INTERNATIONAL

Designation: C1899 − 21

Standard Test Method for Flexural Strength of Continuous Fiber-Reinforced Advanced Ceramic Tubular Test Specimens at Ambient Temperature[1]

This standard is issued under the fixed designation C1899; 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 covers the determination of flexural strength, including stress-strain response, under monotonic loading of continuous fiber-reinforced advanced ceramic tubes at ambient temperature. This test method addresses tubular test specimen geometries, test specimen/grip fabrication methods, testing modes (force, displacement, or strain-control), testing rates (force rate, stress rate, displacement rate, or strain rate), and data collection and reporting procedures.

1.2 In this test method, an advanced ceramic composite tube/cylinder with a defined gage section and a known wall thickness is subjected to four-point flexure while supported in a four-point loading system utilizing two force-application points spaced an inner span distance that are centered between two support points located an outer span distance apart. The applied transverse force produces a constant moment in the gage section of the tube and results in uniaxial flexural stress-strain response of the composite tube that is recorded until failure of the tube. The flexural strength and the flexural fracture strength are determined from the resulting maximum force and the force at fracture, respectively. The flexural strains, the flexural proportional limit stress, and the flexural modulus of elasticity in the longitudinal direction are determined from the stress-strain data. Note that flexural strength as used in this test method refers to the maximum tensile stress produced in the longitudinal direction of the tube by the introduction of a monotonically applied transverse force, where 'monotonic' refers to a continuous, nonstop test rate without reversals from test initiation to final fracture. The flexural strength is sometimes used to estimate the tensile strength of the material.

1.3 This test method is intended for advanced ceramic matrix composite tubes with continuous fiber reinforcement: unidirectional (1D, filament wound and tape lay-up), bidirectional (2D, fabric/tape lay-up and weave), and tridirectional (3D, braid and weave). These types of ceramic matrix composites can be composed of a wide range of ceramic fibers (oxide, graphite, carbide, nitride, and other compositions) in a wide range of crystalline and amorphous ceramic matrix compositions (oxide, carbide, nitride, carbon, graphite, and other compositions). This test method may also be applicable to some types of functionally graded tubes such as ceramic fiber-wound tubes comprised of monolithic advanced ceramics. It is not the intent of this test method to dictate or normalize material fabrication including fiber layup or number of plies comprising the composite, but to instead provide an appropriate and consistent methodology for discerning the effects of different fabrication or fiber layup methods on flexural behavior of resulting tubular geometries.

1.4 This test method does not directly address discontinuous fiber-reinforced, whisker-reinforced, or particulate-reinforced ceramics, although the test methods detailed here may be equally applicable to these composites if it can be shown that these materials display the damage-tolerant behavior of continuous fiber-reinforced ceramics.

1.5 The test method is applicable to a range of test specimen tube geometries based on the intended application that includes composite material property and tube radius. Therefore, there is no "standard" test specimen geometry for a typical test setup. Lengths of the composite tube, lengths of the inner span, and lengths of the outer span are determined so as to provide a gage length with uniform bending moment. A wide range of combinations of material properties, tube radii, wall thicknesses, tube lengths, and lengths of inner and outer spans section are possible.

1.5.1 This test method is specific to ambient temperature testing. Elevated temperature testing requires high-temperature furnaces and heating devices with temperature control and measurement systems and temperature-capable testing methods that are not addressed in this test method.

1.6 This test method addresses tubular test specimen geometries, test specimen preparation methods, testing rates (that is, induced applied moment rate), and data collection and reporting procedures in the following sections:

[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.

Current edition approved July 1, 2021. Published August 2021. DOI: 10.1520/C1899-21.

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

1.8 *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.

1.9 *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
C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
C1683 Practice for Size Scaling of Tensile Strengths Using Weibull Statistics for Advanced Ceramics
C1684 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature—Cylindrical Rod Strength
D3878 Terminology for Composite Materials
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E83 Practice for Verification and Classification of Extensometer Systems
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
IEEE/ASTM SI 10 American National Standard for Metric Practice

3. Terminology

3.1 *Definitions:*

3.1.1 The definitions of terms relating to flexural testing appearing in Terminology E6 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 as listed in Practice E1012 and Terminologies C1145, D3878, and E6 are shown in the following with the appropriate source given in parentheses. Additional terms used in conjunction with this test method are defined in the following:

3.1.2 *advanced ceramic, n*—a highly engineered, high-performance, predominantly nonmetallic, inorganic, ceramic material having specific functional attributes. **(C1145)**

3.1.3 *breaking force [F], n*—the force at which fracture occurs. **(E6)**

3.1.4 *ceramic matrix composite (CMC), n*—a 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)**

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

3.1.6 *flexural fracture strength [FL^{-2}], n*—the flexural stress at the moment induced when the material breaks.

3.1.6.1 *Discussion*—The flexural fracture strength defined here does not account for the nonlinear stress-strain response of a material beyond the proportional limit and therefore, in its simplicity, may not represent the actual strength potential of that material.

3.1.7 *flexural strength [FL^{-2}], n*—the maximum tensile component of flexural stress which a material is capable of sustaining.

3.1.7.1 *Discussion*—Flexural strength is calculated from the maximum bending moment induced during a flexural test carried to rupture and the original cross-sectional dimensions of the test specimen. The flexural strength defined here does not account for the nonlinear stress-strain response of a material beyond the proportional limit and therefore, in its simplicity, may not represent the actual strength potential of that material.

3.1.8 *four-point-¼-point flexure, n*—configuration of flexural strength testing where a specimen is symmetrically loaded at two locations that are situated one quarter of the overall span away from the outer two support bearings. **(C1145)**

3.1.9 *gage length [L], n*—the original length of that portion of the specimen over which strain or change of length is determined. **(E6)**

3.1.10 *matrix cracking stress [FL^{-2}], n*—the applied tensile stress^{-2} at which the matrix cracks into a series of roughly parallel blocks normal to the tensile stress. **(C1145)**

[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.

3.1.10.1 *Discussion*—In some cases, the matrix cracking stress may be indicated on the stress-strain curve by deviation from linearity (proportional limit) or incremental drops in the stress with increasing strain. In other cases, especially with materials which do not possess a linear portion of the stress-strain curve, the matrix cracking stress may be indicated as the first stress at which a permanent offset strain is detected in the unloading stress-strain (elastic limit). **(C1145)**

3.1.11 *modulus of elasticity [FL^{-2}], n*—the ratio of stress to corresponding strain below the proportional limit. **(E6)**

3.1.12 *modulus of resilience [FLL^{-3}], n*—strain energy per unit volume required to elastically stress the material from zero to the proportional limit indicating the ability of the material to absorb energy when deformed elastically and return it when unloaded. **(C1145)**

3.1.13 *modulus of toughness [FLL^{-3}], n*—strain energy per unit volume required to stress the material from zero to final fracture indicating the ability of the material to absorb energy beyond the elastic range (that is, damage tolerance of the material).

3.1.13.1 *Discussion*—The modulus of toughness can also be referred to as the cumulative damage energy and as such is regarded as an indication of the ability of the material to sustain damage rather than as a material property. Fracture mechanics methods for the characterization of CMCs have not been developed. The determination of the modulus of toughness as provided in this test method for the characterization of the cumulative damage process in CMCs may become obsolete when fracture mechanics methods for CMCs become available. **(C1145)**

3.1.14 *monotonic, adj*—a continuous, nonstop test rate without reversals from test initiation to final fracture.

3.1.15 *proportional limit [FL^{-2}], n*—the greatest stress that a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law).

3.1.15.1 *Discussion*—Many experiments have shown that values observed for the proportional limit vary greatly with the sensitivity and accuracy of the testing equipment, eccentricity of loading, the scale to which the stress-strain diagram is plotted, and other factors. When determination of proportional limit is required, the procedure and sensitivity of the test equipment should be specified. **(E6)**

3.1.16 *slow crack growth, n*—subcritical crack growth (extension) which may result from, but is not restricted to, such mechanisms as environmentally assisted stress corrosion or diffusive crack growth. **(C1145)**

3.1.17 *transverse loading, n*—forces applied perpendicular to the longitudinal axis of a member. Transverse loading causes the member to bend and deflect from its original position, with internal tensile and compressive strains accompanying the change in curvature of the member. Also called flexural loading.

3.1.18 *unit cell size, n*—the smallest section of fabric-weave architecture required to repeat the textile pattern.

4. Summary of Test Method

4.1 In this test method, a composite tube/cylinder with known wall thickness and supported over an outer loading span is loaded transversely over an inner loading span. The monotonically applied transverse force results in a uniaxial, nonuniform flexural stress-strain response of the composite tube that is recorded until failure of the tube. The ultimate flexural strength and the fracture flexural strength are determined from the resulting maximum transverse force and the transverse force at fracture, respectively. The flexural strains, the proportional limit flexural stress, and the modulus of elasticity in the longitudinal direction are determined from the flexural stress-strain data.

4.2 Flexural strength as used in this test method refers to the maximum tensile stress produced in the longitudinal direction of the tube by the introduction of a monotonically applied transverse force. Monotonic refers to a continuous, nonstop test rate without reversals from test initiation to final fracture.

4.3 This test method is applicable to a range of test specimen tube geometries based on a nondimensional parameter (β) that includes composite material properties, tube radius, and wall thickness. Therefore, there is no "standard" test specimen geometry for a typical test setup. Lengths of the composite tube and other test specimen parameters are determined so as to provide an inner span length as a gage length that is subjected to a constant moment that results in a uniaxial but nonuniform flexural stress in the gage section. A range of combinations of material properties, tube radii, wall thicknesses, tube lengths, inner gage lengths, and outer gage lengths are possible. It is not the intent of this test method to dictate or normalize material fabrication including fiber layup or number of plies comprising the composite, but to instead provide an appropriate and consistent methodology for discerning the effects of different fabrication or fiber layup methods on flexural behavior of resulting tubular geometries.

5. Significance and Use

5.1 This test method may be used for material development, material comparison, quality assurance, characterization, and design data generation.

5.2 Continuous fiber-reinforced ceramic composites (CFCCs) may be composed of continuous ceramic-fiber directional (1D, 2D, and 3D) reinforcements which are often contained in a fine-grain-sized (<50 µm) ceramic matrix with controlled porosity. Usually these composites have an engineered thin (0.1 to 10 µm) interface coating on the fibers to produce crack deflection and fiber pull-out.

5.3 CFCC components have distinctive and synergistic combinations of material properties, interface coatings, porosity control, composite architecture (1D, 2D, and 3D), and geometric shape that are generally inseparable. Prediction of the mechanical performance of CFCC tubes (particularly with braid and 3D weave architectures) may not be possible by applying measured properties from flat CFCC plates to the design of tubes. This is because fabrication/processing methods may be unique to tubes and not replicable to flat plates, thereby producing compositionally similar but structurally and morphologically different CFCC materials. In particular, tubular components comprised of CFCC material form a unique synergistic combination of material, geometric shape, and reinforcement architecture that is generally inseparable. In other words, prediction of mechanical performance of CFCC tubes generally cannot be made by using properties measured from flat plates. Strength tests of transversely loaded CFCC tubes provide information on mechanical behavior and strength for a material subjected to a uniaxial, nonuniform stress.

5.4 Unlike monolithic advanced ceramics that fracture catastrophically from a single dominant flaw, CMCs generally experience "graceful" fracture from a cumulative damage process. Therefore, while the volume of material subjected to a nonuniform, uniaxial flexural stress for transversely loaded tube test may be a significant factor for determining matrix cracking stress, this same volume may not be as significant a factor in determining the ultimate strength of a CMC. However, the probabilistic nature of the strength distributions of the brittle matrices of CMCs requires a statistically significant number of test specimens for statistical analysis and design. Studies to determine the exact influence of test specimen volume on strength distributions for CMCs have not been completed. It should be noted that tensile flexural strengths obtained using different recommended test specimens with different volumes of material in the gage sections may be different due to these volume effects. Practice C1683 provides guidance on the scaling of statistical parameters for strength to account for differences in effective volume, effective area, or both.

5.5 Flexural strength tests provide information on the strength and deformation of materials under stresses induced from transverse loading of tubes. Nonuniform but uniaxial stress states are inherent in these types of tests, and subsequent evaluation of any nonlinear stress-strain behavior must take into account the asymmetric and anisotropic behavior of the CMC under multiaxial stressing. This nonlinear behavior may develop as the result of cumulative damage processes (for example, matrix cracking, matrix/fiber debonding, fiber fracture, delamination, etc.) which may be influenced by testing mode, testing rate, processing effects, or environmental effects. Some of these effects may be consequences of stress corrosion or subcritical (slow) crack growth that can be minimized by testing at sufficiently rapid rates as outlined in this test method.

5.6 The results of flexural strength tests of test specimens fabricated to standardized dimensions from a particular material or selected portions of a part, or both, may not totally represent the strength and deformation properties of the entire, full-size end product or its in-service behavior in different environments.

5.7 For quality control purposes, results derived from standardized flexural strength test specimens may be considered indicative of the response of the material from which they were taken for, given primary processing conditions and post-processing heat treatments.

5.8 The flexural behavior and flexural strength of a CMC are dependent on its inherent resistance to fracture, the presence of flaws, damage accumulation processes, or combinations thereof. Analyses of fracture surfaces and fractography, though beyond the scope of this test method, are highly recommended.

6. Interferences

6.1 Inherent variability in constituents and their properties; variations in material fabrication practices, fiber alignment, delamination, and internal porosity; and damage induced by improper specimen machining are all known causes of data scatter in CMCs.

6.2 Test environment (vacuum, inert gas, ambient air, etc.), including moisture content (for example, relative humidity), may have an influence on the measured flexural strength. In particular, the behavior of materials susceptible to slow crack growth fracture will be strongly influenced by test environment and testing rate. Conduct testing to evaluate the maximum strength potential of a material in inert environments or at sufficiently rapid testing rates, or both, so as to minimize slow crack growth effects. Conversely, testing can be conducted in environments and testing modes and rates representative of service conditions to evaluate material performance under use conditions. When testing is conducted in uncontrolled ambient air with the intent of evaluating maximum strength potential, monitor and report relative humidity and temperature. Testing at humidity levels >65 % relative humidity (RH) is not recommended. Report any deviations from this recommendation.

6.3 Surface preparation of test specimens, although normally not considered a major concern in CMCs, can introduce fabrication flaws that may have pronounced effects on flexural stress mechanical properties and behavior (for example, shape and level of the resulting stress-strain curve, tensile flexural strength and strain, proportional limit flexural stress and strain, etc.). Machining damage introduced during test specimen preparation can be either a random interfering factor in the determination of ultimate strength of pristine material (that is, increased frequency of surface-initiated fractures compared to volume-initiated fractures) or an inherent part of the strength characteristics to be measured. Surface preparation can also lead to the introduction of residual stresses. Universal or standardized test methods of surface preparation do not exist. It should be understood that final machining steps may or may not negate machining damage introduced during the initial machining. Thus, test specimen fabrication history may play an important role in the measured strength distributions and should be reported. In addition, the nature of fabrication used for certain composites (for example, chemical vapor infiltration or hot pressing) may require the testing of test specimens in the as-processed condition (that is, it may not be possible to machine the test specimen faces).

6.4 Uniaxial flexural tests inherently produce nonuniform stress distributions with maximum and minimum stresses occurring at the surface of the test specimen, leading to fractures originating at surfaces or near geometrical transitions. In addition, when deformations or strains are measured at surfaces where maximum or minimum stresses occur, measurement of strains will depend on the location of the strain-measuring device on the test specimen. Similarly, fracture from surface flaws may be accentuated or suppressed by the presence of the nonuniform stresses caused by bending.

6.5 Fractures that initiate outside the inner load span (defined as the gage section of the test specimen and subjected to a constant moment) may be due to factors such as stress concentrations or geometrical transitions, extraneous stresses introduced by fixtures/load apparatuses, or strength-limiting features in the microstructure of the specimen. Because such non-gage section fractures will usually constitute invalid tests, provide an explanation when differentiating between valid and invalid tests.

6.6 Flexural testing of a tube can produce a tensile stress at both the outer fiber of the outer diameter and seemingly on the inner diameter as well. Therefore, there is a probability of failure initiation occurring at the inner diameter of the tube. For simplicity, calculations of stress in this test method implicitly assume that failure will initiate at the outer fiber. However, it is also possible that like failure could occur wherever there is a sufficient axial tensile stress for such failure. This is a particularly important consideration if the outer diameter is machined during fabrication and the inner diameter is not.

6.7 Dimensions of as-fabricated tubes may produce geometric dimensions and shapes (for example, noncircular cross sections) that do not fit the assumptions of the stress calculations. Depending on the level of deviations from these assumptions, these may need to be accounted for in the subsequent interpretation of the material behavior and resulting strength calculations.

6.8 Nonlinear material behavior beyond the proportional limit makes the definitions of flexural strength and flexural fracture strength based on linear behavior overly simplistic. Therefore, additional analyses to account for the nonlinear behavior and its effect on the determination of the "true" flexural strength and "true" flexural fracture strength may be necessary but are beyond the scope of this test method.

7. Apparatus

7.1 *Testing Machines*—Machines used for applying transverse forces to test fixtures for flexural strength testing shall conform to the requirements of Practices E4. The force used to induce the transverse force shall be accurate to within ±1 % at any force within the selected force range of the testing machine as defined in Practices E4. An illustrational schematic showing pertinent features of the flexural strength testing apparatus is shown in Fig. 1.

7.2 *Fixtures:*

7.2.1 *General*—Flexural test fixtures are generally composed of two parts: (*1*) self-contained flexure test fixture with two components: movable inner span assembly guided by a fixed outer span assembly, and (*2*) attachments to the test machine such as a threaded push rod attached to the movable inner span and a flat platen on which the flexure test rests.

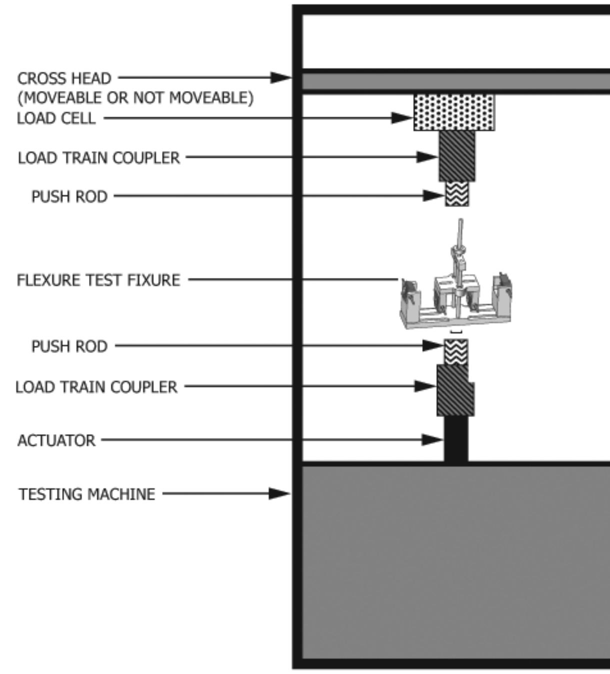

FIG. 1 Schematic Diagram of One Possible Apparatus for Applying a Transverse Force to a Flexure Test Fixture for Conducting a Flexural Strength Test of a CMC Tube (for illustration purposes only)

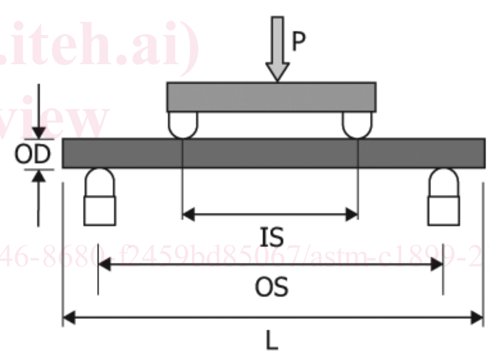

FIG. 2 Details of Terms Used to Calculate Applied Moment

Examples of flexure test setups applied to CMC tubular test specimens are contained in Appendix X1 and shown in Figs. X1.1-X1.4.

7.2.2 The only flexure test configuration used in this test method is four-point-¼-point. The inner span (IS) is determined from analytical calculations based on test material properties and tube dimensions such as the tube outer diameter (OD). Once the IS is determined, the outer span (OS) is determined as twice the inner span. Fig. 2 illustrates a four-point flexure test setup with nomenclature.

7.3 *Test Spans:*

7.3.1 Based on previous studies (**1, 2**)[3] inner span and outer span can be estimated from a material/geometry parameter such that:

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

$$\text{IS} > 9/\beta$$

$$\beta = \sqrt[4]{\frac{3(1 - v^2)}{(r_i^{tube})^2 t^2}} \tag{1}$$

$$\text{OS} = 2 \times IS$$

where:

v = Poisson's ratio of test material,
r_i^{tube} = inner radius of tubular test specimen, and
t = wall thickness of tubular test specimen.

NOTE 1—Example 1 is for a commercial CMC (v = 0.15) tube with outer diameter of 0.50 in. and tube wall thickness of 0.05 in. In this case, $\beta = \sqrt[4]{\frac{3(1 - v^2)}{(r_i^{tube})^2 t^2}} = \sqrt[4]{\frac{3(1 - 0.15^2)}{\left(\left[\frac{0.5 - 2(0.05)}{2}\right]\right)^2 0.05^2}} = 13.08\ (1/\text{in.})$ such that $\text{IS} \geq \frac{9}{\beta} = \frac{9}{13.08} = 0.69$ in. and OS = 2 × IS = 2 × 0.69 in. = 1.38 in.

NOTE 2—Example 2 is for a commercial CMC (v = 0.15) tube with outer diameter of 100 mm and tube wall thickness of 2 mm. In this case, $\beta = \sqrt[4]{\frac{3(1 - v^2)}{(r_i^{tube})^2 t^2}} = \sqrt[4]{\frac{3(1 - 0.15^2)}{\left(\left[\frac{100 - 2(2)}{2}\right]\right)^2 2^2}} = 0.133\ (1/\text{mm})$ such that $\text{IS} \geq \frac{9}{\beta} = \frac{9}{0.133} = 67.38$ mm and OS = 2 × IS = 2 × 67.38 mm = 134.77 mm.

7.3.2 An additional empirical condition (**3**) placed on the inner and outer spans to avoid shear failures and emphasize flexural stresses is IS ≥ 2 OD which is equal to OS ≥ 4 OD. Use the greater of the two IS and OS values calculated in 7.3.1.

7.4 *Loading Points*—"Cradles" are used to avoid point loads at the contact point of the roller and curved surface of the tubular test specimen without crushing the thin wall of the tube. These cradles take various forms as illustrated in Appendix X1 and Appendix X2 (**2, 4-6**).

7.4.1 A cradle may be lined with an elastomer to conform to the outer surface of the test specimen. As an example, rubber (**2, 4**) has been cut to shape using a water jet.

7.5 *Strain Measurement*—When measured, strain on the tensile surface of the tube in flexure should be determined by means of a suitable extensometer/deflectometer, strain gages, or appropriate whole-field strain methods. If Poisson's ratio is to be determined, the tubular test specimen must be instrumented to measure strain in both longitudinal and lateral transverse (that is, circumferential) directions.

7.5.1 *Extensometry*—Extensometer systems used for testing of CMC tubular test specimens shall satisfy Practice E83, Class B1 requirements and are recommended to be used in place of strain gages for test specimens with gage lengths of ≥25 mm and shall be used for high-performance tests beyond the range of strain gage applications. Calibrate extensometer systems periodically in accordance with Practice E83. For "clip-on" extensometers mechanically attached to the test specimen, make the attachment so as to cause no damage to the specimen surface. In addition, the "clip-on" extensometer should be centered in the constant moment section of the flexure test specimen bounded by the two loading points of the inner span. The gage length of the extensometer should not exceed IS-2×(cradle length) to minimize effects of the loading point contacts within the inner span.

7.5.2 *Strain Gages*—Alternatively, strain can also be determined directly from strain gages. Strain gages should be centered in the constant moment section of the flexure test specimen bounded by the two loading points of the inner span. Maximum length of the longitudinal strain gage should be IS-2×(cradle length) to minimize effects of the loading point contacts within the inner span. In addition, minimum length of the longitudinal strain gage should be either three unit cells of the fiber architecture or 9 to 12 mm and minimum width should be three unit cells of the fiber architecture or 6 mm. These recommended strain gage dimensions may make the use of strain gages on small-diameter tubular test specimens impossible because of strains due to initial curvature and averaging of strains as the strain gage installation curves up the outside of the test specimen toward the neutral axis.

NOTE 3—Note that measuring strain on composite materials using strain gages is problematic that is further exacerbated by the curved surfaces of tubular test specimens and, therefore, may not be appropriate for certain combinations of test materials and test specimen dimensions. Ideally, to eliminate the effect of misaligned uniaxial strain gages, three-element rosette strain gages should be mounted on the tensile surface of the tubular test specimen to determine maximum principal strain that should be in the longitudinal direction. Unless it can be shown that strain gage readings are not unduly influenced by localized strain events such as fiber crossovers, strain gage lengths specified in 7.5.2 should be used. Note that larger strain gages may be required for fabric reinforcements to average the localized strain effects of the fiber crossovers. However, larger strain gages adhered to the curved surfaces of the tubular test specimens may have an initial strain due to tube curvature that may render the strain reading unusable. Strain gages, surface preparation, and bonding agents should be chosen so as to provide adequate performance on the subject materials. Suitable strain recording equipment should be employed. Note that many CMCs exhibit high degrees of porosity and surface roughness and therefore require surface preparation, including surface filling, before the strain gages can be applied.

7.5.3 *Whole-Field Strain Measurement*—Digital image correlation (DIC) is a whole-field, optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images (**7, 8**). The resulting image shows the strain distribution over the surface of the tube.

NOTE 4—Several methods can be used to measure the whole-field displacement distribution using DIC. Typically, an image is recorded before deformation at a particular brightness distribution and then a similar brightness distribution is searched for in the image after deformation. The displacement components of a pixel located at the center of the subset are determined, and the displacement distributions are obtained by repeating this procedure for corresponding pixels. To determine strain, a local approximation is used in which a least-squares fit for five side-by-side data points and each point strain is determined using partial differentiation. In this case, the length of the five data points is equivalent to the "gage length" for the strain evaluation. The complete strain distribution can be obtained by repeating this procedure for the full field. DIC (**7, 8**) can employ a digital camera with minimum of 1940 × 1480 pixels capability and a 12-bit resolution equipped with a telecentric lens to measure displacement and strain field on the surface of the tubular test specimen. A photograph is taken every second on an area of about 10 × 12 mm^2 (or on the order of one unit cell of the fiber architecture). A high-contrast speckle pattern can be obtained on the test specimen surface by applying a matte randomized painting in order to produce an efficient image correlation. A ring-shaped source with a monochromatic light can provide a homogeneous and uniform illumination to improve the signal-to-noise ratio.

7.6 *Data Acquisition*—At a minimum, obtain an autographic record of transverse force and gage section transverse deflection or longitudinal strain versus time. Either analog chart recorders or digital data acquisition systems can be used for this purpose, although a digital record is recommended for ease of later data analysis. Ideally, use an analog chart recorder or plotter in conjunction with the digital data acquisition system to provide an immediate record of the test as a supplement to the digital record. Recording devices shall be accurate to within ±0.1 % for the entire testing system including readout unit as specified in Practices E4, and shall have a minimum data acquisition rate of 10 Hz, with a response of 50 Hz deemed more than sufficient.

7.6.1 Record strain or elongation of the gage section, or both, similarly to the force or as independent variables of force. Crosshead displacement of the test machine may also be recorded but should not be used to define deflection or strain in the gage section. A deflectometer (for example, mechanical or optical) at the midpoint of the gage section can be used to measure maximum transverse deflection.

7.7 *Dimension-Measuring Devices*—Micrometers and other devices used for measuring linear dimensions shall be accurate and precise to at least one half the smallest unit to which the individual dimension is required to be measured. For the purposes of this test method, measure cross-sectional dimensions to within 0.02 mm, thereby requiring dimension-measuring devices with accuracies of 0.01 mm.

8. Hazards

8.1 During the conduct of this test method, the possibility of flying fragments of broken test material is high. The brittle nature of advanced ceramics and the release of strain energy contribute to the potential release of uncontrolled fragments upon fracture. Provide means for containment and retention of these fragments for later fractographic reconstruction/analysis and to prevent respiration or injury. Polymer shields can be used to encircle the test fixture and test specimen and to capture specimen fragments.

8.2 Exposed fibers at the edges of CMC test specimens present a hazard due to the sharpness and brittleness of the ceramic fiber. Inform all those required to handle these materials of such conditions and the proper handling techniques.

9. Test Specimens

9.1 *Test Specimen Geometry:*

9.1.1 *General*—The geometry of tubular test specimens is dependent on the ultimate use of the flexural strength data. For example, if the flexural strength of an as-fabricated component is required, the dimensions of the resulting test specimen may reflect the wall thickness, tube diameter, and length restrictions of the component. If it is desired to evaluate the effects of interactions of various constituent materials for a particular CMC manufactured via a particular processing route, then the size of the test specimen and resulting gage section (that is, inner span, IS) will reflect the desired volume to be sampled. In addition, calculated outer span, OS, plus the overall length of the test specimen will influence the final design of the test specimen geometry. Tubular test specimens in flexure experience the highest tensile stresses at the outer diameter surface with the lowest tensile stresses at the inner diameter surface.

9.1.1.1 The following subsections discuss the required flexural strength tubular test specimen geometries, although any geometry is acceptable if it meets requirements for fixture dimensions and test specimen dimensions as well as acceptable fracture locations of this test method. Deviations from the recommended geometries may be necessary depending upon the particular CMC being evaluated. Stress analyses of untried test specimen geometries should be conducted to ensure that stress concentrations that can lead to undesired fractures outside the gage section do not exist. Stress analyses can indicate the magnitude of such stress concentrations while revealing the success of producing a nonuniform uniaxial stress state in the gage section of the test specimen. The CMC material designer/user, the CMC material producer, and the testing house shall mutually agree to a test specimen geometry specification with defined specimen dimensions, tolerance requirements, and finishing conditions.

9.1.2 *Test Specimen Dimensions*—Although the inner and outer diameters as well as wall thickness of CMC tubes can vary widely depending on the application, analytical and experimental studies have shown **(1-4)** that one can maximize the chances of obtaining a successful test by using consistent ranges of overall tube length as follows.

$$L_t \geq \mathrm{OS} + 6 \times (\text{unit cell size of the material}) \quad (2)$$

NOTE 5—Example 3 uses the results of Note 1 for the example of a commercial CMC (v = 0.15) tube with outer diameter of 0.50 in. and tube wall thickness of 0.05 in. Inner and outer spans are calculated as IS ≥ 0.69 in. and OS ≥ 1.38 in., respectively, per 7.3.1. However, using 7.3.2, IS ≥ 2 × OD = 2 × 0.50 = 1.00 in. and OS = 2 × IS = 2.00 in., both of which are greater than those calculated in 7.3.1. For an example of a composite test material comprised of a 5-harness satin weave (five warp yarns, five weft yarns, 0.06 in. yarn spacing, and 0.06 in. yarn width), the unit cell length is 0.30 in. and unit cell length is 0.30 in. Using these unit cell dimensions, the overall tube length is L_t ≥ OS + 6 × (unit cell size) = 2.00 in. + 6 × (0.30 in.) = 3.80 in.

NOTE 6—Example 4 uses the results of Note 2 for the example of a commercial CMC (v = 0.15) tube with outer diameter of 100 mm and tube wall thickness of 2 mm. Inner and outer spans are calculated as IS ≥ 67.38 mm and OS ≥ 134.77 mm, respectively, per 7.3.1. However, using 7.3.2, IS ≥ 2 × OD = 2 × 100 = 200 mm and OS = 2 × IS = 400 mm, both of which are greater than those calculated in 7.3.1. For an example of a composite test material comprised of a 5-harness satin weave (five warp yarns, five weft yarns, 1.48 mm yarn spacing, and 1.48 mm yarn width), the unit cell length is 7.4 mm and unit cell length is 7.4 mm. Using these unit cell dimensions, the overall tube length is L_t ≥ OS + 6 × (unit cell size) = 400 mm + 6 × (7.4 mm) = 444.4 mm.

9.2 *Test Specimen Preparation:*

9.2.1 Depending upon the intended application of the flexural strength data, use one of the following test specimen preparation procedures. Regardless of the preparation procedure used, report sufficient details regarding the procedure to allow replication.

9.2.2 *As-Fabricated*—The tubular test specimen should simulate the surface/edge conditions and processing route of an application where no machining is used; for example, as-cast, sintered, or injection molded part. No additional machining