FAILURE INITIATION IN EPDM LAP JOINTS IN A LAP SHEAR TEST

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This paper examines the modes of deformation and failure in an EPDM lap joint when it is subjected to shear. An analytical model which characterizes the nature of stress distribution in the lap joint is developed and used to predict the load displacement curve for lap shear. The results of the analytical simulation indicate that while the failure loads in a lap joint test are governed by the shear strength of the adhesive, the displacements of the joint at failure are governed mainly by the stress-strain properties of the membrane. Comparison of analytical and experimental load-displacement plots show that the experimental curve is softer than the analytical curve, and deviates from the analytical curve at a shear stress level about one-tenth of the shear strength of the lap joint. This stress level is identified as the failure initiation stress τ_0, and corresponds to the first breakage of interfacial bonds between the substrate and the adhesive. It is suggested that τ_0 will be sensitive to surface characteristics of the substrate and that it plays an important role in determining the mechanics of failure of the lap joint.

KEYWORDS

Analytical model, damage, EPDM lap joints, failure initiation, lap shear test.

INTRODUCTION

Lap joints are potential sites for initiation of failure and subsequent leakage in an elastomeric roofing system. Mechanical loads due to temperature decrease and wind uplift induce shear loads on the joint. Caulking due to a mismatch of members at a joint will introduce peel loads on the joint. These loads cause axial and bending stresses in the membrane, and shear and tensile stresses in the adhesives or the adhesive-substrate interface. Lap shear tests and standard peel tests are now used in the industry as indicators of joint strength and integrity for these two modes of deformation.

Lap shear tests have fallen into disrepute in the roofing industry due to the apparent insensitivity of the lap shear strengths to the surface features of the membranes that are known to affect the seam performance.[1] No suitable explanation regarding this low sensitivity to surface parameters of the substrate has been advanced. Some insight into the influence of the surface characteristics could be obtained if the mechanics of deformation in a lap joint or the conditions for initiation and propagation of a crack in a lap joint during a lap shear test were well understood.

In this paper, an attempt is made to establish a basic understanding of lap shear. Shear deformations associated with an EPDM lap joint adhered with butyl adhesive are characterized with the help of a simple one-dimensional mathematical model. Material constitutive relations for the axial deformation of the substrate and shear deformation of the adhesive are used in the model to simulate the short term load-displacement behavior of a joint in a lap shear test. Load-displacement curves are also obtained experimentally. The point of departure between the experimental and analytical curves is taken as an indicator of the initiation of failure in the lap joint. From this study, the stress at failure initiation in an EPDM lap joint due to short-term loading was found to be approximately ten times lower than the shear strength of the lap joint. The long-term creep behavior of the joint, which is important to assess the integrity of the joint over the life-span of the roof, depends on the viscous properties of the adhesive and is not considered in the present study.

STATICS OF A LAP JOINT

Consider a simple lap joint normally encountered on roofs (Figure 1(a)). Single lap joints are structurally unstable systems since there is an inherent eccentricity in the joint when first loaded, as shown in Figure 1(b). Stability of an elastomeric lap joint is obtained by the rotation of the joint so that the loads become collinear, (see Figure 1(c)). In this case, substrate sections that are sufficiently far away from the joint experience only axial stresses. From equilibrium considerations (see Figure 1(d)), the shear and normal forces at the interface between the adhesive and the membrane are given by

$$T = F.\cos\alpha \qquad (1)$$
$$N = F.\sin\alpha$$

where F is the load on the joint; T,N are the shear and peel forces on the adhesive, respectively; and α is the angle of deformation. It is clear from Equations 1 that for a flexible substrate with small values of α, the peel forces on the adhesive are negligibly small. For the lap geometries that are normally used on roofs (lap lengths of 75-100mm (3-4 in.), substrate thickness of 1.14mm (0.045 in.) and adhesive thickness of .254mm (0.010 in.)), the value of α is approximately 1.4°. For such low values of α, the influence of N in the overall deformation of the lap joint may safely be neglected.

BEHAVIOR OF EPDM IN UNIAXIAL TENSION

Uniaxial tension tests were conducted on samples of EPDM as per ASTM D 412 (Standard Test Methods for Rubber Properties in Tension). The rate insensitivity of elastomers has been confirmed by testing the EPDM samples at cross head displacement rates ranging from 25 mm/min. to 500 mm/min., corresponding to the standard displacement rates that can be applied using the instron machine. The average test results are plotted in Figure 2 which show that the nominal tensile stress at failure is approximately 10.3 MPa (1500 psi) and the associated engineering strain is approximately 400 percent.

A phenomenological model that describes the observed tensile stress-strain behavior is developed for EPDM. Phenomenological models are derived from assumed forms of potential functions which form the basis for deriving the stress-strain relations for a material.[2] One such phenomenological model proposed by Ogden,[3] based on assumptions of incompressibility of rubbers, is used to derive the following stress-strain relations for EPDM (for details of derivation see reference 4).

$$f = C.[(\lambda^2 - \lambda^{-2.5}) + s. (\lambda^{-4} - \lambda^{0.5})]$$

or

$$f = C.g(\lambda,s)$$

where

$$g(\lambda,s) = (\lambda^2 - \lambda^{-2.5}) + s.(\lambda^{-4} - \lambda^{0.5}) \tag{2}$$

f = nominal tensile stress in the material

λ = extension ratio $= 1 + \epsilon = 1 + \dfrac{\partial u}{\partial x} = 1 + u_x$

ϵ = axial strain in the substrate

u = axial displacement in the substrate

and

C,s are two independent parameters for the model.

It has been found that C = 372 KPa (54 psi) and s = −1.852 gives the best fit to the observed experimental data. This is illustrated in Figure 2. It can be seen in the figure that the proposed model fits the experimental data very well up to $\lambda = 2$ and in an approximate sense for $\lambda \blacktriangleright 2$.

BEHAVIOR OF BUTYL ADHESIVE IN SIMPLE SHEAR

The bulk shear properties of butyl adhesive are measured by means of a thick-adhered lap shear test. This test involves application of the adhesive on relatively rigid substrates (such as aluminum) and pulling the substrates apart so that the adhesive is subjected mainly to shear stresses as illustrated in Figure 3. The test gives average properties that are believed to be adequate for most applications and has been preferred to torsional shear test for many adhesives.[5]

A typical shear stress-strain plot obtained from the shear tests is shown in Figure 4(a). It can be seen that the adhesive exhibits a considerable amount of plastic flow in shear. A wide range of shear strengths (41 KPa to 103 KPa (6 psi to 15 psi)) have been obtained[4] in the laboratory and are probably due to the varying amounts of solvent voids that get entrapped in the thick layers of adhesives that have been tested. The adhesive has been modelled as a bilinear elastic-plastic material in shear with elastic strains of the order of 150 percent and plastic strains of 600 percent as shown in Figure 4(b). Mathematically, the bilinear model may be characterized as

$$\tau = G.\,\gamma = G.(u/h) \text{ for } \gamma \underline{\blacktriangleleft} \gamma_{el} \tag{3}$$

$$\tau = \tau_f \text{ for } \gamma_{el} \blacktriangleleft \gamma \blacktriangleleft \gamma_f$$

where τ is the shear stress in the adhesive, γ_{el} and γ_f are the elastic shear strain and failure shear strain, respectively, and G is the shear modulus of the adhesive.

An examination of the failed surfaces of the sheared samples (Figure 5) indicates that the adhesive material is highly stretched into thin narrow strands before rupture. This phenomenon is similar to the formation of crazes in glassy polymers.[8] In such materials, the material remains homogeneous and deforms elastically until it reaches its yield stress. The deformation of the polymer after the yield strains is associated with the growth of crazes which effectively increase the size and concentration of voids in the polymer. The deformation of butyl adhesive in shear could be visualized to be of a similar kind. The failure of the adhesive could be defined in terms of a critical percentage of voids that will increase the diffusion of moisture through the adhesive in any typical joint. In the present analysis, the authors define the shear strain producing the critical percentage of voids to be 600 percent.

STRESS ANALYSIS OF ELASTOMERIC LAP JOINT

The present analysis predicts the shear stress distribution in the adhesive layer. Only axial deformations in the membranes and shear deformations in the adhesive material are considered. The lower and the upper membranes are assumed to deform independent of each other as if they have been attached to a rigid substrate through an adhesive layer of thickness h. The deformations in the adhesive due to the independent deformations of each of the half lap joints are added to each other so as to construct the total deformations of the full lap joint as shown in Figure 6. It may be observed in Figure 6, that the center of rotation of different sections of the joint varies across the thickness of the joint. In a full lap joint, the deformations of either membranes are likely to influence the deformations in the other membrane. In the present analysis, these influences are ignored. The additional axial deformations are likely to be uniform along the length of the lap and of the same magnitude in either membranes. Therefore, they would introduce very little shear in the adhesive. Thus, while the shear deformations of the adhesive predicted by this analysis are likely to be accurate, the authors expect some error in the axial deformations predicted by this model.

The substrate is modelled using the uniaxial tensile model (Equation 2) and the adhesive is modelled as number of shear springs having shear properties described by Equation 3. Volkersen[6] originally derived the expression for shear stress distribution in an elastic joint under similar assumptions and his analysis is extended here to analyze joints with elastomeric substrates and elastic-plastic adhesives.

Equilibrium Equations

Adhesives with Linear Elastic Material Models—Consider the half lap joint of Figure 7 which shows the upper substrate of thickness, d, being adhered to a rigid substrate by an adhesive layer of height, h. For any element of length, dx, and of width, w, the axial load, F, on the substrate is resisted by the shear stress due to the adhesive. Thus,

$$dF/dx = \tau.w$$

The axial load is related to the axial stress f by the relation

$$F = f.d.w$$

Hence,

$$df/dx = f_x = \tau/d \tag{4}$$

Equation 4 gives the relationship between the rate of decay of the axial stress in the substrate and the shear stress in the adhesive. The decay of the axial stress f should further be in such a way that it reduces to zero at x = 0 and the integral of shear stresses along the length of the joint should be equal to the applied load.

Substitution of Equations 2 and 3 in Equation 4 yields a nonlinear differential equation with variable coefficients (for $\gamma \blacktriangleleft \gamma_{el}$) of the form

$$h(\lambda,s).u_{XX} = \beta'.u$$

where

$$h(\lambda,s) = \frac{\partial g(\lambda,s)}{\partial \lambda}$$

and

$$\beta' = \frac{G}{C.d.h} \tag{5}$$

The solution of Equation 5 is a function of the nonlinear parameter h(λ,s). If h(λ,s) is a constant, say K, Equation 5 reduces to a linear differential equation, the solution to which is of the form[4]

$$u = \frac{(u_{xo})}{(\sqrt{\beta_1})} \frac{.\cosh(\sqrt{\beta_1}.x)}{\sinh(\sqrt{\beta_1}.L)} \; ; \; \beta_1 = \beta'/K \tag{6}$$

where u_{xo} is the axial strain in the substrate at x = L. When h(λ,s) is a function of x, the authors still approximate the solution of Equation 5 to be of the form given by Equation 6 but adjust the value of the parameter K = h(λ,s) such that Equation 5 is satisfied on an average over the region x = 0 to x = L. Specifically, a point collocation procedure is used to iterate for the parameter K that solves Equation 5 exactly at any given collocation point x_o. The authors further chose x_o such that the weighted residual of the Equation 5 is minimized over the region x = 0 to x = L. It has been found in this study that the total error was within 5 percent when $x_o = L^4$ was chosen.

Adhesives with Elastic-Plastic Material Model—Once the extreme fiber strain of the adhesive has reached its elastic limit, the material begins to deform plastically and the elastic strain variation is pushed further into the lap. The governing equation in the zone of plasticity is given by

$$\frac{d(F - F_{lin})}{dx} = \tau_m.w \tag{7}$$

where F is the applied load, F_{lin} is the load corresponding to the linear elastic limit of the adhesive and τ_m is the plastic flow strength in shear of the adhesive. Substituting the expressions for stresses from Equation 4, and the stress-strain law from Equation 2 into Equation 7, and integrating over the plastic zone, the following expression is determined

$$g(\lambda,s) = \frac{\tau_m}{Cd}.(L - L_o) \tag{8(a)}$$

where L_o is the elastic zone of the lap joint. Equation 8(a) could be solved for λ using

$$\lambda(x) = g^{-1}(f(x)/C,s) \tag{8(b)}$$

for any given L_o, which when integrated along the length of the joint will yield the shear displacements due to plastic flow of the adhesive.

Stresses and Strains in the Adhesive

The stresses and strains in the adhesive are calculated by superposing the deformations of the two half lap joints. Hence,

$$\gamma_{adh} = \frac{u_u + u_l}{h}$$

$$\begin{aligned} \text{and } \tau_{adh} &= G.\,\gamma_{adh} \text{ for } \gamma_{adh} \blacktriangleleft \gamma_{el} \\ &= \tau_f \text{ for } \gamma_{el} \blacktriangleleft \gamma_{adh} \blacktriangleleft \gamma_f \end{aligned}$$

where γ_{adh} and τ_{adh} are, respectively, the shear strains and shear stresses in the adhesive, and u_u and u_l are the displacements of the upper and lower half lap joints, respectively. For $\gamma_{adh} \blacktriangleleft \gamma_{el}$, u_u and u_l are given by the elastic solution given by Equation 6. For $\gamma_{adh} \blacktriangleright \gamma_{el}$, the shear displacements are computed by integrating the axial strains in the substrate which vary as per Equation 8(b).

Stresses and Strains in the Substrate

The stresses in the substrate are given by

$$f(x) = \frac{1}{d} . \int_0^L \tau_{adh}(x).dx \tag{10}$$

and the strains are compatible with shear strains and are given by Equation 8(b). Additional strains are introduced in either membranes as the load is transferred into them by the other membrane through the adhesive. The present analytical model is incapable of capturing these additional strains in the substrate.

RESULTS OF ANALYTICAL SIMULATION

To understand the behavior of an elastomeric lap joint the authors simulate the load-displacement curve of a typical lap joint using their analytical model. A lap joint with a length of 50mm (2 in.), width of 50mm (2 in.) and an overhang length (L_1 of Figure 7) of 38mm (1.5 in.) is considered. An EPDM substrate 1.14mm (0.045 in.) thick and a butyl adhesive 0.254mm (0.01 in.) thick is used. The plastic flow strength τ_f of the adhesive was assumed to be 76 kPa (11 psi). This joint is subjected to shear loads, and the authors are interested in predicting the deformation and failure of such a lap joint assembly.

As the lap joint is loaded, the adhesive initially gets deformed elastically giving rise to exponentially decaying shear stresses as shown in Figure 8. It may be noted that at this stage the load is carried almost entirely by the end regions of the lap joint and the mid-region constituting about 60 percent of the lap length is not loaded. As the joint is loaded further, the end regions yield and the mid-regions get further activated to carry the additional loads. The plastic zone will continue to grow into the lap joint with increase in loads until one of the failure conditions are satisfied for the joint.

The shear strength of the lap joint is given by integrating the shear stresses along the length of the lap joint. The total crosshead displacement in a lap shear test is the sum of the displacements due to axial strains in the overhang region of the joint (L_1), and the displacements due to shear strains in the adhesive (which are in turn coupled to the axial strains in the membrane over the lap length). The overall deformation of the lap joint assembly will, therefore, depend upon the relative stiffness of the joint length with respect to the overhang regions of the joint.

The modes of failure of the joint influence the simulated response. Assuming the adhesive layer is very thin, the adhesive merely transmits shear stresses and has little influence on the overall deformation of the joint assembly. Physically, such joints may be idealized as nondeforming rigid blocks that are flanked on either sides by flexible overhangs. For such joints, the flexibility of the assembly is dictated by the overhang regions of the substrate, and the failure occurs when the interface strength of the adhesive is reached as illustrated in Figure 9. On the other hand, if the adhesive layer thickness is comparable to the thickness of the membrane, the strain induced failure of the adhesive will govern the overall response of the assembly. The failure in such a case is initiated when the adhesive strains reach a prescribed limit. The exponential decay of stresses and strains in the joint may result in failure initiation at lap ends even before the mid-regions of the lap are deformed appreciably. Failure of the joint by this mode of deformation is also illustrated in Figure 9. It was observed that the plastic zone has extended only up to 40 percent of the overall lap length when the adhesive failed in this mode.

LAP SHEAR TESTS ON EPDM LAP JOINTS WITH BUTYL ADHESIVES

EPDM lap joints with butyl adhesive having the same geometric parameters as in the analytical simulation were tested in shear in the laboratory. The specimens were prepared by applying the adhesive on each membrane and splicing the membranes after allowing the adhesive to dry for 15 minutes. A steel roller was rolled over the splice to ensure adequate bonding as per the standard application procedure recommended for such joints.[8] Nine such specimens were prepared and were allowed to cure at room temperature and normal humidity conditions for seven days before testing. The average thickness of the adhesive in the lap joint was 0.284mm (0.0112 in.). The joints were loaded at a rate of 50 mm/min. (2 in./min.).

The load-displacement curves for the lap joint are plotted. The maximum failure load observed was 197 N (44.21 pounds) with an associated displacement of 284mm (11.19 in.). A typical load-deflection curve is shown in Figure 10. It was visually observed that the delamination between the membranes initiates at very early stages of load history. The failed samples indicated that the delamination was mainly at the interface of adhesive and the membrane. The load-deflection response of a lapless rubber piece having the same overall dimensions as the lap joint assembly is also plotted in Figure 10. The striking similarity of the deformation response of the two curves indicates that effective stiffness of the joint is the same as the overhang regions of the lap joint assembly, and that the deformation response is insensitive to a propagating crack.

FAILURE INITIATION IN A LAP SHEAR TEST

Comparison of the theoretical and the experimental load-displacement curves in Figure 10 indicates that the responses are similar up to a critical stress τ_0. The authors hypothesize that the delamination between the membranes initiates at this stress. The theoretical and the experimental curves deviate at this point due to the differences in the stiffness of the joint between the analytical simulation and the actual response. A propagating crack apparently allows for a greater slip between the membranes and enhances its flexibility bringing it closer to the flexibility of the overhang region. The authors propose that τ_0 is a measure of the interfacial strength between the substrate and the adhesive and is likely to be sensitive to the presence of external agents (such as release agents or dirt particles).

Leakage in roofs due to moisture ingress occurs because of flaws that are either inherently present in the lap joints of roofing membrane or are initiated by external forces. Greater attention should be devoted to the conditions of initiation of these flaws in the joints as characterized by the interfacial strength, rather than purely mechanical indicators such as the lap shear strength or the peel strengths. Estimation of the interfacial strength between the membrane and the adhesive, as outlined in this paper, will necessitate a more detailed characterization of the stress-strain response of the membrane and the adhesive, rather than merely using the ultimate strength of these materials in design. This paper demonstrates a systematic procedure to identify the critical parameters that need to be considered while assessing the integrity of a lap joint when it is subjected to shear loads. A similar procedure is likely to throw insights into the behavior of the joint in peel.

SUMMARY AND CONCLUSIONS

The behavior of an EPDM joint in lap shear has been simulated analytically based on a uniaxial model which assumes only axial strains in the substrate and only shear strains in the adhesive. The model uses an Ogden's model to characterize the axial strains in EPDM and a bilinear elastic-plastic model to characterize the shear strains in the adhesive. Lap shear tests that were conducted in the laboratory indicated that the failure in the lap joint was mainly at the interface between the substrate and the adhesive. The experiments show a softer response of the joint than the analytical predictions. The stress at which the experimental curve deviates from the analytical curve is identified as the stress at which interfacial crack starts propagating in a lap joint. This stress plays as significant a role as the lap shear strength τ_f in characterizing the mechanics of failure in shear of a lap joint. It is recommended that the crack initiation stress τ_0 be used by the roofing industry in the design of leak-proof joints subjected to shear loads.

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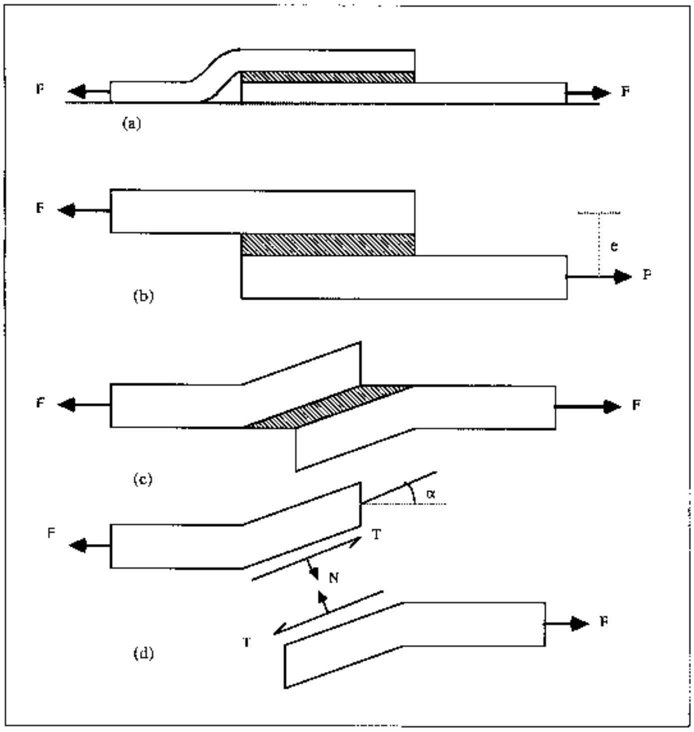

Figure 1 *Behavior of a flexible substrate:*
(a) Lap joint configuration as present on roofs.
(b) Physical model of the joint showing the initial eccentricity of loads.
(c) Deformation of the joint to bring the loads collinear.
(d) Shear and peel forces in the joint.

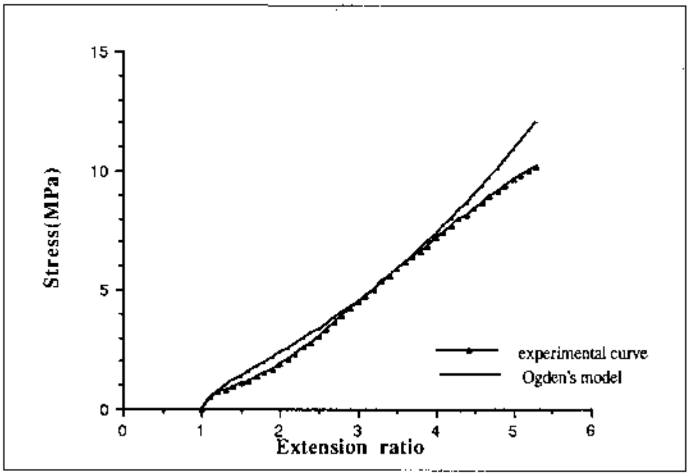

Figure 2 *Uniaxial stress-strain curve for EPDM—Comparison of experimental curve with Ogden's model.*

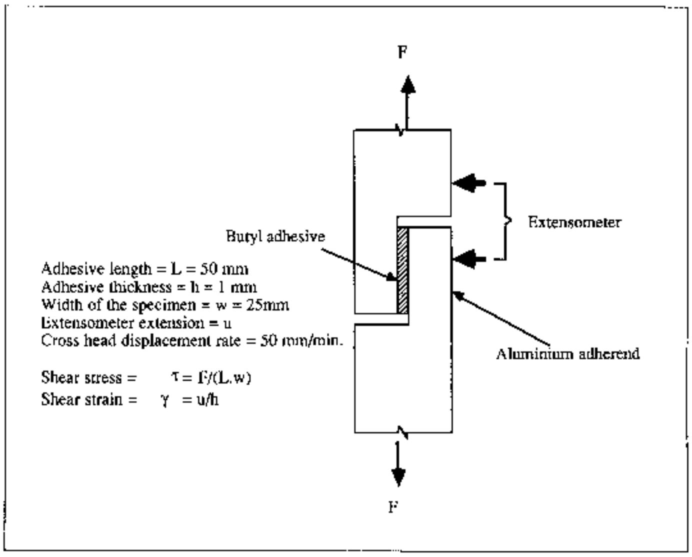

Figure 3 *Thick adhered lap shear tests of butyl adhesive.*

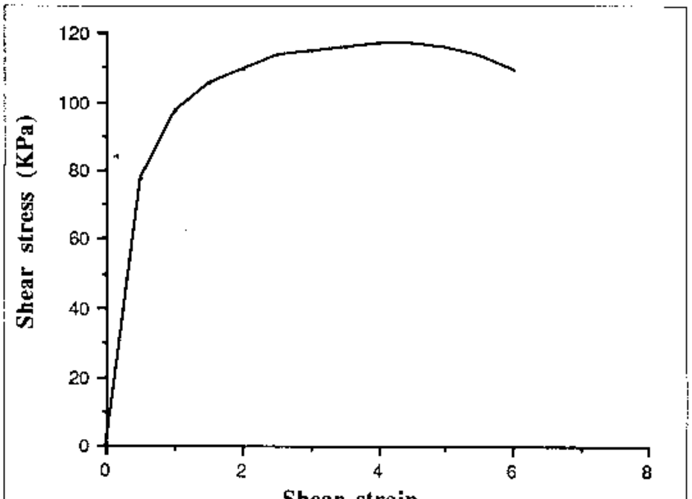

Figure 4(a) *Shear stress-strain plot of butyl adhesive.*

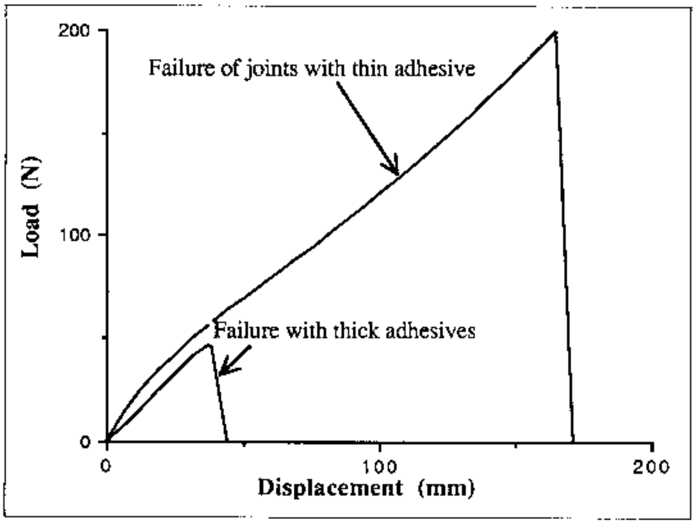

Figure 9 *Analytical simulation of load-displacement curve of lap joint showing different modes of failure.*

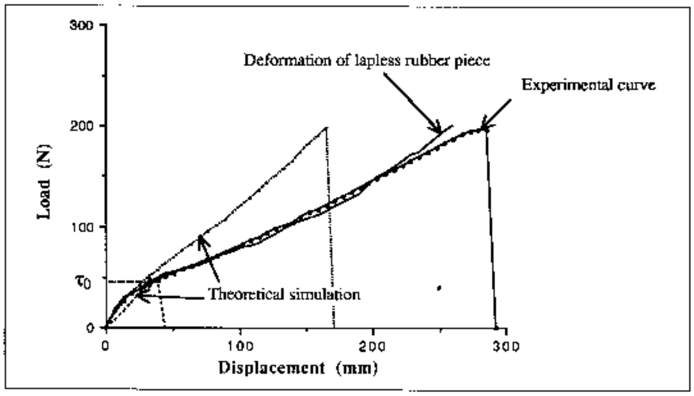

Figure 10 *Lap joint test results—Comparison of experimental results with theoretical simulation.*