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Cleavage Behavior of Bonds Made with Adherends Capable of Plastic Yield

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Synopsis

The failure behavior of adhesive joints under cleavage stresses depends upon the thickness of the adherend. With thick, rigid adherends failure occurs by rapidly propagated adhesive rupture. Thinner adherends can exhibit plastic flexural yield, the subsequent adhesive failure then being progressive and strain-limited, and occurring only in the region of bond directly adjacent to the yielding adherend. A fairly sharp discontinuity between these two types of behavior occurs over a small range of adherend thickness T. Work to rupture can differ by more than an order of magnitude, for otherwise identical joints having T above or below the transitional range (around T_c). For $T > T_c$ the applied load P causing rupture is proportional to $T^{1.5}$ while the moment arm remains constant, as predicted by Yurenka. For $T < T_c$ the turning moment during failure is proportional to T^2 and is substantially independent of the nature of the adhesive. Empirically, the radius of the yielded adherend after failure is proportional to T. The manner of interaction of various adhesive mechanical properties in defining P in the two ranges and, thereby, T_c, are related to this and other empirical correlations. The initial free moment arm in the joint, L, determines the stability of peel at initiation of adhesive rupture. Reducing L leads ultimately to instability. The change of controlling factors as $L \to 0$ is discussed.

INTRODUCTION

Adhesive joints are at their weakest when subjected to cleavage stresses, and the possibility of accidental application of such stresses to joints often restricts the use of bonding for structural purposes. Conventional tests for adhesives under such stresses have used either completely rigid adherends[1] or at least one thin, flexible adherend.[2,3] In the former tests the joint fails by a single total rupture, while in the latter "peel" occurs, an adherend being detached progressively from the joint at substantially constant load. The latter case has been extensively analyzed,[4,5] the Hookean behavior of both adherend and adhesive commonly being assumed.

We have examined the cleavage behavior of joints between cold-rolled mild steel adherends, using several types of adhesive. Steel of thicknesses from 0.012 to 0.070 in. was used. This range includes most of the gages of steel that might be considered for assembly by bonding, with the exception of some canning steels. For several adhesives a change in failure behavior occurs over a fairly small range of steel thicknesses. However, this is not due simply to the difference between progressive peel of a thin Hookean adherend and rapid cleavage from a thicker such adherend. The transition occurs when the load required to rupture the adhesive is just able to cause permanent plastic deformation of the adherend. The effect of adherend plastic yield upon the cleavage behavior of joints does not appear to have been previously studied.

The observed behavior will be related to the mechanical properties of adhesive and adherend and to joint geometry. We also discuss the relation of the observed "peel with plastic yield of adherend" to the types of peel previously considered.

The symbols used in this paper are listed in the Nomenclature.

EXPERIMENTAL

Materials

Steel was selected from a single batch of $^1/_8$ in. hot-rolled plates. These were extensively analyzed and mechanically tested in order to verify their homogeneity. MEAN ANAL.: C, 0.029; S, 0.012; P, 0.007; N, 0.0025; Mn 0.31%. The metal was cold-rolled to the required thicknesses and annealed at 680°C. The product showed fairly uniform ultimate tensile strengths but an appreciable scatter of yield strengths σ_y mean 32,100 lb-f./in.^{2}, standard deviation 3000 lb-f./in.^{2} The deviation within samples of equal T ranged from 950 to 3600 lb-f./in.^{2} The variability was assigned to the differing rolling reductions and to imperfect uniformity of temperature in the annealing furnace. Metal of equal nominal T was randomized before use: nominal values of T were 12, 15, 18, 21, 25, 30, 35, 41, 48, 58, and 70×10^{-3} in.

Ten adhesives were used, of a range of chemical types and mechanical properties. They were obtained from four different suppliers and were all offered as suitable, under appropriate conditions, for bonding of sheet steel. Their mechanical properties were determined on free films. The adhesives were cured on tin plate under the same conditions as used when bonding with the adhesive, standard $^1/_2$-in.-wide tensile test specimens were cut from the coated metal, and the cured films were stripped by amalgamation of the tin and tested by dead loading.

Table I lists the adhesives with their chemical nature as far as is known, curing cycle, and mechanical properties. Adhesives 3 and 6 were significantly viscoelastic, so the properties quoted for these systems are only approximate.

Methods

The test specimen finally adopted was as shown in Figure 1, with $L = L'$ = 1 in. This was preferred over simple T-shaped specimens, because it allowed definite and reproducible moment arms, could be produced without large fillets, and avoided complications due to unbending of adherends during joint failure. Generally, only one adherend of this specimen yielded dur-

TABLE I
Nature, Cure Cycles, and Properties of Adhesives

No.	Nature	Cure cycle, min./°C.	Init. mod., 10^3 lbf./in.^{2}	Approx. elastic limit		Failure		Work to rupture, in.-lbf./in.^{3}
				Stress, lbf./in.^{2}	Strain	Stress, lbf./in.^{2}	Strain	
1	Epoxy–dicyandiamide	40/200	370	2100	0.006	2750	0.011	17
2	Epoxy–modified polyamine	30/100	420	4100	0.011	5000	0.016	43
3	Modified epoxy–polyamine	60/90	4	0	0.000	1400	0.360	252
4	Epoxy–polyamide	30/100	220	2700	0.015	4150	0.036	80
5	Filled epoxy–polyamide	30/100	50	700	0.013	1450	0.117	111
6	Curable vinyl plastisol	20/180	0.6	0	0.000	300	0.520	87
7	Vinyl–phenolic	15/165[a]	95	800	0.009	1200	0.016	11
8	Nitrile–phenolic	120/180[a]	41	1500	0.036	1950	0.062	68
9	Polyamide hot melt	Momentary/120	32	300	0.009	800	0.060	26
10	Polyamide hot melt	Momentary/120	—	—	—	—	—	—

[a] Under about 100 lbf./in.^{2}

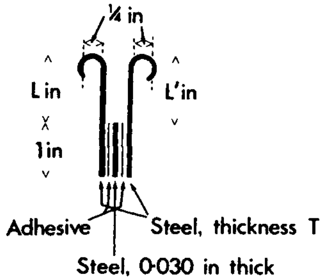


Fig. 1. Cross section of standard test specimens.

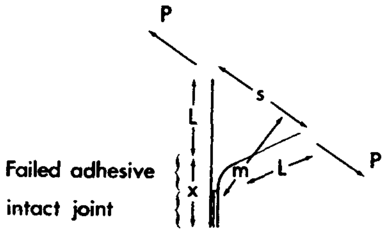


Fig. 2. Geometry during general peeling failure with adherend yield.

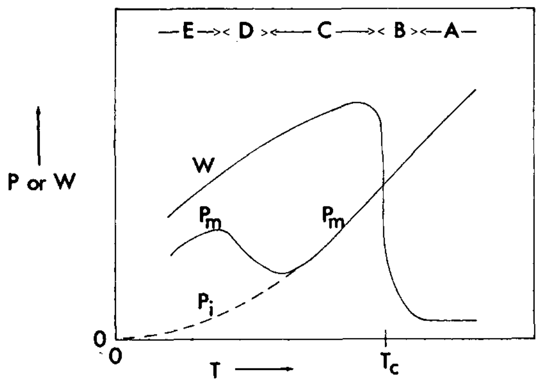


Fig. 3. Schematic variations of P and W with T.

ing failure, as shown schematically in Figure 2. Yield of the second adherend was slight or zero and occurred, if at all, only before steady peel had begun. A specimen design having arms of unequal length, $L = 1$ in., $L' = 1.05$ in., was tested in attempts to obtain consistent yielding of one or other adherend; however, it did not give more reproducible results than did the symmetrical specimen. Some specimens with differing values of L $(=L')$ were also tested, with adhesive 6, a different batch of steel ($T = 0.040$ in.) being used.

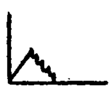
Joints were made up from 6 × 4 in. or 6 in. square pieces of steel of the thickness for test, bonded via two adhesive layers to a 6 × 1 × 0.030 in.

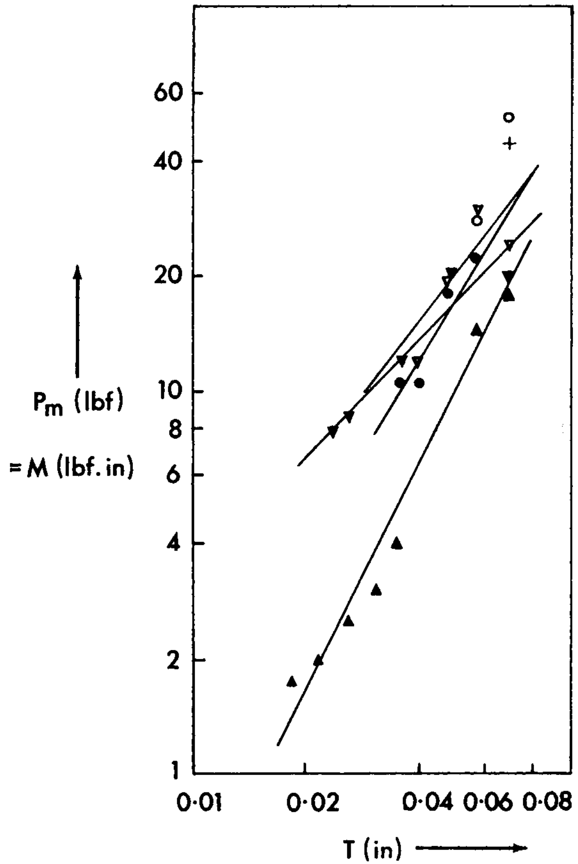
steel spacer stuck between and adjacent to their 6-in.-long edges. Before bonding all faying surfaces were cleaned with trichloroethylene, abraded with 36 HF alumina disks, and again swabbed with fresh trichloroethylene. Cure cycles were as in Table I, light clamping pressure (ca. 5 lb-f./in.^{2}) being used except for adhesives 7 and 8. All bonds made from any one adhesive were assembled and cured together. For all adhesives except 8 (which was used as a 0.010 in. film), glue-line thickness was controlled by insertion of 0.003 in. nichrome wire in the bonded areas, arranged parallel to the axes of the finished test specimens. Preliminary trials had shown that peeling load varied little with glue-line thickness in the range 0.0002 to 0.010 in., a thickness of 0.004 in. giving a slightly higher load than greater or lesser thicknesses.

The large samples were cut by a bandsaw to give individual specimens 1 in. wide. These were clamped in a jig, designed to prevent stressing of the bonded area, and bent and trimmed to the configuration of Figure 1.

The loops of the specimens were mounted into special adapters in a Hounsfield Tensometer by way of $^1/_4$-in. diameter mandrels, which were free to rotate in their bearings. A crosshead separation rate of $^1/_2$ in./min. was adopted for the main test series. Automatic plots of load versus crosshead travel were taken during tests.

TABLE II
Types of Joint Failure

Type	Typical load versus extension (P–s) trace	Mode of failure	Degree of adherend flexural yield
A		Sudden complete cleavage	Nil
B		Stepwise cleavage	Slight or zero
C		Progressive peel without oscillation of load	Considerable
D		As C	As C
E		As C	As C
F		As C	As C



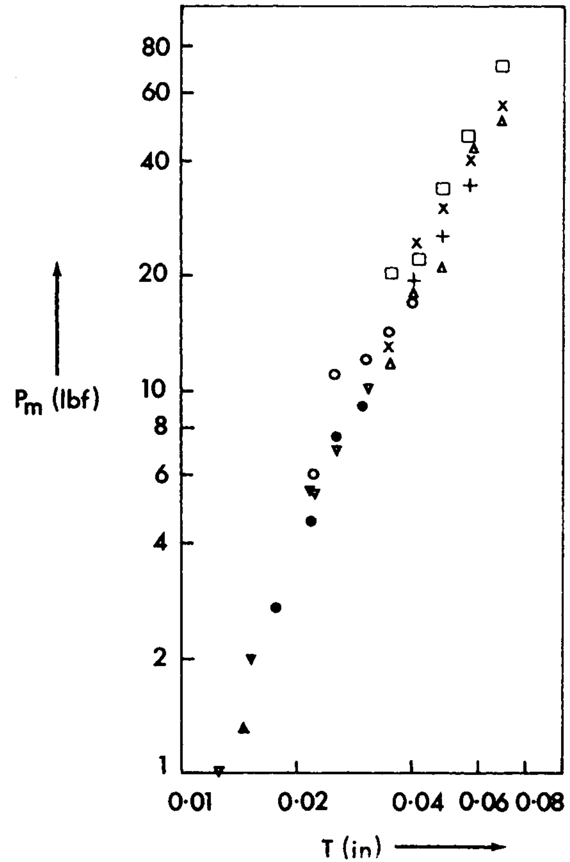
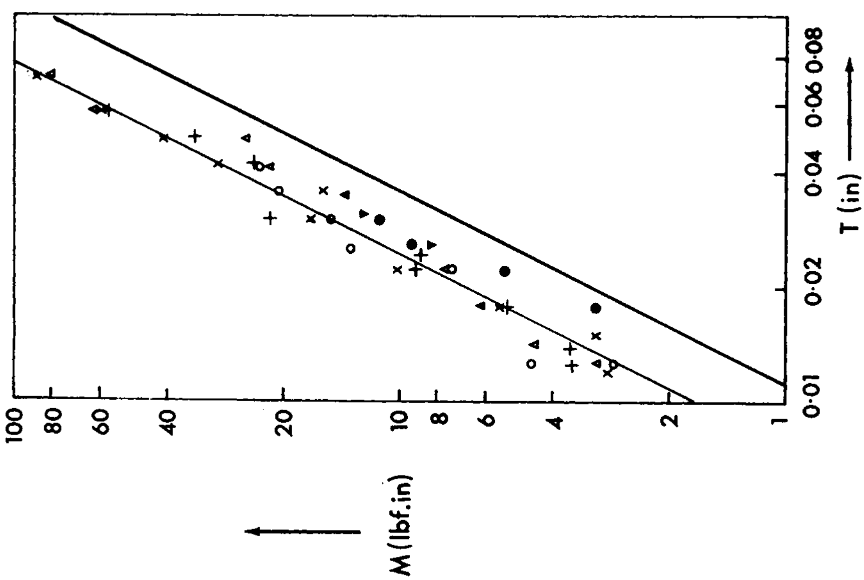


Fig. 4 (left). Plots of P_m versus T for individual adhesives, in joints failing by cleavage. See Table III for symbols.

Fig. 5 (right). P_m values for six adhesives, in joints failing by type C peel. See Table III for symbols.



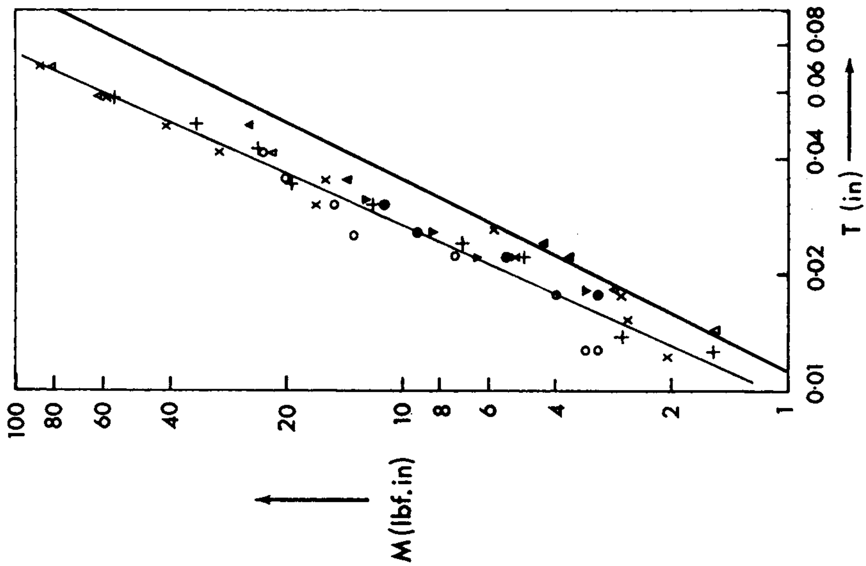


Fig. 6 (left). Calculated M versus T. $M = P_m m_m$ for type C failures, plus $M = 2P_m r_f$ for type E failures. See Table III for symbols.

Fig. 7 (right). Calculated M versus T. $M = P_m m_m$ for type C failures, plus $P_i m_m$ for types D and E failures. See Table III for symbols.

RESULTS

In every case only one of the two glue-lines in a specimen ruptured. Whenever adherend yield occurred, the glue-line failing was that adjacent to the yielding adherend. Failures were generally cohesive.

Six different types of bond failure were distinguished, and their characteristics are given in Table II. Type F occurs only with specimens having $L < 1$ in. Failures of types A and B (see Table II) entail rapid crack propagation and occur without permanent (plastic) deformation of the adherends. Failures of types C, D, E, and F proceed by slow progressive failure of the glue-line, with concurrent plastic flexural yield of the adherend adjacent to the rupturing adhesive. As a result, plots of joint work-to-rupture against T show a sharp discontinuity at $T \approx T_c$, at which point cleavage gives away to such peel as the failure mode.

For the main test series the maximum loads P_m reached during joint opening and the work-to-rupture values W vary with T, as indicated

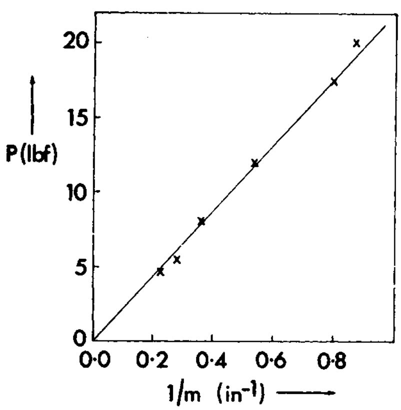


Fig. 8. Variations of P_f with $1/m_f$ at various L.

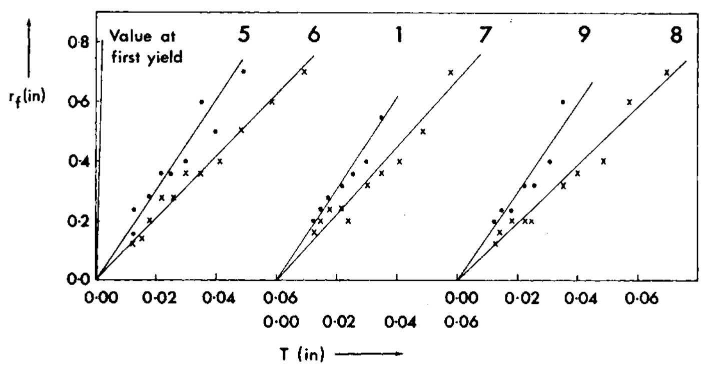


Fig. 9. Plots of r_f versus T for yielded adherends. The numbers indicate the adhesive, and the extreme left-hand plot gives calculated values of r at initiation of adherend plastic yield.

TABLE III
Joint Test Results

Adhesive			Behavior over 0.070 in. adherends			Slopes[a] of log P_m versus log T		Intercept of log P_m versus log T at T = 0.030 in., as P_m, lbf.
Number	Symbol in figures	T_c, in.	P, lbf.	Type of failure	Mean r_f/T	Cleavage region	Peel region	
1	●	0.032	27	A	15	1.65 ± 0.25	2.7 ± 0.2	10
2	▲	0.015	18	A	—	1.95 ± 0.2	—	—
3	□	0.08+	70	B–C	≈10	—	2.6 ± 0.3	12
4	▼	0.021	20	A	—	1.0 ± 0.2	—	—
5	○	0.045	52	A	15	—	1.35 ± 0.25	11
6	×	0.08	55	B–C	10.5	—	2.05 ± 0.2	9.5
7	+	0.062	42	A	11	—	2.0 ± 0.1	10
8	△	0.070	49	B–C	9.5	—	2.35 ± 0.15	7
9	▽	0.035	28	A	14.5	1.35 ± 0.65	2.5 ± 0.15	10

[a] With standard deviations.

schematically in Figure 3. Not all adhesives show the full range of behavior within the range of values of T studied. The P_m's for failures of types A, B, and C increase smoothly with T for any given adhesive, despite the discontinuity in failure mode. The loads P_t corresponding to the "plateaux" on the plots for failures of types D and E fall on the same curves of P versus T, although the P_m values attained after the final load increases lie above such plots.

The second transition, from C to E failures, occurs gradually.

Most of the P–T data are presented in log–log form in Figures 4 and 5, while those relating to failures of types D and E are also incorporated in the analytical presentations, Figures 6 and 7. See also Table III. The results of experiments with samples of varying L are displayed in Figure 8.

The final radii of all deformed adherends were measured, the bent regions appearing to have substantially circular form. These radii increase linearly with T (Fig. 9) but are substantially independent of L at constant T.

ANALYSIS

Variation of Joint Failure Behavior with *T*

Most of the mathematical analyses of peel in the literature[4,5] consider peel of a single elastic adherend from a rigid, inertial, and irrotational backing, under a force applied in the plane of the flexible adherend at the point of its own action. They are generally developed to account for the behavior of peeling bonds, as the angle of action of the force to the backing adherend varies, with resulting changes in the stress mode causing rupture of the adhesive. The derived relations are, therefore, inappropriate for any part of our data or, indeed, for any case in which forces are applied substantially normally to joints that involve incompletely flexible adherends.

The analysis of Yurenka[2] appears, however, appropriate to some of our data. The P_m for failures of types A and B, which occur with essentially elastic behavior of the adherend, are in fact proportional to $T^{1.5}$ (Fig. 5 and Table III). This is consistent with Yurenka's conclusion, that the applied moment at bond failure should be proportional to $T^{1.5}$ for elastic adherends, since in the absence of major (and therefore permanent) substrate deformation the moment arm in our test piece is constant at 1 in. The catastrophic nature of these failures renders the available P values liable to extensive scatter, and thus the slopes of log P versus log T for individual adhesives differ appreciably. However, none of the regression lines for individual adhesives have slopes differing significantly from 1.5, and the mean of the slopes of these lines is 1.5 with 95% confidence limits of $\pm 0.3_5$.

A cumulated plot of log P versus log T for all peeling failures of the C type (Fig. 5) shows much less scatter than does that for cleavage failures (Fig. 4), although both more adhesives and more points are included in Figure 5. The data for individual adhesives give linear plots, with less scatter than the plots for cleavage cases, because of the progressive nature of the failures. P_t values fit these linear plots for failures of types D and E, and the regression parameters in Table III are based on the use of these values together with the P_m for the simpler type C failures. The mean slope of such plots is 2.2, significantly greater than 1.5.

The similarity of the intercepts of the regression lines for these data, at a central value of T, suggests that the plots may be members of a common population. A common load-limiting factor may thus operate for all adhesives in the peeling region, this of course varying with T.

In "peeling" cases the adherend undergoes plastic yield. Cantilever beams collapse by formation of a "plastic hinge" at the point where the turning moment is greatest, which is adjacent to the support[6] or to the unfailed adhesive in cleaving joints. As a peeling joint progressively fails, the plastic hinge moves to stay at the point of greatest moment and thus remains adjacent to the unfailed adhesive. Each successive element of adherend thus bends plastically only as long as the adhesive adjacent to it remains intact.

The effective moment arms m vary during peeling failures, owing both to the opening out of the joint and to the movement of the center of rotation of the yielding adherend, which is at the momentary point of adhesive failure. The variations of m with s were determined graphically for several r/L ratios, with the construction indicated in Figure 2 and the following assumptions:

(*1*) Yield is confined to one adherend.

(*2*) The initially free length of this adherend does not yield.

Both of these first two assumptions are experimentally substantially true; slight deviations from them do not greatly affect the conclusions of the following analysis.

(*3*) The yielded form of the adherend is a circle. This appears true and is reasonable in view of the observed progressive yielding failure of elements of adherend under constant applied loads.

(*4*) Plastic yield affects substantially the entire adherend thickness, so that spring-back on final removal of load is slight, and r_f is approximately equal to r during peel. This assumption is justified, since all r_f are $<15T$, whereas r for incipient yield is $470T$ (see Case and Chilver,[7] equation 15.5).

Figure 10 plots the dimensionless ratio m/L, thus deduced, against s/L at selected values of r/L. In this figure the two extreme curves at either end of the r/L scale are included only to show the trend of such plots; the experimental data all lie within the range $0.7 \geqslant r_f/L \geqslant 0.12$. Curves within this range are plotted only up to the maximum s/L values attainable by our specimens.

Under the stipulated conditions the applied moment M should be constant[7] during equilibrium peel of a given specimen, with plastic yield of an adherend.

From the curves of Figure 10 the values of m/L lie on fairly long and flat plateaus during much of the joint opening (increase of s). During the resulting period of essential constancy of m peel therefore occurs with ad-

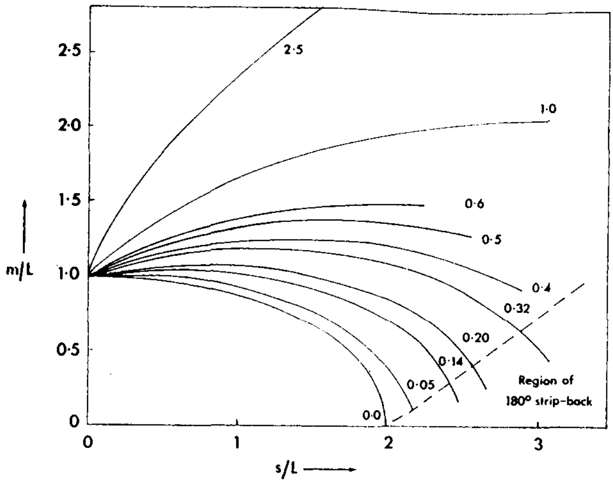


Fig. 10. Variation of m/L with s/L at the indicated constant r/L. In the marked bottom right-hand corner region 180° strip-back occurs. Also see text.

herend yield at essentially constant P. This accounts for the substantially level P–s curves for C types of failure and for the early plateaus in curves for D and E types of failure. The final rise in P during failures of the latter types was noted to occur around the values of s at which m in Figure 10 begins to decrease, while the final P_m values then obtained are consistent with operation of a decreased moment arm, limited to a minimum of $2r$ by the geometry of 180° peel-back. Certain cases of "C" failures with high r values show P values slowly declining during (stable) peel, as required by the initial ascent of curves of m/L versus s/L for large values of r/L. See also the next section below.

Maximum values of m were extracted from Figure 10 and used in calculations of the moments M operating during peel. These moments are plotted in Figures 6 and 7, which differ only in that in Figure 6 the data for E failures are incorporated as the moment operating during the final limiting 180° strip-back, equal to $2P_m r_f$, whereas in Figure 7 the moment operative during the early plateau stage of D and E failures is inserted, equal to $P_i m_m$. The latter values may not be as well defined as the former.

The data for six adhesives show little scatter in these plots. No point deviates from the mean line by more than a factor of 1.8; the scatter is much less at higher values of T, where both P and r are more precisely determinable. The mean slopes in these two figures are 2.0 and 2.2, respectively, in good accord with the required value of 2 for plastic collapse of a cantilever beam.[7] Such collapse is thus the common moment-limiting mechanism for all adhesives, hinted at previously on consideration of Figure 5.

The lower lines in Figures 6 and 7 correspond to the fully plastic moments of resistance[7] for 1-in.-wide beams of the steel used, equal to $8000T^2$ lbf./in. The mean lines through our computed moment data in fact fall at worst a factor of 2.1 above these theoretical maxima. Evidently, therefore, our approximations result in some systematic overestimation of the effective moment arms operative during peel. Many factors could contribute to this, but the greatest are probably the slight yield of the opposite adherend, the ambiguity of the point of load application due to our method of loading of specimens, overestimation of M in C failures showing some decrease of P with increasing s, and the operation of an extended zone of adherend plastic yield[7] with its center remote from the last surviving adhesive. The last effect, if the adhesive failure in fact occurs adjacent to the extreme outside edge of the zone of the adherend surface undergoing plastic extension, could alone account for a factor of about 1.5 of the discrepancy.

Empirically, r_f is proportional to T. At initiation of plastic adherend collapse $r \approx 470T$. This corresponds to values of r enormously greater than the r_f values actually observed. The adherends therefore exert their maximum possible moments of resistance, constant for given T.

Since for our data $15 \geqslant r_f/T \geqslant 9.5$, then, as long as $L/T \gtrsim 10$ and $r_f/L \lesssim 1$, the m_m values do not diverge greatly from 1, and the nature of the adhesive has little effect upon the peeling load P or P_i. The influence of the adhesive upon r_f/T is comparable to that upon P at given T. This suggests that the main influence of the adhesive upon P in the peeling region may be by way of r_f, the final rupture of the adhesive adjacent to the yielding region of the adherend surface being strain-limited. Plastic collapse of the adherend of course prevents the moment at the adhesive from ever rising to the level required by Yurenka's analysis and thus causing tensile failure of the adhesive. Failure of adhesive at constant shear strain can readily be shown to lead to a constant r/T relationship at constant glue-line thickness. However, since the range of r_f/T values is not greater than the scatter of points in Figures 6 and 7 this conclusion cannot be verified from our data. Strain-limited adhesive failure provides a simple explanation of the observed smooth non-oscillating nature of peeling failures over plastically yielding adherends.

The value of T_c, the adherend thickness at which peeling failure gives way to cleavage rupture, is thus defined by the intersection of two plots of $\log M$ versus $\log T$. That for the peeling range, of slope 2, is universal for a given adherend. In principle it is calculable, but the approximations noted above necessitate the introduction of an empirical constant, ≈ 2, into the appropriate equation $M = \sigma_y b T^2/4$. This constant may vary with joint geometry or adherend material. The lines of $\log M$ versus $\log T$ for the cleavage region, of slope 1.5, are peculiar to individual adhesives. High M for adherend gages in the cleavage region, which for our test specimens implies high P_m, should therefore correlate with high T_c. Such a correlation in fact holds for $T = 0.070$ in. Comparing columns 3 and 4 of Table III, we find a correlation coefficient of 0.90. Provided, therefore, that cleavage rupture occurs, it would appear that ultimately single tests conducted over a (standard) stiff adherend could provide the simplest available means of estimating T_c values for adhesive–adherend combinations. This quantity is evidently a critical design parameter for adhesives that may be exposed to cleavage stresses.

No strong correlations have been found between T_c (or P_m for 0.070 in. adherends) and any adhesive property. Both are weakly positively correlated with adhesive failure strain and work-to-rupture and negatively correlated with adhesive tensile and yield strength and modulus. These

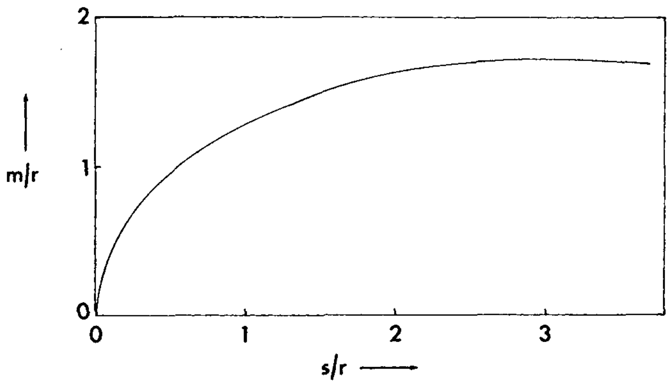


Fig. 11. Variations of m/r with s/r at $L = 0$.

correlations are consistent with Yurenka's formula for cleavage moment, $M = (EbT^3tw/12)^{0.5}$. Rather surprisingly, r_f/T appears to be correlated (negatively) with T_c, suggesting that similar (although unidentified) adhesive properties may be desirable in obtaining not only high T_c but also low r_f/T in the peeling region.

The Influence of Variation of the Initial Free Moment Arm, L

The practical significance of the above conclusions depends upon the ease with which they can be extrapolated to joints with L/r, L/T, and L/x ratios outside the ranges covered by this study. The influence of differing L may be observed merely in changes of P because of variation in joint moment arms at constant failure moment or, more drastically, in changes of T_c or of the entire pattern of behavior on varying T at differing L values. Certain extrapolations may, however, be justified.

With high L the plots of m/L versus s/L reach a limiting form (Fig. 10) not unlike those for the lower values of r/L studied herein. Stable peel with yield is therefore expected below T_c, with P_m/P_t ratios for D and E failures increasing with L, provided that x/L is maintained at a sufficiently high value. Because of the high x and s values required for display of this behavior the late increase in P therein is not likely often to be useful as a "fail-safe" mechanism in joints. Low loads can cause initiation of such peeling failures with high L, but the large distances of travel required of the point of application of force render this an unlikely limiting mode of failure of, for example, shear joints of $T < T_c$, accidentally stressed normal to their plane.

With low L instability of initial "peel with yield" develops as r/L rises significantly above about 0.5. This is due to the unbounded increase of the initial slope of m/L versus s/L on increasing r/L. The limit condition for $L = 0$ is plotted in Figure 11 (as m/r versus s/r) and illustrates the total initial instability expected of joints with no initial free moment arm, with a plateau region of m/r reached only shortly before 180° strip-back sets in (s/r ca. 3). Initial failure will in such cases evidently again be defined solely by adhesive tensile strength,[2] so moment-defined failure plots must not be extrapolated unjustifiably close to $L = 0$ conditions.

Data obtained with varying L substantially verify these conclusions. The occasional fall-off of P with increasing s during C failures of the usual test specimens ($L = 1$ in.) has already been noted. With $L < 1$ in. a new type of failure becomes evident, designated F in Table II. The initial load peak corresponds to peel initiation with $m \approx L$; the final level (when attained), to $m = m_m$. Figure 8 confirms the constancy of moment (final load P_f times m corresponding to final s) for six values of L, $4 \geqslant L \geqslant 0.25$. The P_mL values for the samples showing F failure ($L = 0.5$ and 0.25 in.) also fit fairly well onto this plot but are omitted, being far to the right of the figure. Work-to-rupture and r_f show only slight and unsystematic variations over this range of L; all r_f are 1.0–1.2 in.

Initially unstable failure of type F is clearly of the type frequently observed in T-peel experiments, with samples of low but undefined L.[3,8] The sharpness of the initial load peak is then due to low T, causing low r, so that s/r and thus m/r rapidly thereafter attain their limiting values (180°), and stable peel starts. The terminology used by some workers,[3,8] describing P_m as "absolute" but the final P_f as a "relative Schalfestigkeit," would seem therefore unjustified. The "absolute" value will be extremely sensitive to the small and ill-defined initial moment arm in such tests.

Nothing in the theoretical formulae for either plot of log M versus log T gives any reason to expect a shift in either plot, with consequent shift of T_c, on varying of L. However, the factors causing divergence of the practical data from theory in the peeling range may be influenced by L and may thereby vary T_c, the value of which is very sensitive to vertical shift of either line of log M versus log T.

The unstable failure behavior of joints of low L at first sight seems not dissimilar to the cleavage ruptures of joints to elastically behaving adherends of high T. In a limit experiment with the materials used in the specimens of Figure 8 and $L = 0.05$ in. in a "T-peel" sample, the plot of P versus s dropped so sharply as to appear of type A rather than type F. The joint adherends were nonetheless plastically deformed. The r_f and work-to-rupture found were not very different from those for the samples of Figure 8.

SUMMARY AND CONCLUSIONS

A majority of the adhesives examined can support loads sufficient to induce major plastic flexural yield of steel adherends, even when the latter are of quite substantial thicknesses. To a first approximation this can occur when the required moment for cleavage or peel with elastic adherend deformation, which according to Yurenka is $(EbT^3tw/12)^{0.5}$, exceeds the plastic moment of resistance of the adherend, $\sigma_y bT^2/4$. At adherend thicknessess below the critical value for such adherend yield, which we have called T_c, a progressive peeling failure occurs at moments independent of the nature of the adhesive. Joint work-to-rupture is thus greatly increased on decreasing T to below T_c.

Selection of an adhesive which can provide such fail-safe peeling behavior in joints could be facilitated by ranking adhesives on the basis of their failure moments in joints made with adherends showing fully elastic behavior up to rupture.

The production of test data on adhesive peel and cleavage in such a standard form would seem much preferable to continued use of the current mixture of empirical test procedures.[1–3] Yurenka has discussed this requirement.[2] The A.S.T.M.[1] cleavage test might be suitable as such a general method. However, the test specimen of Bepristis,[9] which differs from our samples principally in requiring sufficient adherend thickness to ensure elastic behavior, may prove easier to fabricate in quantity. On a more sophisticated plane, determinations of adhesive joint fracture toughness by methods such as those of Mostovoy and Ripling[10] and Ripling et al.[11] may yield more fundamental data on adhesive cleavage strength, which may also be useful for technical comparisons of adhesives.

The influence of adherend properties on the plots of M versus T, the intersection of which defines the ranges of T over which the two types of failure operate, can be deduced from the two formulae given above. For given adhesive–adherend systems a change of T, to obtain peeling behavior with plastic yield, may be desirable in order to obtain progressive joint rupture and consequent enhanced work-to-rupture, even though the load required to initiate peel may thereby be reduced. However, sufficiently large free initial moment arms L must then be selected, to avoid serious initial instability during peel.

An adhesive may appear weak in cleavage in a given joint either because it has low cleavage strength in Yurenka's sense of the word, with a consequently too low T_c, or because it can only induce high r values during peel with adherend deformation, even in the bonding of adherends of $T < T_c$.

It seems likely that most metallic adherends and, probably, also many polymeric ones will show a region of "peel with adherend yield" at sufficiently low T. The type of discontinuity observed between elastic and plastic adherend behaviors in peel should therefore be of fairly general occurrence. Peel (as opposed to catastrophic cleavage) occurring with elastic adherend behavior should be characterized by oscillating loads, the means of which obey a $T^{1.5}$ law. It could thus be readily distinguished from peel with plastic adherend deformation, even if the latter occurred with concurrent adherend unbending.

Further work is required on the behavior of joints with very low initial moment arms (and on the effect of adherend work hardening and unbending in such joints), and upon the precise mechanics of adherend yield. The manner of the transition from moment-determined to load-determined failure as $L \rightarrow 0$ particularly requires clarification.

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Nomenclature

P	Momentary load on joint during failure
P_i	Load on joint during "first plateau" stages of D and E types of failure
P_m	Maximum load attained during joint failure
P_f	Final load during *F* failure
σ_y	Yield stress of adherend
E	Elastic modulus of adherend
b	Width of adherend
T	Thickness of adherend
t	Thickness of adhesive layer
T_c	Thickness of adherend corresponding to transition from peel to cleavage behavior, see text
L, L'	Initial unbonded lengths in test specimens or other cleaving joints
x	Initial bonded length in joints
s	Momentary spacing of free ends of adherends during peel
m	Momentary moment arm during peel
m_m	Maximum of m as s varies
m_f	Final moment during F failure
r	Momentary radius of yielding adherend during peel
r_f	Final radius of plastically yielded adherend
M	Applied moment
W	Joint work-to-rupture
w	Product of notch tensile strength and tensile strain at failure, for an equivalent Hookean adhesive

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