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Mode I and Mode II Analysis of Graphite/Epoxy Composites Using Double Cantilever Beam and End-Notched Flexure Tests

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ABSTRACT

The critical strain energy release rates associated with debonding of the adhesive bondlines in graphite/epoxy IM6/3501-6 interlaminar fracture specimens were investigated. Two panels were manufactured for this investigation; however, panel two was layed-up incorrectly. As a result, data collected from Panel Two serves no real purpose in this investigation. Double Cantilever Beam (DCB) specimens were used to determine the opening Mode I interlaminar fracture toughness, G_{Ic} , of uni-directional fiber re-inforced composites. The five specimens tested from Panel One had an average value of $946.42\text{J}/\text{m}^2$ for G_{Ic} with an acceptable coefficient of variation. The critical strain energy release rate, G_{IIc} , for initiation of delamination under in-plane shear loading was investigated using the End-Notched Flexure (ENF) Test. Four specimens were tested from Panel One and an average value of $584.98\text{J}/\text{m}^2$ for G_{IIc} was calculated. Calculations from the DCB and ENF test results for Panel One represent typical values of G_{Ic} and G_{IIc} for the adhesive debonding in the material studied in this investigation.

INTRODUCTION

Laminated composite structures exhibit a number of different failure modes. These include fiber fracture, matrix failure, fiber-matrix debonding within individual layers, delamination or separation of adjacent layers, buckling, and transverse cracking through one or more layers. However, the various modes interact and can occur concurrently and also sequentially. Regions prone to interlaminar delamination include free edges, joints, cutouts, voids, inadvertently damaged areas, and defects resulting from fabrication. Because composite materials can be joined with some sort of adhesive, debonding is a potential failure mode in composite materials. Knowledge of the interlaminar fracture toughness and strain energy release rates is of critical importance in composite design.

A major weakness of laminated composite structures is the composite's susceptibility to delamination. The resistance to delamination can be characterized by the delamination fracture toughness, measured as energy dissipated per unit area of crack growth. Delamination in composites can occur due to tensile stresses (Mode I), in-plane shear stresses (Mode II) and out-of-plane tearing stresses (Mode III). In this study, Mode I and Mode II deformations were investigated and are illustrated below in Figure 1. Mode I loading deformation is the classic opening mode while Mode II is the type of deformation that involves shearing.

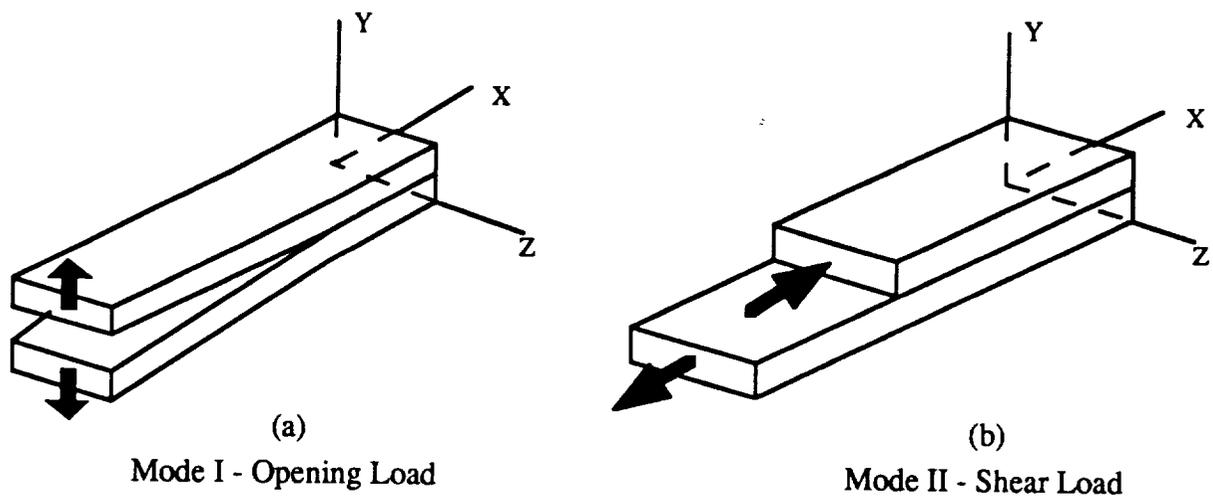


Figure 1. Two Basic Modes of Delamination

An essential part in establishing design guidelines for preventing debonding is the ability to predict the load level at which delamination occurs. In fracture mechanics, there are several criteria used to predict the onset of crack growth. These include the critical stress intensity factor, the critical crack opening displacement and the critical strain energy release rate. The stress intensity factor is a measure of the rate at which the crack tip stresses approach infinity. The crack opening displacement is a measure of the opening between the crack faces. The energy release rate is defined as the change in energy of a structure containing a crack per unit increase of crack area.

At the onset of crack growth, the fracture mechanics parameter reaches a critical value. This critical value is a material property, implying that it is independent of geometric and loading characteristics such as crack length and type of loading. The criterion for debonding examined in this study is the critical strain energy release rate. Applying energy conservation, as a crack grows, a certain amount of energy is released from the cracked specimen per unit area of the newly generated crack surface. The rate of change of this strain energy per unit area is called the energy release rate and is denoted by G . The critical value of the energy release rate at which the crack extends is denoted by G_c . Mode I energy release rate is produced by the opening mode deformation and is denoted by G_I . The Mode II component of energy release rate associated with the shearing mode deformation is denoted by G_{II} .

To determine opening Mode I interlaminar fracture toughness, G_{IC} , the double cantilever beam specimen, using piano hinges, was utilized, as shown in Figure 2. The DCB test is used with unidirectional laminated composites that are manufactured with a thin insert at one end imbedded at the mid-plane to imitate a crack, or to serve as a delamination initiator. One end of the DCB specimen is opened by applying a force on the hinges which are bonded to the specimen while a plot of load versus displacement is recorded.

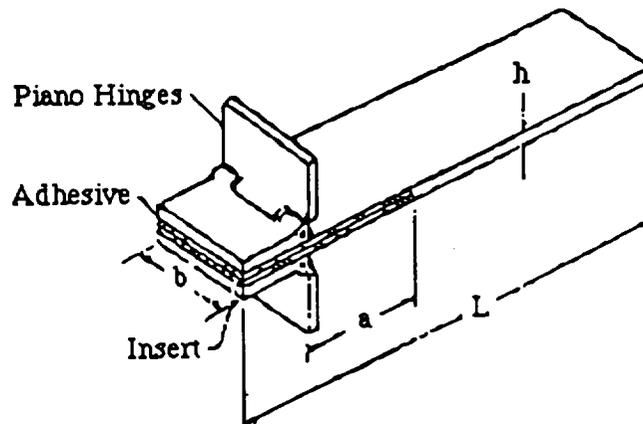


Figure 2. Double Cantilever Beam Specimen

In the calculation of G_{IC} , linear elastic behavior is assumed because the zone of nonlinear deformation at the delamination front is small relative to the specimen thickness. In DCB testing, as the delamination grows from the insert, the calculated values of G_{IC} first increase monotonically and then stabilize upon further growth. In this test method, a resistance curve (R-curve) depicting G_{IC} as a function of delamination length, is generated. A sample R-curve is shown in Figure 3. This curve illustrates the initiation and propagation of a delamination in a unidirectional specimen.

Two initiation values of G_{IC} are obtained from the load-displacement plots. These values, along with subsequent propagation values, are used to generate an R-curve. First, the onset value of G_{IC} is calculated from the load and displacement at the point of deviation from linearity, or at the

onset of non-linearity (NL). At this point, it is assumed that delamination begins to grow from the insert in the interior of the specimen. The NL value represents a lower bound value for G_{Ic} and is used in determining failure criteria for laminated composite structures. For brittle matrices, the NL value is typically the same point at which delamination is observed to grow from the insert at the specimen edges; however, for tough matrix composites, a region of non-linearity may precede the visual delamination at the edges. Second, a visual initiation value for G_{Ic} is recorded corresponding to the first time delamination was visually observed to grow from the insert on the specimen edges.

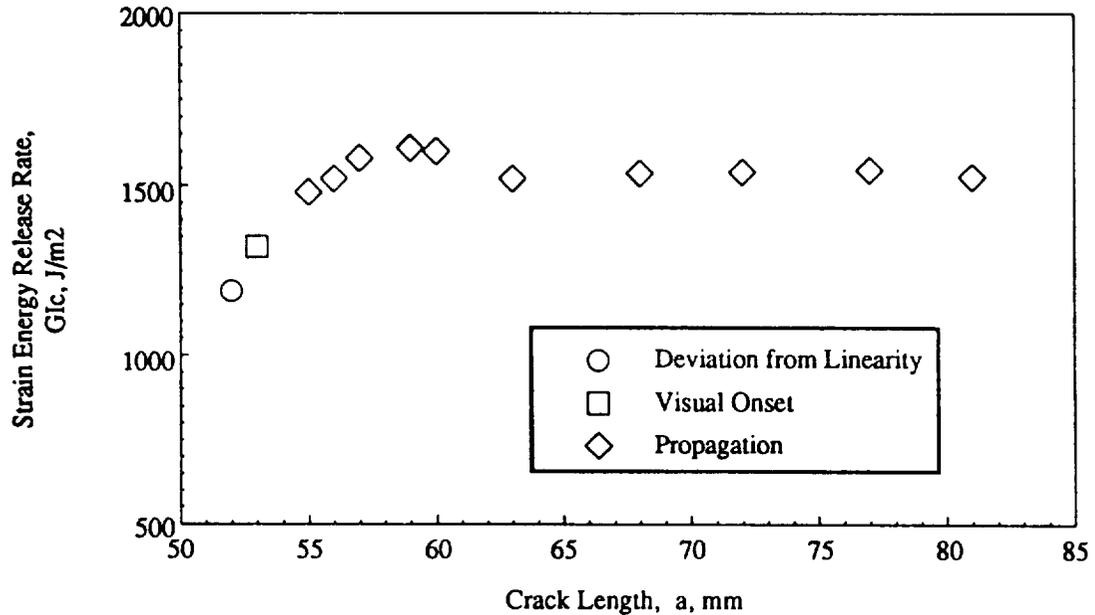


Figure 3. Sample R-Curve

To determine the critical strain energy release rate, G_{IIc} , for initiation of delamination under Mode II (in-plane shear) loading, tests were performed using the End-Notched Flexure (ENF) specimen loaded in three-point bending as shown in Figure 4. In general, the configuration, i.e. specimen thickness and distance between supports, is chosen such that large displacements would be avoided and transverse shear effects minimized.

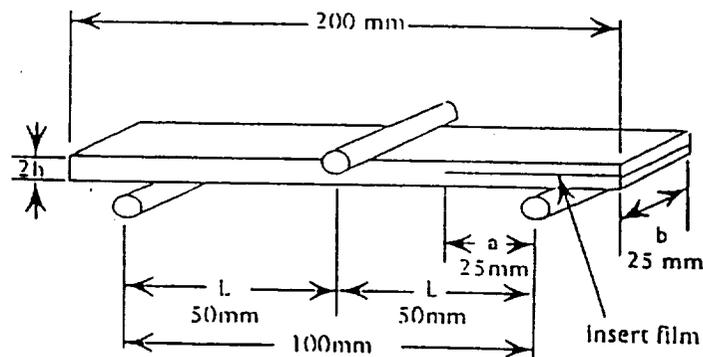


Figure 4. End-Notched Flexure Specimen

The ENF test consists of loading a split laminate beam specimen in a three-point bend fixture. Analytical methods derive a relationship between compliance and crack length using a least squares linear regression. Here, elastic material behavior was assumed.

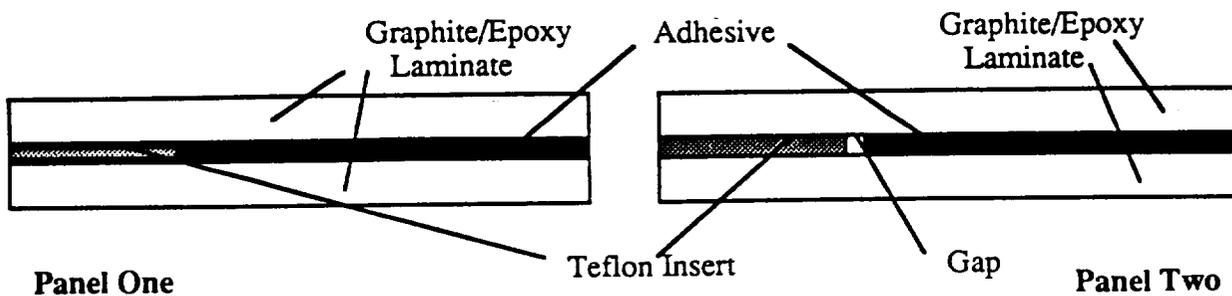


Figure 5. Panel Configurations

Two different graphite/epoxy IM6/3501-6 panels were manufactured at Boeing for this investigation as shown in Figure 5. Panel One contained a teflon insert embedded between two sheets of adhesive and the adhesive bondline thickness was nominally 5mil or 0.005". The adhesive ran the entire length of the specimen. The insert thickness was nominally 0.024mm. Panel Two also had a teflon insert with an average thickness of 0.0506mm; however, it was butted up against one layer of adhesive. Again, the adhesive bondline thickness was nominally 5mil. It should be noted that there was a gap, approximately 4mm long, between the insert and adhesive in this panel. This gap was filled by the 3501-6 resin matrix of the composite during the cure cycle. The adhesive used for both panels was a grade 8, 350°F cure film adhesive, American Cyanamid 1515. The average thickness and width measurements for Panel One specimens were 0.2805" and 1.0051", respectively, and 0.2797" and 1.0034", respectively, for Panel Two specimens.

PROCEDURE

DCB Testing

Experimental Investigation

The width and thickness measurements, for each specimen, taken at the midpoint and at 25mm from each end, were made to the nearest 0.05mm. Average values were calculated and recorded. Both edges of the specimen were coated with a thin layer of water-based typewriter correction fluid to assist in the visual detection of the onset of delamination. The first 5mm from the insert were marked in 1mm increments while the remaining 20mm were marked in 5mm increments.

Piano hinges were then attached to the specimens using Hysol 3904, a high-strength, high-temperature glue. The specimen was continuously loaded in displacement control at a rate of 0.5mm/min and a plot of load versus displacement was created by an X-Y chart recorder. A monocular with a magnification of seven was used to aid in observing delamination growth as it extended along one edge.

When delamination extended beyond the end of the insert, a hash mark was made on the load versus displacement plot and was labeled a_0 . As the delamination grew, the front continued to be observed, and, as it passed each pencil mark, a hash mark was made on the plot and labeled appropriately. For example, point a_1 represents the delamination growth 1mm ahead of the insert. After delamination exceeded 25mm, the X-Y plotter was turned off and the specimen was loaded in the machine until it broke open.

Analytical Investigation

Three data reduction methods for calculating values were followed as per ASTM Standard D5528-94a. These are: a modified beam theory (MBT), a compliance calibration method (CC), and a modified compliance calibration method (MCC).

Modified Beam Theory (MBT) Method - The beam theory expression for the strain energy release rate of an ideal double cantilever beam is:

$$G_I = \frac{3P\delta}{2ba} \quad (1)$$

where P = load,
 δ = load-point displacement,
 b = specimen width,
 a = delamination length.

However, since the beam is not perfectly built-in, some rotation may occur at the delamination front and the value of G_I will be overestimated. In order to compensate for this, the DCB specimen is treated as if it contains a slightly longer delamination, $a + |\Delta|$, where Δ is determined experimentally by a least squares plot of the cube root of the compliance, $C^{1/3}$, as a function of delamination length, a . Compliance, C , is defined as the ratio of load-point displacement to applied load, δ/P . The Mode I interlaminar fracture toughness is then calculated as:

$$G_{mbt} = G_I = \frac{3P\delta}{2b(a+|\Delta|)} \quad (2)$$

In addition, the modulus, E_{1f} , can be determined by

$$E_{1f} = \frac{64(a+|\Delta|)^3P}{8bh^3} \quad (3)$$

Compliance Calibration (CC) Method - A plot of $\log(\delta_i/P_i)$ versus $\log(a_i)$ is generated using the visually observed delamination onset values and propagation values. With a calculated slope, n , the fracture toughness can be found as follows:

$$G_{cc} = G_I = \frac{nP\delta}{2ba} \quad (4)$$

Modified Compliance Calibration (MCC) Method - Using the delamination length normalized by the thickness, a/h , and the cube root of the compliance, $C^{1/3}$, a least squares plot is generated. The slope of this line is called A_1 . Here, the fracture toughness can be calculated from:

$$G_{MCC} = G_I = \frac{3P^2C^{2/3}}{2A_1bh} \quad (5)$$

ENF Testing

Experimental Investigation

The following method is based on *A Protocol for Interlaminar Fracture Testing* currently being used in an ASTM Round Robin Test program. In order to initiate delamination, a film was placed at the laminate mid-plane during molding, as seen in Figure 4. This film should be as thin as possible to minimize the disturbance to the composite. Furthermore, the specimen edges were coated with a thin layer of water-soluble typewriter correction fluid from the insert tip and extending toward the center of the specimen. This allowed the initiation of delamination to be seen more easily.

The specimen was loaded in a three point bending fixture. Before loading the specimen, a small load was applied to the specimen to hold it in position in the fixture, and the location of the supports were marked on the specimen. A displacement gauge, mounted upside down under the specimen, was used to measure the load-point displacement.

Dimensions and Load Rate - The width and thickness of each specimen was measured to the nearest 0.025mm at the midpoint and at 10mm from each end. Here, three thickness measurements were made: one measurement close to each edge and one at the center. Average values of width and thickness measurements were then recorded.

The specimen was loaded in displacement control at a rate of 0.5mm/min. Load vs. load-point displacement was recorded during loading using an X-Y plotter.

Compliance Calibration - For each specimen, an experimental compliance calibration is required. The specimen was initially positioned in the ENF apparatus so that the delamination length, a , equaled zero, meaning that the insert is outside the outer load point of the apparatus. A pencil mark was made on the specimen directly above the center of the outer loading pin. Next, the specimen was loaded and unloaded in the elastic range while the load-displacement behavior was recorded. This procedure was repeated with delamination lengths of $a = 15, 20, 25, 30, 35$ and 40mm .

Testing From the Insert - The specimen was positioned in the test fixture so that $a/L = 0.5$. Again, a mark was made on the specimen surface to indicate the outer load point. The specimen was then loaded at the stated load rate until delamination began and the load dropped. The specimen edge was also visually monitored for the initiation of delamination growth.

Analytical Investigation

After testing, the specimen was broken open by hand and the distance from the outer load point mark to the inside tip of the delamination starter film was measured. This initial delamination length was measured at the edges and center of the specimen and a mean value was obtained. The mean lengths from the marks made during the compliance calibration were also measured and recorded.

From the compliance calibration curves, compliance values were calculated for each corresponding delamination length. Compliance is defined as the ratio of displacement to load.

Using the values of mean crack length, a , and the corresponding values of compliance, C , a least squares linear regression of the form $C = C_0 + ma^3$ was performed and the values of C_0 and m were recorded. Therefore, the expression for G_{II} becomes:

$$G_{II} = \frac{3ma^2P^2}{2b} \quad (6)$$

where $a = 25\text{mm}$,

$P = \text{load}$,

$m = \text{slope of line from least squares linear regression}$,

$b = \text{specimen width}$.

A line tangent to the initial linear portion of the loading curve was drawn; any initial deviation from linearity due to seating of the load fixture was ignored. The point at which the load displacement curve deviated from the tangent line was determined. The load and displacement corresponding to this point was used to obtain G_{IIcNL} . In addition, the maximum load and corresponding displacement was used to calculate G_{IIcMAX} .

RESULTS

DCB Testing

A summary of the DCB test results is shown in Table A. Note that the G_{mbt} value is the lowest calculated value for G as predicted by the Modified Beam Theory. Upon examining the data collected from Panel One, a large coefficient of variation (CV) is found because the data gathered from Specimen 1-1 is significantly higher than the other four specimens from the same panel. If Specimen 1-1 is disregarded in statistical calculations, values of 867.25 J/m², 49.64 and 5.72% are then found for the mean, standard deviation, and CV, respectively. The notably high values for Specimen 1-1 are due to a relatively high load (approximately 60 lbs.) and large displacement corresponding to a_{NL} . However, since no physical defects were observed before or after the test, it has not been determined why Specimen 1-1 had such a high non-linear load.

Table A. Graphite/Epoxy G_{Ic} Data Summary

Panel One				Panel Two			
Specimen	G_{mbt}^*	G_{cc}^*	G_{mcc}^*	Specimen	G_{mbt}^*	G_{cc}^*	G_{mcc}^*
1-1	1263.1	1316.8	1370.5	2-1	133.5	136.6	145.0
1-3	831.8	866.8	893.5	2-3	167.5	169.7	173.6
1-5	903.9	929.1	922.7	2-5	150.2	155.4	175.2
1-7	915.6	941.1	948.0	2-7	112.8	116.5	121.5
1-9	817.7	843.5	927.2	2-9	147.0	148.3	152.0
Average:	946.42	979.46	1012.38	Average:	142.20	145.30	153.46
Std. Dev.:	182.17	192.99	201.14	Std. Dev.:	20.42	20.07	22.21
CV (%):	19.25%	19.70%	19.87%	CV (%):	14.36%	13.81%	14.47%

*All G values are in J/m²

The results obtained from Panel Two largely differ from those gathered from Panel One because of the different panel configurations. Because of the epoxy filled gap between the insert and adhesive, a load drop was observed for all five specimens at around 25 lbs. Therefore, 25 lbs. was used as the point of non-linearity as compared to about 54 lbs. for specimens 1-3, 1-5, 1-7, and 1-9. This discrepancy caused the calculated toughness values for Panel Two to be about 6.5 times smaller than the values for Panel One. The values of G_c found for Panel Two are representative of values for a graphite composite, while Panel One is indicative of the stronger adhesive.

ENF Testing

Table B compares the ENF test results for Panels One and Two. Panel One exhibited appropriate behavior during testing. The non-linear points were easily determined. Specimens 1-2, 1-6, and 1-8 had non-linear loads at approximately 2020N (450 lbs.) while 1-4 had a higher non-linear load of 2257N, or 507 lbs. This high non-linear load, in addition to scatter in the calculated values of m (slope from linear regression), led to a high coefficient of variation of 21.06%. However, if Specimen 1-4 is excluded from statistical calculations a very respectable CV of 6.93% is found. It was not determined why specimen 1-4 had such a high non-linear load. However, its failure load was consistent with the other three specimens as shown in Table B. Calculated values of $G_c(MAX)$ only differed by 11.57% since all the maximum loads were in the range of 4600 lbs.

In examining the results calculated for Panel Two, the discrepancy in values as compared to Panel One is due to the 4mm epoxy filled gap. Upon examining the results from Panel Two, one will notice a significant discrepancy in the values of $G_c(NL)$. The $G_c(MAX)$ could not be calculated for this panel because of the gap between the insert and adhesive.

Table B. Graphite/Epoxy G_{IIc} Data Summary

Panel One

Specimen	P(NL)*	P(MAX)*	Gc(NL)*	Gc(MAX)*
1-2	2012.8	4581.67	487.1	2523.9
1-4	2257.5	4659.51	769.2	3276.9
1-6	2035.1	4637.27	523.9	2720.4
1-8	2012.8	4692.87	559.7	3042.4
Average:			584.98	2890.90
Std. Dev.:			126.34	334.52
CV (%):			21.60%	11.57%

Panel Two

Specimen	P(NL)*	Gc(NL)*
2-2	3436.25	1395.9
2-4	3458.49	1394.9
2-6	3325.04	1271.6
2-8	3080.39	1237.4
Average:		1324.95
Std. Dev.:		82.54
CV (%):		6.23%

*P values are in N, G values are in J/m^2

CONCLUSIONS

The DCB and ENF data collected from Panel One is consistent with similar adhesives. Even though a high CV was calculated for Panel One specimens, one must realize that a small number of specimens were tested. If a larger pool of specimens were tested, more reliable and more accurate results could be found. Due to a gap between the insert and adhesive, results from Panel Two serve no real purpose in this investigation. In regards to Panel One, the average value for G_{Ic} is $946.42 J/m^2$ while the average G_{IIc} value is $584.98 J/m^2$. These results illustrate that a crack in the adhesive requires more energy to grow in the opening mode than the shearing mode. This is just the opposite of what is typically observed for delamination within the composite.

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