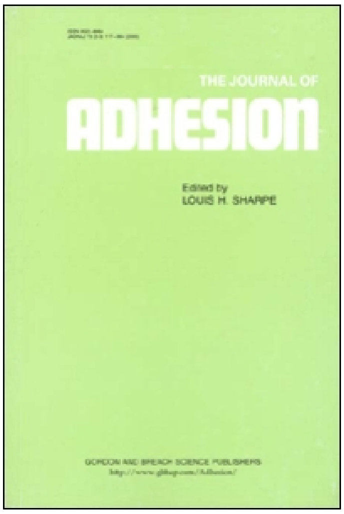

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An Adhesion Paradox

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Note

An Adhesion Paradox

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In the study of the adhesion of solids, a curious paradox has arisen. The paradox concerns the strength of adhesive bonds in two test geometries, the pull-off and the peel test, illustrated in Figure 1.

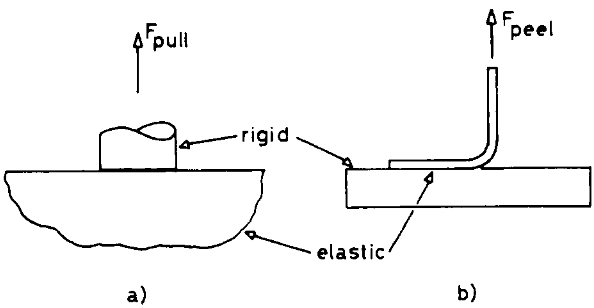

FIGURE 1 (a) Pull-off test (b) Peel test.

The peel test is very simple theoretically because the work done by the peel force may be equated, in equilibrium, to the energy required to create new surfaces, providing the energy expended in stretching the film is negligible.[1,5] If the surface energy is γ per unit area of adhesive bond, and the strip is of width b, then the peel strength is given by

$$\frac{F_{peel}}{b} = \gamma \qquad (1)$$

Likewise, the pull-off force may be related to the surface energy by assuming that, on separating the surfaces, the adhesive forces decay very rapidly with distance, so that all the work done by the pull-off force is expended as the surfaces move apart by about 10^{-7} cm. For a joint of area A, the energy balance is

$$F_{\text{pull}} \times 10^{-7} = \gamma A \tag{2}$$

and the pull-off strength is

$$\frac{F_{\text{pull}}}{A} = 10^{7}\gamma \tag{3}$$

According to this simple argument the pull-off strength should be greater than the peel strength by a factor of 10^7. Typical experimental results,[2] as Table I demonstrates, do not support this theory, since in practice, there is

TABLE I

	Peel strength dyne cm^{-1}	Pull-off strength dyne cm^{-2}
Theoretical	10^2–10^4	10^9–10^{11}
Experimental	10^5–10^7	10^6–10^8

only an order of magnitude difference between the peel strength and pull-off strength.

The paradoxical observation is that, although the experimental peel strength is greater than the equilibrium value of surface energy, a fact which may be explained by experimental deviations from equilibrium, the observed pull-off strengths are much *less* than the theoretical ones. Attempts have been made to explain this discrepancy in terms of small cracks which produce stress concentrations.

A more likely explanation of this paradox is that equation (2) is over-simplified. In fact, an equilibrium theory of the pull-off test should include the effect of elastic deformation of the materials. When this effect is included, the pull-off strength becomes[4]

$$\frac{F_{\text{pull}}}{A} = \left(\frac{8\pi}{1-\nu^2}\frac{E\gamma}{a}\right)^{\frac{1}{2}} \tag{4}$$

where E is Young's modulus

γ is surface energy

ν is Poisson's ratio

a is radius of die

Equation (4), analogous to the criterion of Griffith,[3] gives more reasonable theoretical values of pull-off strength than does equation (3). Also it may be noted that the pull-off geometry of Figure 1, although it apparently contains no weakening flaws, includes a large virtual crack, since the rigid die may be

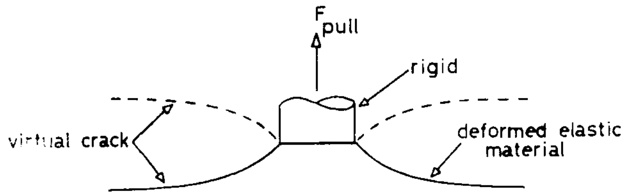

FIGURE 2 Virtual crack in the pull-off test.

replaced by the mirror image of the deformed elastic material (Figure 2). This geometry, which now represents a fracture experiment on a deeply notched cylindrical bar, again gives equation (4) as the criterion for crack propagation providing that the surface energy is increased by a factor of two.

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