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Peel Testing of Adhesive Bonded Metal

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INTRODUCTION

When a bonded adhesive joint is gradually forced apart from the edges inward, the tearing of the adhesive which occurs is called peeling. Experience in the field and the laboratory has shown that an unbonded area in a bonded panel can become a localized source of failure which will progressively become enlarged when the panel is subjected to sufficiently high static or alternating loads. Because this type of failure can be produced by normal loads which are relatively small compared to the shear loads which structural adhesives are capable of withstanding, peel strength of metal adhesives is a property to be considered. However, even if peeling-type failures are not encountered in service, a suitable peel test is a valuable process inspection tool for producers and consumers of adhesive bonded assemblies.

The usual approach in determining the peel strength of bonded panels has been to build a copy of a currently used peel testing machine and to amass a quantity of data with the purpose of establishing some arbitrary minimum value of acceptable peel strength for design or process control purposes. Ordinarily, correlation between these results and those of other types of peel testers on the same material is unsuccessful and the method is at best a qualitative comparison of a series of otherwise identical specimens.

Although more difficult, an ultimately more fruitful approach is first to investigate mathematically the nature of peel strength with the idea of arriving at a useful formula or theory and then to design a machine which will adequately control, test, and measure the important variables involved. This latter procedure, therefore, has been attempted in this paper.

DISCUSSION

Mathematical Determination of Peeling Stresses

The principal quantities used have the following definitions and units:

β = mathematical constant equal to $\sqrt[4]{K/4EI}$ or $\sqrt[3]{P_0/y_0/2EI}$ or $\sqrt[4]{E_0/4EIt}$ in.$^{-2}$

where EI is the flexural rigidity of each metal skin, E is its modulus of elasticity in psi and I the moment of inertia about its neutral axis of bending, in.^{4}/in. width; E_0 is the modulus of elasticity of adhesive bond layer, psi; ϵ_0 is the maximum tensile strain of adhesive bond layer, equal to y_0/t, in./in.; t is the thickness of adhesive bond layer, in.; K is Timoshenko's "modulus of foundation," i.e., of the adhesive, equal to E_0/t, lb./in.^{2}/in.; L is the length of moment arm between point of application of load P and point of peel, in.; M is the peeling moment, in. lb.; M_0 is the peel strength equal to P_0/β, or $S_0/2\beta^2$, in. lb.; P is the load required to peel the skin at a point L inches from P, lb./in. width; P_0 is the load required to initiate peeling when $L = 0$, lb./in. width; S is the tensile stress at point x, lb./in.^{2}; S_0 is the notch tensile stress at rupture, lb./in.^{2}; x is the distance along skin measured from point of peeling, in.; y is the deflection of skin at point x measured from its unstressed position, in.; and y_0 is the maximum deflection when peeling occurs at $x = 0$, $M = 0$, and $P = P_0$, in.

Timoshenko's theory of bending of beams on an elastic foundation[1] can also be applied to the adhesive peel problem. Figures 1 and 2 illustrate the applicable load picture. The basic assumption which is made is that the prismatic skin is supported along its entire length by a continuous elastic foundation, such that when the skin is deflected, the intensity of the continuously distributed reaction at every section is proportional to the deflection at that section. Under such conditions, the reaction per unit length of the skin can be represented by the expression, Ky, in which K, called by Timoshenko the "modulus of the foundation," denotes the reaction per unit length, provided the deflection is equal to unity. The simple assumption that the continuous reaction of the adhesive is proportional to the deflection

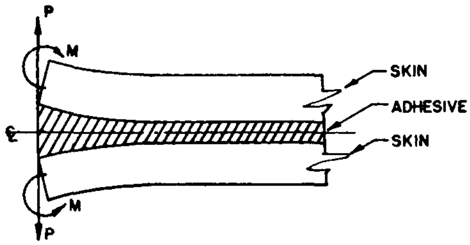

Fig. 1. Externally loaded peel joint.

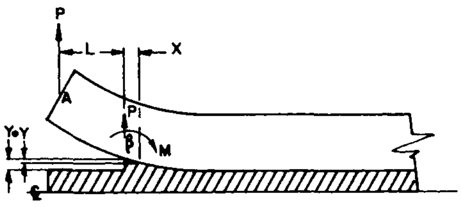

Fig. 2. Partially failed peel joint.

is in agreement with actual conditions in most cases.

In studying the deflection curve of the skin, the differential equation used by Timoshenko in his original theory:

$$EI(d^4y/dx^4) + Ky = 0 \quad (1)$$

together with applicable boundary conditions:

$$EI(d^2y/dx^2)_{x=0} = -M \quad (2)$$

$$EI(d^3y/dx^3)_{x=0} = -P \quad (3)$$

leads to the following solution:

$$y = (e^{-\beta x}/2\beta^3 EI)[P \cos \beta x + M(\cos \beta x - \sin \beta x)] \quad (4)$$

where the constant β is equal to

$$\beta = \sqrt[4]{K/4EI} = \sqrt[4]{E_0/4EIt} \quad (5)$$

This solution can be verified by substituting it into eq. (1).

Of particular interest is the deflection, $y = y_0$, at $x = 0$ when $M = 0$ and $P = P_0$, where P_0 is the force which is required to rupture the bond between the skin and the adhesive at the start of peeling

$$y_0 = P_0/2\beta^3 EI \quad (6)$$

or solving for β:

$$\beta = \sqrt[3]{(P_0/y_0)/2EI} \quad (7)$$

Substituting eq. (6) into eq. (4):

$$y/y_0 = (e^{-\beta x}/P_0)[P \cos \beta x + M(\cos \beta x - \sin \beta x)] \quad (8)$$

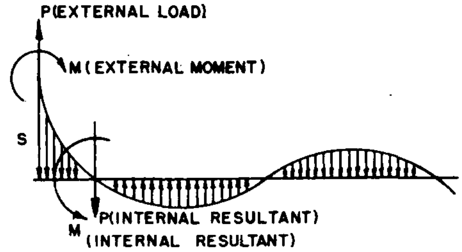

Fig. 3. Force equilibrium diagram.

This deflection equation of the skin under the combined influence of load P and moment M has a wave form with gradually reduced amplitude when plotted (see Fig. 3).

Since L may theoretically vary from 0 to ∞, the following three special cases of eq. (8) are of particular interest.

Case 1

When $L = 0$, $M = 0$, P is equal to its maximum value, P_0, and the first crack is about to start and initiate further progressive peeling failure in the bond (see Fig. 1), eq. (8) reduces to:

$$y/y_0 = e^{-\beta x} \cos \beta x \quad (9)$$

Case 2

When $L = \infty$, $P = 0$, and M is equal to its maximum value M_0 (see Fig. 2), eq. (8) reduces to:

$$y/y_0 = (e^{-\beta x}/P_0)\beta M_0 (\cos \beta x - \sin \beta x) \quad (10)$$

At $y = y_0$, $x = 0$, eq. (10) reduces to

$$1 = \beta M_0/P \quad (11)$$

Combining eqs. (10) and (11):

$$y/y_0 = e^{-\beta x} (\cos \beta x - \sin \beta x) \quad (12)$$

The two curves represented by eqs. (9) and (12) have been plotted in Figure 4. It should be noted that the shape of the deflection curve of an adhesive bond subjected to peeling is not dependent on the magnitude of the peeling load or moment but only on the magnitude of β, which in turn for eq. (5) is a function only of the moduli and thicknesses of the metal and the adhesive. An interesting item of these curves is that at certain locations ahead of the point of peel, negative deflections producing compressive stresses in the adhesive are developed which are equal to 7 to 21% of the maximum elongations or tensile stresses. The wave form of the deflection curves are so rapidly damped by the function $e^{-\beta x}$ that secondary tensile and compressive stresses and deflections even

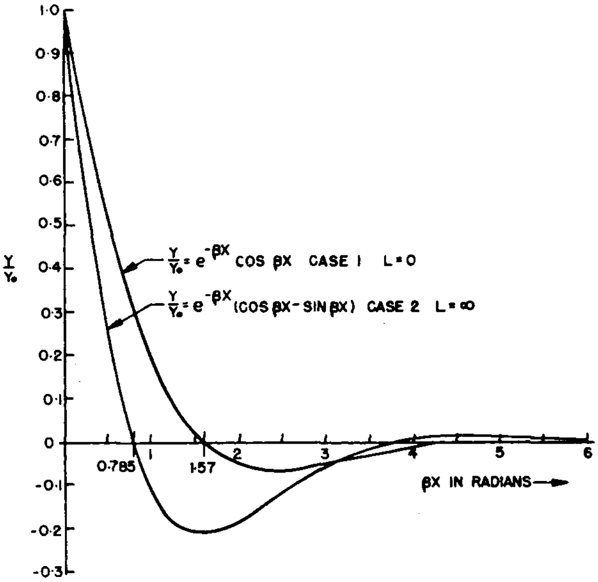

Fig. 4. Deflection curves of adhesive bonds subjected to peeling.

further ahead of the point of peel are negligible. Inspection of the force diagram in Figure 3 shows that the internal compressive stresses reinforce the internal tensile stresses in producing an internal moment to resist the applied external moment on the skin, but that they also reinforce the applied load on the skin. Fortunately, as seen by the deflection curves of Figure 4, the negative deflection, and hence also the compressive stress, is lower at $L = 0$ when P is highest and higher at $L = \infty$ when M is the highest. An important thing to be learned from the comparison of these two curves is that already it becomes quite obvious that establishing any kind of meaningful experimental measure of peel strength will be impossible unless the moment arm L of the external load is kept constant. A final observation which should be noted concerns the relative locations of the zero deflection of crossover points, of the two curves. This point occurs at $x = \pi/2 = 1.57$ for the first case and at $x = \pi/4 = 0.785$ for the second case. What this means is that twice as much of the adhesive is deflected in the former than in the latter case.

Case 3

When $y = y_0$, $x = 0$, we obtain a general relationship between the load P and moment M at point B (see Fig. 2). Equation (8) reduces to:

$$y_0/y_0 = 1 = 1/P_0\,(P + \beta M) \tag{13}$$

where $M = PL$ or

$$P/P_0 = 1/(1 + \beta L) \tag{14}$$

A plot of eq. (14) will represent a family of curves all having a maximum positive value at $L = 0$ and approaching zero as L approaches infinity (Fig. 5). It can readily be seen that for large values of β, the curves approach zero more rapidly.

We can also plot the moment, $M = PL$, for each of the curves in Figure 4 versus L by obtaining the product PL of each point (see Fig. 6).

From Figures 5 and 6 it can be concluded that when a peel test is conducted as shown in Figure 2, the load P will have a maximum value at the beginning of the test but will decrease rapidly as the specimen peels and L becomes longer. At the same time the moment PL increases from zero to a maximum at $L = \infty$. The value of

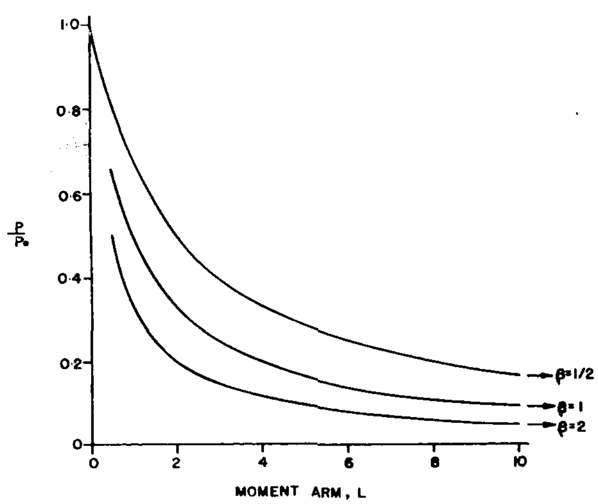

Fig. 5. Variation of peeling load versus moment arm for various values of β.

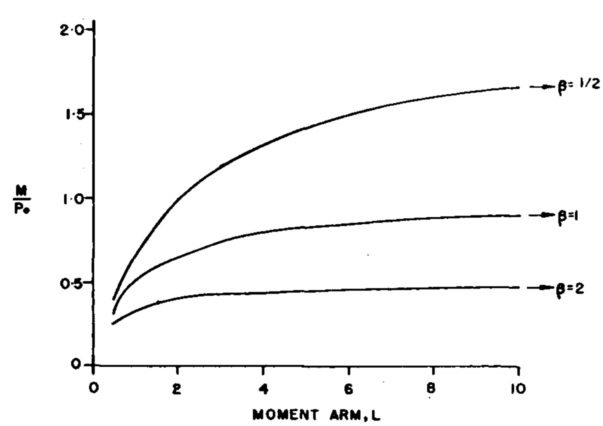

Fig. 6. Variation of peeling moment versus moment arm for various values of β.

maximum moment can be obtained from eq. (13) as follows:

$$P_0 = P + \beta M \quad (15)$$

$$M = (P_0 - P)/\beta \quad (16)$$

$$\lim_{P \to 0} M = M_0 = P_0/\beta \quad (17)$$

hence as P approaches zero, M approaches a maximum asymptotic value of P_0/β. This maximum value is called M_0 and was previously similarly derived in eq. (11).

Mathematical Definition of Peel Strength

Another form of eqs. (7) and (17) which is more meaningful can be obtained if the external load P_0 and deflection y_0 are expressed in terms of the stresses and strains in the adhesive. This can be done by equating the external and internal forces in a peel specimen shown in Figures 2 and 3, i.e.,

$$P_0 = \int_0^\infty S dx \quad (18)$$

Assuming that the adhesive obeys Hooke's law so that the stresses S at each point are proportional to the strains, $\epsilon = y/t$ we can write:

$$E_0 = S/(y/t) = S_0/(y_0/t) = S_0/\epsilon_0 \quad (19)$$

The deflection curve for y, eq. (9), $y/y_0 = e^{-\beta x} \cos \beta x$, of the skin at the start of the peel test together with eq. (19) can now be used to eliminate S from eq. (18):

$$P_0 = \frac{E_0 y_0}{t} \int_0^\infty e^{-\beta x} \cos \beta x \, dx \quad (20)$$

Although this integral has an indefinite limit it has a finite solution, i.e.,

$$P_0 = E_0 Y_0/2t\beta \quad (21)$$

By employing eq. (21) in combination with Hooke's law relationship [eq. (19)], the definition of β [eq. (7)] and M_0 [eq. (17)] can be rewritten in terms of stresses and strains rather than loads and deflections, i.e.,

$$\beta = \sqrt[4]{E_0/4EIt} \quad (22)$$

and

$$M_0 = \frac{S_0}{2\beta^2} = \frac{S_0}{\sqrt{E_0/EIt}} = \frac{S_0}{\sqrt{(S_0/\epsilon_0)/EIt}} = \sqrt{EIt(S_0\epsilon_0)} \quad (23)$$

Equation (23) will be accepted as a *definition of peel strength.* Qualitatively this relationship explains many of the factors which affect the peel strength concept; for example:

1. Effect of skin thickness on peel strength. An increase in skin thickness will increase the moment of inertia I in eq. (23) and hence increase the peel strength M_0. This is a generally accepted fact, although it should be observed that this variation occurs in accordance with the square root of I and hence the $^3/_2$ power of the thickness.

2. Effect of skin material on peel strength. Comparing the peel strengths of specimens having steel or aluminum skins of the same gage, eq. (23) predicts that the former will be greater than the latter and that this relationship will vary as the square root of the two moduli.

3. Effect of adhesive material or its thickness on peel strength. Other things being equal, eq. (23) predicts that peel strength of an adhesive increases with thickness and decreases with modulus and that this also varies as the square root of these properties.

4. Effect of tensile strength of adhesive bond on peel strength. This has been a debatable effect because experiment and observations have indicated that in many cases high tensile strength adhesives result in low-peel strength metal-bonded constructions. However, even this apparent contradiction can be explained if it is understood that not tensile strength but tensile strength in the presence of a notch or notch tensile strength S_0 of an adhesive determines the maximum value that the peel strength M_0 can attain. Thus, a brittle high-tensile strength adhesive will have a low-notch tensile strength and hence a low peel strength. Rubber-based adhesives improve this condition but these are less desirable from a creep standpoint. Furthermore, at very low temperatures they become brittle and less resistant to peeling. Also their stress-strain behavior is not linear so that the assumption that the metal skin is bonded to an elastic foundation would not be exactly accurate. These considerations lead to the implication that peel strength is related to tearing strength and has significance only for a bonded specimen which has already failed, i.e., contains a notch in the bond. So important is this distinction that it may be considered as a verbal definition of peel strength or a rule by which a test may be judged whether it is related to a peeling or not, i.e., "peel strength is the resistance of an adhesive bond to *further* failure." Since most other adhesive bond strength tests such as bending, shear, compression, creep, and fatigue are all conducted on unfailed panels, there does not seem to be any valid reason for the hope that peel strength is proportional to any of these other properties and hence may be correlated with, or replaced by, one of them. Furthermore, even in most peel tests the first point of the test should not be considered because previous failure had not yet occurred.

It is interesting to note in eq. (23) that for a series of peel specimens which have the same geometry and composition, β should be a constant and hence the peel strength will be a function of S_0 only, the initial tensile stress in the presence of a notch. Another form of this equation relates peel strength to the area under the notch tensile stress-strain curve for an adhesive.

REVIEW OF SUITABLE PEEL TEST METHODS

Edge Bending Load Peel Tester

De Bruyne and Houwink[2] have mentioned the British bending peel test, Figure 7, in which a central load is applied to a bar to which a stiff beam is cemented to a central portion on the lower side.

To eliminate the uncertainty of peeling taking place alternately at the two ends instead of uniformly, in the case of the bonded panel construction, one edge can be peeled preferentially as shown in Figure 8. The type of peeling load curve which results is like that of Figure 5.

If a peel test is conducted as shown in Figure 8, the only data required is the reaction at A, P_0, and the change in distance between A and B, y_0, at the start of peeling. Of course, in order to classify as a genuine peel test a fine notch must be present at A when P_0 is obtained, but generally if the specimen is left unnotched a crack will appear at A in the course of the test just before failure occurs and this important condition will have been fulfilled. From these readings and flexural rigidity EI of the skin the peel strength can be calculated:

$$M_0 = \frac{P_0}{\beta} = \frac{P_0}{\sqrt[3]{P_0\, y_0/2EI}} \tag{24}$$

Needless to say, the experimental difficulties of measuring y_0 in eq. (24) are formidable. However, this difficulty can be avoided by plotting simultaneous values of P and L from the test in Figure 8 and curve fitting equation (14):

$$P/P_0 = 1/(1 + \beta L) \tag{25}$$

to the experimental data as shown, for example, in Figure 5. Only the peak values of P/P_0 need be plotted and an average curve drawn through the experimental points. Using the coordinates P_1, L_1, and P_2, L_2 from two convenient points of the average curve proceed as follows:

$$P_1 + \beta P_1 L_1 = P_0 \tag{26}$$

$$P_2 + \beta P_2 L_2 = P_0 \tag{27}$$

$$P_1 - P_2 + \beta(P_1 L_1 - P_2 L_2) = 0 \tag{28}$$

$$\beta = \frac{P_1 - P_2}{P_2 L_2 - P_1 L_1} \tag{29}$$

by definition peel strength is defined by the relation:

$$M_0 = P_0/\beta \tag{30}$$

$$M_0 = \frac{P_1 + \beta P_1 L_1}{\beta} \tag{31}$$

$$M_0 = \frac{P_1 + \dfrac{P_1 - P_2}{P_2 L_2 - P_1 L_1} P_1 L_1}{\dfrac{P_1 - P_2}{P_2 L_2 - P_1 L_1}} \tag{32}$$

$$M_0 = \frac{P_1 P_2 L_2 - P_1 P_2 L_1}{P_1 - P_2} \tag{33}$$

$$M_0 = P_1 P_2 \left(\frac{L_2 - L_1}{P_1 - P_2}\right) \tag{34}$$

Hence, if preferred, (34) may also be used to determine the average peel strength of a bonded panel.

The advantages of the edge bending load peel test are as follows.

1. The factor β, and hence the effects of the skin and adhesive thicknesses and materials, is taken into consideration.

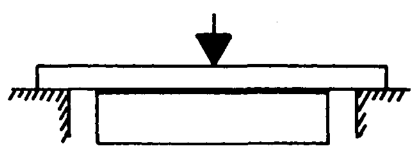

Fig. 7. Bending peel test.

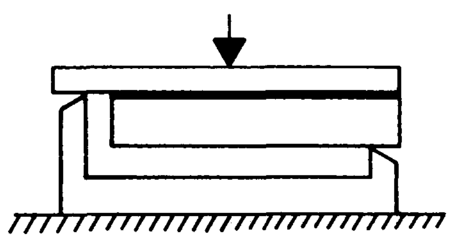

Fig. 8. Edge bending peel test.

2. Very little equipment is required, the only necessary elements being a specimen which can be specially made or cut from a production part, a simple peel jig, a scale, and a compression testing machine. Of course, with a slight modification in the method of loading the edge of the specimen, a tensile testing machine can be used as well.

3. The recorded forces and moment arms are a measure of the peel strength directly, as no additional force is required to deform the metal skins.

4. Within reason there is no limitation on the maximum thickness and width of the metal skins which can be peeled.

5. Curvature of the skin at the point of peel is allowed to assume its own natural shape, and futile attempts to force it to conform to a circular shape are avoided.

The disadvantages of the edge bending peel test are as follows.

1. The measurement of the moment arm L of the edge bending load is complicated by the uncertainty of location of the crack. Furthermore, the only practical measuring instrument is a scale which must be read by an operator, and hence autographic records are not possible.

2. The use of this method is limited to thick-skinned bonded panels. The minimum thickness depends on too many factors to permit stating an actual value; however, it is generally limited to those skins which are not stressed plastically during the test.

The T Peel Test

In England an interesting peel test called the "Chadwick peel test" by de Bruyne[2] has been devised for testing soldered strips of metal. Independently originated by the author for metal adhesives, it has been termed the "T peel test" in this country.[3] This test is shown in Figure 9.

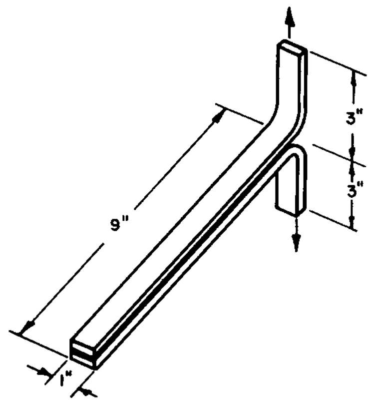

Fig. 9. The T peel test.

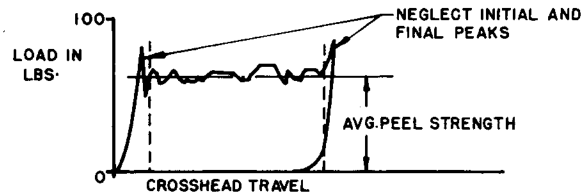

Fig. 10. Autographic peel test record.

Figure 10 shows a typical autographic load curve of the T peel test wherein peel strength is taken as the average value of the center portion of the curve. This method of test is primarily intended for determining the comparative peel resistance of adhesives in any laminated assemblies where the adherends are flexible enough to bend through an angle of at least 90 to 180° without breaking. It was adopted for metal adhesive peel testing when it became apparent that the various drum-type testers were not only more complicated but also less meaningful for the purpose. The specimen for the ASTM D-14 peel test consists of two 0.032 in. 24ST3 6 × 12 in. sheets with 6 × 9 in. bonded areas. This panel can then be sheared into 1 × 12 in. strips which can be tested individually or it can be pulled as one piece. In either case the 3-in. unbonded areas are bent at right angles by hand, and pulled in any standard tensile tester with autographic recording facilities. The test receives its names from the T shape of the specimen while it is being tested.

After the failure has been started and a constant radius of curvature obtained, the load required to continue peeling will remain fairly constant. No corrections are required for the force required to bend the face. The specimen will fail symmetrically unless different thicknesses of faces are used. Even then the test is not impractical, however, the failures will tend to become adhesive on the thinner face. With equal faces the radii of curvature will vary with the peel strength of the adhesive used and this property of the test favors strong adhesives and penalizes weak ones. This increases the sensitivity of the test and is not considered to be a disadvantage. In any case the same thing occurs in the climbing drum peel test.

The T peel test is not practical for brittle low peel strength adhesives. This is not so much a reflection on the test as it is an expression of the fact that peel strength is a property that brittle adhesives do not have. If a peel test were to rate such adhesives favorably it would not be a fair test. Many rubber-based adhesives are very brittle and notch sensitive at low temperatures. Their radical drop in peel strength is dramatically demonstrated with the T peel test. Low or high temperature tests are easy to conduct. Specimens can be removed or inserted into the work chamber in a matter of seconds thereby insuring shorter temperature restabilizing periods.

The T peel test is well suited for production quality control testing also. Peel specimens in practically any widths and gages can be bonded simultaneously with a bonded assembly or cut from it if an excess is allowed. If the entire length of strip is bonded, one end can be separated easily after a short immersion in Dry Ice and alcohol by means of a light blow with a hammer.

Four-Inch Diameter Drum Peel Tester

The 4-in. diam. drum peel tester,[4] or its equivalent, was at one time widely used. In its operation, the initially straight face of the sandwich panel specimen is gradually wrapped around the periphery of a rotating 4-in. diam. drum (Fig. 11), and the average torque required to overcome the resistance of the adhesive bond is registered and reported as peel strength.

The advantages of the 4-in. diam. drum peel tester are as follows.

1. The drum can be used in conjunction with a tensile testing machine thereby utilizing the load weighing mechanism of available equipment.

2. A commercial cantilever torque wrench can be secured to the axis of the drum and a less accurate but portable peel tester can be devised.

3. Peel strength is based on an average reading over a considerable length of the specimen.

The disadvantages of the 4-in. drum peel tester are as follows.

1. The measured torque not only includes the resistance of the adhesive to peeling but also the torque required to bend the face around the periphery of the drum. Furthermore, the magnitude of the torque to bend the face not only increases with its thickness but also its length and hence limits the use of this test to thin gage or flexible faces less than one drum circumference in length. Some investigators have suggested correcting the peel strength readings by subtracting previously determined values of the torque to bend the face alone from the total torque at each point. However, this procedure is doubtful because the geometry of the face, and hence the torque required to bend it alone is not the same in the two cases. It can be seen that if the correction is large and the peel strength small, the errors introduced would be high.

2. Although the circular drum was intended to force the face to conform to a circular, and hence constant, shape while being peeled from the core, this condition is theoretically impossible and a small opening or separation between the drum and bonded face is always visible during peeling (see Fig. 1). This opening has a significant influence upon the magnitude of the peel strength, and unfortunately, variations in its size and shape during the test produce large fluctuations in the peel strength. Some investigators have reported increased values of peel strength by subjecting the upper face to tension by means of dead weights and pulleys as shown by the force F in Figure 11, thereby decreasing the size of the opening. In this case, of course, the additional torque on the drum required to raise the weight must be subtracted from the total apparent peeling moment in order to obtain the actual peel strength. In any event, this method introduces additional complications which will be discussed further in the description of the 4-ft. diam. peel tester.

3. The factor β is not included in the calculations of peel strength, and therefore the effects of face thickness and material are not taken into consideration.

4. The minimum values of the autographic torque are not minimum values of peel strength but the results of sudden relaxing of the face and changes of the opening whenever a strong point has been ruptured. Hence, they should not carry any weight in determining the average peel strength and only the maximum points should be used.

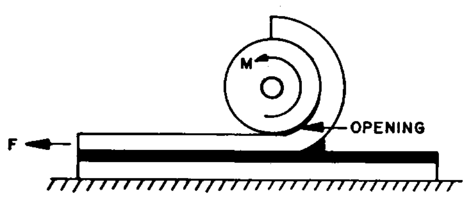

Fig. 11. Four-inch diameter drum peel tester.

Four-Foot Diameter Drum Peel Tester

The 4-ft. diam. drum peel tester developed by the author[5,6] is similar in operation to the 4-in. diam. drum peel tester, but it attempts to improve the accuracy of its measurements by decreasing the amount of bending absorbed by the face as it is peeled and also by decreasing the size of the opening between the drum and the face. Since it ob-

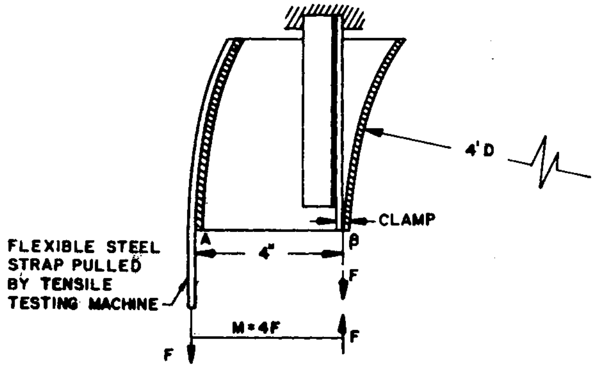

Fig. 12. Four-foot diameter peel tester.

viously is impractical to employ a tester using the entire 4-ft. drum, only a small portion or sector of the drum equal in circumference to the length of the peel specimen is necessary. The shape of the sector and the method of applying the torque are shown in Figure 12.

In operation, one end of the specimen is fastened to one crosshead of a tension testing machine and the flexible steel strap is pulled by the other crosshead. Under these conditions the boxlike sector rotates and travels upward. If an autographic curve is plotted during the test, the peel strength is taken as the average product of the peak values of the tensile force F and the moment arm, 4 in. It is interesting to note that the force F at point A in Figure 12 is equivalent to a tensile force F and a moment $4F$ at B. This can be shown by placing equal and opposite forces F at B. The addition of the tensile force at B tends to reduce the size of the opening between the tester and the face of the specimen and in this respect is an improvement over the 4-in. diam. drum peel tester which requires an additional load to accomplish the same result. By a suitable modification of the method of loading, the diameter of the 4-ft. drum could have been 4 in. or any other size desired. The advantages and disadvantages of both circular drum peel testers are the same in all other respects.

The Climbing Drum Peel Test

The climbing drum peel tester was first suggested nine years ago by the author[5] for testing honeycomb sandwich specimens and was latter applied by the Forest Product Laboratory[7,8] to peel testing of metal adhesives as well as honeycomb sandwiches. It consists of a hollow lightweight drum with two diameters similar to a spool (see Fig. 13).

The smaller diameter, usually 4 in., is attached to one face of the specimen and the larger diameters,

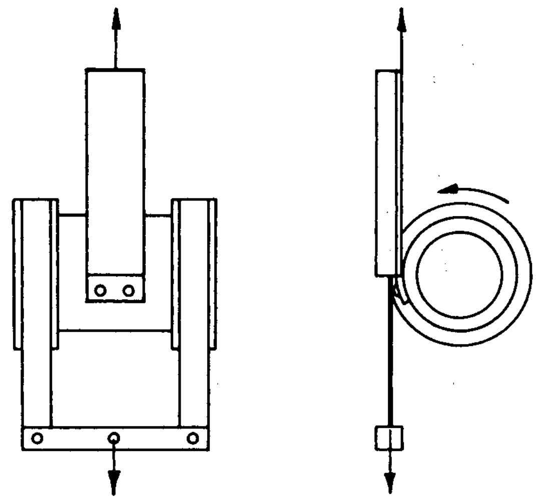

Fig. 13. Climbing drum peel tester.

usually $4^1/_2$ or 5 in. are rotated counterclockwise by means of a crossbar and flexible steel straps. As the face is peeled from the heavier backing strip, the drum moves upward, whence the name, "climbing drum peel tester."

If an autographic record of the load versus crosshead travel is obtained, it is fairly uniform once peeling has started. However, this record also includes the pull required to counteract the weight of the tester as well as the pull required to bend the facing. Correction of these forces is approximated by preliminary testing of a single strip of unbonded facing material.

If one of the two bonded metal strips were not thicker and heavier than the other, a peel test could not be conducted because both would simply be wrapped around the drum. This extra gage not only increases the cost of each specimen but also the use of strips with two different thicknesses has a serious effect on the type of adhesive failures obtained.

Whenever two bonded strips are peeled apart, the type of failure produced *tends to be* adhesive failure on the strip with the smaller radius of curvature. On the other hand, if the strips are peeled apart symmetrically with the same radius of curvature, the failure will be either adhesive or cohesive, whichever is the weaker. Hence the climbing drum peel test with its unequal faces favors adhesive-types failures.

CONCLUSIONS

Now what can be finally concluded from the preceding about the "peel strength" of a metal adhesive bond and about peel testing in general?

For one thing, it is known that as far as the adhesive joint itself is concerned, its peel strength can be narrowed down to a single physical property, namely, the area under its tensile stress-strain curve. However, the thing that differentiates the peel test from, say, a butt tension test, is that there must first have been a partial failure (i.e., a notch) around the periphery of the joint so that the ultimate tensile stress which is reached in the root of the notch is really the notch tensile stress. Because a metal adhesive joint can fail either in cohesion or adhesion, a notch or peel failure can progress through the body of the adhesive or along either of its faying surfaces. Hence the peel strength is determined by whichever of these three notch tensile strengths is the lowest. If we compare the relative importance of the notch tensile strength with, say, the modulus or thickness of the adhesive or the adherends, we find the former to be the more importance because it is raised to the first power in the definition of peel strength whereas the latter terms all appear under the square root sign.

Comparing some of the various known peel tests, it is found that they each have their own advantages and disadvantages, but as long as one so standardizes any test that all important variables are kept constant, then they should all provide the same qualitative measure of either the notch tensile strength of the adhesive bond, or the work required to complete the failure of a partially failed bond. Although the author does not now know of a good method for measuring either of these properties in a simple and direct way such as metallurgists have in the notch tensile test, he believes that if such a method could be found, it would quickly replace all the other present peel tests.

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Synopsis

In this paper the subject of peel is divided into two parts: (*1*) A mathematical determination of peeling stresses in an adhesive bond due to the applied peeling loads which leads to a mathematical definition of "peel strength." (*2*) A review of suitable peel test methods examined in the light of this definition. Employing the assumption that the adhesive bond behaves as an ideal homogeneous elastic material under load, the classical derivation of the deflection of a loaded beam on an elastic foundation is applied to the calculation of peel strength of a metal adhesive. This theory results in a mathematical definition of peel strength and offers a reasonable explanation of the effects of the important variables such as metal and adhesive thickness and strength properties and provides a basis for the comparison and evaluation of the few testing methods presently in use.

Résumé

On divise le sujet de l'enlèvement d'une couche déterminée en deux parties: (*1*) la détermination mathématique des tensions d'arrachement d'un lien adhésif dues à l'application de poids, qui mène à la définition mathématique de la force d'enlèvement; (*2*) la revue des diverses méthodes expérimentales adéquates à cette mesure à la lumière de la définition. En admettant que le lien adhésif se comporte comme un matériau élastique idéal et homogène sous l'action d'un poids, on applique la déduction classique de la déflection du trajet chargé à une base élastique au cas du calcul de la force d'enlèvement d'un adhésif métallique. La théorie donne une définition mathématique de la force d'enlèvement et fournit une explication raisonnable des effets des variables importantes, telles l'épaisseur du métal et de l'adhésif et les propriétés de ténacitè; elle donne une base à la comparaison et à l'évaluation des quelques méthodes d'essais actuellement en usage.

Zusammenfassung

In der vorliegenden Mitteilung wird der Ablösevorgang in zwei Abschnitten behandelt: (*1*) Eine mathematische Bestimmung der Ablösungsspannungen in einer Adhäsionsverbindung, welche durch die angewendete Ablösungsbelastung verursacht werden; das führt zu einer mathematischen Definition der "Ablösungsfestigkeit." (*2*) Ein Überblick über die im Lichte dieser Definition kritisch betrachteten, brauchbaren Ablösetestmethoden. Unter der Annahme, dass sich die Adhäsionsverbindung unter Belastung als ein ideales homogenes elastisches Material verhält, wird die klassische Ableitung der Ablenkung eines belasteten Balkens auf einem elastischen Fundament zur Berechnung der Ablösungsfestigkeit eines Metall-Adhäsionsmittels verwendet. Diese Theorie führt zu einer mathematischen Definition der Ablösungsfestigkeit und bietet eine hinlängliche Erklärung des Einflusses wichtiger Variabler, wie Metall- und Klebschichtdicke und Festigkeitseigenschaften und liefert eine Grundlage für Vergleich und Bewertung der wenigen, gegenwärtig verwendeten Testmethoden.