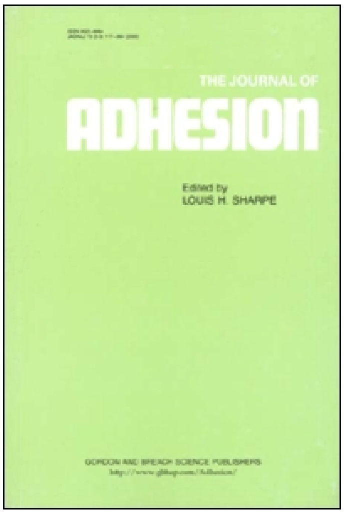

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PEELING SHEAR AND CLEAVAGE FAILURE DUE TO TAPE PRESTRAIN

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In 1960 Kaelble published data for the peeling of several tapes secured by pressure-sensitive adhesives at a range of peeling angles. Several of the cellophane tapes showed a small dropoff or "jog" in the value of the peeling force of approximately 0.1–0.2 lbf when the peel angle was in the range of 20–40 degrees. The jog was associated with a relatively rapid change in decohesion mechanism from one of cleavage to one in which shear played a much larger role, and a similar but much larger effect was noted with metal foil tapes. These observations were in contrast to data presented some months earlier in which no such "jog" had been seen using a similar cellophane tape tested in much the same way. The setup for all of these tests consisted of a stripping wheel to which the tape had been roll-bonded by a wheel of 1/2 inch diameter loaded at an intensity of 6 lbf/inch. Although there have been several attempts to explain the dropoff in peel force, none have been entirely successful so far. An analysis of this effect is presented based on the magnitude of the prestrain in the tape introduced by the roller bonding method of attaching the tape to the stripping wheel. This is consistent both with these observations and some further tests we have ourselves conducted at lower than usual peeling angles.

Keywords: Peel test; Shear failure; Cleavage failure

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INTRODUCTION

The peel test is commonly used to determine the strength of adhesive joints. In its simplest form, a thin flexible strip that has been bonded to a rigid surface is peeled away from the substrate. Peeling may be carried out by applying a constant force and monitoring the rate of tape detachment, although it is more common to remove the strip at a constant rate and measure the peeling force that is applied to the debonding surfaces by the tension in the tape. Such tests are simple to carry out and have the advantage of representing a real mode of failure of adhesive tapes. Despite the fact that tests of this sort have been in use for a number of decades and, indeed, form the basis of a number of national and international test standards, variations in the way the test is carried out can lead to significant variations in the apparent work of detachment. Important experimental factors include the angle at which the adhering tape is detached, the rate at which detachment occurs, the nature (both micro and macro) of the solid surface to which the tape is bonded, the temperature and relative humidity of the environment, and the details of the conditioning process employed as well as the mechanical and physical properties of the tape and the adhesive themselves. The interaction of these variables and the interpretation of the

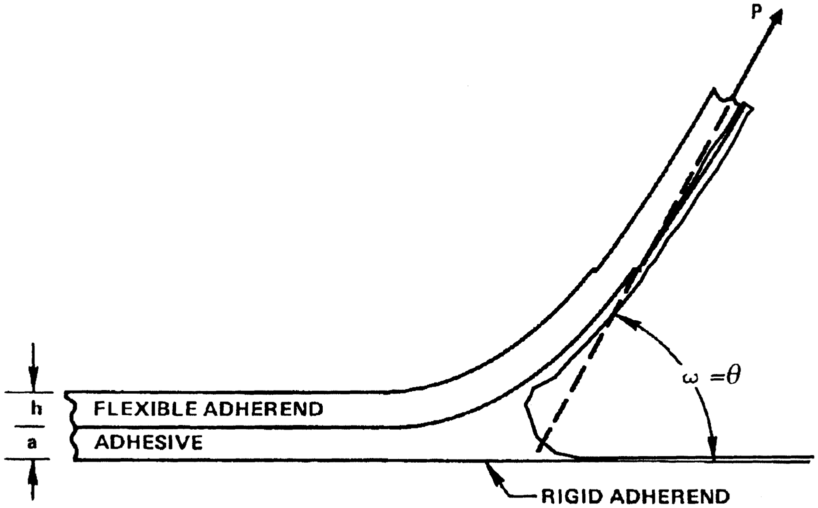


FIGURE 1 A simplified view of a peel test from a plane surface. In the majority of commercial (as opposed to specially generated experimental) flexible tapes the adhesive layer is significantly thinner than the flexible adherend.

experimental data generated are still proving fertile ground for research. However, in this article we wish to examine some features of some early experimental data which, although generated over 40 years ago, still remain somewhat puzzling.

In 1959 Kaelble [1] published peeling data for cellophane/rubber-resin–based adhesive tape detached from a cellophane surface at peeling angles ranging from about 20–170 degrees. The peeling angle, θ, is defined in Figure 1, and in this study the equipment, which is illustrated schematically in Figure 2, made use of a stripping wheel about 150 mm in diameter. The rotational speed of the wheel was geared to that of the cross-head of the tensile testing machine by the tension line in such a way that the peel speed was always the same as the cross-head translation speed: this is in contrast to the more usual arrangement involving stripping the tape from an inclined plane where there is a necessary velocity ratio between v, the peel speed, and v_{ch}, the speed of the cross-head of the machine, as indicated by the inset on

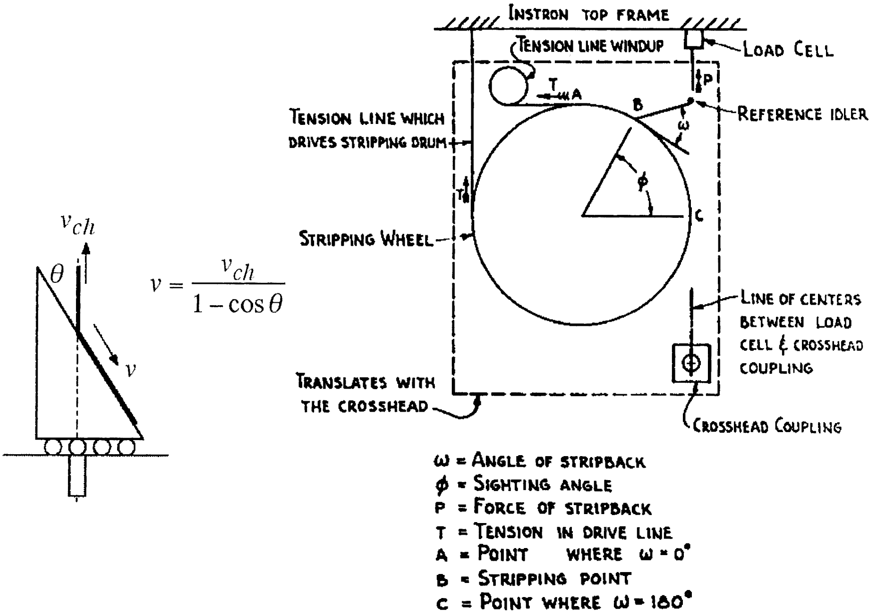
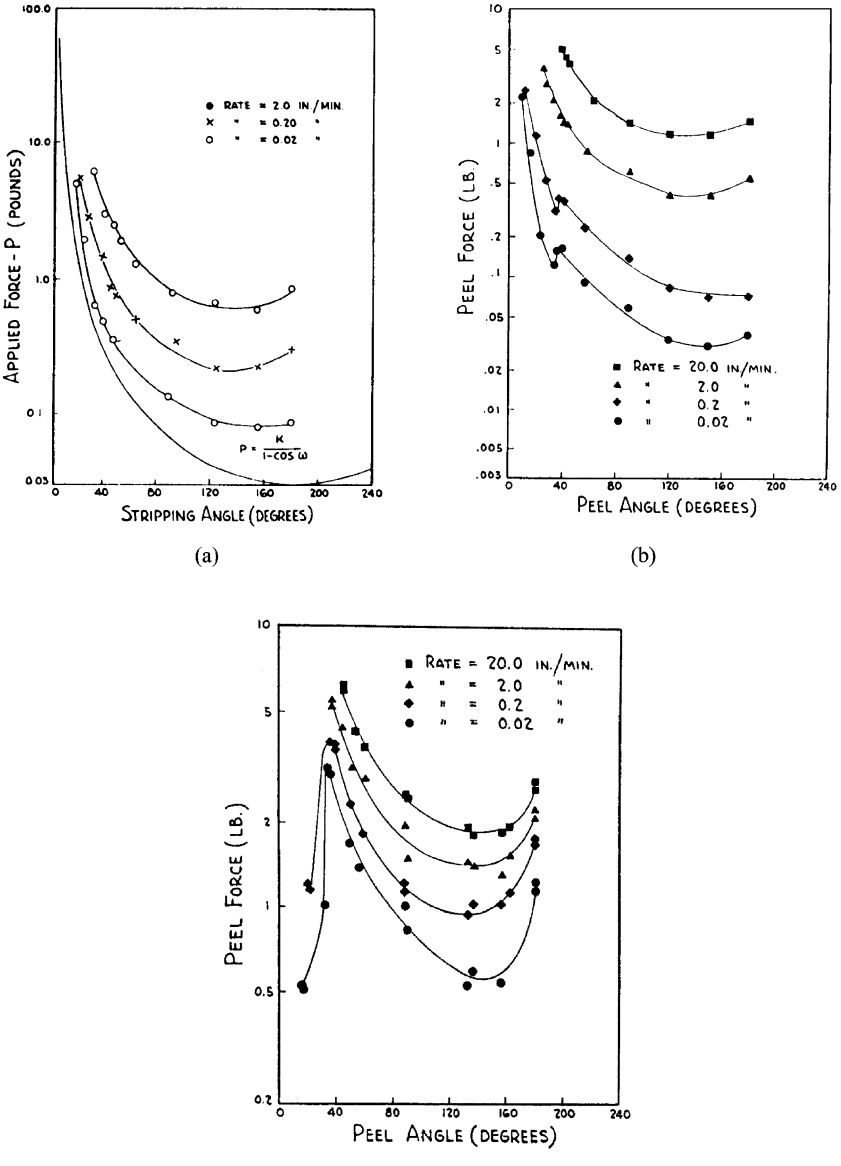


FIGURE 2 Schematic sketch of the "stripback" or peeling device used by Kaelble in the work reported in Refs. [1] and [3]. The inset shows the relation between the peeling speed and the machine cross-head speed in the more conventional inclined plane arrangement (Reproduced with permission of the Society of Rheology).

Figure 2. The results for several tape materials, of which an example is reproduced as Figure 3a, showed characteristic variations of the peel force, P, with peel angle, which are generally in accord with a



(a)

(b)

(c)

relationship of the form

$$\frac{P}{b} = \frac{G}{1 - \cos\theta}, \tag{1}$$

an equation originally due to Rivlin [2], in which G is a quantity that has the dimensions of energy per unit area and b is the width of the tape. It is clear from inspection of these early data that for this material combination the numerical value of G is dependent on the rate at which the tape is peeled (to a first approximation G is proportional to (peel rate)$^{\alpha}$ where α is of the order of 0.5). It is to be expected that this velocity dependence is principally associated with the rheological behaviour of the adhesive rather than the tape. The derivation of Equation (1) idealises the tape as being infinitely stiff in tension yet infinitely flexible when considered as a beam in bending. In reality, of course the tape must possess both longitudinal elasticity—perhaps linear, although not necessarily so—and also some bending stiffness. A more complete analysis that accounts for the first of these is given in Appendix A.

If the tape is linearly elastic with modulus E, then G, the effective fracture or decohesion energy, will be related to the peel force, P, by the equation

$$G = (1 - \cos\theta)\frac{P}{b} + \frac{P^2}{2b^2Eh}, \tag{2}$$

where the tape thickness is h (see Appendix A, Equation (A1) with $F = 0$). If G is known, then this quadratic can be readily solved to provide the numerical value of P.

In the following year, using the same equipment and very similar specimens, Kaelble [3] reported data in which, although the general form of the curves was similar, there was consistently an interesting additional feature, which can be seen in the graphs reproduced in Figure 3b. At low rates of peeling, a significant falloff or "jog" in value

◀———

FIGURE 3 In both cases the thickness of the cellophane tape was 0.0015 in. In (a) the adhesive thickness was 0.001 in and in (b) 0.0018 in. The data in (b) shows the dropoff or jog referred to in the text at peel angles in the range of 35–40°. Although most evident at the slowest peeling speeds, the effect is still there at a speed of 0.2 in/min. The value of the energy factor K (equivalent to G_c in the text) in (a) at a speed of 0.02 in/min is approximately $42\,\mathrm{J\,m^{-2}}$. (c) Peel force versus peel angle for soft aluminium tape. ((a) From Kaelble [1], (b) and (c) From Kaelble [3]; reproduced with permission of the Society of Rheology.)

of the peel force was observed when the peeling angle was in the range of 20–40 degrees. This was followed by a recovery to a curve of the same general form that had been reported in Kaelble [1]. This jog is very obvious in the data acquired at the two lower peeling rates of 0.02 in/min and 0.2 in/min. If the original data are plotted on a linear scale, it is also a clear, though less well pronounced, feature when peeling at 2 in/min. The test conditions and the physical and mechanical data relevant to the tape and the adhesive used in these tests are summarised in Table 1. Examination of the data of Figures 3a and 3b suggests that the energy for decohesion in the tests of Figure 3a—the earlier work—is about twice that of the corresponding tests in Figure 3b. The value of G is consistent with the slowest speed curve in Figure 3a and is approximately 0.24 lbf/in (42 J m^{-2}).

The only apparent substantive difference between the tape in Figure 3b and the tape in Figure 3a was that the adhesive was rather thicker, *viz*. 0.0018 in (37 micron) compared with 0.001 in (25 micron). However, this would not seem to be the crucial difference, as Kaelble also provides in the later paper data for a cellophane tape with a thinner adhesive layer, only 0.0002 in (5 micron) thick, which also show a clear jog at the same two low peeling speeds. In his discussion Kaelble associates this "maxima-minima" in the peel force *versus* peel angle data with a transition from essentially a cleavage mechanism of decohesion, *i.e*., Mode I, to one involving predominantly boundary shear, *i.e*., Mode II. The phenomenon was also observed at low peeling angles and low peeling speeds with a glass cloth tape (Figure 10 in Kaelble [3]), and there was also a very clear maximum (if not a minimum) with a soft aluminium foil tape: these data are shown as Figure 3c.

Kaelble subsequently remarked [4] that all of the data in Kaelble [1] and Kaelble [3] were developed in a single summer, and the data with a peel falloff was obtained concurrently with the rest of the data and was only later separated for independent analysis in Kaelble [3]. In a subsequent analysis of peeling, Mylonas [5] discussed the Kaelble [3] data. He suggested that this apparently anomalous variation of peeling force may be connected with a viscoelastic effect in the rubber-resin adhesive. On the other hand, Christensen *et al*. [6], in experiments involved with the measurement of the peel front of natural rubber-resin pressure-sensitive adhesives, found that deformation of the adhesive is approximated by uniaxial elongation at varying rates. This result suggests that viscoelasticity is not the important variable, at least for adhesives under tests at constant and low peeling rates; indeed, it is difficult to see how adhesive rheology could generate jogs of this sort at values of peeling angle that are substantially insensitive to more than two orders of magnitude of change in the peeling rate.

TABLE 1 Test Conditions and Material Properties of Kaelble [1, 3]

Peeling conditions	Reference	Tape	b	h	I	E	Adhesive a
25°C, ~50% relative humidity, peeling speed 0.02 in/min (0.51 mm/min or 8.5 μms^{-1})	Kaelble [3], Figure 8 (reproduced as Figure 3a here)	Cellophane	0.5 in (12.7 mm)	0.0015 in (38 micron)	1.45×10^{-10} in^4 (60.4×10^{-6} mm^4)	1.64×10^5 psi (1.13 GPa)*	rubber-resin 0.001 in (25 μm)
	Riulin [2], Figure 9 (reproduced as Figure 3b here)	Cellophane	0.5 in (12.7 mm)	0.0015 in (38 micron)	1.45×10^{-10} in^4 (60.4×10^{-6} mm^4)	1.64×10^5 psi (1.13 Gpa)*	rubber-resin 0.0018 in (37 μm)
	Riulin [2] Figure 11 (reproduced as Figure 3c here)	Aluminium	0.5 in (12.7 mm)	0.002 in (51 micron)	3.33×10^{-10} in^4 (139×10^{-6} mm^4)	10×10^6 psi (70 GPa)	rubber-resin 0.0012 in (31 μm)

*We believe this figure to be in error and have used a value of 6.8×10^5 psi (4.69 GPa) as used by Kaelble himself in later publications.

In any discussion of the falloff of peel force over a small angular peeling region at low rates it is necessary to consider the equipment, the operator action, the test conditions, and most importantly why one set of data might differ from another under apparently identical conditions. From that point of view it is instructive to note the differences in the techniques employed in these early investigations from those more commonly adopted in later work. Briefly, they are

1. the rate of peeling when this effect was clear was low—typically an order of magnitude or so lower than for the majority of other later studies (an often-recommended peeling speed is 10 mm/min, about twenty times the rate used in the work discussed here;
2. the substrate from which the tape was peeled was curved rather than plane; and finally
3. the way in which the tape was bonded to the substrate was different in this work from the method used in later studies, or at least in those studies where this has been specified.

It is conventional to identify two potential modes of failure at the interface between a flexible tape and a rigid substrate. Cleavage is driven by stresses that are normal to the interface and is strongly localised to the region where the flexible member becomes detached. Shear failure is driven by shear stresses parallel to the bond and can be distributed over a significant length. Kaelble suggested that cleavage stress and shear stress interacted in some way to cause the unusual falloff in peel force in the region of 20–40 degrees. Civil engineers display such combinations of two or more potential failure mechanisms as "interaction diagrams", but, as Mylonas [5] wrote, "To explain the anomalous behaviour of P by a discontinuous transition from one failure mechanism to another one would have to accept a discontinuous interaction law... *and*... it is doubtful that such 'concave' fracture criteria can be accepted for the failure criteria of elastic materials" (p. 444).

The objective of this contribution is to present a possible explanation of the anomalous peeling effects reported by Kaelble. We suggest that the explanation for the jogs in the published results does not lie with adhesive rheology—although, of course, this is essential in explaining the way in which peel forces over the full range of peel angles increase as the peel rate is changed—but that at least part of the explanation lies in the degree of prestrain developed in the tape when it was applied to the rigid substrate.

THE MECHANICS OF PEEL TESTS

Analytical modelling of the peeling process has a long history, not least because the phenomenon has important industrial and commercial implications. One school of analysis considers in detail the stress field around the point of tape detachment in an analogous fashion to the stresses found adjacent to a crack tip. However, there are difficulties in generating both a physical understanding and a mathematical model of the propagation of a crack through an adhesive layer which bonds two dissimilar materials. It is, therefore, not surprising as Kinloch and Williams have pointed out [7], that most workers have adopted an approach that is based on neither considering the details of the stress distribution at the peel front nor the corresponding stress intensity factors, but that instead employs an energy balance. A particular value, say G_c, is ascribed to the adhesive detachment energy, which is the energy needed to peel unit area of the joint whether this be cohesively through the glue layer or along one of the interfaces. Equation (2), or those derived in a like manner, with G set equal to G_c, can then be used to describe the way in which peel force, P, varies with angle, θ. Implicit in this scheme is the independence of the value of G_c to variables such as the peel angle and the thicknesses of the tape and adhesive. Of course, it has to be recognised that since the value of G_c includes any significant plastic or viscoelastic energy dissipation that occur locally near the crack tip, its value will be both rate, humidity, and temperature dependent. One of the current challenges in the application of the energy argument is to account accurately for any extensive plastic deformation that may occur either in the flexible peel arm or at its “root” where it curls away from the substrate with a typically small radius of curvature [8].

Effects of Plastic Deformation on Peeling Energy

The derivation of Equation (2) (see Appendix A) assumes that the tape deformation is elastic everywhere. Energy might be dissipated in plastic deformation in uniaxial plastic strain within the peel arm or by bending—both perhaps at the small radius within the tape as it curls away from decohesion zone, or by reverse plastic bending within the peel arm. Taking account of the former mechanism converts Equation (2) into a relationship of the form

$$G_c = \frac{P}{b}(1 + \varepsilon - \cos\theta) - h\int_0^{\varepsilon} \sigma \, \mathrm{d}\varepsilon, \qquad (3)$$

where ε is the maximum tensile strain in the tape and the stress/strain characteristic of the tape material is assumed known. When there is energy dissipated in bending as well as in irrecoverable tensile deformation of the peel arm, the effective fracture energy is reduced by a further term, ΔG, thus

$$G_c = \frac{P}{b}(1+\varepsilon-\cos\theta) - h\int_0^{\varepsilon}\sigma\,\mathrm{d}\varepsilon - \Delta G, \tag{4}$$

where ΔG is a complex function of tape properties and process parameters: the nature of this correction term has been discussed by a number of authors and there are both analytic and numerical procedures for its evaluation. Kinloch *et al.* [8] have determined an analytical form of this relation which is also available in a downloadable electronic form [9]. In the case of tapes used in the experimental work considered here, principally because of the low value of the tape thickness, the magnitudes of these modifying terms to the value of G, and hence G_c, established from Equation (2) are small—*i.e.*, generally much less than 10%.

Bending Prestrain

An additional source of stored elastic energy, available to drive debonding of the tape, is that stored within the tape due to its bending during placement on the stripping wheel. Following a similar energy analysis to that of Appendix I, taking into account the change of elastic energy due to bending to radius ρ of the stripping wheel, in the absence of plastic dissipative terms, G_c will be given by

$$G_c = \frac{P}{b}(1+\varepsilon-\cos\theta) + \frac{h^3E}{8\rho^2}. \tag{5}$$

Application of this equation to the peeling of the cellophane tape used by Kaelble shows a negligible effect for bending of the tape on the stripping wheel; this well be true for any tape material (*i.e.*, condition where h is small) and any sensibly curved surface since then $h/\rho \ll \sqrt{E}$.

CLEAVAGE AND SHEAR FAILURE MODES

The energy arguments described above distinguish only between a cleavage failure and shear failure at the point of decohesion through the numerical values of the corresponding energy terms conventionally designated G_{Ic} and G_{IIc}. At any given peel angle the favoured mode of failure will be that which requires the least input of energy from the external agent, *i.e.*, the lowest value of peeling force P which, in general, will correspond to the lower value of the energy terms. For *isotropic* bulk materials Mode I is invariably the lower energy fracture mode, *i.e.*, $G_{Ic} < G_{IIc}$. However, the tape peeling process is not one involving an isotropic body but a rather complex layered structure. In the geometry of Figure 1 crack propagation is constrained to the adhesive layer or one of the interfaces, and thus when considering potential failure modes attention should be given both to the possibility that in these rather special circumstances $G_{IIc} < G_{Ic}$ or that mixed mode fracture occurs with $G_{I/IIc} < G_{Ic}$. In either case, peeling with an element of shear would be energetically preferred.

When peeling an essentially transparent adherend at these very low speeds the process zone immediately ahead of the peel front can be readily observed, as it appears “frosted” and opaque in comparison with the greater part of the adhered tape. Even with the naked eye a difference in its extent can be seen as the peel angle is decreased. At larger angles the process zone is short, perhaps only a small fraction of a millimetre, while at low peel angles this zone is significantly extended. The direct observation that at low peel angles there can be decohesion either entirely or, at least, partially by shear suggests that in these circumstances $G_{I/IIc} < G_{Ic}$. However, it is equally true that at high peel angles shear is *not* the preferred mode but that then decohesion is by cleavage. To understand what might contribute to this switch in mechanism it is useful to consider in a little more detail the conditions that might be thought necessary to initiate tape decohesion by shear. The force P in the tape can be resolved into its normal and tangential components, *i.e.*, $P\sin\theta$ and $P\cos\theta$: if now we suppose that the in-plane component of the tape tension must reach some threshold value characteristic of the tape, the adhesive, and the ambient conditions for the shear mode to be initiated, then this is equivalent to imposing the condition that, for decohesion to move from cleavage to shearing,

$$P \geq \frac{\text{constant}\ \mathrm{C}_1}{\cos\theta}. \tag{6}$$

Once this condition has been met, by virtue of the reduction in the value of the peel angle, the adherend can become detached from the substrate by either an essentially shear failure in the adhesive or, perhaps more realistically, an effectively mixed mode process with graduations of components of Mode I and Mode II, until the operating

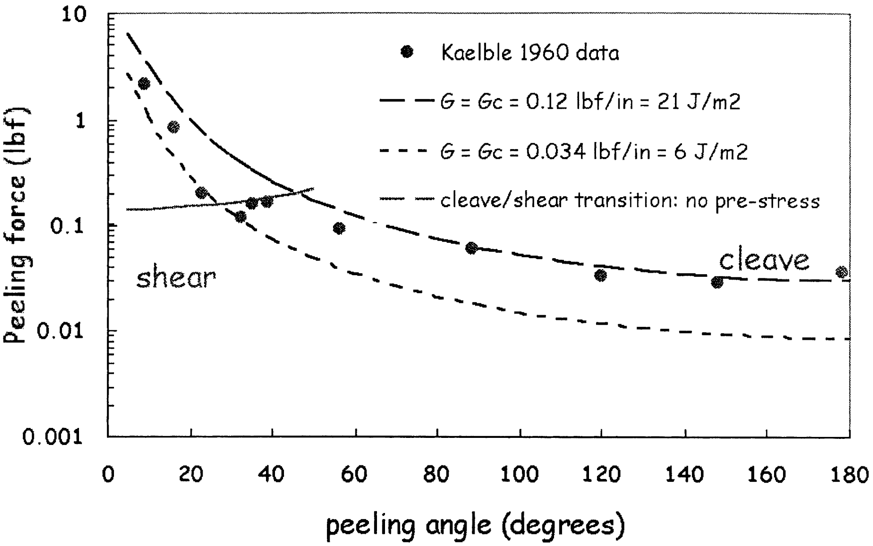


FIGURE 4 Transition from Mode I cleaving failure to Mode II decohesion by shear. The data points are those shown in Figure 3b. To fit the curves shown, the value of G_c has been taken as 0.12 lbf/in or 21 J m^{-2} for cleaving failure and 0.034 lbf/in (6 J m^{-2}) for shear. The transition from one mode to the other occurs as indicated as the peel angle changes from 40° to 30°.

point of the process has become established as one of almost pure shear. Now, the relationship between peel force and peel angle will resume the form of Equations (2) or (3), but with the value of G_c associated with shearing, *i.e.*, G_{IIc}, which numerically lower than G_{Ic}. Figure 4 shows the data from Kaelble's later work, *i.e.*, those of Figure 3b, but with the curves for Equations (2) superimposed with values of G_c equal to 0.12 lbf/in (21 J m^{-2} and 0.034 lbf/in (6 J m^{-2}) and (6) with the constant set at 0.14 lbf (0.61 N), a value that has been chosen to coincide with the discontinuity in the experimental data set.

Effects of Tensile Prestrain

One of the important experimental conditions concerns the way in which the tape is stuck to the substrate. This is now specified in the appropriate standards although this differs somewhat from one national set to another. (see Appendix B). Consider now the effect of a tensile prestrain equivalent to a force, F, applied to the tape as it is effectively placed on the substrate surface. The form of Equation (2) will be modified, becoming (see Appendix A)

$$G = \frac{P}{b}(1 - \cos\theta) + \frac{(P - F)^2}{2b^2Eh}. \tag{7}$$

This prestrain in the tape can also have an effect on the subsequent transition from peeling by cleaving to decohesion by shear. If, as a result of the conditioning process, the tape is left with such a residual tensile strain, then it follows that within the adhesive layer near its ends there must be a shear stress distribution whose total summation value is just sufficient to equilibrate the residual tension, F. This local residual load must be overcome by the appropriate component of the applied force, *i.e.*, $P\cos\theta$, before the tape can be released by shear. This means that the condition for the operating point to move from the higher energy cleaving curve to the lower energy shearing curve, while still being given by an equation of the form of Equation (6), will now have the constant C_1 increased in numerical value to, say, C_2. It is not straightforward to determine how the increase in the constant, *i.e.*, the quantity $(C_2 - C_1)$, is related to F, as this would need a knowledge of the detailed distribution of the shear stress, but for simplicity we might write that shear failure requires that

$$\frac{C_1}{\cos\theta} < P \leq \frac{C_1 + F}{\cos\theta}. \tag{8}$$

DISCUSSION AND ADDITIONAL EXPERIMENTS

The interpretation of the experimental results of Kaelble in 1959 and 1960 [1, 3] that we present here suggest that for some flexible tape/adhesive combinations the decohesion energy by shear in essentially either a Mode II or mixed Mode failure is less than that by cleaving in Mode I. However, shear failure is only initiated at very low peel angles because a necessary condition for it to occur is that the component of the tape tension acting in the direction of the adhered tape exceeds some characteristic value. If the process of attachment leaves the tape in a state of residual tension then, other things being equal, the transition from cleaving to shear is delayed until smaller peel angles than would be the case in a stress-free tape. This phenomenon has not often been observed because the necessary angle is outside the range of those that are usually investigated—the standard recommended protocol suggests peel angles of between 60° and 180°. However, in the bulk $G_I < G_{II}$ the situation in an adhesive or peeling joint is complex: a Kinloch [10] alludes to the experimental observations of Bascom *et al.* [11, 12] who found (albeit in angled scarf joint tests) that the fracture energy for a mixedmode failure, $G_{Ic/IIc}$, could be less than either G_{Ic} or G_{IIc} individually. In their analysis, which was based on a finite element (FE) simulation, Crocombe and Adams [13] considered the case of mode mixity, although their model is limited by their assumption that both transverse and shear stresses within the decohesion zone have distributions of the same form. In the case of a flexible adherend attached by a pressure-sensitive adhesive (PSA), the value of G_{Ic} will contain within it the potentially significant contribution of the energy absorbed by the formation, extension, and collapse of local fibrils of adhesive generated as part of the essentially tensile decohesion process.

We have carried out some simple tests to attempt to validate some of these ideas. Regrettably, we do not have available the same equipment or the same tapes that were used by Kaelble in his original work but have rather used a rig of what has come to be established as a more conventional design, which is illustrated by the inset in Figure 2. The flexible tape adheres to a substrate consisting of a 3 mm thick plate of stainless steel of the sort specified in ASTM 1000; this is clamped to a set of angled blocks that can be bolted together to change the peeling angle in steps of 5°. The assembly of blocks is supported by a low friction linear bearing which is mounted horizontally on the lower platen of a small tensile testing machine. The free end of the tape is gripped, *via* a swivel joint, in the cross-head of the machine, which also carries the load cell. The speed of the cross-head can be varied continuously from a lower limit of less than 0.5 mm/min (0.02 in/min).

Figure 5 shows the variation of peeling force with peel anlge for samples of a commercial cellulose acetate tape (3M No. 810 Scotch® Magic, 3M, St. Paul, MN, USA) peeled at a cross-head speed of 0.5 mm/min. Although this does not represent a constant peel speed (as discussed above), subsidiary experiments have shown that, at least at these low peeling speeds, the acrylic adhesive on this tape has a very low rate sensitivity. In particular, when expressed as a simple power law from a log/log plot of decohesion energy *versus* peel speed the index is close to 0.07. The tape was attached to the stainless substrate using the procedure recommended in ASTM D1000 which will generate a minimal prestrain or preload in the tape as illustrated in Figure 6a. The dotted curves are obtained from Equation (2) using measured values of tape modulus and fitted values of G_c, *viz.* 90 J m^{-2} and 50 J m^{-2}. At values of peel angle close to 90° the data lie on the higher energy curve, while at low angles it is a much better fit to

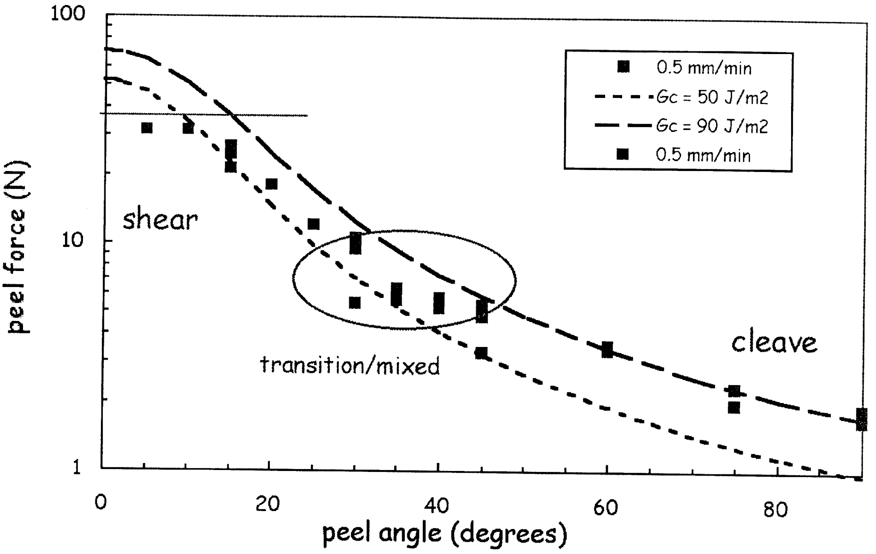


FIGURE 5 Peel tests from a polished stainless steel surface using a proprietary cellophane tape with pressure-sensitive acrylic adhesive. At angles close to 90° decohesion is by cleavage, while at angles below 30° the mechanism is dominated by shear. The transition occurs over a range of peel angles initiating at about 45°. The breaking strength of the tape is ca. 37 N.

the curve for 50 J m^{-2}. The transition from one to the other initiates a peel angle of about 45° and is complete by about 30°. The maximum tension that this tape, which is 19 mm in width, can sustain is about 37 N. Figure 7 shows corresponding data for a series of peel tests using tape from the same batch, off the same steel surface, but which was placed in contact with the substrate and rolled in accordance with the ASTM standard while loaded in tension. This tension was achieved by stretching the tape in a small specially constructed jig that imposed a prestrain of between 2 and 3% before attachment to the steel substrate. This strain corresponds to a load, F, of approximately 30 N. The dotted curves superposed in Figure 7 are obtained from Equation (7); once again there is a move from a higher energy curve, with G_c equal to 85 J m^{-2}, to one of 50 J m^{-2}, but now this transition is delayed until a significantly smaller peel angle and extends over a smaller angular range—it is much more like the jog evident in Kaelble [3].

We are now in a position to return to the data of Figures 3a and 3b—or at least those results obtained at the slowest peeling rate. The immediate question is, why should there have been in these

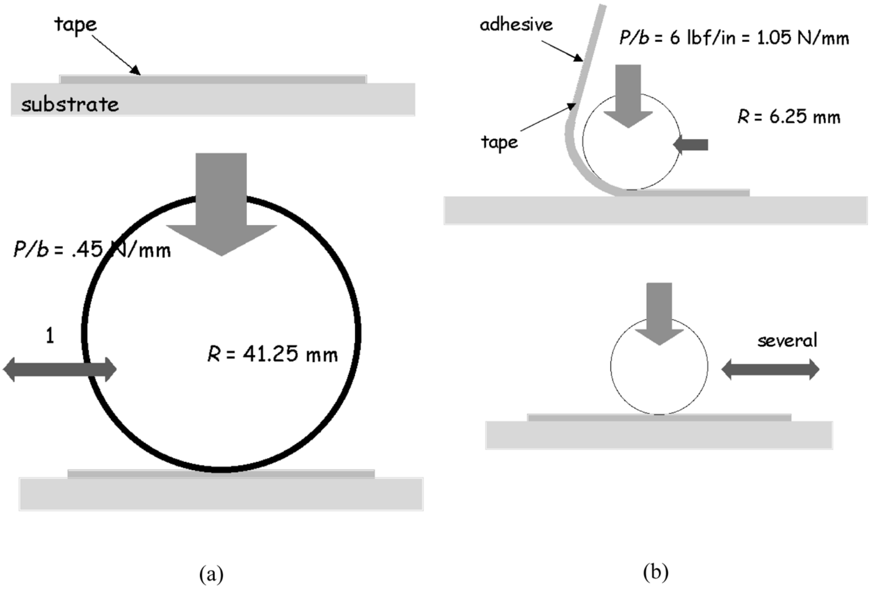


FIGURE 6 (a) Current standards require the tape to be fixed to the substrate with negligible pretension and then rolled by comparatively large roller for a single pass. (b) In the tests described in Kaelble [3] and Mylonds [5] the tape was roller bonded to the substrate by a much smaller, more intensely loaded roller; this procedure will generate an increased residual prestrain in the tape.

experiments a pretension within the tape sufficient to inhibit the energetically favourable change, *via* mixed modality, from decohesion by cleavage to loss of contact dominated by shear? We suggest that the explanation lies in the details of the process of attachment that was used which, by virtue of both the intensity of the loading and the small radius of the roller, was much more severe than has now become conventional. This is illustrated in Figure 8; current practice is to form the bond between the tape and the surface with minimal tension imposed on the tape. Once this has been done the tape is rolled no more than twice with a rubber-tired roller of relatively large diameter and modest load intensity, *viz.* 41.25 mm radius and 0.45 N/mm. In the early experimental work the tape was applied to the surface by a much smaller radius (6.25 mm) bonding roller under a higher specific loading of 12 lbf/in equivalent to 1.05 N/mm. This procedure will introduce significantly enhanced levels of prestrain and so will inhibit the transfer from cleavage to shear failure as the peel angle is reduced. We suggest that this is what is happening in Figure 3a;

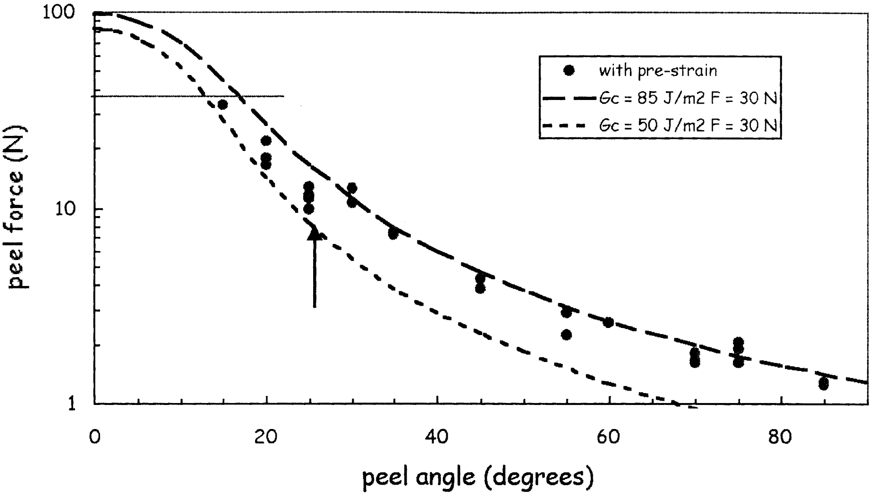


FIGURE 7 Peel tests on a cellophane tape that has been prestrained by about 2.5% before attachment to the stainless steel substrate. The transition from decohesion by cleavage, or Mode I, to a mechanism involving a much greater contribution of shear, or Mode II, now occurs over a narrower band of angles and is delayed until a peel angle of less than 30° as indicated.

cleavage failure is essentially maintained down to the smallest angle that was investigated. However, in the data displayed in Figure 3b the transition is seen within the range of peel angles explored. In a sense this is the more "normal" situation and this change in mode of decohesion was seen in the majority of cases that were tested. We can only surmise that for one reason or another the specimens of Figure 3a carried a particularly high level of residual stress. This jog or "maxima or minimum" requires that the fracture energy for a Mode II (or a mixed Mode I/Mode II mechanism) is less than simple Mode I, *i.e.*, that G_{IIc} or $G_{I/IIc} < G_{Ic}$ and that the testing is carried to very low peel angles—probably less than 30° and at a sufficiently low speed to prevent the effect being swamped by a rate-dependent viscous mechanism. The speeds employed here are several orders of magnitude smaller than those at which a fall in peel force has been observed associated with a glass transition phase change in the adhesive [14].

Figure 7 shows the data from this earlier work of Figure 3a, but with the dotted curve for Equation (7) superimposed with values of G_c equal to 0.24 lbf/in (42 J m^{-2}) and a preload equivalent to a force of about 4 lbf (18.6 N) supposed generated by the way in which the tape was attached to the substrate; this is equivalent to a strain of

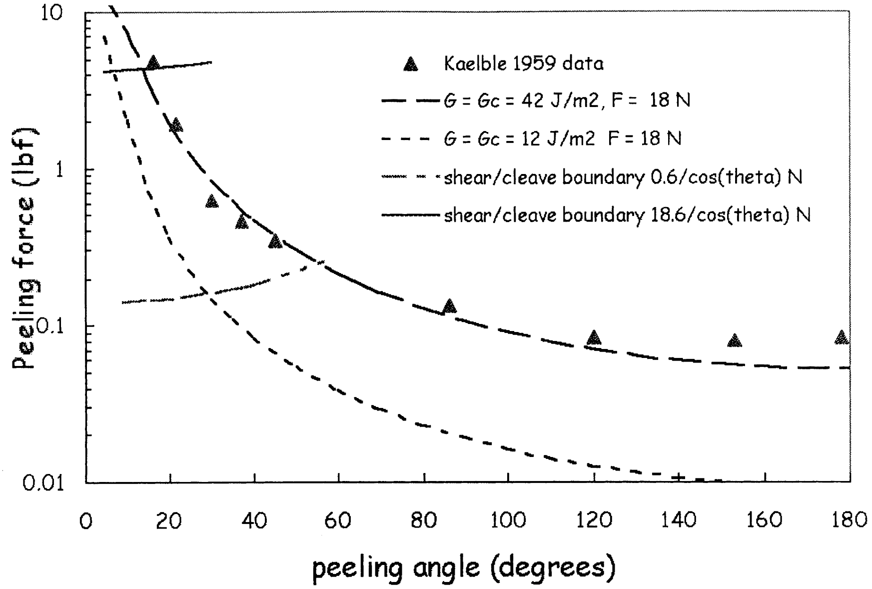


FIGURE 8 Effect on peeling by prestretching the tape. The data points are those shown in Figure 3a. To fit the curves shown, the value of G_c has been taken as 0.24 lbf/in or 42 J m^{-2}, and the pretension in the tape F set at 4 lbf (18.6 N). The effect of this preload is to move the angle at which the transition from cleaving, or Mode I, to shearing occurs to very small peel angles.

approximately 0.8%. The major effect that this has is to postpone any transition from decohesion by a mechanism of essentially cleavage or Mode I failure to one involving some significant element of Mode II shearing to much lower peel angles as indicated by the curves derived from Equation (8). With this high level, *i.e.*, 4 lbf, of preload the transition would not have been seen by Kaelble at peel angles of 20° or more. In Appendix B we suggest an approximate analysis from which the level of preload for a given conditioning procedure can be estimated: this suggests that the method used by Kaelble, illustrated in Figure 6b, would normally generate a residual load in the tape of approximately 7.3 N (*ca.* 1.6 lbf) rather than the 18 N level shown in Figure 7. Under normal circumstances we would not expect this to be sufficient to suppress the transition from cleaving to shearing at angles within the range investigated, hence our feeling that it is the data of Figure 3a that is out of the ordinary rather than that of Figures 3b and 3c.

The mechanism suggested here requires that the energy for decohesion involving significant shear of the adhesive bond should be less

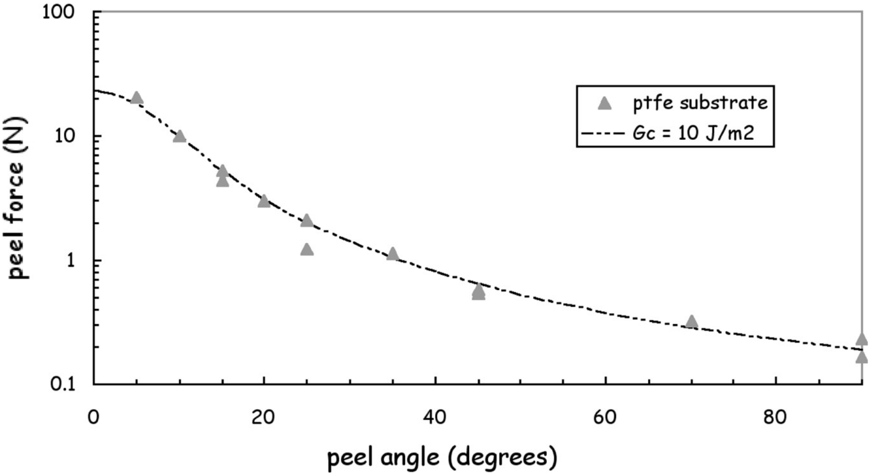


FIGURE 9 When peeling from a much lower energy surface, decohesion by cleaving or Mode I can be maintained over the full range of peeling angles from 90° to 5°. Experimental tape is identical to that used in obtaining the data of Figs. 5 and 7.

than that required for tensile cleaving. If this is not the case there will be no energetic argument for the transition from one mechanism to the other. The tape used in our additional experiments adheres, albeit with reduced tenacity, to a PTFE or Teflon® surface when attached using the same procedure as used for the data of Figures 5 and 7. The experimental results for subsequent peeling are displayed in Figure 9: they generate a good fit to the curve of Equation (2) with a value of G_c equal to $10\,\mathrm{J\,m^{-2}}$. In this case there is no visible change in mechanism with decreasing peel angle, the mechanism of decohesion remaining essentially cleaving/Mode I failure all the way from 90° to 5°

CONCLUSIONS

On the basis of a re-examination of some of the early work on tape stripping, as well as some additional experiments of our own, we conclude that when peeling a flexible tape from a solid surface there can be a transition from a mechanism of decohesion relying on cleavage or Mode I failure to one with a much greater component of shear. This change in mechanism requires that the specific energy for decohesion involving shear is less than that for decohesion by cleavage. This switch in mechanism is apparent only at low peeling angles, typically less than 40°, when the component of the applied tape tension acting parallel to the adhesive interface reaches some critical value. This critical value of peel force is influenced by the residual stress generated within the tape by the process of attachment to the rigid substrate. Increasing the pre-strain has the effect of moving the transition to lower numerical values of the peel angle and reducing the range of angles over which it occurs, leading to an apparent jog or discontinuity in the data. If the tape is attached to the substrate in such a way as to be left with a sufficiently large tensile strain, then this jog may be effectively suppressed as it moves outside the experimental range of peel angles conventionally explored.

NOTATION

a	adhesive thickness
A	area of contact of tape
b	tape width
E	tape modulus
F	preload force within tape
h	tape thickness
I	second moment of area
L	length
P	peeling force
P_R	rolling force in tape application
R	roller radius
U	elastic energy
x, y	coordinates
v	peel speed
v_{ch}	cross-head speed
V	volume
ε	tensile strain
θ	peeling angle
ν	Poisson's ratio
ρ	radius of curvature of stripping wheel
σ	tensile stress
G	peeling energy
G_c	decohesion energy at failure

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APPENDIX A: PEELING TAPE FROM A PLANE SURFACE

The length $\mathrm{d}L_0$ is detached from the surface by the tape tension of magnitude P applied to the tape of width b. The peeling angle is of magnitude θ, as illustrated in Figure A1. A point on the tape originally at A_1 moves to position A_2 so that the work done by the force $\boldsymbol{P}$, *i.e.*, the drop in its potential energy, $\mathrm{d}U_p$ is $\boldsymbol{P}.\ \mathbf{A}_1\mathbf{A}_2$. We suppose that the tape was attached to the surface with built-in strain, ε_1, while in the free arm the strain is ε_2. In reality there are complex geometric and stress conditions around the point of detachment, but to a first approximation we can consider the tape to have an axial stiffness related to its Young's modulus, E, but to be infinitely flexible in bending. Within the incremental volume of tape, $\mathrm{d}V$, represented by the length, $\mathrm{d}L_0$, or contact area, $\mathrm{d}A$, the incremental

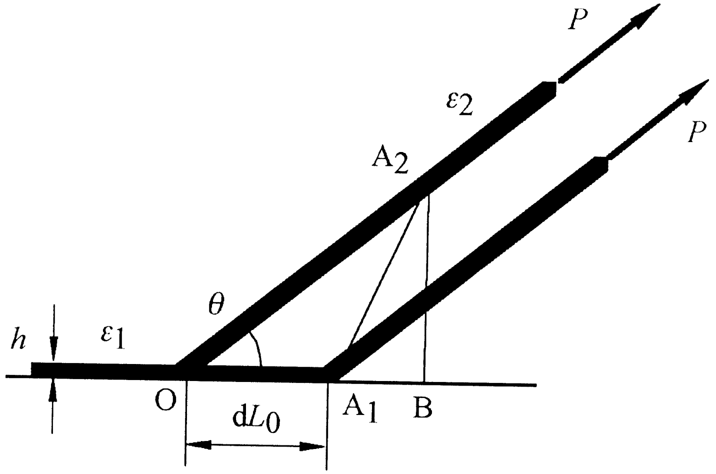

FIGURE A1 A simplified view of peeling tape from a plane surface. The length dL_0 is detached from the surface by the tape tension of magnitude P applied to the tape of width b. The peeling angle is of magnitude θ. A point on the tape originally at A_1 moves to position A2 so that the work done by the force $\boldsymbol{P}$ is $\boldsymbol{P}.A_1A_2$. The tape was attached to the surface with built-in strain ε_1 while in the free arm the strain is ε_2. In reality there are complex geometric and stress conditions around the point of detachment.

stored elastic energy will be

$$dU_{E1} = \frac{1}{2}E\varepsilon_1^2 dV = \frac{F^2}{2b^2Eh}dA,$$

where F is the effective "preload" that generates the tensile strain ε_1 in the tape. In the final position after detachment, this same volume of tape has elastic energy

$$dU_{E2} = \frac{P^2}{2b^2Eh}dA,$$

but $dU_p = \boldsymbol{P}.\mathbf{A_1A_2} = P\cos\theta(\mathrm{OB} - \mathrm{OA_1}) + P\sin\theta A_2B$ and $\mathrm{OB} = \mathrm{OA_2}\cos\theta$, thus $dU_p = POA_2 - Pcos\theta \mathrm{O}A_1$.

Since $OA_1 = dL_0, OA_2 = (1-\varepsilon_1)(1+\varepsilon_2)dL_0$, and $dL_0 = dA/b$, it follows, provided that $\varepsilon_1\varepsilon_2 \ll 1$, that

$$dU_p = \frac{P}{b}(1-\cos\theta)dA + \frac{P(P-F)}{b^2Eh}dA.$$

Thus the energy released per unit area, G, in going from the initial to the final position is given by

$$G = \frac{\mathrm{d}U_p}{\mathrm{d}A} - \frac{\mathrm{d}U_{E1} + \mathrm{d}U_{E2}}{\mathrm{d}A} = \frac{\mathrm{P}}{b}(1-\cos\theta) + \frac{(P-F)^2}{2b^2Eh}. \qquad \text{(A1)}$$

If G is equal to G_c, the critical value that will allow decohesion of the tape to proceed, the associated critical value of the peeling force, P, can be found by solving the quadratic, so that

$$\frac{P}{bEh} = \frac{F}{bEh} - (1-\cos\theta) + \sqrt{(1-\cos\theta)^2 + \frac{2G_c}{Eh} - \frac{2F}{bEh}(1-\cos\theta)}. \qquad \text{(A2)}$$

We claim no originality for this formulation; Equation (A2) follows closely Equation (5.108) in Maugis [15]. We include it for the assistance of those unfamiliar with the peeling problem.

APPENDIX B: PRESTRAIN INDUCED BY ROLL BONDING

Standard test methods, for example, ASTM D1000 and BS EN1939 (1997) for pressure-sensitive adhesive-coated tapes, provide guidance for the way in which the bond of the tape to the substrate should be made. This is characteristically by passing a roller of a prescribed diameter carrying a specified radial load over the tape at a recommended speed and for a specified number of passes. British Standard EN1939 (1996) requires that the tape is applied to a stainless steel surface initially polished to a mirror finish then abraded longtitudinally to give no scratches more than 4 microns in depth and a transverse roughness of between 0.05 and 0.4 microns; it is then conditioned by being rolled by a metal roller of diameter at least 50 mm and mass corresponding to a load intensity of 2 kgf/cm, *i.e.*, 1.96 N/mm. ASTM D1000, on the other hand, while specifying a similar stainless steel substrate, requires conditioning by a rubber-covered roller (Durometer hardness 80) of diameter 3.25 in (82.6 mm) and of a specified mass. The load intensity is not set as such and could be as low as 2.6 lbf/in (*i.e.*, 0.45 N/mm or 0.46 kgf/cm).

Some of the early work investigating the mechanics of adhesion was carried out with bonding conditions different from either of these standard procedures; for example, the adhesive bonds discussed in this article and presented by Kaelble [1, 3] were produced by roll bonding with a much smaller diameter steel roller, *viz.* 0.5 in, with a load of approximately 6 lbf per inch.

To estimate the residual strain the roll bonding process (illustrated in Figure 6b) leaves in the tape; consider Figure A2, which is highly schematic in that whether the roller is of diameter 0.5 in or 3.25 in it is very much greater than the thickness of the tape, h. As the roll moves forward so the tape is compressed—and if, as is universally the case, the tape width, b, is very much greater than thickness, h—then conditions are effectively plane strain. In addition, if the material of the tape is incompressible, so that $\nu = 0.5$, then compressive strains in the through thickness direction must produce tensile longitudinal strains of the same magnitude. The role of the adhesive in retarding the axial displacement of the tape relative to the substrate is tricky to model; at one extreme this effect could be neglected, so modeling the interface between the tape and the substrate as a frictionless boundary: the other extreme would be to consider them rigidly bonded together, in which case the extension induced in the tape by rolling will be negligible. A simple experiments is instructive: a 100 mm

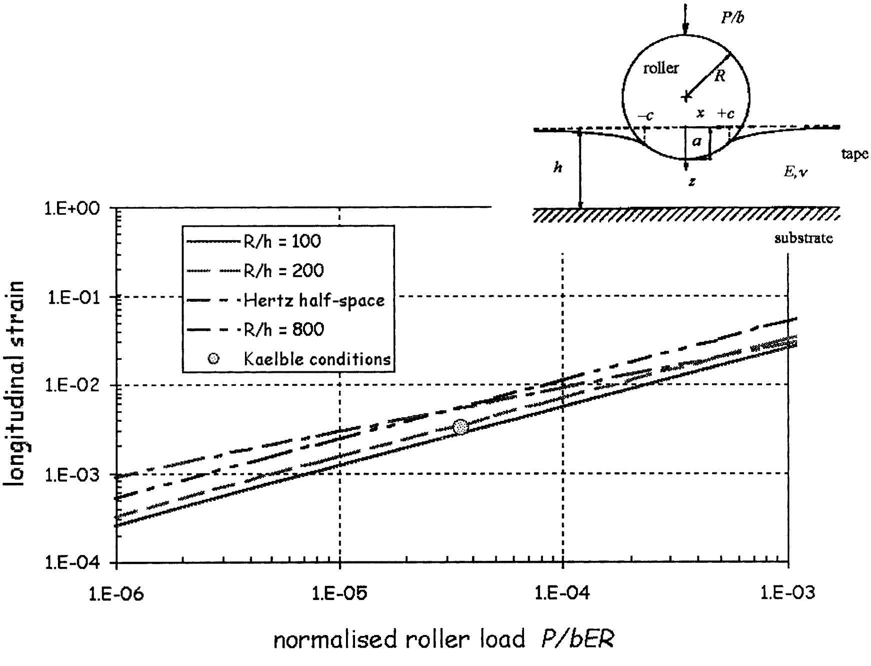

FIGURE A2 Longitudinal strain introduced into the elastic tape by the roll-bonding process, illustrated in the insert, as measured by the normalized roller load. For the conditions in Kaelble [3] the normalized roller load is approximately 3.5×10^{-5}, as indicated.

length of vinyl electrical tape (to BS60454) was roller bonded onto a Perspex® surface using a roller with a diameter of 0.5 in. The observed extension of the tape was on the order of 5 or 6%. The adhesive from a similar length of tape was then removed by washing with an appropriate solvent and the experiment repeated with a very similar quantitative result; the observable extension of the tape was only marginally greater. This observation suggests that in the roll-bonding arrangement used in the early peeling experiments discussed here the rolling conditions can be most appropriately modeled by assuming that the tape in advance of the bonding roller can extend freely over the substrate surface as a result of the imposed compression in the zone immediately beneath the roll.

The problem of an elastic layer compressed between a cylindrical roller and a rigid substrate and against which the layer can either freely or not at all has been considered by a number of authors [16, 17], and these are discussed in Johnson [18]. For the case when the elastic layer is thin (*i.e.,* $h \ll a$ in Figure A2) the results of the numerical analysis by Ablas and Kuipers [17] are relevant, although the analytic argument presented by Johnson [18] can be followed. If conditions are assumed to be plane strain, and setting $\sigma_{xx} = 0$, we may write

$$\begin{aligned} Eex_{xx} &= -v\sigma_{yy} - v\sigma(z) \\ 0 &= \sigma_{yy} - v\sigma(z) \\ E\varepsilon_{zz} &= \sigma(z) = v\sigma_{yy}, \end{aligned}$$

but $\varepsilon_{zz} = -\frac{1}{h}\left[\delta - \frac{x^2}{2R}\right]$ and thus, since $\sigma(z) = 0$ at $x = \pm a$,

$$\sigma(z) = -\frac{E}{1-v^2}\frac{a^2}{2Rh}\left(1 - \frac{x^2}{a^2}\right).$$

Load per unit lenth $P_R/b = \int_{-a}^{a} p(z)dx$, hence

$$a^3 = \frac{3}{2}\frac{1-v^2}{E}RhP_R/b.$$

If the tape material is incompressible so that $v = 0.5$, it follows that $\varepsilon_{xx} = -\varepsilon_{zz}$.

When $x = 0$ the longitudinal strain can then be evaluated as

$$\varepsilon_{xx} = 0.541\left(\frac{P_R}{bER}\right)^{2/3}\left(\frac{R}{h}\right)^{1/3}.$$

This agrees well with the numerical results of Alblas and Kuipers [16]. For practical tapes and rollers the first of these nondimensional groups, *i.e.*, P_R/bER, is likely to be less than 0.01 and the second, R/h, at least 50 or more. Figure A2 shows the effect that rolling might be expected to have on the development of residual strains within the tape for this range. Shown for comparison is the surface strain in a Hertzian line contact on an incompressible half space. In the case of a tape of width 0.5 in and thickness 0.0015 in of modulus 6.8×10^5 psi, rolled with a roller of radius 0.25 in with a loading of 6 lbf/in, $\varepsilon_{xx} = 0.32\%$, and the effective preload tension is 1.63 lbf or 7.3 N.