DOUBLE CANTILEVER BEAM FRACTURE TOUGHNESS TESTING OF SEVERAL COMPOSITE MATERIALS

FINAL REPORT

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Introduction

Double-cantilever beam fracture toughness tests were performed by the Composite Materials Research Group on several different unidirectional composite materials provided by NASA Langley Research Center. The composite materials consisted of Hercules IM-7 carbon fiber and various matrix resin formulations. Multiple formulations of four different families of matrix resins were tested: LaRC - ITPI, LaRC - IA, RPT46T, and RP67/RP55. Table 1 presents the materials tested and pertinent details supplied by NASA. For each material, three replicate specimens were tested. Multiple crack extensions were performed on each replicate.

Specimen Configuration and Test Methods

As received from NASA, the test specimens were nominally 1 inch wide, 6 inches long, and between 0.125 inch and 0.145 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. For the first set of specimens (see Table 1 below), the hinges were bonded to the specimens and reinforced with small pieces of shim stock wrapped around the portions of the specimen and hinge surface that were coincident. Initial testing of specimens with unreinforced, bonded-only hinges proved unsuccessful; this was due at least in part to the higher applied loads necessary to propagate the cracks in the specimens with short crack initiation inserts. For the

TABLE 1

NASA LANGLEY DOUBLE CANTILEVER BEAM
FRACTURE TOUGHNESS TEST SYSTEMS

Material	Panel No.	Details	Ship Date
IM7/LaRC ITPI	GD1433	3% polymer stoichiometric offset	2/12/92
	ITPI404	4% polymer stoichiometric offset	2/12/92
	GD1430	4.75% polymer stoichiometric offset	2/12/92
	GD1436	5.5% polymer stoichiometric offset	2/12/92
	ITPI412	2% polymer stoichiometric offset	2/27/92
IM7/LaRC IA	GD1466	4.5% polymer stoichiometric offset	6/22/92
	GD1468	4% polymer stoichiometric offset	6/22/92
	GD1491	3.5% polymer stoichiometric offset	6/22/92
	GD1488	3% polymer stoichiometric offset	6/22/92
IM7/RP46T	GD1495	1,500 formula molecular wt.	8/3/92
IM7/RP63T	GD1496	3,000 formula molecular wt.	8/3/92
IM7/RP64T	GD1497	5,000 formula molecular wt.	8/3/92
IM7/RP65T	GD1498	7,000 formula molecular wt.	8/3/92
IM7/RP67T	GD1500	10,000 formula molecular wt.	8/3/92
IM7/RP47T	GD1501	21,000 formula molecular wt.	8/3/92
IM7/RP67	JJS1179		8/19/92
IM7/RP55	JJS1183		8/19/92
	JJS1193		8/19/92
IM7/LaRC IA	GD1510	1% polymer stoichiometric offset	9/10/92
	GD1514	2% polymer stoichiometric offset	9/10/92

remainder of the specimens tested, the hinges were bolted to the specimen using the technique presented in Ref. [2].

For the majority of the tests, the cracks were extended approximately one-half inch from the end of the Kapton insert prior to testing, as per Ref. [1]. The initial crack length prior to testing was therefore nominally 0.5 inch measured from the hinge pivot or 1.25 inch measured from the specimen end. For the first set of specimens, the precrack length was increased to between 1 and 1.5 inches to reduce the load on the hinge adhesive. The crack length prior to testing for these specimens was therefore nominally between 1.75 and 2.25 inches. 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 of 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 0.5 inch or more from the end of the insert prior to testing.

The testing was performed in an Instron 1125 universal electromechanical testing machine with conventional mechanical wedge-action grips. A universal joint was used in the load train. A crosshead speed of 2mm/minute was used for the majority of the tests, although some were conducted at 5mm/minute. The crosshead speed had no discernible effect upon the results.

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 appended to this report. 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. A sample of the chart areas were also verified with a planimeter as well.

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:

$$G_{IC} = \frac{3P^2C^{\frac{2}{3}}}{2A_1bh}$$

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 included in the Appendix. 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.

Test Results

The individual and average critical strain energy release rates from both methods of data reduction for all materials tested are presented in Table 2. Figures 1 through 4 are column plots of the average results grouped by major resin type. Individual calculation

TABLE 2

NASA LANGLEY DOUBLE CANTILEVER BEAM FRACTURE TOUGHNESS TEST RESULTS

Material	Panel No.	Details	Calculation Method (See Notes 3 and 4)	Individual G_{1C} Values			Average G_{1C}
IM7/LaRC ITPI	GD1433	3% offset[1]	Area[3]	1.427	1.639	1.511	1.526
			MCC[4]	1.199	1.139	1.454	1.264
	ITPI404	4% offset[1]	Area	1.469	1.906	1.653	1.676
			MCC	1.519	1.950	1.663	1.711
	GD1430	4.75% offset[1]	Area	1.176	1.198	1.267	1.214
			MCC	1.403	1.171	1.288	1.287
	GD1436	5.5% offset[1]	Area	1.429	1.156		1.293
			MCC	1.374	1.156		1.265
	ITPI412	2% offset[1]	Area	2.179	1.617	1.865	1.887
			MCC	2.131	1.600	1.870	1.867
IM7/LaRC IA	GD1466	4.5% offset[1]	Area	2.128	2.016		2.072
			MCC	2.277	1.972		2.125
	GD1468	4% offset[1]	Area	1.939	1.735	1.782	1.819
			MCC	1.798	1.583	1.716	1.699
	GD1491	3.5% offset[1]	Area	1.876	1.591	1.596	1.688
			MCC	1.615	1.754	1.519	1.629
	GD1488	3% offset[1]	Area	1.709	1.605	1.455	1.590
			MCC	1.680	1.537	1.405	1.541
	GD1510	1% offset[1]	Area	2.027	2.111	2.076	2.071
			MCC	1.896	1.864	1.699	1.820
	GD1514	2% offset[1]	Area	2.058	2.588	2.238	2.295
			MCC	1.806	2.190	1.798	1.931

Material	Panel No.	Details	Calculation Method (See Notes 3 and 4)	Individual G_{1C} Values			Average G_{1C}
IM7/RP46T	GD1495	1,500[2]	Area	0.785	0.696	0.866	0.782
			MCC	0.663	0.602	0.690	0.652
IM7/RP63T	GD1496	3,000[2]	Area	1.532	1.348	1.373	1.418
			MCC	1.319	1.055	1.114	1.163
IM7/RP64T	GD1497	5,000[2]	Area	1.561	1.418	1.517	1.499
			MCC	1.483	1.235	1.269	1.329
IM7/RP65T	GD1498	7,000[2]	Area	1.847	1.806	1.748	1.800
			MCC	1.548	1.655	1.573	1.592
IM7/RP67T	GD1500	10,000[2]	Area	1.869	1.739	1.967	1.858
			MCC	1.728	1.436	1.740	1.635
IM7/RP47T	GD1501	21,000[2]	Area	2.176	2.123	2.477	2.259
			MCC	2.401	1.661	2.227	2.096
IM7/RP67	JJS1179		Area	2.118	1.820	2.006	1.981
			MCC	1.914	1.485	1.798	1.732
IM7/RP55	JJS1183		Area	1.571	1.439	1.099	1.370
			MCC	1.375	1.053	0.873	1.100
	JJS1193		Area	0.651	0.844	0.783	0.759
			MCC	0.566	0.724	0.620	0.637

[1]Resin Polymer Stoichiometric Offset Ratio
[2]Formula Molecular Weight of Resin
[3]Area method of G_{1C} Calculation per Ref. [1]
[4]Modified Compliance Calibration (MCC) method of G_{1C} Calculation per Ref. [3]

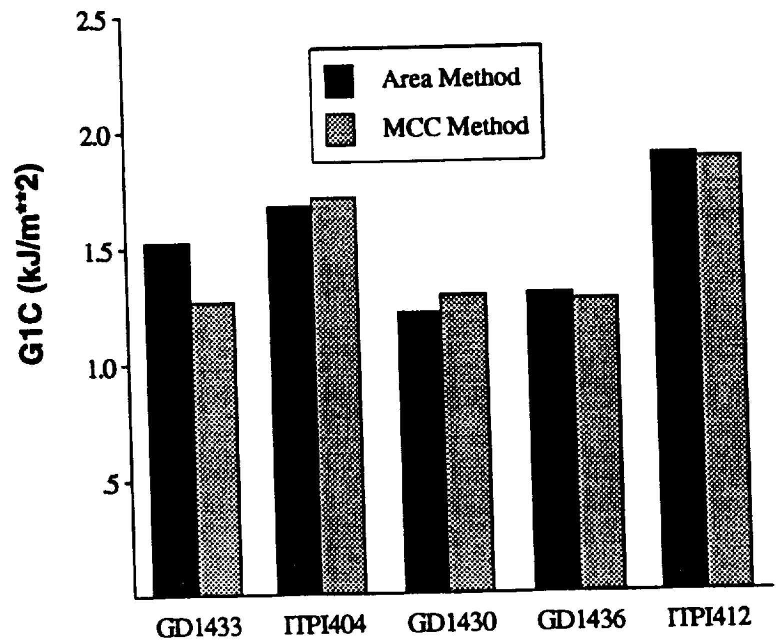

Figure 1. Double Cantilever Beam Fracture Toughness Test Results for IM7/LaRC ITPI Composites.

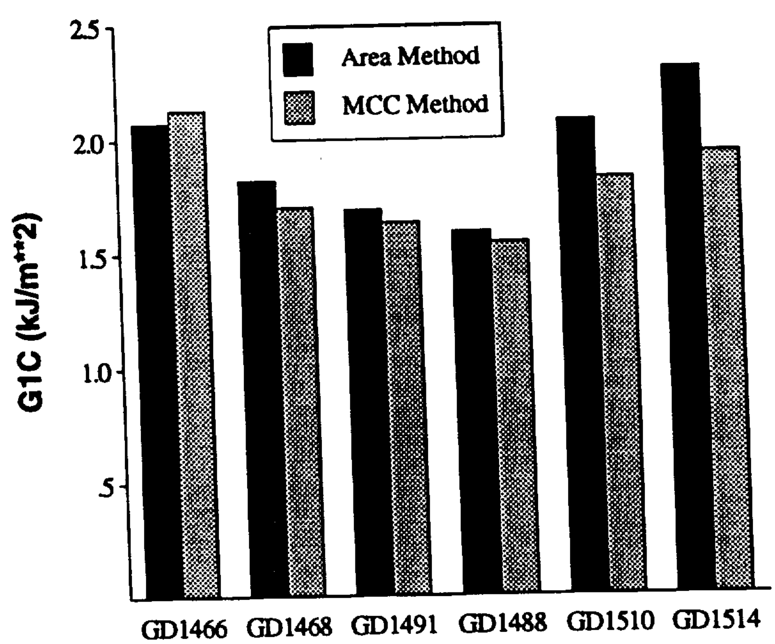

Figure 2. Double Cantilever Beam Fracture Toughness Test Results for IM7/LaRC IA Composites

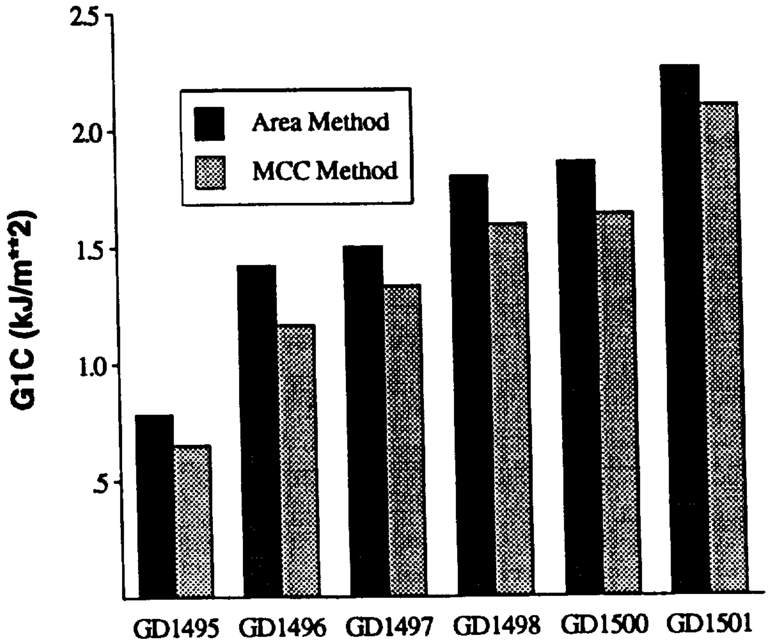

Figure 3. Double Cantilever Beam Fracture Toughness Test Results for IM7/RP46T Series Composites.

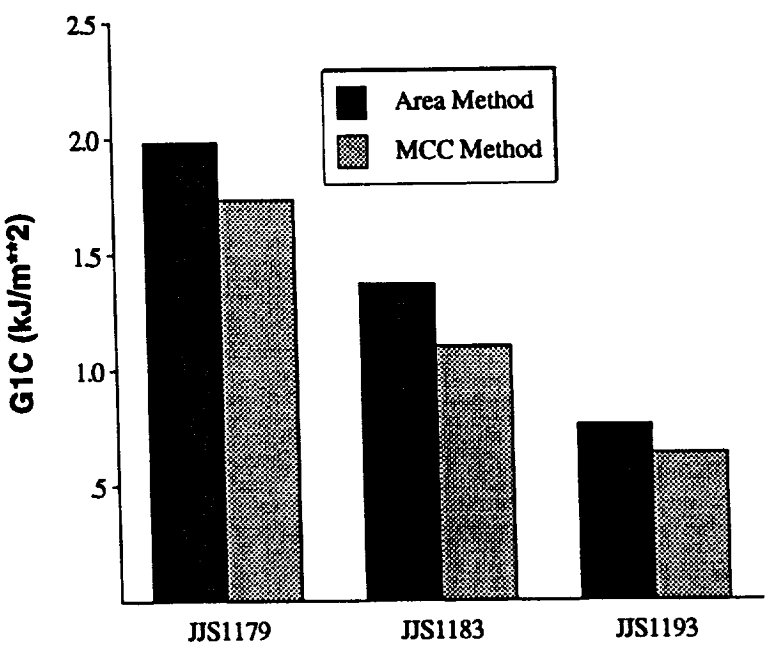

Figure 4. Double Cantilever Beam Fracture Toughness Test Results for IM7/RP67 and IM7/RP55 Composites.

worksheets for each replicate tested are in the Appendix. Included in each worksheet are the G_{IC} values for each crack extension.

As can be seen in the figures, the two methods used to determine G_{IC} yielded similar results. The ranking of the materials by fracture toughness was identical in all but one instance: the area method indicated that the fracture toughness of laminates GD1466 and GD1510 were nearly the same. On the other hand, the modified compliance calibration method indicated that the G_{IC} of laminate GD1466 was greater than that of the second laminate.

Although the relative fracture toughness of the materials did not change with the data reduction technique, the specific G_{IC} results were slightly different in some materials. In others, the results were nearly identical.

Most of the materials tested exhibited stable crack extensions such as that shown in Figure 5. However, laminate numbers GD1466, GD1468, and GD1491 of the LaRC IA family of resins exhibited run-arrest extensions as shown in Figure 6. In the tests of these materials, the load increased without visible crack extension and then the crack instantaneously grew by several millimeters while the load dropped correspondingly. Ref. [3] states that such run-arrest behavior is beyond the scope of the proposed method. The other references do not discuss this behavior.

All of the G_{IC} values in Table 2 were calculated for crack extensions of approximately 0.5 inch. For laminate numbers GD1466, GD1468, and GD1491, which exhibited the run-arrest behavior, each G_{IC} calculation encompassed several of the stick-slip type extensions, each much less than 0.5 inch. An attempt was made to calculate the G_{IC} for these single crack extensions. Although not reported herein, the G_{IC} values determined for these single extensions were significantly greater than the values in the table.

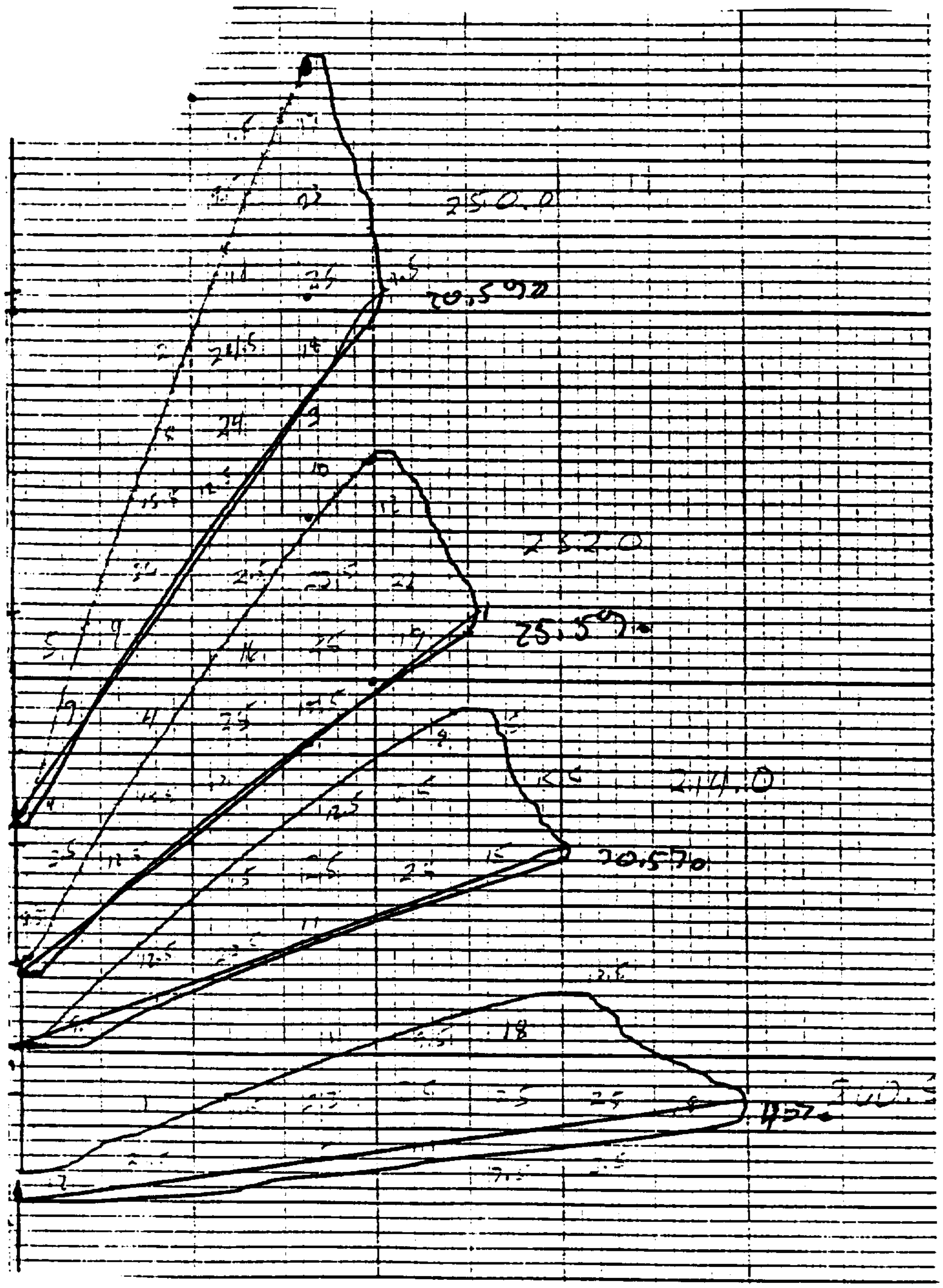

Figure 5. Typical Load-Displacement Curve for Material Exhibiting Stable Crack Extension.

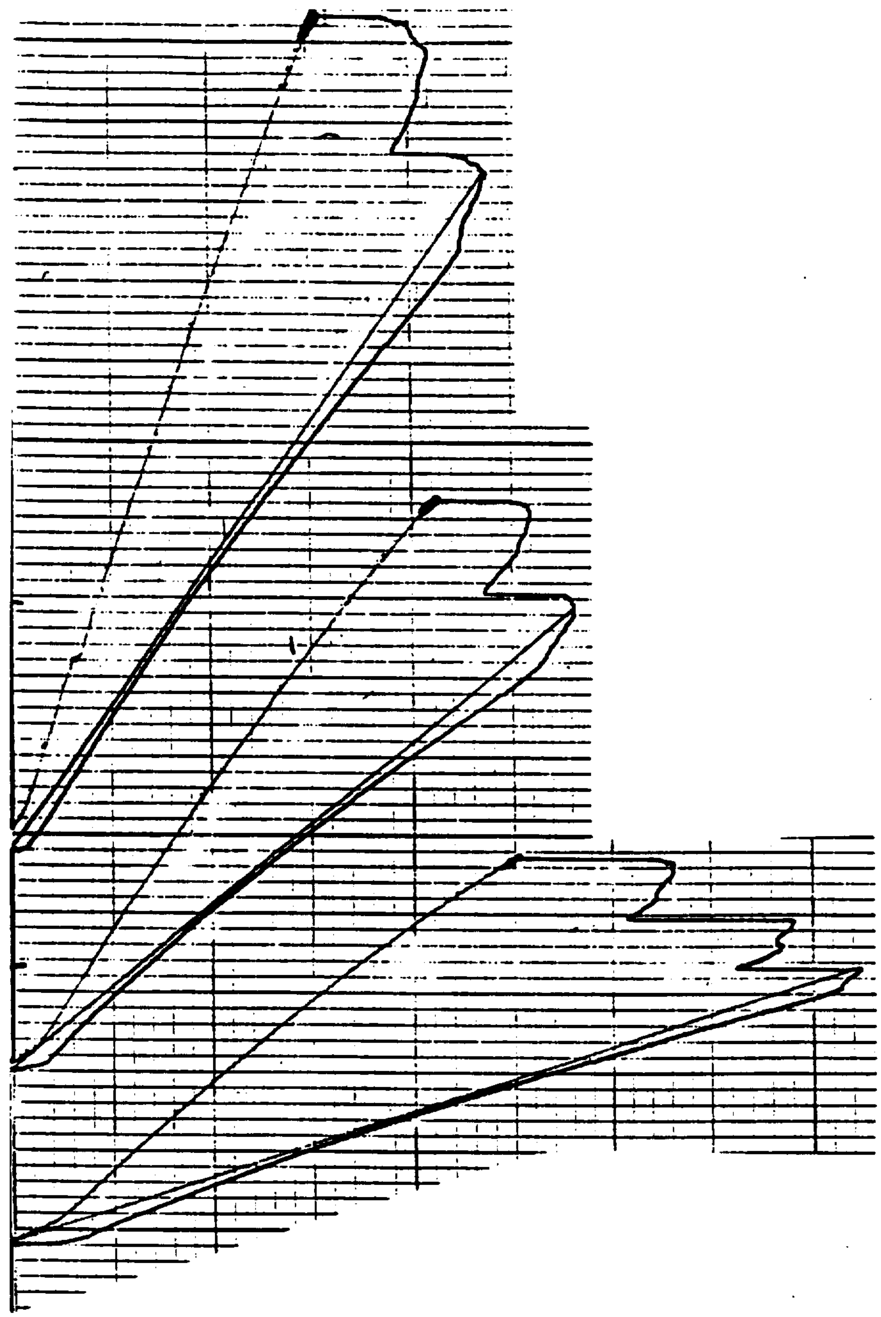

Figure 6. Typical Load-Displacement Curve for Material Exhibiting Run-Arrest Unstable Crack Extension.

REFERENCES

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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.
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