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Review of Fracture in Adhesive Joints Considering Rocket Motor Application

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The paper presents a review of existing research on fracture problems in adhesively bonded joints. Both the theoretical background and studies dealing with specific design problems are discussed. Investigations that employed experimental techniques to detect fracture are also included. The work that addresses effects of such important phenomena as residual thermal stresses and viscoelasticity is analyzed. Bond fracture in solid rocket motors is discussed to illustrate an array of problems facing a designer of adhesive joints. Difficulties associated with the analysis of adhesive joints in solid rocket motors are discussed.

Nomenclature

b	= bielastic constant
f_1, f_2	= functions dependent on material properties, geometry, and loading
K_I	= stress intensity for opening mode I, MPa m$^{1/2}$
K_{II}	= stress intensity for sliding mode II, MPa m$^{1/2}$
K_{Ic}, K_{IIc}	= critical stress intensities for modes I and II, MPa m$^{1/2}$
ν	= Poisson's ratio
ν_1	= Poisson's ratio of material with lower modulus of elasticity
σ_x	= stress in the x direction, MPa
σ_z	= normal out-of-plane stress, MPa

Introduction

THE integrity analysis of adhesive joints includes two steps. At the first step, the stress analysis yields a tensor of stresses at each point of the adhesive and adherend layers. From this stress field, strength criteria can be used to indicate material failure at a certain combination of stresses. If the adhesive layer is shown to fail, it is reasonable to assume that this resin-type material will develop cracks. On the other hand, cracks and voids can exist in the structure as a result of a manufacturing process. In both cases, fracture mechanics is necessary to predict the integrity of the adhesive bond under each possible combination of loads.

The theoretical research on general problems of adhesive and cohesive fracture is reviewed in the first part of the paper. The second part outlines the studies on specific fracture problems in adhesive joints. The third part illustrates a practical fracture problem concerned with adhesive layers in solid rocket motors.

Cohesive and Adhesive Fracture

Two types of cracks can exist in an adhesive joint: cohesive cracks within the adhesive layer, and adhesive cracks on the interface between two adjacent layers, as shown in Figs. 1a and 1b, respectively. Note that although the thickness of the adhesive layer is usually less than 1 mm, cohesive fracture is possible, i.e., there is enough space for the crack to propagate within the adhesive layer.

An approach to cohesive fracture can be traced to Refs. 1–3. For the state of plane strain, these solutions can be represented in the Cartesian coordinate system with the origin located at the tip of the crack (Fig. 2), in the form[4]

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \cos\tfrac{1}{2}\theta \begin{Bmatrix} 1 - \sin\frac{1}{2}\theta \sin\frac{3}{2}\theta \\ 1 + \sin\frac{1}{2}\theta \sin\frac{3}{2}\theta \\ \sin\frac{1}{2}\theta \cos\frac{3}{2}\theta \end{Bmatrix}$$

$$+ \frac{K_{II}}{\sqrt{2\pi r}} \begin{Bmatrix} -\sin\frac{1}{2}\theta\left(2 + \cos\frac{1}{2}\theta \cos\frac{3}{2}\theta\right) \\ \sin\frac{1}{2}\theta \cos\frac{1}{2}\theta \cos\frac{3}{2}\theta \\ \cos\frac{1}{2}\theta\left(1 - \sin\frac{1}{2}\theta \sin\frac{3}{2}\theta\right) \end{Bmatrix}$$

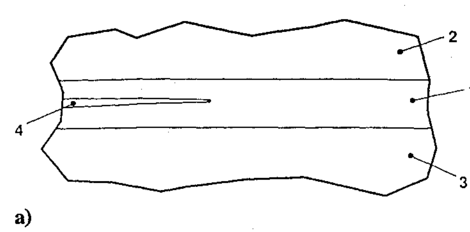
$$+ \text{(higher-order terms)}$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \tag{1}$$

The tearing mode of fracture is not considered here.

The stresses given by Eq. (1) represent crack-tip stresses and are a result of the complex-variable solution of the plane problem of the theory of elasticity for a linear elastic material. In the linear analysis they are superimposed on the stresses that exist in the material in the absence of the crack.

Note that the cohesive fracture within the adhesive layer is more complicated than the problem of an infinite homogeneous plate crack[1–3] because of the presence of two adjacent layers. These layers require the satisfaction of the continuity conditions for displacements and stresses along straight boundaries between the layers. Other factors that contribute to the difficulties of the solution are



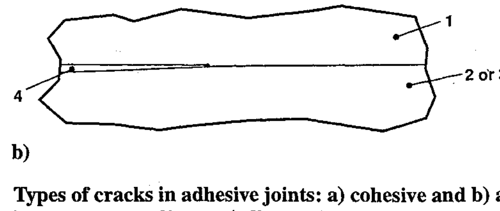


Fig. 1 Types of cracks in adhesive joints: a) cohesive and b) adhesive; 1, adhesive layer; 2, 3, adjacent (adherend) layers; 4, crack.

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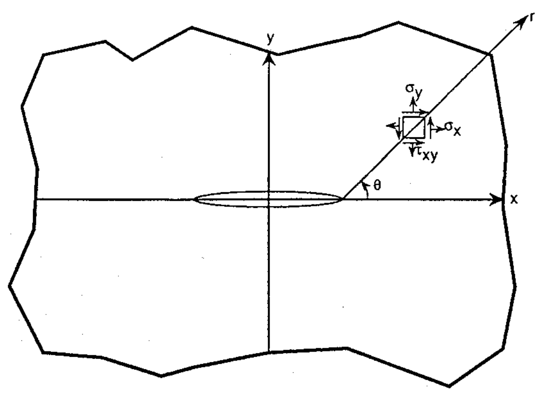

Fig. 2 Cartesian and polar coordinate systems with the origins at the tip of the crack. In the case of an interface crack, the boundary between the two materials is $y = 0$.

associated with possible viscoelastic and thermal effects, including an influence of temperature on material properties and thermal residual stresses. Nevertheless, Eq. (1) reflects the important features of the solution that will be retained in more complicated cases. The crack-tip stresses reach a maximum at the crack tip. In an elastic formulation these stresses are infinite at the tip, although in reality they are limited by the presence of a plastic zone. The presence of such a zone in a rubber-type material should be considered with some skepticism. However, nonlinear elastic behavior at large deformations and, possibly, viscoelastic properties should come into consideration, instead of or in addition to plasticity, to explain the ability of such materials to withstand excessive stresses at the crack tip. No analytical solution of the stress problem at the crack tip is known that would include viscoelastic and geometrically and physically nonlinear effects.

Crack propagation in linear viscoelastic solids was considered in Refs. 5 and 6 by using two approaches to evaluate a crack growth rate. One of these approaches was based on the balance of energy at the tip of the crack, and the other used the maximum strain as a criterion of material failure. This subject was also investigated in Refs. 7–9.

In the case of an adhesive fracture between two adjacent layers, theoretical solutions have been developed.[10–14] The analysis was continued in Ref. 15. The solution is obtained using the Muskhelishvili complex-function approach to represent displacements, stresses, and the stress function in the plane linear theory of elasticity. The boundary conditions include zero stresses on the crack surface, continuous normal stresses in the y direction, and shear stresses and displacements across the bondline $y = 0$ (Fig. 2). The only discontinuity that may exist along the bondline is related to normal stresses in the x direction, which are present only if there is a load acting along the crack axis.[14] In particular, the normal stresses in the y direction and the shear stresses along the bondline were shown to be of the form[16,17]

$$\sigma_y(x = r, y = 0) = \frac{f_1}{\sqrt{2\pi r}}[K_{\mathrm{I}} \cos(b \ln r) + K_{\mathrm{II}} \sin(b \ln r)]$$
$$\tau_{xy}(x = r, y = 0) = \frac{f_2}{\sqrt{2\pi r}}[K_{\mathrm{II}} \cos(b \ln r) - K_{\mathrm{I}} \sin(b \ln r)] \quad (2)$$

Obviously, in the absence of external stresses acting in the x direction, $\sigma_x = 0$ along the bondline $y = 0$. The transverse normal stress corresponding to the plane strain problem becomes $\sigma_z(x = r, y = 0) = \nu\sigma_y$.

The so-called bielastic constant corresponding to plane strain conditions in the case of a large mismatch between the moduli of elasticity of bonded materials ($E_z/E_1 \gg 1$) is[16]

$$b = \frac{1}{2\pi} \ln(3 - 4\nu_1) \quad (3)$$

Note that an analytical solution of the type presented in Eq. (2) implies an oscillatory character of crack-tip stresses and displacements, including the areas of overlap between materials on the opposite faces of the crack. In spite of these limitations, the solution retains its usefulness for evaluating stress intensity factors in the vicinity of the crack tip.

Rice and Sih[14] presented explicit expressions for the stress intensity factors for semi-infinite interface cracks and for interface cracks in an infinite plate. They recommended that these stress intensity factors be used in a criterion for crack growth that must be established experimentally. Obviously, a comprehensive approach to the fracture analysis of the bondline should include evaluation of stress intensity factors at various phases of life of the structure and the application of a crack growth criterion.

A number of recent papers have dealt with various aspects of interface fracture.[18–20] In particular, Rice[20] discussed an effect of a small zone of nonlinear material response at the crack tip on the complex stress intensity factor associated with an elastic interface crack. The solution of Ref. 15 can be particularly interesting for modeling of cohesive fracture in adhesive layers. This solution concentrates on the propagation of cracks in the immediate vicinity of the interface and may be considered as a bridge between cohesive and adhesive fracture, because it illustrates an effect of material boundary conditions on the cohesive crack.

A recent paper[21] presents an analysis of a mixed-mode interface fracture in elastoplastic solids. This solution can be useful for the analysis of adhesive joints if the adherends work within a plastic range, as well as in the case where adhesive material exhibits plastic properties. Note that the previously mentioned studies dealing with adhesive fracture assumed that bonded solids are infinite or semi-infinite. In reality, the thickness of the adhesive layer is limited (usually less than 1 mm).

Adherends are thicker than the adhesive layer, but an assumption that their thickness is large enough to consider them semi-infinite in the direction perpendicular to the bond can be an oversimplification as well. Therefore, a refined analysis should address the problem of limited thicknesses of bonded materials. This makes techniques used for the analysis of delaminations in composite plates attractive for a study of the adhesive fracture. Although a detailed review of these techniques is outside the scope of the paper, mention is made of the studies in Refs. 22–24. In addition to theoretical solutions, these papers include bibliographies on the subject. These solutions can be adapted to the materials and geometry of adhesive joints. However, although existing theoretical studies can present a useful foundation for the analysis of adhesive joints, a numerical finite-element solution may present advantages both in terms of accuracy as well as from the point of view of time required for the analysis.

Problems of Fracture in Adhesive Joints

In the previous section general studies of cohesive and adhesive fracture have been considered. In this section attention is concentrated on bond problems in adhesive joints.

Two techniques are used in fracture analysis. The first is based on the consideration of stresses, and the second deals with the energy of the system. Examples of the application of a stress-based technique are the references dealing with general problems of adhesive and cohesive fracture referred to in the previous section. However, in numerous problems the analysis based on energy considerations is useful. This analysis is often employed in conjunction with a numerical method such as the finite-element method. Note that energy methods are often easier to incorporate in an experimental study because, even in nonlinear problems, the energy release is quantifiable through measurements of the crack growth. Accordingly, numerous references dealing with fracture of adhesive joints concentrate on measurements or evaluations of the fracture energy (or adhesive fracture energy), defined as the energy absorbed during formation of a new surface.

The specific problems of adhesive fracture were addressed in a theoretical and experimental investigation of adhesive joints. The investigation noted that the cracks started at the ends of the adhesive layer, i.e., in the area of significant stress concentrations. The theoretical solution utilized the previous work of Cherepanov.[11] Experiments were conducted on steel and Plexiglas® adherends bonded by an epoxy adhesive layer. The results of these experiments were in a qualitative agreement with the solution for a crack propagating through an interface of two dissimilar materials. The fracture energy was shown to remain approximately constant during the crack propagation.

Fracture toughness, defined as a critical value of the stress intensity factor corresponding to mode I fracture or also as the amount of fracture energy, represents a very useful characteristic, since it is usually both unique for a given material and independent of problem's geometry. The concept of fracture toughness has been extended to interface cracks, and an extensive program of measurements of this parameter has been undertaken. The specimen materials and geometries were varied, and various factors, such as temperature and bond thickness, were considered. The list of papers dealing with measurements of the fracture toughness is extensive, but Refs. 21–29 are representative. An outline of standard adhesive tests is given in Refs. 16 and 30 with discussions of tensile, shear, and peel tests, as well as a brief presentation of adhesive fracture mechanics.

Nondestructive techniques used to evaluate the strength of adhesive joints include ultrasonic testing,[31–37] acoustic emission and the associated acoustic-ultrasonic method,[38,39] vibrational technique (i.e., the analysis of fundamental frequencies and damping[40]), and moiré interferometry.[41,42] Strain gauges can be successfully used to detect cracks[43] that are only 0.2 mm long.

An interesting experimental study[44] of major variables that affect adhesive joint failure in mode I used an epoxy adhesive and two types of rubber-modified epoxy. The substrates were aluminum alloy or mild steel. The experimental specimens represented double-cantilever beam joints. An important conclusion was that the adhesive fracture behavior is strongly affected by the adhesive bond thickness, which implies that fracture of this kind is influenced by the viscoelastic and plastic response of the material in front of the crack tip. The optimum thickness of the bond resulting in a maximum adhesive fracture energy was measured and found in good agreement with numerical results. These numerical results were obtained on the assumption that the adhesive fracture energy reaches the maximum value when the size of the plastic deformation zone extends to the adhesive boundary interface. Several important observations were noted.[44] First of all, the fracture of the joint was cohesive, i.e., the cracks propagated within the adhesive layer. In addition, the authors identified two conflicting factors that affect the regime of the crack propagation, namely, size of the deformation zone, and constraints superimposed by the adjacent high-modulus substrates.

An illustration of the effect of the deformation zone on the crack propagation can be found in a finite-element analysis.[45] This analysis is based on a modified complementary energy principle, and the authors used a superelement in the region of the tip of the crack. The singular stress behavior was modeled by properly selected stress functions and the use of the complex-variable technique. It was shown that as the adhesive layer becomes thinner, the zone of high stresses deforms and extends farther along the adhesive layer (Fig. 3). Accordingly, the shape of the plastic deformation zone changes and the adhesive fracture energy increases. However,

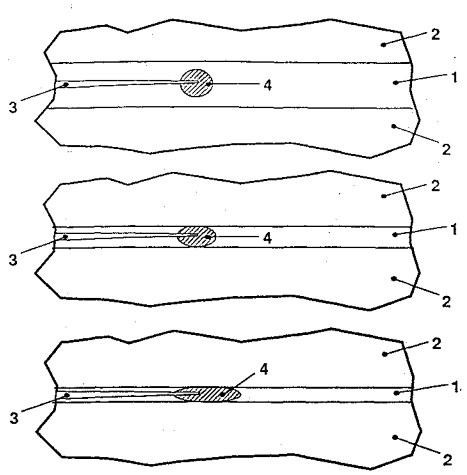

Fig. 3 Changes of a deformation zone with the bond thickness: 1, adhesive layer; 2, adherend layers; 3, crack; 4, deformation (plastic) zone.

at a certain thickness, the constraints associated with the presence of the adjacent layers become dominant and the fracture energy begins to decrease. These observations suggest that there is an optimum thickness of the adhesive layer. Note, however, that a maximum value of the fracture energy, corresponding to the optimum thickness, was shown to shift to larger bond thicknesses with increasing temperature.[46] Therefore, if operational temperatures experienced by the joint can fluctuate, an optimum thickness becomes meaningless.

Reference 47 analyzes the influence of the thickness of an adhesive layer on the energy release rate in double-cantilever beams. The investigation treated the adherends as built-in cantilevers that were supported by an elastic foundation used to model the adhesive layer over a part of the span. The energy solution was obtained from a beam analysis. It was found that the energy release rate is affected by the thickness of the adhesive layer. Moreover, the stress intensity factor K_I was found to be proportional to the fourth root of the adhesive layer thickness. The length of the crack also affected both the strain energy release rate and the stress intensity factor. The approach employed was later modified[48] so that the energy release rate was expressed in terms of local stresses in the adhesive layer. A simple formula was obtained where the energy release rate of a double-cantilever beam is given as a function of the maximum peel stress and the maximum transverse shearing stress.

An interesting conclusion was obtained[49] in a study in which fracture of double-cantilever beams was considered with composite adherends. It was found that, even if a starter predelamination flaw, artificially introduced into the structure, was in the adhesive layer, cracks initiated and propagated between the plies in the composite adherends. The authors explained this phenomenon as due to small thickness of the interply layers. This explanation is reasonable in view of the previous discussion on the optimum thickness of bonds.

The authors of Ref. 50 performed an experimental study of the influence of the thickness of adherends of double-cantilever beams on the fracture toughness. Joints with thicker adherends were shown to have higher fracture toughness, although the rate of increase in fracture toughness decreases with increasing thickness of the adherends.

The effect of the geometry of the adhesive joint on its mode I fracture resistance was also investigated[51] using a finite-element method. Special quarter-point singularity elements were used at the crack tip. It was shown that the opening stresses ahead of the crack are affected by the thickness of the adhesive layer and the stiffness of the adherends in the thickness direction. The latter conclusion probably points to the three-dimensional nature of the problem. In contrast, the thickness of the adherends and their longitudinal stiffness did not have a significant effect on the opening mode stresses.

Another factor that can affect fracture mechanics of single-lap joints is geometric nonlinearity, i.e., large deformations and rotations.[52] For example, the ends of a single-lap joint can experience large rotations. Nonlinear effects on the cohesive fracture were studied and found to have a pronounced influence on the strain energy release rates in modes I and II. The analysis was performed using a finite-element method based on the minimum potential energy.

The authors of Ref. 53 attempted to introduce a so-called engineering failure envelope based upon local deformation parameters, to describe fracture characteristics of adhesive joints. A finite-element analysis was performed that showed that the boundary of the singular region where linear fracture mechanics cannot be applied is at a distance of the adhesive layer thickness from the corner of the adhesive joint. It was proposed to use an engineering failure envelope based on deformations near the free edge of the joint but outside the singular region.

In addition to the papers discussed, a number of other authors have also employed a finite-element method to evaluate fracture characteristics of adhesive joints.[43,54,55] Another numerical method used for the analysis of cracks is a finite difference method.[56] In this investigation, elastoplastic behavior of the adherends was included, and the adhesive layer was modeled by coupled nonlinear tension and shear springs. The authors claim that their solution is less complex than a finite-element analysis.

Silberman et al.[57] presented an algorithm for the analysis of the strength of adhesive joints that included the effects of the chemical composition of the adhesive and adherend materials. Such an

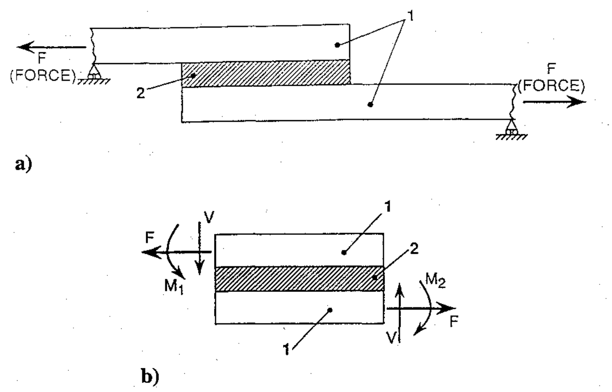

Fig. 4 Generic adhesive sandwich: a) single-lap joint and b) sandwich; 1, adherends; 2, adhesive layer; F, M_1, M_2, V, reactions of the separated parts of the adherends.

approach may represent an important refinement of the analysis that incorporates physical chemistry of the formation of adhesive joints and fracture mechanics in a unique formulation.

An interesting analytical method for the solution of the cohesive fracture problem was presented by Fernlund and Spelta.[58–60] They treated a joint as a structural sandwich consisting of the layers of adhesive and adherend materials (Fig. 4). The joint was treated as a free body where the reactions at the end cross sections represent the effect of adjacent parts of the adherends. This method was first introduced in Ref. 61, where it was used to estimate the stresses in the joint. A closed-form analytical solution was obtained for the strain energy release rate. This solution can be applied to both geometrically and physically nonlinear joints. An exact solution for the stress intensity factors was obtained for the case of linear elastic joint materials.

Reference 62 presents a closed-form solution for the energy release rate of clamped shear adhesive joints with a crack. The solution was in agreement with numerical results obtained using a finite-element code (ABAQUS). However, this solution has to be treated with caution, since traction-free boundary-conditions at the free edge of the adhesive layer were violated. This boundary-condition violation could yield a significant error because expressions for the stresses were used to derive the energy release rate.

An approach to failure of adhesive joints based on the value of the J integral was associated[63] with a critical value of the integral. The solution was obtained for linear elastic, perfectly plastic, and linear strain-hardening adhesive materials.

The problem of the effect of the mode of loading on fracture toughness has been the subject of a number of studies. Reference 64 shows that the fracture energies of adhesives in modes II and III are equal. Therefore, the analysis can be confined to the G_I–G_{II} plane. Tests for mode I usually employ double-cantilever beam (DCB) specimens,[65] whereas mode II fracture is usually analyzed using end-notched flexure (ENF) specimens.[66]

Existing mixed-mode methods of testing were discussed in Refs. 67–69. Examples of techniques for mixed-mode testing are off-axis unidirectional coupons with a crack parallel to the fiber direction, cracked-lap shear specimens, and antisymmetric test fixtures.[67] Conclusions obtained from the existing research on mixed-mode fracture in adhesive joints include:

1) The fracture energy in modes II and III is significantly higher than the energy corresponding to mode I. For example, in experiments[67] the fracture energies of modes I and II differed by a factor of 5.2.

2) The bond thickness affects the adhesive fracture energy and the energy curve in the G_I–G_{II} plane.[64,69]

3) The fracture energy is affected by a triaxial state of stress at the tip of the crack. This effect is particularly pronounced in extremely thin bonds on the order of several micrometers.[69]

A simple analytical criterion for mixed-mode fracture was proposed in Ref. 70:

$$\left(\frac{K_I}{K_{Ic}}\right)^m + \left(\frac{K_{II}}{K_{IIc}}\right)^n = 1 \tag{4}$$

Table 1 Experimental constants in Eq. (4)

Source	m	n
McKinney (1972)	1	2
Jurf and Pipes (1982)	2	2
Liechti and Freda (1989)	1	1
Yoon and Hong (1990)	2	3

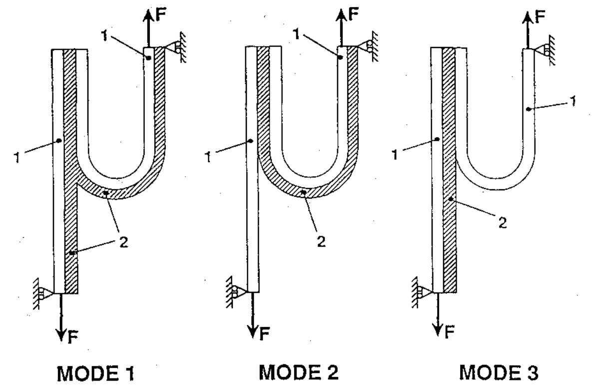

Fig. 5 Modes of fracture in peel joints: F, peel force; 1, adherends; 2, adhesive layer.

Although this criterion is very convenient, the values of constants found by different investigators vary, as shown in Table 1. Obviously, the large scatter of the constants in this table indicates a necessity for additional experimental research to formulate a reliable mixed-mode fracture criterion.

To conclude this section, we review the work done on fracture of peel joints (Fig. 5). An energy-based approach to adhesive failure has been considered by a number of investigators. In particular, Ref. 71 showed that joint failure can be characterized by the energy required for a debonding of a unit area of the interface, i.e., the adhesive fracture energy. The investigation of adhesive joints included a tensile joint, a pure shear joint, and a peel joint. Some of the conclusions for the peel joint were incorporated in Ref. 72. Reference 71 showed that the adhesive fracture energy depends on the rate of debonding, i.e., it increases from the levels predicted by thermodynamic theory at low rates of debonding to values that are higher by two or three orders of magnitude at high rates when the adhesive approaches a glasslike state. This rate of debonding illustrates the necessity to incorporate viscoelastic effects in the studies of fracture of adhesive joints. Based on the results in Ref. 71, it was suggested that the adhesive fracture energy consists of two components: the reversible work of adsorption and the irreversible work of deformation of the adhesive layer in the process of debonding. The adhesive fracture energy has dimensions of force per unit length, and in the peel-test case, the adhesive-fracture energy is equal to the peel force per unit width of the adhesive layer.

Reference 73 showed experimentally and analytically that the adhesive failure energy of tensile, shear, and peel joints is the sum of the energy that is viscoelastically dissipated during the process of crack propagation and the intrinsic adhesive failure energy. Obviously, the viscoelastic portion of the energy is dependent on the rate of crack propagation and temperature. The intrinsic failure energy is the amount of energy required for crack propagation in the absence of viscoelastic effects and is important as an illustration of a significant influence of viscoelasticity on the integrity of adhesive joints, including peeling joints. Another study[74] dealing with the viscoelastic aspects of the peel test considered slowly growing peel cracks using a modified Griffith theory.

The advantages of the peel test in obtaining the adhesive fracture energy in bond systems have been discussed.[16] The authors indicated that the peel specimen allows a researcher to model various combinations of mode I and mode II loads by adjusting the peel angle. On the other hand, another study[75] using a geometrically nonlinear finite-element method to study the peel test with an initial crack, came to the opposite conclusion. According to that research, the peel angle does not affect the relative amounts of modes I and II loading at the crack tip. These opposite conclusions from Refs. 16 and 75 imply that additional experimental and numerical studies on the effect of the peel angle on a relationship between different modes of fracture are necessary.

Reference 76 used an elastic–perfectly-plastic model to evaluate the fracture toughness of a very thin metallic film during a steady peel propagation. This paper is useful for understanding the peel process. The authors also conducted an experimental study to elucidate the effects of geometry and material properties. The results showed that the peel force has a peak at the first phase of loading, i.e., prior to separation of the adherends. The force drops when the separation starts. If the peeling is steady-state, the peeling force remains constant during the subsequent phase of the peeling process. However, if the strip is very thin, of the order 20×10^{-6} m or less, the peeling force fluctuates. The authors attributed these fluctuations to the nature of the peeling of a very thin film, which comprises a series of discontinuous unstable crack propagations. This explanation seems reasonable.

In conclusion, note that fracture of peel joints can occur by three modes shown in Fig. 5. The actual mode of fracture depends on the peel rate and temperature. A rubber-to-glass transition of the adhesive material occurring at high peel rates and low temperatures affects the process and the fracture mode.

Example of Adhesive Fracture in Solid Rocket Motors

A typical solid rocket motor (SRM) consists of a case, internal insulation, an adhesive layer, and solid propellant. The case can be manufactured either from a filament-wound composite material or from a metal (titanium steel alloys, nickel steel alloys, or high-yield steels). The internal insulation can be a rubber-type material. The adhesive layer is usually applied to the insulation to provide reliable bonding with the propellant. It can be in the form of an elastomeric liner or a material that initiates a chemical bonding reaction at the boundary between the insulation and the propellant. A typical thickness of an elastomeric liner is between 0.5 and 1.0 mm, although in some liners it is close to 2 mm. This represents a sufficient thickness to warrant concern about internal mechanical processes, such as cohesive and adhesive cracking. The propellant can be modeled as a rubber-type, nearly incompressible elastic material.[77]

A significant research effort on the prediction of failure of SRMs has been conducted by the industry.[78–80] However, in spite of this effort, adhesive fracture remains a serious problem in SRMs. The major structural problems that have to be addressed include difficulties in tracing a comprehensive history of stresses and strains; the necessity to develop accurate models of constituent materials, including those of the adhesive layer and insulation; and uncertainty of material properties due to processing and manufacturing.

Some of the problems listed above can be traced to thermal residual stresses, temperature-dependent properties, and viscoelastic effects. For example, it is necessary to incorporate the effects of temperature on all material properties, including moduli of elasticity and shear, Poisson's ratios, and coefficients of thermal expansion. Indeed, although heat does not penetrate beyond the immediate vicinity of the burning surface, unzipping cracks often initiate in the areas of the adhesive layer adjacent to this surface. Therefore, any numerical or analytical model employed to predict adhesive failure must take account of degraded material properties. Another thermal effect that has to be traced throughout the life of a SRM is related to residual thermal stresses accumulated during the cooldown period.

Viscoelastic properties of various materials in SRMs should not be disregarded without a detailed discussion. All materials (composite case, insulation, adhesive, and propellant) can be viscoelastic. A quasistatic model may (or may not) be sufficient for the cooldown analysis when the temperature decreases at a slow rate of 2.7 to 40°F per day. However, during firing this model is unacceptable. Creep has to be considered, as a result of storage loads. Obviously, these loads depend on the storage regime, and therefore the problems of storage and design have to be addressed simultaneously.

In summary, a comprehensive design of SRMs should address the following problems:

1) Constitutive relations for the materials that form the joint (adhesive, insulation, propellant, and case). A linear elastic model is the simplest one, and sometimes it can be quite sufficient for an accurate analysis. More complicated models can include plastic effects, viscoelasticity, and viscoplasticity. Obviously, creep and sometimes stress relaxation become important considerations in SRMs subjected to storage loads that can act over a long period of time.

2) Temperature-dependent material properties. The significance of this factor cannot be overestimated. It is important to emphasize that all properties can be affected, i.e., moduli of elasticity and shear, Poisson's ratios, and coefficients of thermal expansion. If the case is manufactured from a composite material, the number of material characteristics that have to be considered increases dramatically. However, even in the case where all layers are formed from isotropic materials, properties of four layers (adhesive, insulation, propellant, and case) have to be specified prior to any meaningful analysis. Obviously, the temperature of the case material during firing is lower than that of the adhesive layer or insulation. However, knowledge of temperature-dependent properties of the case is necessary for evaluating thermal residual stresses after the cooldown period. Aerodynamic heating coincident with firing may be another consideration. Note that, except in the cooldown regime, the temperature will be a function of the thickness coordinate within the insulation and the case. Therefore, the properties of the corresponding materials will vary throughout their thickness.

3) Analysis of loading regimes. Cooldown thermal residual stresses represent a very important factor that has to be superimposed on the stresses in the subsequent phases of the SRM life. While storage loads may be relatively low, they may be related to possible creep. Finally, the loads during firing can cause a catastrophic failure because of an instantaneous unzipping of the bondline.

Geometric nonlinearity does not seem to be a serious problem in SRMs with the propellant inside. This is due to a monolithic structure of the joint and to the presence of a solid block of propellant that would limit deformations. An exception is the case where the adhesive layer is discontinued on part of the surface. The ends of the layer can experience significant rotations that may contribute to a local nonlinearity. Another potential situation where geometric nonlinearity could be significant is postcure deformation of empty cases.

This discussion illustrates that design of an adhesive joint can involve numerous complex problems that have to be treated simultaneously. It is often unacceptable to decouple the problems. An analysis of cohesive or adhesive fracture may yield meaningless results if residual thermal stresses, viscoelasticity of adhesive and adherend materials, and effects of temperature on the properties of these materials are disregarded.

Conclusions

This paper represents a review of existing research on fracture problems in adhesively bonded joints. An analysis of adhesive and cohesive fracture in adhesively bonded joints should follow the stress analysis to guarantee the integrity of a joint. This analysis should incorporate environmental effects, including effects of temperature (and moisture) on the properties of the materials, as well as thermal residual stresses. Viscoelastic properties of adhesive and, if necessary, adherend materials should be reflected in the constitutive equations. The present state of the art in the problem of adhesive fracture is still incomplete. More studies are necessary, including development of analytical models, numerical analyses, and experimental research, to present a comprehensive outline of the problem and to provide reliable design tools.

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