PLANNING ACTIVITY REPORT FOR NDE OF ADHESIVE BONDED STRUCTURES

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ABSTRACT

Following a workshop held at the Rockwell International Science Center, Thousand Oaks, California in January, 1979, an ad hoc planning activity was undertaken to set forth a program plan to address the needs in NDE for adhesive bonded structures. The objectives of the planning activity were to develop a program rationale and strategy, determine the existence of reasonable approaches, and to propose a detailed plan of action for review at the annual DARPA/AF meeting in September, 1979. The plan encompasses the basic elements of an accept/reject methodology based on fracture mechanics, expected developments of valid flaw growth models, stress analysis, and non-destructive measurement techniques. A central issue is the prospect for determining a valid non-destructive measure of strength for the bonded joint as might be reflected in the tendency for preexistent flaws to propagate under environmental loads.

I. PROGRAM SCOPE AND STRATEGY

This program plan is directed toward methods of establishing the reliability of adhesive bonds as may be employed in primary aircraft structures. Similar approaches may be inferred for fiber-reinforced resin matrix composites in particular instances where matrix-dominated failure modes and delaminations are involved. The central strategy for the plan is based on the concept that the structural design process for bonded joints must e well-established and validated in order that ccept/reject decisions might be made from nonestructive measurements information. The plan is resented in the context of a decision methodlgy, characterized by a systems approach, which is xpected to provide a useful framework regardless f the state of development of the various system lements. An essential prerequisite is the knowldge of primary failure initiating defects.

A search of field repair information reveals hat a very high percentage of adhesive bond failres experienced on aircraft structures to date ave been associated with local damage and intruion of the environment (usually moisture). While e most experience has been gained on bonded aluinum honeycomb secondary structure, it may be asonably assumed that damage and environmental trusion may occur at the edges of bonded panels more highly loaded primary structural joints. note of caution which should be added on possie inferences from field experience concerns the re recent developments in pre-bonding surface eparations and their relationship to bond durality. Prior to the PABST(6,7) program, limited formation existed on newer surface treatments, h as phosphoric acid anodization, which proms vast improvements in durability. If future ded joints incorporate these treatments, it is sible that the modes of joint failure may dif from those shown by prior field experience. any case, flaws are likely to occur from a iety of sources and are likely to grow under rational loads.

Defects, as considered in this plan, are ased to include a range of geometrical or bounded defects such as cracks and inclusions, as well as boundaryless defects such as uncured or moistured-softened adhesives. The interaction of these "extrinsic" or bounded flaws with the "intrinsic" material state is often a necessary consideration in the use of failure models involving polymeric materials.

One of the more perplexing issues in the evaluation of bonded joint reliability is a determination of the relative importance of the interface between adherend and adhesive and the condition of the adhesive itself. In recent years the designation "interphase" is often employed, since the transition from adherend to adhesive is frequently a material combination of finite thickness, however, ill-defined for analytical purposes. While some program suggestions for the assessment of the structural capability of the interphase in a manufactured joint might be made, it is most likely that measurements and intepretation of failure in this region will continue to be a doubtful undertaking. The structural reliability of the interphase may be enhanced by the careful and complete monitoring of prepared adherend surfaces and adhesives before the joint is formed in the manufacturing process.

An operational definition of strength for adhesive bonds is needed to provide a figure of merit for non-destructive evaluation. At present no single strength characteristic may be uniquely defined. As an operational premise, however, failure will be defined as that condition in which the structure has lost its ability to support the required load. Failures, therefore, may occur due to growth of cracks, and due to geometric instabilities. The growth of a crack (disbond) is presumed to be the principal failure mechanism of concern in adhesive bonded joints, and fracture mechanics should provide material factors most likely to be rated as measures of strength.

As a point of initial departure, the summary statements from the ARPA/AFML workshop held on January 19, 1979, will be used. Six areas of investigation were listed as encompassing the needed, and potentially fruitful, program activities leading to the goal of reliable adhesive bonded structures. These areas were identified as follows:

1. Flaw growth models (plus nucleation).
2. Stress and fracture analysis.
3. Quality control for bond preparation.
4. Adhesive bulk property measurement correlatable with strength.
5. Cure state monitor.
6. Development and refining of an integrated methodology.

An attempt at providing a methodology as required by item 6 above was made in the form of a logic flow for a structural reliability system as shown in Fig. 1.

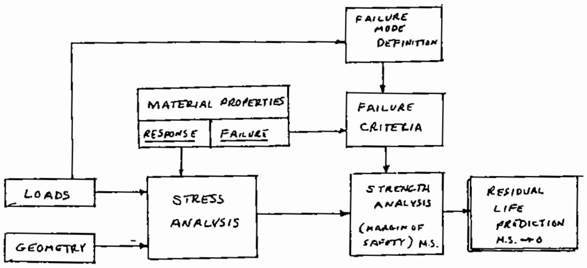


Fig. 1 Elements of a life prediction methodology for structural adhesives.

The diagram shown in Fig. 1 is a simplified schematic system showing the principal elements of the structural design process. Central to the entire methodology is a stress analysis which accepts input in terms of part geometry, environmental loads and a quantitative description of the material properties which encompass those material characteristics necessary to define the distribution of stresses throughout the part. We define this set of material properties by the term response. A second set of properties of equal importance in the strength analysis is referred to simply as failure. A proper definition of a failure "property" would fit the requirement for an operational figure-of-merit for material strength.

The failure criteria as specified in the diagram is an analytical statement of exceedance in which the intrinsic failure limit of a material is compared with the stress and strain requirements generated by the stress analysis. A failure model is implied in which critical stresses and/or strains are incorporated along with relevant material properties.

The output of the strength analysis is presumed to be a structural margin of safety (M.S.) and the life prediction is then based upon the timewise projection of the margin in zero. Life prediction assumes that the mode of failure is known and has been incorporated in the failure criteria. Each structural part subjected to the analysis is expected to demonstrate particular failure modes under the operating loads when the capability of the structure is exceeded. Failure may be the result of an overload or of degraded material properties. Exaggerated loads are sometimes used to fail parts intentionally in order to more clearly define potential failure modes. This procedure is called overtesting.

The methodology outlined in Fig. 1 may be used to examine the non-destructive evaluation process for adhesively bonded structures in terms of needed advances in measurement, analysis and interpretation of extrinsic and intrinsic flaws. As described thus far the process has not accounted for elements related to the inspection process other than a need for quantifiedd material properties, loads and geometries. It was stated earlier that fracture mechanics holds promise as an approach for providing figures of merit for accept/reject decisions. In the context of the elements shown in Fig. 1, the application of fracture mechanics may lead to a failure criterion based on flaw growth to a critical size. Using for present discussion a viscoelastic analog of the Griffith energy balance relationship, i.e.,

$$\sigma_c = k \sqrt{\frac{E(t)\gamma_c(t)}{a}} \qquad (1)$$

where σ_c is the critical stress required for crack growth, $E(t)$ is a time dependent modulus, $\gamma_c(t)$ is a time dependent cohesive fracture energy, a is a crack length, and k is a geometrical factor, we find that several of the necessary elements for non-destructive evaluation are specified. The material property $E(t)$ representing the response and $\gamma_c(t)$ representing the failure characteristics indicated in Fig. 1 are incorporated in the expression, as well as crack length which could be the object of definition by non-destructive inspection methods. Both $E(t)$ and $\gamma_c(t)$ may be considered material properties which manifest the existence of intrinsic flaws as discussed earlier, as possibly related to poor cure or moisture softening. While Eq. (1) may not be a sufficiently general or correct statement of the conditions necessary for flaw growth, it is illustrative of the kind of relationship needed for this study. Accepting for the moment that non-destructive investigation methods are available to characterize the geometric flaw, the intrinsic property $E(t)$ should be measurable as well since it reflects a small deformation response. Dielectric cure monitors are typical of the measurements which provide information on the intrinsic state of a material, non-destructively. Unfortunately, the determination of $\gamma_c(t)$ requires a series of destructive tests. Since, however, both $E(t)$ and $\gamma_c(t)$ are apparently linked by the same physical mechanisms which determine their time-dependent character, there is some hope that indirect assessments of $\gamma_c(t)$ may be made from a knowledge of $E(t)$.

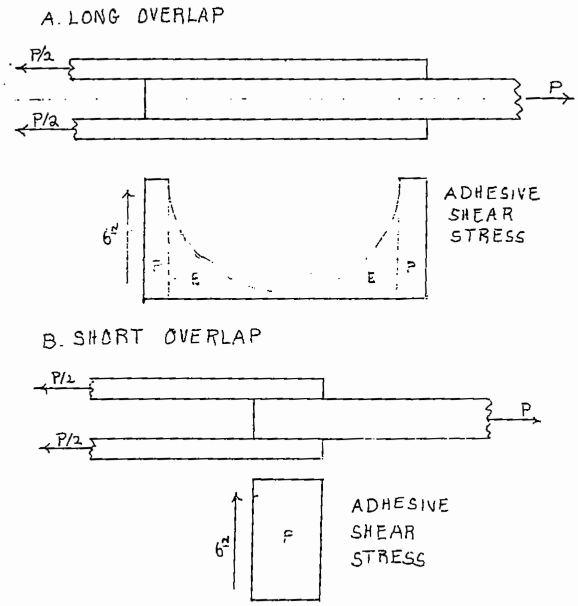
The discussion to this point has been based entirely on a deterministic approach to failure prediction. In any real case the bonded joint will contain distributed flaws, and both material properties and loads must be interpreted by probabilistic considerations. Accept/reject decisions will be based on measurable conditions of crack size, load history and material state, all viewed against a backdrop concerned with the probability of failure. The generation of a data base on the distribution of naturally occurring flaws forms a part of the program methodology.

II. TECHNICAL DISCUSSION

This brief discussion treats the central aspects of reliability in adhesive bonded structures which are displayed in Fig. 1. In each of these areas considerable advances in design concepts and property utilization are evident. One issue in any newly proposed program in reliability and life assessment of adhesive bonded structures is how to implement already available analytical tools. This section describes an approach to achieving this important objective.

A. Background

Load transfer between the adherend and adhesive elements of a bonded structure is accomplished by minute differential displacements between these elements.(1,2) Bonded joints cannot be designed on the basis of a uniformly stressed adhesive over the entire bonded area. In regions of high stress, typically at the bond edges and in the immediate vicinity of a damaged area the adhesive may be loaded beyond its elastic yield stress and display high damping and fracture energy due to viscous flow processes. In regions of low stress normally removed some distance from edges and damage zones the adhesive layer is below its yield stress and displays a high elastic modulus and creep resistance with low damping. Figure 2a shows a profile view of a long overlap shear joint with plastic stress of higher magnitude at the bond edges and elastic stresses of lower magnitude in the center region of the bond. Figure 2b shows a short overlap shear joint in which the stresses are essentially uniform due to high adherend stiffness and uniform plastic shear stresses are displayed by the adhesive interlayer over the entire joint. The oversimplified stress profiles of Fig. 2 ignore the cleavage (tension-compression) stress distributions which are highly localized at the bond edges and the stress distributions through the thickness of the adhesive layer which are known to strongly affect fatigue life of an adhesively bonded structure.(3,4)



g. 2 Influence of lap length on bond stress distribution.

Recent studies of the structural properties of esives by Renton(4) provide new recommendations adhesive test specimens and procedures for defining the engineering structural property of adhesive interlayers using low cost test methods. A thick adherend single-lap shear test, a rectangular butt joint tensile test, and a rectangular scarf joint test were selected and analyzed by Renton.(4) The stress-strain properties of FM73 and FM400 (NARMCO Div., Celenese Corp.) structure adhesives were evaluated using these three test geometries. Based on limited data a promising correlation between adhesive free film properties and thick adherend shear test data was shown.

Studies by Clark and coworkers(5) show that the most prevalent critical bond line defects are crack like voids, circular voids, and porosity, and that these voids can be detected by state-of-the-art NDE (non-destructive evaluation). Defects not detected by state-of-the-art NDE such as weak bonds due to surface contamination, and improper adhesive cure state were excluded from study. These studies show that flaw growth initiates in the regions of high stress concentration near bond edges and flaws and that this growth can be detected by available NDE methodology. Hot-humid environments and low cyclic fatigue rate which lower the adhesive elastic yield stress promote higher flaw growth rates. This study also showed that regions of very thin bond line act to produce adhesive stress concentrations and sites of selective crack initiation and growth.

The Primary Adhesive Bonded Structures Technology Program (PABST) was initiated by the Air Force(6,7) to demonstrate adhesive bonding in highly loaded, primary aircraft structures. In the PABST program the actual stress-strain response of the adhesive was represented by an elastic-plastic idealization of the actual shear stress-strain curve(3,5) as shown in Fig. 3. The idealized stress-strain response (dashed curve, Fig. 3) describes the actual failure stress and strain of the adhesive and the same strain energy to failure which fixes the effective initial elastic modulus, as shown in Fig. 4 different adhesives can show substantially different strength, extensibility and strain energy at room temperature due to differing curve structure and chemistry. At different temperatures, as shown in Fig. 5, a ductile adhesive will display significant changes in stress-strain response as will also occur with changes in moisture content and strain rate. The data summary of Table 1 shows that two to three fold changes in ductile adhesive strength and deformation properties are encountered over the service temperature range encountered in the PABST design and test program.

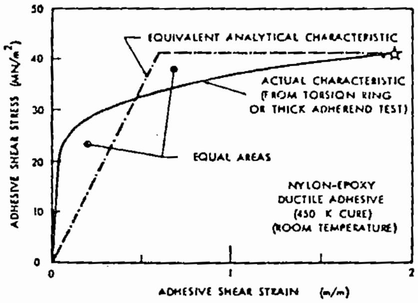


Fig. 3 Elastic-plastic idealization of adhesive shear stress-strain response.

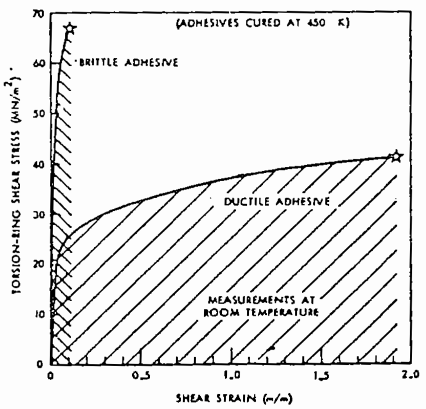


Fig. 4 Comparison between typical shear stress-strain respones of brittle and ductile structural adhesives.

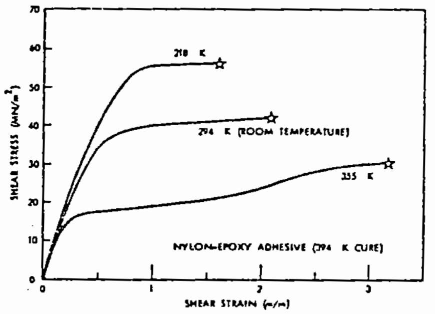


Fig. 5 Typical effects of temperature on ductile adhesive stress-strain response.

Table 1
Typical Adhesive Properties Used in PABST Bonded Joint Analysis(5)

Temperature (°F)	-50	70	140
Effective Shear Modulus (psi)	80,000	70,000	40,000
Shear Strength (psi)	6,000	5,000	2,500
Yield Strain (in/in) = (m/m)	0.075	0.071	0.063
Fracture Strain (in/in) = (m/m)	0.50	1.00	1.50

As mentioned earlier, the failure of ductile adhesives is localized at the regions of high stress at bond edges and near defect regions. Fracture mechanics recognizes and treats three macroscopic modes of crack tip loading as shown in the upper view of Fig. 6. These pure modes of crack tip loading usually appear in combined form in the usual fracture tests used to evaluate adhesive bond strength as shown in the lower view of Fig. 6.

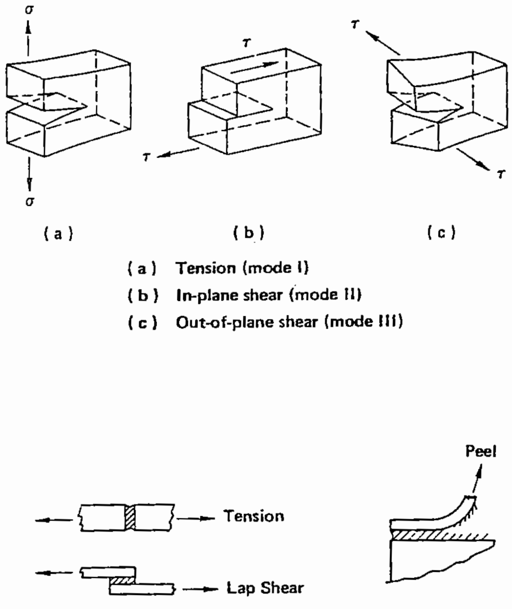


Fig. 6 Schematic diagram of tension, lap shear, and peel tests (lower view) and principal fracture mechanics modes for crack propagation analyses (upper view).

Assuming an idealized fracture mode of loading, the microscopic process by which adhesives undergo failure may be highly heterogeneous as illustrated by the schematic diagram of crazing as shown in the views of Fig. 7. Structural adhesives are microscopically heterogeneous with even unmodified epoxy networks showing evidence of two phase structure as evidenced by a modular fracture surface. Fracture mechanics analysis is only recently becoming interested in the role of adhesive morphology on fracture energy, fatigue life and structural reliability. The intrinsic scatter in fatigue lifetimes may be dominantly influenced by the samll scale micromorphology of the adhesive phase which is known to dramatically influence fracture energy of adhesive joints.

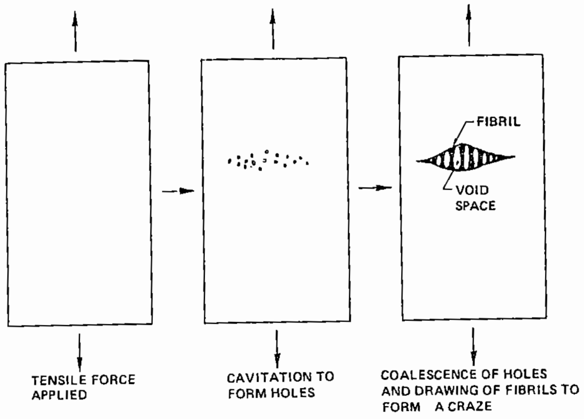


Fig. 7 Schematic diagram of crazing induced by applying tensile force to a polymer. Crazes form at right angles to the direction of stress.

The statistical distribution of adhesive joint strengths (failure load per bonded area) has been shown in a number of studies(8,9) to follow the standard Weibull distribution function. The Weibull function reflects an extreme value statistic which attributes failure to a single critical defect. When adhesive bonded structures are designed for high structural reliability the average bond strength (Survival Probability = $S = 0.50$) is much less significant than the achieved strength which correlates with high survival probability $0.99 > S < 1.00$. The important issues of adhesive and joint design for high reliability has recently been reviewed by Kaelble(10,11) as part of a Defense Advanced Projects Agency/Air Force sponsored program. Data presented in this review shows that epoxy structural adhesives display Weibull distributions for cohesive strength in free film form that correlate closely with Weibull distributions of lap shear strengths for epoxy structural adhesives in metal-to-metal joints. The intrinsic structural defects which initiate the cavitation and crazing process shown in Fig. 7 become the subject of materials and process optimization in a generic materials fracture properties study task.

Joint strength and the distribution of joint strengths needs to be directly related to microdefect properties (size, structure, molecular force character, etc.) and the intrinsic distribution of these properties. In other words, the lack of a fundamental materials and process related understanding and control of intrinsic craze zone initiators (see Fig. 7) will continue to lower confidence in high reliability performance of adhesive bonded structures.

B. Approach

1. Materials Characterization

A minimum listing of important subject areas for quantitative materials and process characterization includes:

1. Prepared surface quality assurance.
2. Interphase property measurement.
3. Adhesive chemical and rheological characterization.
4. Bulk properties of adhesive in the joint.
5. Corrosion processes.

Materials selection and process optimization which occurs in preliminary structural design makes extensive use of the above characterizations. This type of quantitative information is only recently being utilized in the nondestructive evaluation (NDE) and life assessment of bonded structures.(10,11) Key detailed materials and process characterization road maps are already developed and available for material and process haracterization. Figure 8 presents a detailed low chart and methodology for quantitative chem- cal characterization of adhesives, coatings, and omposite matrix materials based upon epoxy resin hemistry. In Fig. 9 a detailed flow chart for hysical and mechanical response is presented. he flow chart of Fig. 9 includes studies of ydrothermal aging, failure surface analysis (low- r section Fig. 9) which is combined with data om manufacturing simulation (upper section g. 9). These data are combined in a data analy- s (lower box Fig. 9) which draws upon available ructure property relations to replace empirical rrelations with failure data defined by discrete ysical or chemical processes.

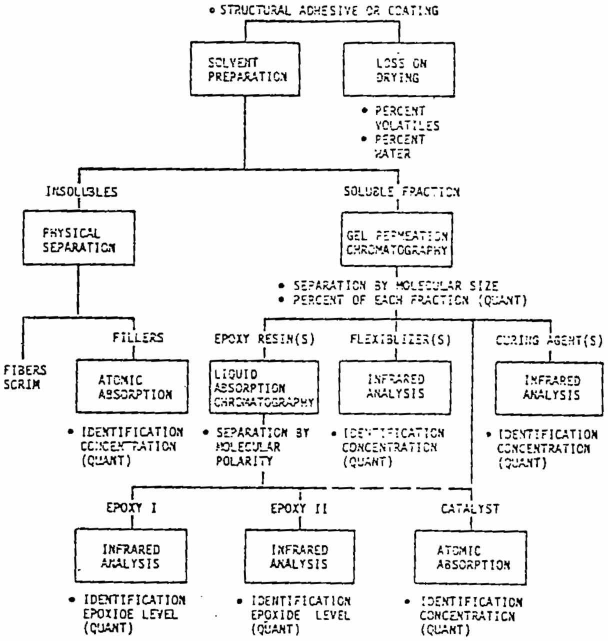


Fig. 8 Chemical analysis.

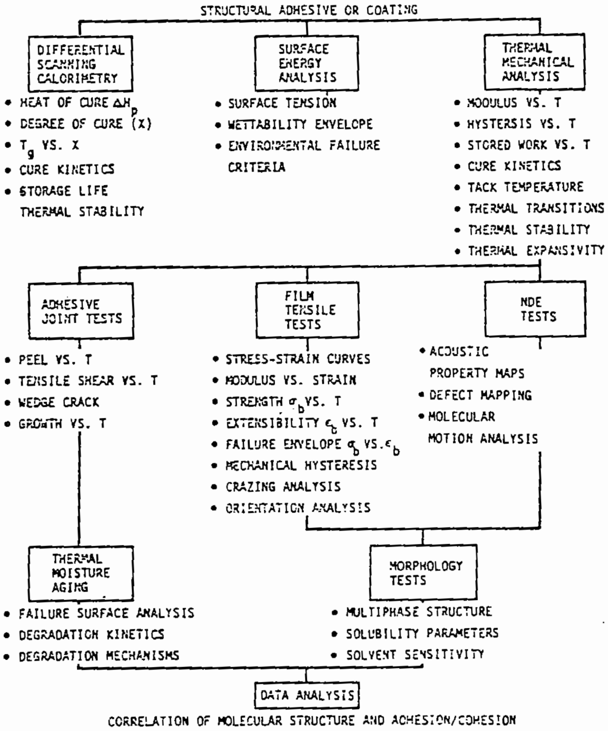


Fig. 9 Physical and mechanical analysis.

2. Loads Definition

During laboratory investigations of a research or development nature it is customary, if not mandatory, to deal with relatively simple loading situations. Before embarking on a research effort such as is before us, it is important, however, to classify the types of loads and their possible effects on bond (strength) performance.

We distinguish two ingredients in the description of loads or forces acting on bond geometries: a spatial distribution of forces or tractions and their time history. The simplest case arises in situations leading to what one refers to as proportional loading: this type of loading results when the distribution of forces remains invariant in time but the magnitude of the forces or tractions vary. For example, the time-varying pressurization of a fuselage would fall into this category. A special case results when constant loads are applied to a bonded structure. Most laboratory tests fall in this category.

Problems associated with Non-proportional loading are more difficult to deal with, both analytically and experimentally: applied force distributions vary with time and must be reckoned within realistic use environments. An example of this type of loading is given by a (bonded) shaft that is first loaded in axial tension and then subjected to twist.

With regard to loading histories (under proportional or non-proportional loading) one distinguishes monotonic loading (continuously increasing or decreasing loads with time-constant loads as limit cases) and non-monotonic loads. The latter are either of a cyclic or of a purely random nature. Cyclic loads are relatively easily applied in most laboratory environments when they are of the purely sinusoidal type but require less readily available equipment if arbitrarily varying proportional loading histories are required. The latter comprises the cases of random loading which are particularly difficult to deal with whenever one is confronted with history-dependent material behavior such as results with the use of polymeric bonding agents.

If and when our predictive capability of bonded joint behavior progresses to the point where we can predetermine failure behavior for arbitrary load distributions and histories, such distinctions are not necessary. However, in parallel to the failure response of metal structures and monolithic polymer structures, we anticipate that we shall lack this complete capability for more time to come; as a result we shall have to be continuously aware of the possibility of different deformation and failure responses as a result of different load histories.

So far, we have dealt here with applied mechanical forces. It is equally important to consider forces induced in bonded joints during exposure to varying environment. Normal dilation, either as a result of polymer-cure or of normal changes during use; cure-shrinkage; and swelling due to weather or other solvent infusion are factors that give rise to mechanical forces acting on the bond line. To date little more than lip-service has been given to the recognition of these facts, but we think that the time is here when the latter, seemingly less important factors in bond loading, are assessed, particular attention being given to their effect on the long-range performance of bonds.

3. Stress Analysis

As for the performance analysis of any loadbearing structure, a stress and deformation analysis is a necessary ingredient to a life and failure estimate. Today all fracture and deformation failures are based on concepts evaluated within frameworks of solid mechanics analyses of varying degrees of refinement. The degrees of analysis sophistication is often a somewhat debatable issue. Most often it is clear that a simple P-over-A analysis does not form a sufficient criterion and an extremely refined fracture analysis with microstructural material refinements at the crack tip would represent "over-kill." While it has become obvious that a simple P-over-A analysis is insufficient for design purposes, the question as to what constitutes sufficient analysis procedures is yet being debated. No doubt that question will be answered progressively and through trial-and-error procedures in an engineering way.

We distinguish historically two types of analyses: those that deal with stress components averaged over the thickness of the bond, termed for present purposes "thickness-averaged stress analyses," and those in which attention is paid to the detailed distribution that is resolved throughout the bond thickness. It is our opinion that only the latter type of analysis has promise of aiding in the formulation of a framework of predictive failure analysis. That this is so is readily apparent when one inspects newly bonded test samples which have been loaded without inducing gross failure. Fractures are observed readily in regions of stress concentrations which are clearly not identified by a thickness-averaged analysis.

There are several high stress regions that figure prominently in a bonded joint: edges and corners at adherend-to-adhesive interfaces develop high stresses due to material discontinuities. Within the assumptions underlying linearly (visco)-elastic analyses, the stresses may become unbounded at certain points. While the unboundedness is a consequence of the linearity assumption and does not exist in reality, to ignore the location of these excessively high stress regions as the thickness-averaged analysis would do would be folly.

When failure proceeds by the propagation of crack, the stresses at the tip of that crack are again very high and, again within the framework of linearly (visco)-elastic stress analysis, their character depends on whether the crack tip is located at the interface or is embedded in the adhesive. Interface (or interphase) cracks exhibit an oscillatory crack tip stress field that is not supported by physical reasoning and is due to the linearization of the problem. At any rate, the domain in which this anomalous stress-field behavior acts is so small that, from a practical point of view, it is most probably unimportant.

Most practical bonded joints employ adhesive on a carrier or scrim cloth. The adhesive interlayer is thus really a composite and inhomogeneous mateial, and it is not clear at this time under which circumstances this fact can be neglected or must be accounted for.

In connection with cracked bond lines a way of structural failure analysis has developed which we term, for lack of a better term, "thickness-averaged fracture mechanics." We mention this here because of the implication for the requisite stress analysis. In this approach to the bond failure problem, the adhesive layer and its response is ignored. The attendant stress analysis is thus confined to adherends and the adhesive layer merely serves as a guide for the propagation of the crack.

In opposition to this simplification we must recognize that the stress fields in bonded joints have three-dimensional character. No more is this obvious than when one observes the distinct failure patterns in laboratory specimens which arise from these three-dimensional stress fields. Such facts not withstanding, one is most likely forced to extract maximal information out of two-dimensional analyses, be they of a closed form or other analytical nature or derived from finite element loads.

In most engineering fields drawing on structural or continuum stress analyses, there exists a body of information on characteristics of stress distributions. Stress analysis of bonded joints has been a stepchild of bond strength investigators, primarily because their background did not point up the need for an improved understanding of that aspect in joint failure prediction. As a result we are, at present, short of a body of stress analysis results. It is not that we lack the capability; it is merely that that capability has not been exercised enough. No doubt that deficiency will be removed as time goes on.

It may be illustrative to relate experience in this regard that comes from our early experience with engineering of solid propellant rocket motors. Analysis tools were being developed or were available as they are now. However, we learned that for certain configurations involving high volume constraint, standard notions of stress distributions were rather inadequate (for nearly incompressible solids). Bonded joints place similarly high deformation constraints on the adhesive; the consequences of this are not explored nor understood. Recent results in failure studies simulating long-time endurance failure indicate that such effects are important. In another instance the common notion of what constitutes 'rigid" adherends relative to the adhesive has een questioned.

These isolated examples of deviations in tress distribution from an apparently accepted orm make us believe that attention needs to be ocused on this area.

A discussion of stress analyses and their ap- lication to bonded joint failure prediction would t be complete without calling attention to the ed for stress analysis validation. Specifi- lly, one is here concerned with examining in ich respect, and by how much, any assumptions derlying currently available analysis codes inearly elastic, elastic-plastic) violate or roborate the physical situation. In particu- , our visco-elastic stress analysis capability very limited and assumptions in this regard are n more in need of checking than those already tioned.

Since stresses cannot be measured directly, validation procedure must involve the compari- of a displacement field resulting from theory experiment. Strain gages are, in general, of le usefulness because they are large compared to the thickness of the bond; they may be useful in verifying the surface strain distribution in thin adherends. Other than that, one is bound to rely on displacement measurements. These may be checked at particular points with various displacement gages, or possibly in limited regions, by optical interferometry or speckle interferometry. Verification of deformation in highly stressed domains promises to be very difficult in realistically dimensioned joints because the regions in which they occur are so small.

4. Failure Modelling

We consider two basic types of structural failure: (a) loss of ability of a structure to carry an assigned load and (b) excessive deformation. The latter failure mode is analyzed and predicted completely by a component stress analysis (probably not a linear analysis) and we therefore point out once more the need for advances in our capability to successfully deal with deformation analyses of structural bonds. We shall not concern ourselves with this aspect of failure in this section.

The loss of load carrying ability of a bond is (apart from problems derived from extreme flow of the adhesive) clearly tied to fracture. Therefore an analysis of failure in bonded joints is almost synonymous with the steady fracture progression in a special class of structures.

The problem of bond strength has been investigated for a long time. Most of that effort in the past has been spent on developinng "better adhesives"(12-14) or studying the interface problem.(14-17) Less attention has been directed towards the mechanics of the failure process in the bond-joint geometry.(18-20) Because of its promise as an effective and efficient construction method and because of a basic lack of understanding of joint strength in spite of the extensive chemistry related research, the mechanics aspects of the problem are now being exercised more intensively. In that connection several basic problems have been posed, none of which are resolved in a satisfactory manner though ongoing work is making strides towards practical solutions. Today, the failure of bonded joints is approached largely through the problem of peel testing on the one hand(21) and through what we have referred to as thickness-averaged fracture mechanics on the other. Peel is often associated with soft adhesives and thickness-averaged fracture mechanics with rigid adhesives, although that distinction is not systematically adhered to, since peel tests are also used to evaluate rigid adhesives.

The two approaches differ primarily with respect to the choice of the test geometry. Peel approaches the adhesion problem by specifying relatively thin adherends which undergo large (elastic or elasto-plastic) deformations (see Fig. 10). Test results or analyses are concerned with <u>net</u> forces acting on the adhesive system and the <u>resulting</u> deformations with no or a minimum of attention paid to the detailed process in the adhesive. Thickness-averaged fracture mechanics deals primarily with (two-dimensional) plate or beamlike geometries, two pieces of plate being joined along a line by an adhesive layer (see Fig. 11). Since the adhesive layer is usually thin compared to the thickness of the plates the

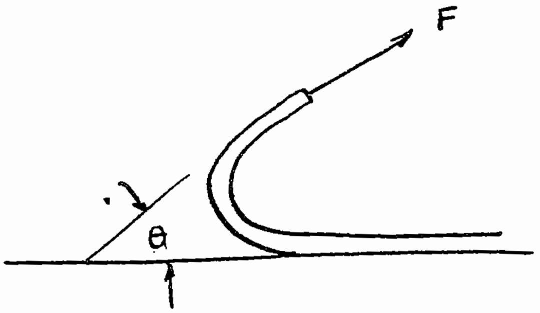


Fig. 10 Peel test geometry

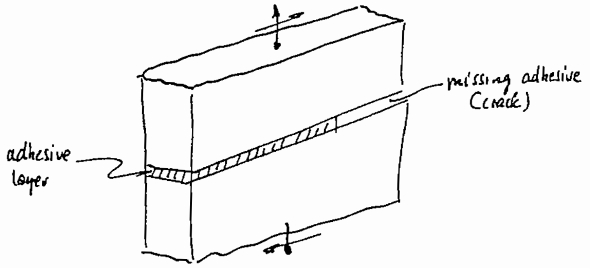
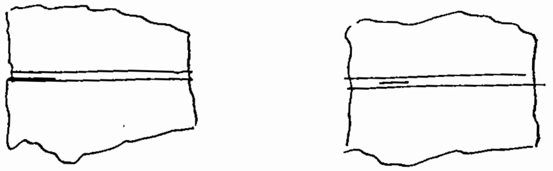


Fig. 11 Standard test geometry used for thickness-averaged fracture mechanics.

thickness of the adhesive layer is deemed negligible, thus reducing the plate problem to the fracture of a homogeneous plate containing a weak internal material plane. The problem is then further analyzed by fracture mechanics concepts developed for homogeneous solids and defining average properties for the adhesive layers. While this appears on first sight a very reasonable approach to a complicated problem, we shall see later that there are pitfalls inherent in this approach. Suffice it to say here that thickness-averaged fracture mechanics makes certain fracture parameters a function of bond thickness whereas in ordinary fracture mechanics such quantities are interpreted as material constants. This limitation poses special difficulties in a technology where bond thickness variations are a fact of life, and where the variations may have to be carefully measured post factor (by ultrasonics?). If time-dependent adhesive properties must be considered, such parameters become rate- or time-dependent quantities which, in the context of thickness-averaged fracture mechanics, would be functions of the bond line thickness also. Both the approaches of peel and of thickness-averaged fracture mechanics to bond fracture have in common that they neglect, by and large, the details of the processes in the adhesive itself. Beyond this similarity there has apparently not been established any quantitative relation between peel and thickness-averaged fracture mechanics. In fact, we are not aware of that question being raised. Instead we experience laboratory tests employing either approach and application of the resulting data to design problems that involve geometries somewhat intermediate to those characteristics of peel and thickness-averaged fracture mechanics. Since the peel mode involves large deformations, in particular much larger than those involved in thickness-averaged fracture mechanics, it is clear that such indiscriminate use of bond strength test results is potentially dangerous. In other words, since bonding is applied to structural adherends of widely varying thicknesses neither the conditions commensurate with peel nor thickness-averaged fracture mechnanics prevail. It appears mandatory therefore to examine the conditions that lead to joint fracture in more detail than either the peel mode or thickness-averaged fracture mechanics can portray.

In order not to mislead the reader, we should mention here that mathematical analyses are being made for layered elastic systems wherein one or more layers contain cracks. Such problems are intended to model the formation and propagation of cracks in adhesive layers and thus the part of the initial process of the adhesion failure. For analytical reasons the geometries are simple and of the type shown in Fig. 12. While these geometries appear reasonable choices, they are not necessarily based on observations preceding joint fracture. What concerns us is not so much the necessary simplicity in the analytical modelling but the prospect that this assumed simplicity prejudices the interpretation of the fracture process which interpretation should be derived from direct observation preceding any modelling and analysis.



Interface unbond
two-dimensional
or penny-shaped
unbond

Embedded crack
two-dimensional
or penny-shaped
(penny-shaped crack
on bond midplane)

Fig. 12 Two-dimensional bond fracture geometeries.

Connected with this concern is the observation that virtually all information on the fracture process is derived from the post facto appearance of the fractured joint. Reconstruction of the fracture process is thus often made ambiguous because the source of fracture surface features are second-guessed. The need to intensify work on fractographic studies is pointed out later.

There does not exist to date a nearly comprehensive theory of bond fracture. However, once one decides that a quantitative account of the failure process is imperative for a predictive failure theory, one needs to cope with the fact that cracks exist in many shapes and forms and can respond in different ways, depending on the applied loads.

Flaws or cracks may pre-exist in a bond as manufacturing defects or may develop under loading. Cracks located in the interior of a bond area are less detrimental than those located near edges or in stress singularities. Apparently interior flaws have little effect on the strength of a new or intact joint. This is so because by far most of the load transfer in bond-parallel loading is effected near the bond ends. The severity of flaws in a structural integrity sense depends thus on its location relative to the (current) bond end. If cracks grow from the edge, an interior flaw becomes thus more critical.

In principle the ideas of fracture mechanics are equally applicable to bonded joints as they are to monolithic structures. The differences enter through the materials, in particular polymers, which are not part of a standard engineering repertoire, and through difference in geometries. The latter, especially through the ubiquitous interface boundaries in joint geometries, complicate matters.

Some other features, not normally observed in monolithic fractures, need to be pointed out. In terms of a standard test geometry, a smooth crack front is expected as depicted in Fig. 13. However, it can be shown that in slow model tests a crack may not propagate with a smooth front. Instead the crack front appears (in plain view) as in Fig. 14. It appears thus that present test methods, which are geared to relatively short-term data gathering, could easily (and probably will) misrepresent failure modes encountered under long-time loading. The interaction of the crack tip stress field with the bond interfaces gives rise to changes in the crack path direction, especially when coupled with non-proportional loading. For example, depending on the loading on an adhesive bond, a centrally located crack may grow to the interface. An understanding of whether it stops or grows along the interface requires a fracture criterion that is more general than those developed for cracks propagating along their original axis or in their original plane.

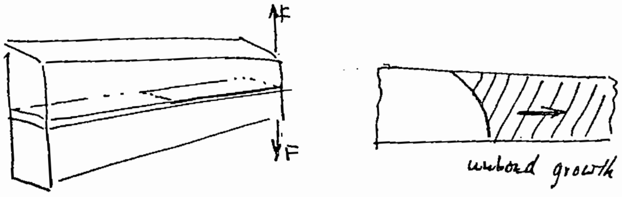
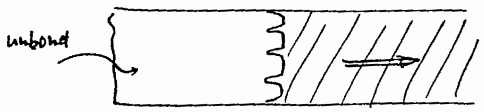


Fig. 13 Crack front in standard tet



g. 14 "Finger" development at front of unbond "Finger" spacing is very regular, shown approximately to scale.

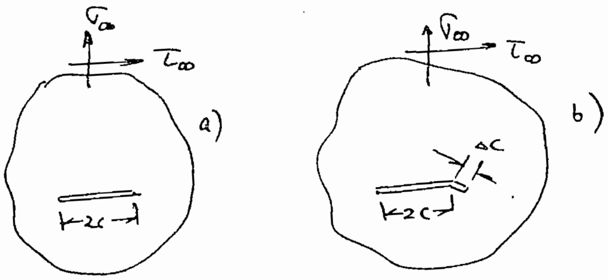


Fig. 15 Non-linear crack growth.

The (two-dimensional) problem of crack exten- on under loads such that the extension makes ne angle with the original crack has been solved the homogeneous solid. Figure 15 shows the metry before (a) and after (b) crack extension a small amount Δc. The criterion for the tical load at which the crack extends as well the direction is based on an argument of max- l energy release in the crack propagation pro- s. The ratio of difference in the (negative) potential energy between the original and crack-extended geometry and the extension Δc is maximized to determine the orientation of the crack extension for a limit $\Delta c \to 0$. The crack is judged to propagate when this maximal energy release rate was just equal to the (constant) intrinsic fracture energy of the material.(22)

The interesting result of such a rather difficult energy analysis is that the much simpler approximate stress criterion gave closely the same result: The stress criterion(23) asserts that fracture occurs along that ray emanating from the crack tip normal to which the tensile stress attains a maximum value with respect to angular orientation of the ray. Crack growth starts when the stress intensity associated with this maximum stress reaches a critical value. As a result of this favorable comparison, an extension of the stress criterion for brittle fracture can be made to crack extension under arbitrary loading. A key development in that extension to fracture development in a three-dimensional context rested heavily on the experimental findings(24) that under a mode III (antiplane shear) loading a crack does not propagate along its original plane but develops crack extensions that spiral from one of the initial crack surfaces around the crack front to the other crack surface in a somewhat helical path (see Fig. 16). The resulting crack-extended geometry is distinctly three-dimensional.

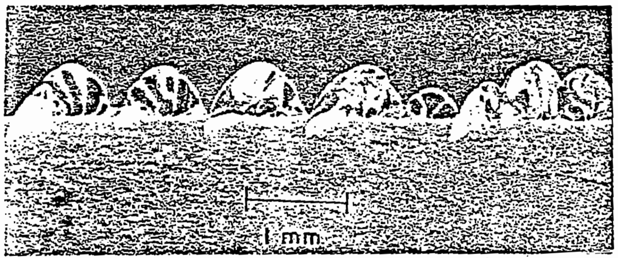


Fig. 16 Cracks generated in antiplane shear.

It follows from the two-dimensional energy analysis results -- which compare well with careful experiments -- and from the just-mentioned findings in mode III failure, that the extension of cracks under general loading should not be analyzed by methods which assume the growth process to occur in the plane of the original crack.

We turn now to a discussion of phenomena in fracture modelling that are concerned with time dependence of the process.

1) Time dependent fracture. The time dependence of the failure process may have several causes. Among these the

a) Viscoelastic properties of the adhesive certainly play a dominant role. While to date "rigid" adhesives are treated (almost?) invariably as time independent, recent tests on typical (supposedly rate-insensitive) adhesives have been shown to exhibit a surprising amount of stress relaxation (on the order to 10 - 20%) within minutes of test start.(25) In the same vein it is known that bonds lose a significant amount of load-carrying ability in a few days' loading; this observation points to significant viscoelastic influence, too. For this reason it is necessary to characterize the viscoelastic behavior of any adhesive.

b) Rate dependence influenced by the geometry. It is a well-documented fact(26) that in peel experiments the path of fracture moves from a intra-adhesive location at high rates of failure propagation (low temperature) to an (apparent?) interface failure at low rates of failure growth (high temperature). Beyond the suggestion that intra-adhesive failure is the result of void formation and coalescence (when uncrosslinked adhesives are used), which void formation does not occur in near-interface failure, this phenomenon is not understood. Gent and Petrich(27) even contend that cavitation may not be responsible for the change in failure mode.

A plausible explanation of this phenomenon in connection with relatively rigid adhesives appears to be related to a combination of non-linear material behavior and the geometry.

The high stresses at the tip of a crack or unbond cause a local mechanical degradation. This irreversible damage occurs in a limited zone, say a typical dimension a. If the crack is embedded in a solid with all geometric dimensions large compared to a we speak of small-scale damage (in metals: small-scale yielding). For small-scale damage fracture characterization can be accomplished in terms of a single parameter, the stress intensity factor, say, without reference to the size of a of the damage zone. This is so because in a characterization test the geometry is taken so that does not enter the considerations. As long as the critical stress intensity factor criterion is applied to geometries in which a is small compared to all other dimensions, this parameter need not be considered.

In this connection we need to mention a phenomenon observed in fatigue failures. When a bond is subjected to "small" cyclic loads (fatigue), fracture occurs along an interface; but when the crack has grown to sufficiently large dimensions so that "catastrophic" failure sets in, then crack propagation occurs through the center of the bond (scrim area). What happens apparently is that during the (low level) fatigue loading, the zone at the crack front is small enough not to play a significant role in the stress distribution. When the load transmitted to the crack-tip in the final stages becomes large as catastrophic fracture approaches, that is no longer the case.

c) Initial propagation and other transient histories of growth. To date, problems in viscoelastic fracture and unbonding have been considered primarily in the context of steady cracking rates. From this viewpoint the rate of crack growth is essentially a function of the instantaneous stress intensity factor. Cracks and unbonds are observed to start propagating with time delay after load application. In some highly crosslinked materials this delay can be interpreted simply as the time required to increase the stress intensity to the point where the flaw growth accelerates to a measurable rate. On the other hand, the deformation and degradation of the material at the crack tip is time dependent so that some of the delay is attributable to deformation without flaw growth. Similar phenomena must occur under (transient) cyclic loading when the flaw grows, on the average, less than the length of the damage zone (long-time fatigue). We thus face a question, the answer to which is important in structural life prediction: Is a substantial portion of the structural life taken up by processes to get the flaw to a growth stage or is the life determined (almost entirely?) by its growth rate? The answer is vitally important in connection with fatigue of polymers. Resolution of that question requires experimental methods that provide high resolution of the deformations at the front of a flaw.

d) Effect of moisture on time-dependent fracture. The observation that cracks can propagate slowly (10^{-7} to 10^{-2} mm/sec) in inorganic (silicate) glasses is often attributed to the influence of moisture. This influence is greatest in the highly stressed region around the tip of the flaw. We would expect that the same is true where polymers are concerned, as long as they are not totally inert to moisture. We know that moisture ingression is a form of plasticization and results in a shortening of the material relaxation times. Due to the highly dilated molecular structure at the crack tip, the diffusion process should be accelerated, and it is just in this critical domain where the creep behavior is accelerated by moisture. One would expect therefore, a dominant effect of moisture on failure rates in some polymers; among these we count the epoxies and polyurethanes, polymers which are used structurally in large quantities.

e) Effect of temperature on fracture and unbonding. For thermorheologically simple elastomers (above the glass transition temperature) it is well established that the rate of failure propagation and temperature are connected by the time-temperature super position scheme. This is true with respect to both cohesive and adhesive failure. While the sensitivity of viscoelastic relaxation to temperature changes decrases notably as a polymer is cooled down through the glass transition temperature, there is every reason to believe that a time-temperature superposition is valid in rigid polymers (below the glass transition temperature). Problems may arise for filled polymers (hard particulate filler, scrim cloth, "toughened" with rubber particles) which are usually not thermorheologically simple.

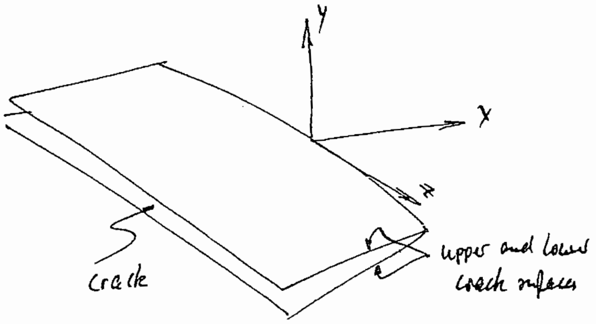
We consider next in more detail phenomena associated with crack geometries:

2) Load Criterion for Fracture. It follows from the discussion of the influence of temperature on the time history of the fracture process

that temperature changes also induce stresses in a composite structure. Often a temperature increase is used to model the speed-up of the viscoelastic responses (accelerated testing). If this is done it is also necessary to understand the effect of temperature on the mechanical state of stress. For "rigid" polymers this problem leads certainly to dealing with polymer behavior near the glass transition.

The (possibly) thermally induced stresses combine with those due to mechanical loading. We have discussed these already jointly in connection with the stress analysis.

a) Mode interaction.* We shall consider next the response of a crack or cracklike flaw in a bonded joint or composite to mechanical loads. This we do initially without reference to time dependence. We first define some terminology: With reference to Fig. 17, let point A lie on the smooth periphery of a planar crack and establish a Cartesian coordinate system with z tangent to the periphery at point A and x contained in the plane of the crack. With reference to this coordinate system we define the three primary modes of crack deformation, modes I, II and III in standard fracture terminology. These modes describe the relative motion of the upper and lower crack surfaces espectively parallel to the y, x and z direc- ions. We speak of a mode-interaction problem if he loading is such that fracture propagation re- ults in the presence of more than one deformation ode.



g. 17 Local coordinate system at crack front.

In monolithic cracked structures the mode- eraction problem has been considered recently everal authors; a fairly comprehensive review hat problem is documented in Ref. 22. How- , in connection with bonded joints the motion crack is inhibited by the proximity of the tively rigid and infrangible adherends. One therefore have to re-examine the mode- raction problem for the bond problem. Speci- questions arising in this context relate to: fracture path(s) as a function of the relative itude of modes I, II and III; how does this path depend on the relative strength of the interface adhesion and the cohesive strength of the adherend; what is the functional relation between the three modes of deformation at fracture; is such a relation invariant under time-dependent failure processes?

The next question that needs to be considered relates to the fracture path. Fracture in bonded joints is observed to occur along (or near) the interface or in the adhesive. There is no documented criterion that relates the path of fracture to the loads acting on a joint apart from the general criterion that the crack follows a path requiring minimum energy expenditure.

In this connection it is pertinent to discuss the problem of proper test data interpretation for design applications. Suppose an adhesive layer between two relatively rigid adherends is subjected to a general loading up to fracture initiation in a geometry such as is shown in Fig. 18. This type of geometry is a standard way to evaluate the strength of adhesion by thickness-averaged fracture mechanics. Fractures appear (not necessarily visible on the surface) such as indicated in Fig. 18 by solid lines without total failure of the specimen. Upon further loading these cracks may join along the dotted lines in Fig. 18. Generally, cracks open initially so that the newly created fracture surfaces separate. However, as the cracking process continues, a complicated fracture pattern may result.

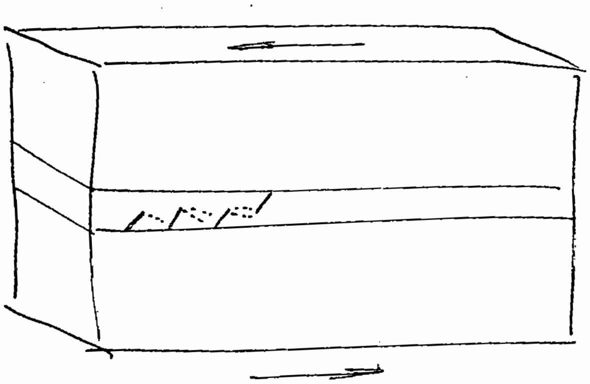


Fig. 18 Fracture path and sequence in shear test.

b) Initiation. Opinions seem to diverge on the importance of initiation in the failure or cracking process. There are those who hold that a "properly designed" bonded joint should never develop a crack and others who claim that cracking cannot be avoided at bond terminations and that bond-life depends on suppression or retardation of continued growth through suitable bonding agents. Apparently observations diverge on this point because we do not understand sufficiently well the interaction of bond geometry, stress field and material properties.

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definition of the interaction problem is often sloppy. When writers have in mind thickness- aged fracture mechanics only the deformation of the adherends in the bond-termination region is idered. Therefore, motion of the adherends apart and normal to the bondline is interpreted as a ck opening" model (mode I). However, if we consider the detailed stress distribution around the of a disbond between adherend and adhesive, then the deformation under the same loading on the ends produces both mode I and II motions, the mode II being induced through Poisson coupling from I.

Of dominant concern in this regard are the high discontinuity stresses acting almost invariably at the bond termination. Some studies are available that deal with shaping the adherends near to bond termination (tapering) to minimize these stresses. However, the interactions of such geometric variables with bond material characteristics such as nonlinear or "plastic" deformations need to be explored. Standard fracture mechanics principles do not apply for the initiation phase as long as a crack or disbond cannot be identified. Only at the end of this initiation phase can this be done so that time dependent fracture mechanics processes apply. It may be possible, however, to explore the initiation problem through energetics involving appearance of cracks or disbonds of discrete length or size.

5. Fractography. Fracture of homogeneous bodies involves characteristics of the fracture surface features which allow often the reconstruction of the fracture process. These features have been studied completely empirically and constitute an important body of information in fracture analysis.

Similar observations are in progress in the study of bonded joints, most of them presumably as an adjunct in ongoing failure studies. It would be advantageous, however, to structure a program more systematically about fractographic questions, in particular in connection with NDI type investigations. Such a program should comprise NDI of bonded joints subjected to various load histories and (etched) removal of the metal adherends for examination of the fracture feature in the adhesive, probably a painstaking task.

III. PROGRAM PLAN

The program plan is described in the "roadmap" format common to Air Force planning documentation. This format allows the program content to be viewed in context, with interrelationships among the separate work units to be displayed against a time-line. Since there are programs currently underway and in planning by the agencies, it is particularly important to discover those which provide necessary or complementary activity to the main thrust of this plan. These programs will be shown as well with their output contributing at specific time periods in the plan. The most pertinent ongoing effort is indicated on the first block of the roadmap entitled Fatigue Behavior or Adhesive Bonds (Contractor: General Dynamics/Fort Worth). Each block on the roadmap diagram indicates a logical work package with its own objective; however, combinations or further subdivision may be appropriate as the implementation of the plan proceeds. A work package description is included for each block on the roadmap, in which the objective, scope, approach and resource needs are outlined. Finally, a funding summary by fiscal year is provided.