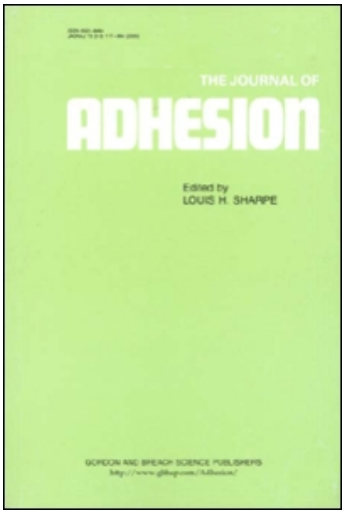


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# Theory and Analysis of Peel Adhesion: Adhesive Thickness Effects

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# Theory and Analysis of Peel Adhesion: Adhesive Thickness Effects

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The existing assumptions concerning boundary stress concentrations in peel adhesion are extended to treat the effects of adhesive thickness. In adhesive bonds involving the all-angle peeling of a flexible elastic adherend from a rigid substrate the varying of adhesive thickness is shown theoretically to predict a proportional increase of peel force (P) with adhesive interlayer thickness (a) when the product ($\beta Ca$) of the cleavage stress concentration $\beta$, cavitation scale factor C, and adhesive thickness a is less than unity. When the product ($\beta Ca$) becomes greater than unity the new theory predicts that cleavage stresses concentrate within a fractional layer of the total adhesive thickness f(a) and the peel force P tends to achieve a constant value $P_{max}$. This new theory is verified by experimental studies and the experimental analysis suggests new optimizations in the design and measurement of the peel adhesive bond.



## INTRODUCTION

An analysis of the mechanics and internal stress distributions of peeling a flexible adherend from a rigid substrate over a spectrum of peel angles ranging from simple shear, peel angle $\omega = 0$, to high angle peel back with peel angle $\omega = \pi$ rad $= 180$ degrees has been developed by Kaelble[1,2] and extensively reviewed in the literature.[3–6] More recently this theory has been extended to formally analyze the rate-temperature dependance of viscoelastic interlayers[7,8] and to directly analyze the micro-mechanics of peeling.[9–11] The present theory of peel predicts, at constant peel rate and temperature, that the peel force (P) is proportional to the adhesive interlayer thickness (a).

Several well controlled experimental studies of peel adhesion by Gardon[12] and Johnston[13] show that, at constant peel rate and temperature, the peel force (P) is proportional to thickness (a) for a range of adhesive thickness typical of commercial pressure sensitive tape constructions where $a \leq 0.0025$ cm. However, when the adhesive thickness is further increased the curve of peel force (P) versus (a) is shown to plateau and display nearly constant values of (P) which are nearly independent of adhesive thickness. The objective of this paper is to extend the theory and analysis of peel to provide a more general analysis of adhesive thickness effects.

## THEORY

The peel mechanics model developed by Kaelble[1,2] is schematically represented in Figure 1. The upper view of Figure 1 shows the side view of an elastic flexible member of thickness (2h) and a viscoelastic adhesive layer of thickness (a) bonded to a rigid adherend. The cleavage (Mode I) and shear (Mode II) stress distributions at the bond boundary are shown in the lower left views of Figure 1. The cleavage stresses are zero for positive (X) and display a highly attenuated response with alternating regions of tension and compression interior from the bond boundary.

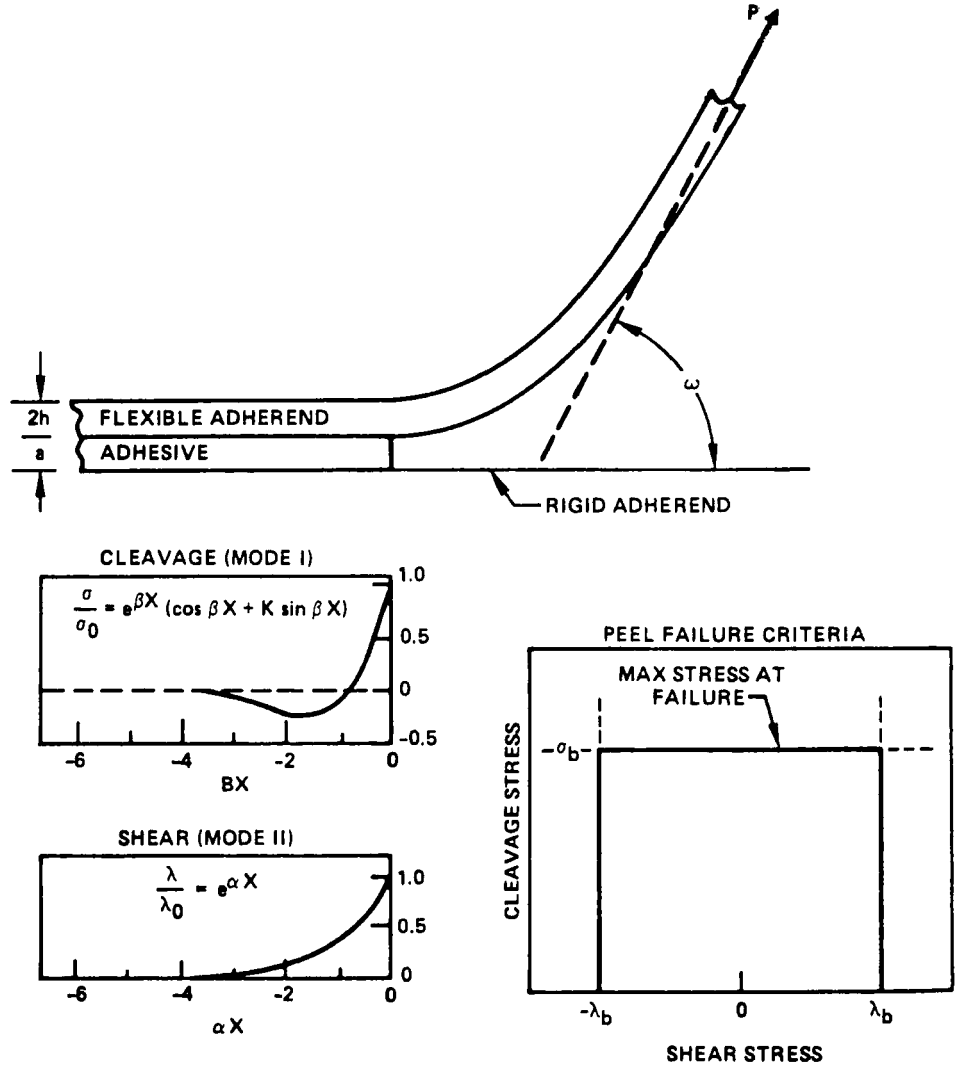


FIGURE 1 Peel mechanics (upper & left views) and failure criteria (lower right view).

The shear stress distribution is a simple exponential decay with monotonically decreasing shear stress as distance increases into the bond interior from the boundary. The predicted forms for these cleavage and shear stress distributions are confirmed by direct stress analysis of pressure sensitive tapes.[11] The failure criteria for this peel model is shown in the lower right portion of Figure 1. The bond will fail in cleavage when the cleavage stress reaches a critical value described by the stress $\sigma_b$ (at peel angle $\omega = 180$ deg) and by shear under the maximum critical shear stress $\lambda_b$ (at peel angle $\omega = 0$).

The peel model of Figure 1 has been incorporated into a system of computerized models for the time-temperature dependant properties of both adhesives and flexible members.[14] Significant operating parameters in this model are the shear ($\alpha$) and cleavage ($\beta$) stress concentration factors as defined by the following standard relations:

$$\alpha = \left(\frac{G}{2Eha}\right)^{1/2} \tag{1}$$

$$\beta = \left(\frac{3Y}{8Eh^3a}\right)^{1/4} \tag{2}$$

where E is the flexible member tensile modulus and G and Y are the respective adhesive shear and tensile viscoelastic modulus. The stress concentrations $\beta$ and $\alpha$ are identified in the respective cleavage and shear stress functions shown in the lower left view of Figure 1.

The central assumption concerning the effective adhesive cleavage thickness f(a) is set forth in the following new relations adapted from microfracture mechanics in fiber reinforced composites:[14]

$$f(a) = aF + ((1 - F)/C\beta) \tag{3}$$

$$F = \exp - (\beta Ca)^{10} \tag{4}$$

The parameter C in Eq. 4 defines the cavitation scale factor which modifies the predominating effect of the cleavage stress concentration $\beta$ in limiting the effective adhesive thickness f(a) where $a \simeq \beta C$.

The peel cleavage force $P_c$ and shear force $P_s$ are given by the following standard relations:[2]

$$P_c = \sigma_0 b\,(1 - K)/2\beta \tag{5}$$

$$P_s = \lambda_0\, b/\alpha \tag{6}$$

where b = bond width, $\sigma_0$ = boundary cleavage stress and $\lambda_0$ = the boundary shear stress.

The dimensionless internal stress parameter K is $K = 1.0$ peel angle $\omega = \pi$ and is defined at other angles by the following standard relation:[2]

$$K = \frac{\beta\, m_c}{\beta\, m_c + \sin\omega} \tag{7}$$

where $m_c$ is the cleavage moment arm of the applied peel force P. In the computerized peel model[14] the value of K is solved iteratively for each peel angle. In the standard peel model the peel force P is calculated by the following standard relation based on the equilibrium of forces in steady state peel:[2]

$$P = (P_c^2 + P_s^2)^{1/2} \tag{8}$$

In the modified peel model presented here the effective adhesive thickness ratio f(a)/a is applied to reduce Equation 8 in the following manner:

$$P = (f(a)/a)\,(P_c^2 + P_s^2)^{1/2} \tag{9}$$

The modified peel mechanics represented by Equation 9 is obtained by retaining the standard derivation of peel mechanics presented in Equation 8 and substituting a front factor representing the effective reduction in adhesive thickness when the product $\beta Ca \geq 1.0$.

For a viscoelastic adhesive interlayer both G and Y the respective shear and tensile modulus and $\lambda_0$ and $\sigma_0$ the respective shear and tensile boundary stresses are time and temperature dependent. The viscoelastic theory of peel provides the following relations between peel rate $\dot{c}$ and the internal adhesive response:[7-9]

$$\dot{c} = \frac{1}{t_c\beta} = \frac{1}{t_s\alpha} = \frac{\nu_c}{\beta} = \frac{\nu_s}{\alpha} \tag{10}$$

where $t_c$ and $\nu_c$ are the respective cleavage relaxation time and radial frequency determined by $\beta$ and $t_s$ and $\nu_s$ the respective shear relaxation time and radial frequency determined by $\alpha$. Since it is usual that $\beta >> \alpha$ the cleavage mechanism of peeling is normally characterized by shorter relaxation times and higher frequency that the shear mechanism at constant peel rate $\dot{c}$. In other words, the above viscoelastic theory of peel describes separate time scales and mechanisms for cleavage and shear response when $\beta >> \alpha$.

An alternative general expression for peel force in steady state peel is derived from the equilibrium of moments of force as expressed by the following relation:[2]

$$P = ba\left[\frac{K\sigma_0}{(2Y)^{1/2}} + \frac{3^{1/2}\lambda_0 \cos\omega}{(2G)^{1/2}}\right]^2 (1 - \cos\omega)^{-1} \tag{11}$$

where bond width b, adhesive thickness a and peel angle $\omega$ appear as independent variables. By applying the derivation of this discussion to Equation 10 we substitute the effective adhesive thickness f(a) of Equation 3 for thickness (a) to obtain the following more general expression:

$$P = bf(a)\left[\frac{K\sigma_0}{(2Y)^{1/2}} + \frac{3^{1/2}\lambda_0 \cos\omega}{(2G)^{1/2}}\right]^2 (1 - \cos\omega)^{-1} \tag{12}$$

It follows that Equation 9 and Equation 12 are equivalent new and more general statements for peel force P which emphasize different aspects of adhesive joint design.

## RESULTS AND DISCUSSION

Figure 2 displays the T-peel data of Gardon at four constant peel rates of a single pressure sensitive tape where specific peel force P/b plotted versus adhesive thickness a. A region of initial proportionality between P/b and a is evident in the initial slope of the curves of Figure 2. As adhesive thickness increases beyond a = 5 to 10 μm all the curves of Figure 2 flatten to show that increasing adhesive thickness beyond a = 50 μm in magnitude produces only minor increases in peel force. The curves of Figure 2 also show that increasing the peel rate $\dot{c}$ delays the flattening of P/b versus a until higher magnitudes of adhesive thickness. Higher peel rates increase the cleavage stress concentration factor β by the increase in adhesive tensile modulus Y with reduced relaxation time. At constant peel rate, increasing the adhesive thickness decreases the stress concentration factor β, other factors constant, as shown in Equation 2. Thus the theory developed in the previous section predicts both features of the experimental curves of Gardon shown in Figure 2 as mentioned above.



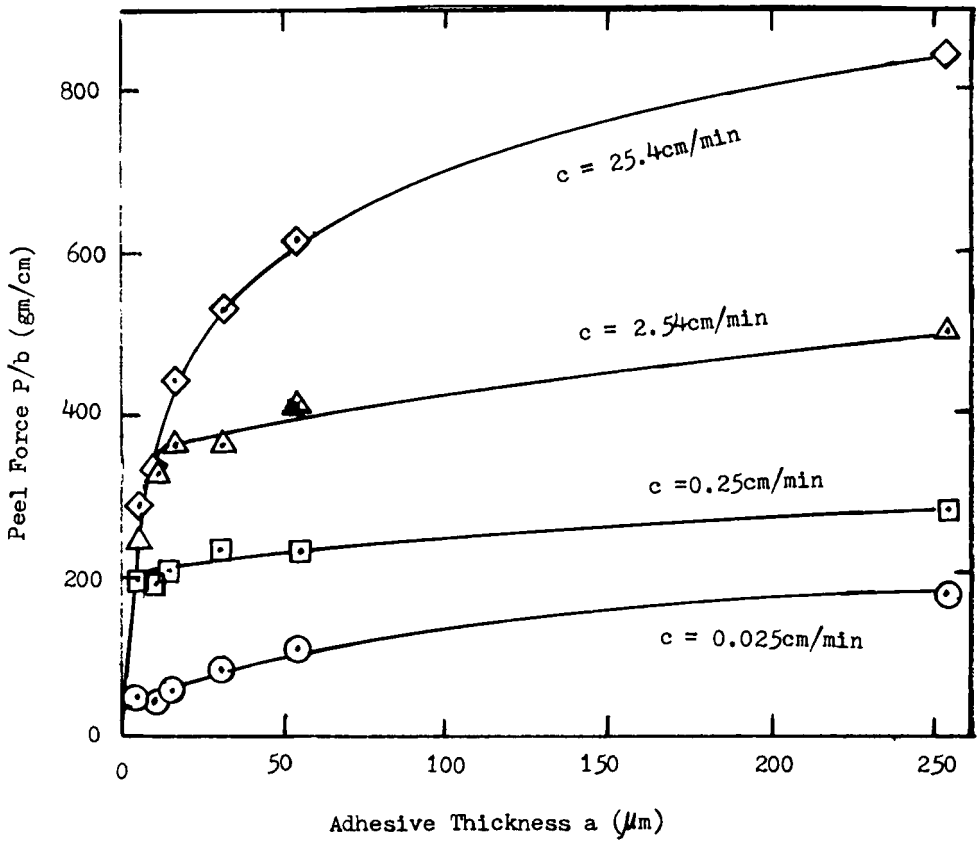


FIGURE 2 Dependence of T-peel force (P/b) upon adhesive thickness (a) at several peel rates. Acrylic polymer adhesive is Rhoplex HA-8. Flexible adherends are 40.5 μm thick cellophane. Constant room temperature T ≈ 23C and total peel angle ω = 180 deg. (data from Ref. 12).

In Figure 3 is shown the data of Johnston[13] in which each curve represents a different viscoelastic adhesive composition combined with a common flexible member. The general features of each peel force versus adhesive thickness curve are quite distinct indicating that the polyester film, the common flexible adherend for the three curves of Figure 3, does not dominate the slope of P/b vs a curves of this study.

One notes in both Figure 2 and Figure 3 a general result that shows a maximum linear slope in the P/b vs a curves as adhesive thickness approaches zero thickness. This limiting response is predicted by standard peel theory as embodied in the general peel relations of Equation 8 and Equation 11. The new result of the theory developed here, and described by Equation 9 and Equation 12 is shown in the

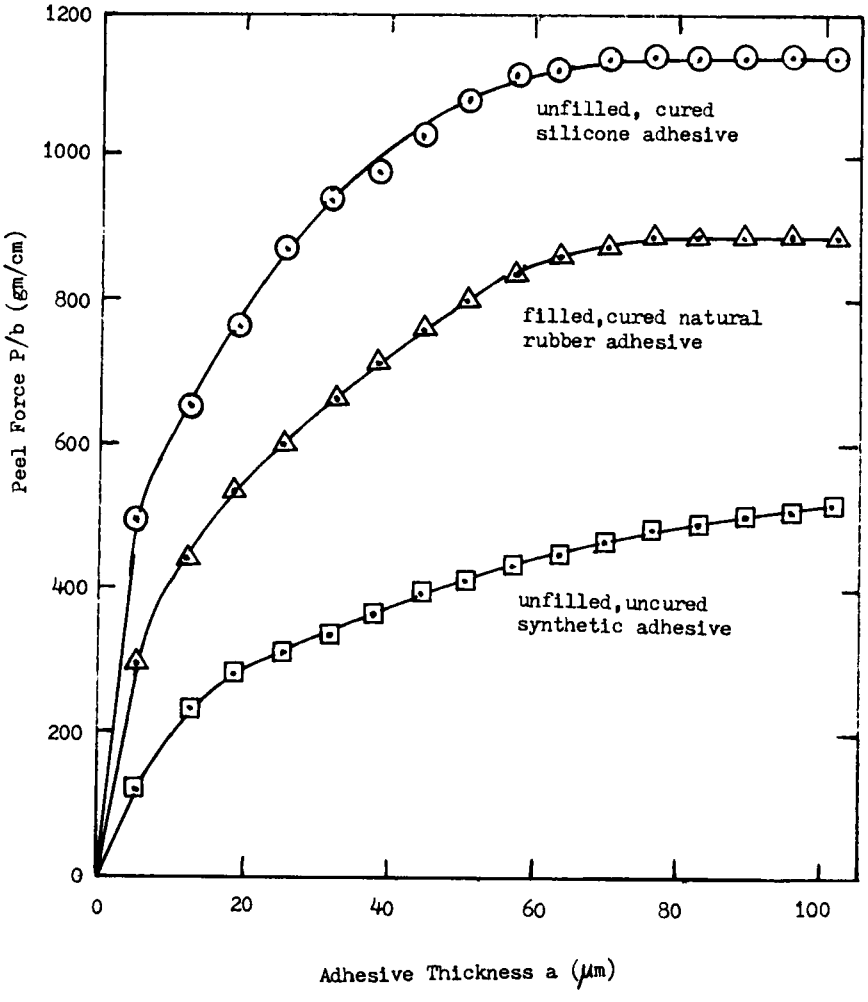


FIGURE 3 Effect of adhesive thickness (a) upon peel force (P/b) for three adhesives on a common flexible adherend of polyester film of thickness $2h = 12.6$ μm. Constant room temperature T≈ 23C and peel angle $\omega = 180$ deg. (data from Ref. 13).

calculated curve of specific peel force versus adhesive thickness, P/b vs a, as shown in Figure 4. The data utilized to generate curves of P/b vs a and fractional effective adhesive f(a)/a vs a in Figure 4 are developed from experimental master curves of peel force and adhesive relaxation modulus reported by Kaelble[10] and summarized in Table I. The curves of Figure 4 show the calculated curve of P/b vs a is linear until an adhesive thickness of a = 35 μm then flattens as the fractional effective adhesive f(a)/a diminishes with increased adhesive thickness as defined by Equation 3. The computed curve of P/b vs a in Figure 4, as generated by the general relations of new theory in Equation 9 and Equation 12, is consistant with the experimental curves of Figure 2 and Figure 3. One notes in Figure 4 that the computed P/b vs a curve represents a constant time t = 1.0 which correlates with a peel rate $\dot{c}$ = 2.0 cm/min at an adhesive thickness a = 20 μm. At constant time and temperature

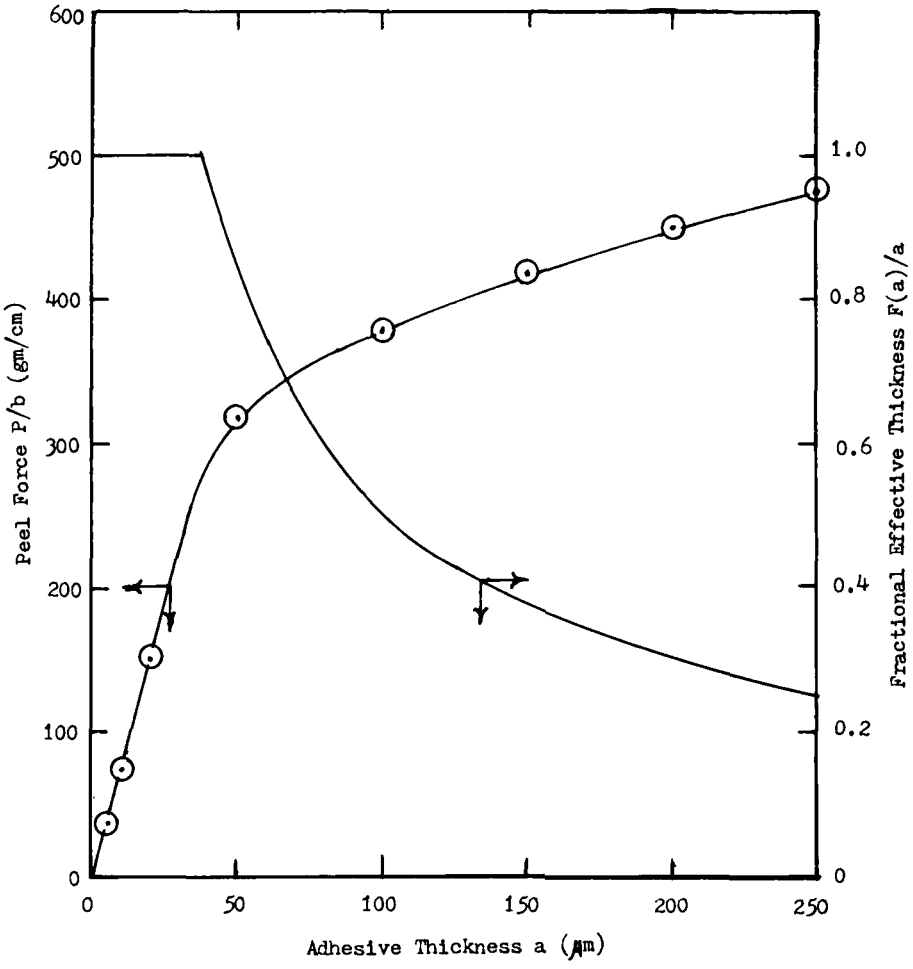


FIGURE 4 Calculated curves of peel force (P/b) and fractional effective adhesive (f(a)/a) versus adhesive thickness (a) at constant temperature T = 296K = 23C, time t = 1.0, and peel angle ω = 180 deg.

TABLE I
Experimental values of Peel Properties for a pressure sensitive tape with cellulose acetate flexible member (h = 12.7 μm, E = 3.45 E4 bar, b = 1.27 cm) equimolar heopentyl: t-butyl acrylate adhesive (a = 22.9 μm, $M_n = 1.03 \cdot 10^6$ gm/mole, Tg = 230 K) at 296 K obtained from master curves. —data from Ref. 10

| t (s) | Y(t) (bar) | $\sigma_0$ (bar) | G(t) (bar) | $\lambda_0$ (bar) | $\dot{c}$ at a = 20 μm (cm/min) |
|---|---|---|---|---|---|
| .01 | 5.34 | 60 | 1.78 | 30 | 96 |
| 0.1 | 4.75 | 40 | 1.58 | 20 | 10.1 |
| 1.0 | 3.00 | 30 | 1.00 | 15 | 2.0 |
| 10 | 1.68 | 20 | .562 | 10 | 0.13 |
| 100 | .948 | 5.0 | .316 | 2.5 | 0.015 |

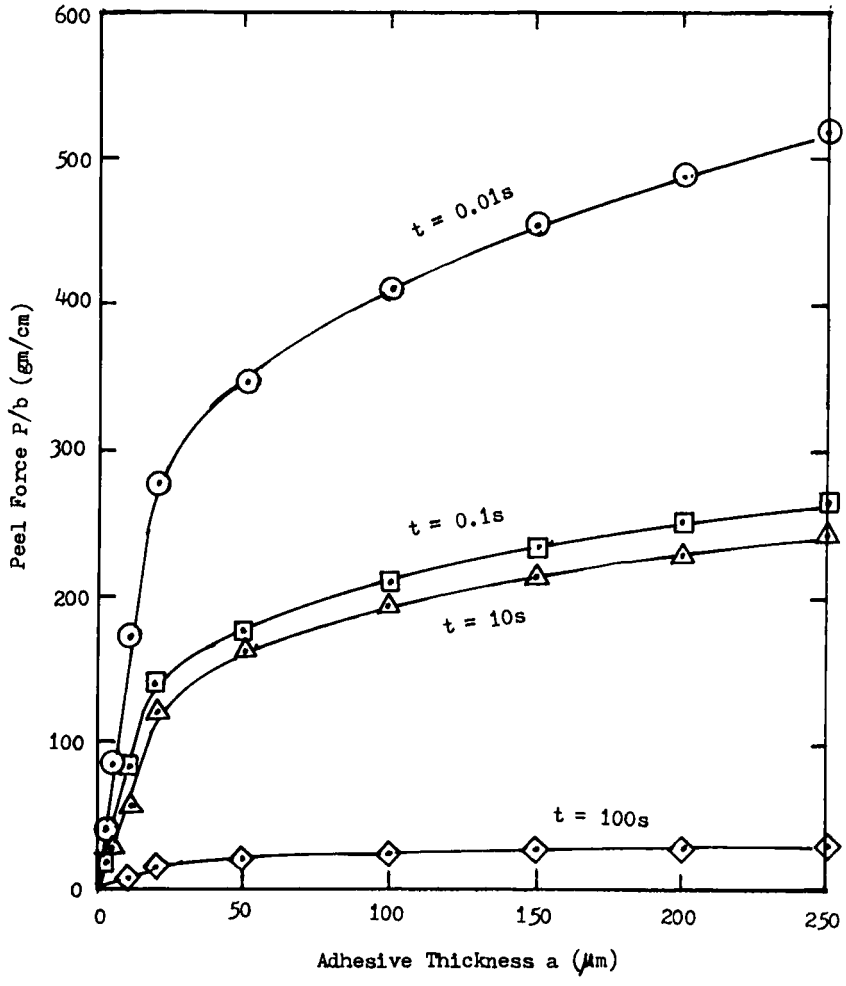


FIGURE 5 Calculated peel force (P/b) versus adhesive thickness (a) at four response times for the adhesive t = 0.01, 0.1, 10, and 100s at T = 296K = 23C and peel angle ω = 180 deg.

the peel rate gradually diminishes as the one-fourth power of increased adhesive thickness as predicted by Equation 2 and Equation 10. The computed peel rates for a typical adhesive thickness of a = 20 μm are summarized in the right column of Table I.

The effect of varying the time scale and therefore the peel rate ċ upon the computed curves of P/b vs a for the tape system described by Table 1 are shown in Figure 5. Inspection shows the computed curves of Figure 5 compare closely with the general features of the experimental curves due to Gardon shown in Figure 2 and discussed above. It should be pointed out that the only adjustable parameter in the computed curves of Figure 4 and Figure 5 is the cavitation scale factor C which appears in all calculations as C = 10. This constant parameter appears to

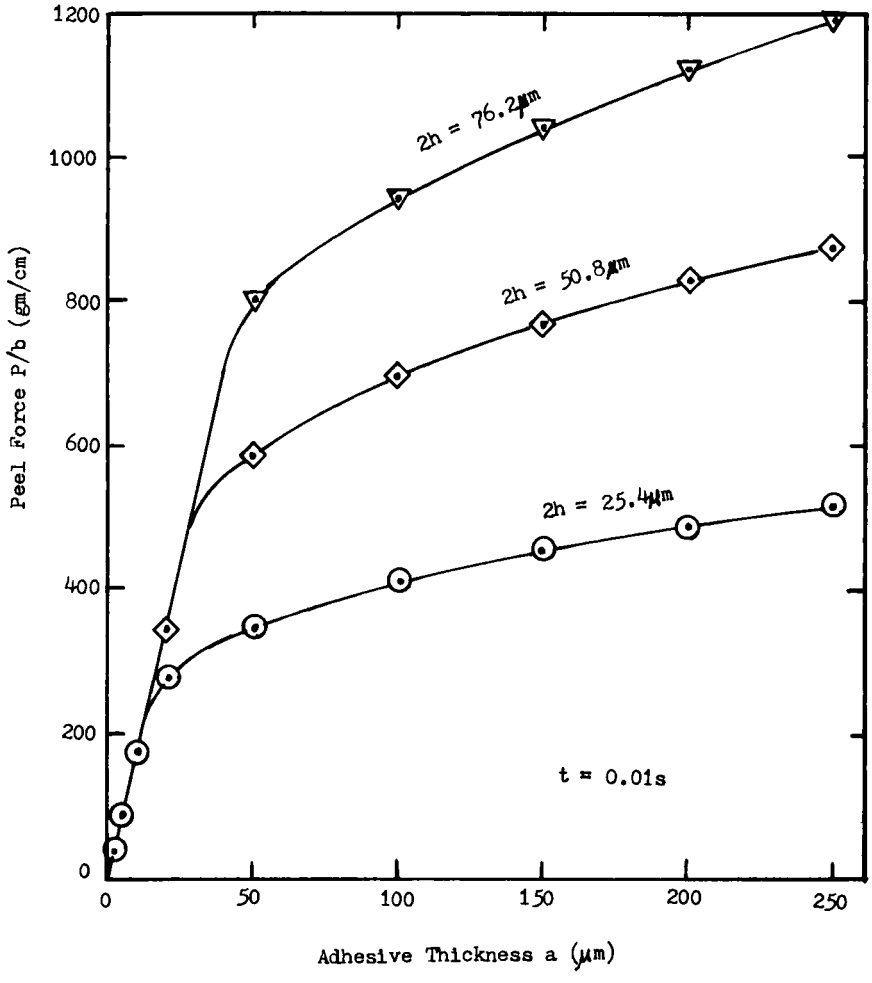


FIGURE 6 Calculated curves of peel force (P/b) versus adhesive thickness (a) for differing flexible adherend thickness 2h = 25.4, 50.8, and 76.2 μm at constant temperature T = 296K = 23C, time t = 0.01, and peel angle ω = 180 deg.

describe the condition where microscopic interfacial or bulk cavities in the adhesive interact with the stress gradients of the cleavage stress field described by the stress concentration factor $\beta$ in Equation 2.

The effect of varied flexible member thickness 2h upon the computed P/b vs a curves of a tape described in Table 1 for $t = 0.01s$ is shown in the calculated curves of Figure 6. One notes in Figure 6 that the P/b vs a curves superimpose for conditions where adhesive thickness is $a < (1/C\beta)$. Only in the nonlinear range of P/b vs a does increasing the flexible member thickness increase the magnitude of the calculated peel force P/b at constant adhesive thickness when other factors are held constant. This new result shown in Figure 6 would appear to have important potential applications in pressure sensitive tape design. For an optimized tape design it would appear that a critical balance of flexible member thickness 2h and adhesive thickness a would coincide with the condition that $\beta Ca = 1.0$ for the particular time-temperature condition of tape use being optimized. This new theory also suggests that the measurement of the internal cleavage and shear stress distributions of peeling, as detailed in several studies,[9-11] represents an important direct means of further testing and implementing the optimization of peel mechanics design.



## SUMMARY AND CONCLUSIONS

This discussion presents an important extension of peel mechanics which treats the nonlinear effects of adhesive thickness upon the peel force at varied peel rate, temperature and peel angle. The new theoretical relations are shown to correlate reasonably with experimental studies of peeling of pressure sensitive adhesive tapes where peel angle $\omega = 180$ deg. The new theoretical model also points out the optimum balance of flexible member to adhesive thickness is achieved when the product $\beta Ca = 1.0$ where a is adhesive thickness, C the cavitation scale factor, and $\beta$ the cleavage stress concentration.

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