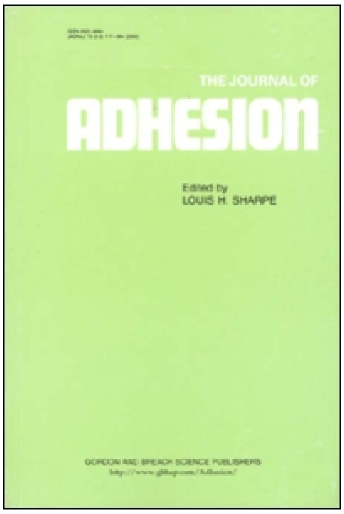


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# Predicting Bond Strength

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# Predicting Bond Strength†

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Methods are presented for predicting the load carrying capability of a bonded joint using relatively simple laboratory test samples. It is first shown that using an average stress criterion can lead to errors of an order of magnitude in predicted load carrying capability. A fracture mechanics approach is then shown to predict failure load accurately in a joint bonded with either a polyurethane or a relatively brittle epoxy when proper consideration is given to loading mode, temperature, and load rate. The principal contribution of this paper is in extending fracture mechanics theory to regions where classical singular points do not exist. Analyses are combined with test data to deduce an "inherent" flaw size.

KEY WORDS Adhesives; structural analysis; fracture mechanics; testing; bond strength; prediction of failure load.

## INTRODUCTION

One factor retarding the use of adhesives is our inability to predict the strength of a bonded joint using our present standard laboratory tests and our standard method of interpreting the output from such tests.

An engineer is often required to obtain bond strength data from laboratory-size samples and infer the strength of a given bonded

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joint from these data. A straightforward approach would be to prepare and test several standard laboratory specimens using the adhesive type and surface preparation technique to be evaluated. The strength of these standard bond tests is usually reported as an average failure stress, which is defined as the breaking load per unit of bond area. This stress is then compared with the average stress that exists in the joint being evaluated when its maximum load is applied. However, if the joint geometry, loading time, and other conditions are not identical to that of the laboratory test conditions, the direct comparison can lead to unsafe joint designs.

The reason that the direct comparison of average stress values is not valid is that average stresses do not account for variations in stress within the bonded joint. Other factors must also be accounted for including loading mode (direction of load application with respect to a crack or debond termination line), loading rate, joint temperature, adhesive thickness, joint geometry, residual stresses, moisture content and moisture distribution within the adhesive, adherend stiffness, and adhesive stiffness and compressibility (Poisson's ratio). Each one of these factors can change the load carrying capability of a joint by more than a factor of two. Improper testing and data interpretation can, therefore, lead to predictions of load carrying capability of a given bonded joint that are in error in excess of an order of magnitude.

Since the average stress in a bondline is generally not a reliable tool for predicting failure in a bonded joint, an alternative approach is required. If it is hypothesized that failure of a bonded joint occurs when the stress (or some functional of the stresses) reaches a critical value, one might evaluate the stress at each point in a test specimen bondline. The value of the maximum stress(es) at which the bond broke would be termed the bond stress capability. The next step would be to evaluate the stresses at each point in the joint bond when it is subjected to its maximum expected load. The highest resulting stress (or stress functional) at any location in the bond would then be termed the joint requirements. The amount by which the bond capability exceeded the joint requirement would provide the margin of safety of the joint.

This procedure has been very useful in homogeneous materials except when a notch or crack (360-degree notch) is present in the material. In such cases, the stresses are not defined at the notch tip when linear elastic analyses are employed; *i.e.*, the notch tip is a point of stress singularity. One normally relies on a fracture mechanics analysis to predict load carrying capability for such geometries.

Notches in an adhesive and initial debonds are obvious points of bondline stress singularity. In addition, many bond termination geometries are points of singular stress.[1,2,3,4] Thus, for debonds initiating at bond edges, even in the absence of voids or initial debonds, both the joint requirement and bond capability must be quantified in terms of fracture mechanics parameters. Bond failure does not always initiate at a point of apparent stress singularity. Thus a failure criterion which is applicable to both singular and nonsingular points is highly desirable. Our approach is to determine an "inherent" flaw size from which energy release rates can be calculated, whether failure initiates within a bonded joint or at the bond edge. These inherent flaws may be related to those that exist naturally in all bonds due to such things as air bubbles, local surface discontinuities, etc.

The applicability of a fracture mechanics approach to bondline strength prediction can be validated by determining fracture mechanics parameters such as critical energy release rate ($G_c$) and inherent flaw size ($a_0$) from laboratory tests and using these values to predict the load carrying capability of other bonded joints. Agreement of predicted and measured values from a wide variety of geometries would build confidence in the approach.

Our efforts in validating a bond strength prediction technique were initiated using relatively simple materials and are progressing to more complex materials as described below.

## VERIFICATION FOR LINEAR ELASTIC MATERIAL

A polyurethane (Solithane 113 Morton Thiohol, Inc.) to polymethylmethacrylate (PMMA) joint was selected for the initial study. Solithane 113 is a nearly incompressible linear elastic material for temperatures above 70°F and load times longer than 0.005 seconds. The Solithane to PMMA bond strength is low enough to allow "adhesive" failure.

Testing was completed using this bond system in test specimens with the various geometries depicted in Figure 1. A small amount of

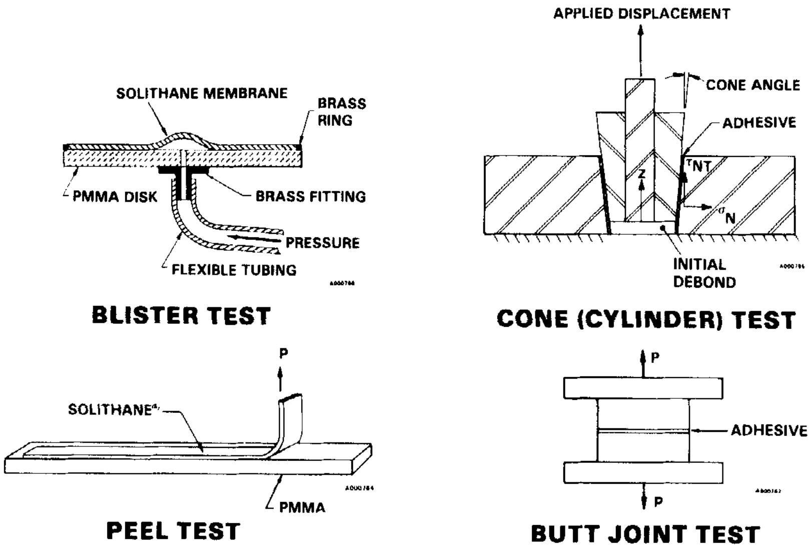


FIGURE 1 Adhesive testing configurations.



debond was initiated in each specimen prior to loading. The load rate was adjusted such that debond propagated in each specimen in $35 \pm 10$ seconds. The resulting critical energy release rates are dependent on loading mode[4,5] as shown below (this phenomenon has also been reported by Trantina[6] and Johnson[7]):

| **Dominant Mode** | **Test** | $G_c$, **J/m² (in.-lb/in.²)** |
|---|---|---|
| I | 90° Peel | 31 (0.18) |
| | Thick Blister | 30 (0.17) |
| | Butt Joint in Tension | 23 (0.13) |
| II | Thin Blister | 72 (0.41) |
| | Cylinder Pull-Out | 60 (0.34) |
| III | Butt Joint in Torsion | 102 (0.58) |

As explained in References 4, 5, and 8, the specimens are not purely Mode I, II, and III as depicted in the above table. There is, in reality, a fairly significant Mode II component in both the

90-degree peel and thick blister (19 percent Mode II) specimens while the butt joint in tension has less than 2 percent Mode II loading. This may be one reason for the relatively low critical energy release rate for the butt joint in tension. In addition, since failure loads are proportional to the square root of critical energy release rate, failure load predictions would differ by only 14 percent when 23 is used in place of 31 for the critical energy release rate.

The fairly close agreement in critical energy release rates for the tests dominated by Mode I loads, supports the use of a fracture mechanics approach for these materials and loading mode when an initial debond is present. However, most bonded joints do not have a known initial debond. One approach to bond strength prediction is to assume the bondline has an inherent flaw of size, $a_0$, and base the failure theory on the energy release rate for the inherent flaw. The applicability of this approach is illustrated below.

Three sets of five Solithane/PMMA buttons were tested using the test fixture of Figure 2. The following average failure loads, $P_{cr}$,



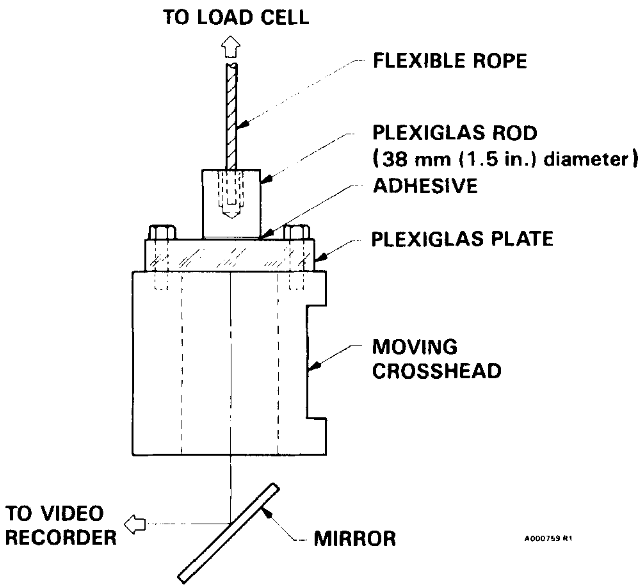


FIGURE 2 Transparent tensile test apparatus.

were obtained:

| Adhesive Thickness, mm | (in.) | Initial Debond, mm | (in.) | $P_{cr}$, N | (lb) |
|---|---|---|---|---|---|
| 6.38 | (0.251) | 3.30 | (0.130) | 286 | (64) |
| 6.17 | (0.243) | 6.45 | (0.254) | 138 | (31) |
| 0.71 | (0.028) | $a_0$ | | 1430 | (322) |

The average critical energy release rate from the first test set was 23 J/m$^2$ (0.13 in.-lb/in.$^2$). With this value of $G_c$, the failure load for the 6.45 mm (0.254 in.) flaw was predicted to be 146 N (35 lb). This value compares closely to the measured 138 N (31 lb) load.

The inherent flaw size, $a_0$, is defined as the amount of debond necessary to produce the proper critical energy release rate, 23 J/m$^2$ (0.13 in.-lb/in.$^2$), at the measured peak load, 1430 N (322 lb), in specimens with no initial debond. For the Solithane to PMMA bond, the inherent flaw size was determined to be 0.076 mm (0.003 in.).

Once $G_c$ and $a_0$ are known, the load capability of other bonded joints can be predicted. This is demonstrated by predicting the change in bond strength with adhesive thickness in butt joint tests (Figure 2). Adhesive thicknesses between 0.15 mm and 25 mm (0.006 in. and 1.0 in.) produced failure loads ranging from 1900 N (430 lb) for thin bonds, to 180 N (40 lb) for thick bonds (Figure 3). Adhesive failure initiated at the bond edges for joints thicker than 2.5 mm (0.1 in.) and near the centerline for joints thinner than 2.5 mm (0.1 in.). Both the failure loads and debond initiation points were predicted using fracture mechanics theory as illustrated by the solid curve in Figure 3.

The analytical prediction was made by assuming that an inherent flaw of 0.076 mm (0.003 in.) existed at the bond edge and extended around the periphery of the specimen (axisymmetric flaw). With this flaw, an energy release rate was found for each adhesive thickness. A second analysis was then completed by assuming the inherent flaw existed at the specimen center and again evaluating energy release rate as a function of adhesive thickness. The data from the two resulting analyses are plotted as the square root of energy release rate per unit load versus bond thickness in Figure 4.

For thin bonds, the energy release rate is greater for a center flaw

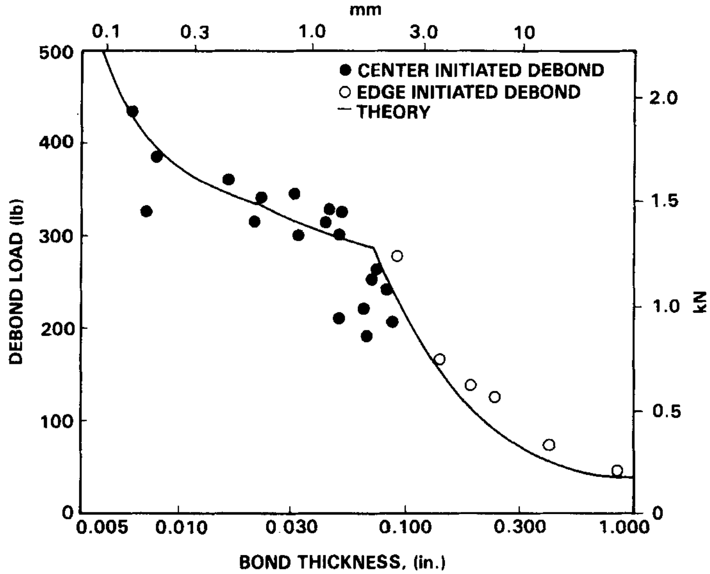


FIGURE 3 Effect of adhesive thickness on debond load—polyurethane.

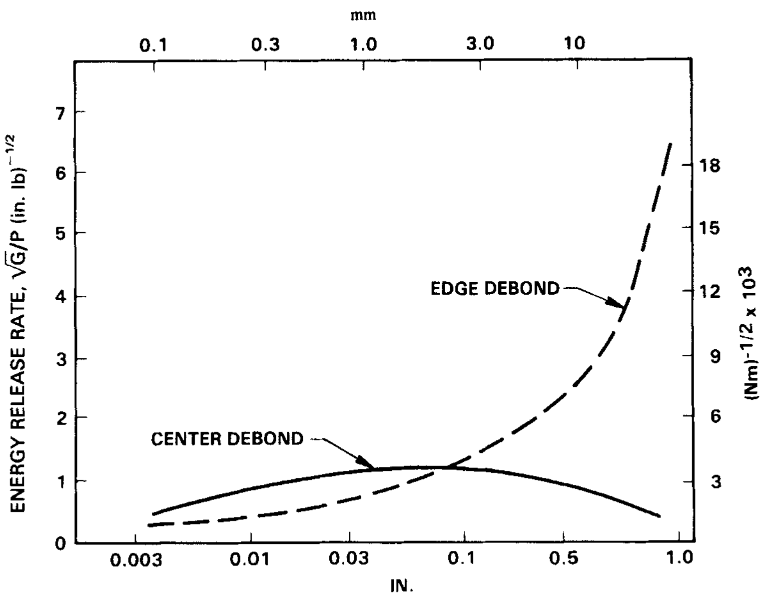


FIGURE 4 Energy release rate for 0.076 mm (0.003 in.) debond.

than for edge flaws, therefore debond is predicted to initiate at the specimen radial center. The energy release rate increases with bond thickness (strength drops) until the bond thickness is 2.3 mm (0.09 in.). When the adhesive thickness exceeds 2.3 mm (0.09 in.) the energy release rate for edge debonds exceeds that for center debonds. Thus the transition from center to edge debonds is properly predicted from the analysis.

The use of an inherent flaw size in conjunction with the energy release rate approach to failure was felt to be necessary because of the discontinuity in energy release rate as the debond size approaches zero and to allow a common failure criterion to be used for edge-initiated debonds (singular point) and internally-initiated debonds.



## VERIFICATION FOR BRITTLE EPOXY

The fracture mechanics approach was also evaluated with a nearly linear elastic brittle epoxy (Figure 5a). A critical energy release rate of 32 J/m$^2$ (0.18 in.-lb/in.$^2$) was obtained for 29 mm (1.13 in.) diameter tensile buttons with an initial debond of 2.5 mm (0.1 in.) and a failure load of 7.1 kN (1600 lb) (average for 10 tests). The critical load of 4.2 kN (954 lb) was then predicted for buttons with 5.1 mm (0.2 in.) initial flaws. This prediction was within one percent of the test results.

A series of 10 specimens with no initial debonds was then tested. These specimens had an adhesive thickness of 1.7 mm (0.068 in.) and

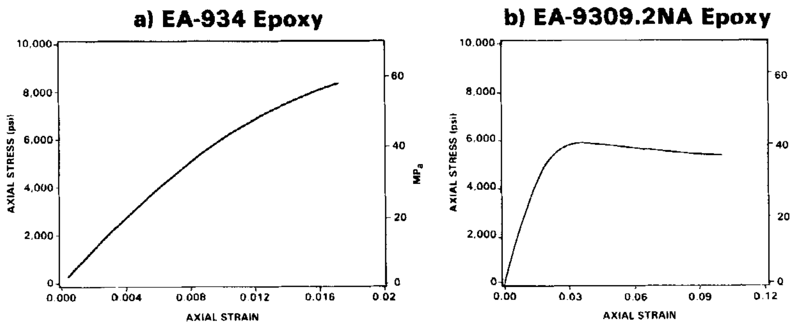


FIGURE 5 Stress–strain curves for two epoxy systems.

failed at an average of 21 kN (4760 lb). These data are summarized in the following table:

| Initial Debond | | Failure Load | | |
|---|---|---|---|---|
| mm | (in.) | kN | (lb) | Result |
| 2.5 | (0.1) | 7.1 | (1600) | $G_c = 32\ J/m^2$ (0.18 in.-lb/in.$^2$) |
| 5.1 | (0.2) | 4.3 | (967) | 1% prediction error |
| $a_0$ | | 21 | (4760) | $a_0 = 0.025$ mm (0.001 in.) |

To obtain the inherent flaw size, the energy release rate was calculated using finite element techniques, (Figure 6) as a function of debond length for small initial debonds at the specimen outer diameter. A failure load of 21 kN (4760 lb) was used in computing the energy release rate. Since this was the failure load obtained from the test data, the ordinate in Figure 6 is the critical energy release rate. However, the critical energy release rate was determined to be 32 J/m$^2$ (0.18 in.-lb./in.$^2$) from the first set of tests (initial debond 2.5 mm, 0.1 in.). Thus, it can be determined from the Figure 6 plot that the bond system has inherent flaws of 0.25 mm (0.001 in.). The two parameters—critical energy release



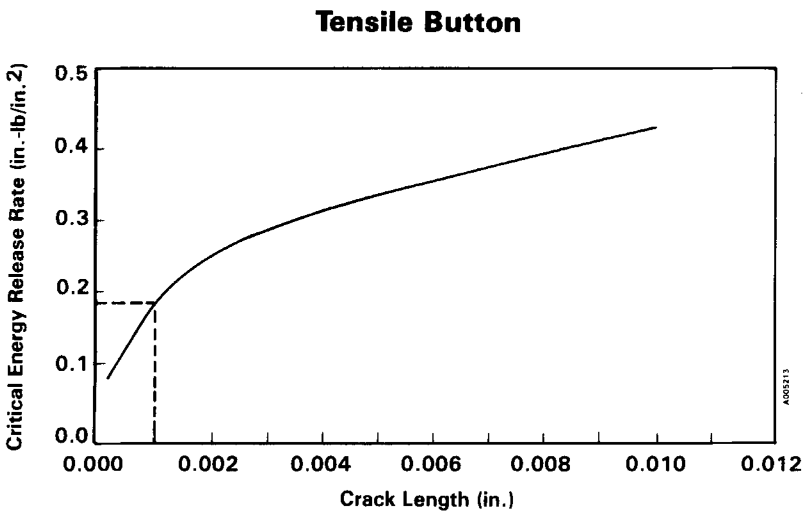


FIGURE 6 Critical energy release rate for EA-934 tensile buttons.

rate and inherent flaw size—are then felt to characterize the bond capability.

A series of tensile button tests was then completed where adhesive thickness ranged from 0.127 mm to 13.3 mm (0.005 in. to 0.525 in.). Average values (10 replications) from these tests are presented in Table I. An attempt was made to adjust the load rate to obtain a constant load time to failure. However, the resulting load times were not constant. Thus, additional testing was completed to allow an empirical correction of the first data set.

Three sets of 0.27 mm (0.060 in.) bondline tensile adhesion buttons were tested at different displacement rates to assess the effects of strain rate on tensile strength. The three displacement rates used were 0.022 mm/min (0.005 in./min), 0.22 mm/min (0.050 in./min), and 2.2 mm/min (0.500 in./min). Ten buttons were tested at each rate. The resulting data from these tests were empirically fit by the following equation:

$$P_{cr} = a\left(\frac{\dot{u}}{h}\right)^n$$

where $P_{cr}$ is the failure force and $\dot{u}$ is the displacement rate. Therefore, the ratio of critical loads $P_{cr1}/P_{cr2}$ for different rates and thicknesses may be expressed:

$$\frac{P_{cr1}}{P_{cr2}} = \left(\frac{\dot{u}_1 h_2}{\dot{u}_2 h_1}\right)^n$$

The test data were then adjusted as shown in Table I. These

TABLE I
Tensile adhesion tests with EA-934 epoxy adhesive[a]

| **Adhesive thickness, mm (in).** | **Load rate, mm/min (in./min)** | **Failure load, kN (lb)** Measured | Adjusted | Predicted |
|---|---|---|---|---|
| 0.13 (0.005) | 1.27 (0.050) | 30.1 (6770) | 32.2 (7230) | 34.8 (7820) |
| 0.58 (0.023) | 1.27 (0.050) | 24.8 (5570) | 25.4 (5720) | 26.2 (5900) |
| 1.73 (0.068) | 1.27 (0.050) | 21.1 (4770) | 21.2 (4760) | 21.0 (4710) |
| 3.30 (0.130) | 1.91 (0.075) | 16.2 (3650) | 16.1 (3620) | 14.6 (3280) |
| 13.30 (0.525) | 2.54 (0.100) | 10.6 (2380) | 10.1 (2280) | 9.4 (2120) |

[a] Hysol Division, Dexter Corp.

adjusted data are plotted as a function of bond thickness in Figure 7. Using the critical energy release rate of 32 J/m$^2$ (0.18 in.-lb/in.$^2$), the inherent flaw size of 0.025 mm (0.001 in.) and a curve of energy release rate as a function of bond thickness (Figure 8), the effect of adhesive thickness on bond strength was predicted. The predicted values presented in Table I and Figure 7 show very close agreement with measured results. Thus, we feel that the reason for adhesive strength changes corresponding to adhesive thickness (at least for polyurethane and brittle epoxies) is completely accounted for by changes in energy release rate.

For all tensile button tests with epoxy, edge-initiated failures are predicted since the energy release rate for an inherent flaw size of 0.025 mm (0.001 in.) is greater for an edge-initiated failure than for failures initiated internally. There was no direct experimental verification of the failure initiation point, since opaque adherends and adhesives were used. The observed failures were primarily cohesive within the adhesive layer. However, in most cases a small area of adhesive failure existed near the bond edge. Our hypothesis is that failure initiated at the adhesive/adherend interface adjacent to the bond edge. Failure then propagated into the adhesive to the



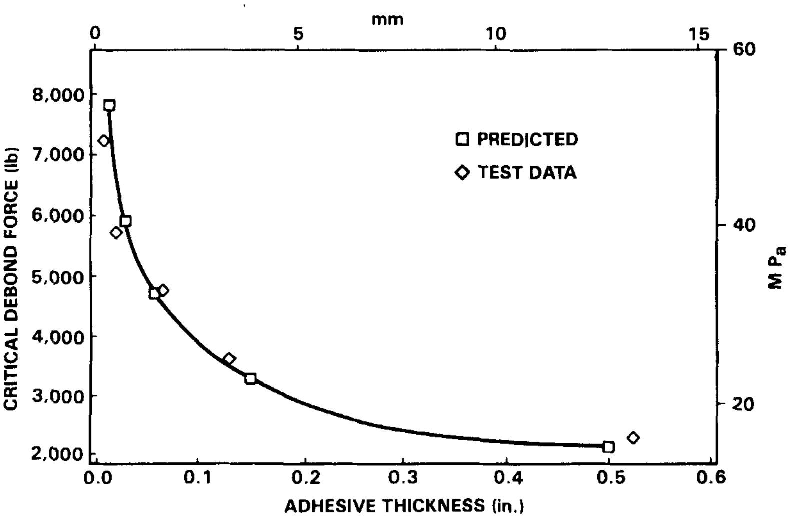


FIGURE 7 Effect of adhesive thickness on debond load—EA-934 epoxy.

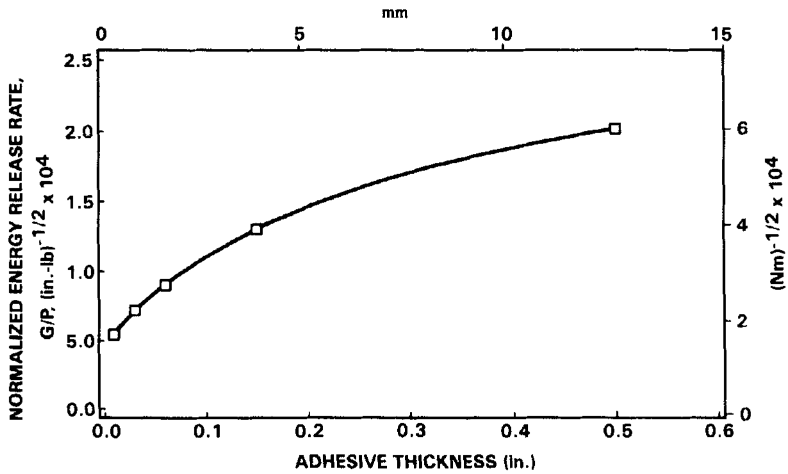


FIGURE 8 Energy release rate versus adhesive thickness, Poisson's ratio = 0.34, $a_0 = 0.025$ mm (0.001 in.).

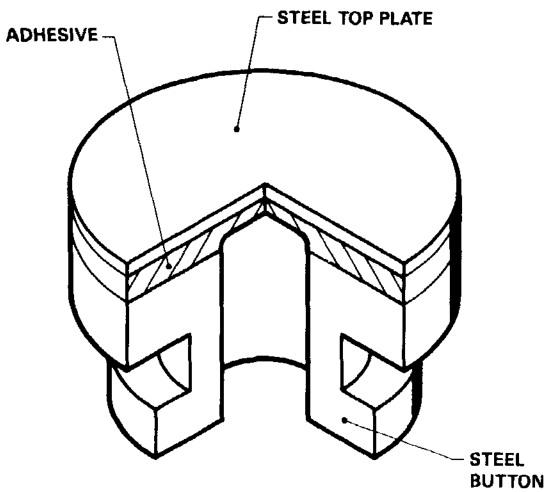


FIGURE 9 Blister test specimens.

bond axial center, then continued through the center of the adhesive layer.

The calculated values of critical energy release rate and inherent flaw size were then successfully used to predict failure in the modified blister test illustrated in Figure 9. A failure pressure of 2360 was calculated. This was within five percent of the average test value from 11 test specimens.

The fracture mechanics approach has shown very promising results for a linear epoxy loaded in Mode I. Further work is in progress to extend the theory to Mode II loads, to nonlinear adhesives, and to show the effects of temperature and load rate on the failure criterion.



## CONCLUSIONS

It is concluded that average stress determined from bond tests is a very poor predictor of failure in bonded joints. Furthermore, other stress failure criteria have serious deficiencies due to stress singularities which exist at notches, debonds, and bond termination points. Fracture mechanics theory has shown very promising results in Mode I loading of both a polyurethane and a linear epoxy. Further work is progressing to extend the theory to include nonlinear adhesives. The effect of load rate and temperature also need to be studied. For some test specimens, such as peel geometries, large deformations and rotations complicate analysis. Further work needs to be completed to reconcile these effects.

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