**Designation: D 5528 – 94a**

# Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites[1]

This standard is issued under the fixed designation D 5528; 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 describes the determination of the opening Mode I interlaminar fracture toughness, $G_{Ic}$, of unidirectional fiber-reinforced polymer matrix composites using the double cantilever beam (DCB) specimen (Fig. 1).

1.2 This test method is limited to use with composites consisting of unidirectional carbon fiber tape laminates with brittle and tough 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 6.5).

1.3 The values stated in SI units are to be regarded as the standard. The values given 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.*

## 2. Referenced Documents

2.1 *ASTM Standards:*

D 883 Terminology Relating to Plastics[2]

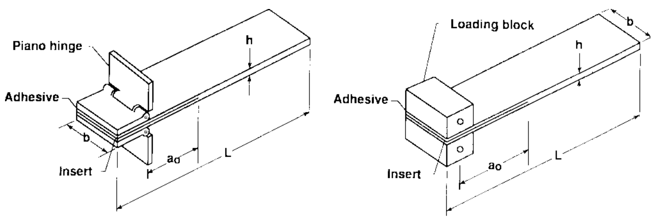
D 2651 Guide for Preparation of Metal Surfaces for Adhesive Bonding[3]

D 2734 Test Methods for Void Content of Reinforced Plastics[4]

D 3171 Test Method for Fiber Content of Resin Matrix Composites by Matrix Digestion[5]

D 3878 Terminology of High-Modulus Reinforced Fibers and Their Composites[5]

D 5229/D 5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials[5]




(a) with piano hinges (b) with loading blocks

**FIG. 1 Double Cantilever Beam Specimen**

E 4 Practices for Force Verification of Testing Machines[6]

E 6 Terminology Relating to Methods of Mechanical Testing[6]

E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[7]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[7]

E 456 Terminology Relating to Quality and Statistics[7]

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[7]

## 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. 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.

3.2.2 *Mode I interlaminar fracture toughness,* $G_{Ic}$—the critical value of *G* for delamination growth due to an opening load or displacement.

3.2.3 *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,

[1] This test method is under the jurisdiction of ASTM Committee D-30 on High Modulus Fibers and Their Composites and is the direct responsibility of Subcommittee D30.06 on Interlaminar Properties.

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[2] *Annual Book of ASTM Standards*, Vol 08.01.

[3] *Annual Book of ASTM Standards*, Vol 15.06.

[4] *Annual Book of ASTM Standards*, Vol 08.02.

[5] *Annual Book of ASTM Standards*, Vol 15.03.

[6] *Annual Book of ASTM Standards*, Vol 03.01.

[7] *Annual Book of ASTM Standards*, Vol 14.02.

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

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

3.3 *Symbols:*

3.3.1 $A_1$—slope of plot of $a/b$ versus $C^{1/3}$.

3.3.2 $a$—delamination length.

3.3.3 $a_0$—initial delamination length.

3.3.4 $b$—width of DCB specimen.

3.3.5 $C$—compliance, $\delta/P$, of DCB specimen.

3.3.6 $CV$—coefficient of variation, %.

3.3.7 $da$—differential increase in delamination length.

3.3.8 $dU$—differential increase in strain energy.

3.3.9 $E_{11}$—modulus of elasticity in the fiber direction.

3.3.10 $E_{1f}$—modulus of elasticity in the fiber direction measured in flexure.

3.3.11 $F$—large displacement correction factor.

3.3.12 $FAW$—fiber areal weight.

3.3.13 $FD$—fiber density.

3.3.14 $G$—strain energy release rate.

3.3.15 $G_{Ic}$—opening Mode I interlaminar fracture toughness.

3.3.16 $h$—thickness of DCB specimen.

3.3.17 $L$—length of DCB specimen.

3.3.18 $L'$—half-width of loading block.

3.3.19 $m$—number of plies in DCB specimen.

3.3.20 $N$—loading block correction factor.

3.3.21 $NL$—point at which the load versus opening displacement curve becomes non-linear.

3.3.22 $n$—slope of plot of Log C versus Log a.

3.3.23 $P$—applied load.

3.3.24 $P_{max}$—maximum applied load during DCB test.

3.3.25 $SD$—standard deviation.

3.3.26 $t$—distance from loading block pin to center line of top specimen arm.

3.3.27 $U$—strain energy.

3.3.28 $VIS$—point at which delamination is observed visually on specimen edge.

3.3.29 $V_f$—fiber volume fraction, %.

3.3.30 $\delta$—load point deflection.

3.3.31 $\Delta$—effective delamination extension to correct for rotation of DCB arms at delamination front.

3.3.32 $\Delta_x$—incremental change in Log a.

3.3.33 $\Delta_y$—incremental change in Log C.

## 4. Summary of Test Method

4.1 The DCB shown in Fig. 1 consists of a rectangular, uniform thickness, unidirectional laminated composite specimen, containing a nonadhesive insert on the midplane which serves as a delamination initiator. Opening forces are applied to the DCB specimen by means of hinges (Fig. 1a) or loading blocks (Fig. 1b) bonded to one end of the specimen. The ends of the DCB are opened by controlling either the opening displacement, or the crosshead movement, while the load and delamination length are recorded.

4.2 A record of the applied load versus opening displacement is recorded on an $X$-$Y$ recorder, or equivalent real-time plotting device or stored digitally and post processed. Instantaneous delamination front locations are marked on the chart at intervals of delamination growth. The Mode I interlaminar fracture toughness is calculated using a modified beam theory or compliance calibration method.

## 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 is useful for product development and material selection. Furthermore, a measurement of the Mode I interlaminar fracture toughness, 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 effect of fiber surface treatment, local variations in fiber volume fraction, and processing and environmental variables on $G_{Ic}$ of a particular composite material.

5.2.2 To compare quantitatively the relative values of $G_{Ic}$ for composite materials with different constituents.

5.2.3 To develop delamination failure criteria 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 nonlinear 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 In the DCB test, as the delamination grows from the insert, a resistance-type fracture behavior typically develops where the calculated $G_{Ic}$ first increases monotonically, and then stabilizes with further delamination growth. In this test method, a resistance curve (R-curve) depicting $G_{Ic}$ as a function of delamination length, will be generated to characterize the initiation and propagation of a delamination in a unidirectional specimen (Fig. 2). The principal reason for the observed

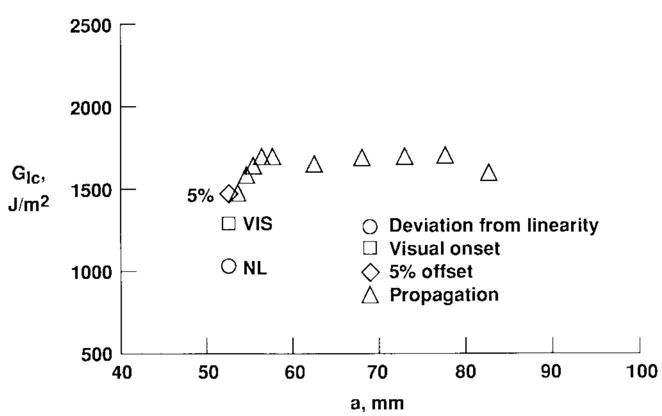



FIG. 2 Delamination Resistance Curve (*R*-curve) From DCB Test

resistance to delamination is the development of fiber bridging **(1-3)**.[8] This fiber bridging mechanism results from growing the delamination between two zero-degree unidirectional plies. Because most delaminations that form in multi-ply laminated composite structures occur between plies of dissimilar orientation, fiber bridging does not occur. Hence, fiber bridging is considered to be an artifact of the DCB test on unidirectional materials. Therefore, the generic significance of $G_{Ic}$ propagation values calculated beyond the end of the implanted insert is questionable, and an initiation value of $G_{Ic}$ measured from the implanted insert is preferred. Because of the significance of the initiation point, the insert must be properly implanted and inspected (8.2).

6.3 Three definitions for an initiation value of $G_{Ic}$ have been evaluated during round-robin testing **(4)**. These include $G_{Ic}$ values determined using the load and deflection measured (1) at the point of deviation from linearity in the load-displacement curve (NL), (2) at the point where delamination is visually observed on the edge (VIS) measured with a microscope as specified in 7.5, and (3) at the point where the compliance has increased by 5 % or where the load has reached a maximum value (5 %/max) (see Section 11). The NL $G_{Ic}$ value, which is typically the lowest of the three $G_{Ic}$ initiation values, is recommended for generating delamination failure criteria in durability and damage tolerance analyses of laminated composite structures (5.2.3). All three initiation values can be used for the other purposes cited in the scope (5.2.1 and 5.2.2). However, physical evidence indicates that the initiation value corresponding to the onset of non-linearity (NL) in the load versus opening displacement plot corresponds to the physical onset of delamination from the insert in the interior of the specimen width **(5)**. In round-robin testing of AS4/PEEK thermoplastic matrix composites, NL $G_{Ic}$ values were 20 % lower than VIS and 5 %/max values **(4)**.

6.4 Delamination growth may proceed in one of two ways: (1) by a slow stable extension, or (2) by a run-arrest extension, where the delamination front jumps ahead abruptly. Only the first type of growth is of interest in this test method. An unstable jump from the insert may be an indication of a problem with the insert. For example, the insert may not be completely disbonded from the laminate, or may be too thick resulting in a large neat resin pocket, or may contain a tear or fold. Furthermore, rapid delamination growth may introduce dynamic effects in both the test specimen and in the fracture morphology. Treatment and interpretation of these effects is beyond the scope of this test method.

6.5 *Application to Other Materials, Layups, and Architectures*:

6.5.1 The DCB test has been used extensively for unidirectional glass fiber reinforced tape laminates with single-phase polymer matrices, but corrections may be needed for anticlastic bending effects. Toughness values measured on unidirectional composites with multiple phase matrices may vary depending upon the tendency for the delamination to wander between various matrix phases. Brittle matrix composites with tough adhesive interleafs between plies may be particularly sensitive to this phenomenon, resulting in two apparent interlaminar fracture toughness values: one associated with a cohesive type failure within the interleaf and one associated with an adhesive type failure between the tough polymer film and the more brittle composite matrix.

6.5.2 Non-unidirectional DCB configurations may experience branching of the delamination away from the midplane through matrix cracks in off-axis plies. If the delamination branches away from the midplane, a pure mode I fracture may not be achieved due to the coupling between extension and shear which may exist in the asymmetric sublaminates formed as the delamination grows. In addition, non-unidirectional specimens may experience significant anti-clastic bending effects which result in non-uniform delamination growth along the specimen width, particularly affecting the observed initiation values.

6.5.3 Woven composites may yield significantly greater scatter and unique R-curves associated with varying toughness within and away from interlaminar resin pockets as the delamination grows. Composites with significant strength or toughness through the laminate thickness, such as composites with metal matrices or 3D fiber reinforcement, may experience failures of the beam arms rather than the intended interlaminar failures.

## 7. Apparatus

7.1 *Testing Machine*—A properly calibrated test machine shall be used which can be operated in a displacement control mode with a constant displacement rate in the range from 0.5 to 5.0 mm/min (0.02 to 0.20 in./min). The testing machine shall conform to the requirements of Practices E 4. 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.

7.3 *Opening Displacement Indicator*—The opening displacement may be estimated as the crosshead separation provided the deformation of the testing machine, with the specimen grips attached, is less than 2 % of the 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 *Load Versus Opening Displacement Record*—An *X-Y* plotter, or similar device, shall be used to make a permanent record during the test of load versus opening displacement at the point of load application. Alternatively, the data may be stored digitally and post processed.

7.5 *Optical Microscope*—A travelling optical microscope with a magnification no greater than 70×, or an equivalent magnifying device, shall be positioned on one side of the

[8] The boldface numbers in parentheses refer to the list of references at the end of this test method.

specimen to observe the delamination front as it extends along one edge during the test. This device shall be capable of pinpointing the delamination front with an accuracy of at least ±0.5 mm (±0.02 in.). A mirror may be used to visually determine any discrepancy in delamination onset from one side of the specimen to the other. Other methods, such as crack length gages bonded to a specimen edge, may be used to monitor delamination length provided their accuracy is as good as the optical microscope so that delamination length may be measured to the accuracy specified above.

7.6 The micrometer(s) shall use a suitable size diameter ball-interface on irregular surfaces such as the bag-side of a laminate, and a flat anvil interface on machined edges or very smooth tooled surfaces. The accuracy of the instruments shall be suitable for reading to within 1 % of the sample width and thickness. For typical specimen geometries, an instrument with an accuracy of ±2.5 μm (0.0001 in.) is desirable for thickness measurement, while an instrument with an accuracy of ±25 mm (0.001 in.) is desirable for width measurement.

## 8. Sampling and Test Specimens

8.1 Test laminates must contain an even number of plies, and shall be unidirectional, with delamination growth occurring in the zero degree direction.

8.2 A nonadhesive insert shall be inserted at the midplane of the laminate during layup to form an initiation site for the delamination (see Fig. 1). The film thickness shall be no greater than 13 μm (0.0005 in.). Specimens should not be precracked. By not precracking, an initiation value free of fiber bridging may be obtained and included in the R-curve. A polymer film is recommended for the insert to avoid problems with folding or crimping at the cut end of the insert as was observed for aluminum foil inserts during round-robin testing **(4)**. For epoxy matrix composites cured at relatively low temperatures, 177°C (350°F) or less, a thin film made of polytetrafluoroethylene (PTFE) is recommended. For composites with polyimide, bismaleimide or thermoplastic matrices that are manufactured at relatively high temperatures, greater than 177°C (350°F), a thin polyimide film is recommended. For materials outside the scope of this test method, different film materials may be required. If a polyimide film is used, the film shall be painted or sprayed with a mold release agent before it is inserted in the laminate. **Caution**—Mold release agents containing silicone may contaminate the laminate by migration through the individual layers. It is often helpful to coat the film at least once and then bake the film before placing the film on the composite. This will help to prevent silicone migration within the composite.

8.3 *Specimen Dimensions*:

8.3.1 Specimens shall be at least 125 mm (5.0 in.) long and nominally between 20 to 25 mm (0.8 to 1.0 in.) wide, inclusive.

NOTE 1—Round-robin testing on narrow and wide specimens yielded similar results indicating that the DCB specimen width is not a critical parameter.

8.3.2 Panels shall be manufactured, and specimens cut from the panels, such that the insert length is approximately 63 mm (2.5 in.), (see Fig. 1). This distance corresponds to an initial delamination length of approximately 50 mm (2.0 in.) plus the extra length required to bond the hinges or load blocks. The end of the insert should be accurately located and marked on the panel before cutting specimens.

8.4 The laminate thickness shall normally be between 3 and 5 mm (0.12 and 0.2 in.). The variation in thickness for any given specimen shall not exceed 0.1 mm. The initial delamination length, measured from the load line to the end of the insert, shall normally be 50 mm (2.0 in.). However, alternative laminate thicknesses and initial delamination lengths may be chosen that are consistent with the discussions given as follows. However, if load blocks are used to introduce the load, very low values of *a/h* are not recommended. For small values of *a/h* (<10) the data reduction procedures given in Section 12 may not be accurate.

8.4.1 For materials with low-flexural modulus or highinterlaminar fracture toughness, it may be necessary to increase the number of plies, that is, increase the laminate thickness, or decrease the delamination length in order to avoid large deflections of the specimen arms. The specimen thickness and initial delamination length, $a_0$, shall be designed to satisfy the following criteria **(6)**:

$$a_0 \leq 0.042 \sqrt{\frac{h^3 E_{11}}{G_{Ic}}} \tag{2}$$

$$h \geq 8.28 \sqrt[3]{\frac{G_{Ic} a_0{}^2}{E_{11}}} \tag{3}$$

where:

$a_0$ = initial delamination length,
$h$ = specimen thickness, and
$E_{11}$ = lamina modulus of elasticity in the fiber direction.

However, if the ratio of the opening displacement at delamination onset, δ, to the delamination length, *a*, is greater than 0.4, the large deflection corrections in Annex A1 must be incorporated in the data reduction. If these corrections are needed for any delamination length, they should be applied for all delamination lengths.

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

8.6 *Sampling*—Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens, such as the case of a designed experiment. For statistically significant data the procedures outlined in Practice E 122 should be consulted. The method of sampling shall be reported.

8.7 *Load Introduction*:

8.7.1 The piano hinges or loading blocks shall be at least as wide as the specimen (20 to 25 mm).

8.7.2 *Piano Hinges*—A pair of piano hinge tabs shall be bonded to the end of each specimen as shown in Fig. 1a. The hinge tabs shall be made of metal, and shall be capable of sustaining the applied load without incurring damage. The maximum load anticipated during a DCB test of a material with a known modulus, $E_{11}$, and anticipated value of $G_{Ic}$, may be estimated by **(7)**.

$$P_{max} = \frac{b}{a}\sqrt{\frac{h^3 E_{11} G_{Ic}}{96}} \tag{4}$$

8.7.3 *Loading Blocks*—The distance from the loading block pin to the center line of the top specimen arm (distance $t$ in Annex A1) shall be as small as possible to minimize errors due to the applied moment arm. These effects will be reduced sufficiently **(7)** by choosing a distance, $t$, such that

$$t \leq \frac{h}{4} + 0.01\sqrt{\frac{0.0434h^3 E_{11}}{G_{Ic}} + a^2} \tag{5}$$

If this criteria cannot be met, then the corrections for loading block effects in Annex A1 should be used to reduce the data.

8.7.4 The bonding surfaces of the loading blocks or hinges and the specimen shall be properly cleaned prior to bonding in order to ensure load transfer without debonding of the tabs from the specimen during the test. If debonding occurs, the specimen should not be reused if there is physical evidence that a delamination initiated when the bond failed, or if an increased compliance is observed upon reloading.

8.7.4.1 *Surface Preparations of the Specimen*—The bonding surface of the specimen may be lightly grit-blasted or scrubbed with sandpaper, then wiped clean with a volatile solvent, such as acetone or methylethylketone (MEK), to remove any contamination.

8.7.4.2 *Surface Preparation of the Loading Hinge Tabs or Blocks*—The loading hinge tabs or blocks may be cleaned as in 8.7.4.1. If this procedure results in a bond failure between the specimen and the tabs, it may be necessary to apply a more sophisticated cleaning procedure based on degreasing and chemical etching. Consult Guide D 2651 for the surface preparation procedure that is most appropriate for the particular metal used for the hinges.

8.7.5 Bonding of the hinges to the specimen shall be performed immediately after surface preparation. The material recommended for bonding is a room temperature cure adhesive. However, in some cases a superglue, such as cyanoacrylate, has been found to be sufficient. The adhesive may benefit from a postcure if the specimens are dried after the tabs are mounted. Glass beads may need to be added to some adhesives, or other forms of bondline control may be needed in order to maintain a uniform bond thickness. The loading tabs shall be aligned parallel with the specimen, and with each other, and held in position with clamps while the adhesive cures.

## 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 interlaminar fracture toughness data are desired for laminates in a dry condition, use Procedure D of Test Method D 5229/D 5229M.

## 11. Procedure

11.1 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.

11.2 Coat both edges of the specimen just ahead of the insert with a thin layer of water-based typewriter correction fluid, or equivalent, to aid in visual detection of delamination onset. Mark the first 5 mm (0.2 in.) from the insert on either edge with thin vertical lines every 1 mm (0.04 in.). Mark the remaining 20 mm (0.8 in.) with thin vertical lines every 5 mm (0.2 in.). The delamination length is the sum of the distance from the loading line to the end of the insert (measured in the undeformed state) plus the increment of growth determined from the tick marks.

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 As load is applied, measure the delamination length, $a$, on one side of the specimen. The initial delamination length, $a_0$, is the distance from the load line to the end of the insert. Do not try to locate the end of the insert by opening the specimen. If it is difficult to see the end of the insert on the specimen edge, or to locate the end of the insert from the original mark on the panel, try the following: (1) rub the edge of the specimen in the local area near the insert with a soft lead pencil, (2) polish the edge of the specimen. If none of the above methods are suitable, mark graduations on the specimen edge from the center of the loading pin. When the specimen is loaded, the length of the initial delamination may be determined from these graduation marks. When the delamination grows from the insert, take the first propagation reading at the next whole 1-mm mark. Then, take readings for the next four 1-mm increments of delamination growth and subsequent 5-mm increments as specified above.

11.5 The end of the specimen opposite the grips should be supported 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.

11.6 Set an optical microscope (see 7.5), or an equivalent magnifying device, in a position to observe the motion of the delamination front as it grows along one edge. This device shall be capable of pinpointing the delamination front with an accuracy of at least ±0.5 mm (±0.02 in.).

11.7 The specimen is loaded continuously in displacement control. Apply load to the specimen at a crosshead (or servohydraulic ram) displacement rate of 0.5 mm/min (0.02 in./min) and record the load versus displacement trace on an *X-Y* chart recorder. The loading rate may be increased after the first 5 mm (0.2 in.) of delamination growth.

11.8 Visually observe the delamination front at the end of the insert on either edge. When the delamination grows from the end of the insert, mark the location as $a_0$ on the plot of load versus opening displacement (Fig. 3). Continue to observe the delamination front along the edge as it grows and mark the delamination front position on the load versus opening displacement trace in the sequence $a_1$, $a_2$, ... $a_N$, as shown in Fig. 3. For the first 5 mm (0.2 in.) of crack growth, record instantaneous delamination front positions at 1-mm intervals, or the closest interval possible. The first point to be indicated on the *X-Y* plot after the delamination grows from the insert (point $a_1$) shall be approximately 1 mm ahead of the insert border. After the first 5 mm (0.2 in.) of delamination growth from the insert border, every 5 mm (0.2 in.) of delamination growth will be indicated on the *X-Y* plot. If possible, observe delamination growth periodically along the opposite edge to determine if the growth is uniform. If delamination growth is not uniform, measure the delamination length on both edges and record the average. The difference in the delamination length between the two edges should not exceed 2 mm.

11.9 When the delamination has extended 25 mm (1 in.) or more beyond the insert border, unload the specimen and stop the test machine. Load and displacement are recorded throughout the test, including the unloading cycle. The unloading may be performed more quickly.

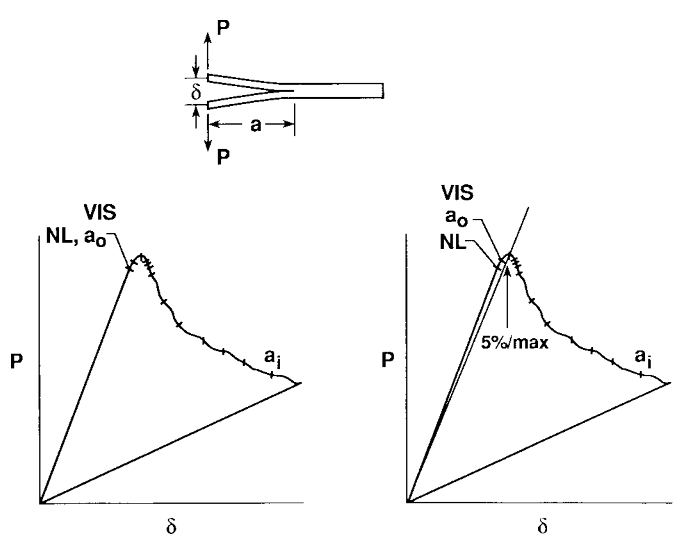
11.10 If an alternative method for monitoring delamination growth is used, such as crack growth gages bonded to the specimen edges, it should collect data in accordance with the principles, accuracy, and magnification as set out in detail above.

11.11 *Interpretation of Test Results*—Several initiation $G_{Ic}$ values may be determined from the load-displacement plots and used along with subsequent propagation values to generate the *R*-curve. These initiation values are indicated on a typical *R*-curve shown in Fig. 2 and are described below. For each of these techniques, the initial delamination length, $a_0$, should be used to calculate $G_{Ic}$.

11.11.1 *Deviation from Linearity (NL)*—An initiation (or onset) value for $G_{Ic}$ should be calculated from the load and displacement at the point of deviation from linearity, or onset of non-linearity (NL). This calculation assumes that the delamination starts to grow from the insert in the interior of the specimen at this point **(5)**. The NL value represents a lower bound value for $G_{Ic}$. For brittle matrix composites, this is typically the same point at which the delamination is observed to grow from the insert at the specimen edges (Fig. 3a). For tough matrix composites, however, a region of nonlinear behavior may precede the visual observation of delamination onset at the specimen edges, even if the unloading curve is linear (Fig. 3b).

11.11.2 *Visual Observation (VIS)*—A visual initiation value for $G_{Ic}$ should be recorded corresponding to the load and displacement for the first point at which the delamination is visually observed to grow from the insert on either edge using the microscope or mirror, or both, specified in 7.5.

11.11.3 *5 % Offset/Maximum Load (5 %/Max)*—A value of $G_{Ic}$ may be calculated by determining the intersection of the load-deflection curve, once it has become nonlinear, with a line drawn from the origin and offset by a 5 % increase in compliance from the original linear region of the load-displacement curve (Fig. 3b). If the intersection occurs after the maximum load point, the maximum load should be used to calculate this value.




(a) brittle matrix (b) tough matrix

**FIG. 3 Load Displacement Trace from DCB Test**

## 12. Calculation

12.1 *Interlaminar Fracture Toughness Calculations*—Three data reduction methods for calculating $G_{Ic}$ values have been evaluated during round-robin testing **(4)**. These consisted of a modified beam theory (MBT), a compliance calibration method (CC) and a modified compliance calibration method (MCC). Because $G_{Ic}$ values determined by the three different data reduction methods differed by no more than 3.1 %, none of the three were clearly superior to the others. However, the MBT method yielded the most conservative values of $G_{Ic}$ for 80 % of the specimens tested **(4)**. Hence, the MBT data reduction method is recommended. The area method **(8)** is not recommended because it will not yield an initiation value of $G_{Ic}$ or a delamination resistance curve.

12.1.1 *Modified Beam Theory (MBT) Method*—The beam theory expression for the strain energy release rate of a perfectly built-in (that is, clamped at the delamination front) double cantilever beam is as follows:

$$G_I = \frac{3P\delta}{2ba} \quad (6)$$

where:
$P$ = load,
$\delta$ = load point displacement,
$b$ = specimen width, and
$a$ = delamination length.

In practice, this expression will overestimate $G_I$ because the beam is not perfectly built-in (that is, rotation may occur at the delamination front). One way of correcting for this rotation is to treat the DCB as if it contained a slightly longer delamination, $a + |\Delta|$, where $\Delta$ may be determined experimentally by generating a leasts square plot of the cube root of compliance, $C^{1/3}$, as a function of delamination length (Fig. 4). The

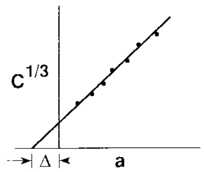



FIG. 4 Modified Beam Theory

compliance, $C$, is the ratio of the load point displacement to the applied load, $\delta/P$. The values used to generate this plot should be the load and displacements corresponding to the visually observed delamination onset on the edge and all the propagation values. Calculate the Mode I interlaminar fracture toughness as follows **(7)**:

$$G_I = \frac{3P\delta}{2b(a + |\Delta|)} \quad (7)$$

This approach also allows the modulus, $E_{1f}$, to be determined as follows:

$$E_{if} = \frac{64(a + |\Delta|)^3 P}{\delta b h^3} \quad (8)$$

The values of $E_{1f}$ obtained should be independent of delamination length **(7)**. However, $E_{1f}$ may increase with delamination length because of fiber bridging.

12.1.2 *Compliance Calibration (CC) Method*—Generate a least squares plot of log ($\delta_i/P_i$) versus log ($a_i$) using the visually observed delamination onset values and all the propagation values. Draw a straight line through the data which results in the best least-squares fit. Calculate the exponent $n$ from the slope of this line according to $n = \Delta_y/\Delta_x$, where $\Delta_y$ and $\Delta_x$ are defined in Fig. 5. Calculate the Mode I interlaminar fracture toughness as follows **(9)**:

$$G_I = \frac{nP\delta}{2ba} \quad (9)$$

12.1.3 *Modified Compliance Calibration (MCC) Method*—Generate a least squares plot of the delamination length normalized by specimen thickness, *a/h*, as a function of the cube root of compliance, $C^{1/3}$, as shown in Fig. 6, using the visually observed delamination onset values and all the propagation values. The slope of this line is $A_1$. Calculate the Mode I interlaminar fracture toughness as follows **(10)**:

$$G_I = \frac{3P^2C^{2/3}}{2A_1bh} \quad (10)$$

## 13. Report

13.1 A recommended data reporting sheet is shown in Annex A1. The report shall include the following (reporting of items beyond the control of a given testing laboratory, such as

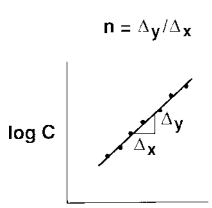



FIG. 5 Compliance Calibration

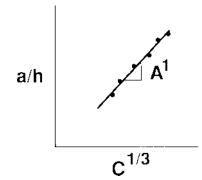



FIG. 6 Modified Compliance Calibration

might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

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, and loading rate.

13.5 *Test Results*:

13.5.1 Load-displacement curves indicating load and displacement at first deviation from nonlinearity (NL) and at visual onset of delamination from either edge (VIS). Upon unloading, if the load doesn't return to zero, damage may have been induced in the beam arms. Note this on the data reduction sheet.

13.5.2 Intercept, $\Delta$, for each specimen if modified beam theory (MBT) method is used to reduce the data.

13.5.3 Slope, $n$, of log ($\delta_i/P_i$) versus log ($a_i$) plot for each specimen if compliance calibration (CC) method is used to reduce the data.

13.5.4 Slope, $A_1$, for each specimen if modified compliance calibration (MCC) method is used to reduce the data.

13.5.5 Delamination resistance curve for each specimen, including the NL, VIS, and 5 %/max values of $G_{Ic}$ defined in 12.1, with the following exceptions:

13.5.5.1 If a postmortem 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.

13.5.5.2 If any propagation value is less than the NL value of $G_{Ic}$, then no valid initiation value may be reported.

13.5.6 Report the number of specimens tested and the mean, standard deviation, and coefficient of variation (standard deviation divided by the mean) of quantities in 13.5.2-13.5.5.

## 14. Precision and Bias

14.1 Table 1 shows results from round-robin tests conducted in 1987 on AS4/BP907, in 1989 on AS4/3501-6, in 1990 on AS4/PEEK specimens with aluminum inserts, and in 1991 on AS4/PEEK specimens with polyimide film inserts. Table 1 also shows the number of laboratories involved, the number of tests per laboratory, and other pertinent information on the type and thickness of the inserts used. These interlaboratory test programs were designed using Practice E 691 as a guide. Further information on the statistical interpretation of the results may be found in Ref **(4)**.

TABLE 1 Summary of Round-Robin Data

| Round | Material | Number of Laboratories | Tests/Laboratory | Insert | Average Mean, $G_{Ic}$, kJ/m$^2$ | $S_r$ | $(CV)_r$, % | $S_R$ | $(CV)_R$,% |
|---|---|---|---|---|---|---|---|---|---|
| I | AS4/BP907 | 9 | 3 | 25-µm PTFE | 0.400$^A$ | 0.028 | 7.0 | 0.077 | 19.3 |
| II | AS4/3501-6 | 3 | 3 | 13-µm Kapton | 0.085$^A$ | 0.015 | 17.6 | 0.014 | 16.5 |
| II | AS4/PEEK | 3 | 4 | 13-µm Kapton | 0.983$^B$ | 0.132 | 13.4 | 0.178 | 18.1 |
| III | AS4/PEEK | 16 | 4 | 13-µm aluminum foil | 1.439$^B$ | 0.187 | 13.4 | 0.261 | 18.1 |
| III | AS4/PEEK | 5 | 4 | 7-µm aluminum foil | 1.727$^B$ | 0.226 | 13.0 | 0.140 | 8.1 |
| IV | AS4/PEEK | 10 | 3 | 13-µm Kapton | 1.303$^B$ | 0.180 | 13.8 | 0.207 | 15.9 |
| V | AS4/PEEK | 9 | 5 | 7.5-µm Upilex | 1.182$^B$ | 0.126 | 10.8 | 0.111 | 9.4 |
| V | AS4/PEEK | 9 | 5 | 13-µm Upilex | 1.262$^B$ | 0.132 | 10.5 | 0.110 | 8.7 |

$^A$ VIS Values using CC Method.
$^B$ NL Values using MBT Method.
Round I & II—ASTM round robin
Round III—ASTM & JIS data from international round robin
Round IV—Static tests from ASTM fatigue round robin
Round V—ASTM/JIS/ and ESIS data from international round robin

14.2 *Precision*—The following should be used for judging the acceptability of results (see Practice E 177):

14.2.1 *Repeatability*—Duplicate test results (obtained by the same operator using the same equipment on the same day) from an individual laboratory for the same material should be considered suspect if they differ by more than the $r$ value for that material, where $r = 2.8\ S_r$, and $S_r$ is the average of the standard deviations for each participating laboratory.

14.2.2 *Reproducibility*—The average result reported by one laboratory for a given material should be considered suspect if it differs from the average measurement of another laboratory, or from measurements in the same laboratory taken by a different operator using different equipment, for the same material by more than the $R$ value for that material, where $R = 2.8\ S_R$, and $S_R$ is the standard deviation from the mean value of $G_{Ic}$ obtained by all participating laboratories.

NOTE 2—These precision data are approximated based on limited data from round-robin test programs **(4)**, but they provide a reasonable basis for judging the significance of the results. The ability to measure the delamination front position, as well as the actual variation in material properties from one panel to another, may yield $G_{Ic}$ values with greater variations.

14.3 *Bias*—No other test method exists for determining the Mode I interlaminar fracture toughness of composite laminates. Hence, no determination of the bias inherent in the DCB test is available.

## 15. Keywords

15.1 composite materials; delamination; double cantilever beam; interlaminar fracture toughness; Mode I

# ANNEX

**(Mandatory Information)**

## A1. LARGE DISPLACEMENT AND END BLOCK CORRECTIONS

A1.1 Large displacement effects shall be corrected by the inclusion of a parameter, $F$, in the calculation of $G_I$ **(11)**.

$$F = 1 - \frac{3}{10}\left(\frac{\delta}{a}\right)^2 - \frac{3}{2}\left(\frac{\delta t}{a^2}\right) \quad \text{(A1.1)}$$

where $t$ is shown in Fig. A1.1 for piano hinges. This parameter, $F$, accounts for both the shortening of the moment arm as well as tilting of the end blocks. For specimens with loading blocks, the distance from the end of the insert to the load line shall be at least 50 mm for the influence of the blocks to be neglected. If not, a second parameter, $N$, a displacement correction, shall also be included to account for the stiffening of the specimen by the blocks **(11)**.

$$N = 1 - \left(\frac{L'}{a}\right)^3 - \frac{9}{8}\left[1 - \left(\frac{L'}{a}\right)^2\right]\left(\frac{\delta t}{a^2}\right) - \frac{9}{35}\left(\frac{\delta}{a}\right)^2 \quad \text{(A1.2)}$$

where $L'$ and $t$ are shown in Fig. A1.1 for end blocks.

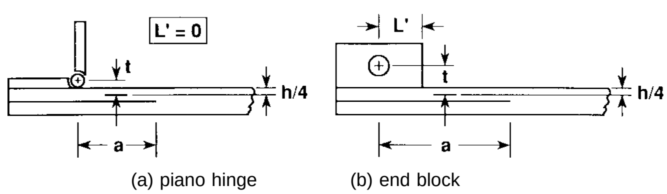



**FIG. A1.1 Methods for Introducing Opening Load to DCB Specimen**

A1.2 To apply these corrections to either the modified beam theory (MBT) or the compliance calibration (CC or MCC) methods, do the following:

A1.2.1 If piano hinges were used to introduce the opening load, multiply $G_I$ by $F$ to obtain the corrected value of $G_I$.

A1.2.2 If end blocks were used to introduce the opening load, determine the corrected compliance, $C/N$, where plotting compliance versus crack length for determining $\Delta$, $n$, or $A_1$ (see

| DCB STANDARD DATA REPORTING SHEET | LAB: | DATE: |
|---|---|---|

| Material: | Producer: | | Panel No.: | Max Cure Temp.: | | FAW = | $V_f$ = |
|---|---|---|---|---|---|---|---|
| Specimen No. | Avg. b (mm) | Avg. h (mm) | Max Δh (mm) | Insert Material | | Insert Thickness | |
| Hinge Type: | Hinge Size: | | Block Size: | Surface Prep.: | | Adhesive: | |
| Test Temp.: | Test %RH: | | Load Rate: | $a_0$ = | Δ= | n = | $A_1$ = |

| $a_0$ (mm) | δ (mm) | P (N) | δ/$a_0$ | $G_{Ic}$ (kJ/m$^2$) | MBT | CC | MCC | Comments |
|---|---|---|---|---|---|---|---|---|
| | | | | NL | | | | |
| | | | | VIS | | | | |
| | | | | 5% | | | | |

| a (mm) | δ (mm) | P (N) | δ/a | $G_{Ic}$ (kJ/m$^2$) | MBT | CC | MCC | Comments |
|---|---|---|---|---|---|---|---|---|
| | | | | Prop | | | | |
| | | | | Prop | | | | |
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**FIG. A1.2 DCB Standard Data Reporting Sheet**

12.1.1-12.1.3), then multiply $G_I$ by *F/N* to obtain the corrected value of $G_I$.

A1.3 These corrections are small for short delamination lengths in 3-mm thick specimens of 60 % $V_f$ carbon composites, but they may be larger for thin (that is, more flexible) specimens or for long delamination lengths.

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