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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.

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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