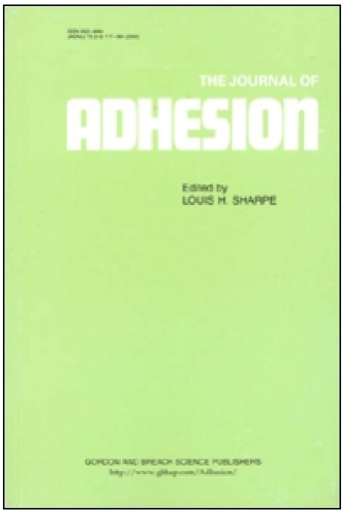

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Comparison of Peel and Lap Shear Bond Strengths for Elastic Joints With and Without Residual Stresses

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Comparison of Peel and Lap Shear Bond Strengths for Elastic Joints With and Without Residual Stresses

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Debonding energies have been calculated from peel and lap shear experiments on rubber strips bonded together with a pressure-sensitive acrylic adhesive layer. In some cases, one strip was held stretched during bonding, to create joints with built-in stresses. Good agreement was obtained in all cases, provided that elastic strain energy was taken into account, the work of debonding being about $180\,J/m^2$. For thick rubber strips, about 3–4 mm or greater, the strain induced by peel or shear forces was rather small and the assumption of linear elastic behavior was found to be satisfactory. Good agreement was then obtained with the relations derived by Kendall.[1,2]

KEY WORDS Lap shear; peel; shear strength; residual stress; shrinkage stress.

1 INTRODUCTION

Peel and lap shear tests are simple and widely-used methods of measuring the strength of an adhesive bond. But the results are not easily compared. The peel force per unit width of the joint can be directly interpreted as an energy G_a required to debond unit area of the interface. On the other hand, it is usual to describe the strength of a lap shear joint by the mean shear stress causing debonding. But the joint does not fail in shear by simultaneous debonding of the entire bonded area. Instead, the bond fails first at a highly stressed site, usually at one edge, and failure then spreads across the interface.

Kendall calculated the strength of a lap-shear joint on this basis[1,2] using Griffith's energy-balance approach, and showed that the debonding energy deduced from lap shear measurements on model joints agreed well with that given by a simple peeling experiment. However, Kendall assumed that the stress-strain relationship in tension for the two adhering strips was a linear one and the strains were small. These assumptions are not necessarily true for thin strips, which might be stretched to large strains during bonding or detachment.

The theory is reviewed here and measurements on extensible rubber strips are compared with predictions made with and without the assumption of small strains.

If one of the strips is stretched when it is bonded to the other, the joint is made more resistant to separation, at least for prestrains below a critical level at which the strips spontaneously debond on release from the preload. Both the strengthening effect of initial prestrains and the critical degree of prestrain at which spontaneous debonding occurs can be calculated on the basis of elastic strain energy contributions to the work of debonding, assuming that the intrinsic bond strength is unchanged by prestretching. Some measurements are reported of the peel and lap shear strengths of joints prepared by bonding a stretched rubber strip to an unstretched one. Such joints can be regarded as models of adhesive joints prestressed due to a variety of causes; for example, by shrinkage of one layer on setting or by differential thermal contraction.

2 THEORETICAL CONSIDERATIONS

Work is expended in two ways in peeling. First, the detached strip is stretched, to a strain of e, say, requiring input of strain energy U per unit volume. If it was already stretched to a strain of e^* in the bonded state, before peeling, with a corresponding amount of strain energy U^* per unit volume stored in it, then the additional energy supplied is $U - U^*$. Secondly, an amount of energy G_a is expended per unit area of interface in debonding the adhering surfaces. (It is assumed that G_a is the same for stretched and unstretched adhering surfaces, but we note that unit area of surface becomes $(1 + e^*)^{1/2}$ in the stretched state.) Thus, the work done by the peel force F during detachment of a strip of unit length in the unstrained state (given by Fx where x is the displacement of the point of application of the force) is equal to the sum of these two terms,

$$Fx = [G_a(1 + e^*)^{1/2} + (U - U^*)t]w \quad (1)$$

where t is the unstrained thickness and w is the unstrained width of the peeling strip.

From geometrical considerations (Figure 1) x is given by

$$x = [1 + e - (1 + e^*) \cos \theta] \quad (2)$$

where θ is the peel angle. The debonding energy G_a is then obtained from Eqs. (1) and (2),

$$G_a(1 + e^*)^{1/2} = (F/w)[1 + e - (1 + e^*) \cos \theta] - (U - U^*)t. \quad (3)$$

In the case of linear elasticity, the strains e and e^* are given by F/wtE and F^*/wtE, where E is the tensile (Young's) modulus of the strips, F^* is the residual tension in the strip before separation, corresponding to the strain e^*, and the strain energies U and U^* are given by $(F/wt)^2/2E)$ and $(F^*/wt)^2/2E$. Thus, for

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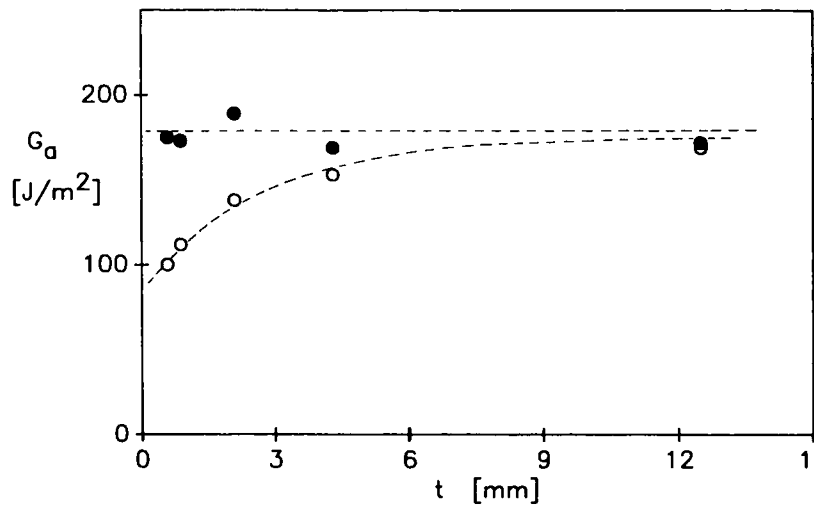

FIGURE 7 Debonding energy *vs.* strip thickness, calculated from lap shear measurements: ○, using Eq. (16); ●, using Eq. (15).

calculated from them assuming that the strips were linearly elastic, Eq. (4), or that they were non-linearly elastic, Eq. (3). The results are plotted in Figure 8 against the thickness of the rubber strips for various amounts of prestrain e^*. When the strips were assumed to be linearly-elastic the results were not constant but depended on the strip thickness, especially for thin strips. On the other hand, when non-linearly elastic behavior of the strips was taken into account, then the

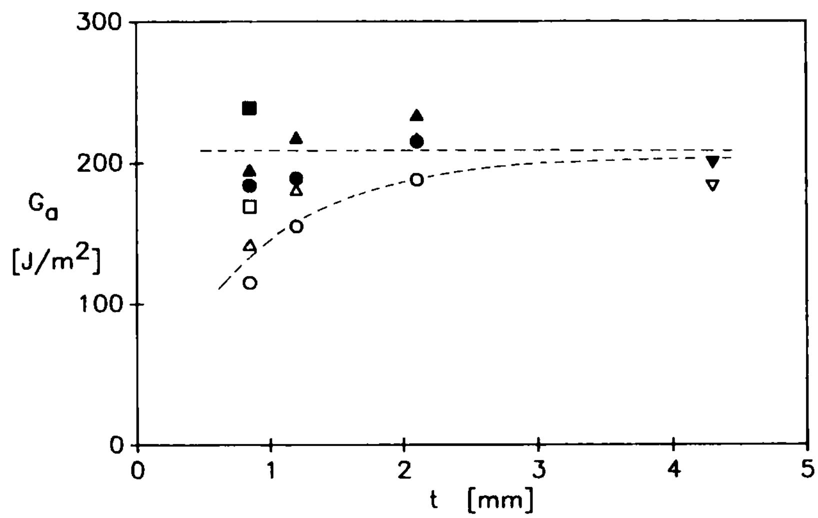

FIGURE 8 Debonding energy *vs.* strip thickness, calculated from peeling measurements on prestrained samples: ▽, ▼, $e^* = 0.10$; ○, ●, $e^* = 0.25$; △, ▲, $e^* = 0.30$; □, ■, $e^* = 0.60$. Open symbols from Eq. (4), filled symbols from Eq. (3).

calculated values were approximately constant, independent of the strip thickness. Moreover, the average value, about 210 J/m^2, was close to that obtained from peeling and lap shear measurements on unprestressed joints, Figures 6 and 7.

(b) *Lap shear strength* In order to calculate debonding energy for prestressed lap shear joints in the most general case, Eq. (11), it is necessary to deduce the strains e_1 and e_2 in the two bonded strips under the failure force F. This was done by trial and error, using Eqs. (12) and (13). Values obtained in this way are given in Table 4, together with the results for G_a calculated from them. As can be seen in Figure 9, these values of G_a are approximately constant at about 160 ± 20 J/m^2, close to the value deduced from peeling measurements, and independent of the strip thickness, whereas values calculated on the basis of linearly-elastic behavior using Eq. (14) are much smaller for thin strips and not independent of the strip thickness. We conclude that it is necessary to take into account non-linear elastic behavior of rubber strips to predict the effect of large prestrains on peel and lap shear strengths.

(c) *Strengthening effect of prestresses* As shown by the failure forces given in Tables 3 and 4, prestressed joints were more resistant to separation than non-prestressed joints. The maximum increase in strength was about 50 percent. But, at a critical amount of prestrain, denoted in Table 4 by e_c^*, the joints spontaneously debonded on releasing them from the prestress. Values of debonding energy have been calculated from the corresponding pre-tension forces F_c^*, using Eq. (11). They are included in Table 4. They are seen to be in good

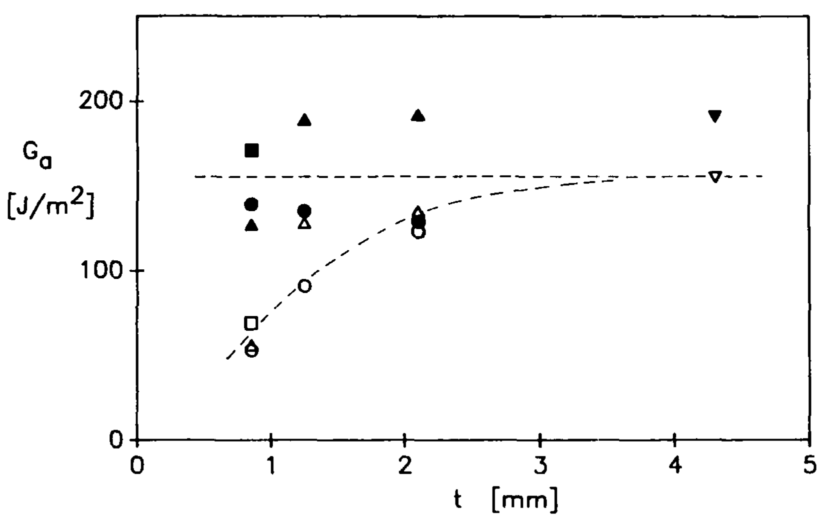

FIGURE 9 Debonding energy *vs.* strip thickness, calculated from lap shear measurements on prestrained samples: ▽, ▼, $e^* = 0.10$; ○, ●, $e^* = 0.25$; △, ▲, $e^* = 0.30$; □, ■, $e^* = 0.60$. Open symbols from Eq. (14), filled symbols from Eq. (11).

agreement with values determined directly from measurements of failure forces. Thus, the maximum amount of prestress that a joint can withstand is also given correctly by fracture energy considerations.

5 CONCLUSIONS

Peel and lap shear debonding forces are related by a common failure criterion: that a critical amount of energy G_a is needed for debonding. This conclusion of Kendall has been verified again for adhering rubber strips of a wide range of thickness, bonded together with various amounts of residual stress. But it has proved necessary to take into account both the relatively large strains that rubber can undergo during detachment, especially when the strips are thin, and the non-linear elastic response of rubber. Otherwise, the inferred debonding energies are too small, by factors of up to 3 or 4 in the present experiments.

Acknowledgements

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Appendix

Mix formulations in parts by weight and vulcanization conditions were as follows: natural rubber, 100; zinc oxide, 5; stearic acid, 2; accelerator (Santocure), 1; sulfur, 2.5. Vulcanization was effected by heating for 30 min. at 150°C.