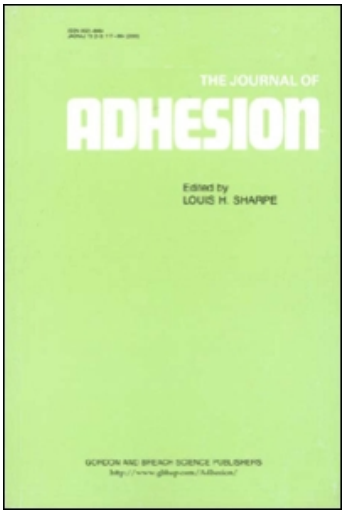

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Fracture Mechanics: A Tool for Evaluating Structural Adhesives

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Fracture Mechanics: A Tool for Evaluating Structural Adhesives†

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Some of the basic concepts of fracture mechanics are reviewed, emphasizing those aspects of the discipline that are applicable to the evaluation of structural adhesives.

Test methods for measuring both the plane strain fracture toughness of joints, i.e. $\mathcal{G}_{IC}$, and the resistance of joints to crack extension in the presence of an aggressive environment, i.e. $\mathcal{G}_{ISCC}$, are also described.

INTRODUCTION

Structural adhesive joints are more limited in the ways they can fail than are monolithic structures of metal or plastic. The latter may fail because they are too springy, i.e., their elastic deformation is excessive, or they may permanently deform if their inelastic strength properties are deficient, or they may fracture. Adhesive joints, on the other hand, are limited to such a small fraction of the total volume of a structure that even large elastic or inelastic deformations are generally tolerable since they would be insignificant in the deformation of the over-all structure. Hence, prevention of fracture is the critical problem.

Designing to prevent fracture in adhesive joints can be done in a manner that is analogous to designing to prevent excessive deformation. To be

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certain that a structure will not deform permanently in service requires two types of information, as shown in Table I: a stress analysis of the part is needed to determine the maximum stress, σ_1, that might be encountered in service, and this stress must be compared with a material property, e.g., the yield strength, σ_Y, to determine whether or not the design stresses can be tolerated.

What are the quantities analogous to σ_1 and σ_Y for prevention of brittle fracture? In seeking these, it is helpful to examine the surfaces of fractures that occur in service. On doing this, it becomes apparent that fracturing, unlike flow, is associated with the occurrence of pre-existing flaws that are introduced in manufacturing or service. Fractures form progressively by the extension of these flaws, which in adhesives might be air bubbles, dirt or unbonded regions. Further, structural adhesives are inherently brittle when tested uniaxially, and this characteristic is accentuated when they are used in thin layers where deformation is further restricted because of the multiaxial stress state imposed by the proximity of high modulus adherends.

The combination of fracturing with very little permanent deformation, and crack growth from pre-existing flaws suggests that fracturing of adhesive joints can be described by the techniques of fracture mechanics. With this discipline, two quantities can be defined: one is a parameter that describes the stress field at a crack tip, and the other, the fracture toughness, identifies the critical value of this parameter at which a slow moving or stationary crack jumps ahead. The first of these is analogous to the stress σ_1 and the second to the yield strength, if σ_Y is considered as the critical stress at which a slowly deforming member suddenly deforms rapidly under the action of a continuously increasing load.

DEFINITIONS OF FRACTURE MECHANICS TERMS

To describe these two fracture parameters, it is necessary to examine the stress at the tip of a crack, and determine how these stresses might cause the crack to extend. Just as a material can flow inelastically under the action of a tensile or shear force, fracture can occur in more than one mode. If a crack is made to extend by a tensile force acting in a direction normal to the crack surface, Figure 1a, fracturing is said to occur by Mode I. If the crack extending force is one of forward shear, Figure 1b, fracturing is by Mode II, and for side-wise shear, Figure 1c, fracturing is by Mode III. Since most materials are far less resistant to crack extension under the action of a normal load than under a shear load, Mode I fracturing has been of most interest in fracture mechanics.

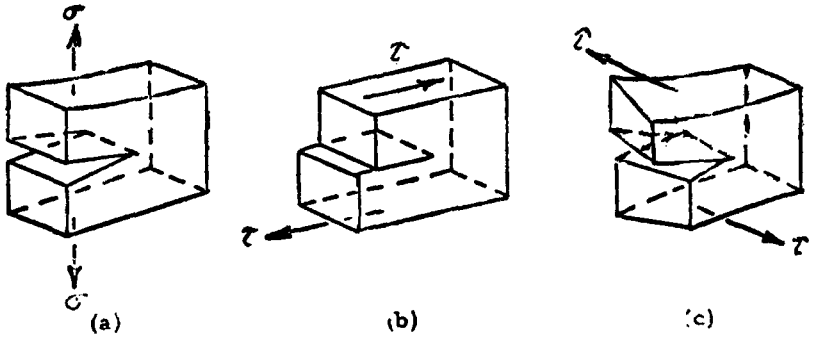

FIGURE 1 Fracture modes under which a crack can extend

A crack might be expected to extend by any of these modes when the stresses at the crack tip attain some critical value. Describing these stresses is readily done since the complete stress field at the tip of the crack is identified by a single parameter. For instance, for Mode I cracking, Irwin[1] has shown that

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} f_1(\theta)$$

$$\sigma_x = \frac{K}{\sqrt{2\pi r}} f_2(\theta) \qquad (1)$$

$$\tau_{xy} = \frac{K}{\sqrt{2\pi r}} f_3(\theta)$$

and

$$\sigma_z = \nu(\sigma_y + \sigma_x) \qquad \text{for plane strain}$$

$$\sigma_z = 0 \qquad \text{for plain strain}$$

where ν = Poisson's ratio
and the stresses, r and θ are indicated in Figure 2.

The parameter K is a function of the specimen or structure shape, crack length, and applied load. It is seen to have the dimensions of (pounds/inch^2) (inches$^{1/2}$) in the British system and is referred to as the stress-intensity-factor. When a continuously increasing load is applied to a pre-cracked structure, K increases, and at its critical value, the stationary or slow moving crack abruptly jumps ahead. This critical value of K, the fracture toughness, is denoted as K_C. The applied value of K, i.e., K_i, then can be considered as analogous to the design stress σ_1 and the critical value K_C, analogous to σ_Y.

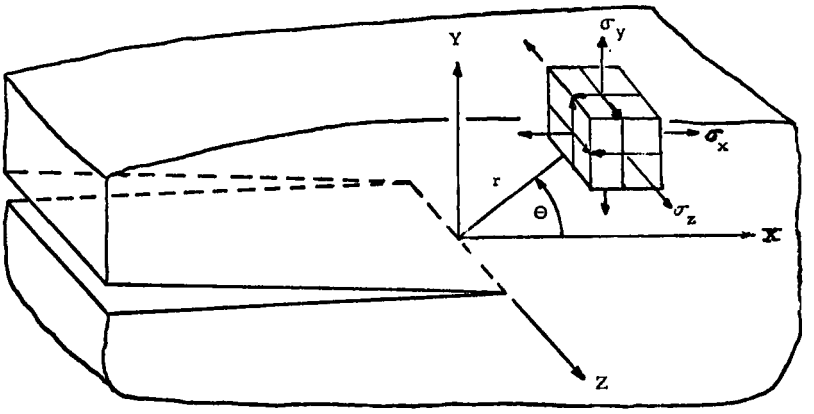

FIGURE 2 Designation of stresses near a crack tip

Like σ_Y, K_C is dependent on temperature and loading rate. The two values are unalike, however, in their response to changes in stress state. The "yield criterion" makes it possible to measure σ_Y under one state of stress, e.g., uniaxial, and from this, predict the load at which permanent deformation will occur in a structure subjected to any multi-axial stress system. The existence of a "yield criterion" implies that the flow properties of all materials respond similarly to a change in stress state. Such is not the case for fracturing. As the thickness direction constraint at a crack tip is increased, the stress state approaches one of plane strain, and K_C decreases. The lower limiting value of K_C for plane strain fracturing is denoted K_{IC}, and is thought to be a material property. The value of K_{IC}, i.e., the measure of fracture resistance under a condition of plane strain, cannot be predicted from K_C, the measure of fracture resistance under plane stress. Because of their analogy with σ_1 and σ_Y, K_1 and K_{IC} are added to Table I.

TABLE I
Information required to prevent ductile or brittle fracture

Information from stress analysis	Material property
Ductile failure	
σ_1	σ_Y
Brittle failure	
K_1	K_{IC}
$\mathcal{G}_1$	$\mathcal{G}_{IC}$
Stress corrosion cracking	
$\mathcal{G}_1$	$\mathcal{G}_{ISCC}$

Similar considerations would lead to limiting critical values of K for fracturing in Mode II or III, and these are identified as K_{IIC} and K_{IIIC}. Very few measurements of the latter have been made, however.

In attempting to evaluate K_I and K_{IC} in adhesive joints, the need for a stress analysis at the crack tip poses a serious limitation. For monolithic materials, on which fracture mechanics has been most commonly used, the stress field at the crack tip for a number of specimens or structural shapes has been developed (see ref. 2). The analyses that would be required to describe the stress field at the tip of a crack that lies in a thin layer of a low modulus material near a high modulus one would be much more involved. Consequently, it is convenient to define fracture toughness in terms of energy rather than stresses for heterogenous systems. Indeed such a definition is a direct outgrowth of Griffith's[3] work on glass.

The strain-energy-release-rate, $\mathcal{G}$, is defined as the energy required to extend a pre-existing crack an infinitesimal unit of area. Since adhesives are brittle, cracks extend under a condition of plane strain, i.e., with essentially no contraction in the thickness direction, so that the symbol for fracture toughness in terms of strain-energy-release rate is $\mathcal{G}_{IC}$.

An expression for $\mathcal{G}_{IC}$ can be developed in a straight-forward manner by considering a pre-cracked specimen of the type shown in Figure 3a. In order to obtain the energy lost to the growing crack we must examine the energy stored in the system before and after crack extension. This can be done by using the load, P, displacement, Δ, diagram Figure 3b, and calculating the total energy before and after a finite amount of crack motion. This difference in total energy becomes, in the limit, the value of $\mathcal{G}_{IC}$. To determine $\mathcal{G}_{IC}$, we first write the total energy, $U_{(a_1)}$, that will be available to

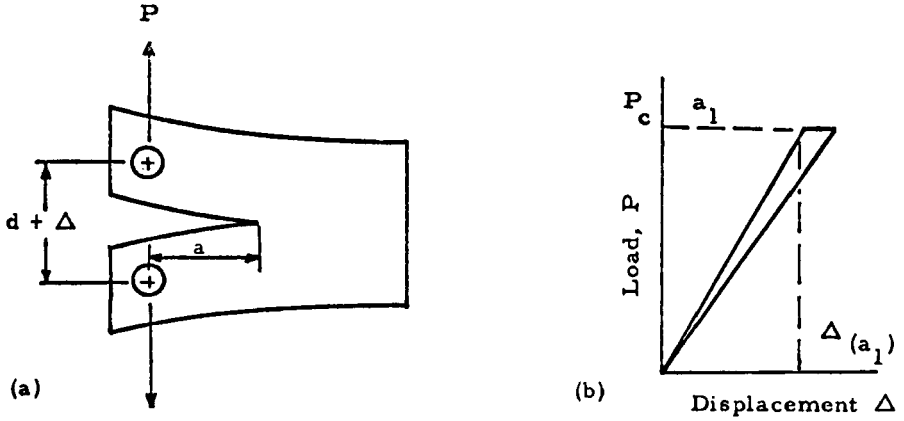

FIGURE 3 Schematic drawing of (A) crack extending under load, (B) P–Δ diagram

the specimen for an initial crack length, a, and at the critical load, P_c, where the crack will begin to extend, viz:

$$U_{(a_1)} = \frac{P_c \Delta_{(a_1)}}{2}$$

The reciprocal slope of the P-Δ line is defined as the compliance of the specimen, characteristic of our crack length:

$$C_{(a_1)} = \Delta_{(a_1)}/P_c$$

Substituting this value of compliance into our initial expression for total energy we obtain:

$$U_{(a_1)} = \frac{P_c^2 C_{(a_1)}}{2}$$

If we assume the crack extends infinitesimally at constant load the expression for the energy lost to the growing crack per unit of area for a crack of unit width, b, is

$$\mathcal{G}_{IC} = \frac{dU}{dA} = \frac{dU}{bda} = \frac{P_c^2}{2b}\left(\frac{\partial C}{\partial a}\right)_P \tag{2}$$

For loads less than P_c, the applied strain-energy-release rate is identified as $\mathcal{G}_1$. It is seen that in the British system, $\mathcal{G}$ has the units of in.-lbs./in.^{2} which reduces to lbs./in. so that $\mathcal{G}$ is also described as the crack-extension force.

Both of these measures of fracture toughness, K_{IC} and $\mathcal{G}_{IC}$ have the capability of predicting the load under which a structure will fail in service. If $\mathcal{G}_{IC}$ is evaluated by means of a laboratory test for a specific adhesive system, and the service structure made with this adhesive can be analyzed to obtain the value of $\mathcal{G}_1$, the structure obviously will not fail in service if $\mathcal{G}_i < \mathcal{G}_{IC}$. Even in those cases where an analysis is not possible $\mathcal{G}_{IC}$ can be used for material evaluation to rate adhesive joints.

Since K_{IC} and $\mathcal{G}_{IC}$ are both measures of the same property, one would expect these to be related, and indeed Irwin has shown this to be the case :

$$\mathcal{G} = \frac{K^2}{E} \qquad \textit{for plane stress}$$

$$\mathcal{G} = \frac{K^2(1 - \nu^2)}{E} \qquad \textit{for plane strain}$$

where

E = Young's modulus.

TEST SPECIMEN GEOMETRY

To evaluate $\mathcal{G}_{IC}$ for an adhesive, two stiff adherends can be joined together by a layer of adhesive as shown in Figure 4a. If the adhesive is pre-cracked and the specimen loaded through the two pin holes, a P-Δ diagram of the type shown schematically in Figure 4b is obtained. To evaluate $\mathcal{G}_{IC}$ the

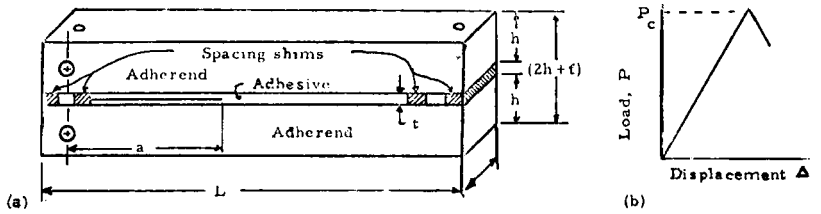

FIGURE 4 Adhesive specimen used for measuring G_{IC}; Typical load-displacement diagram obtained on (a).

critical load P_c is read from the diagram, and the quantity dC/da in Eq. (2) is calculated from the formulas of strength of materials by considering the specimen as consisting of two cantilever beams[4] with uniform height, h, Young's modulus, E, and span equal to the crack length a. Hence,

$$\frac{dC}{da} = \frac{8}{Eb}\left[\frac{3a^2}{h^3} + \frac{1}{h}\right] \tag{3}$$

The first term in the bracket is the contribution to compliance due to bending, and the second one the contribution due to shear. Experimental compliance calibrations showed that the actual specimen deflected more under a given load than the cantilever beam formula predicted. This additional deflection is due to some rotation of the beam at the assumed "built-in" end. The nature of this additional displacement is such that the beam appears a fixed amount longer than the actual crack length. This apparent extra length denoted a_0 can be simply added to the beam (or crack) length in expression (3) and thought of as a "rotation" correction to the "built-in" beam.

Hence:

$$\mathcal{G}_{IC} = \frac{4P_c^2}{Eb^2h^3}\left[3(a + a_0)^2 + h^2\right] \tag{4}$$

If the specimen in Figure 4a is reasonably long, it can be loaded to P_c to obtain a value of $\mathcal{G}_{IC}$. After the crack jumps, the specimen can be reloaded to obtain a second value of $\mathcal{G}_{IC}$, etc. The P-Δ diagrams resulting from such a series of tests is shown in Figure 5. As the crack gets longer, i.e., a increases,

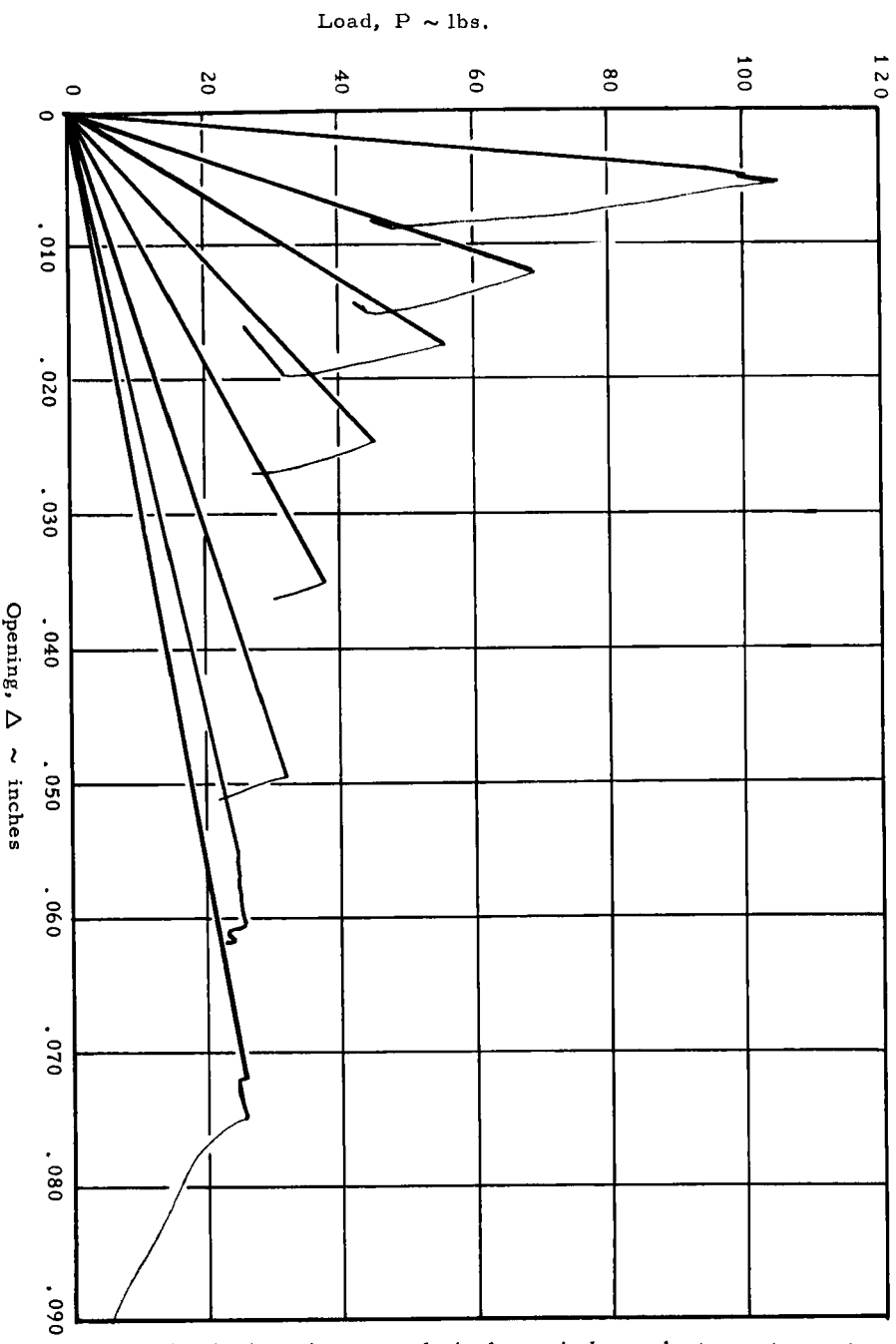

FIGURE 5 Eight load-opening curves obtained on a single sample at room temperature for aluminum-epoxy-aluminum

P_c decreases to maintain a constant value of $\mathcal{G}_{IC}$. Obviously, the calculation of $\mathcal{G}_{IC}$ by Eq. (4) requires that one monitor both P_c and a for each calculation of $\mathcal{G}_{IC}$. Testing can be simplified, however, if the specimen is contoured so that the compliance changes linearly with crack length. If dC/da is a constant, the relationship between $\mathcal{G}$ and P is independent of a, and evaluating $\mathcal{G}_{IC}$ only requires that one monitor the critical load, P_c, as the crack extends.

To develop a linear compliance specimen, its height is varied so that the quantity $(3a^2/h + 1/h)$ in Eq. (3) is constant. Hence,

$$\frac{3a^2}{h^3} + \frac{1}{h} = m \tag{5}$$

and

$$\mathcal{G}_{IC} = \frac{P_c^2}{2b^2}\frac{8}{E}m \tag{6}$$

There are, of course, any number of m values that can be used in designing a specimen. A convenient contour for testing adhesives is $m = 90$ in.$^{-1}$, and as shown in Figure 6, this approaches a contour angle of 7°. Contoured specimens of this type are referred to as tapered-double-cantilever-beam (TDCB) specimens.

The very high m number or low taper angle would cause a large bending stress on the plane of the crack if the specimen were monolithic. Because of the low modulus of the adhesives compared with that of the adherends, these bending stresses are not significant. If bulk specimens of the adhesive materials are to be tested, the bending stresses tend to cause one or the other arm to break off. This problem is minimized by using lower m numbers, i.e., by making the beams stiffer, and adding side grooves to the specimens to direct the crack in the desired plane of extension. When the specimens are made stiffer, the description of m as given by Eq. (5) is satisfactory for designing linear compliance specimens but cannot be used to calculate $\mathcal{G}_{IC}$, because the assumptions used in beam theory become increasingly invalid as the beam height to length ratio increases. In place of m an experimental value determined from compliance calibrations and designated as m' is required. Hence, the toughness for monolithic specimens having low m values is defined as

$$\mathcal{G}_{IC} = \frac{P_c^2}{2b_n}\frac{8}{Eb}m' \tag{7}$$

where

b_n = specimen width at crack plane

b = gross specimen width

SPECIMEN MANUFACTURE

Preparation of tapered-double-cantilever beam (TDCB) specimens for adhesive testing is relatively simple. The adherends are first machined to the proper contour according to Figure 6. Extra screw holes are added to the pieces as shown so that the two half adherends can be bolted together with shims at either end. The shims determine the joint thickness. The adherends are, of course, cleaned by using the procedure applicable to the

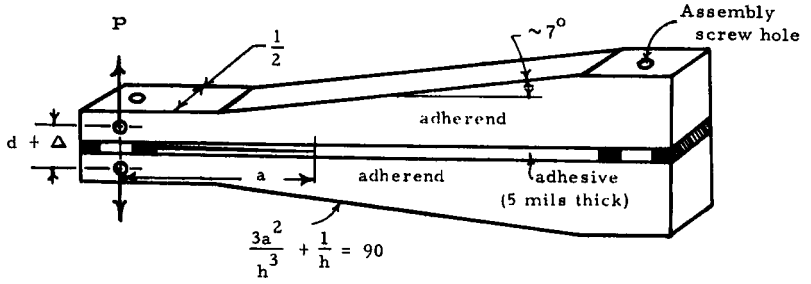

FIGURE 6 Contoured double cantilever beam adhesive specimen ($m = 90$).

specific adherend material. If primers are to be used, the bond surfaces of the cleaned adherends are coated prior to assembly. For fluid adhesives that can be poured, Teflon tape is placed on one broad side of the assembled specimen to form a dam between the two separated bond surfaces, and the adherend is poured into the dam starting from one end. For adhesives that are too thick to pour the two bond surfaces are "buttered" prior to assembly, and the excess adhesive squeezed out in the course of tightening the assembly screws to the proper bond thickness. Joints to be made from ribbon adhesive, such as scrim filled epoxies, are manufactured somewhat differently. For these, the scrim tape is placed between the cleaned and primed adherends and the assembly is placed in a fixture through which a uniform load can be applied over the entire specimen length. Shims are not used, and the joint thickness is determined by the load and temperature cycle used for curing the joint material. To align the specimen during manufacture of the joint, the two assembly screws are replaced by dowel pins.

SHAPE OF P-Δ CURVES

Evaluating $\mathcal{G}_{IC}$ can be done in any of the common tensile test machines. A continuously increasing load is applied to the specimen and a P-Δ diagram is obtained by using a directly mounted extensometer. The P-Δ diagram

obtained on an X-Y recorder, while not required to obtain $\mathcal{G}_{IC}$—only the load is needed—does serve to monitor crack extension since, at constant load, extension is a linear function of displacement. Two types of P-Δ diagrams have been obtained as shown in Figure 7. Curves of type A are

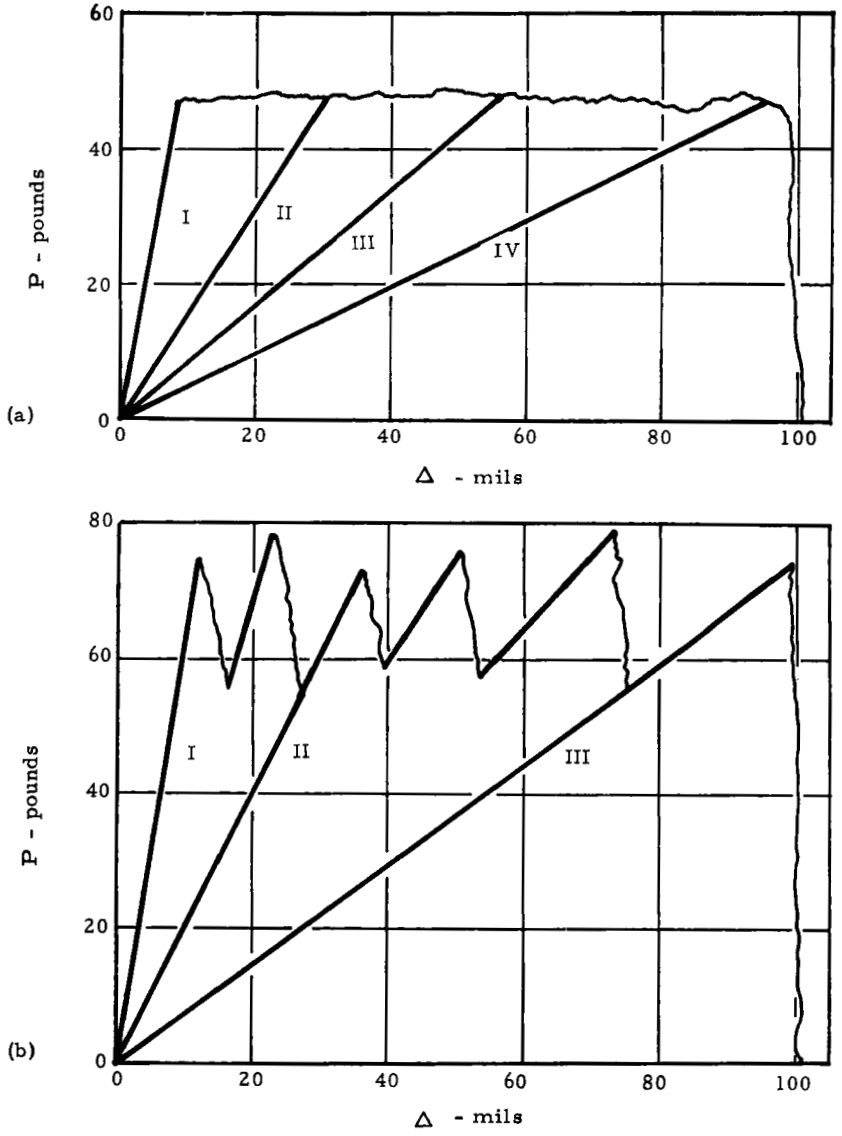

FIGURE 7 Two types of P-Δ curves: (a) Stable ("flat") behavior; (b) Unstable ("peaked") behavior. Numbers on diagrams indicate unloading and reloading lines.

obtained on rate insensitive materials, and curves of type B on rate sensitive ones. For curves B, two instability loads are apparent: the higher of these values, P_c, is used (in Eq. 6) to calculate a value of initiation toughness, $\mathcal{G}_{IC}$, i.e., the crack-extension-force to cause a stationary or slow extending crack to jump ahead. The lower critical load, P_a, is used to calculate a value to arrest toughness, $\mathcal{G}_{IA}$, i.e., the crack extension force required to arrest a running crack. For rate insensitive materials, $\mathcal{G}_{IC}$ and $\mathcal{G}_{IA}$ are identical and the crack extension rate, $\dot{a}$, is dictated by the displacement rate of the test machine crosshead, $\dot{\Delta}$. For the TDCB specimen $\dot{a}$ is proportional to $\dot{\Delta}$ at constant load and this proportionality constant is calculated as follows:

$$\frac{dC}{da} = \text{constant} = \frac{8}{Eb} m'$$

Since $$C = \Delta/P$$

at constant P

$$\frac{dC}{da} = \frac{1}{P}\frac{d\Delta}{da}$$

Hence $$da = d\Delta(Eb/8\,Pm')$$

or in terms of time derivatives:

$$\dot{a} = (Eb/8\,Pm')\,\dot{\Delta} \tag{8}$$

For curves of type B, $\dot{a}$ exceeds the $\dot{a}$ predicted from the crosshead determined $\dot{\Delta}$ at initiation. However $\dot{a}$ decreases over the interval of the crack jump, and must equal zero at the instant P_a is read. If $\dot{\Delta}$ is continuously increased until it satisfies the relationship given by Eq. (8), B type curves might be expected to change to A type.

The type of toughness data that has been obtained on a number of adhesives, tested in both the joint and bulk form, under a continuously rising load, is given in Refs. 6, 7, 8, 9, 10.

STRESS CORROSION CRACKING

Service failures generally occur in two steps. The pre-existing crack first extends slowly at a $\mathcal{G}$ value less than the critical one because of stress corrosion cracking and/or fatigue. When the crack reaches its critical length, final

separation then occurs abruptly. The limiting conditions for these steps would be an accidental overload where essentially all of the extension occurs abruptly and sustained loads, carried for long times, in which case most of extension is slow. Consequently, brittle fracture must be concerned with both slow sub-critical cracking at $\mathcal{G}_i < \mathcal{G}_{IC}$ as well as with rapid fracture at $\mathcal{G}_i \geq \mathcal{G}_{IC}$. Slow cracking of adhesive joints, under sustained load, occurs because of stress corrosion cracking (SCC) where water (generally in the form of vapor) is the aggressive environment. The techniques of fracture mechanics can also be used to study such cracking. Indeed the linear compliance feature of the TDCB specimens make it ideal for studying sub-critical crack growth. The test procedure consists simply of precracking the specimen, applying a dead load to it such that the applied load is less than the critical load for fast fracture, i.e. $\mathcal{G}_1 < \mathcal{G}_{IC}$ while it is held in the aggressive environment, and monitoring $\dot{\Delta}$ which is proportional to $\dot{a}$. When such tests are conducted and $\dot{a}$ is plotted as a function of $\mathcal{G}_i$ as shown in Figure 8, two characteristics of SCC become apparent. First, there is threshold level of $\mathcal{G}_i$, identified as $\mathcal{G}_{ISCC}$ below which SCC does not occur in a reasonable time, and above $\mathcal{G}_{ISCC}$, $\dot{a}$ is a function of $\mathcal{G}_i$. The value of $\mathcal{G}_{ISCC}$ has essentially the same use in material evaluation and design of joints to be used in an aggressive atmosphere that $\mathcal{G}_{IC}$ has for fast fracture. Namely, if $\mathcal{G}_{ISCC}$ is measured in a laboratory test, and if this measured value is not exceeded in service, the structure would not be expected to fail. For this reason, the value $\mathcal{G}_{ISCC}$ is added to Table I.

Slow crack growth would also occur under the action of an alternating load, but so little data is available on crack growth in adhesive joints under the action of an alternating load that application of fracture mechanics techniques to this type cannot be described at present.

MODE II FRACTURING

The techniques of fracture mechanics permit analysis of Mode II fracturing in the same fashion as described for Mode I. Loading is such that shear forces are largest near one end of the joint, constraining Mode II fracture initiation to occur at this point, Figure 9.

The critical crack extension force in shear then is $\mathcal{G}_{IIC}$ and occurs when P equals P_{IIC}. The expression relating $\mathcal{G}_{II}$ and P_{II} is identical to that relating $\mathcal{G}_I$ and P_I since they are derived in the same manner, i.e.

$$\mathcal{G}_{IIC} = \frac{P_{IIC}^2}{2b}\left(\frac{dC}{da}\right)_P$$

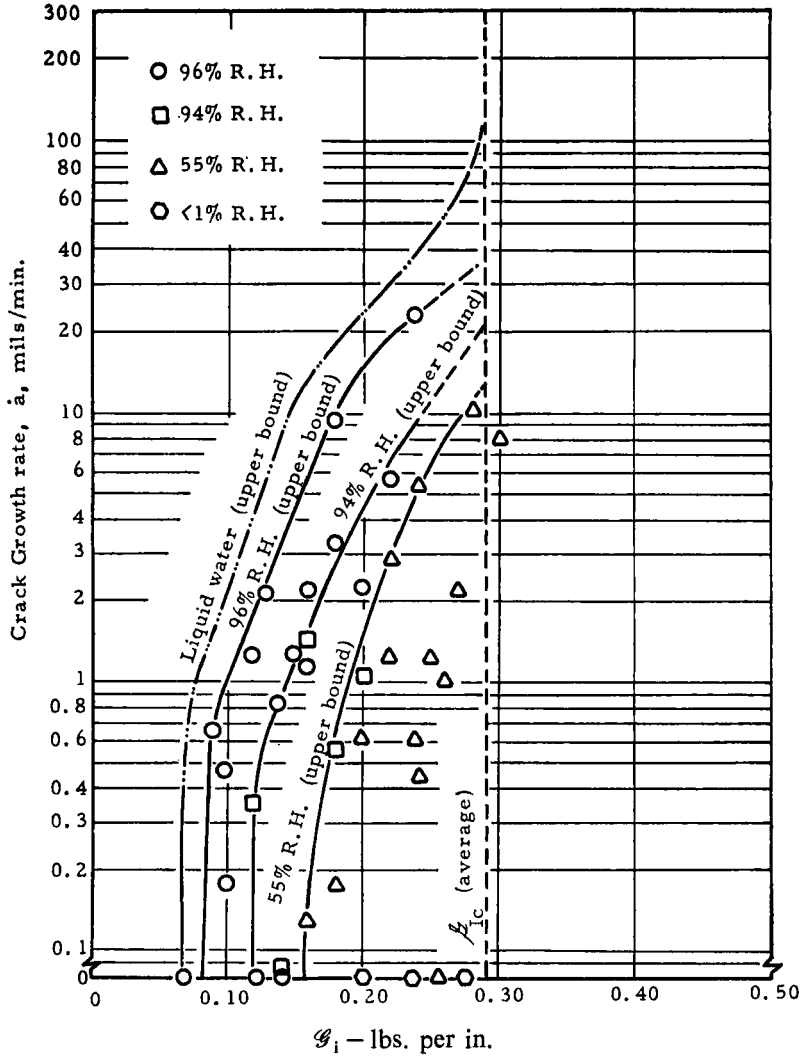

FIGURE 8 Stress corrosion cracking of an epoxy adhesive as a function of Relative humidity.

For the prismatic specimen shown in Figure 9 (dC/da) can be derived from the elastic properties of the adherends. For adherends of width, b, height, h, and elastic modulus, E the compliance of the system at a crack length a_1 is

$$C_{(a_1)} = \frac{\Delta_{(a_1)}}{P_c} = \frac{2a_1}{bhE}$$

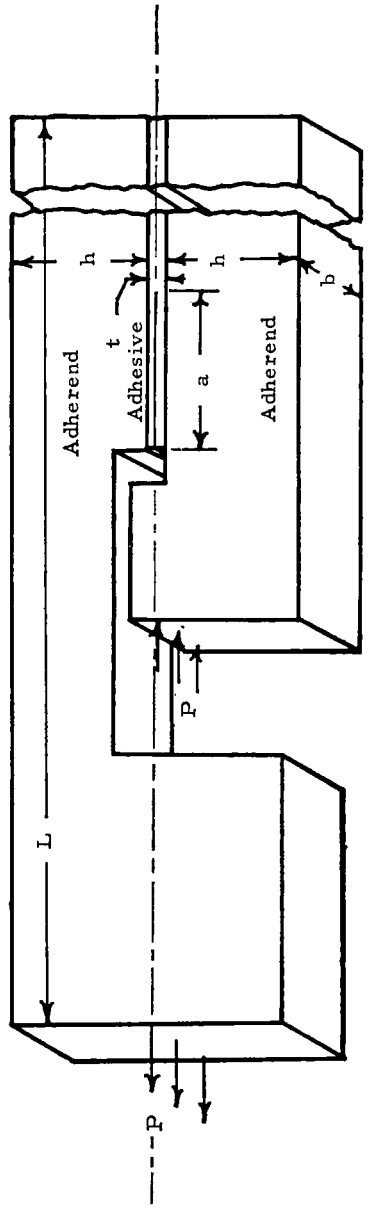

FIGURE 9 Test specimen configuration for $\mathcal{G}_{IIc}$ measurement.

This expression assumes that each adherend contributes to the compliance by uniaxial extension or compression, thus the total length of reacting

material contributing to $C_{(a1)}$ is equal to $2a_1$. Thus the derivative of this expression with respect to crack length is a constant, viz:

$$\left(\frac{dC}{da}\right) = \frac{1}{bhE}$$

and the expression for $\mathcal{G}_{IIC}$ using this type of specimen is:

$$\mathcal{G}_{IIC} = \frac{P_{IIC}{}^2}{b^2hE} \tag{9}$$

Adhesive specimens of the shape described have been made and tested. However, pure shear fractures have never been observed. Testing consisted of putting a Mode I crack in the material, after which the specimen is subjected to Mode II loading. During loading there was audible evidence of crack formation and extension although the P-Δ diagram continued to extend linearly without a change in slope. Rapid fracturing eventually occurred with complete specimen fracture at a calculated $\mathcal{G}_{II}$ value more than 20 times that obtained for $\mathcal{G}_{IC}$. This is in contrast to Mode I testing where crack growth occurs by controlled steps and which should be the case for the test geometry used for Mode II toughness evaluation. Fracture surface examination showed that the crack did not propagate in shear from the Mode I precrack. Instead, crack growth had occurred by Mode I forces in the Mode II field, i.e. at a 45° angle to the long axis of the specimen. The audible cracking observed during the test were the re-initiation and propagation of new cracks from the interface of each adherend. These could be seen on the fracture-plane. In light of these results Mode II loading alone would have little use from a fracture mechanics viewpoint since crack growth still occurs as a result of Mode I forces.

COMPARISON OF FRACTURE MECHANICS TYPE TESTS TO OTHERS

Since the application of fracture mechanics to adhesive joints requires the introduction of new testing concepts, it is helpful to compare these with the more standard testing methods. Most tests on adhesive joints are variations of button, lap-shear or peel tests. For the first of these, two cylindrical sections are joined as a butt joint and the test consists of measuring the maximum load required to separate the two in tension. Test results are reported as units of stress, e.g., lbs/in.^{2}.

A large number of modifications of the lap-shear tests are made. In this case the adhesive is loaded in shear (at least on a macro basis) and results are again reported in units of stress required to cause full separation. Both of these tests are thought to measure a combination of flow and fracture

properties of the adhesive, and both are used because they appear to duplicate service loading. Actually, however, for both of these, fracturing depends on the distribution of pre-existing flaws, at least for high strength structural adhesives, and as a consequence it is not possible to scale either button tests or lap-shear tests from laboratory sized specimens to full scale structures. Actually, for tests such as single lap-shear, failures do not appear to occur from shear, but instead, occur progressively from tensile fracturing that is initiated at the end of the over-lap.

The peel test, on the other hand, does use a starter crack, and unlike the first two tests, yields results in energy rather than stress terms. However, in the course of cracking the adhesive, substantial plastic flow takes place in the adherend. This irrecoverable loss of energy accounts for the high apparent fracture energies measured by this method since the test really measures the sum of this irrecoverable energy and the adhesive fracture separation energies. Consequently, to make a comparison between adhesive systems using peel tests, all test conditions must be alike, i.e., the same adherend material and thickness. Using the criteria of fracture mechanics for specimen design, all adherend parameters are extraneous to the value of $\mathcal{G}_{IC}$ measured, since the test is designed so that no energy is lost to them during the course of crack extension. This allows a number of properties to be measured which are impossible with the peel test, e.g., comparison of a given adhesive with different adherends.

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