INTERNATIONAL

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Standard Test Method for Monotonic Axial Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramic Tubular Test Specimens at Ambient Temperature[1]

This standard is issued under the fixed designation C1773; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method determines the axial tensile strength and stress-strain response of continuous fiber-reinforced advanced ceramic composite tubes at ambient temperature under monotonic loading. This test method is specific to tube geometries, because fiber architecture and specimen geometry factors are often distinctly different in composite tubes, as compared to flat plates.

1.2 In the test method a composite tube/cylinder with a defined gage section and a known wall thickness is fitted/bonded into a loading fixture. The test specimen/fixture assembly is mounted in the testing machine and monotonically loaded in uniaxial tension at ambient temperature while recording the tensile force and the strain in the gage section. The axial tensile strength and the fracture strength are determined from the maximum applied force and the fracture force. The strains, the proportional limit stress, and the tensile modulus of elasticity are determined from the stress-strain data.

1.3 This test method applies primarily to 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 are 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).

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.

1.5 The test method describes a range of test specimen tube geometries based on past tensile testing of ceramic composite tubes. These geometries are applicable to tubes with outer diameters of 10 to 150 mm and wall thicknesses of 1 to 25 mm, where the ratio of the outer diameter-to-wall thickness (d_O/t) is typically between 5 and 30.

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 grips and loading fixtures, which are not addressed in this test method.

1.6 The test method addresses test equipment, gripping methods, testing modes, allowable bending stresses, interferences, tubular test specimen geometries, test specimen preparation, test procedures, data collection, calculation, reporting requirements, and precision/bias in the following sections.

1.7 *Units*—The values stated in SI units are to be regarded as standard.

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 precautionary statements are given in Section 8.

[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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***A Summary of Changes section appears at the end of this standard**

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

C1273 Test Method for Tensile Strength of Monolithic Advanced Ceramics at Ambient Temperatures

C1557 Test Method for Tensile Strength and Young's Modulus of Fibers

D3878 Terminology for Composite Materials

D5450 Test Method for Transverse Tensile Properties of Hoop Wound Polymer Matrix Composite Cylinders

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

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E251 Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages

E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application

3. Terminology

3.1 *Definitions:*

3.1.1 Pertinent definitions, as listed in Terminology C1145, Practice E1012, Terminology D3878, and Terminology E6, are shown in the following with the appropriate source in bold type. 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 *axial strain, n*—the average of the longitudinal strains measured at the surface on opposite sides of the longitudinal axis of symmetry of the test specimen by two strain-sensing devices located at the mid length of the reduced section. **E1012**

3.1.4 *bending strain, n*—the difference between the strain at the surface and the axial strain. In general, the bending strain varies from point to point around and along the reduced section of the test specimen. **E1012**

3.1.5 *ceramic matrix composite, 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**

3.1.6 *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**

3.1.7 *fracture (breaking) force, $P_{fracture}$, n*—the force at which the test specimen ruptures, breaking into two or more pieces.

3.1.8 *fracture strength, S_f, n*—the tensile stress at which the test specimen ruptures, breaking into two or more pieces or where the applied force drops off significantly. Typically, a 10 % force drop off is considered significant.

3.1.9 *gage length, l_O, n*—the original length of that portion of the test specimen over which strain or change of length is determined. **E6**

3.1.10 *matrix cracking stress, n*—the applied tensile stress at which the matrix in the composite cracks into a series of roughly parallel blocks normal to the tensile stress.

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).

3.1.11 *modulus of elasticity, E, n*—the ratio of stress to corresponding strains below the proportional limit. **E6**

3.1.12 *modulus of resilience, U_r, 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.

3.1.13 *modulus of toughness, U_t, 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 CFCCs have not been developed. The determination of the modulus of toughness as

[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.

provided in this test method for the characterization of the cumulative damage process in CFCCs may become obsolete when fracture mechanics methods for CFCCs become available.

3.1.14 *proportional limit stress, σ_o, n*—the greatest stress that a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law). **E6**

3.1.14.1 *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 stress is required, the procedure and sensitivity of the test equipment should be specified.

3.1.15 *percent bending, n*—the bending strain times 100 divided by the axial strain. **E1012**

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 *stress corrosion, n*—environmentally induced degradation that results in the formation and growth of cracks and/or damage in glasses and many ceramics when subjected to the combined action of a corroding agent and stress. **C1145**

3.1.17.1 *Discussion*—Such environmental effects commonly include the action of moisture, as well as other corrosive species, often with strong temperature dependence.

3.1.18 *tensile strength, S_u, n*—the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum force during a tension test carried to rupture and the original cross-sectional area of the test specimen. **E6**

3.1.19 *tow, n*—in fibrous composites, a continuous, ordered assembly of essentially parallel, collimated filaments, normally without twist and of continuous filaments. **D3878**

3.1.20 *uniaxial tension, n*—the application of tensile force coaxially with the long dimension of the test specimen.

4. Summary of Test Method

4.1 This test method involves the testing of a ceramic composite tube/cylinder with a known wall thickness in monotonic uniaxial tension at ambient temperature. The prepared test specimen with a defined gage section is fitted/bonded into a loading fixture and the test specimen/fixture assembly is mounted in the testing machine. The test specimen is loaded in axial tension while recording the applied force and resulting strain. The axial tensile strength S_u and the fracture strength S_f are determined from the maximum applied force and the fracture force. The axial strains, the proportional limit stress, and the tensile modulus of elasticity are determined from the stress-strain response data.

4.2 Tensile strength as used in this test method refers to the tensile strength obtained under monotonic uniaxial loading. In uniaxial loading, the force is applied coaxially with the long dimension of the tube test specimen. Monotonic refers to a continuous nonstop test rate with no reversals from test initiation to final fracture.

4.3 This test method is applicable to a range of test cylinder specimen geometries and sizes, which are described and considered in Section 9. A single fixed test specimen geometry cannot be defined because there is a wide range of composite cylinder configurations in use and development. The different described test specimen geometries are typically applicable to tubes with outer diameters of 10 to 150 mm and wall thicknesses of 1 to 25 mm, where the ratio of the outer diameter-to-wall thickness (d_O/t) is between 5 and 30.

5. Significance and Use

5.1 This test method provides information on the uniaxial tensile properties and tensile stress-strain response of a ceramic composite tube—tensile strength and strain, fracture strength and strain, proportional limit stress and strain, tensile elastic modulus, etc. The information may be used for material development, material comparison, quality assurance, characterization, and design data generation.

5.2 Continuous fiber-reinforced ceramic composites (CFCCs) are composed of continuous ceramic-fiber directional (1D, 2D, and 3D) reinforcements in a fine-grain-sized (<50 µm) ceramic matrix with controlled porosity. Often these composites have an engineered thin (0.1 to 10 µm) interface coating on the fibers to produce crack deflection and fiber pull-out. These ceramic composites offer high-temperature stability, inherent damage tolerance, and high degrees of wear and corrosion resistance. As such, these ceramic composites are particularly suited for aerospace and high-temperature structural applications (**1, 2**).[3]

5.3 CFCC components have a distinctive and synergistic combination 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) cannot be made by applying measured properties from flat CFCC plates to the design of tubes. Direct uniaxial tensile strength tests of CFCC tubes are needed to provide reliable information on the mechanical behavior and strength of tube geometries.

5.4 CFCCs generally experience "graceful" fracture from a cumulative damage process, unlike monolithic advanced ceramics which fracture catastrophically from a single dominant flaw. The tensile behavior and strength of a CFCC are dependent on its inherent resistance to fracture, the presence of flaws, and any damage accumulation processes. These factors are affected by the composite material composition and variability in material and testing—components, reinforcement architecture and volume fraction, porosity content, matrix morphology, interface morphology, methods of material fabrication, test specimen preparation and conditioning, and surface condition.

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

5.5 The results of tensile 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.

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

6. Interferences

6.1 Interferences in the testing of ceramic composite tubes arise from nine factors—material variability, dimensional variability in the test specimen, test specimen size and volume effects, surface condition variability, fabrication effects, misalignment and bending stresses, gripping and bonding failures, test environment variability, and out-of-gage failures. All of these factors have to be understood and controlled for valid tests. These interference factors are discussed in detail in Annex A1.

7. Apparatus

7.1 *Tensile Testing Machine,* comprised of the following components and illustrated schematically in Fig. 1.

7.1.1 *Fixed Member*—A fixed or essentially stationary member to which one end of the tension specimen/fixture assembly can be attached.

7.1.2 *Movable Member*—A movable member to which the opposite end of the tension specimen/fixture assembly can be attached.

7.1.3 *Drive Mechanism,* for imparting to the movable member a uniform controlled velocity with respect to the fixed member, this velocity to be regulated as specified in 10.2.4 and Annex A5.

7.1.4 *Force/Load Measurement*—A suitable force measurement device capable of showing the total tensile force carried by the test specimen. This device shall be essentially free of inertia lag at the specified rate of testing and shall indicate the applied force with an accuracy of ±1 % or better within the selected force range of the testing machine. The accuracy of the force measurement device shall be verified in accordance with Practices E4.

7.1.5 *Construction Materials*—The fixed member, movable member, drive mechanism, load train, and fixtures shall be constructed of such materials and in such proportions that the total system compliance of the system contributed by these parts is minimized.

7.2 *Gripping Fixtures*—Various types of gripping devices may be used to transmit the measured force applied by the testing machine to the tubular test specimens. Because of the

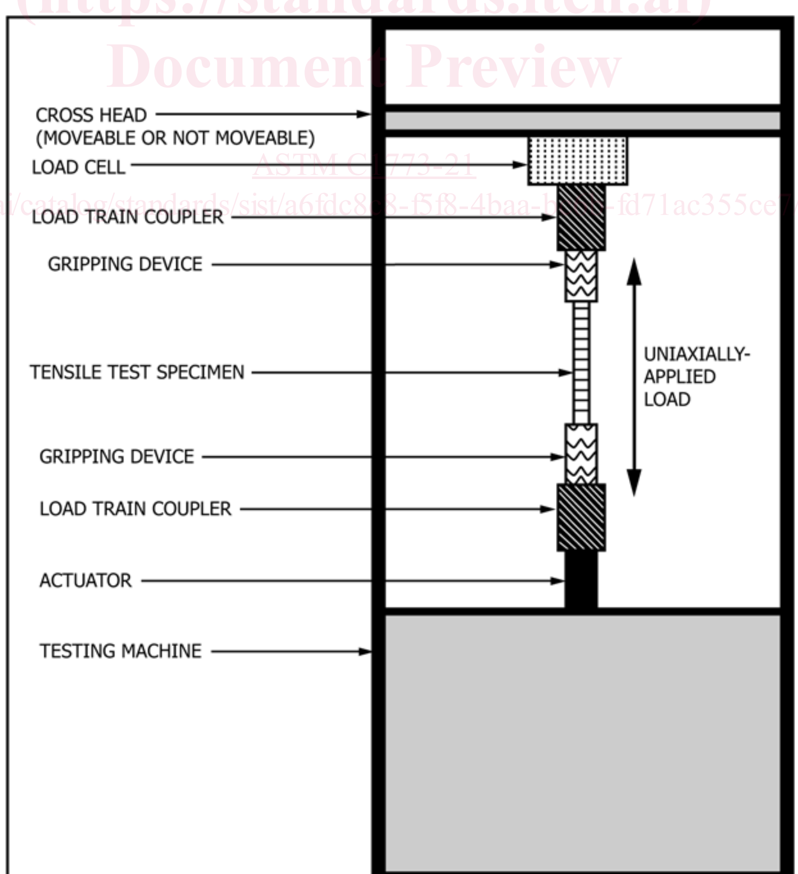


FIG. 1 Tensile Test Apparatus

brittle nature of the matrices of CFCCs, gripping devices must have a uniform, continuous contact with the entire gripped section of the tubular test specimen. (Line contact, point contacts, and nonuniform pressure can produce Hertizan-type stresses leading to crack initiation and fracture of the test specimen in the gripped section.) Gripping devices can be classed generally as those employing active grip fixtures and those employing passive grip interfaces as discussed in the following section and in Annex A3.

7.2.1 *Active Grip Fixtures*—Active grip interfaces use the direct application of a normal gripping force (through mechanical, hydraulic, or pneumatic action) to the grip section of the test specimen. These active grips commonly use split circular collets that encircle the outer circumference of the tube and grip the tube through a lateral or wedging action. This gripping action transmits the uniaxial force applied by the test machine by friction between the collet faces and the tubular test specimen. Examples, descriptions, and design/use factors for active grips are discussed in A3.1.

7.2.2 *Passive Grip Fixtures*—Passive grip interfaces transmit the force applied by the test machine to the tubular test specimen through a direct adhesive bond into the grips or by mechanical action between geometric features on the test specimen and the grip fixture. Examples, descriptions, and design/use factors for passive grips are discussed in A3.3.

7.2.3 *Load Train Couplers*—Various types of devices (load train couplers) may be used to attach the active or passive grip assemblies to the testing machine. The load train couplers in conjunction with the type of gripping device play major roles in the alignment of the load train and minimizing any extraneous bending stresses imposed in the test specimen. Load train couplers can be classified generally as fixed and nonfixed and are discussed in A3.6.

7.2.3.1 *Fixed Load Train Couplers*—Fixed couplers usually employ concentricity (x,y alignment) and angularity adjusters to minimize load train misalignments. With fixed load train couplers, alignment verification must be performed as discussed in 7.2.4 and Annex A4.

7.2.3.2 Fixed load train couplers are preferred in monotonic testing of CFCCs because they maintain a uniform stress across the composite when localized deformation occurs in the test specimen.

7.2.3.3 *Nonfixed Load Train Couplers*—Nonfixed couplers produce self-alignment of the load train during the movement of the crosshead. Generally the coupling devices rely upon freely moving linkages to eliminate applied moments as the load train components are loaded. Knife edges, universal joints, hydraulic couplers, or air bearings are examples of such devices. The operation of the nonfixed couplers must be verified for allowable bending as discussed in 7.2.4 and Annex A4.

7.2.4 *Allowable Bending and Load Train Alignment*—Extraneous and excessive bending stresses from misalignment in uniaxial tensile tests can cause or promote nonuniform stress distributions and premature failure. These bending stresses are minimized by aligning the load train for concentricity and angularity. The tensile test load train shall be properly aligned and verified in all tests.

7.2.4.1 This verification of the alignment and maximum percent bending shall be conducted at a minimum at the beginning and end of each test series. Annex A4 provides additional details on bending issues and alignment methods for CFCCs, along with a detailed procedure for verification of load train alignment, based on Practice E1012.

7.2.4.2 The recommended maximum allowable percent bending at the onset of the cumulative fracture process (for example, matrix cracking stress) for composite test specimens in this test method is 5 %.

7.3 *Strain Measurement*—Strain should be determined by means of either a suitable extensometer or bonded resistance strain gages. If Poisson's ratio is to be determined, the tubular test specimen must be instrumented to measure strain in both axial and circumferential directions.

7.3.1 *Extensometers*—Extensometers used for tensile testing of CFCC tubular test specimens shall satisfy Practice E83, Class B-1 requirements. Extensometers are recommended to be used in place of strain gages for test specimens with gage lengths >25 mm and shall be used for high-deformation tests beyond the strain range of strain gages. Extensometers shall be calibrated periodically in accordance with Practice E83. For extensometers mechanically attached to the test specimen, the attachment should be such as to cause no damage to the specimen surface. In addition, the weight of the extensometer should be supported so as not to introduce bending stresses in the test specimen greater than those allowed in 7.2.4.2.

7.3.2 *Strain Gages*—Although extensometers are commonly used for CFCC strain measurement, strain can also be determined with bonded resistance strain gages and suitable strain recording equipment. The strain gages, surface preparation, and bonding agents should be chosen to provide adequate performance on the subject materials. Gage calibration certification shall comply with Test Methods E251. A general reference on strain gages for composites is Tuttle and Brinson (**3**). Some guidelines on the use of strain gages on ceramic composites are as follows.

7.3.2.1 *Strain Gage Length*—Unless it can be shown that strain gage readings are not unduly influenced by localized strain events such as fiber crossovers, strain gages should not be less than 9 to 12 mm in length for the longitudinal direction and not less than 6 mm in length for the transverse direction. When testing woven fabric composites, the strain gages should have an active gage length that is at least as great as the characteristic unit cell (repeating unit) of the weave; this averages the localized strain effects of the fiber crossovers.

7.3.2.2 *Surface Preparation*—Many CFCCs have high degrees (>5 %) of porosity and surface roughness and therefore require surface preparation (such as surface filling with epoxy) before the strain gages can be applied and fully bonded to the surface. Reinforcing fibers in the composite should not be exposed or damaged during the surface preparation process.

7.3.2.3 *Temperature Considerations*—Consideration of some form of temperature compensation for the strain gages is recommended, even when testing at standard laboratory atmosphere. Temperature compensation is required when testing in nonambient temperature environments.

7.3.2.4 *Transverse Sensitivity*—Consideration should be given to the transverse sensitivity of the selected strain gage/s. This is particularly important for a transversely mounted gage used to determine Poisson's ratio, because composites often have markedly different moduli in different directions in the fiber architecture. The strain gage manufacturer should be consulted for recommendations on transverse sensitivity corrections and effects on composites.

7.3.2.5 Poisson's ratio is easily determined with biaxial (0° to 90°) strain gage rosettes which measure the strain in both the axial and circumferential directions.

7.3.3 *Data Acquisition*—At the minimum, an autographic record of applied tensile force and gage section elongation (or strain) versus time should be obtained. 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.

7.3.3.1 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.

7.3.3.2 Strain or elongation of the gage section, or both, should be recorded either 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 displacement or strain in the gage section, especially when self-aligning couplers are used in the load train.

7.3.4 *Dimension Measurement Devices*—Ball or anvil-type micrometers should be used for measuring the test specimen inner and outer diameters, to an accuracy of 0.02 mm or 1 % of the measured dimension, whichever is greater. Flat, anvil-type micrometer or calipers of similar resolution may be used for measuring the overall test specimen length and the defined gage length.

7.3.5 *Conditioning Chamber*—When conditioning CFCC materials at non-ambient environments, an environmental conditioning chamber with a controlled temperature and humidity levels is required. The chamber shall be capable of maintaining the required temperature to within ±3 °C and the required relative humidity level to within ±5 %. Chamber conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals.

7.3.6 *Environmental Test Chamber*—When testing materials at other than ambient laboratory conditions (high/low humidity, high/low temperatures, or both), the environmental chamber shall be capable of maintaining the gage section of the test specimen at the required temperature to within ±3 °C or the required relative humidity level to within ±5 %, or both. Chamber conditions shall be monitored during the test either on an automated continuous basis or on a manual basis at regular intervals.

7.3.7 *Calibration and Standardization*—The accuracy of all measuring equipment shall have certified calibrations that are current at the time the equipment is used.

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. Means for containment and retention of these fragments for later reconstruction and fractographic analysis is highly recommended. (Plastic shields can be used to encircle the test fixture and to capture specimen fragments.)

8.2 Exposed fibers at the edges of CFCC test specimens present a hazard due to the sharpness and brittleness of the ceramic fiber. All those required to handle these materials should be well informed of such conditions and the proper handling techniques.

9. Test Specimens

9.1 *Geometry Considerations*—CFCC tubes are fabricated in a wide range of sizes and geometries and across a wide spectrum of different reinforcement fibers, distinctive ceramic matrix materials, and markedly different fabrication methods. In addition, the fiber architecture for CFCC tubes has a broad range of configurations with different fiber loadings and directional variations. It is currently not practical to define a single test specimen geometry that is applicable to all CFCC tubes.

9.2 The selection and definition of a tubular test specimen geometry depends on the purpose of the tensile testing effort. For example, if the tensile strength of an as-fabricated component with a defined geometry is required, the dimensions of the resulting tensile 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 CFCC manufactured via a particular processing route, then the size of the test specimen and resulting gage section will reflect the size and geometry limits of that processing method. In addition, grip devices and load train couplers (as discussed in Section 7 and Annex A3) will influence the final design of the test specimen geometry.

9.3 *Test Specimen Dimensions*—This test method is generally applicable to tubes with outer diameters of 10 to 150 mm and wall thicknesses of 1 to 25 mm, where the ratio of the outer diameter-to-wall thickness (d_O/t) is commonly between 5 and 30.

9.4 *Test Specimen Geometries*—Tubular test specimens are classified into two groups—straight-sided specimens and contoured gage specimens, as shown in Figs. 2 and 3. Contour gage specimens are distinctive in having gage sections with thinner wall thicknesses than the gripping sections. Both types of test specimens can be used in active and passive grips.

9.4.1 Annex A2 provides different examples of straight-sided and contoured gage test specimen tube geometries along with geometry, design, fabrication, and preparation information. However, any CFCC tube geometry is acceptable if fracture failure occurs consistently in the designated gage section with minimal extraneous bending stresses. Deviations from the example geometries are permitted depending upon the particular CFCC tube being evaluated.

9.4.2 Although straight-sided tubular test specimens are easier to fabricate and are commonly used, tube test specimens with contoured gage sections are preferred to promote tensile

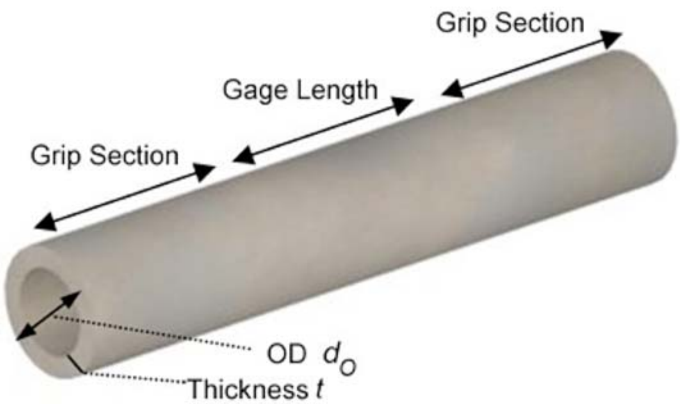


FIG. 2 Schematic of Straight-Sided Tube Specimen

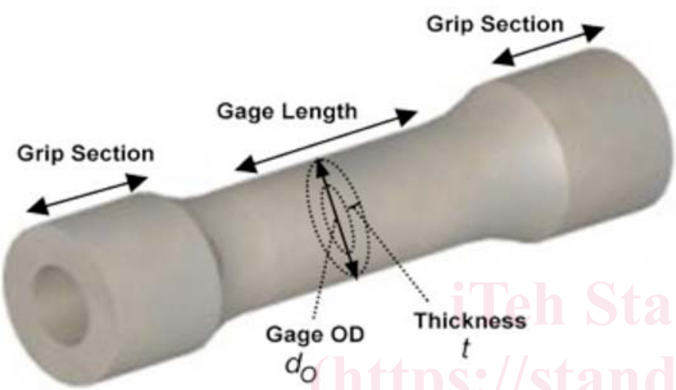


FIG. 3 Schematic of Contoured Gage Section Tube Specimen

failure in the uniformly stressed gage section. The contoured gage sections are formed by integral thick-wall grip sections in the composites or by adhesively bonded collars/sleeves in the grip sections (Annex A2). A key factor in contoured gage section specimens is the minimizing of any stress concentrations at the geometric transitions into the gage sections.

9.5 *Baseline Fabrication*—The composition, architecture, and fabrication processing of the CFCC composite must be well defined and suitably controlled to produce components and test specimens with acceptable, repeatable, and uniform physical and mechanical properties. The composition, fiber architecture, fabrication processing, and lot identification should be fully determined and documented.

9.6 *Test Count and Test Specimen Sampling*—A minimum of five valid test specimens is required for the purposes of estimating a mean/average. A greater number of valid test specimens may be necessary if estimates regarding the form of the strength distribution are required. The procedures outlined in Practice E122 should be used to estimate the number of tests needed for determining a mean with a specified precision. If material cost or test specimen availability limits the number of possible tests, fewer tests can be conducted to determine an indication of material properties. Test specimens should be selected and prepared from representative CFCC samples that meet the stated testing objectives and requirements. The method of sampling shall be reported.

9.7 *Dimensional Tolerances and Variability*—Dimensional tolerances will depend on the specific selected specimen geometry, the method of manufacturing, and the performance requirements of the CFCC application. It is common for CFCC tubes to have significant diametral variability (1 to 5 mm) in the as-fabricated condition, particularly for larger diameter tubes. The gage section may or may not be machined to a specific tolerance (A2.7). Any significant (>2 %) dimensional variability in the OD and ID should be determined and recorded.

9.8 Nondestructive evaluation (ultrasonics, thermal imaging, computerized tomography, etc.) may be used to assess internal morphology (delaminations, porosity concentrations, etc.) in the composite. Record these observations/measurements and the results of any nondestructive evaluations and include them in the final report.

9.9 *Surface Measurement*—In some cases it is desirable, but not required, to measure surface roughness in the gage section to quantify the surface condition. Methods such as contacting profilometry can be used to determine surface roughness parallel and perpendicular to the tensile axis across a sufficient area to adequately characterize the surface. When measured, surface roughness should be reported.

9.10 *Test Specimen Storage and Handling*—Care should be exercised in handling, packaging, and storage of finished test specimens to avoid the introduction of random surface flaws. In addition, attention should be given to pre-test storage of test specimens in controlled environments or desiccators to avoid unquantifiable environmental (for example, humidity) degradation of test specimens prior to testing.

10. Test Procedure

10.1 Any deviation from this test method shall be described in detail in the test report.

10.2 *Test Plan Parameters and Factors*—The following test specimen parameters and experimental test factors have to be defined in detail as part of the test plan.

10.2.1 The test specimen geometry, sampling method, test specimen preparation procedure, and any environmental conditioning or test parameters (temperature, humidity, time), or combinations thereof.

10.2.2 The desired tensile properties and the data reporting format.

10.2.3 An estimate of the tensile properties for the CFCC being tested (tensile strength and strain, modulus of elasticity, etc.). This information is used to determine the required capabilities and range of the test apparatus—load frame, load cells, grips, extensometers, strain gages, etc.

10.2.4 Test modes and rates can have distinct and strong influences on fracture behavior of advanced ceramics, even at ambient temperatures, depending on test environment or condition of the test specimen. Test modes may involve force, displacement, or strain control. Recommended rates of testing are intended to be sufficiently rapid to obtain the maximum possible tensile strength at fracture of the material. Typically, fracture should occur within 5 to 60 s after the start of the test. Annex A5 describes the different test modes and provides guidance on how to choose a test mode and rate. In all cases, the test mode and rate must be reported.

10.2.5 The method of strain measurement (extensometer, strain gauge, or both) and the strain measurement plan (type and gage length of extensometer, type and number of strain gauges, locations/positions, and control/measurement system) should be noted and reported.

10.3 *Test Specimen Preparation*—Test specimen preparation consists of three steps—conditioning, measurement, and strain gauge installation (if used).

10.3.1 *Conditioning*—Condition the test specimens at the desired temperature, humidity, and time, per the test plan.

10.3.2 *Test Specimen Measurement*—Conduct 100 % inspection/measurements of all test specimens for surface condition (cracks, surface flaws, surface porosity, etc.). Note that the frequency of valid gage section fractures and minimal bending in the gage section are dependent on test specimen dimensions being within the desired tolerances.

10.3.2.1 Measure the outer diameter (d_O), the internal diameter (d_i), or the wall thickness (t), or both, of the gage section of each test specimen to within 0.02 mm or 1 % of the measured dimension, whichever is greater. Make three measurements around the circumference on at least three different cross-sectional planes along the length of the gage section. Record and report the measured dimensions and locations of the measurements for use in the calculation of the tensile stress. Use the average of the multiple measurements in the stress calculations [$d_i = d_o - 2t$].

10.3.2.2 To avoid damage in the gage section area it is recommended that these measurements be made either optically (for example, an optical comparator) or mechanically using a self-limiting (friction or ratchet mechanism) flat, anvil-type micrometer with anvil diameter of at least 5 mm. In all cases the resolution of the instrument shall be as specified in 7.3.4.

10.3.2.3 Exercise caution to prevent damage to the test specimen gage section. Ball-tipped micrometers may be preferred when measuring test specimens with rough or uneven nonwoven surfaces.

10.3.2.4 Alternatively, to avoid damage to the gage section (or in cases where it is not possible to infer or determine gage section wall thickness), use the procedures described in 10.13 to make post-fracture measurements of the gage section dimensions. Note that in some cases, the fracture process can severely fragment the gage section in the immediate vicinity of the fracture, thus making post-fracture measurements of dimensions difficult. In these cases, it is advisable to do pre-test measurements per 10.3.2 to ensure reliable measurements.

10.3.2.5 Measure and record the overall length of the test specimen and the length of the gage section, if it is defined.

10.3.2.6 If needed, measure the surface finish of the gage section of the test specimens using a suitable method (see 9.7).

10.3.3 *Strain Gage Installation*—Attach strain gages to the test specimen per the strain measurement test plan, ensuring that strain gages are properly oriented and securely bonded to the test specimen per the manufacturer's instructions. (Strain gage installation can also be done after the test specimen is bonded into the grip fixtures.)

10.4 *Test Specimen Assembly/Fixturing*—Two test specimen factors have to be considered in specimen assembly/fixturing—the use of end plugs and the method of adhesive bonding.

10.4.1 *End Plugs*—End plugs may be used in active gripping to prevent collapse in the grip sections. If end plugs (A3.2) are being used in the test (for active gripping), insert and bond the two end plugs into the test specimen, using the designated adhesive and alignment procedure. Ensure that the end plugs are centered in the test specimen and at the proper depth. Cure the adhesive per the manufacturer's specifications.

10.4.2 *Adhesive Bonding into the Grip Fixtures*—If adhesive bonding grip fixtures are being used (Annex A3), the test specimen should be secured into the two end fixtures by filling the fixture cavities with the adhesive material (prepared per the manufacturer's instructions). Position the test specimen into the two grip fixtures and use an alignment fixture to ensure that the two end fixtures and the test specimen are aligned concentrically. Cure the adhesive per the manufacturer's specifications. After curing, measure the free length/distance between the end fixtures at four points at 90° intervals around the specimen/fixture circumference. Significant deviations (>2 %) in the measured length are an indication of test specimen or grip section misalignment.

10.5 *Load Train Alignment and Bending Stress Assessment*—If load train alignment is done with a "dummy" specimen, adjust/verify the alignment of the load train, per the guidance in 7.2.4 and Annex A4.

10.6 *Test Specimen Insertion*—Each grip system and test specimen geometry (as described in Section 7, Annex A2, and Annex A3) will require a unique procedure for mounting the test specimen in the load train. If special fixture components are required for each test, these should be identified and noted in the test report.

10.6.1 Mount the test specimen/assembly into the grips and load train, ensuring that the test specimen is properly positioned and aligned in the grips. Tighten the grips evenly and firmly to the degree necessary to prevent slippage of the test specimen during the test but not to the point where the specimen would be crushed.

10.6.2 If strain gages are used to monitor bending, the strain gages should be zeroed with the test specimen attached at only one end, so that it is hanging free. This will ensure that bending due to the grip closure is factored into the measured bending.

10.6.3 If load train alignment is done with the actual test specimen, adjust/verify the alignment of the load train, per the guidance in 7.2.4 and Annex A4.

10.6.4 Mark the test specimen with an indelible marker as to top and bottom and front (side facing the operator) in relation to the test machine. In the case of strain-gaged test specimens, orient the test specimen such that the "front" of the test specimen and a unique strain gage coincide (for example, Strain Gage 1, designated SG1).

10.7 *Extensometers and Strain Gages*—Mount/connect the extensometer/s on the test specimen, if an extensometer is being used. Connect the lead wires of any strain gages to the conditioning equipment and allow the strain gages to equilibrate under power for at least 30 min prior to conducting the verification tests. This will minimize drift during the test.

10.8 *Test Environment*—If an environmental test chamber is being used, condition the test specimen at the defined temperature and humidity for the designated period of time. Record the environmental conditions and the "time to equilibrium" for each test.

10.9 *Testing Machine Setup*—Activate and adjust the testing machine for initial crosshead position, zero load, and desired test mode and test rate. Set the mode and speed of testing so that the failure occurs in less than 60 s, using the guidance in Annex A5.

10.10 *Data Collection Equipment*—Assemble and activate the data recording instrumentation for force and strain, setting the range, sensitivity, and recording/data collection rate.

10.11 The tensile test is conducted in the following sequence.

10.11.1 Determine and record the ambient temperature and the relative humidity in accordance with Test Method E337.

10.11.2 Initiate the data acquisition. Preload the test specimen to the designated force level, if necessary.

10.11.3 Initiate the primary test mode and record force versus strain (or displacement) continuously.

10.11.4 Load the test specimen to fracture failure. Record the maximum force, the fracture force, and the corresponding strain (or extension). Fracture is marked by specimen breakage and separation or where the applied force drops off significantly. Typically, a 10 % force drop off is considered significant. The maximum force and the fracture force should be measured within ±1.0 % of the force range and noted for the report.

10.11.5 After specimen fracture, disable the action of the test machine and the data collection of the data acquisition system. Carefully remove the test specimen halves from the grips. Take care not to damage the fracture surfaces by preventing them from contact with each other or other objects. Place the test specimen halves along with other fragments from the gage section into a suitable, protective package/container for later analysis.

10.12 *Invalid and Censored Tests*—A valid individual test is one which meets all the following requirements—all the testing requirements of this test method are met and final fracture occurs in the uniformly stressed gage section.

10.12.1 Fracture/failure occurring in the grip sections is an invalid test. Failure outside the designated gage section and within one specimen diameter of the grip/bond boundary on the specimen and the test fixture may be a grip failure, and should be considered as a censored test.

10.12.1.1 Note that results from test specimens fracturing outside the uniformly stressed gage section are not recommended for use in the direct calculation of an average/mean tensile strength or fracture strength for the entire test set. Results from test specimens fracturing outside the gage section (or outside the extensometer gage length of straight-sided test specimens) are considered anomalous and can be used only as censored tests (that is, test specimens in which a tensile stress at least equal to that calculated by Eq 4 was sustained in the uniform gage section before the test was prematurely terminated by a non-gage section fracture) as discussed in Practice C1239 for the determination of estimates of the strength distribution parameters. From a conservative standpoint, in completing a required statistical sample (for example, N = 5) for purposes of average strength, test one replacement test specimen for each test specimen that fractures outside the gage section.

10.12.2 A significant fraction (>10 %) of invalid or censored failures (or both) in a sample population shall be cause to re-examine the means of force introduction into the material. Factors of concern that can produce invalid tests include the alignment of the test specimen in the fixture, alignment of the fixtures in the grips, collar materials, and the adhesive used to bond the test specimen to the fixture.

10.13 *Post-Test Measurement and Analysis:*

10.13.1 *Dimensions*—Measure and report the gage section OD and ID dimensions at the fracture location to ±0.02 mm, if the gage section has not been overly fragmented by the fracture process. Use these post-test dimension measurements to calculate the stresses in Section 11. If a post-test measurement of the OD and ID dimensions cannot be made due to fragmentation, then use the average dimensions measured in 10.3.2.

10.13.2 *Fracture Location*—Measure and report the fracture location relative to the midpoint of the gage section. The convention used should be that midpoint of the gage section is 0 mm with positive (+) measurements toward the top of the test specimen as tested (and marked) and negative (–) measurements toward the bottom of the test specimen as tested (and marked).

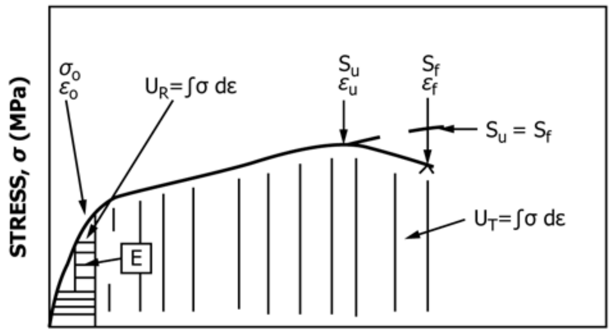
10.13.3 *Post-Test Fractographic Examination*—Visual examination and light microscopy of the fracture surfaces should be conducted to determine the mode and type of fracture (that is, brittle or fibrous) as a function of composite composition and architecture, material variability, damage accumulation, and failure zones. In addition, subjective observations can be made of the length of fiber pull-out, fracture plane orientation, degree of interlaminar fracture, and other pertinent details of the fracture surface. The results of the fractographic analysis should be reported.

11. Calculation of Results

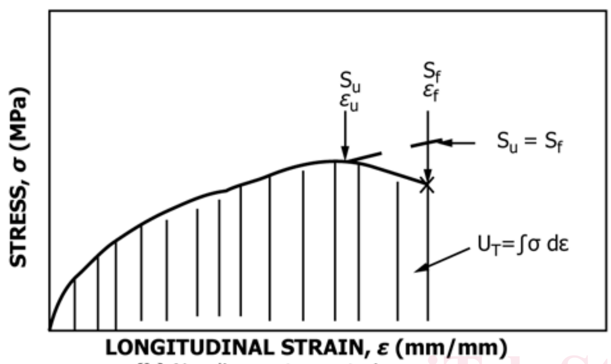
11.1 *Discussion of Stress-Strain Responses for Different CFCCs (Graphs)*—Various types of CFCC material, due to the nature of their constituents, processing routes, and prior mechanical history, may exhibit vastly different stress-strain responses as illustrated schematically in Fig. 4(a), (b), and (c). Therefore, interpretation of the test results will depend on the type of response exhibited. Points corresponding to the following calculated values are shown on the appropriate diagrams.

NOTE 1—At the high-strain portions of the curves, two different possible behaviors are depicted: cases where stress drops prior to fracture (solid line) and cases where stress continues to increase to the point of fracture (dashed line).

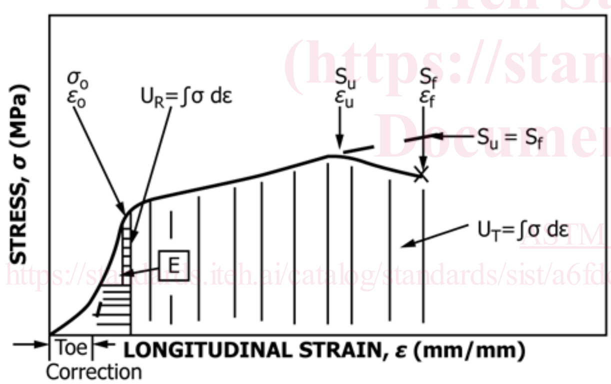
11.2 *Engineering Stress and Strain Calculation*—Calculate the engineering stress as:



(a) Stress-strain curve with a linear region



(b) Non linear stress-strain curve



(c) Stress-strain curve with a linear region and toe

FIG. 4 Examples (a, b, c) of CFCC Stress-Strain Curves

$$\sigma = P/A \quad (1)$$

where:

σ = the engineering stress in units of MPa,
P = the applied, uniaxial tensile force at any time in units of N, and
A = the original cross-sectional area of the test specimen in units of mm^2.

The cross-sectional area A of the tube specimen is calculated as:

$$A = \frac{\pi(d_o^2 - d_i^2)}{4} = \pi t(d_o - t) \quad (2)$$

where:

d_o = the average outer diameter of the gage section in units of mm as detailed in 10.3.2 or 10.13.1,
d_i = the average inner diameter of the gage section in units of mm as detailed in 10.3.2 or 10.13.1, and
t = the average wall thickness of the gage section in units of mm as detailed in 10.3.2 or 10.13.1.

11.2.1 *Engineering Strain Calculation:*

11.2.1.1 *Extensometer Strain Calculation*—For strain measurement by extensometer, calculate the engineering strain as:

$$\varepsilon_{xx} = (l - l_o)/l_o \quad (3)$$

where:

ε_{xx} = the engineering strain (no dimensions), either axial (ε_{11}) or transverse (ε_{22}) based on the orientation of the extensometer,
l = the gage length (extensometer gage length) at any time in units of mm, and
l_o = the original/extensometer gage length in units of mm.

11.2.1.2 *Strain Gage Calculation*—If bonded strain gages are being used, the appropriate strain values are obtained independently of the test specimen gage length. The average principal strains (axial ($\varepsilon^a{}_{11}$), circumferential ($\varepsilon^a{}_{22}$), or both) are calculated in the following three-step process.

(1) Correct the experimental strain gage readings ($\varepsilon^x{}_{11}$, $\varepsilon^x{}_{22}$, or both) for transverse sensitivity for each strain gage (single or rosette) to give the corrected strain gage readings ($\varepsilon^c{}_{11}$, $\varepsilon^c{}_{22}$, or both).

(2) Calculate separately the principal strains ($\varepsilon^i{}_{11}$, $\varepsilon^i{}_{22}$, or both) for each strain gage (single or rosette) using the transverse corrected strain gage readings.

(3) Calculate the average principal strains ($\varepsilon^a{}_{11}$, $\varepsilon^a{}_{22}$, or both) in the test specimen by taking the average of the principal strains ($\varepsilon^i{}_{11}$, $\varepsilon^i{}_{22}$, or both) from all the mounted strain gages. (See Test Method D5450 Section 12 for a full description of strain calculation with multiple strain gages.)

11.2.1.3 Note that in some cases the initial portion of the stress-strain ($\sigma - \varepsilon$) curve shows a nonlinear region or "toe" followed by a linear region as shown in Fig. 4(c). This toe may be an artifact of the test specimen or test conditions (for example, straightening of a warped test specimen) and thus may not represent a property of the material. The $\sigma - \varepsilon$ curve can be corrected for this toe by extending the linear region of the curve to the zero-stress point on the strain axis as shown in Fig. 4(c). The intersection of this extension with the strain axis is the toe correction that is subtracted from all values of strain greater than the toe correction strain. The resulting $\sigma - \varepsilon$ curve is used for all subsequent calculations.

11.3 *Axial Tensile Strength and Strain Calculation:*

11.3.1 Calculate the axial tensile strength using the following equation as:

$$S_u = P_{\max}/A \quad (4)$$

where:

S_u = the tensile strength in units of MPa,
P_{max} = the maximum force prior to failure in units of N, and
A = the original cross-sectional area in the gage section, $\pi(d_o^2 - d_i^2)/4 = \pi t(d_o - t)$ in units of mm^2.

11.3.1.1 Determine the axial strain at tensile strength, ε_u, as the axial engineering strain (ε_{11}) corresponding to the tensile strength measured during the test.

11.4 *Axial Fracture Strength and Strain Calculation:*

11.4.1 Calculate the axial fracture strength using the following equation as:

$$S_f = P_{fracture}/A \tag{5}$$

where:

S_f = the fracture strength in units of MPa,
$P_{fracture}$ = the fracture force (breaking force) when the test specimen separates into two or more pieces, in units of N, and
A = the original cross-sectional area in the gage section, $\pi(d_o^2 - d_i^2)/4 = \pi t(d_o - t)$ in units of mm^2.

In some instances the tensile strength and the fracture strength are equal ($S_u = S_f$) as shown by the dashed line in Fig. 4(a), (b), and (c).

11.4.2 Determine axial strain at fracture strength, ε_f, as the axial engineering strain (ε_{11}) corresponding to the fracture strength measured during the test. In some instances as shown by the dashed line in Fig. 4(a), (b), and (c), $\varepsilon_u = \varepsilon_f$.

11.5 *Elastic Tensile Modulus*—Calculate the modulus of elasticity as follows:

$$E = \Delta\sigma/\Delta\varepsilon \tag{6}$$

where E is the modulus of elasticity and $\Delta\sigma/\Delta\varepsilon$ is the slope of the $\sigma - \varepsilon$ curve within the linear region as shown in Fig. 4(a) and (c). Note that the modulus of elasticity may not be defined for materials that exhibit entirely nonlinear $\sigma - \varepsilon$ curves as shown in Fig. 4(b).

11.6 *Poisson's Ratio*—Calculate Poisson's ratio (if circumferential strain is measured) as follows:

$$\nu = -\Delta\varepsilon_{22}/\Delta\varepsilon_{11} \tag{7}$$

where ν is Poisson's ratio, and $\Delta\varepsilon_{22}/\Delta\varepsilon_{11}$ is the slope of the linear region of the plot of circumferential strain, ε_{22}, versus axial strain, ε_{11}. Note that Poisson's ratio may not be defined for materials which exhibit nonlinear $\sigma - \varepsilon$ curves over the entire history as shown in Fig. 4(b) (although this must be verified by plotting ε_{22} versus ε_{11} to determine whether or not a linear region exists).

11.7 *Proportional Limit Stress and Strain Calculation*—Determine the proportional limit stress, σ_o, by one of the following methods. Note that by its definition the proportional limit stress, σ_o, may not be defined for materials that exhibit entirely nonlinear $\sigma - \varepsilon$ curves as shown in Fig. 4(b).

11.7.1 *Offset Method*—Determine σ_o by generating a line running parallel to the same part of the linear part of the $\sigma - \varepsilon$ curve used to determine the modulus of elasticity in 11.5. The line so generated should be at a strain offset of 0.05% (0.0005 mm/mm). The proportional limit stress is the stress level at which the offset line intersects the $\sigma - \varepsilon$ curve. See Fig. 5 for a graphical illustration of this technique.

NOTE 2—In some CFCC materials with low fracture strain values (<1 %) and relatively steep second-stage stress-strain slopes, an offset strain of 0.05 % is too large and gives an inaccurate assessment of the proportional limit stress. In such cases, an alternate offset strain value should be defined and reported to give an accurate value for the proportional limit stress. As an example, some researchers use a 5 % calculation to determine an offset strain, shown as follows:

Offset strain (%) = 5 % × (nominal proportional limit stress) / (elastic modulus). Fig. 6 shows a stress-strain curve with 0.01 % and 0.05 % strain offsets to determine the proportional limit stress.

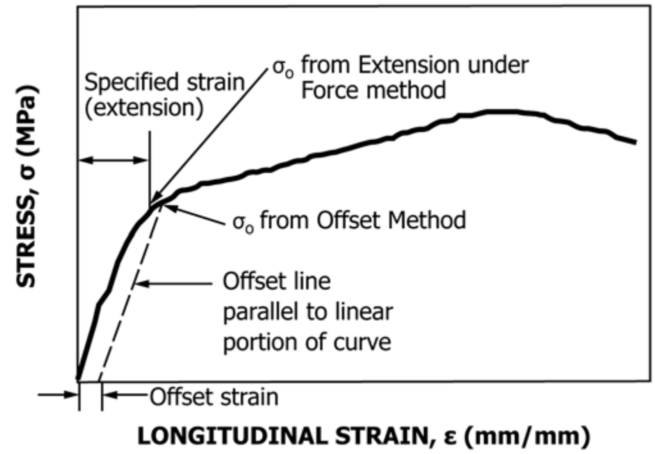


FIG. 5 Schematic Diagram of Methods for Determining the Proportional Limit Stress and Strain

11.7.2 *Extension Under Force Method*—Determine σ_o by noting the stress on the $\sigma - \varepsilon$ curve that corresponds to a specified strain. The specified strain may or may not be in the linear region of the $\sigma - \varepsilon$ but the specified strain at which σ_o is determined must be constant for all tests in a set with the specified strain reported. See Fig. 5 for a graphical illustration of this technique.

11.7.3 *Deviation from Linearity Method*—Determine σ_o by noting the stress, σ_i, on the $\sigma - \varepsilon$ curve at which there is a specified percent deviation (for example, %dev = 10) from the stress calculated from the elastic relation, $\sigma = E\varepsilon_i$ such that:

$$\%\text{dev} = 100\left[\frac{(E\ \varepsilon_i) - \sigma_i}{\sigma_i}\right] \tag{8}$$

where:

σ_i and ε_i = the i-th stress and corresponding strain, respectively, on the $\sigma - \varepsilon$ curve, and
E = the axial modulus of elasticity.

The proportional limit stress is determined such that $\sigma_o = \sigma_i$ when %dev first equals or exceeds the specified value when evaluating increasing σ_i and ε_i starting from zero.

11.7.4 *Strain at Proportional Limit Stress*—Determine the strain at proportional limit stress, ε_o, as the strain corresponding to the proportional limit stress determined for the test.

11.8 *Modulus of Resilience (U_R)*—Calculate the modulus of resilience as the area under the linear part of the $\sigma - \varepsilon$ curve or alternatively estimated as:

$$U_R = \int_o^{\varepsilon_o} \sigma\, d\varepsilon \approx \frac{1}{2}\sigma_o\varepsilon_o \tag{9}$$