DOUBLE CANTILEVER BEAM and END NOTCHED FLEXURE FRACTURE TOUGHNESS TESTING OF TWO COMPOSITE MATERIALS

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FINAL REPORT

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Introduction

Two different unidirectional composite materials were provided by NASA Langley Research Center and tested by the Composite Materials Research Group within the Department of Mechanical Engineering at the University of Wyoming. Double cantilever beam and end notched flexure tests were performed to measure the mode I (crack opening) and mode II (sliding or shear) interlaminar fracture toughness of the two materials. The two composites consisted of IM7 carbon fiber combined with either RP46 resin toughened with special formulation of LaRC IA resin, known as JJS1356; or PES chain extended thermoplastic resin known as JJS1361.

Double Cantilever Beam Specimen Configuration and Test Methods

As received from NASA, the test specimens were nominally 0.5 inch wide, 6 inches long, and 0.2 inch thick. A 1 inch long Kapton insert at the midplane of one end of the specimen (placed during laminate fabrication) facilitated crack initiation and extension. It was noted that the specimens provided were smaller than the nominal 1.5 inch wide, 9.0 inch long configuration specified in Ref. [1, 2]. Similarly, the Kapton inserts in Ref. [1 - 3] were of greater length than those in the present specimens. Hence, the data below should not be compared directly to those generated with the referenced methods. No preconditioning was performed on the specimens prior to testing.

In general, the methodology presented in Ref. [1] was used for the present work. Crack opening loads were introduced to the specimens via piano hinges attached to the main specimen faces at a single end of each specimen. Hinges were bolted to the specimens using the technique presented in Ref. [2].

The cracks were extended a small distance from the end of the Kapton insert prior to testing, as per Ref. [1]. Just before precracking, the sides of the specimens were coated with water-soluble typewriter correction fluid to aid in crack visualization. Scribe marks were then made in the coating at half-inch intervals.

Although Ref. [1, 2] specify that the crack should be manually propagated approximately 0.5 inch from the end of the insert prior to testing, the more recent work referenced in Ref. [3] indicates that the initial crack extension (the extension starting from the end of the insert) is the most indicative of material behavior in composite structures. It would therefore have been preferable to include the initial crack extension in the present data. As mentioned above, this was not possible because the cracks were manually extended prior to testing.

The testing was performed in an Instron 1125 universal electromechanical testing machine with conventional mechanical wedge-action grips and an in-line universal joint at a crosshead speed of 2mm/minute.

To conduct a test, the free half of each hinge was placed in the grips and the chart recorder was nulled. The crosshead was then moved at a fairly high crosshead rate (20 mm/minute) until just prior to crack extension, at which point the crosshead rate was reduced to 2mm/minute and the loading was continued until the crack had extended about 0.5 inch. The crack length was measured with dial calipers and the specimen was then unloaded. This process was repeated several times; most specimens were subjected to 5 crack extensions. The crack length was measured on each side of the specimen from an imaginary line between the two hinge pivots to the crack front, and the crack lengths from each side were averaged for use in the calculations. As mentioned above, the procedure from Ref. [1] was followed. The methods presented in Ref. [2, 3] are similar, except that the specimen is not unloaded at the end of each crack propagation. Also, in Ref. [3], the free end of the specimen is supported.

Load versus crosshead displacement curves were recorded on the Instron chart during each test and are included below. The beam deflections were measured with the crosshead displacement unit integral to the testing machine, rather than at the specimen. Although it is preferred to directly measure the displacement of the specimen halves at the hinge pivot, time constraints precluded this option. The wedge grips were preloaded and the load train was kept as simple and short as possible to minimize extraneous displacements.

Two different data reduction techniques were used to calculate the critical strain energy release rate G_{IC} for each material. The first, known as the energy-area integration method, involved the measurement of the area enclosed by each individual load - propagation - unload excursion and was taken from Ref. [1]. The G_{IC} values were then determined from the following formula:

$$G_{IC} = \frac{\Delta A}{w(a_2 - a_1)}$$

where:

$\Delta A =$ included area of one crack extension

$(a_2 - a_1) =$ crack extension

$w =$ specimen width

Several G_{IC} values for each specimen were determined, one from each crack extension. The specimen average was then calculated. The included areas on the charts were measured manually.

The modified compliance calibration method (MCC) from Ref. [3] was also used to determine G_{IC} values. For this method, the following formula was used:

$$G_{IC} = \frac{3P^2C^{\frac{2}{3}}}{2A_1 bh}$$

where:

$P =$ the load at propagation

$C =$ the specimen compliance

A_1 = slope of a least squares plot of the delamination length (normalized by specimen thickness) versus the cube root of the compliance

b = specimen width

h = specimen thickness.

Specimen compliances were taken directly from the load - displacement curves on the Instron chart. In those instances where non-linearity was evident in the load - displacement curves, the compliance was estimated with a straight line drawn parallel to the most linear portion of the curve from the zero-load axis to the peak load point. These lines are visible in the curves appended to this report. This method also yields a single G_{IC} value for each crack extension. Complete descriptions of the two methods are provided in the respective references.

End-Notched Flex (ENF) Specimen Configuration and Test Method

As received from NASA, the test specimens were nominally 0.5 inch wide, 6 inches long, and 0.2 inch thick. A 1 inch long Kapton insert at the midplane of one end of the specimen (placed during laminate fabrication) facilitated crack initiation and extension. These specimens were the same dimensions as the double cantilever beam test specimens and were taken from the same laminates.

In general, the method presented in Ref. [4] were used for the ENF testing. To summarize, the specimens were precracked in tension by wedging the specimen open prior to testing so that the crack extended a small distance from the edge of the Kapton insert. The specimen was then placed in a three-point flexure fixture with a 4 inch span such that the crack tip was midway between the loading nose (the center loading pin) and the outer loading pin. The distance from the crack tip to the outer loading pin contact line was then measured with dial calipers and recorded. Testing was conducted in an Instron 1125 electromechanical testing machine by loading the specimen at a crosshead speed of 2mm/minute until the crack propagated. Load versus crosshead displacement curves were recorded on the Instron chart during each test and are included below. As for the DCB testing, the beam deflections were measured with the crosshead displacement unit integral to the testing machine.

For two specimens of each material type, compliance calibrations were performed to determine the relationship between compliance and crack length, which is necessary for the modified beam theory data reduction technique discussed below. Bending compliance was determined by loading the previously tested specimen in the flexure fixture to a load less than that required to propagate the crack, with the crack length (the distance from the crack tip to the center of the outer loading pin) set to 0.75 inch, 1 inch, 1.25 inch, 1.5 inch, and 2.0 inch. In this way, the compliance was determined for a range of crack lengths.

Two different data reduction techniques taken from Ref. [4] were used to calculate the critical strain energy release rate G_{IIC} for each material. The first, derived from beam theory, utilized the following formula:

$$G_{IIC} = \frac{9a^2P_c^2\,(C_T - C_M - C_S^*)}{2b(2L^3 + 3a^3)}$$

where:

a = the distance from the crack tip to the contact line on the outer loading pin

b = the specimen width

L = the total span (4 inches)

P_c = critical load for fracture

C_T = measured compliance

C_M = machine compliance

C_S^* = modified shear compliance, where $C_S^* = \dfrac{1.2L + 0.6a - 0.2l^3/a^2}{4bhG_{13}}$

G_{13} in this case estimated to be 1.0 Msi.

The second method, incorporating the compliance calibration data, used the following formula:

$$G_{IIC} = \frac{3P_c^2 m a^2 b_0}{2b^2}$$

where:

P_c , a, and b are as defined above

m = the slope of the least squares fit to the compliance versus crack length cubed data

b_o = the width of the specimen used for compliance calibration

Double Cantilever Beam Test Results

The average DCB test results are presented in Table 1. These values are the averages of the results from both of the methods described above. The individual results for both methods are included in the Appendix, as are the load deflection plots and the spreadsheets used to calculate the results. As can be seen in Table 1, the specimens from JJS1361 exhibited considerably greater resistance to interlaminar fracture than the specimens from JJS1356. The results calculated using the area method (see appendix) were slightly higher than those calculated using the compliance calibration method, but in both cases JJS1361 had the greater G_{IC}.

End-Notched Flex Test Results

The average ENF test results are presented in Table 2. Since two compliance calibrations were performed for each material type, it was possible to calculate two different G_{IIC} values using this technique. For those specimens which were used to perform the compliance calibration, only a single value was calculated. The values in Table 2 are the averages of the results from the beam theory reduction technique and both of the results from the compliance calibration reduction. As can be seen in the table, JJS1361 exhibited much greater G_{IIC} values than JJS1356. As with the DCB results, the relative performance of the two materials was not dependent on the reduction technique, even though they yielded slightly different values.

Table 1
Double Cantilever Beam Fracture Toughness
Test Results for Two Composite Materials

Specimen No.	G_{IC} in. lb/in^2	G_{IC} kJ/m^2
JJS1356-1	0.66	3.74
3	0.60	3.41
5	0.98	5.59
7	0.89	5.06
9	0.86	4.93
11	0.71	4.06
Average	0.78	4.47
Std. Dev.	0.15	0.85

Specimen No.	G_{IC} in. lb/in^2	G_{IC} kJ/m^2
JJS1361-1	1.06	6.03
3	1.39	7.93
5	1.21	6.92
7	1.04	5.97
9	1.29	7.40
11	1.30	7.46
Average	1.22	6.95
Std. Dev.	0.14	0.80

Table 2

End-Notched Flexure Fracture Toughness
Test Results for Two Composite Materials

Specimen No.	G_{IIC} in. lb/in^2	G_{IIC} kJ/m^2
JJS1356- 2	1.64	0.29
4	1.29	0.23
6	2.09	0.37
8	1.27	0.22
10	2.11	0.37
Average	1.68	0.29
Std. Dev.	0.41	0.07

JJS1361- 2	4.81	0.84
4	7.10	1.24
6	4.15	0.73
8	7.92	1.39
10	8.19	1.43
Average	6.43	1.13
Std. Dev.	1.84	0.32

REFERENCES

1. L. A. Carlsson and R. B. Pipes, *Experimental Characterization of Advanced Composite Materials,* Prentice Hall, Englewood Cliffs, New Jersey, 1987.
2. NASA Reference Publication 1092, *Standard Tests for Toughened Resin Composites, Revised Edition,* National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, July, 1983.
3. *Draft Proposed Standard Test Method for Mode I Interlaminar Fracture Toughness of Continuous Fiber Reinforced Composite Materials,* American Society for Testing and Materials, Philadelphia, Pennsylvania, 1992.
4. *Test Procedure for the End Notched Flexure (ENF) Test ASTM D30.02 Round Robin,* American Society for Testing and Materials, Philadelphia, Pennsylvania, 1988.

APPENDIX A

ADDITIONAL DATA TABLES

Table A1
Double Cantilever Beam Fracture Toughness Test Results for Two Composite Materials

Specimen No.	Area-Integration Method G_{IC} (in. lb/in^2)	MMC Method G_{IC} (in. lb/in^2)	Average G_{IC} (in. lb/in^2)
JJS1356-1	0.74	0.57	0.66
3	0.68	0.52	0.60
5	1.15	0.81	0.98
7	0.93	0.85	0.89
9	0.81	0.92	0.86
11	0.80	0.62	0.71
Average	0.85	0.71	0.78
Std. Dev.	0.17	0.17	0.15

1	1.16	0.95	1.06
3	1.46	1.32	1.39
5	1.27	1.15	1.21
7	1.04	1.05	1.04
9	1.34	1.24	1.29
11	1.35	1.26	1.30
Average	1.27	1.16	1.22
Std. Dev.	0.15	0.14	0.14

Table A2
End Notched Flexure Fracture Toughness Test
Results for Two Composite Materials

Specimen No.	G_{IIC} (in. lb/in^2) Area-Integration Method	MMC Method	MMC Method[1]	Average of Three Values
JJS1356- 2	1.65	1.54	1.73	1.64
4	1.40	1.17	1.30	1.29
6	2.02	2.17		2.09
8	1.27	1.19	1.33	1.27
10	2.02	2.20		2.11
Average	1.67	1.65	1.45	1.68
Std. Dev.	0.35	0.51	0.24	0.41
JJS1361- 2	5.52	4.43	4.48	4.81
4	7.18	7.01	7.09	7.10
6	4.38	3.92		4.15
8	7.73	8.11		7.92
10	8.57	7.95	8.04	8.19
Average	6.68	6.28	6.54	6.43
Std. Dev.	1.70	1.98	1.84	1.84

[1] Using compliance calibration from different specimen