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DURABILITY (LIFETIME) PREDICTIONS
ADHESIVELY BONDED STRUCTURES

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A brief review of past and current methods for life time or durability assessment of engineering structures is given. It is noted that adhesively bonded structures exhibit all the features that compromise the durability of metals and polymers plus additional features related to the interface between the adhesive and the adherend. A discussion of current techniques on adhesives is given which suggests that they discriminate between various surface treatments but do not give good qualitative information for a design engineer. A mechanics approach to the prediction of durability based upon nonlinear viscoelastic constitutive and failure laws is outlined which includes moisture diffusion, temperature, and other effects. It is suggested that the critical issue in durability predictions for adhesion science is the development of methods of measuring the properties of the various components in an adhesive joint. A technique based upon a new beam test for adhesion is outlined together with a new digital image correlation technique for measuring strain at the micro scale. The integration of these elements into a research technique to address time-dependent properties in situ are discussed.

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DURABILITY (LIFETIME) PREDICTIONS

FOR

ADHESIVELY BONDED STRUCTURES

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TABLE OF CONTENTS

Abstract

A brief review of past and current methods for lifetime or durability assessment of engineering structures is given. It is noted that adhesively bonded structures exhibit all the features that compromise the durability of metals and polymers plus additional features related to the interface between the adhesive and the adherend. For this reason the durability or lifetime evaluation process for adhesive joints is both more necessary and more difficult than those for other materials. On the other hand, most current methods for determining durability of adhesively bonded structures are based upon empiricism. Part of the empiricism is related to methodologies used for testing and the subsequent utilization of results. A brief discussion of current techniques is given which suggests that they discriminate between various surface treatments but do not give good qualitative information for a design engineer. A mechanics approach to the prediction of durability based upon nonlinear viscoelastic constitutive and failure laws is outlined. This includes a discussion of the manner of incorporating polymer and interfacial moisture diffusion, temperature, and other effects. It is suggested that the critical issue in durability predictions, indeed in adhesion science, is the development of methods of measuring the properties of the various components in an adhesive joint. A technique based upon a new beam test for adhesion is outlined whereby good values for all needed engineering design properties of the adhesive (such as shear relaxation modulus, G, as well as modes I and II fracture toughnesses) can be obtained. Integral to the procedure is a new digital image correlation technique for measuring strain at the micro scale. The integration of these elements into a research technique to address time-dependent properties in situ are discussed.

INTRODUCTION

Durability is a major concern when structural components are designed utilizing new materials. For metals these concerns are largely related to the conditions of fatigue wherein a small flaw will initiate and grow to critical size such that catastrophic fracture will result (1). For polymers, additional durability concerns are raised by the intrinsic viscoelastic or time dependent behavior of the mechanical properties. That is, not only will flaws grow to be of critical size as for metals, but stiffness and strength characteristics will degrade with time to the extent that rupture may occur without the formation of a well defined flaw or crack. Further, the mechanical properties of polymers are strongly influenced by temperature, moisture content, aging, and other factors. Most of these effects associated with polymer memory are well known and are directly related to molecular structure (2). Thus, the failure or fracture process for polymers is quite different from those of metals and a good bit more complicated.

The durability of adhesives includes all the features of metals and polymers plus additional problems created by the interface between the adhesive and the adherends. Actually as shown in Fig. 1, no discrete interface exists. Rather, the diffuse zone composed of the adherend surface or oxide layer, the polymer surface, and any absorbed matter make up what is more properly called an interphase. Moisture, temperature, and other environmental parameters effect this region in a manner different than the way they effect either the adherend or the adhesive. In fact, many feel that durability concerns for adhesively bonded joints are predominately related to the interphase and, for this reason, usual approaches as applied to metals and polymers will not work (3). It should be noted that the size of the interphase is on the order of Angstroms and, at present, no definitive measurement techniques are available to quantify the mechanical properties of this region. The development of methods to accomplish this task is one of the foremost challenges currently confronting the solid mechanics community (4).

Frequently, the intended life of a structure is of much greater length than that which can be reasonably observed in the laboratory. For example, the life of automobiles, airplanes, bridges, or other engineering structures may be anywhere from five to one hundred years or longer. Obviously a testing program to observe response over such a time scale is not feasible. For this reason, there is a need to make observations over a short time scale and to extrapolate to a long time scale.

From these few remarks, it is clear that the design objective of an engineer, where durability is concerned, is to predict the life of a bonded joint, which might be anywhere from five to twenty years or longer, under severe conditions of temperature, moisture, or other factors. No clear and definitive engineering procedure presently exists to accomplish this task for adhesively bonded structures. The purpose of the present discussion is to review and critique those procedures now available and to suggest possible new approaches.

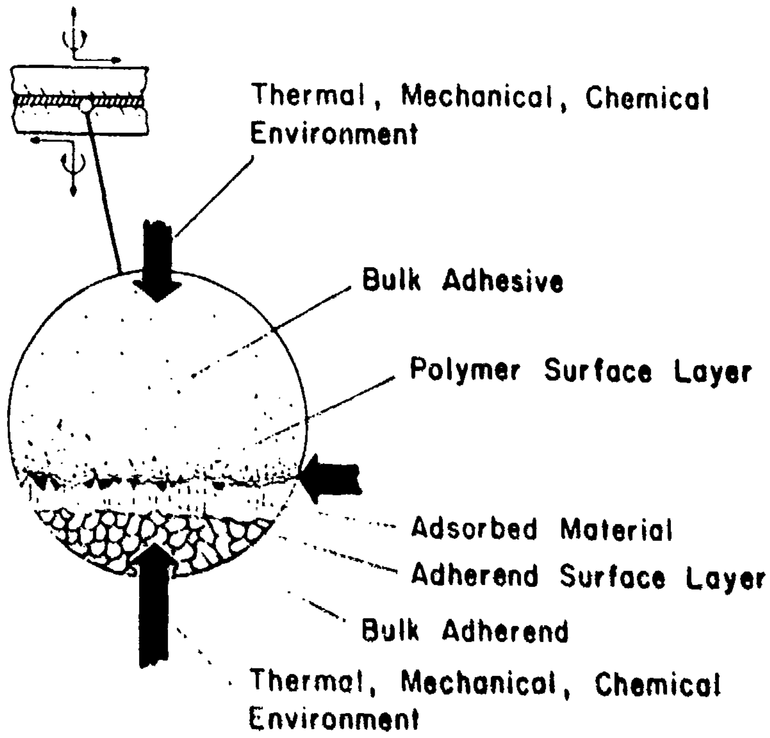


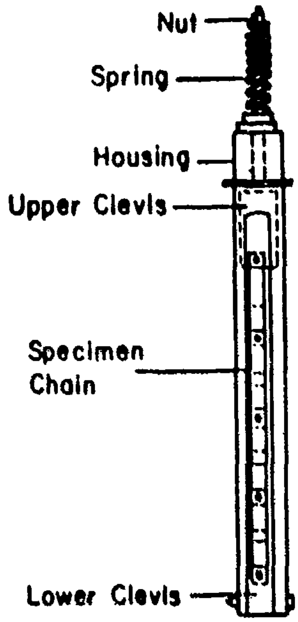
Figure 1. An adhesive joint and its interphase

CURRENT PROCEDURES FOR ASSESSING BOND DURABILITY

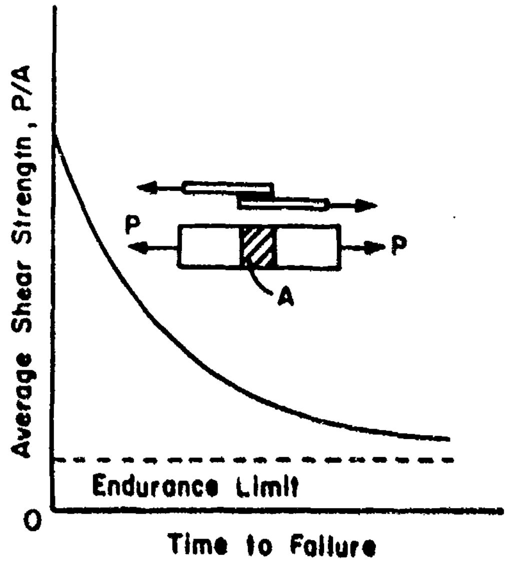
Undoubtedly bond durability is most often evaluated using lap shear test techniques. These might be the traditional single lap, the symmetric lap and/or the thick adherend, RAAB, or others. However, of these the ASTM standard single lap geometry is more frequently used than others but also with a large amount of controversy. The standard procedure is to apply a sustained load using a fixture such as the 3M device shown in Fig. 2a. The fixture including the loaded specimens is placed in an environment and the time required for rupture to occur is determined. The lap shear strength is found by dividing the applied load by the overlap area. The results of a series of tests are plotted as shown schematically in Fig. 2b. Usually a strength or endurance limit will exist below which failure will not occur. Thus, presumably the engineer will have a lower bound on which to base a design. Unfortunately, the strength so found is an average shear value which has little or no relation to the complex stress state in the joint which caused the failure. Thus, it is difficult to use the number obtained for rational design.

The best use of the sustained load test is the qualitative evaluation of surface treatments such as those performed by Filbey and Wightman (5) as shown in Fig. 2c. Here specimens of Ti-6Al-4V were subjected to several surface treatments, bonded with FM 300

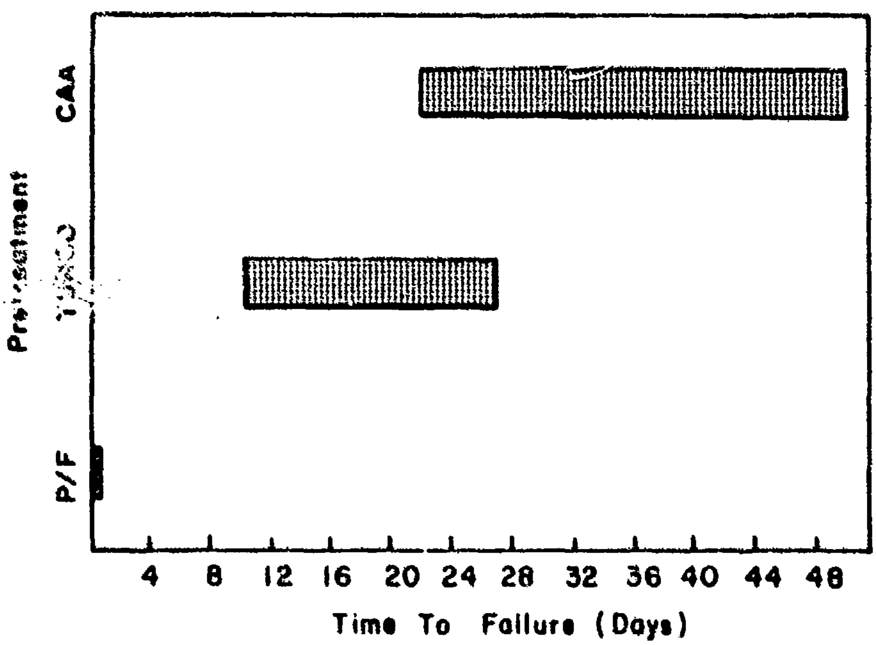
U, and tested under the same constant load and environmental conditions. Quite obviously, the test procedure discriminates well among the surface treatments used.



a. 3M test fixture



b. Creep rupture strength



c. Durability of Ti-6Al-4V and FM 300 U

Figure 2. Stress durability testing with lap specimens

Probably the most reliable procedure at present is that provided by the double cantilever beam (DCB) fracture test shown in

Fig. 3. Here bonded adherends containing a crack are loaded by equal and opposite forces. Using compliance techniques it is possible to determine the fracture energy necessary to cause crack propagation. The test has been widely used to study the rate of crack growth under constant load conditions (da/dt) or under cyclic load (da/dN) for various environments (3,6). The idea is to find a threshold value for the fracture toughness as shown in Fig. 4 such that fracture will not occur. This procedure presupposes that a critical crack can be detected using non-destructive inspection techniques. If so, then the part can be taken out of service prior to failure.

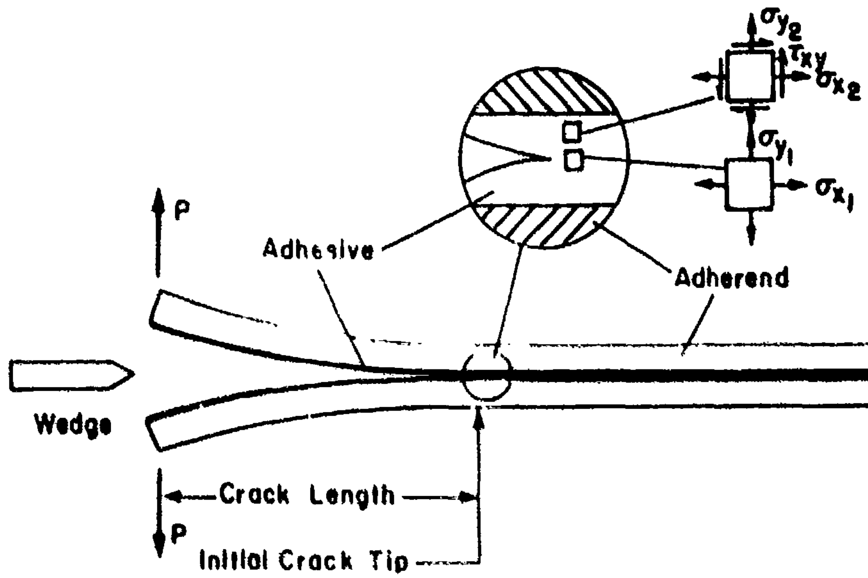


Figure 3. The DCB fracture test

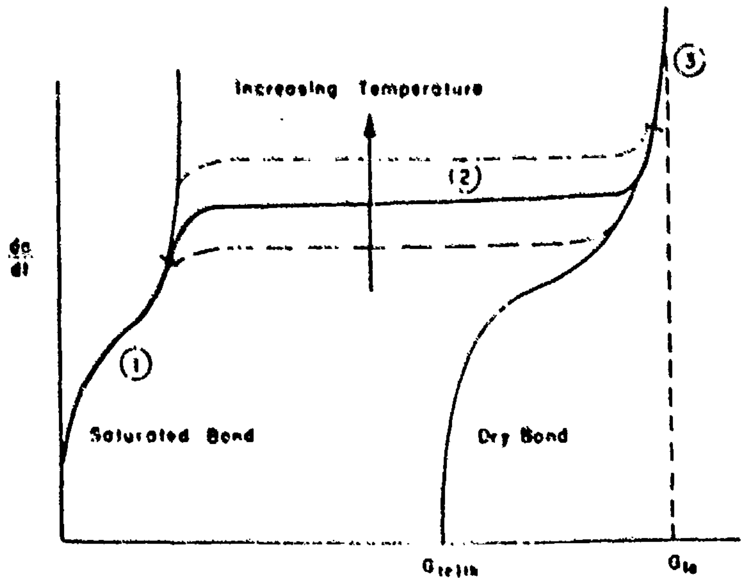


Figure 4. Crack growth rates as a function of environment

Hunston et al.(7) have used the DCB test to measure the fracture toughness of adhesives under a variety of conditions. The results of one study are shown in Fig. 5 in which the strain-energy release rate as a function of bondline thickness is given. The fact that the bondline thickness can be optimized for maximum fracture resistance is due to the effect of constraint on the shape and extent of the crack-tip plastic zone. Thus, if maximum benefits of toughening mechanisms are to be utilized, cognizance of the effects of constraint by the adherends on the adhesive must be considered. Further, it should be recognized that the plastic zone and/or damage zone is altered from that one would find in the bulk adhesive due to the competing factors of restriction and constraint.

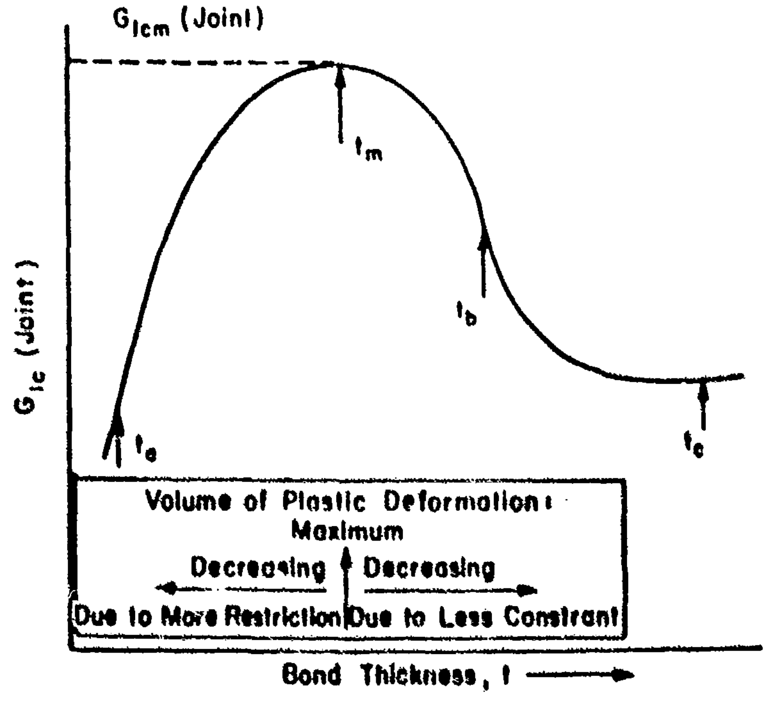


Figure 5. Variation of fracture toughness with bond thickness

Even though much good information can be obtained from the DCB test, it is not without disadvantages. Adherends are most often tapered in order to obtain a constant GIC value. Thus, the specimen geometry is not easy to produce. The taper is obtained from an elastic analysis which does not explicitly include the properties of the adhesive. Some of these deficiencies have been aleviated [Lefebvre et al.(8)] by using a beam on elastic foundation approach to the analysis of the double cantilever sandwich beam. The arrangement shown in Fig. 6 was used to study the neoprene rubber bonded to two steel adherends to form a sandwich. In reality the rubber was treated as the adhesive layer because the effect of the adhesive on joint toughness was negligible. As a result the analysis is appropriate for the traditional DCB adhesion test. The addition of a spring creates the possibility of a constant fracture toughness even though the adherends are not tapered.

With the apparatus shown in Fig. 6 it was possible to study the cathodic delamination of rubber-to-steel adhesive joints. The results of this study are those shown in Fig. 4 which shows the crack rate as a function of strain-energy release rate. Three regions of response were noted and can be described as conditions in which moisture precedes crack propagation (region one), moisture and crack propagation occurring simultaneously (region two), and crack propagation preceding moisture diffusion. It is clear that moisture and/or electro-chemistry play an important role in crack propagation or durability and that, due to these effects, a threshold value of toughness may not exist. For this reason, methods to incorporate the effects of moisture and electro-chemistry into life prediction techniques and engineering design are essential.

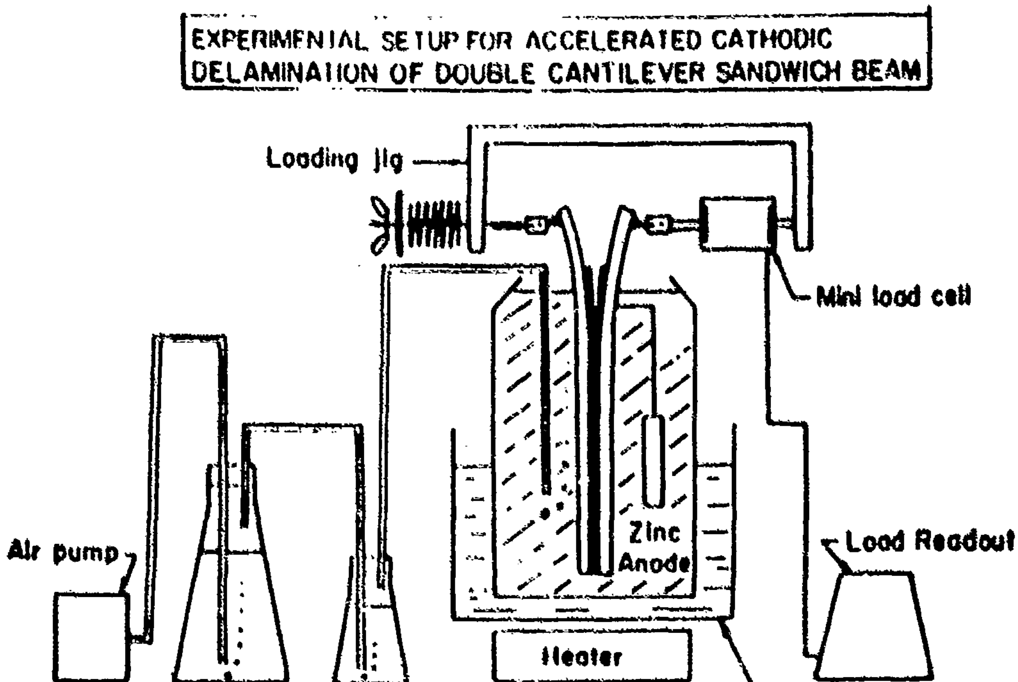


Figure 6. Apparatus used to study the accelerated cathodic delamination of rubber-to-steel bonds

In recent years, the wedge test has been used extensively to evaluate surface treatments under adverse environmental conditions as a means of determining the durability of bonded joints. The only difference between the wedge test and the DCB test is that in the latter a wedge is driven into the bond creating a crack of known length. The specimen is then immersed in the desired environment and crack propagation as a function of time is measured. Depending on the rate of crack propagation as well as the character of the fracture surface or the location of the crack, i.e., cohesive or adhesive, durability can be assessed qualitatively. If the load needed to insert the wedge is measured as well as crack length with time, the fracture toughness or strain-energy release rate can be determined which gives a measure of the fracture resistance for the combination of materials and conditions used. This number can be used in a quantitative manner for design. However, the test is still primarily used in a qualitative manner as the exact crack length is difficult to monitor and the exact state of environmental penetration (moisture diffusion) is difficult to assess.

Filbey and Wightman (5) have studied durability using the wedge test for the same materials described before. The results are shown in Fig. 7. As may be observed, this test gives the same results obtained with the 3M test. That is, crack movement was very rapid for the P/F treatment while that for CAA and Turco was virtually non-existent.

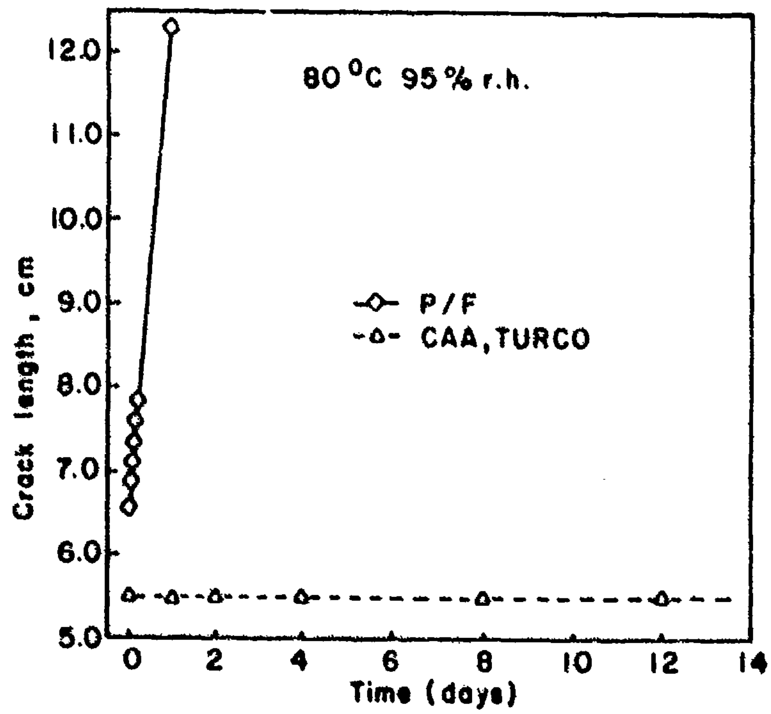


Figure 7. Durability results from wedge test on Ti-6Al-4V bonded with Fm 300 U

It is appropriate to point out that one reason for the success of both the DCB and wedge tests is due to the known bi-axial tensile stress state in front of the crack (see Fig. 3). Quite obviously, the crack singularity causes the highest stress to be at the crack tip. There is no shear stress at the crack tip. Away from the crack tip, the tensile stress decreases and a shear stress develops. However, the intensity of the tensile stress at the interface due to its close proximity to the singularity is not significantly different than that at the crack tip. If the surrounding material, including the interfacial region, is of nearly the same strength as that at the crack tip, cohesive fracture will result. On the other hand, if the strength at the interface has been seriously degraded by the environment (e.g., moisture diffusion) then failure is most likely to occur at that location. Thus, the wedge test fundamentally defines the quality of the interface in comparison to the quality of the adhesive at the crack tip. It is important to note that this is done only in relation to the effect of a tensile stress field and may not, therefore, be representative of prototype failure which most often is designed to fail in shear. In this sense, the stress durability test may be a better test as it more nearly represents design practices and, if the overlap is long enough, fails in a manner more like the prototype.

CONSTANT SHEAR, BI-AXIAL AND/OR MIXED MODE TESTING

As outlined in the last section, lap shear tests do not give quantitative modulus and strength data which can be used directly to evaluate joint performance. Several reasons for this deficiency are obvious. First, deformations are created by a complex, and unknown, mixture of shear and bi-axial stresses. Second, deformations which are measured are due to a complex combination of local strains in the adhesive, the interphase region, and the adherends. That is, current methods do not allow the separate measurement of strains at a local point in the adhesive and the interphase separately. Third, since neither the strains or stresses are known at a local point it is not possible to relate either to failure mechanisms.

Stress and strain distributions can be found using the finite element method or other numerical techniques but not unless the properties are already known. Therefore, lap tests cannot generally be used to obtain accurate properties which can be used for engineering design.

Parenthetically, the above comments should not be misconstrued to imply that the current design practices of obtaining properties from average stresses and strains for design are unsafe. By conservative design, extensive testing, and adequate safety factors safe bonded structures are produced. However, the need for better procedures is obvious.

Fracture testing as described in the previous section can give good information on the relative merits of surface treatments as well as quantitative fracture toughness values for design but only under mode I loading conditions. Many designers argue that "real" structures do not fail in mode I but rather under a combined state which is often principally mode II.

For the above reasons, there is a strong interest in the adhesion community to develop new test specimen geometries of bonded joints in which only a uniform state of tensile or shear stress exists. Several specimens are shown in Fig. 8 which are currently being evaluated for this purpose. The Iosipescu is a beam in four point bending with a precisely machined notch which gives a condition of pure shear at the location of the notch. This specimen has been used to study the effect of shear on joint toughness by Jonath (9). A tensile load can be imposed to obtain any desired combination of tension and shear. Also, cracks can be included to study mixed mode fracture behavior.

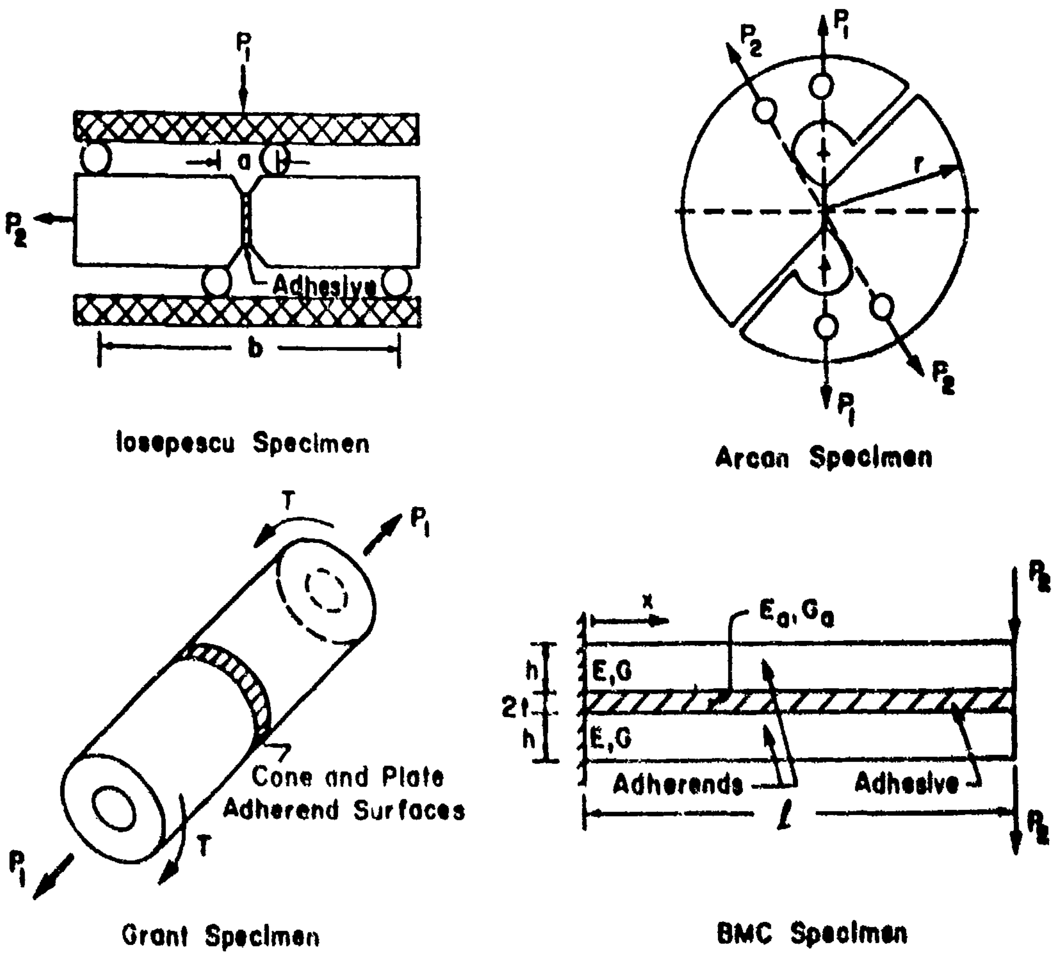


Figure 8. Pure shear and/or mixed mode test specimens

The Arcan specimen shown in Fig. 8 also gives a pure shear field by the incorporation of a precisely machined notch as shown and has been suggested as an appropriate shear test for adhesives (10). By varying the orientation of the load with respect to the notch any combination of tension and shear can be achieved. This specimen has been investigated extensively by Liechti (13) who has used the finite element method to optimize the geometry for pure shear and to minimize residual stresses due to shrinkage. Again cracks can be included to study mixed mode fracture.

A new cone and plate geometry being developed by Grant (13) gives a more uniform shear state than the standard napkin ring specimen (6). An axial load can be added to give a combination of tension and shear. This test is not amenable to the study of fracture, however.

The Iosipescu and the Arcan each have the limitation of not being a simple geometry to produce. For this reason and others, Brinson et al.(14) have suggested a cantilever beam test shown also in Fig. 8 as a means of obtaining pure shear properties. The unique feature is to load the specimen by equal forces on each adherend as shown. By so doing, a pure shear state is obtained. However, the shear stress is not uniform with length. It is a maximum at the free end and, contrary to popular conception, zero at the fixed end. Moussiaux et al.(15, 16) have obtained an analytical closed form solution for the shear stress in the adhesive layer in terms of the joint geometry. (Additional details are presented elsewhere in this volume.) A crack can be introduced at the free end and pure mode II can be studied. By loading the top and bottom differently any combination of mode I and II can be achieved. As the pure shear state varies with length it is possible to study damage development in a controlled manner. Current efforts are directed at obtaining analytical solutions for fracture, stress analysis of the interface, extension for a non-linear viscoelastic material, and experimental verification.

PROPOSED DURABILITY PREDICTION PROCEDURE

The prediction of durability or life is essentially the same as predicting at what future point in time failure will occur. The fundamental issue in such a prediction is the determination of mechanical properties associated with a known stress state and their correlation to mechanisms of failure. From a mechanics standpoint, many attempt to use properties determined from test of the bulk material in association with finite element programs. However, bulk adhesive properties at failure are not the same as those in a bonded joint. Further, moisture and/or corrosion effects for joints are clearly different from bulk behavior as is obvious from an examination of the effect of various surface treatments on joint durability given in Figs. 2 and 7.

The specimen geometries outlined in the preceding section and shown in Fig. 8 allow the testing of adhesive bonds under a known state of pure shear stress, pure tensile stress or some combination thereof. Thus, the first step is to utilize these or other specimens to determine isochronous stress-strain curves for pure tension and shear from zero load to failure similar to those shown schematically in Fig. 9. These curves are best determined using creep testing rather than relaxation testing because in the latter, creep and relaxation of the adhesive layer often occurs simultaneously (17). Experience indicates that modern adhesives such as the modified epoxies popular in the aircraft industry will exhibit nonlinear viscoelastic effects as well as large strains (13, 18, 19). (The failure stresses and strains given in Fig. 9 are typical of those measured in tension for the bulk resin and in shear with the thick adherend specimen.) Creep failures may not occur until after many years of exposure to a complex load and environment history.

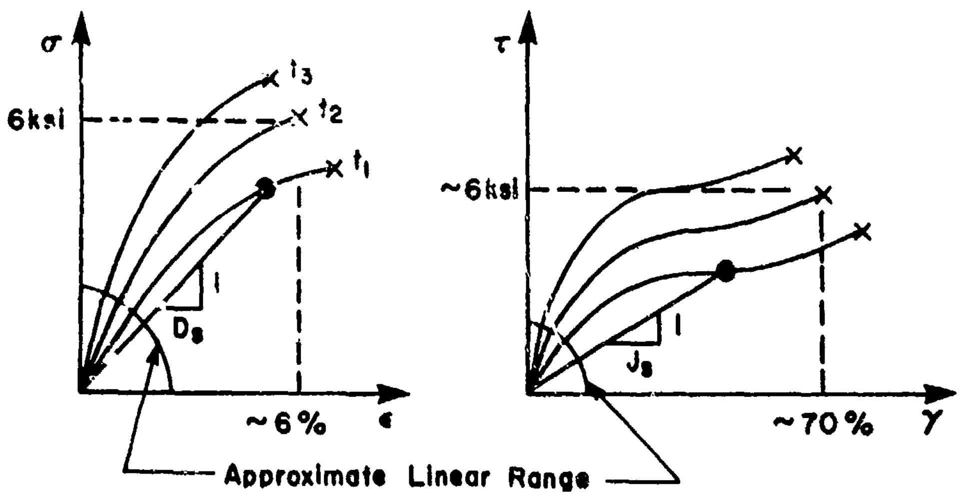


Figure 9. Isochronous stress-strain curves for tension (left) and shear (right).

One method to represent the non-linear data shown in Fig. 9 is using either a secant or tangent modulus which would obviously vary as a function of stress, time, and environment. By using a time-temperature-moisture-stress-superposition-principle (TTMSSP), a property surface can be generated similar to the one shown in Fig. 10. The surface could, of course, be shifted to obtain the modulus for any desired combination of parameters. Failure would be the trace of the termination of the surface. Such a concept has been outlined in detail by Landel (20) for elastomeric materials. The suggestion here is that similar ideas can be accomplished for the glassy range.

The use of TTMSSP techniques would allow the extrapolation of short term data (minutes or hours) to usable long term properties (months or years). To accomplish this most efficiently, constitutive and failure mathematical models are needed. These would then be incorporated into a finite element model to make predictions of stress and strain distributions as a function of time. From the known stress states, the failure model would predict the time to rupture. Actually, it should be possible to determine how damage initiates and develops until rupture occurs. The finite element model which incorporates these features being developed by Roy and Reddy (21) is reported elsewhere in the present volume.

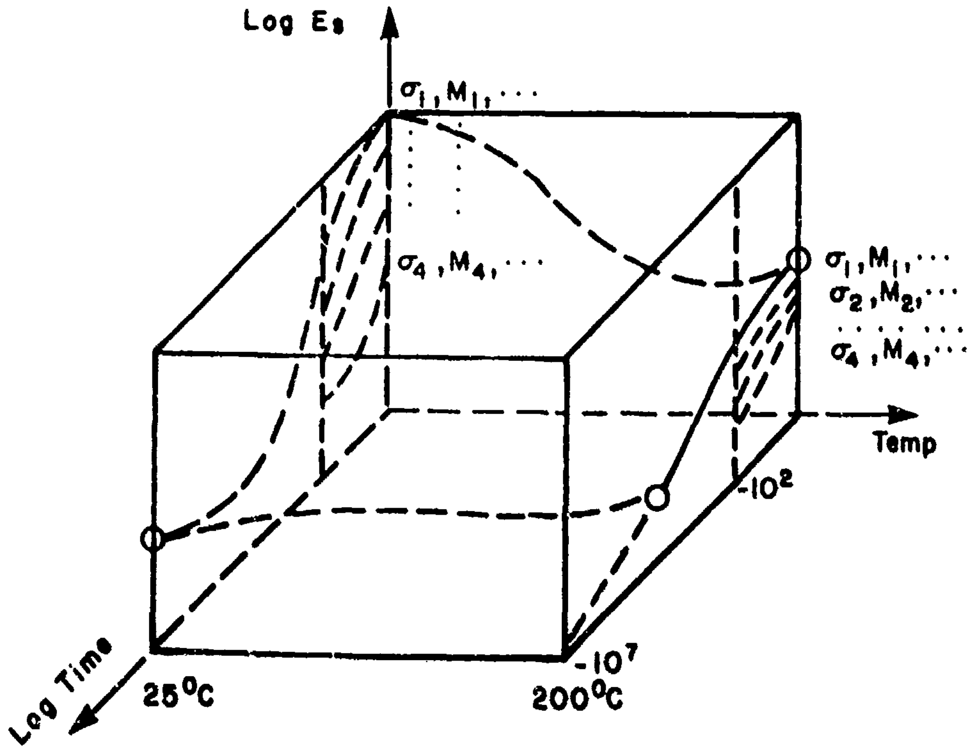


Figure 10. Surface for adhesion properties

A schematic outline of the proposed methodology is shown in Fig. 11. While the ultimate goal is to make prototype predictions, it is suggested that the technique should be used first to predict damage development and subsequent failure in a specimen other than the one from which property information was obtained. In other words, if the process is practical it should be possible to predict durability results for lap specimens tested in the 3M fixture similar to those shown in Fig. 2.

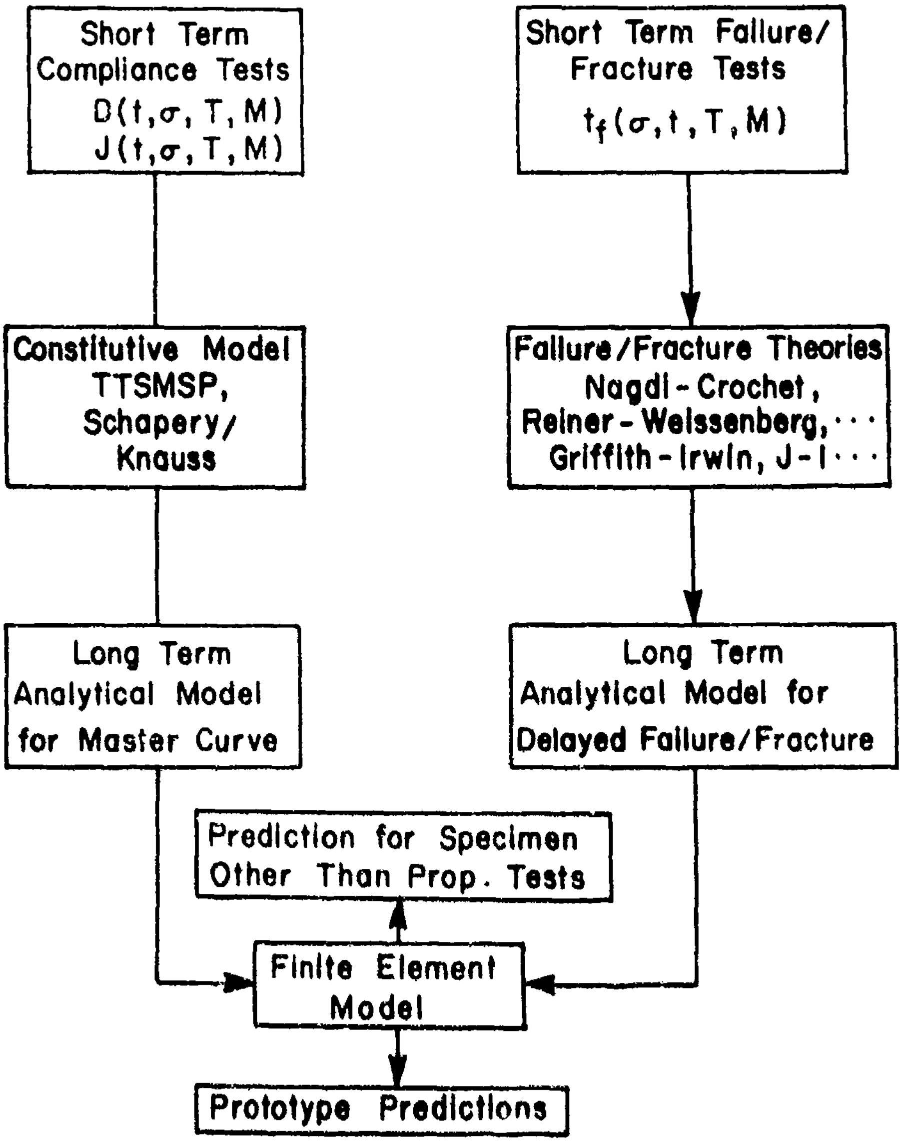


Figure 11. Schematic of durability prediction procedure

CONSTITUTIVE MODELS

A single integral non-linear viscoelastic constitutive model has been used in our previous efforts to develope a durability prediction method for composites (22). Our work to date used only uniaxial tensile creep and creep recovery data. Because the state of stress in a bonded joint is three dimensional, it is necessary to consider a modification to adapt the non-linear approach for this case. This can be accomplished by separating the stress and strain tensors into devaitoric (shear) and dilatational (hydrostatic) components. The non-linear hereditary integral equations then become,

$$2\gamma(t) = g'_o J_o \tau + g'_1 \int_o^t \bar{J} (\psi - \psi') \frac{d(g'_2\tau)}{dt'} dt' \qquad [1]$$

and

$$3\bar{e}(t) = g'_o B_o \bar{\sigma} + g'_1 \int_o^t \bar{B}(\psi - \psi') \frac{d(g'_2\bar{\sigma})}{dt'} dt' \qquad [2]$$

where

$$\psi = \int_o^t \frac{dt'}{a_\tau} \text{ or } \psi = \int_o^t \frac{dt'}{a_{\bar{\sigma}}} \qquad [3]$$

Equation (1) gives the value of the shear strain, $\gamma(t)$, as a function of the shear stress, τ, with J(t) = $J_o + \bar{J}(t)$ being the linear shear compliance. Similarly, equation (2) gives the volumetric strain, $\bar{e}(t)$, as a function of volumetric stress, $\bar{\sigma}$, with $B(t) = B_o + \bar{B}(t)$ being the linear bulk compliance. The parameters g_o, g_1, g_2 and g'_o, g'_1, g'_2, are nonlinear functions of stress which must be found by experiment. The reduced time parameter given by equation (3) also defines the additional stress-dependent shift factors, a_τ and $a_{\bar{\sigma}}$.

Earlier efforts of Schapery (23) and Brinson et al. (24) have used a power law to approximate the linear compliances. However, the modified power law is suggested for future work as with this form it is possible to capture the equilibrium compliance or the rubbery plateau. This form for the shear creep compliance is given as:

$$D(t) = D_o + \frac{[D_\infty - D_o]}{[1 + a/t]^n} \qquad [4]$$

The difficulty in using this form for life predictions is the experimental determination of J_∞. Hiel (25) and Brauer [26] have suggested using the time-temperature-super-position- principle (TTSP) for this purpose. The slope of the master curve so generated would give the creep exponent, n which is unlikely to be effected by temperature. However, care should be used with all shifting procedures to properly include all necessary vertical shifts. Otherwise, large errors will potentially result.

Some may prefer to use a prony series for the representation of the linear compliances, J(t) and B(t). However, the advantage of a power law is its simplicity plus the ability to relate each term in [4] to specific physical phenomena. Both could easily be incorporated into a numerical program to fit data and each can be used as necessary in a finite element program.

The bulk compliance in equation [2] is not directly obtainable by measurement but can be calculated using [2]

$$B(t) = 9D(t) - 3J(t) \qquad [5]$$

where _(t) and J(t) are determined using the test specimens given in Fig. 8. Caution should be used as significant errors are possible with this approach. For this reason, there is a need to obtain the bulk compliance with a bonded specimen but a procedure to do so is not immediately obvious.

Knauss (27) has suggested a single integral non-linear viscoelastic representation similar to that given by equations [1] - [3] but with only the single non-linear parameter of the time scale shift factor, $a_{\bar{\sigma}}$. He points out that this factor is caused by changes in volume not only due to volumetric stress but also due to moisture and temperature changes. The shift factor is related to fractional free volume through the expression,

$$\ln a_{\bar{\sigma}} = K\left(\frac{1}{f} - \frac{1}{f_0}\right) \qquad [6]$$

in which K is a constant and f_0 is the equilibrium fractional free volume. The fractional free volume in turn is related to changes in temperature, volumetric stress and moisture concentration by,

$$f = f_0 + \alpha\,\delta T + B\delta\sigma + \gamma_c \delta C \qquad [7]$$

in which α is the coefficient of thermal expansion, γ is the coefficient of moisture diffusion and other quantities are as previously defined. The quantities α and γ are recognized to be memory functions the same as B(t). Thus, the volumetric shift factor given in equation [6] is related to the history of thermal, moisture, and volumetric stress effects on the adhesive by convolution integrals where the memory functions are the coefficient of thermal expansion, the coefficient of moisture expansion and the volumetric creep compliance.

The unique feature of the Knauss approach is that it is possible to insert information on molecular concepts directly into a continuum constitutive model. The suggestion herein is to combine the Schapery and Knauss approaches into a general constitutive theory for adhesives and other time-dependent materials.

Lefebvre (28) has related the coefficient of moisture diffusion, D, to the fractional free volume using,

$$\ln \frac{DT_0}{D_0 T} = K'\left(\frac{1}{f} - \frac{1}{f_0}\right) \qquad [8]$$

where K' is a constant and other quantities are as previously defined. Using equation [7], he develops an expression for the moisture diffusion coefficient analogous to the Knauss shift factor. In other words, the diffusion coefficient is related to history-dependent volumetric expansions caused by changes in temperature, moisture content, and volumetric stress through convolution integrals where the memory functions are the coefficient of thermal expansion, the coefficient of moisture expansion, and the volumetric compliance.

The approach described above is related only to the effect of temperature, moisture, and stress on the bulk resin. These same factors may affect bonded joints in a manner different from the bulk because of the existence of the interphase. Lefebvre (28) has also developed an approach to interfacial moisture diffusion which includes among other things the disjoining pressure created by the migration of water to the interface and a chemical potential. Both bulk and interfacial diffusion concepts are included in a generalized or non-linear Fickian model of moisture penetration for an adhesive joint.

These approaches are being implemented into the finite element model discussed elsewhere in this volume (21).

Parenthetically, it is appropriate to point out that Hiel (29) has developed an approach to moisture diffusion based upon the same irreversible thermodynamic approach used by Schapery (23) to derive a non-linear viscoelastic constitutive law on which equations [1] - [3] are based.

Time-dependent failure laws must be incorporated into any computational durability prediction procedure. Time and space constraints do not permit a discussion herein but it is appropriate to point out that several procedures have been used in our previous durability prediction efforts for polymers and composites (22). One procedure is a method to predict time-dependent yielding using concepts of viscoplasticity (30). The other is an energy based approach due to Reiner and Weissenberg (31). The latter appears to be the easiest way to incorporate time-dependent failure into a computational model (29). One advantage of the BCM specimen given in Fig. 8 is that it may be possible to observe and monitor damage development in a controlled manner.

An alternate method to include failure in a computational model is through the use of fracture mechanics. The specimens in Fig. 8 can be used to determine mixed mode fracture toughnesses for adhesive joints. It is possible to initiate the crack either in the adhesive or at the interface. By so doing, it is conceptually possible to evaluate the mixed mode fracture toughness for cohesive as well as adhesive fracture as a function of surface treatment, environmental and electro-chemistry effects. Our intent is to accomplish this through the use of the BCM specimen in conjunction with the apparatus shown in Fig. 6.

MEASUREMENT METHODS

In order to obtain the isochronous stress-strain plots shown in Fig. 9, it is necessary to know both the stress and strain at a point. The stress is calculated from a known solution involving only geometry and loading of the specimen. The fact that material properties are required to obtain the stress distributions for lap as well as other specimen geometries is the key reason for their limitation as a means of determining engineering material properties for design. With each specimen in Fig. 8, it is possible to calculate the stress associated with failure using only the applied load and the geometry of the specimen.

The determination of the strain must be accomplished by measurement. The fundamental basis of the first three specimens of Fig. 8 is that the shear stress state is constant and uniform over its entire length providing that no axial loads are applied. Unfortunately, there will always be a small region near the boundary where the stress will deviate from uniformity. One excellent use of the finite element method is to assist in the production of specimen geometries where such pertubations are minimized. If a truly pure state of shear stress can be achieved, the idea would be that, because the metal adherends are very stiff compared to the adhesive, only the total relative deformation of the adherends would need be measured. Thus, the measurement of strain is greatly simplified. However, our experience indicates that, just as with the thick adherend specimen and the measurement of strains using a Kreiger gage, deformations of the adherends are a significant portion of the total deformation. In other words, especially for stiff adhesives, it is not possible to obtain accurate properties only measuring total joint deformation.

Quite obviously such an approach cannot give any information about deformations due to the interphase.

The BCM specimen geometry can be optimized such that the shear stress is constant over a significant portion of its length. For this situation, the same argument about determining strains would apply.

For the forgoing reasons, a technique is needed by which strains can be directly measured in the adhesive layer. Further, it would be desirable to have a technique which could measure strains in regions approaching the interphase. Obviously, such would only be possible with the aid of a microscope, preferably a scanning electron microscope. Two approaches which have great promise are under development. The first is a stereo imaging technique due to Davidson (32) where strain measurements are determined from stereo photograph pairs of a specimen loaded in the scanning electron microscope. At present, only the deformation field in front of fatigue cracks in metals and composites have been studied. However, currently an effort is being made by Davidson to determine the strain field in single lap specimens provided by the author.

A second approach due to Ranson (33) appears to be especially suitable for use on adhesive joints. A schematic of his measurement system is shown in Fig. 12. The heart of the system is a digitizing camera which monitors light intensity and provides a means of identifying surface features or texture on a local scale with the aid of a microscope. The surface features of a test specimen are scanned, digitized, and stored in a computer before and after deformation. That is, under load a local region undergoes a distortion as well as movement to a new location as shown in Fig. 13. By recognizing identifying features associated with the unique texture of each point scanned, it is possible to develop software to determine the local strain at a point and the distribution of strain from point to point. The technique appears to be ideally suited to the measurement of strains in the adhesive layer and to map strain distributions across the interface layer.

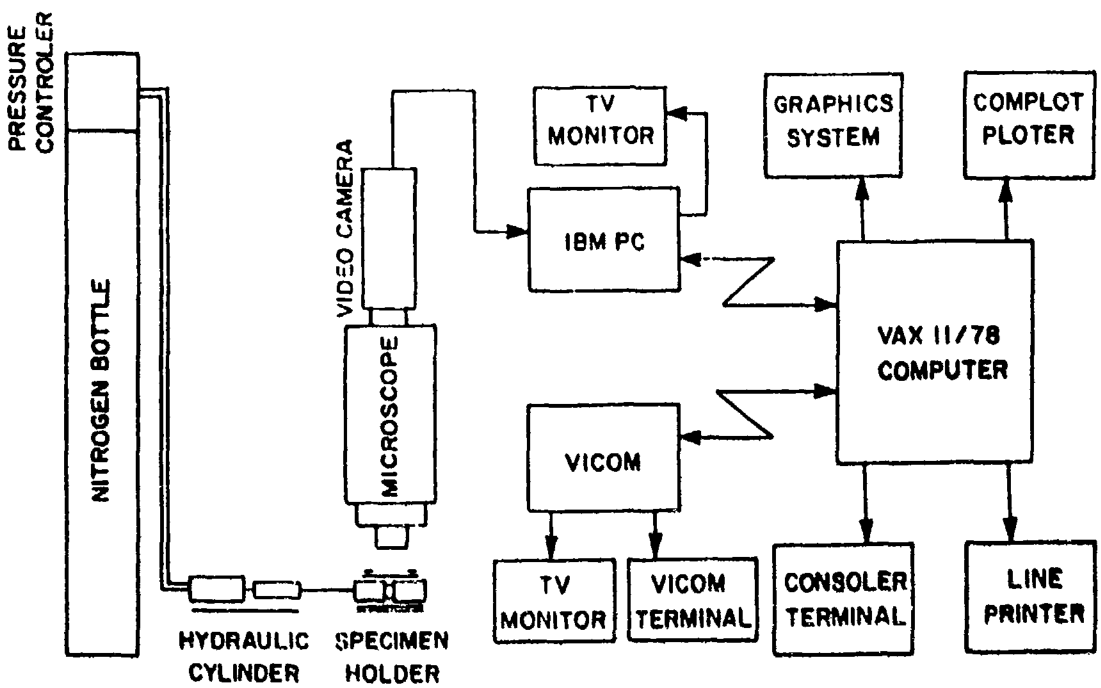


Figure 12. Schematic of Ranson Measurement System

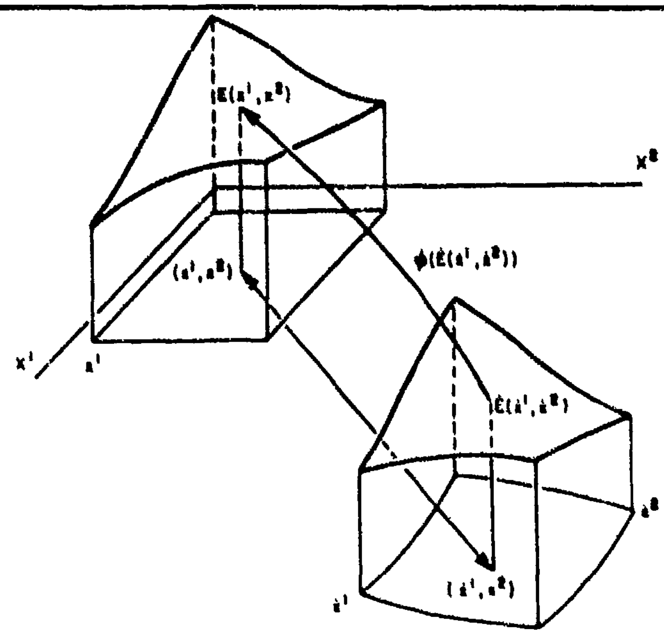


Figure 13. Intensity surface before and after deformation

By using Ranson's technique in association with the BCM specimen and the test arrangement shown in Fig. 6, it is hoped that a better understanding of adhesion properties can be obtained. The information gained will be utilized in a finite element program to predict, in advance, durability results similar to those given in Figs. 2 and 7.

SUMMARY AND CONCLUSIONS

A general discussion of methods for durability assessment were presented. It was pointed out that lap specimens have been used extensively to obtain good qualitative information when the joint has been exposed to environmental effects, especially temperature and moisture. One advantage of lap shear testing was indicated to be that they include mixed mode failure effects similar to prototype joints. Limitations were related to the lack of a detailed knowledge of the stress field and associated deformation and failure mechanisms in the joint.

Fracture specimens were indicated to have become popular as a means of evaluating the effects of surface treatments and, thus, joint durability. Their great advantage was described as a simple well defined tensile stress state for which failure mechanisms can be readily understood. Their limitation was due to the lack of mixed mode information more like that needed for prototype design.

Several new specimens currently being investigated which can give good information on pure shear or pure tensile modulus and strength properties as well as fracture information were discussed. A new procedure was described whereby durability predications can be made using a rational mechanics approach to the determination of quantitative adhesion properties and utilizing these in a finite element program. Constitutive models needed to represent materials response were outlined. Further, a means of measuring properties using a new surface identification technique was presented.

Such investigations as those outlined hold the promise of obtaining detailed information about adhesion properties (adhesive and interface) under controlled stress conditions which can be useful in understanding joint failure and associated mechanisms. If so, such information can be incorporated into finite element or other computational codes such that durability of a bonded structural component can be determined in the initial engineering design. Such procedures are being developed at Virginia Tech in the Center for Adhesion Science.

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15. Supplementary Notes

16. Abstracts

A brief review of past and current methods for life time or durability assessment of engineering structures is given. It is noted that adhesively bonded structures exhibit all the features that compromise the durability of metals and polymers plus additional features related to the interface between the adhesive and the adherend. A discussion of current techniques on adhesives is given which suggests that they discriminate between various surface treatments but do not give good qualitative information for a design engineer. A mechanics approach to the prediction of durability based upon nonlinear viscoelastic constitutive and failure laws is outlined which includes moisture diffusion, temperature, and other effects. It is suggested that the critical issue in durability predictions on adhesion science is the development of methods of measuring the properties of the various components in an adhesive joint. A technique based upon a new beam test for adhesion is outlined together with a new digital image correlation technique for measuring strain at the micro scale. The integration of these elements into a research technique to address time-dependent properties in situ are discussed.

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