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DEVELOPMENT OF COMPOSITE MATERIAL TEST METHODOLOGY FOR FRACTURE TOUGHNESS/DAMAGE TOLERANCE

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ABSTRACT

Fracture toughness testing techniques for composite materials are reviewed for simplicity, applicability to filament wound systems, and correlation with fracture mechanics principles. Toughness test results are presented for homogeneous epoxy and graphite reinforced epoxy.

ACKNOWLEDGEMENT

I would like to express my appreciation to all the directors and personnel of the NASA/ASEE SFFP at MSFC for their efforts to produce an effective summer of research. I particularly want to thank my NASA counterparts: Dr. W. J. Patterson, Mr. Frank Ledbetter, and Mr. Mike Clemons for their valuable time and assistance in the discussion and execution of this research.

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INTRODUCTION

The Space Shuttle Orbiter is the primary vehicle in the NASA space transportation system. It will remain so for the remainder of this decade. The Orbiter can carry a crew of seven and a sixty five thousand pound load into an equatorial orbit and back to earth. The load the Orbiter can carry into a polar orbit is reduced due to the lower available energy at launch. To increase the available payload to a polar orbit NASA is using composite materials in the Solid Rocket Boosters (SRB) to reduce the launch weight of the vehicle.

Composite materials are some the most advanced materials available today. Composite materials are particularly effective in aerospace applications due to their high stiffness to weight ratio and due to the fact that they can be tailored to provide stiffness in particular directions. Composite materials are also particularly sensitive to damage. Seemingly small impacts or loads can introduce flaws into the matrix of the composite, there by reducing the overall or ultimate strength of the composite.

Fracture mechanics is the field within solid and/or structural mechanics which deals with the behavior of a solid in the presence of flaws or cracks. The early work in the field of fracture mechanics has led to the realization that the resistance of a material to particular modes of fracture is a material property. This material property is the critical stress intensity factor (K), or expressed in different terms, the critical strain energy release rate (G). This study deals with methods of determining these material properties for composite materials.

OBJECTIVES

The objectives of this study are:

(1) Review existing fracture toughness testing techniques for composite materials and metals to determine the best available methods.

(2) Determine the fracture toughness of the matrix material and the composite material used in the SRB filament wound case.

REVIEW OF FRACTURE TOUGHNESS TESTING TECHNIQUES

There are a large number of fracture toughness testing techniques presented in the literature of fracture mechanics. The review was directed primarily at methods which are used to find the mode I, or opening mode, critical stress intensity factor for composite materials and methods which use test specimens which are easily produced.

NASA Standard Tests

The ACEE Composites Project Office at NASA Langley Research Center has contributed to the development of five standardized fracture toughness tests for composite materials. These tests are designed for application to aircraft structures. The test procedures are presented in reference [1]. The tests are: (1) compression after impact test, (2) edge delamination tension test, (3) open hole tension test, (4) open hole compression test, and (5) hinged double cantilever beam test.

Compression After Impact Test

In this test a specimen is subjected to an impact load after the method of the falling weight test (described later) and then loaded in compression. The compression after impact test does not lead to the determination of a value of the critical stress intensity factor or strain energy release rate. The test produces a value of the failure stress and strain in the presence of flaws.

This test is not directly applicable to the current study because it does not lead to determination of a material property. However, the principle of the test is applicable to methods for studying the damage tolerance, or life, of composite materials. Filament wound systems are used primarily in pressure vessel applications. As such, they are usually loaded in tension. Thus, for the study of filament wound systems it is natural that the test be modified to a tension after impact test.

Edge Delamination Tension Test

The edge delamination tension test is used to determine the critical strain energy release rate for interlaminar fracture. In this test a composite laminate layup with free edges is subjected to a uniaxial tensile load. The G_c is found from the value of strain where the stress-strain plot departs from linearity.

This test is not directly applicable to the current study because it does not lead to a mode I critical strain energy release rate. Inaddition, it is not possible to determine the mode of crack propagation. Thus, the material property found is some unknown combination of the three primary material properties, G_{Ic}, G_{IIc}, and G_{IIIc}.

Open Hole Tension Test

The open hole tension test is used to determine the ultimate tensile strength of a composite laminate in the presence of a 1/4 inch diameter hole. The test does not produce a material property. Rather, it yields an estimate of the strength of the composite in the presence of a stress riser. This test is not applicable to the present study.

Open Hole Compression Test

As with the open hole tension test this test does not lead to the determination of a material property. The result is an estimate of the compressive strength of a composite in the presence of a stress riser. This test is not applicable to the present study.

Hinged Double Cantilever Beam Test

This test is used to determine the critical strain energy release rate for delamination of a composite material. The specimen, shown in Figure 1, is loaded via hinges bonded to the composite laminate. An initial delamination is introduced by the use of a Teflon separator included in the layup of the laminate. The G_{Ic} value is found from:

$$G_{Ic} = \frac{P\delta\ (3a - 4a_o)}{2ab(a - a_o)}$$

where P is the force applied to the specimen, a is the crack length, b is the width, δ is the opening of the crack at the hinges, and a_o is a parameter found from the flexure approximation.

Note that this critical strain energy release rate is for delamination of the composite laminate. Strictly speaking this property is related to manufacturing process for the laminate and the quality of the laminate, not to the composite itself. However, in the fracture of composites the direction of crack propagation is not what one expects based experience with fracture of homogeneous materials. For example, a crack introduced across the ply of a laminate and the laminate is loaded in tension in the ply direction, the crack propagates along the ply. Rather than across the ply as is expected with homogeneous materials. Therefore, this test with some modifications is important to this study.

This test has one very important benefit and one large detraction. The benefit is that the initial flaw or crack has a very small radius at the crack tip, as is found in nature. The detraction is that to achieve this small crack tip radius the test specimen must be layed-up explicitly for the test. It cannot be a piece cut from an existing system.

ASTM Test Methods

The American Society for Testing Methods (ASTM) has established numerous test procedures for fracture toughness testing of metals and plastics. The society has not, at this time, established test procedures for composite materials. Never the less, the procedures established for homogeneous materials are important to review for their applicability to composite materials.

The test methods prescribed by the ASTM are directed primarily at determining the mode I fracture toughness. The tests differ primarily in the geometry of the test specimen. For tension tests the geometries used are: the Compact Test specimen (ASTM E399, E813) [2,3], an arc-shaped test specimen (ASTM E399) [2], and a disk-shaped compact test specimen (ASTM E399) [2]. There are two bending test geometries: the three-point bending test (ASTM E399, E813) [2,3], and the four-point bending test (ASTM E399). An additional test prescribed by the ASTM for fracture toughness testing is the impact resistance test (ASTM D3029) [4].

ASTM Tension Tests

The specimen geometries prescribed by the ASTM for tensile fracture toughness testing are not particularly applicable to composite materials. The Compact Test specimen requires a large amount of material. The arc-shaped specimen and the disk-shaped compact test specimen are designed for application to systems with small (less than 12 inches (30.4 cm)) radii. These test geometries are not considered important to this study.

ASTM Bending Tests

In these tests a precracked specimen is loaded as a simply supported beam. The three-point bending test is shown in Figure 2. The three- and four-point bending tests differ in the loading condition at the crack. In the three-point specimen the stress at the crack tip is a combination of normal and shear stresses. In the four-point specimen the stress at the crack tip is pure normal stress. The geometry of the test specimen is the same for either method of loading. This geometry is easily produced from existing composite systems. Difficulty arises in introducing a crack with an infinitesmal radius at the crack tip. In metals testing an initial crack is introduced by fatigue. This is not possible for composite materials. Hence, an error is introduced in the procedure: the critical stress intensity factor is found for a blunt crack. This value is greater than that determined for a sharp crack. The three-point bending test is used for toughness testing in this study.

ASTM Impact Resistance Test

This test, also referred to as the falling weight test, is used to determine the energy necessary to fracture the test specimen. At this time there is no correlation between the energy to fracture the specimen and the conventional fracture toughness parameters, the critical strain energy release rate and the critical stress intensity factor. However, it is expected that the parameters are related.

In this test a weight is raised to a specified height and then released to fall on to the test specimen. If cracks are observable on the side of the specimen opposite the impact, then the weight is reduced and the test repeated on another specimen. If cracks are not observed, then the weight is increased and the test repeated on another specimen. The fracture energy is found from the average of the energies used in the tests. This test was used in this study.

Other Methods

As stated previously, there are numerous methods for fracture toughness testing described in the literature. Four of these methods were also considered in this study. They are the double cantilever beam test, the tapered double cantilever beam test, the roof-top three-point bending test specimen, and the thru-cracked plate.

Double Cantilever Beam Test

This test is similar to the hinged double cantilever beam test described earlier. Figure 3 shows a schematic of the double cantilever beam specimen. The test specimen is machined out of an existing system. As with the hinged double cantilever beam the force and opening of the crack are measured to determine the fracture toughness property of the material. This test has the advantage over the hinged double cantilever test since it can be used for an existing system. There is an additional advantage for this method, due to the length of the specimen, the crack does not propagate thru the specimen instantaneously. Instead, the crack propagates in a series of steps thru the specimen. Thus, a single specimen can yield a number of results. This test is important to this study.

Tapered Double Cantilever Beam Test

This test is nearly identical to the double cantilever beam test discussed previously. The exception is that the height of the cantilever is tapered to lead to a uniform value of the force necessary to propagate the crack. This test requires a considerable amount of material and yields results identical to those found with the double cantilever beam test. This test was used in this study.

Roof-Top Three-Point Bending Test

The test specimen used in this test has geometry identical to the specimens used in the three- and four-point bending test. The difference is the shape of the notch used. In the three-point bending test the notch used is as shown in Figure 4. The roof-top three-point bending test specimen has a notch as shown in Figure 5. This notch was originally used by Tattersall and Tappin [5] and applied to composite materials by Beaumont and Phillips [6]. This test determines the work of fracture, a parameter which is not directly related to the conventional fracture toughness parameters. There is a serious difficulty in relating the work of fracture determined by this test to the critical strain energy release rate: due to the shape of the notch the stress state at the notch is three dimensional thus eliminating the simplifying assumptions of plane strain and plane stress. These assumptions are essential to determining the strain energy release rate.

Thru-Cracked Plate Test

This test geometry was used by Griffith in his founding work in fracture mechanics. It was used by Poe and Sova [7] to determine the fracture toughness of composite materials. In this test a plate with a crack thru the thickness of the plate is loaded axially in tension. The test lead Poe to propose a fracture toughness parameter which is independent of the laminate directions. This test was not used in this study.

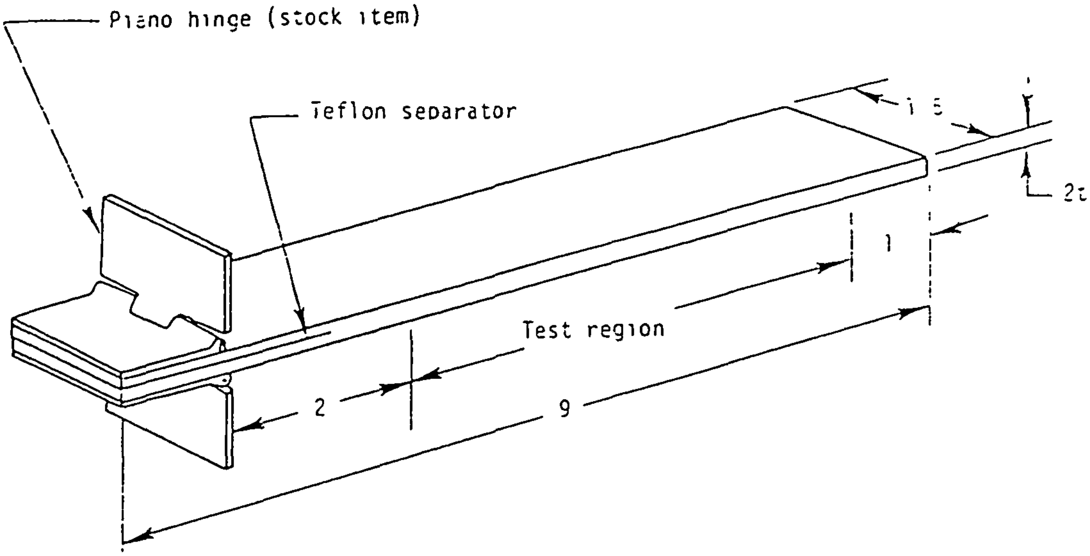

Figure 1. The Hinged Double Cantilever Beam.

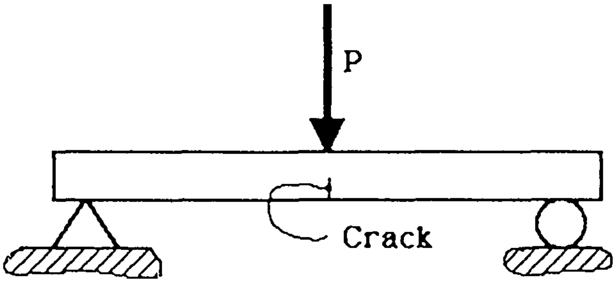

Figure 2. The Three-Point Bending Test Specimen.

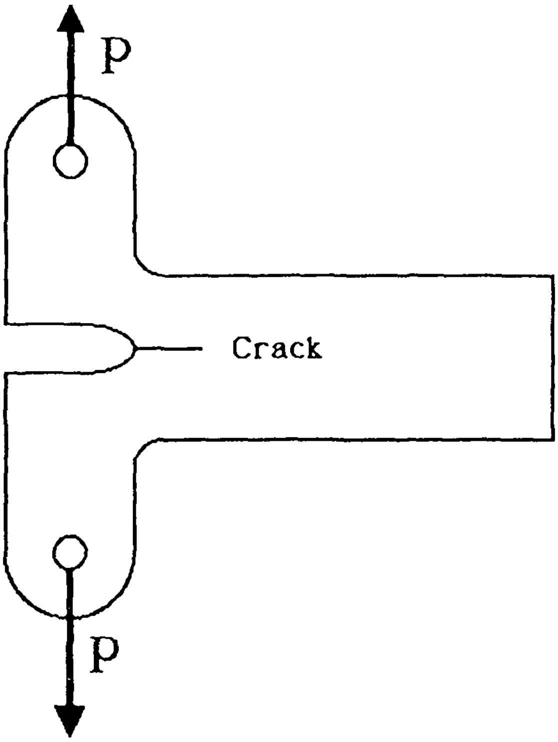

Figure 3. The Double Cantilever Beam Test Specimen.

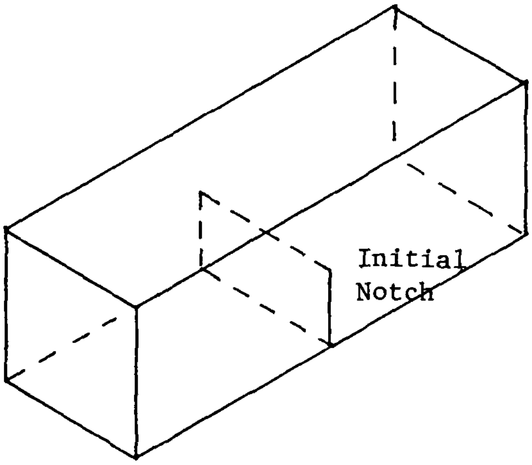

Figure 4. A Schematic of the Three-Point Bending Test specimen Showing the initial notch geometry.

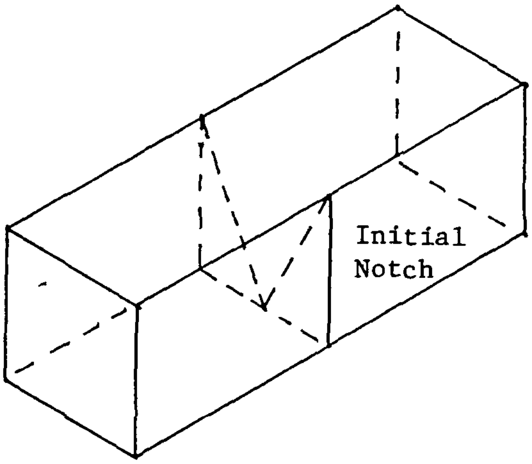

Figure 5. A Schematic of the Roof-top Three-Point Bending Test specimen showing the initial notch geometry.

FRACTURE TOUGHNESS TESTING

Fracture toughness tests were performed on homogeneous samples of the SRB filament wound case (FWC) resin (Hercules Epoxy 55A) and on the FWC composite material (graphite reinforced epoxy). Several of the different fracture toughness tests discussed above were used.

Neat Resin Tests

For testing of the "neat" or homogeneous resin the following tests were used: the three-point bending test, the double cantilever beam test, the tapered double cantilever beam test, and the roof-top three-point bending test. The thicknesses of the test specimens ranged from 0.148 inch (3.76 mm) to 0.5 inch (12.7 mm). Results are listed in Table 1 for the three groups of specimens used. Note that the average value of the stress intensity factor for the group of specimens 0.148 inch thick is significantly higher than the other averages. These pieces were cast at the thickness used in the test. Due to variations in the cure thru the thickness it was obvious that the material was not homogeneous. This tends to explain the higher values of K_{Ic} found.

In conducting the three-point bending tests the test set-up was used to measure the elastic modulus of the material. Table 2 lists the results of these measurements. The values found do not agree with the handbook values for the material. To determine if the test was in error measurements were made using the Rheometrics Dynamic Spectrometer. Figure 6 shows the results from one set of tests. These tests demonstrated that the results found from the three-point bending test were accurate. They also demonstrated quite clearly that the epoxy resin is a nonlinear viscoelastic material, with as much as a 20 percent reduction in the modulus value over 1000 sec. In order to avoid the effect of viscoelastic response on the fracture toughness tests the tests were conducted at a rate above the relaxation rate of the material.

Table 3 lists the critical values of the strain energy release rate determined from the double cantilever beam tests. As indicated in the table the corresponding values of the critical stress intensity factor are considerably above the values determined by the three-point bending tests. An explaination for this result is not readily available. It is conceivable that the different loading rates effects the critical fracture toughness parameter.

The values of the work of fracture determined from the roof-top three-point bending tests are listed in Table 4. There is a factor of 5 difference in the values found with two different geometries. Again, no explaination is offered other than to note that work is used in the viscoelastic response of a material which other wise is not accounted for.

FWC Composite Material Tests

Tests on the FWC material were performed using the three-point bending test and the roof-top three-point bending test. These tests highlighted the fact that composite materials do not behave in the same manner as homogeneous materials. The tests did not lead to the determination of a fracture toughness parameter. This is due to the fact that the cracks did not propagate in an opening mode manner. The initial cracks either extended in an interlaminar shear mode, or sections of the material pulled out of the specimen. The later is an edge effect. This leads to the conclusion that other test procedures must be used to determine the fracture toughness of composite materials.

Table 1. Critical Stress Intensity Factors for Neat Epoxy Determined From Three-Point Bending Tests.

Specimen Thickness inch	Average K_{Ic} psi$\sqrt{in}$	Standard Deviation %
0.148	1839	11.8
0.252	1175	9.1
0.503	1601	3.9

Table 2. Elastic Modulus Values for Neat Epoxy Determined From Three-Point Bending Tests.

Specimen Thickness inch	Average E ksi	Standard Deviation %
0.252	56	2.2
0.503	52.5	4.7

Table 3. Critical Strain Energy Release Rates for Neat Epoxy Determined From Double Cantilever Tests.

Specimen Thickness inch	Average G_{Ic} lb/in	Standard Deviation %	Average K_{Ic} psi$\sqrt{in}$
0.125	9.23	13.3	2201

Table 4. The Work of Fracture for Neat Epoxy.

Specimen Thickness inch	Average Work of Fracture lb/in	Standard Deviation %
0.252	16.21	10.6
0.503	98.72	16.9

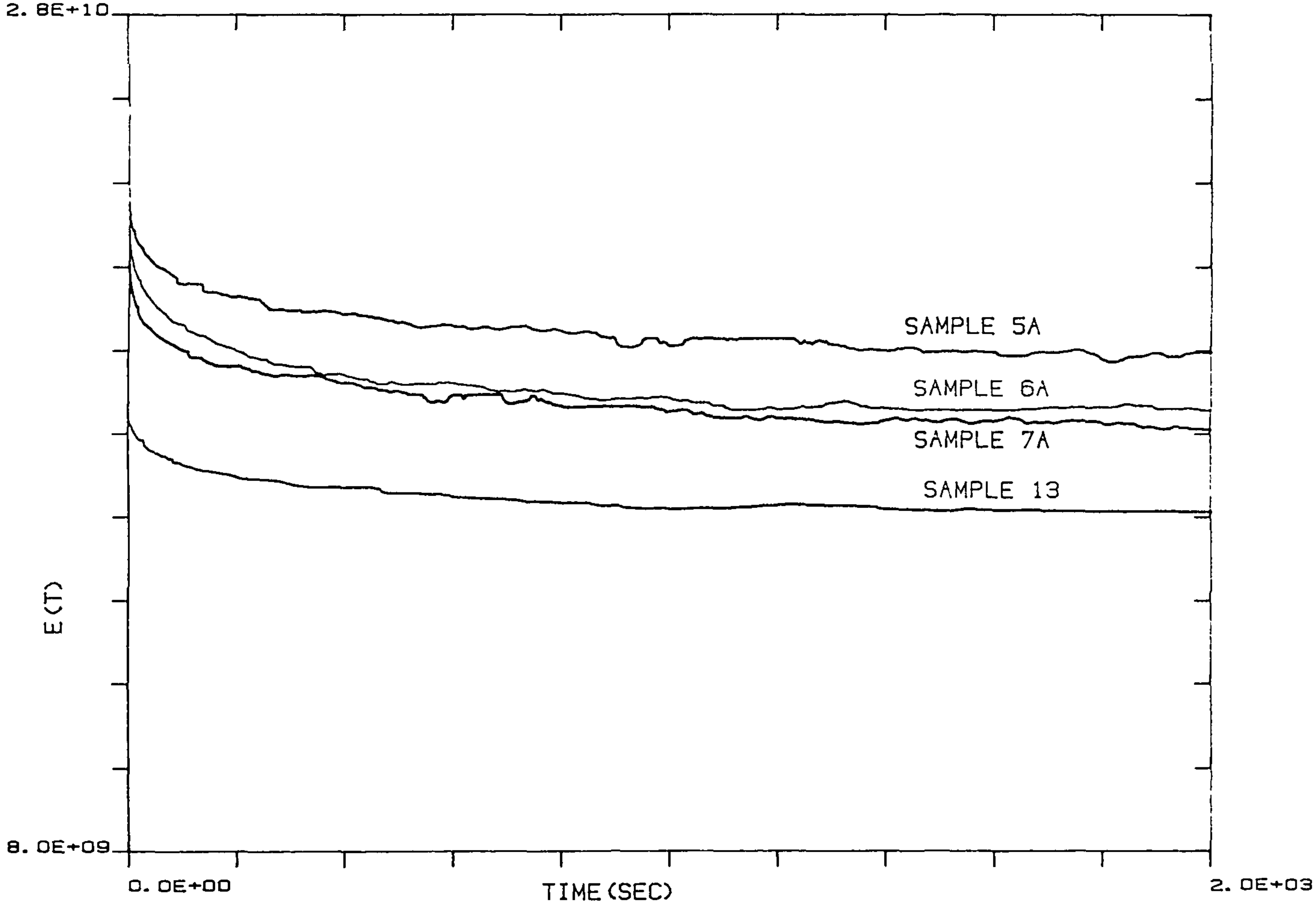

Figure 6. The Stress Relaxation Plot for Hercules 55A Epoxy Resin. The measurements were performed at 0.15% strain, loading a three-point bending specimen. E(t) is in dyne/cm^2.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are:

(1) Fracture toughness parameters for homogeneous materials can be easily determined by either the three-point bending test or the double cantilever test.

(2) The three-point bending test is not effective for determining the fracture toughness of composite materials.

(3) Epoxy is a nonlinear viscoelastic material. This type of behavior may effect the fracture toughness measurements for the neat resin and for the composite material.

The recommendations of this study are:

(1) The hinged double cantilever beam test, the double cantilever beam test, and the thru-cracked plate test methods should be investigated for their applicability to composite material systems.

(2) The use of a tension after impact test to determine the damage tolerance and damage accumulation rate of a composite material should be studied.

(3) A study of the effect of viscoelastic behavior on fracture toughness and filament wound systems should be performed.

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