



Designation: C1940 – 24

Standard Test Method for Critical Mode I Interlaminar Strain Energy Release Rate of (G_{Ic}) Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperatures¹

This standard is issued under the fixed designation C1940; 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 experimental methods and procedures for the determination of the critical mode I interlaminar strain energy release rate of continuous fiber-reinforced ceramic matrix composite (CMC) materials in terms of G_{Ic} . This property is also sometimes described as the mode I fracture toughness or the mode I fracture resistance.

1.2 This test method applies primarily to ceramic matrix composite materials with a 2-D laminate structure, consisting of lay-ups of continuous ceramic fibers, in unidirectional tape or 2-D woven fabric architectures, within a brittle ceramic matrix.

1.3 This test method determines the elastic strain energy released per unit of new surface area created as a delamination grows at the interlaminar interface between two lamina or plies. The term delamination is used in this test method to specifically refer to this type of growth, while the term crack is a more general term that can also refer to matrix cracking, intralaminar delamination growth, or fiber fracture.

1.4 This test method uses a double cantilever beam (DCB) specimen to determine the critical mode I interlaminar strain energy release rate (G_{Ic}). A DCB test method has been standardized for polymer matrix composites (PMCs) under Test Method [D5528](#). This test method addresses a similar procedure, but with modifications to account for the different physical properties, reinforcement architectures, stress-strain response, and failure mechanisms of CMCs compared to PMCs.

1.5 This test is written for ambient temperature and atmospheric test conditions, but the test method can also be used for elevated temperature or environmental exposure testing with the use of an appropriate environmental test chamber, measurement equipment for controlling and measuring the cham-

ber temperature, humidity, and atmosphere, high temperature gripping fixtures, and modified equipment for measuring delamination growth.

1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6.1 Values expressed in this test method are in accordance with the International System of Units (SI) and [IEEE/ASTM SI 10](#).

1.7 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* Specific hazard statements are given in Section 8.

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*²

[C1145 Terminology of Advanced Ceramics](#)

[C1275 Test Method for Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Test Specimens at Ambient Temperature](#)

[C1359 Test Method for Monotonic Tensile Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics With Solid Rectangular Cross Section Test Specimens at Elevated Temperatures](#)

[D2651 Guide for Preparation of Metal Surfaces for Adhesive Bonding](#)

[D3878 Terminology for Composite Materials](#)

¹ This test method is under the jurisdiction of ASTM Committee [C28](#) on Advanced Ceramics and is the direct responsibility of Subcommittee [C28.07](#) on Ceramic Matrix Composites.

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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.

D5528 Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites
E4 Practices for Force Calibration and Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E83 Practice for Verification and Classification of Extensometer Systems
E105 Guide for Probability Sampling of Materials
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E561 Test Method for K_R Curve Determination
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1402 Guide for Sampling Design
E1823 Terminology Relating to Fatigue and Fracture Testing
IEEE/ASTM SI 10 American National Standard for Metric Practice

3. Terminology

3.1 The definitions of terms relating to mechanical testing appearing in Terminology **E6** apply to the terms used in this test method. The definitions of terms relating to fracture testing appearing in Terminology **E1823** apply to the terms used in this test method. The definitions of terms relating to advanced ceramics appearing in Terminology **C1145** apply to the terms used in this test method. The definitions of terms relating to fiber-reinforced composites appearing in Terminology **D3878** apply to the terms used in this test method. Pertinent definitions are shown in the following subsection, with the appropriate source given in bold.

3.2 Definitions:

3.2.1 *advanced ceramic*, n —highly engineered, high performance, predominantly nonmetallic, inorganic, ceramic material having specific functional attributes. **C1145**

3.2.2 *ceramic matrix composite*, n —material consisting of two or more materials (insoluble in one another), in which the major, continuous component (matrix component) is a ceramic, while the secondary component(s) (reinforcing component) may be ceramic, glass-ceramic, glass, metal or organic in nature; these components are combined on a macroscale to form a useful engineering material possessing certain properties or behavior not possessed by the individual constituents. **C1145**

3.2.3 *continuous fiber-reinforced ceramic matrix composite (CFCC)*, n —ceramic matrix composite in which the reinforcing phase consists of a continuous fiber, continuous yarn, or a woven fabric. **C1145**

3.2.4 *fracture toughness*, n —a generic term for measures of resistance to crack extension. **C1145**

3.2.5 *interlaminar*, *adj*—describing objects (for example, voids), events (for example, fracture), or fields (for example, stress) between the plies of a laminate. **D3878**

3.2.6 *mode*, *adj*—one of the three classes of crack (surface) displacements adjacent to the crack tip; these displacement modes are associated with the stress-strain fields around the crack tip and are designated one, two, and three; arabic numerals 1, 2, and 3 are used for the general case, and they represent opening, sliding, and tearing displacements, respectively (see Fig. 8 in Terminology **E1823**); roman numerals are used to specialize the mode to plane strain (I and II) or to antiplane-strain (III). **E1823**

3.3 Definitions of Terms Specific to This Standard:

3.3.1 *crack opening mode (Mode I)*, n —the fracture mode in which the crack faces open away from each other and no crack face shear movement occurs.

3.3.2 *critical mode I interlaminar strain energy release rate* (G_{Ic}), [FLL^{-2} , FL^{-1}], n —the value of strain energy release rate (G) [FLL^{-2} , FL^{-1}] for the onset of delamination growth as a result of an opening force or opening displacement.

3.3.2.1 *Discussion*—When the elastic strain energy (G) stored in the specimen reaches or exceeds a critical value (G_c), energy is dissipated by the creation of new surface area (crack growth) until the stored energy is less than a critical value.

3.3.3 *load point displacement* (δ) [L], n —the force-induced separation vector between the two points of load application on the cantilever arms.

3.3.3.1 *Discussion*—For Mode I crack opening, the direction of the separation vector is normal to the crack plane and parallel to the force vector.

3.3.4 *precrack*, n —a starting delamination, artificially produced from a pre-implanted insert or machined notch, from which subsequent delamination growth occurs.

3.3.5 *resistance curve (R-curve)*, n —a plot of critical mode I interlaminar strain energy release rate (G_{Ic}) versus delamination length (a) for stable delamination advance.

3.3.5.1 *Discussion*—If the material shows R-curve behavior, G_{Ic} will be different at increasing delamination lengths compared to the initial value. The changes can occur because the fracture mechanisms change in mode or amplitude, or both, during crack progression, absorbing more or less strain energy with increasing delamination length. In unidirectional tape laminates, R-curve behavior is often caused by fiber bridging. If there are no changes in energy absorption with delamination extension, the initiation G_{Ic} and the propagation G_{Ic} are equivalent and the material does not show R-curve behavior.

3.3.5.2 *Discussion*—If the propagation values of G_{Ic} reach a stable values, this is sometimes referred to as G_{IR} in reference to R-curve behavior.

3.3.6 *strain energy release rate*, G [FL^{-1}], n —the loss of elastic strain energy, dU , in the test specimen per unit of specimen width for an infinitesimal increase in length, da , of a delamination growing self-similarly under a constant displacement. In mathematical form,

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

where:

G = strain energy release rate,



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

3.3.6.1 *Discussion*—The strain energy release rate is subscripted to identify the mode of load or displacement imparting strain energy in the specimen: Mode I opening (G_I), Mode II sliding or in-plane shear (G_{II}), or Mode III tearing or anti-plane shear (G_{III}).

4. Summary of Test Method

4.1 This test method measures the critical strain energy release rate for mode I interlaminar delamination growth (G_{Ic}) in continuous fiber-reinforced CMC.

4.2 This test method applies primarily to CMC materials with a 2-D laminate structure, consisting of lay-ups of continuous ceramic fibers (in woven fabric and uniaxial tape architectures) within a brittle ceramic matrix.

NOTE 1—Fracture mechanisms and crack propagation paths are often spatially variable within a given CMC test specimen, particularly for laminates with woven fabric reinforcement. These spatial variations are based on anisotropy and inhomogeneity in reinforcement architecture, heterogeneous flaw/pore distribution, anisotropic and heterogeneous stress-strain response, and spatial variations in matrix properties. These architectural, microstructural, and property variations make it difficult in some materials to control the crack propagation and interlaminar fracture to produce a true material property, rather than a structure-dependent property.

NOTE 2—This test method can be used for ceramic composite materials with a non-laminar architecture (containing some 3-D reinforcement) with the understanding that the fracture toughness values in a given plane are strongly affected by the reinforcement in the perpendicular (z) direction and shall be considered as a structure-dependent property, rather than a material property.

4.3 A DCB specimen (Fig. 1) is produced from a continuous fiber CMC laminate. The cantilever arms of the DCB specimen are formed by producing a sharp notch, crack, or delamination in the mid-plane that acts as a crack initiator or source and creates a mid-plane delamination.

4.4 Tensile opening forces are applied to the cantilever beam arms of the DCB specimen by means of loading blocks or piano hinges attached to the two opposing cantilever arms. The applied tensile forces (P) and the load point displacements (δ) of the cantilever arms are recorded, and the resulting extension of the mid-plane delamination (a) is measured and recorded at defined intervals of crack growth corresponding to the applied forces and load point displacements.

4.5 The G_{Ic} is calculated from the applied force (P), the load point displacements (δ), and the delamination lengths (a) measured during the test using a modified beam theory calculation method (or by alternative methods given in Annex A3).

4.6 Multiple data points are required for data reduction, which results in multiple calculations for G_{Ic} . An R-curve of G_{Ic} versus delamination length (Fig. 2) is generated to characterize G_{Ic} as the delamination grows and possibly reaches a steady-state G_{IR} value.

5. Significance and Use

5.1 Interlaminar delamination growth can be a critical failure mode in laminated CMC structures. Knowledge of the resistance to interlaminar delamination growth of a laminated CMC is essential for material development and selection, and for CMC component design. (See (1-8)³ which give G_{Ic} values of 20 J/m² to 800 J/m² for different CMC and carbon-carbon composite systems at ambient temperatures.)

5.2 Conducting this test produces multiple values of G_{Ic} which are traditionally plotted against the delamination length at which that value was measured (see Fig. 2). The specific data of value to the test requestor will depend on the end use that motivated testing.

³ The boldface numbers in parentheses refer to a list of references at the end of this standard.

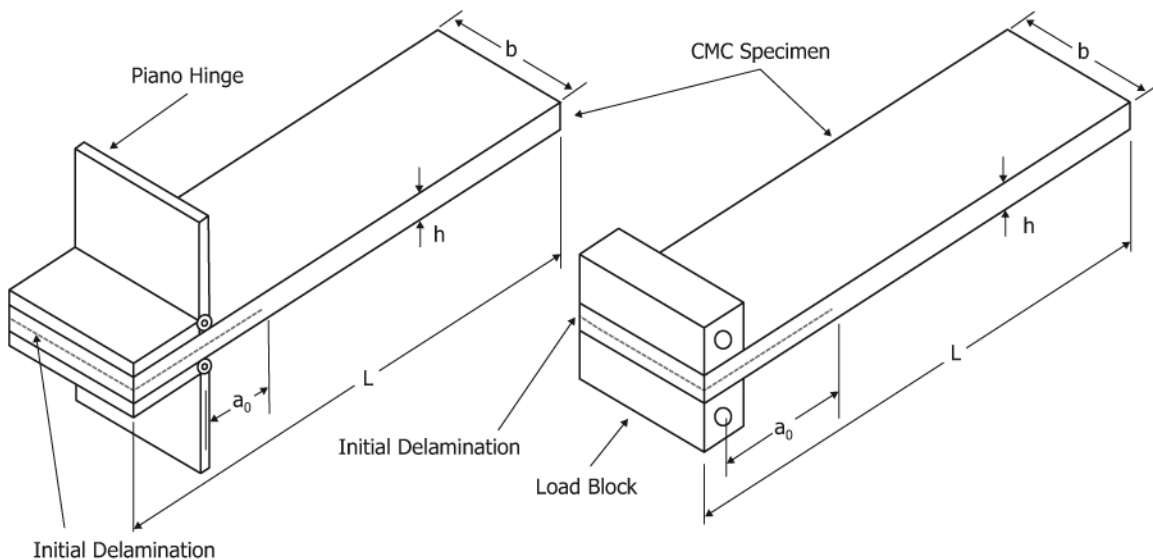


FIG. 1 Double Cantilever Beam (DCB) Test Specimen

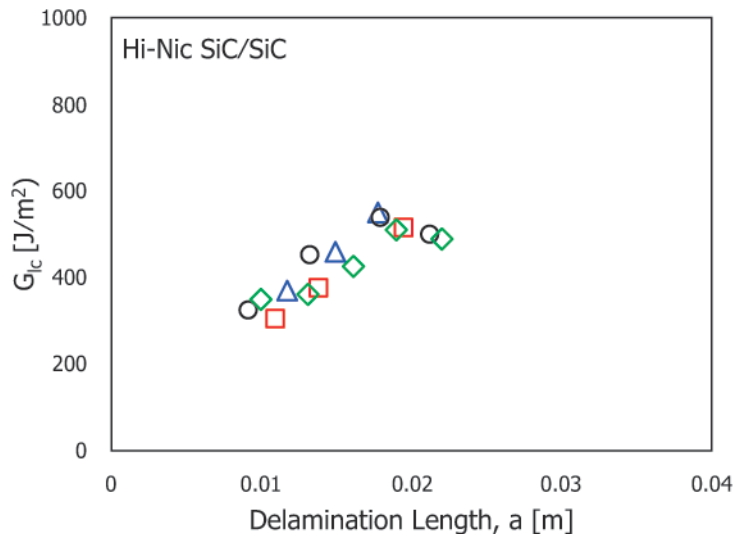


FIG. 2 G_{Ic} SiC-SiC Composite - Multiple Test Specimens (1)

5.2.1 The first increment of growth, initiated from a pre-implanted insert or machined notch, is sometimes described as the non-precracked (NPC) toughness. NPC toughness may be of interest, as it can represent manufacturing or processing defects, such as foreign object debris in a laminate or an error during machining.

5.2.2 The next increment of growth, initiated from the sharp crack tip assumed to be present after the first increment, is sometimes defined as the precracked (PC) toughness. PC toughness may be of interest, as it is more representative of the resistance to delamination growth from a naturally occurring or damage-induced delamination.

5.2.3 The remaining increments of growth, collectively forming an R-curve, provide information on how G_{Ic} evolves as the delamination advances. In unidirectional tape laminates, the R-curve is often increasing due to bridging of nested fibers across the delamination plane, artificially increasing G_{Ic} . For 2-D woven laminates for which there is little interply nesting, the R-curve may be flat.

5.2.4 The increments of growth in which the R-curve is flat, and G_{Ic} has reached a steady state value defined as G_{IR} , may be of interest and may also be useful in design and analysis.

5.3 This test method for measurement of G_{Ic} of CMC materials can serve the following purposes:

5.3.1 To establish quantitatively the effect of CMC material variables (fiber interface coatings, matrix structure and porosity, fiber architecture, processing and environmental variables, conditioning/exposure treatments, etc.) on G_{Ic} and the interlaminar crack growth and damage mechanisms of a particular CMC material;

5.3.2 To determine if a CMC material shows R-curve behavior where G_{Ic} changes with crack extension or reaches a stable value at a given amount of delamination growth. Fig. 2 shows R-curve behavior for a SiC-SiC composite (1);

5.3.3 To develop delamination failure criteria and design allowables for CMC damage tolerance, durability or reliability analyses, and life prediction;

NOTE 3—Test data can only reliably be used for this purpose if there is

confidence that the test is yielding a material property and not a structural, geometry-dependent, property.

5.3.4 To compare quantitatively the relative values of G_{Ic} for different CMC materials with different constituents and material properties, reinforcement architectures, processing parameters, or environmental exposure conditions; and

5.3.5 To compare quantitatively the values of G_{Ic} obtained from different batches of a specific CMC material, to perform lot acceptance quality control, to use as a material screening criterion, or to assess batch variability.

6. Interferences

6.1 Inherent Material Variability:

6.1.1 A major source of variation in G_{Ic} values for CMCs is the variability in the constituents, architecture, microstructure, and properties of the CMC material itself. Material variability occurs in a wide range of material structure and properties – for example, reinforcement architecture variability, local matrix porosity clusters and micro-cracked regions, and fiber interface coating inhomogeneity. This material variability can occur spatially within individual specimens, between specimens, and between production lots. All of these variables can produce regions, sections, or directions with different mechanical response and varying low-energy fracture paths. In some cases, the low-energy fracture path can run through plies and produce crack deflection, migration, new delamination cracks, damage in adjacent ply sections, or combinations thereof.

6.1.2 Directional and spatial differences in material properties and reinforcement architecture along with unbalanced, non-uniform stress distributions can produce directional differences and uneven crack progression at the front of the crack with crack migration or deviation into adjacent plies, and with crack bowing or dragging in the center of the test specimen, compared to the edges of the test specimen.

6.1.3 Some CMC materials are susceptible to hydrolysis and intermediate temperature oxidation which can modify the composition and microstructure, changing the material properties or producing slow crack growth. The test data can be

during unprotected storage, with specific conditioning treatments, or under environmental test conditions and slow strain (creep) conditions.

6.2 Experimental Interferences:

6.2.1 The calculation of G_{Ic} in this test method assumes linear elastic behavior in the cantilever arms. This assumption is valid when the cantilever arms are structurally rigid and strong enough to deform elastically. Nonlinear deformation, damage, and fracture in the cantilever arms invalidates the assumption of linear elastic behavior.

6.2.2 The calculation of G_{Ic} in this test method assumes that the delamination crack starts, extends, and remains in the mid-plane of the test specimen, without deflection, migration, or branching into and through adjacent plies with crack extension. Crack deflection, branching, and multiple crack formations are significant interferences for the test method.

6.2.3 The calculation of G_{Ic} in this test method assumes uniform delamination growth across the specimen width. The recommended method to determine delamination length is the visual observation method, although other methods (see [Annex A4](#)) exist. The visual observation method assumes that the delamination length, as measured at one specimen edge, is representative of overall, uniform delamination growth. Non-uniform delamination growth, which can produce curved, slanted, or wavy delamination fronts, invalidates this assumption.

6.2.4 Delamination growth may initiate and progress in one of two ways: (1) by a slow, stable crack extension/growth or (2) a run-arrest extension, in which the delamination front jumps ahead abruptly with a drop in applied force and then the crack extends further, only with a subsequent increase in applied force ([Fig. 3](#)). Slow, stable crack growth is of primary interest in this test method, because rapid delamination growth may introduce dynamic effects in the test specimen and changes in the fracture morphology. The run-arrest crack growth may develop if the precrack is not sharp enough, or it may be an implicit property of the material.

6.2.5 Precise construction and alignment of the two loading blocks or piano hinges used for load introduction are important to align and balance the two load application points. Misalignment may introduce undesirable load components (that is, mode II or mode III loading).

6.3 Specimen Interferences:

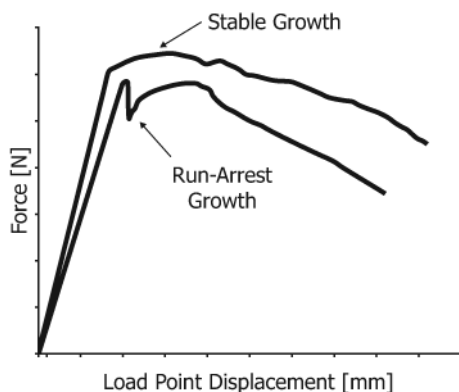


FIG. 3 Stable Growth and Run-Arrest Growth

6.3.1 Specimen thickness (h) and cantilever arm thicknesses (h_1 and h_2 – see [Fig. 4](#)) are key geometric variables determining the mechanical response of the cantilever arms. With thin test specimens and thin cantilever arms, the cantilever arms can be over-strained and shift out of the elastic stress-strain regime. With thick test specimens, cantilever arms that are too thick may exhibit significant amounts of transverse shear deformation, which is not accounted for in the data reduction methods.

6.3.2 The assumption that the specimen is under pure mode I loading is predicated on the bending forces on the cantilever arms being balanced and equivalent. This requires that the thickness of the two arms (h_1 and h_2) are equal and the delamination is located exactly at the mid-plane, but this may be difficult to achieve with small, thin specimens.

NOTE 4—Analysis using Classical Beam Theory assumptions (1) showed that if the thickness of the two cantilever arms are within 20 % of each other ($120 \% \geq h_1/h_2 \geq 80 \%$), the calculated value of G_I is overestimated by 5 % or less. However, overestimation is unconservative, there is no estimate provided for the mode II component introduced due to the asymmetry, and it is also not well known how mixed-mode conditions, with even small components of G_{II} , may effect G_{Ic} . It should therefore be endeavored to keep the cantilever arms as equal as possible.

6.3.3 Calculation of G_{Ic} requires accurate measurement of the delamination tip position through the duration of the test. In some CMCs it is very difficult to visually measure the delamination tip position from the side of the specimen. Techniques can be used to "highlight" the appearance of the crack for accurate visual measurement, but identification can still be difficult.

6.3.4 If G_{Ic} is to be accurately used as a conservative material property for design and analysis purposes, the specimen must be designed such that the linear-elastic fracture mechanics' assumption of a small process zone size relative to the specimen characteristic length holds true. One way to accomplish this is to construct a DCB test specimen based on the geometry recommendations in this test method and with a 0° unidirectional tape architecture, as opposed to a multidirectional layup or a woven fabric laminate architecture.

7. Apparatus

7.1 *Test Machine*—The test machine applies and measures the force and the displacement on the test specimen in a controlled manner. A test machine commonly consists of a test frame, force transducers, and the actuator or drive mechanism with load train components and gripping fixtures. A properly-calibrated test machine shall be used that conforms to the requirements of [Practices E4](#) and can be operated in a displacement control mode.

7.2 *Gripping Devices*—Gripping devices are used to transmit the applied force to the fixtured test specimens and to keep the specimen properly aligned in the load train. The testing machine shall be equipped with appropriate specimen grips to attach to and apply force to the force application fixtures that are bonded or attached to the specimen.

7.2.1 The load train shall have suitable couplers, universal joints, and alignment fixtures to adjust and maintain the linear and angular alignment of the load train to prevent extraneous bending or twisting stresses in the test specimen.

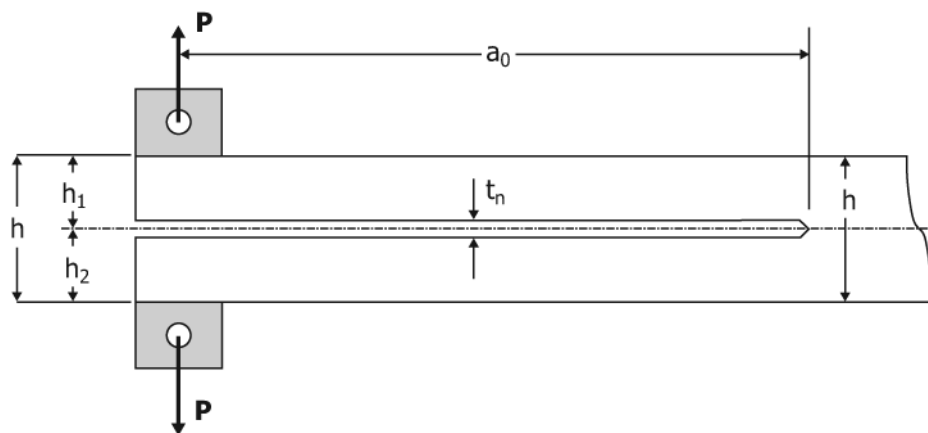


FIG. 4 Starting Notch or Delamination Geometry, Location, and Orientation in the DCB Test Specimen

7.3 Force Application Fixtures—Either piano hinges or load blocks bonded or attached to the specimen act as fixtures for application of force to the specimen by the test machine.

7.4 Force Indicator—The force transducer shall be capable of indicating the total force applied to the test specimen. This device shall be essentially free from inertia lag at the specified rate of testing and shall indicate the applied force with an accuracy of $\pm 1\%$ of the maximum expected force during the test. The force transducer shall conform to the requirements of Practices E4.

7.5 Load Point Displacement Measurement—The load point displacement (δ) between the two points of force application on the two cantilever arms shall be measured with an accuracy of at least $\pm 1\%$ of the total displacement expected during the test. There are three optional methods for measuring the load point displacement:

7.5.1 The load point displacement may be estimated as the test machine cross-head displacement, provided the compliance deformation in the load train with the specimen grips attached is less than 2 % of the load point displacement of the test specimen;

7.5.2 The load point displacement may be indirectly measured with calibrated extensometers or displacement transducers (mechanical or optical) attached to the crack mouth of the DCB specimen;

7.5.2.1 The load point displacement is calculated from the geometric relationship between the crack mouth opening displacement and the load point displacement, which is offset from the crack mouth in the direction of the crack tip.

7.5.2.2 The recommended extensometer/displacement gauge has a working range of not more than twice the displacement expected during the test. Accuracy shall be within $\pm 1\%$ of the expected displacement. When an extensometer/displacement transducer is attached to the loaded end of the test specimen to measure the crack opening mouth displacement, the transducer is supported and counter-weighted to prevent tipping of the free end of the test specimen out of the horizontal plane. With a properly supported transducer, the specimen will have little tendency to rotate and should not introduce extraneous, unbalanced bending stresses.

7.5.3 The load point displacement may be measured by optical microscope or camera devices that directly measure the load point displacement. Accuracy of such devices shall be at least $\pm 1\%$ of the expected displacement.

7.6 In-Situ Delamination Length Measurement—The extension of the delamination in the specimen mid-plane during testing shall be measured to an accuracy of at least ± 0.5 mm. The preferred method to measure delamination length during the test is optically, although other methods may be used.

7.6.1 Delamination length should be measured visually by a traveling optical microscope that follows the delamination tip as the crack extends. The travelling optical microscope, or equivalent magnifying device, should have a magnification no greater than 70 $\times$. It should be positioned on one side of the test specimen to observe the delamination as it extends along one edge of the specimen during the test.

7.6.1.1 A mirror may be used to determine visually any difference in crack extension from one side of the specimen to the other side. Alternatively, a second traveling optical microscope may be used.

7.6.2 Other measurement methods, such as recording vision systems, crack length gauges bonded to the specimen edges, electrical resistance measurement, acoustic emission signal analysis, and digital image correlation measurements may be used to monitor and measure the delamination extension, provided the accuracy meets the ± 0.5 mm requirement.

7.7 Specimen Dimension Measuring Devices—Micrometers, calipers, and other devices used for measuring specimen dimensions (Fig. 1 and Fig. 4) shall be accurate and precise to measure to the required dimensional tolerance levels specified.

7.7.1 The specimen dimensions of width (b) and thickness (h) should be measured with micrometers with a flat anvil on smooth, machined edges and surfaces. A suitable-sized diameter ball anvil should be used on irregular, through-thickness surfaces. For typical specimen geometries, the width should be measured with an instrument with an accuracy of at least ± 0.1 mm. The thickness should be measured with an instrument with an accuracy of at least ± 0.05 mm.

7.7.2 The cantilever arm thicknesses (h_1 and h_2 in Fig. 4) and notch thickness (t_n in Fig. 4) should be measured with an instrument capable of an accuracy of at least ± 0.05 mm. Calipers or optical image analysis may be suitable instruments.

7.7.3 The initial notch length (a_0 in Fig. 1 and Fig. 4) should be measured to an accuracy of at least ± 0.5 mm with an instrument with an accuracy of at least ± 0.2 mm. Calipers or optical image analysis may be suitable instruments.

7.8 *Data Acquisition Requirements*—Use either digital data acquisition systems or analog chart recorders for recording the applied force (P) and load point displacement (δ) versus time. A digital record is recommended for ease of later data analysis. Recording devices shall be accurate to within ± 0.1 % for the entire testing system including the readout unit as specified in Practices E4 and with a recommended minimum data acquisition rate of 10 Hz and recommended minimum response of 50 Hz.

7.9 *Conditioning Chamber*—If test materials and test specimens are to be pre-test conditioned in a defined environment (temperature, humidity, and atmosphere), a temperature/vapor/atmosphere-controlled conditioning chamber is required that is capable of maintaining the required temperature to within ± 3 °C and the required relative humidity/vapor level and atmosphere to within ± 5 %. Chamber environmental conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals during the conditioning treatment.

7.10 This test method covers testing under ambient temperatures. However, if non-ambient temperature testing is conducted, test chambers should meet the below requirements.

7.11 *Cryogenic Test Chamber*—If test specimens are to be tested in a low-temperature environment, a temperature controlled test chamber is required that is capable of maintaining the required temperature to within ± 3 °C. Test chamber environmental conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals during the test.

7.12 *Environmental Test Chamber*—If test specimens are to be tested in an elevated temperature environment or with controlled humidity or atmosphere, a temperature/vapor/atmosphere-controlled test chamber is required that is capable of maintaining the required temperature to within ± 3 °C and the required relative humidity/vapor level and atmosphere to within ± 5 %. Test chamber environmental conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals during the test. See Annex A5 for more detail.

7.13 Safety and containment shields should be placed around the specimen and test fixture to contain and collect fracture fragments.

8. Hazards

8.1 During the conduct of this test, there is a possibility of flying fragments of broken test specimens. The brittle nature of advanced ceramics and the release of elastic strain energy contribute to the potential release of uncontrolled fragments

upon fracture. Plastic shields can be used to encircle the test fixture and specimen, and to capture specimen fragments. Containment and retention of these fragments for later fractographic reconstruction and analysis is highly recommended.

8.2 Exposed fibers at the edges of CMC test specimens present a hazard due to the sharp, brittle nature of the ceramic fiber. Individuals required to handle these materials shall be well-informed of such conditions and the proper handling techniques.

9. Test Specimens

9.1 Test specimens shall be selected and prepared from representative CMC materials that meet the defined testing objectives and material requirements. Guide E105 and Guide E1402 provide guidance and direction on developing a sampling plan. The method of sampling shall be reported.

9.2 *Material Architecture*—The fiber reinforcement architecture in the CMC test specimen should be structured to prevent the interlaminar crack from branching or migrating from the mid-plane into adjacent plies or interfaces.

9.2.1 CMCs composed of tape plies should be unidirectional and consist of only 0° plies, because off-axis plies, such as those oriented at 90° or 45°, are particularly susceptible to crack migration through and into adjacent plies. Orientations other than unidirectional 0° may be used if it can be shown that delamination growth is constrained to the mid-plane interlaminar interface.

9.2.2 CMCs composed of woven fabric plies are generally less susceptible to crack migration and may generally be comprised of any orientation, as long as it can be shown that delamination growth is constrained to the mid-plane interlaminar interface.

9.2.3 If orientations other than purely unidirectional are selected for the fiber reinforcement architecture, the two cantilever arm sub-laminates should each be mid-plane symmetric to avoid the effects of anticlastic bending that may be introduced during testing if the sub-laminates are asymmetric.

9.2.4 This test method can be used for CMCs with a non-laminar architecture containing some 3-D reinforcement, per Note 2, and with the understanding that an interlaminar interface, and thus an interlaminar strain energy release rate, does not exist as conventionally defined.

9.2.5 If the initial delamination will be created using the insertion method (see 9.4.3.3), the laminate must contain an even number of plies. If the initial delamination will be created using the machining method, an even number of plies is recommended, but is not required.

9.3 *Specimen Geometry and Dimensions*—The rectangular test specimens have a recommended length (L) of at least 125 mm and a nominal width (b) from 20 mm to 25 mm inclusive (Fig. 1). The test specimen architecture should be selected to produce a specimen thickness (h) between 3 mm and 5 mm.

9.3.1 When testing woven fabric laminate composites, it is recommended that the specimen width (b) be equal to two or more weave unit cells.