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FRACTURE MECHANICS OF JOINTS

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ABSTRACT

Almost every engineering design requires that component members be connected. A disadvantage of mechanical connections such as bolts, screws or rivets is that they do not uniformly distribute the load; hence large local stresses result. This problem can often be reduced by joining the members adhesively. Major problems with adhesives that have tended to limit their wider usage include: (1) how the strength of an adhesive and the joint in which it is used can reliably be predicted, and (2) what factors tend to limit the strength of an adhesive joint and how they might be eliminated. It is the intent of the authors to show how fracture mechanics might be used to develop a rational philosophy and methodology that will aid in overcoming these problems. The adhesive fracture mechanics approach, in the opinion of the authors, holds the best potential of:

1. Identifying and/or designing the best tests for evaluating a given adhesive
2. Identifying the best and most meaningful fundamental parameters by which adhesives might be characterized, and
3. Making use of these parameters to systematically and optimally design joints and predict their strength and performance.

This presentation reviews the development of the fracture mechanics models, describes several tests that have been used to obtain model parameters, and reviews means by which these might be used to predict the strength of practical joints.

Introduction

The structural designer is often confronted with the question, "Under what conditions would this engineering element or part fail?" To answer this question, one must first decide what constitutes failure. While most of us normally associate failure with a part breaking into two or more pieces, conditions other than fracture can make a part inoperative. Hence, one must first decide what constitutes failure. While the existence of microscopic or atomistic "holes" in materials was recognized, it was generally assumed that their presence was of no design consequence and, as long as material production control techniques were sufficiently reliable to produce microvoids of a small mean size with a low dispersion around the mean size, the use of an average stress or strain criterion was justified.

The Continuum Approach to Design

It is important to realize that failure of structural components has been characterizedly approached in two ways by the analyst. Before recognition of the importance of inherent flaws in the material, the analyst relied upon one of several average stress or strain criteria, e.g., maximum tensile stress, maximum principal strain, maximum octahedral stress, or others, depending usually on experimental evidence and experience. While the existence of microscopic or atomistic "holes" in materials was recognized, it was generally assumed that their presence was of no design consequence and, as long as material production control techniques were sufficiently reliable to produce microvoids of a small mean size with a low dispersion around the mean size, the use of an average stress or strain criterion was justified.
strength, therefore, reflects the presence of flaws, and the dispersion of strength might be viewed as an indication of the uniformity of the flaw distribution. Because most standard materials are made under reasonably strict quality control conditions, it is not surprising to find that some sort of consistent (average) stress or stress-functional criterion can be used to predict failure.

Under more complicated conditions (such as the multiaxial stressing of a rotor disk), it is frequently customary to assume that the failure criterion is based on the octahedral shear stress ($t_{oct}$), which includes the three principal stresses and is defined as

$$t_{oct} = c \sqrt{\frac{1}{2} (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

(1)

Assuming that this criterion (often called the Von Mises yielding criterion) applies, one predicts failure whenever a combination of principal stresses at any point in the part exceeds $t_{oct}$. And how is $t_{oct}$ determined? If Equation (1) is a universal failure criterion, it must also apply to the failure of a simple uniaxial tensile specimen having stresses $\sigma_1 = \sigma_\text{tens}$ and $\sigma_2 = \sigma_3 = 0$. Thus, substituting into Equation (1), one finds that

$$t_{oct} = \sigma_\text{tens}$$

(2)

so that upon solving for the desired constant $c$ and resubstituting into Equation (1), one finds that failure is expected under a multiaxial principal stress combination whenever at some point in the body

$$\sqrt{\frac{1}{2} (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \geq \sigma_\text{tens}$$

(3)

In the more general average stress criterion case denoted as region I in Fig. 1, the failure criterion based upon average principal stresses would have the form

$$F(\sigma_1, \sigma_2, \sigma_3) \geq \sigma_\text{F cr}$$

(4)

where $F$ is some function of the principal stresses at a point in the material and $\sigma_\text{F cr}$ is the value of $F$ at failure.

On the other hand, there are conditions in which discrete flaws, substantially larger than the uniform size distribution normally present, can exist in the material. Such inherent flaws may arise from localized corrosive attack, improper fabrication, micro-deformation associated with casting or forming operations, cyclic loading, accidental surface nicks or cuts or many other sources. Because they are discrete, usually relatively sharp, and larger than the surrounding voids, they may induce additional stress concentrations and provide loci of cohesive fracture initiation.

Ordinary elastic stress concentration factors are used if the flaw shape is not cracklike. However, if the inherent flaws are cracklike, stress concentration factors are useless, because linear elastic theory predicts an infinite concentration factor in the vicinity of a crack tip. Thus, the local stress value will exceed the finite allowable stress experimentally measured for the base material, containing only the reasonably uniform distribution of inherent voids. The strength degradation in such a situation is illustrated by region II of Fig. 1.

Griffith provided the first estimate of degradation as a function of the flaw size by considering the problem of a small, through-line crack in a thin sheet of brittle material (illustrated in Fig. 2a). Theoretically, the stress at the crack tips is (mathematically) infinite for an elastic body, thus giving rise to an infinite local stress at even small applied loadings—a degree of concentration for which Equation (4) is useless. Griffith avoided this problem by considering changes in the strain energy (volume integral of stresses squared), which remains finite. He proposed, in essence, that cohesive fracture would commence at a critical applied stress $\sigma_\text{cr}$, when the incremental loss of strain energy of deformation with increasing fracture area just equaled the work required to create a new fracture surface.* Hence in this case, with the elastic strain energy of deformation ($U$) due to the presence of the crack of length $2a$ being

$$U = \frac{1}{2} \sigma_\text{cr}^2 a$$

one would have fracture whenever

$$\frac{\partial U}{\partial a} \geq \frac{\sigma_\text{cr}^2}{2}$$

(5)

* Actually, Griffith's original hypothesis was that the new criterion of rupture is obtained by adding to the theorem of minimum energy the statement that the equilibrium position, if equilibrium is possible, must be one in which rupture of the solid has occurred, if the system can pass from the unbroken to the broken condition by a process involving a continuous decrease in potential energy.
where \( E \) is Young's modulus, \( A \) is fracture area (both debonded surfaces included), and \( T \) is the surface tension. That is to say, the strain energy of deformation lost in a brittle material as the crack extends is converted into the work to create the new fracture area. From Equation (6), the finite critical applied stress is determined as

\[
\sigma_{cr} = \sqrt{\frac{2E\gamma_a}{\pi a}}
\]

and applies in region II of Fig. 1.

![Figure 2. Comparison of adhesive fracture with cohesive fracture in a Griffith model.](image)

Strictly speaking, the Griffith expression holds only for "brittle materials," where the only energy required to create new surface is that needed to rupture bonds (he experimented with glass). For most materials of structural interest in engineering, this is not the case.

Irwin 3 and Orowan 4 modified the original Griffith formulation by adding a term to account for the plastic energy dissipated as the crack grows. The condition for crack growth then becomes

\[
6W + 6U \geq \Delta T + 6\gamma = 6\gamma_u
\]

where \( 6U \) and \( 6T \) are the elastic strain energy and increase in surface energy, respectively; \( 6W \) is the change in external work during crack growth, \( 6\gamma \); and \( \gamma_u \) is the plastic flow energy dissipated during crack growth. \( \gamma_u \), which we will call the fracture energy, then includes all terms required to create the fracture surface. For metals, plastics, and most other nonbrittle materials \( \gamma_u \) is so much larger than \( 6\gamma \) that the latter can be neglected. Assuming the energy dissipated in crack growth is proportional to the new crack area, we can define a specific fracture energy \( G_c \) (often called the critical energy release rate) such that

\[
6\gamma = G_c A.
\]

Or

\[
G_c = (G_{c1})_B + (G_{c2})_B + (G_{c3})_B + (G_{c4})_B + \ldots
\]

or

\[
\gamma = \gamma_B + \gamma_K + \gamma_P + \gamma_V
\]

where the subscripts B, KE, P, and VE represent the contributions to \( G_c \) due to brittle (surface free energy), kinetic energy, plastic, and viscoelastic effects, respectively. In principle, any other contribution might likewise be added.

The combination of the region I and region II criteria, one flaw-insensitive (region I stress function) and the other dependent upon flaw size (region II fracture criterion), thus permits the designer to determine a maximum allowable design stress for either form of stress distribution.

Existing flaws of dimension greater than the critical flaw size illustrated in Fig. 1 become unstable at stresses lower than \( \sigma_{cr} \) in compliance with the region II criterion. Once it is recognized that Equations (4) and (5) are not competing failure criteria, but instead are complementary, it is possible to approach the design against failure in a more direct manner.

The energy balance to region II failure is described more fully in a recent text prepared by the authors. 7 We note that in the fracture literature one frequently encounters another approach based upon stress intensity factors \( K \). The subscript I is used to designate direction of motion of crack surfaces relative to each other. We refer the reader to Reference 7 and 8 for a more complete discussion. However, it is appropriate here to establish certain basic relationships encountered in fracture mechanics.

We associate a mode I loading with displacements for which the debond surfaces in the debond tip vicinity move directly apart. Mode II is characterized by displacement in which the debond surfaces slide over one another perpendicular to the leading edge of the debond. In mode III, the debond faces slide over one another parallel to the leading edge of the debond. By superimposing combinations of these three modes, any debond surface displacement can be produced.

In terms of the coordinates shown in Fig. 3, the local stresses in the vicinity of a crack in a sheet of linear elastic material are
\[ \sigma_{xx} = \frac{K_I}{\sqrt{\pi a}} \left[ 1 - \sin \frac{\theta}{2} \cdot \sin \frac{3\theta}{2} \right], \quad (10) \]
\[ \sigma_{yy} = \frac{K_I}{\sqrt{\pi a}} \left[ 1 + \sin \frac{\theta}{2} \cdot \sin \frac{3\theta}{2} \right], \quad (11) \]
\[ \tau_{xy} = \frac{K_I}{\sqrt{\pi a}} \sin \frac{\theta}{2} \cos \frac{\theta}{2} \cdot \sin \frac{3\theta}{2}, \quad (12) \]

for the state of plane stress

\[ u = \frac{K_I}{\mu} \sqrt{\frac{1}{2\pi}} \cos \frac{\theta}{2} \left[ 1 - 2v + \sin^2 \frac{\theta}{2} \right], \quad (13) \]
\[ v = \frac{K_I}{\mu} \sqrt{\frac{1}{2\pi}} \sin \frac{\theta}{2} \left[ 2 - 2v + \cos^2 \frac{\theta}{2} \right], \quad (14) \]

where \( v \) is the shear modulus, \( \nu \) is Poisson's ratio, and \( K_I \) represents the stress intensity factor for the crack opening mode. For the case of plane strain the displacement components are

\[ u = \frac{K_I}{\mu} \sqrt{\frac{1}{2\pi}} \cos \frac{\theta}{2} \left[ 1 - 2v + \sin^2 \frac{\theta}{2} \right], \quad (15) \]
\[ v = \frac{K_I}{\mu} \sqrt{\frac{1}{2\pi}} \sin \frac{\theta}{2} \left[ 2 - 2v + \cos^2 \frac{\theta}{2} \right], \quad (16) \]

\[ \frac{G_{IC}}{E} = \frac{K_{IC}^2}{K_{IC}^2} \quad (17b) \]

for plane stress. In addition, for linear elastic materials statically loaded, the following relationships exist:

\[ 2 \frac{U}{\delta A} = G = \frac{1}{E} \left[ k_{I}^2 + k_{II}^2 + (1 + \nu) k_{III}^2 \right], \quad (18) \]

for plane stress

\[ 2 \frac{U}{\delta A} = G = \frac{1}{E} \left[ k_{I}^2 + k_{II}^2 + k_{III} \right], \quad (19) \]

for plane strain. At the critical loads Equation (18) becomes

\[ 2 \frac{U}{\delta A} = G = \frac{1}{E} \left( k_{I}^2 + k_{II}^2 + (1 + \nu) k_{III}^2 \right), \quad (20) \]

For more complicated geometries, energy balance concepts are normally preferred (at least by the authors) because of the direct association with the laws of physics.

In the previous equations we have used the convention that the surface area \( A \) refers to the surface area generated on both surfaces of the crack. This definition is, more or less, arbitrary and leads to no confusion as long as the material property, \( Y_c \), and energy release rate in the body being analyzed have used a common definition of surface area. In fact we have adopted the convention that \( A \) refers to the surface area generated by one surface of debond when referring to adhesive fracture. In this case \( Y_a = G_{CA} \).

Adhesive Fracture Energy

The previous remarks, and Fig. 1, were presented in the context of cohesive fracture. It can be demonstrated that a bonded joint can be treated in a similar manner. The similarity of adhesive and cohesive fracture (illustrated in Figs. 2a and 2b, respectively) from a continuum mechanics viewpoint, and particularly the energy concept of fracture, has been elucidated by Williams. In both cases it is well known that an elastic stress singularity may exist at a sharp geometric discontinuity such as a wedge point, crack tip, or terminus of debond, which depends upon the local boundary conditions, method of loading, and properties of the material or materials. In principle, one finds that for either adhesive or cohesive fracture a general equation of the Griffith type can be written, namely,

\[ \sigma_c = \sqrt{\frac{G_{IC}}{E}} f(E, \nu) g(a) \quad (21) \]

where \( g(a) \) includes geometric and stress intensity factors.
Although the adhesive fracture energy $\gamma_a$ is in the purest sense a material property (e.g., it depends on surface preparation) within a continuum mechanics interpretation, it can denote an adhesive system parameter which may be used subsequently for predicting adhesive fracture.

The restriction of a homogeneous system is certainly not necessary to apply energy methods to region II failure, as long as one can properly account for energy dissipation through the entire system. Thus the application to adhesively bonded systems is direct. In order for debond to propagate over an area $\delta A$ for a given applied load, the following energy balance must be satisfied:

\[ \Delta W = \delta U - \delta E_d = \gamma_a \delta A. \]  

A parameter called the adhesive fracture energy, $\gamma_a$, is included in the energy balance equation to account for the energy in a system that is required to separate two materials. If $\gamma_a$ is interpreted as the energy per unit area required to break bonds, its magnitude will depend only upon the number of bonds existing per unit of debond surface area and the average energy required to break a single bond. Thus $\gamma_a$ for a linear elastic system should be a property of the adhesive bond strength only, independent of loading mode. As with cohesive fracture energy, dissipative energy is included in the adhesive fracture energy, $\gamma_a$, and the debond surface area is assumed planar. The $\gamma_a$ values obtained from laboratory testing, therefore, may be orders of magnitude greater than the energy required to break bonds. The $\gamma_a$ values now represent the strain energy decrease per unit of planar (projected) debond surface area in the process of separating the two materials. This interpretation of $\gamma_a$ is the one used throughout this paper.

In the absence of input work (fixed displacement boundary) and energy dissipation mechanisms such as plastic yielding or viscous flow remote from the debond tip as debond propagates, Equation (22) reduces to

\[ \Delta U \geq \gamma_a \delta A. \]  

In the limit as the debond area approaches zero, the failure criterion is written in terms of energy release rate $dU/dA$, and adhesive fracture energy $\gamma_a$, in the form

\[ \frac{dU}{dA} = \gamma_a. \]  

As shown in Reference 7, if the boundary loads are in terms of surface tractions, the failure condition becomes

\[ \frac{dU}{dA} > \gamma_a. \]  

Numerical methods for calculating the energy release rate are also discussed in Reference 7.

Combinations of mode I and mode II loading are very common in adhesive systems, since fracture may follow the bond line, take place within the adhesive or alternate between the two but in any case usually propagates approximately parallel to the bond surface. Several authors, including Anderson et al. 2, Chang 10, and Trantina 11 have noted a dependence of adhesive fracture energy (or critical stress intensity) on loading mode.

Chang 10 discusses test results using single lap shear joint specimens. By varying the length of overlap in this specimen, it is possible to vary the ratio of mode I and mode II loading at the adhesive adherend interface. It was found that the adhesive fracture energy for a mode II loading was greater than that for a mode I loading. A Griffith analysis of such a joint agreed well with the experiment if the adhesive fracture energy $\gamma_a$ was assumed to be of the form

\[ \gamma_a = K_1^a(s) + K_2^a(t) \]  

where $K_1^a$ and $K_2^a$ are the fractions of the total strain energy attributed to tensile and shear loading of the joint, respectively, and $\gamma_a(s)$ and $\gamma_a(t)$ are the adhesive fracture energies as measured with pure mode I and mode II loadings, respectively.

Trantina 11 used slant edge-cracked plate tests to induce different portions of mode I and mode II loading over a wide range of slant angles and cracklengths. By varying the angle between the adhesive layer and the load line in these specimens, combined-mode fracture toughness values were determined. The trend in these data clearly indicates: (1) a significant increase in the fracture energy as the mode II loading is introduced, (2) the mode II fracture energy is larger than that for mode I (perhaps by as much as a factor of two or more), and (3) a failure criterion that assumes a linear relation between mode I and mode II fracture energies is not applicable for Trantina’s system.

Extensive testing has been completed by the authors 12,13 on one particular adhesive system to demonstrate the importance of mode dependency on evaluation of bond strength. In this study, it is shown that the mode $\gamma_a$ value is more than a factor of two greater than the mode I value and that the mode III value was greater by more than a factor of three.

Although the $\gamma_a$ data show large changes due to loading mode, the engineering implications are not as severe as one might suspect, since the critical stresses are generally related to the square root of $\gamma_a$. Thus, if the actual $\gamma_a$ value is somewhere between the modes I and II values (for instance, 40% higher than the mode I value), a critical stress predicted using the mode I value would be conservative by less than 20%.

A second complication which occurs in adhesive fracture mechanics is the apparent time and temperature dependency of adhesive fracture energy,
even for systems whose bulk behavior is nearly linearly elastic. In linear elastic cohesive systems, no time dependency is noted. However, as noted by Irwin, "Time-effects are expected in adhesive-joint separation, both from the strain-rate sensitivity of high polymer adhesives and from the possible influence of moisture and other environments."

Thus, with the present state of the art, one must select laboratory tests for which temperature, loading rate, and loading mode duplicate as nearly as is possible those in the bondline being analyzed. If there is difficulty in obtaining the desired load rate and/or temperature in the laboratory, it is possible to test specimens at a number of different load rates and temperatures. Then by applying a time-temperature shift of the resulting data in a manner similar to that used in obtaining relaxation moduli for viscoelastic materials one can obtain a master $\gamma_a$ versus log (reduced time) $\log (t)$ curve which may cover many decades of time.

**Experimental Procedures**

To this point we have attempted to develop the basic premises and analytical approach on adhesive fracture mechanics. A number of different sample configurations have been proposed and tested as means of determining critical adhesive parameters. In principle, any specimen for which the energy release rate can be calculated and the load at which debond propagates can be determined could be used to evaluate $\gamma_a$ (or $G_c$). In practice, however, certain geometries have the advantage of being more analytically tractable and/or more convenient in terms of experimental sample preparation and testing. Testing configurations that the authors and others have found particularly useful include, the blister test14,15, cone tests (pull out and twist)16, peel tests17-20, lip shear21, cantilever tests22-24, tensile specimens with the adhesive joint at various angles to the tensile axis25,26, parallel plates loaded in shear and cleavage27 as well as several others.

**Specific Applications**

The fundamental framework of adhesive fracture mechanics has been developed and a number of potential test methods have been tested. We are now in a position to apply this to specific problems. In the time allocated for this presentation no attempt will be made to be all inclusive in giving a listing of some of the problems studied. (In the oral presentation, a few of the studies listed below will be very briefly described.) It is hoped that these problems will serve to show the versatility of the fracture mechanics approach to adhesive failure analysis. The authors like to feel that this approach is not a rigid, narrow set of rules for testing and analysis. Rather, it appears to them that it is a more systematic approach philosophy to adhesive problems that facilitates the acquisition of the most meaningful information from as simple, convenient, and straightforward a test as possible for the particular adhesive of interest. The information thus obtained may then be utilized for prediction of performance in other geometries that may be pertinent. It is hoped that the information thus obtained may then be utilized for prediction of performance in other geometries that may be pertinent. It is hoped that the information thus obtained may then be utilized for prediction of performance in other geometries that may be pertinent. It is hoped that the information thus obtained may then be utilized for prediction of performance in other geometries that may be pertinent. It is hoped that the information thus obtained may then be utilized for prediction of performance in other geometries that may be pertinent.

We would, therefore, like to list a few areas of past study with references so that those with sufficient interest might refer to the original publications for details of the study. This will be followed by brief fracture mechanics analysis for the conditions for debonding between the layers in a laminate composite.

Fracture mechanics methods have been applied to:
- the problem of mode dependence (16, 25, 28, 29)
- the effect of adhesive thickness (7)
- the evaluation of dental adhesives (30)
- an evaluation of barnacle cement (31)
- an evaluation of structural joints (32-33)
- the failure under fatigue of adhesive joints
- the failure of joints subjected to environmental effects (34)
- and many other studies (7, 30-35).

An example might be helpful to demonstrate the techniques of adhesive fracture mechanics, and in particular how it might be used to analyze the behavior of systems that do not readily lend themselves to closed form analytical solutions.

The procedure used to obtain an energy release rate was to calculate the strain energy stored in the laminate for two slightly different debond areas. The strain energy release rate is then approximately equal to the difference in the two strain energy values divided by the difference in total debond area. In equation form

$$\frac{\partial U}{\partial A} = \frac{U_1 - U_2}{A_1 - A_2} = \frac{1571.945 - 1670.950}{(0.100)^2 - (0.104)^2}$$

$= 2730 \text{ in.} \cdot \text{lb/ft}^2$

($27$)

The adhesive fracture mechanics technique has been demonstrated here for a rather simple geometry and loading condition. However, with the present finite element capability any geometry and loading system could be analyzed provided sufficient computer capacity is available. That is, with an arbitrary orthotropic geometry and a given set of displacement, stress, force, thermal or acceleration loads, an energy release rate can be found. If the $G_a$ value has been determined from a laboratory test, the size flaw which would propagate under the given loading system could then be determined.

The adhesive fracture mechanics approach can be briefly outlined with the aid of Figs. 4, 5 and 6. Figure 6 shows schematically a three-layer laminate with a small region of debond between two of the layers. Although this system is of a comparatively simple geometry, it does not readily lend itself to analytical stress
analysis. This does not pose a major problem, however, since numerical methods are available that (with the aid of a computer) make accurate determinations of stress and strain possible for almost any reasonable geometry. In the case of interest here a finite element analysis yielded the axial stress in the vicinity of the crack as shown in Fig. 5 and the crack opening displacement represented in Fig. 6. These can in turn be used to calculate the strain energy present in the system due to the applied loading and how this varies with crack (debond) size. If the material is linearly elastic (as we assume in the case here) only the stresses need be determined in order to calculate the strain energy. The method can, however, be applied equally well to other constitutive relationships as well.

![Figure 4. Laminate composite analyzed.](image)

Figure 4. Laminate composite analyzed.

![Figure 5. Axial stress in Layers 2 and 3 adjacent to debond plane.](image)

Figure 5. Axial stress in Layers 2 and 3 adjacent to debond plane.

Since it is known that the strain energy release rate is proportional to the square of the applied displacement (0.01 in. in this case), the energy release rate for other applied displacements could be calculated for the geometry analyzed as

$$\frac{\Delta U}{\Delta A} = 2730 \left(\frac{\Delta u}{0.01}\right)^2$$

(28)

The adhesive fracture energy is equal to the value of energy release rate at the load which causes a debond to propagate. If the adhesive fracture energy is given by

$$\gamma_a = 2730 \left(\frac{\Delta u_{\text{crit}}}{0.01}\right)^2$$

(29)

One of the challenging problems associated with failure prediction is in determining the critical load as opposed to the maximum load. If tests are being conducted at a constant load rate (displacement or force), it is possible to build up considerable loads after debond initiation. Acoustic emission techniques have been used successfully for particular systems. However, in general, more definitive techniques are required.

We have attempted to outline and demonstrate the utility of adhesive fracture mechanics to:

(1) Evaluate and compare adhesives through a comparison of their fundamental material properties;

(2) Predict loading conditions for failure, if these properties are known (perhaps from standard tests);

(3) Optimize adhesive configuration and adhesive joint design for a given adhesive system;

and (4) Use as a quality assurance tool in conjunction with NDI flaw detection techniques.

In the latter case, if the adhesive system properties such as moduli and specific fracture energy are known, along with the loads to which the system will be exposed it should be possible to predict flaw sizes that will result in failure.
The problem then becomes one of locating and determining the size of flaws in the structure. Those with flaws larger than this critical size would either be discarded or repaired.

One of the authors is presently applying techniques similar to those described here for the space shuttle rocket motor case design. A critical point for the satisfactory solution to detection for small flaws or regions of debond.

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