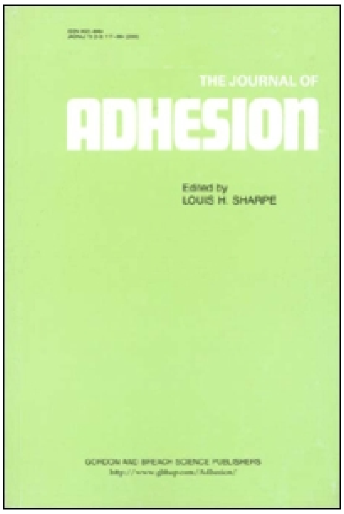

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Stress Distribution during Peeling of Adhesive Tapes

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Stress Distribution during Peeling of Adhesive Tapes

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The pattern of stress distribution observed during the peeling of pressure sensitive tapes is not adequately described by existing theoretical analyses of peel, which make over-simplifying assumptions. In particular, the consequence of filamentation or "legging" in the peeling zone is neglected by the theories. In the present work an attempt is made to assess the effect of filamentation by analysis of the peeling profile obtained by photography. The deflection of the backing film from its unrestricted "bent beam" configuration is interpreted in terms of a "filamentation force". The stress distributions obtained show that filamentation makes an important contribution to the peel force and show good correlation with the results obtained from related systems by a different experimental method.

INTRODUCTION

Theories of peel adhesion are all based on an equation derived from elementary beam bending theory[1] but differ in the mechanical analogue used to represent the behaviour of the adhesive. The theory due to Kaelble,[2] which assumes a Hookean adhesive response, is the most comprehensive and generally considered the most valid for application to pressure sensitive tapes. However, this and other theories assume a sharp bond boundary at the line of separation, thereby neglecting the effects of cavitation and filamentation. This assumption is reflected in the predicted stress distribution (Figure 1) which shows a sudden transition from maximum to zero stress at the bond boundary.

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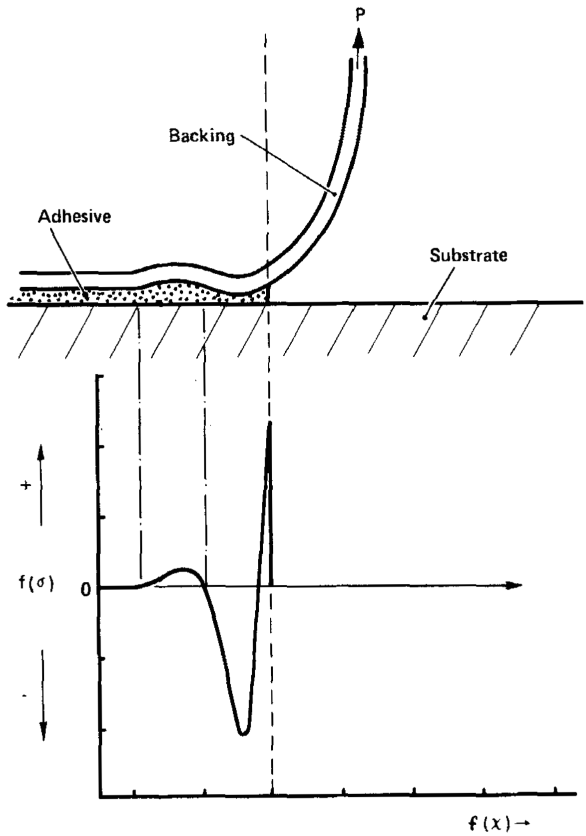

FIGURE 1 Tape profile and typical stress distribution predicted by theory.[2]

Kaelble[3] has succeeded in determining experimentally the distribution of cleavage stress at the adhesive-substrate interface, and has shown that the contribution to peel force by filamentation is significant, even under conditions of adhesive separation when the filaments are visually almost undetectable. Figure 2 shows a representation of the peel profile and associated typical stress distribution as obtained experimentally by Kaelble. His method, using a "split beam" transducer, involves somewhat complex instrumentation. In the present work an attempt is made to obtain a stress distribution from the curvature of the backing member in the region of filamentation. The backing is expected to be deflected from its free "bent beam" curvature by the forces of the filaments and, with the application of reasonable assumptions, should enable the distribution of stress within the bond to be determined.

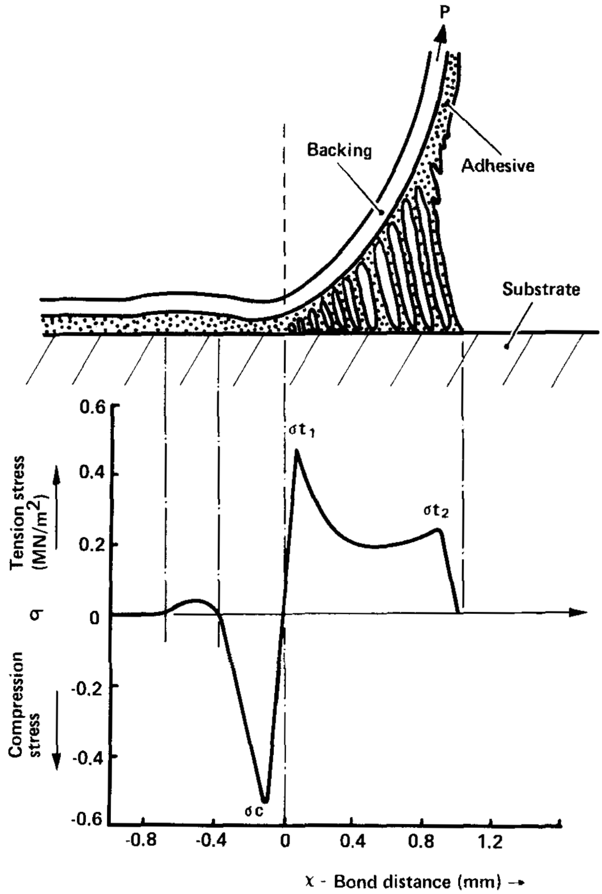

FIGURE 2 Experimental stress distribution obtained and profile assumed by Kaelble.[3]

METHOD

The joint comprises a polyester tape attached via a polybutyl acrylate adhesive to a glass substrate. Its preparation and peeling behaviour have been previously described.[4] Tapes were peeled at an angle of 90° and at 296 K in a tensile testing machine using a specially-designed peeling device (Figure 3) designed to allow both the elevation (x, y) and the plan (x, z) photographs of the peeling zone to be obtained. Only elevation photographs are used in the present work, and the peel force corresponding to each photograph is recorded.

It was found desirable to enlarge the joint for better accuracy and

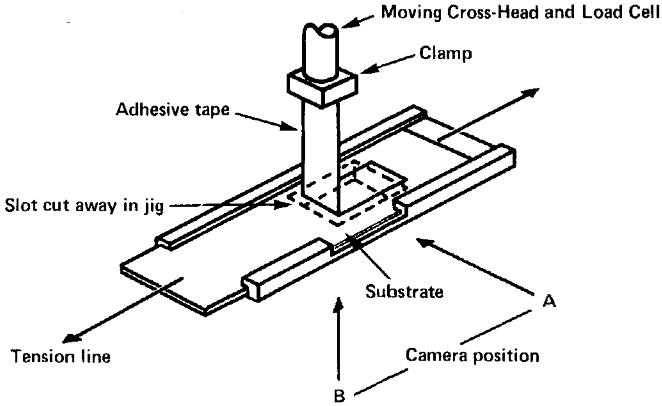

FIGURE 3 Peeling arrangement.

convenience, and scale-up rules were derived from considerations of peeling theory. It was predicted (Appendix 2) that linear scale-up of the backing thickness, adhesive thickness and pulling rate would give rise to a corresponding linear increase in peel force. Tests showed that this was in fact observed (Figure 4). However, due to difficulties in photographing the peeling zone at very high pulling rates, the best results were obtained at a scale factor of twice that of common commercial joints. Typical commercial tape dimensions were taken as 25 μm thickness each of adhesive and backing film.

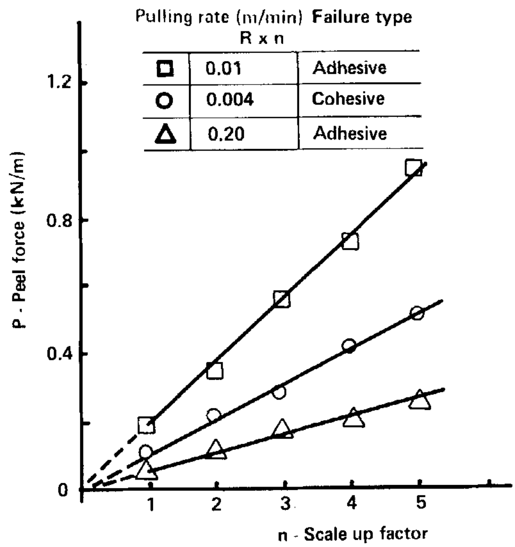

FIGURE 4 Peel force P versus linear scale-up factor n.

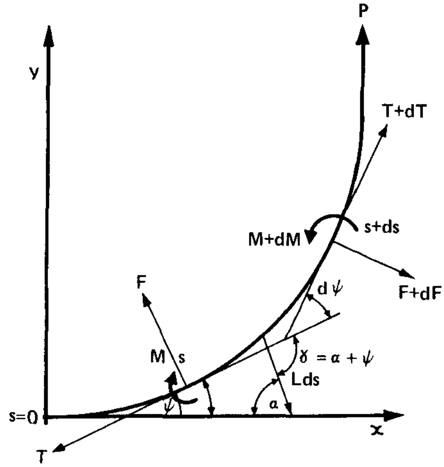

FIGURE 5 Analysis of forces acting on an element of backing between s and $s+ds$ during peeling.

The backing curvature as revealed by the photographs may be expressed in terms of $d\psi/ds$ (Figure 5, and list of symbols) for individual elements of the backing. In order to obtain a shear stress distribution it is then necessary to make the assumptions (i) that the backing is of thin cross section, of infinite length, is Hookean and undergoes negligible deformation in shear and extension, and (ii) that the adhesive is of negligible stiffness compared with the backing, and exerts forces on the backing which are constant over an element of area (Figure 5) and are uniformly distributed across the bond width.

Application of the conditions of equilibrium of forces and moments to the backing element (Figure 5) and use of standard bending deformation equations allows the "filamentation" or "leg" force, L, to be described as a function of s (Appendix 3). Values for $L(s)$ could then be calculated from the measured values of peel force P and angles α, ψ and γ obtained from the corresponding photographs. Both graphical manipulation (earlier results) and a non-linear regression computer programme (later results) were used in making the calculations.

The vertical component of L (i.e. the normal cleavage stress) $L \sin \alpha$ is then plotted against s, fixing $s = 0$ as the point of zero stress 'corresponding to Kaelble's $x = 0$) to give the stress distribution (Figures 6 and 7).

RESULTS AND DISCUSSION

The results of three separate determinations, using nominally identical peeling conditions, show that the method is capable of high reproducibility (Figure 6).

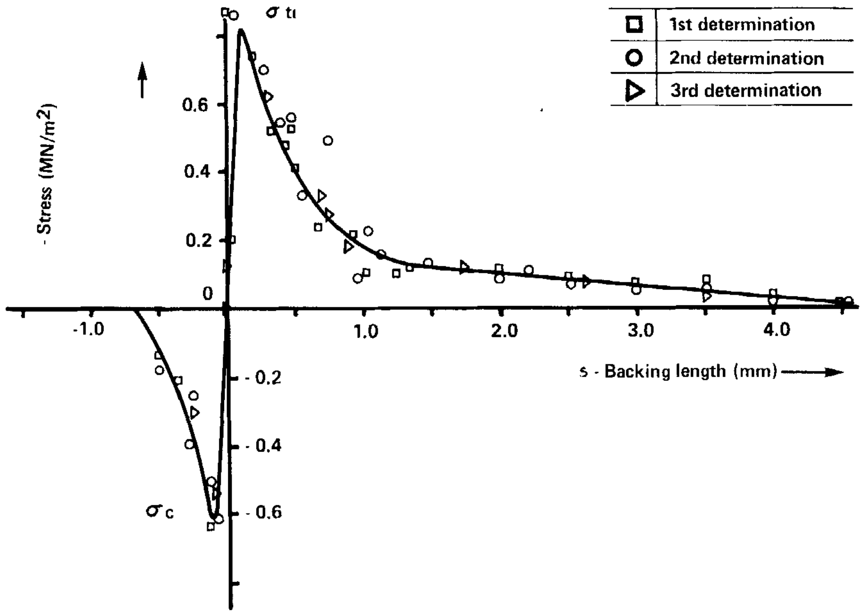

FIGURE 6 Normal stress distribution obtained using Eq. (vi) for a pulling rate of 2.2×10^{-2}m/min and adhesive thickness 5.0×10^{-5}m (scale factor $n = 2$).

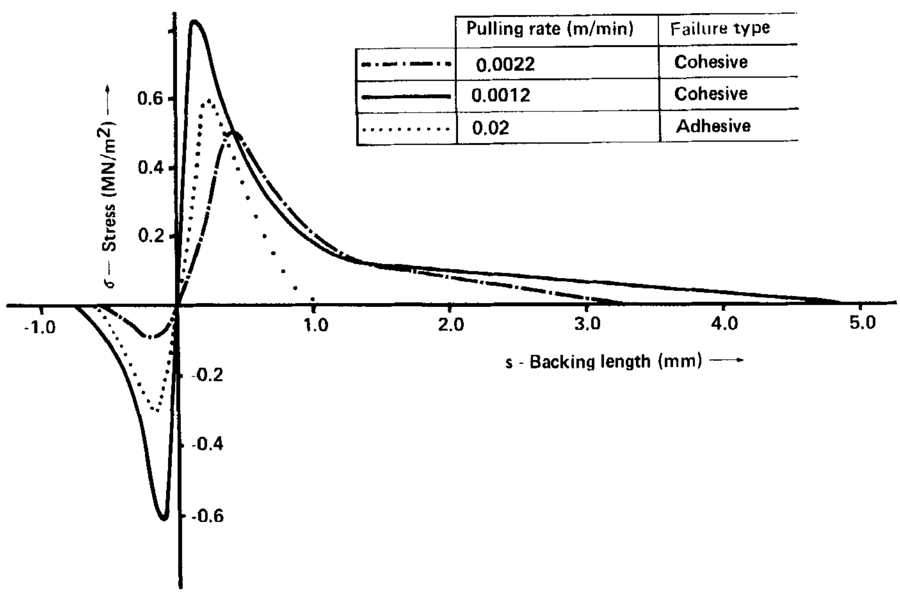

FIGURE 7 Normal stress distribution obtained by using Eq. (vi) at three different pulling rates (scale factor $n = 2$).

The stress distribution, which in this case corresponds to peeling with "cohesive" separation, clearly shows the regions of maximum compressive stress σ_c, and maximum tensile stress σ_{t_1}, as well as the extension of the stress field due to filamentation. The secondary stress maximum σ_{t_2}, within the region of filamentation, reported by Kaelble and shown in Figure 1, is not evident in the stress distributions of the present study. It is suggested that this is because Kaelble used an adhesive based on natural rubber, which can crystallise on extension, whereas in the present study a non-crystallising polymer was used. Further evidence for filamentary strain-induced crystallisation during peeling of NR-based adhesives has recently been presented.[5]

Stress distributions obtained at other rates (Figure 7) are similar in pattern to that shown in Figure 6, except that the area under the curve changes. These and additional results show, when failure is "cohesive" in nature, the area under the curve increases with rate, and the peel force increases accordingly. At the higher rates, where "adhesive" separation occurs, the extension of the stress distribution due to filamentation can be seen to be still significant. At these higher rates, the distances involved (s or x) are quite similar to those of Kaelble, if the joints of the present study are scaled down to dimensions used in his work. The method should in principle be applicable to a wide range of joints involving rubber adhesives and rigid substrates.

CONCLUSIONS

During the peeling of a pressure sensitive tape, the influence of adhesive filamentation on the normal stress distribution may be evaluated from the curvature of the tape in the peeling zone. Results show that the stress distribution, and hence the force required for peeling, may be very significantly affected by filamentation. The results show a good correspondence with those obtained in an earlier experimental study.[3]

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APPENDIX 1

List of symbols

P = externally applied peel force (N/m)
s = distance along the backing from origin (Figure 3) (mm)
F = magnitude of resultant shear force on backing at s
T = magnitude of resultant tensile force on backing at s
M = bending moment of backing about s
L = force due to filaments or legs in backing element of length ds (N/m^2)
E = Young's modulus of backing (N/m^2)
I = moment of inertia of backing cross section about neutral axis ($Kg\ m^2$)
ψ = angle between tangent at s and horizontal (°)
α = angle between filaments and horizontal (°)
γ = angle between tangent at s and filaments ($\gamma = \alpha + \psi$) (°)
σ = stress (N/m^2)
n = linear scale-up factor
$dF, dT, dM, d\psi$ = increments in F, T, M and ψ, respectively, corresponding to the increments ds of backing length between s and $s+ds$
$d\psi/ds$ = exact curvature of backing at s when s has a positive value
a = adhesive thickness
b = bond width
h = half thickness of the backing
Y = Young's modulus of the adhesive
K = Kaelble constant (see appendix 2)
σ_0 = critical stress needed to cause separation
ω = overall angle of peel

APPENDIX 2

Scale up rules for pressure sensitive adhesive tapes

To facilitate the photographic study, the peeling joint (*e.g.* as shown in Figure 2) is required to be scaled up by a simple linear scale factor, so that the peeling profile maintains its overall shape. It is therefore necessary to consider how the various forces, rates and stresses are influenced by this magnification.

Kaeble's analysis[6] provides a general relationship between peel force, peel angle, Young's moduli of the adhesive and backing, and stresses within the adhesive layer. This analysis predicts that, for peeling at 90° angle:

$$P = fb\sigma_0(E/Y)^{0.25}a^{0.25}(2h)^{0.75}(1-K)/\sin\omega \qquad \text{(i)}$$

where f is a constant. K is a dimensionless parameter depending on the moduli of adhesive and backing and is given by Kaelble as:

$$K = \beta M/\beta M + 1$$

where β is a stress concentration factor and describes the dimensions of the damped sinusoidal wave in the attached part of the backing (see Figures 1 and 2). The wavelength of this wave is proportional to $1/\beta$.

It can be shown that, with scale-up of backing thickness by a factor n,

$$\beta(n)M(n) = \beta M$$

so that K is constant for all values of n.

We may now consider the variation with n of other important factors as follows.

Adhesive thickness

The stress concentration factor β in the attached part of the backing is given by Kaelble as:

$$\beta = (Yb/4EIa)^{0.25}$$

Substituting for $I = 2bh^3/3$ we obtain:

$$\beta = (3Yb/8E)^{0.25}(1/h^3a)^{0.25} = N(1/h^3a)^{0.25}$$

where N is constant for scale-up with a tape of constant width and Young's moduli. The latter will be constant provided the adhesive deformation rate is kept constant (see later). For the wavelength of the damped sinusoidal curve (see Figures 1 and 2) (proportional to $1/\beta$) to increase linearly with backing thickness, then:

$$\beta(n) = \beta/n \qquad \text{and} \qquad h(n) = nh.$$

Thus

$$\beta(n) = N(1/h(n)^3a(n))^{0.25}.$$

Substituting for $\beta(n)$ we obtain:

$$a/a(n) = 1/n.$$

Thus, for $1/\beta$ to increase linearly with scale-up, adhesive thickness a should increase linearly with n.

Peel force

For constant width, peel angle and moduli, Kaelble's Eq. (i) shows that:

$$P \,\alpha\, a^{0.25}(2h)^{0.75}$$

i.e.

$$P^4 = 8Fah^3$$

where F is a constant.

Since it has been shown that

$$a(n) = na$$

and, by definition,

$$h(n) = nh$$

then

$$P(n)^4 = 8Fn^4ah^3 = n^4P^4.$$

Thus

$$P(n) = nP.$$

Hence for linear scale-up the peel force P should increase linearly with backing thickness.

Pulling rate

The foregoing considerations assume that the adhesive modulus Y is constant during the scale-up procedure. However, since the adhesives used are viscoelastic polymers and not Hookean materials as assumed by the Kaelble analysis, modulus Y will be strongly dependent on adhesive strain rate, and therefore on rate of pulling, R. It is clear that, in order to preserve a constant adhesive strain rate, *i.e.* a constant frequency ν of the stress wave preceding the line of separation, the pulling rate R must be corrected accordingly.

The frequency of the stress wave is given by Kaelble as:

$$\nu = \beta R/2\pi = R/\lambda$$

We have shown that:

$$\beta(n) = \beta/n;$$

hence, for ν to remain constant,

$$R(n)/\lambda(n) = R/\lambda$$

so that the pulling rate has to increase in proportion with scale-up factor n.

APPENDIX 3

Derivation of filament force from peel force and backing curvature

All forces (per unit width) are assumed to be distributed uniformly across the bond width. With reference to Figure 5, forces lateral to the backing are considered positive if downwards and to the right, forces along the backing positive if upwards and to the right.

Applying the conditions of equilibrium of forces and moments to the element ds of backing:

Across the element:

$$F + (T + dT)\sin d\psi - Lds \sin(\psi + \alpha) - (F + dF)\cos d\psi = 0$$

Along the element:

$$(F + dF)\sin d\psi + (T + dT)\cos d\psi - T + Lds \cos(\psi + \alpha) = 0$$

For the moments of the applied forces:

$$M - (M + dM) + Fds/2 + (F + dF)ds/2 = 0$$

Approximating for small angles:

$$Fd\psi + dT + Lds \cos\gamma = 0 \qquad \text{(i)}$$

$$Td\psi - dF - Lds \sin\gamma = 0 \qquad \text{(ii)}$$

$$dM = Fds \qquad \text{(iii)}$$

From standard beam bending theory:

$$d\psi/ds = M/EI \qquad \text{(iv)}$$

Substituting Eq. (iv) into Eq. (i) and dividing by ds gives:

$$dT/ds = -FM/EI - L\cos\gamma \qquad \text{(v)}$$

Substituting into Eq. (ii) and dividing by ds gives:

$$dF/ds = TM/EI - L\sin\gamma \qquad \text{(vi)}$$

The four fundamental equations, (iii), (iv), (v) and (vi) describe the forces and curvature for the unattached part of the tape.

Eliminating L from Eqs (v) and (vi), then rearranging gives:

$$dT/ds = (\cot\gamma\, dF/ds - FM/EI) - (\cot\gamma\, M/EI)T$$

or

$$dT/ds = B(s) - A(s)T \qquad \text{(vii)}$$

Where $A(s)$ and $B(s)$ represent the bracketed functions of s.

Equation (vii) may be solved for T using an integration factor $Z(s)$ where:

$$Z(s) = \exp \int A(s)\, ds \qquad \text{(viii)}$$

Integration then gives:

$$T(s) = \int B(s)Z(s)ds/Z(s) + k/Z(s) \qquad \text{(ix)}$$

To evaluate k, consider the point at which the backing becomes parallel to the substrate, *i.e.* $s = 0$, $\psi = 0$. At this point:

$$Z(s) = \exp \int A(s)ds = \exp \int \cot \gamma \; d\psi/ds = 1$$

Thus Eq. (ix) at $s = 0$ becomes:

$$T(o) = 0/1 + k/1 = k$$

Equation (ix) for positive values of s then becomes:

$$T(s) = T(o)/Z(s) + \int_o^s B(s)Z(s)ds/Z(s) \qquad \text{(x)}$$

Now that $s = \infty$, peel force P will equal $T(\infty)$, so that:

$$P = T(\infty) = T(o)/Z(s) + \int_o^\infty B(s)Z(s)ds/Z(s) \qquad \text{(xi)}$$

Subtraction of Eq. (xi) from Eq. (x):

$$T(s) = \left[T(\infty)Z(\infty) - \int_s^\infty B(s)Z(s)ds \right] / Z(s)$$

$T(s)$ may thus be evaluated by measuring peel force $P(=T(\infty))$ and measuring angles ψ, α, and γ, as a function of s, from the photographs. The filamentation or "leg force" L may then be obtained from use of Eq. (vi).