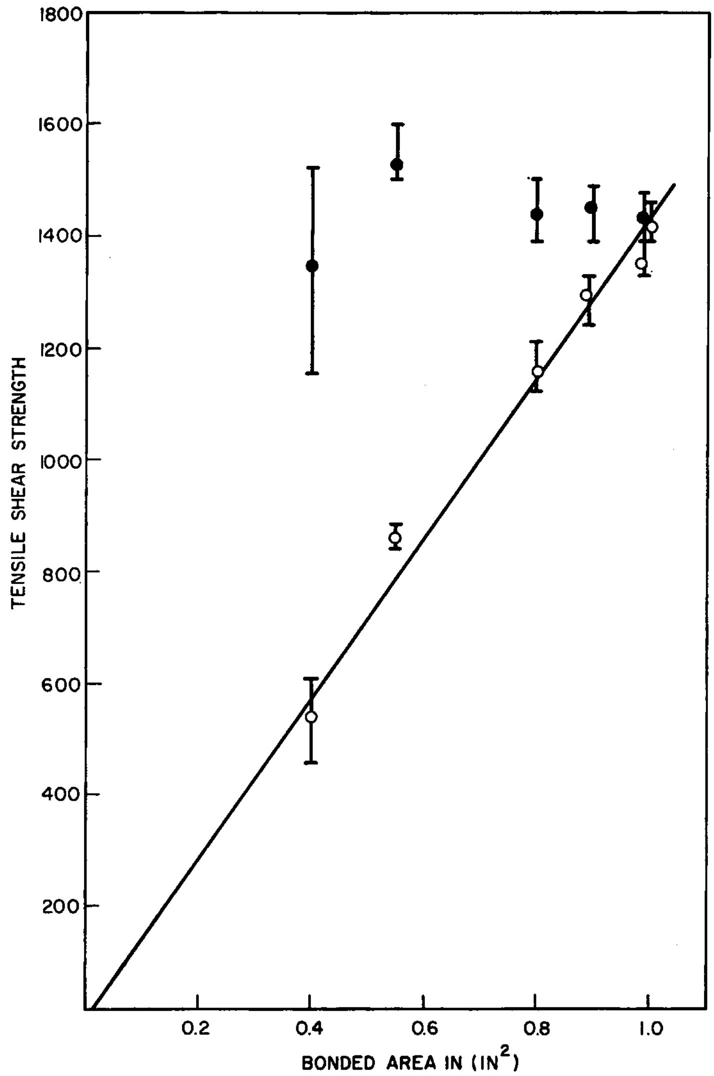

Fig. 2. Tensile shear strength of lap shear specimens having circular defects: (O) measured joint strengths in lb; (●) joint strengths in lb/in.^{2} of bonded area.

tance. Other factors are operative in unsymmetrical defects. In effect, this would imply that the tearing stress in the adhesive is not important in the present type of lap joints. We wish to show in the following that this is due to the ductility of the adhesive and the relatively thin joint.

We compute first the stresses in the adhesive, using Goland and Reissner's results for a relatively flexible or ductile adhesive.[2] The elasticity analysis of these investigators[2] assumes the adhesive to be thin compared with the thickness of the metal sheets at the joint, which is also valid in the present case. The measured Young's modulus of the polyethylene sheet is given in

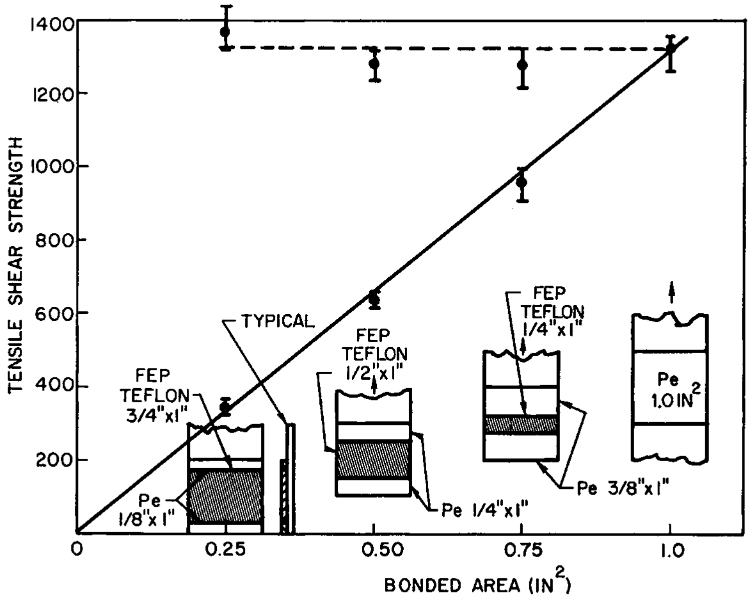

Fig. 3. Tensile shear strength (in lb) of lap shear specimens with rectangular-shaped defects with the major axis of the defect oriented normal to the applied load. Dashed line represents data in lb/in.² of bonded area.

Table I. The other pertinent mechanical properties in Table I for polyethylene and aluminum are collected from the existing literature. Using these data and taking the applied load to be 1300 lb, which is the breaking load, the tearing stress σ and the shearing stress τ in the adhesive are computed from eqs. (49) and (53) of Goland and Reissner[2] (see Appendix) for a 1-in.-long joint with no bonding defect, and the results are shown in Figure 7. The horizontal axis x is the distance from the middle point of the adhesive, and the stress distribution is plotted from $x = 0$ to $x = 0.5$ in. since it is symmetric with respect to the point $x = 0$. In Figure 7 it is seen that, whereas the shearing stress τ is relatively large throughout the adhesive, the tearing stress σ does not become important until one reaches the vicinity of the joint edge. If one assumes that the adhesive fails according to Mises' criterion (in Mises' yield or failure criterion, it is assumed that the material will yield or fail when the distortion energy stored in the material reaches a certain limit) then, for the present case,

$$\frac{\sigma^2}{3} + \tau^2 = k^2 \tag{1}$$

TABLE I

	Young's modulus, psi	Poisson's ratio
Aluminum	10×10^6	0.33
Polyethylene	2×10^4	0.38

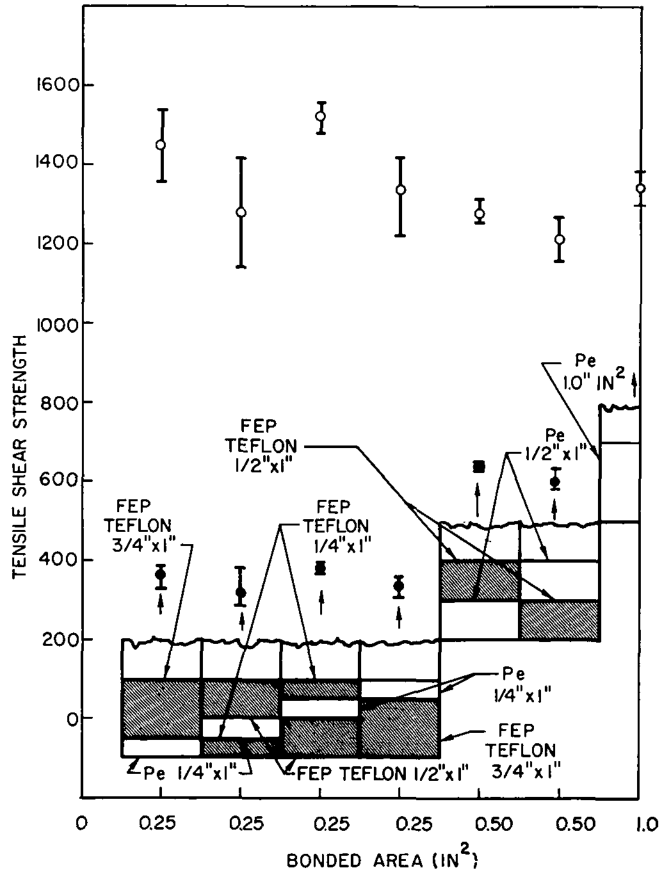

Fig. 4. Tensile shear strength of lap shear specimens with rectangular-shaped defects, with the major axis of the defect oriented normal to the applied load: (●) measured joint strengths in lb; (O) joint strengths in lb/in.^{2} of bonded area.

where k is the yield stress of the adhesive under simple shear. The value of k according to the expression (1) is computed from σ and τ values in Figure 7 and shown in the same figure. This k value is not to be confused with the K value in the Mises' criterion; the latter is the yield stress of the adhesive in simple shear.

In Figure 7 we see that the spread between the τ curve and the k curve is very small, except when $x > 0.49$ in., in which it reaches between 10% and 14% of the k value. This observation suggests that in thin, ductile adhesives, one may neglect the contributions from the tearing stress σ and rewrite the yield criterion in eq. (1) as $\tau = k$. The failure strength T (in pound units) is therefore related to the net bonding area A by

$$T = kA. \tag{2}$$

We now show, by limit analysis of the plasticity theory,[5] why the tensile shear strength of the joint is insensitive to stress concentrations at the bond-

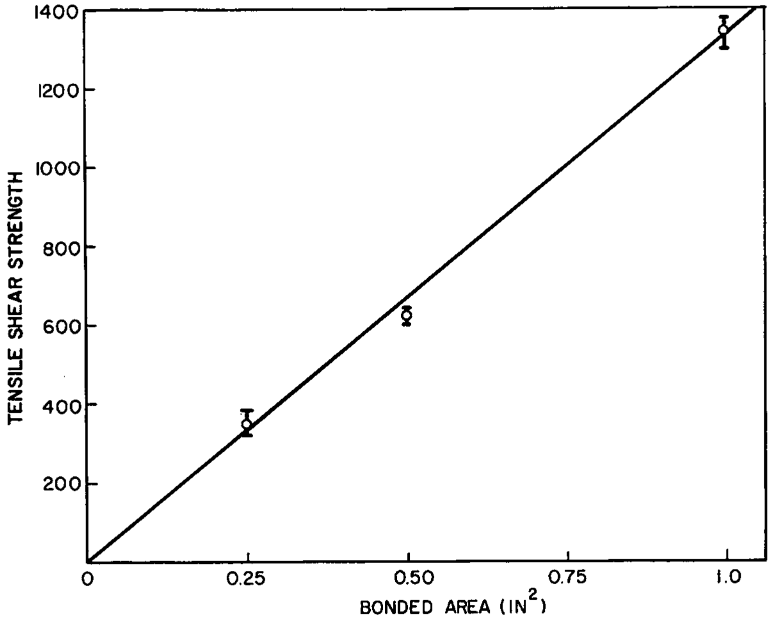

Fig. 5. Composite of the data in Figures 3 and 4.

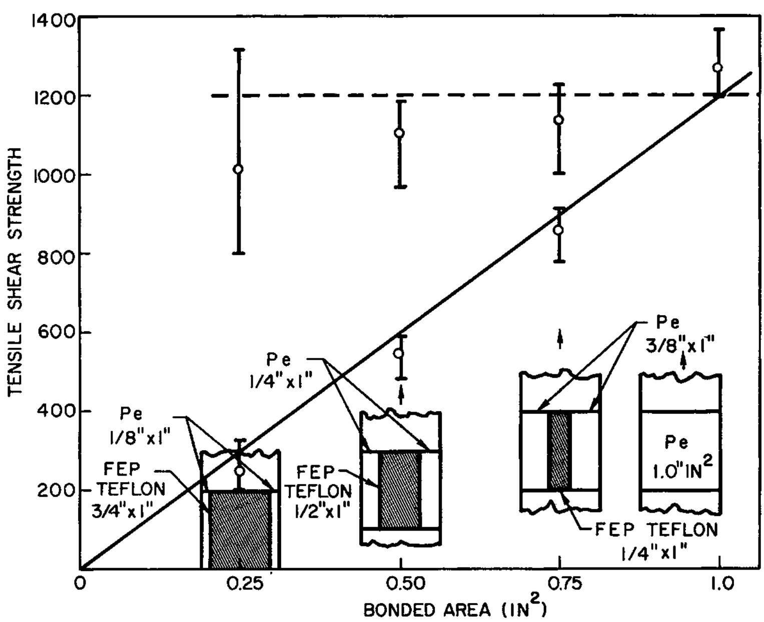

Fig. 6. Tensile shear strength (in lb) of lap shear specimens with symmetrically rectangular-shaped defects, arranged with the long dimension of the film parallel to the long dimension of the aluminum. Dashed line represents data in lb/in.^{2} of bonded area.

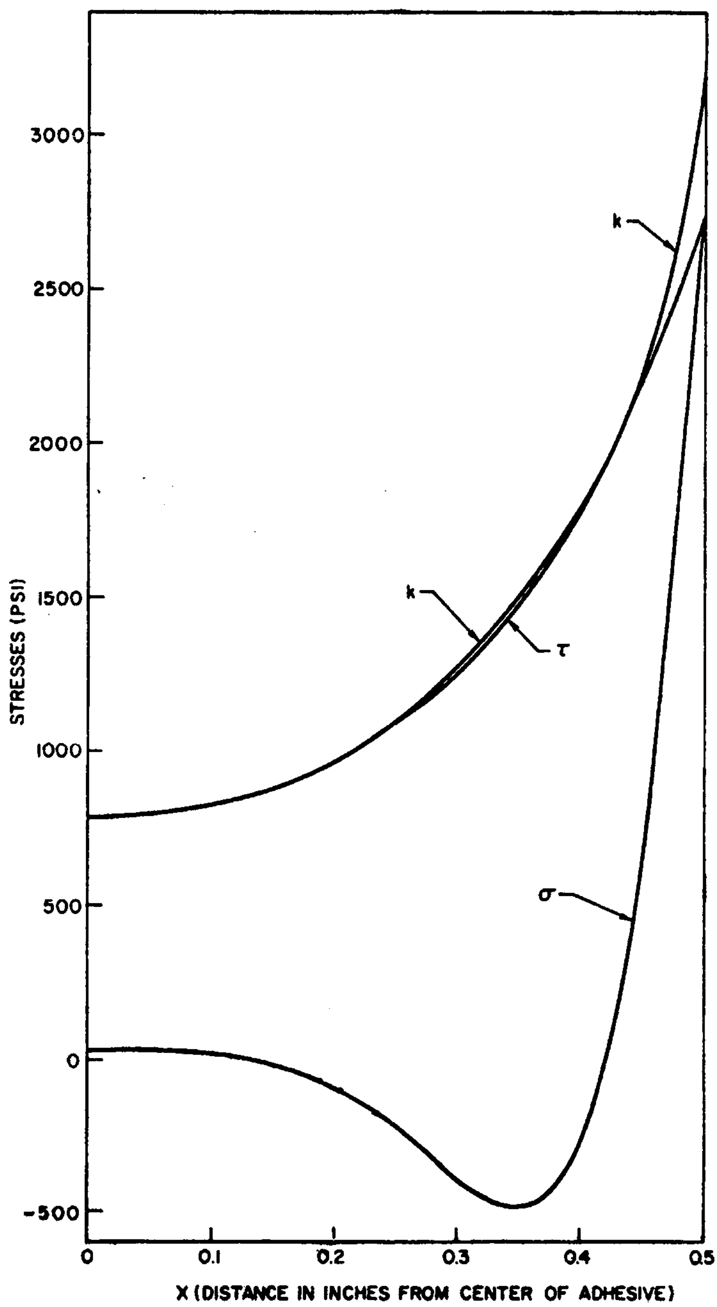

Fig. 7. A variation of the stresses in the adhesive joint as a function of the distance from the center of the adhesive.

ing defects. According to the first theorem of limit analysis, the joint will not flow or fail if the stress field in the adhesive is below the shear strength k of the adhesive. Thus, the load-carrying capacity of the joint is not altered by the highly localized yielding at the bond edges and at the edges of the bonding defects caused by stress concentrations. The second theorem of limit analysis asserts that the load-carrying capacity of the joint is reached when the adhesive yields everywhere within itself. Consequently, the lower and upper bounds of the load-carrying capacity for the present lap joints which fail by shearing mode are equal and the same as that given by eq. (2).

From the foregoing analysis, we conclude that if the adhesive is ductile, edge effects (or stress concentrations at the edges) are not important. This may not be true if the adhesive is brittle, e.g., a rigid epoxy adhesive. For rigid adhesives, edge effects are expected to be prominent.

Appendix

Following Goland and Reissner,[2] we denote the thickness and the width of the adherend by t and c, respectively, and the thickness of the adhesive by η. Then, under an applied load T per unit width of the joint, the shearing stress τ and the tearing stress σ are given by

$$\frac{\tau}{p}\frac{c}{t} = -\,{}^{1}/_{8}\left\{\frac{\beta C}{t}(1 + 3k)\frac{\cosh\left(\frac{\beta C}{t}\cdot\frac{x}{c}\right)}{\sinh\frac{\beta C}{t}} + 3(1 - k)\right\} \tag{1}$$

$$\frac{\sigma}{p}\left(\frac{c}{t}\right)^2 = \frac{1}{\Delta}\left[\left(R_2\lambda^2\frac{k}{2} + \lambda k'\cosh\lambda\cos\lambda\right)\cosh\lambda\frac{x}{c}\cos\lambda\frac{x}{c} + \left(R_1\lambda^2\frac{k}{2} + \lambda k'\sinh\lambda\sin\lambda\right)\sin\lambda\frac{x}{c}\sin\lambda\frac{x}{c}\right] \tag{2}$$

where

$$p = \frac{T}{t},$$

$$\beta^2 = 8\frac{G_c}{E}\frac{t}{\eta},$$

$$k = \frac{1}{1 + 2\sqrt{2}\tanh(m\xi)},$$

$$k' = \sqrt{2m}\,\xi k,$$

$$\xi = \frac{C}{t}\sqrt{\frac{T}{Et}},$$

$$m = \sqrt{\frac{3(1 - \nu^2)}{2}},$$

$$\lambda = \gamma\frac{C}{t},$$

$$\gamma^4 = 6\frac{E_c}{E}\frac{t}{\eta}(1-\nu^2)$$

$$R_1 = \cosh\lambda\sin\lambda + \sinh\lambda\cos\lambda,$$

$$R_2 = \sinh\lambda\cos\lambda - \cosh\lambda\sin\lambda,$$

$$\Delta = {}^1/_2\,(\sinh 2\lambda + \sin 2\lambda),$$

E and E_c are the Young's moduli of the adherend and the adhesive, respectively, and G_c is the shear modulus of the adhesive.

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