Designation: D 6115 – 97 (Reapproved 2004)

Standard Test Method for Mode I Fatigue Delamination Growth Onset of Unidirectional Fiber-Reinforced Polymer Matrix Composites[1]

This standard is issued under the fixed designation D 6115; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method determines the number of cycles (*N*) for the onset of delamination growth based on the opening mode I cyclic strain energy release rate (*G*), using the Double Cantilever Beam (DCB) specimen shown in Fig. 1. This test method applies to constant amplitude, tension-tension fatigue loading of continuous fiber-reinforced composite materials. When this test method is applied to multiple specimens at various *G*-levels, the results may be shown as a *G–N* curve, as illustrated in Fig. 2.

1.2 This test method is limited to use with composites consisting of unidirectional carbon fiber tape laminates with single-phase polymer matrices. This limited scope reflects the experience gained in round robin testing. This test method may prove useful for other types and classes of composite materials, however, certain interferences have been noted (see Section 6.5 of Test Method D 5528).

1.3 The values stated in SI units are to be regarded as standard. The values provided in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

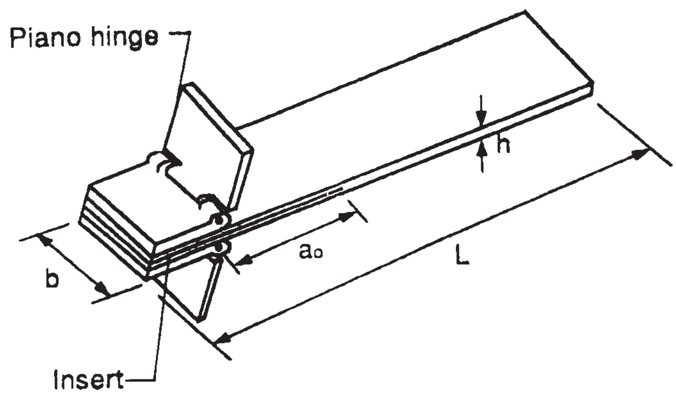

FIG. 1 DCB Specimen with Piano Hinges

2. Referenced Documents

2.1 *ASTM Standards:* [2]

D 883 Terminology Relating to Plastics

D 2584 Test Method for Ignition Loss of Cured Reinforced Resins

D 2651 Guide for Preparation of Metal Surfaces for Adhesive Bonding

D 2734 Test Method for Void Content of Reinforced Plastics

D 3171 Test Method for Constituent Content of Composite Materials

D 3878 Terminology for Composite Materials

D 5229/D 5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D 5528 Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites

E 4 Practices for Force Verification of Testing Machines

E 6 Terminology Relating to Methods of Mechanical Testing

E 122 Practice for Calculating Sample Size to Estimate, With a Specified Tolerable Error, the Average for a Characteristic of a Lot or Process

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E 456 Terminology Relating to Quality and Statistics

E 467 Practice for Verification of Constant Amplitude Dynamic Loads on Displacements in an Axial Load Fatigue Testing System

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E 739 Practice for Statistical Analysis of Linear or Linearized Stress-Life (*S-N*) and Strain-Life (ϵ-*N*) Fatigue Data

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[1] This specification is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.06 on Interlaminar Properties.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E 1049 Practices for Cycle Counting in Fatigue Analysis
E 1150 Definitions Relating to Fatigue[3]

3. Terminology

3.1 Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology D 883 defines terms relating to plastics. Terminology E 6 defines terms relating to mechanical testing. Terminology E 456 and Practice E 177 define terms relating to statistics. Definition E 1150 defines terms relating to fatigue. In the event of conflict between terms, Terminology D 3878 shall have precedence over the other terminology standards.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *crack opening mode (Mode I)*—fracture mode in which the delamination faces open away from each other and in which these faces do not undergo any relative sliding.

3.2.2 *cycles to onset of delamination growth,* N_a—the number of fatigue cycles elapsed until the onset of delamination growth from an implanted thin insert.

3.2.3 *fatigue delamination growth onset relationship, G–N*—the relationship between the peak cyclic value of strain energy release rate to the number of fatigue cycles until the onset of delamination growth, N_a.

3.2.4 *mode I interlaminar fracture toughness,* G_{Ic}—the critical value of G for delamination growth because of an opening load or displacement.

3.2.5 *strain energy release rate, G*—the loss of strain energy, dU, in the test specimen per unit of specimen width for an infinitesimal increase in delamination length, da, for a delamination growing under a constant displacement. In mathematical form:

$$G = -\frac{1}{b}\frac{dU}{da} \quad (1)$$

where:
U = total elastic strain energy in the test specimen,
b = specimen width, and
a = delamination length.

3.3 *Symbols:*

3.3.1 a—delamination length.

3.3.2 a_0—initial delamination length.

3.3.3 b—width of DCB specimen.

3.3.4 C—compliance, δ/P, of DCB specimen.

3.3.5 CV—coefficient of variation, %.

3.3.6 da—infinitesimal increase in delamination length.

3.3.7 dU—infinitesimal increase in strain energy.

3.3.8 E_{II}—modulus of elasticity in the fiber direction.

3.3.9 G—strain energy release rate.

3.3.10 G_{Ic}—opening mode I interlaminar fracture toughness.

3.3.11 $[G_{Ic}]_{av}$—*average values of* G_{Ic} *from the quasi-static tests.*

3.3.12 G_{Imax}—maximum or peak cyclic mode I strain energy release rate.

3.3.13 *G–N*—relationship between the cyclic strain energy release rate and the number of cycles to onset of delamination growth.

3.3.14 h—thickness of DCB specimen.

3.3.15 N—number of elapsed fatigue cycles.

3.3.16 N_a—application dependent value of N at which delamination growth onset will occur.

3.3.17 $N^{1\,\%}_a$—number of fatigue cycles for the value of P_{max} *at* $N = 1$ *to decrease by 1 %.*

3.3.18 N_a^{ViS}—number of fatigue cycles at which the onset of delamination growth is observed.

3.3.19 $N^{5\,\%}_a$—number of fatigue cycles for the value of P_{max} *at* $N = 1$ *to decrease by 5 %.*

3.3.20 P—applied load.

3.3.21 P_{cr}—value of load at the onset of delamination growth from the insert in the quasi-static tests.

3.3.22 P_{max}—maximum cyclic load.

3.3.23 R—ratio of minimum and peak loads P_{min}/P_{max}.

3.3.24 SD—standard deviation.

3.3.25 U—strain energy.

3.3.26 V_f—fiber volume fraction, %.

3.3.27 δ—load point deflection.

3.3.28 δ_{cr}—*value of displacement at the onset of delamination growth from the insert in a quasi-static test.*

3.3.29 δ_{max}—maximum value of cyclic displacement.

3.3.30 δ_{mean}—mean value of cyclic displacement.

3.3.31 δ_{mm}—minimum value of cyclic displacement.

3.3.32 Δ—effective delamination extension to correct for rotation of DCB arms at delamination front.

3.3.33 $[\Delta]_{av}$—average value of Δ from the quasi-static tests.

4. Summary of Test Method

4.1 The Double Cantilever Beam (DCB) shown in Fig. 2 is described in Test Method D 5528.

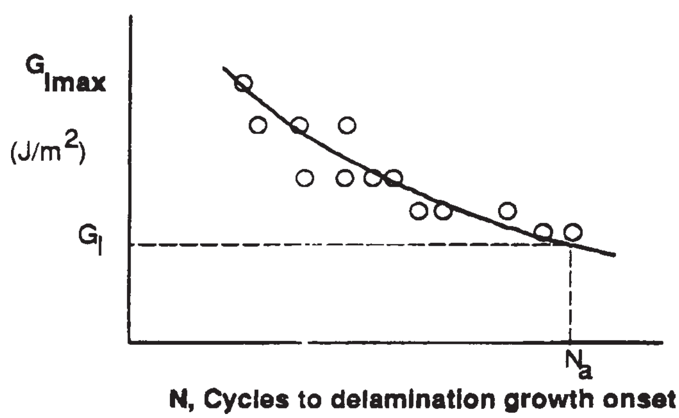

FIG. 2 *G–N* Curve

4.2 The DCB specimen is cycled between a minimum and maximum displacement, δ_{min}, and δ_{max}, at a specified frequency. For linear elasticity and small deflections (δ/a < 0.4) the displacement ratio, $\delta_{min}/\delta_{max}$, is identical to the R-ratio. The number of displacement cycles at which the onset of delamination growth occurs, N_a, is recorded. The mode I cyclic strain energy release rate, for example the maximum value, G_{Imax} is calculated using a modified beam theory or other methods described in Test Method D 5528. By testing several specimens a relationship is developed between G_{Imax} and N_a for the chosen frequency.

[3] Withdrawn.

5. Significance and Use

5.1 Susceptibility to delamination is one of the major weaknesses of many advanced laminated composite structures. Knowledge of a laminated composite material's resistance to interlaminar fracture under fatigue loads is useful for product development and material selection. Furthermore, a measurement of the relationship of the mode I cyclic strain energy release rate and the number of cycles to delamination growth onset, *G–N*, that is independent of specimen geometry or method of load introduction, is useful for establishing design allowables used in damage tolerance analyses of composite structures made from these materials.

5.2 This test method can serve the following purposes:

5.2.1 To establish quantitatively the effects of fiber surface treatment, local variations in fiber volume fraction, and processing and environmental variables on *G–N* of a particular composite material.

5.2.2 To compare quantitatively the relative values of *G–N* for composite materials with different constituents.

5.2.3 To develop criteria for avoiding the onset of delamination growth under fatigue loading for composite damage tolerance and durability analyses.

6. Interferences

6.1 Linear elastic behavior is assumed in the calculation of *G* used in this test method. This assumption is valid when the zone of damage or non-linear deformation at the delamination front, or both, is small relative to the smallest specimen dimension, which is typically the specimen thickness for the DCB test.

6.2 As the delamination grows under fatigue, fiber bridging observed in quasi-static testing (see Test Method D 5528) may also occur. Fiber bridging inhibits the fatigue delamination growth resulting in slower growth rates than if there was no bridging. This results in artificially high threshold values where the delamination ceases to grow or grows very slowly.[4] In addition, the rate of change of the delamination growth rate versus the peak cyclic strain energy release rate for the DCB is very high. Therefore, small variations in the peak cyclic strain energy release rate will result in large changes in the delamination growth rate. For these two reasons, this test method does not monitor the fatigue delamination growth rate. Instead, this test method monitors the number of cycles until the onset of delamination growth from the end of a thin insert. A value of *G* may be defined such that delamination growth will not occur until N_a cycles have elapsed, where N_a is defined by the application, Fig. 1.

6.3 Three definitions to determine the number of cycles until the onset of delamination growth were used during an investigative round robin. These include: (*1*) the number of cycles until the delamination was visually observed to grow at the edge, N_a^{ViS}; (*2*) the number of cycles until the compliance had increased by 1 %, $N^{1\%}{}_a$ (this is approximately equivalent to a 1 % decrease in the maximum cyclic load; and (*3*) the number of cycles until the compliance has increased by 5 %, $N^{5\%}{}_a$ (this is approximately equivalent to a 5 % decrease in the maximum cyclic load). The three techniques gave different results but the $N^{1\%}{}_a$ value is typically the lowest of the three values[5] and is recommended for generating a conservative criterion for avoiding onset of fatigue delamination growth in durability and damage tolerance analyses of laminated composite structures. Because of the difficulties in visually monitoring the end of a delamination during a fatigue test, the visual method is not included in this test method.

6.4 The test frequency may affect results. If the test frequency is high, heating effects may occur in the composite. To avoid these effects, frequency should be chosen to be between 1 and 10 cycles per second (Hz) and should be chosen such that there is no temperature change of the specimen. Other test frequencies may be used if they are more appropriate for the application. The test frequency shall be reported.

6.5 The displacement ratio, δ_{min} / δ_{max}, may have a large effect on the results. Because the DCB specimen cannot be tested in compression the displacement ratio must remain within the following range: $0 \leq \delta_{min}/\delta_{max} < 1$. The displacement ratio shall be reported. Large deflections may be considered by using the corrections given in the Annex of Test Method D 5528.

6.6 The application to other materials, lay-ups and architectures is described in Test Method D 5528.

7. Apparatus

7.1 *Testing Machine*—A properly calibrated test machine shall be used that can be operated in a displacement control mode. The testing machine shall conform to the requirements of Practices E 4 and E 467. The testing machine shall be equipped with grips to hold the loading hinges, or pins to hold the loading blocks, that are bonded to the specimen.

7.2 *Load Indicator*—The testing machine load sensing device shall be capable of indicating the total load carried by the test specimen. This device shall be essentially free from inertia-lag at the specified rate of testing and shall indicate the load with an accuracy over the load range(s) of interest of within ±1 % of the indicated value. The peak cyclic load shall not be less than 10 % of the full scale of the load cell. Section 8.2 details how to estimate the expected peak cyclic load. If the current load cell capacity of the test stand is too large, a low load capacity load cell may be placed in series.

7.3 *Opening Displacement Indicator*—The opening displacement may be estimated as the crosshead separation or actuator displacement provided the deformation of the testing machine, with the specimen grips attached, is less than 2 % of the maximum cyclic opening displacement of the test specimen. If not, then the opening displacement shall be obtained from a properly calibrated external gage or transducer attached to the specimen. The displacement indicator shall indicate the crack opening displacement with an accuracy of within ±1 % of the indicated value once the delamination occurs.

7.4 *Micrometers*—As described in Test Method D 5528.

[4] Martin, R. H. and Murri, G. B., "Characterization of Mode I and Mode II Delamination Growth and Thresholds in AS4/PEEK Composites," *Composite Materials: Testing and Design* (9th Volume), ASTM STP 1059, S. P. Garbo, Ed., 1990, pp. 251–270.

[5] Preliminary data from D30.06 round robin.

8. Sampling and Test Specimens

8.1 The test specimen dimensions and load introduction are as described in Test Method D 5528.

8.2 An estimate of the values of P_{max} during the long duration tests may be required to determine if a smaller load cell is required, per Section 7.2. If quasi-static tests were conducted on identical specimens to those to be fatigue tested, a value of P_{max} may be estimated by assuming the lowest value of peak cyclic strain energy release rate will be 10 % of G_{Ic}. Or, $P_{max} = \sqrt{0.1}\, P_{cr}$, where P_{cr} is the value used to calculate G_k. If this data is not available P_{max} may be determined thus:

$$P_{max} = \frac{b}{a}\sqrt{\frac{h^3E_{11}\ [0.1G_{Ic}]}{96}} \tag{2}$$

where:

h = specimen thickness and
E_{11} = lamina modulus of elasticity in the fiber direction.

Because of the low loads associated with these tests it may be necessary to increase the thickness of the specimens by using more plies.

8.3 It is recommended that void content and fiber volume be reported. Void content may be determined using the equations of Test Method D 2734. The fiber volume fraction may be determined using a digestion per Test Method D 3171.

8.4 *Sample Size*—The minimum number of specimens required if the development of a *G–N* curve is required, is based on that for an *S–N* curve given in Practice E 739 and appears as follows:

Type of Test	Minimum Number of Specimens
Preliminary and exploratory	6 to 12
Research and development testing of components and structures	6 to 12
Design allowables	12 to 24
Reliability data	12 to 24

For statistically significant data, the procedures outlined in Practice E 122 should be consulted. The method of sampling shall be reported.

9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. Conditioning

10.1 *Standard Conditioning Procedure*—Condition in accordance with Procedure C of Test Method D 5229/D 5229M unless a different environment is specified as part of the experiment. Store and test specimens at Standard Laboratory Atmosphere of 23 ± 3°C (73 ± 5°F) and 50 ± 10 % relative humidity.

10.2 *Drying*—If *G–N* data are desired for laminates in a dry condition, use Procedure D of Test Method D 5229/D 5229M.

11. Procedure

11.1 *Quasi-static Tests*—The expression relating compliance to delamination length must be determined first using Test Method D 5528. Specimens from the same batch that will be used for the fatigue tests should be used. For all specimens tested quasi-statically, note an average value of the constants in all the compliance calibration expression, for example, $|\Delta|_{av}$, from the modified beam theory. The parameters for compliance using the other data reductions in Test Method D 5528 may also be used. The average values of G_{Ic}, $[G_{Ic}]_{av}$ and the average value of the critical load point displacement for delamination growth at the end of the insert, $|\delta_{cr}]_{av}$, may also be noted to aid in determining parameters for the subsequent fatigue test.

11.2 Measure the width and thickness of each specimen to the nearest 0.05 mm (0.002 in.) at the mid-point and at 25 mm (1 in.) from either end. The variation in thickness along the length of the specimen shall not exceed 0.1 mm (0.004 in.). The average values of the width and thickness measurements shall be recorded.

11.3 Mount the load blocks or hinges on the specimen in the grips of the loading machine, making sure that the specimen is aligned and centered.

11.4 The end of the specimen opposite the grips may require supporting before loading. The supported end may rise off the support as the load is applied. For laminates that are excessively long, the specimen may need to be supported during loading.

11.5 Determine the initial delamination length, a_o, and record it in Table 1. If the end of the insert cannot be easily seen while the specimen is unloaded then a small displacement may be applied to open up the specimen. This displacement must not exceed the mean cyclic displacement, δ_{mean}, to be used in the fatigue test, calculated later. The exact location of the end of the insert may also be determined after the test by splitting the specimen open.

11.6 Various values of G_{Imax} must be determined to give a complete *G–N* curve, if required, with *N* ranging between the values specific to the application of the data. Start the first test at a $G_{Imax} \simeq 50$ percent $[G_{Ic}]_{av}$. If the specimen geometry for the quasi-static tests are identical to those for the fatigue tests the maximum cyclic displacement, δ_{max} may be obtained from the quasi-static tests as:

$$\frac{\delta^2_{max}}{[\delta_{cr}]^2_{av}} = \frac{G_{Imax}}{G_{Ic}} = 0.5 \tag{3}$$

where $[\delta_{cr}]_{av}$ is the average value of critical displacement for quasi-static delamination growth from the end of the thin insert obtained from the quasi-static tests. Alternatively, for applications where quasi-static data on identical specimens is not available an approximate value for δ_{max} may be calculated as follows: Given that

$$G = \frac{P^2}{2b}\frac{\partial C}{\partial a} = \frac{\delta^2}{2C^2b}\frac{\partial C}{\partial a} \tag{4}$$

then

$$\delta^2_{max} = \frac{2b_{av}[C^2]_{av}\ 0.5[G_{Ic}]_{av}}{\frac{\partial[C]_{av}}{\partial a}} \tag{5}$$

where $[C]_{av}$ is the value of compliance calculated from the delamination length of the fatigue specimen. Record the calculated value of δ_{max} in Table 1.

11.7 From the chosen displacement ratio and δ_{max} calculate the minimum and mean cyclic displacement values, δ_{min} and

DCB FATIGUE DATA REPORTING SHEET	Lab:	Date:

Material:	Producer:	Panel No.:	Max.Cure Temp:	FAW:	V_f
		Max Δh (mm)	Insert Material	Insert Thickness	
Hinge Type	Hinge Size:	Block Size:	Surface prep.:	Adhesive:	
Test. Temp.:	Test %RH:	Frequency	R ratio		

STATIC DATA SUMMARY	$[G_{Ic}]_{av}$	$[\Delta]_{av}$	$[\delta_{cr}]_{av}$

Specimen No.	b_{av}	h_{av}	a_0	δ_{max}	P_{max} @ N=1	G_{Imax}	N^{vis}	$N^{1\%}$	$N^{5\%}$

Number of specimens tested	A	B

TABLE 1 DCB Fatigue Data Reporting Sheet

δ_{mean}, respectively. The test frequency shall be between 1 and 10 Hz unless the application requires a different test frequency. Start the fatigue test and record P_{max} as soon as the values of displacement are correct. Enter this value with the number of cycles at which it was measured in Table 1. If necessary, reduce the frequency to ensure that the displacement ratio is correct and then increase the frequency to the desired amount.

NOTE 1—It is important to achieve the correct displacement ratio as quickly as possible to avoid delamination onset after too many cycles have elapsed.

11.8 The onset of delamination growth will be determined by monitoring a decrease in the compliance.

11.8.1 *Compliance Monitoring*—Record the slope of the displacement-load curve (compliance) and the number of cycles elapsed on a routine basis. It is advantageous to use a data acquisition system for this purpose. It is beyond the scope of this test method to recommend a system. If a particular method is used, report the exact system used. If the compliance values cannot be determined during the test, the test should be stopped at the mean load, unloaded to the minimum displacement while taking a trace of the displacement versus load curve. The specimen should then be reloaded to the mean displacement and the fatigue test continued.

NOTE 2—Ensure that the increase in compliance or the drop in peak load is caused by delamination growth, and not by drifting of the mean load.

11.9 Plot the compliance versus the elapsed cycles and note in Table 1 the number of cycles to give a 1 percent and a 5 percent increase in the compliance at $N = 1$, Fig. 3.

11.10 Stop the test after the first of the following events occurs:

11.10.1 The compliance has increased to above 105 % of its value at $N = 1$.

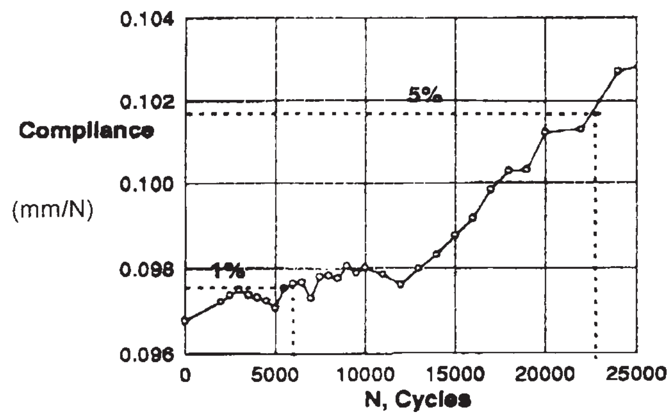

FIG. 3 Compliance Increase Versus Cycles

11.10.2 The test has exceeded the maximum number of cycles desired. A residual test may be conducted according to Test Method D 5528, if required.

11.11 If an alternative method for monitoring the onset of delamination growth is used, such as crack growth gages bonded to the specimen edges, data should be collected according to the principles, accuracy, and magnification as set out in detail above.

11.12 If a complete *G–N* curve is required, further tests should be run at different maximum cyclic displacements.

12. Calculations

12.1 *Maximum Cyclic Strain Energy Release Rate Calculations*—From the values of δ_{max}, P_{max}, a at $N = 1$ and the averaged compliance constant $|\Delta|_{av}$ calculate the actual test G_{Imax} for each specimen from Eq 6:

$$G_{Imax} = \frac{3P_{max}\,\delta_{max}}{2b(a + |\Delta|_{av})} \quad (6)$$

The other expressions for determining G_{max} in Test Method D 5528 may also be used.

12.2 *Correction Factors*—If required, the correction factors specified in Test Method D 5528 must be applied.

12.3 *Log-normal distribution*—If a *G–N* curve has been generated use a log-normal distribution as presented in Practice E 739 for the representation of constant amplitude life data. To accomplish this, substitute G for σ or ϵ in Practice E 739 and N (cycles to delamination growth onset) for N in Practice E 739, the cycles to life.

12.4 *Weibull Distribution*—The two parameter Weibull distribution is commonly used to represent constant amplitude fatigue life data and may be used to represent the *G–N* data if generated. A two parameter Weibull distribution density function for fatigue life may be expressed as:

$$f(N) = \frac{B}{A}\left(\frac{N}{A}\right)^{B-1} \exp\left[-\left(\frac{N}{A}\right)^{B}\right] \qquad (7)$$

The Weibull distribution cumulative function for fatigue life may be given by:

$$F(N) = 1 - \exp\left[-\left(\frac{N}{A}\right)^{B}\right] \qquad (8)$$

It is recommended that the Weibull scale and shape parameters, A and B, be determined using the maximum likelihood technique, refer to Practice E 739.

13. Report

13.1 A recommended data reporting sheet is shown in Table 1. The report shall include the following (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requester):

13.2 *Material*—Complete identification of the material tested; including prepreg manufacturer, material designation, manufacturing process, fiber volume fraction, and void content. Include the method used to determine fiber volume fraction and void content.

13.3 *Coupon Data*—Average nominal thickness and width of each specimen, and maximum thickness variation down the length of the beam, type and thickness of insert.

13.4 *Test Procedure*—Type of load introduction (piano hinges or blocks) and dimensions, drying procedure, relative humidity, test temperature, test frequency and displacement ratio.

13.5 *Test Results*—Curves of Compliance versus elapsed cycles. The number of cycles elapsed to give a 1 % and 5 % compliance increase for each specimen. The *G–N* curve and the values of the curve fits and the Weibull parameters, if a *G–N* curve was generated.

13.6 If a post-mortem check of the tested specimen reveals any tears, folds, or irregular shape at the end of the insert (that is, the insert is not straight and parallel) where the delamination initiated, then no valid initiation value may be reported.

13.7 Report the number of specimens tested.

14. Precision and Bias

14.1 No precision statement for this test method can be offered at this time. Work is in progress to establish a precision statement using E 691. Bias cannot be determined since there is no reference material.

15. Keywords

15.1 composite materials; delamination; double cantilever beam; frequency; maximum cyclic strain energy release rate; mode I; onset of fatigue delamination growth