Designation: C1819 – 15

Standard Test Method for Hoop Tensile Strength of Continuous Fiber-Reinforced Advanced Ceramic Composite Tubular Test Specimens at Ambient Temperature Using Elastomeric Inserts[1]

This standard is issued under the fixed designation C1819; 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 the hoop tensile strength including stress-strain response of continuous fiber-reinforced advanced ceramic tubes subjected to an internal pressure produced by the expansion of an elastomeric insert undergoing monotonic uniaxial loading at ambient temperature. This type of test configuration is sometimes referred to as an overhung tube. This test method is specific to tube geometries, because flaw populations, 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 loaded via internal pressurization from the radial expansion of an elastomeric insert (located midway inside the tube) that is longitudinally compressed from either end by pushrods. The elastomeric insert expands under the uniaxial compressive loading of the pushrods and exerts a uniform radial pressure on the inside of the tube. The resulting hoop stress-strain response of the composite tube is recorded until failure of the tube. The hoop tensile strength and the hoop fracture strength are determined from the resulting maximum pressure and the pressure at fracture, respectively. The hoop tensile strains, the hoop proportional limit stress, and the modulus of elasticity in the hoop direction are determined from the stress-strain data. Note that hoop tensile strength as used in this test method refers to the tensile strength in the hoop direction from the induced pressure of a monotonic, uniaxially-loaded elastomeric insert where monotonic refers to a continuous nonstop test rate without reversals from test initiation to final fracture.

1.3 This test method applies primarily to advanced ceramic matrix composite tubes with continuous fiber reinforcement: uni-directional (1-D, filament wound and tape lay-up), bidirectional (2-D, fabric/tape lay-up and weave), and tridirectional (3-D, 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).

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 is applicable to a range of test specimen tube geometries based on a non dimensional parameter that includes composite material property and tube radius. Lengths of the composite tube, push rods and elastomeric insert are determined from this non dimensional parameter so as to provide a gage length with uniform, internal, radial pressure. A wide range of combinations of material properties, tube radii, wall thicknesses, tube lengths and insert lengths 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 grips and loading fixtures, which are not addressed in this test standard.

1.6 This test method addresses tubular test specimen geometries, test specimen methods, testing rates (force rate, induced pressure rate, displacement rate, or strain rate), and data collection and reporting procedures in the following sections.

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[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).

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 and health practices and determine the applicability of regulatory limitations prior to use.* Specific hazard statements are given in Section 8 and Note 1.

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

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

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

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

E380 Practice for Use of the International System of Units (SI) (the Modernized Metric System) (Withdrawn 1997)[3]

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

SI10-02 IEEE/ASTM SI 10 American National Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 *Definitions:*

3.1.1 The definitions of terms relating to hoop tensile strength 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, Terminology C1145, Terminology D3878, and Terminology 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. (See Terminology C1145.)

3.1.3 *breaking force, n*—the force at which fracture occurs. (See Terminology 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.

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.

3.1.6 *gage length, n*—the original length of that portion of the specimen over which strain or change of length is determined. (See Terminology E6.)

3.1.7 *hoop tensile strength, n*—the maximum tensile component of hoop stress which a material is capable of sustaining. Hoop tensile strength is calculated from the maximum internal pressure induced in a tubular test specimen.

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

3.1.8.1 *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 region 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 during unloading (elastic limit).

3.1.9 *modulus of elasticity, n*—the ratio of stress to corresponding strain below the proportional limit. (See Terminology E6.)

3.1.10 *modulus of resilience, 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.

3.1.11 *modulus of toughness, 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).

3.1.11.1 *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

[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] The last approved version of this historical standard is referenced on www.astm.org.

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.

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

3.1.12.1 *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. (See Terminology E6.)

3.1.13 *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.

4. Summary of Test Method

4.1 In the test method a composite tube/cylinder with a defined gage section and a known wall thickness is loaded by the radial expansion an elastomeric insert (located midway inside the tube) that is compressed longitudinally between pushrods. The elastomericinsert expands under the uniaxial compressive loading of the pushrods and exerts a uniform radial pressure on the inside of the tube. The resulting hoop stress-strain response of the composite tube is recorded until failure of the tube. The hoop tensile strength and the hoop fracture strength are determined from the resulting maximum pressure and the pressure at fracture. The hoop tensile strains, the hoop proportional limit stress, and the modulus of elasticity in the hoop direction are determined from the stress-strain data.

4.2 Hoop tensile strength as used in this test method refers to the tensile strength in the hoop direction from the induced pressure of a monotonic, uniaxially-loaded elastomeric insert where monotonic refers to a continuous test rate with no reversals.

4.3 The test method is applicable to a range of test specimen tube geometries based on a non dimensional parameter that includes composite material property and tube radius. Lengths of the composite tube, push rods and elastomericinsert are determined from this non dimensional parameter so as to provide a gage length with uniform, internal, radial pressure. A wide range of combinations of material properties, tube radii, wall thicknesses, tube lengths and insert lengths are possible.

5. Significance and Use

5.1 This test method (a.k.a., overhung tube method) may be used for material development, material comparison, material screening, material down selection and quality assurance. This test method is not recommended for material characterization, design data generation and/or material model verification/validation.

5.2 Continuous fiber-reinforced ceramic composites (CFCC) are composed of continuous ceramic-fiber directional (1-D, 2-D, and 3-D) 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.

5.3 CFCC components have a distinctive and synergistic combination of material properties, interface coatings, porosity control, composite architecture (1-D, 2-D, and 3-D), and geometric shape that are generally inseparable. Prediction of the mechanical performance of CFCC tubes (particularly with braid and 3-D weave architectures) cannot be made by applying measured properties from flat CFCC plates to the design of tubes. In particular tubular components comprised of CMCs material form a unique synergistic combination of material and geometric shape that are generally inseparable. In other words, prediction of mechanical performance of CMC tubes generally cannot be made by using properties measured from flat plates. Strength tests of internally-pressurized, CMC tubes provide information on mechanical behavior and strength for a multiaxially-stressed material.

5.4 Unlike monolithic advanced ceramics which 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 uniform hoop tensile stress for a single uniformly pressurized 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 hoop tensile strengths obtained using different recommended test specimens with different volumes of material in the gage sections may be different due to these volume effects.

5.5 Hoop tensile strength tests provide information on the strength and deformation of materials under biaxial stresses induced from internal pressurization of tubes. Non-uniform stress states are inherent in these types of tests and subsequent evaluation of any non-linear stress-strain behavior must take into account the unsymmetric behavior of the CMC under biaxial stressing. This non-linear behavior which 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 or alloying effects, or environmental influences. 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 hoop tensile 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 tubular hoop tensile 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 hoop tensile stress behavior and strength of a CMC are dependent on its inherent resistance to fracture, the presence of flaws, or damage accumulation processes, or both. Analysis of fracture surfaces and fractography, though beyond the scope of this test method, is highly recommended.

6. Interferences

6.1 Test environment (vacuum, inert gas, ambient air, etc.) including moisture content (for example, relative humidity) may have an influence on the measured hoop tensile strength. In particular, the behavior of materials susceptible to slow crack growth fracture will be strongly influenced by test environment and testing rate. Testing to evaluate the maximum strength potential of a material should be conducted 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, relative humidity and temperature must be monitored and reported. Testing at humidity levels >65 % relative humidity (RH) is not recommended and any deviations from this recommendation must be reported.

6.2 Surface preparation of test specimens, although normally not considered a major concern in CMCs, can introduce fabrication flaws that may have pronounced effects on hoop tensile stress mechanical properties and behavior (for example, shape and level of the resulting stress-strain curve, hoop tensile strength and strain, proportional limit 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 (i.e., 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).

6.3 Internally-pressurized tests of CMC tubes can produce biaxial and triaxial stress distributions with maximum and minimum stresses occurring at the test specimen surface leading to fractures originating at surfaces or near geometrical transitions. In addition, if deformations or strains are measured at surfaces where maximum or minimum stresses occur, bending may introduce over or under measurement of strains depending on the location of the strain-measuring device on the specimen. Similarly, fracture from surface flaws may be accentuated or suppressed by the presence of the non-uniform stresses caused by bending.

6.4 Friction between the insert and the rough and/or unlubricated inner surface of tubular test specimen can produce compressive stresses on the inner bore of the tube that will reduce that hoop stress in the tube. In addition, this friction will accentuate axial bending stress.

6.5 Fractures that initiate outside the gage section of a test specimen 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. Such non-gage section fractures will usually constitute invalid tests.

7. Apparatus

7.1 *Testing Machines*—Machines used for applying uniaxial forces to elastomeric inserts for hoop tensile strength testing shall conform to the requirements of Practice E4. The axial force used in inducing the internal pressure shall be accurate within ±1 % at any force within the selected force range of the testing machine as defined in Practice E4. A schematic showing pertinent features of the hoop tensile strength testing apparatus is shown in Fig. 1.

7.2 *Fixtures:*

7.2.1 *General*—Compression loading fixtures are generally composed of two parts: *(1)* basic steel test machine grips (for example, hydraulically-loaded v-grips) attached to the test machine and *(2)* push rods that are held rigidly in the test machine grips and act as the interface between the grips and elastomeric insert. A schematic drawing of such a fixture and a test specimen is shown in Fig. 2. A figure showing an actual test setup is shown in Fig. 3. Another variation of the compression loading fixture can use *(1)* compression platens attached to the test machine and *(2)* push rods that are held against the platens in the test machine and act as the interface between the platens and elastomeric insert.

7.2.2 With insert testing, the only 'connection' between the pressurizing 'machinery' and the tube under test is a trapped film of high pressure lubricant (Fig. 2). Tests have shown that this lubricant film retains a constant thickness during testing to the maximum pressure (**1**). The objective is to transmit the applied force from the push rod through the lubricant film to the inner wall of the tube under test. However, evidence indicates that the insert behaves as a hydraulic fluid also up to longitudinal compressions of at least 5 % strain.

7.2.3 *Inserts*—Typically, commercial insert material are used because of the wide range of hardnesses available. The "correct" hardness is chosen by determining the insert force and related pressure at failure of the CMC tubular test specimen.

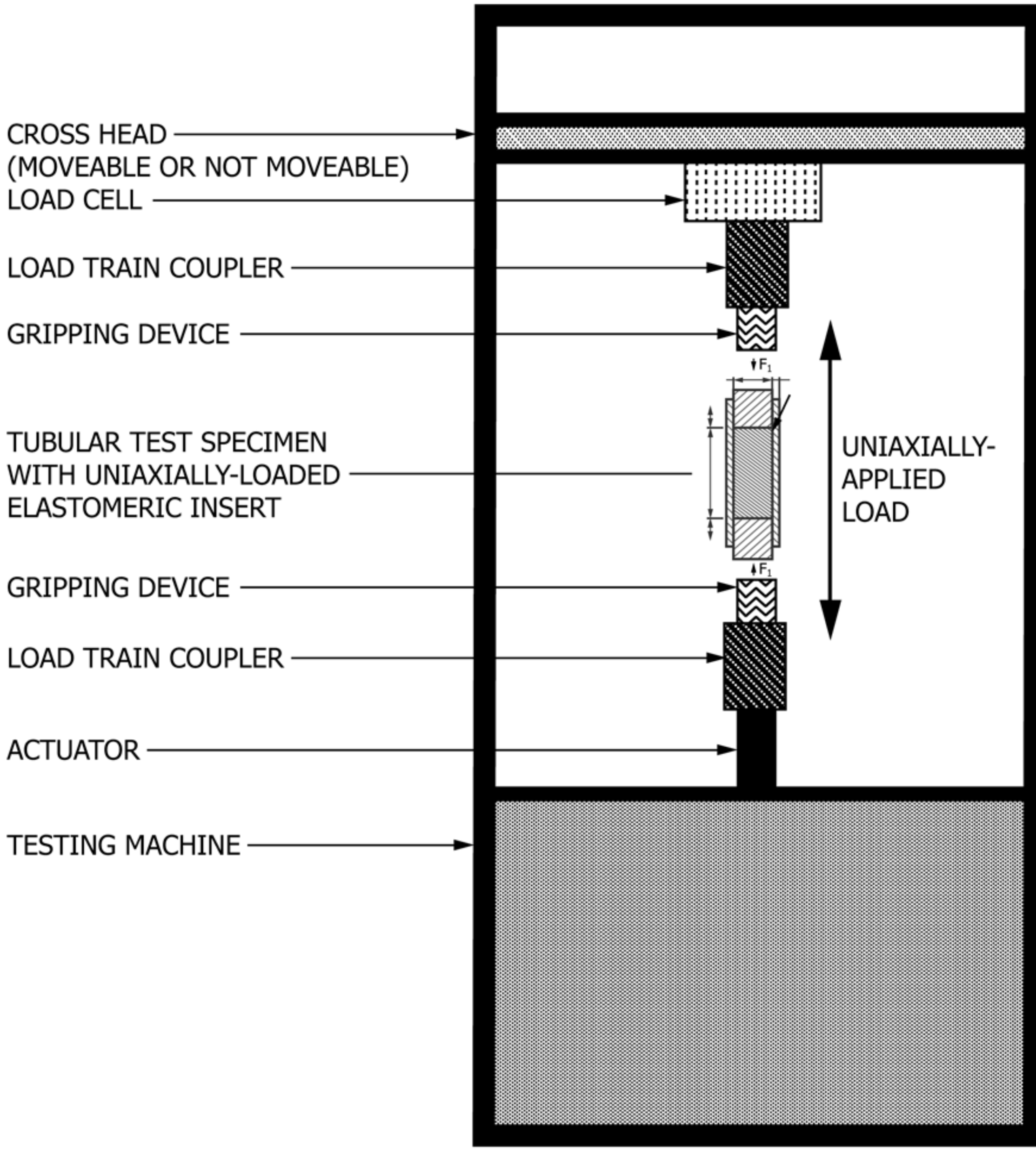


FIG. 1 Schematic Diagram of One Possible Apparatus for Applying a Uniaxial Force to an Elastomeric Insert for Conducting a Internally Pressurized Hoop Strength Test of a CMC Tube

NOTE 1—Common insert materials include urethane (such as Du Pont Adiprene™) or neoprene (**1**) mainly because of the wide range of hardnesses commercially available. Other inert materials successfully employed included silicon rubber such as Dow Corning Silastic™.

7.2.3.1 Inserts can be machined from a pre-cast block or cast "in place" (i.e., inside the tubular test specimen). However, a final grinding to finished size on diameter and length is essential so that end surfaces are perpendicular to diameter.

7.2.3.2 Insert length is chosen based on tubular test specimen dimensions and test material properties. The insert takes up only the central portion of the tube for two reasons: *(1)* tube ends act a guide for the push rods and *(2)* when correctly dimensioned per the requirement of this test method, the unpressurized tube ends can be made such that the stresses in the end surfaces during testing are negligible.

7.2.3.3 Previous studies (**1**)[4] have shown that pressurized length of the tube, L, and hence initial length of the insert should be:

$$L \geq 9/\beta$$

and

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

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

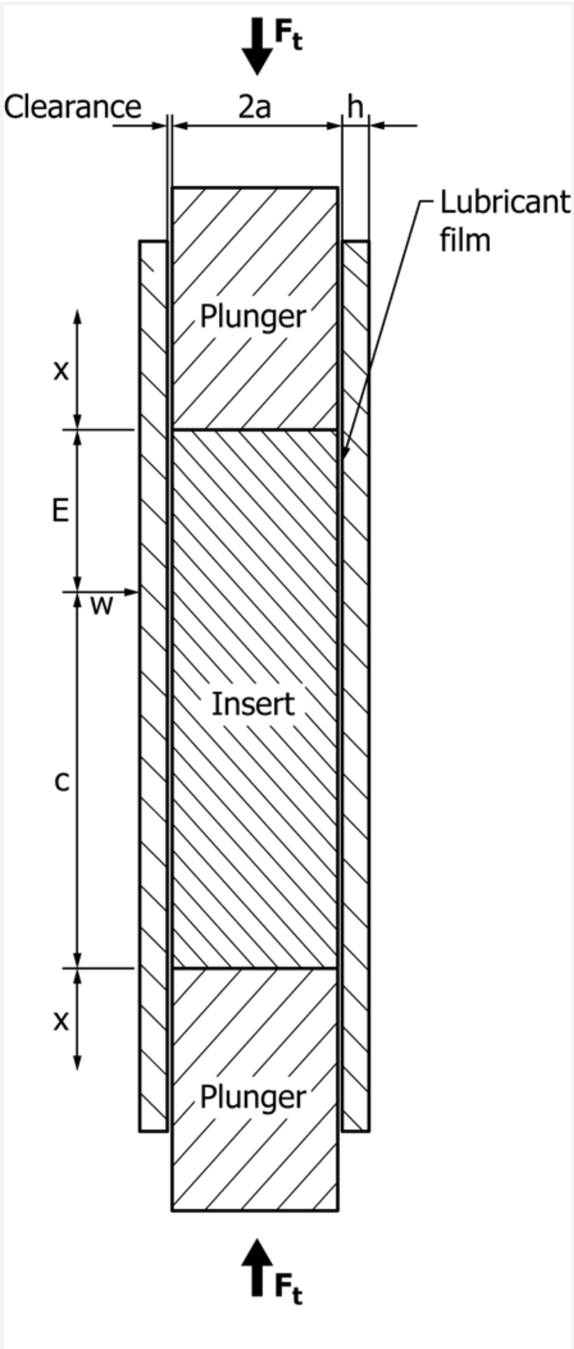


FIG. 2 Schematic of Uniaxially Loaded Insert [Ref 1]

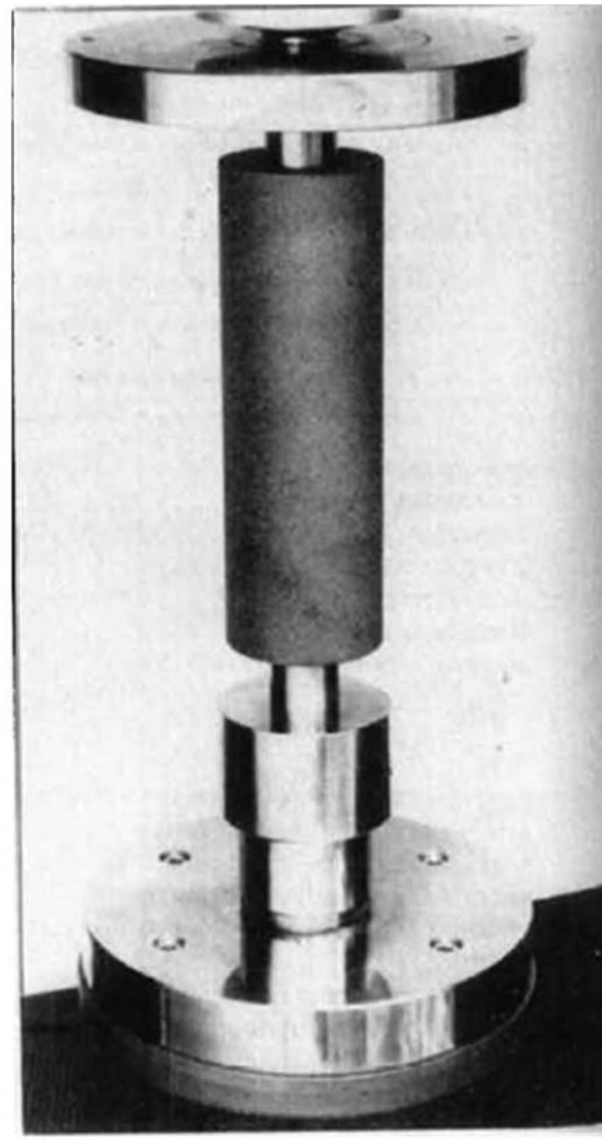


FIG. 3 Example of Test Setup for Uniaxially Loaded Tube [Ref 1]

TABLE 1 Maximum Recommended Insert Pressure

Shore Hardness (A)	Maximum recommended pressure (MPa=N/mm^2)
70	12
90	50
95	~130

where:

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

NOTE 2—Example of a commercial CMC (ν = 0.15) tube with outer diameter of 100 mm and wall and tube wall thickness of 2 mm. In this case $\beta = \sqrt[4]{\frac{3(1 - \nu^2)}{(r_i^{tube})^2 t^2}} = \sqrt[4]{\frac{3(1 - 0.15^2)}{([100 - 2\ (2)]/2)^2 2^2}}$ = 0.133 1/mm such that L = 9/β = 9/0.133 = 67.38 mm.

7.2.4 *Pushrods*—Pushrods are made from any material with sufficient compressive strength to prevent yielding of the pushrod and sufficient stiffness to prevent buckling. Final grinding of the pushrod diameters and pushrod ends is required to meet the requirements for wall clearance, face flatness, and perpendicularity/straightness as shown in Fig. 4.

7.2.4.1 Clearance between the pushrod and tube wall of the test specimen shall fall within the following limits:

$$0.04 \text{ mm} \leq c = \left(r_i^{tube} - r_o^{pushrod}\right) \leq \max\left\{\begin{matrix} 0.04 \text{ mm} \\ 0.05*\left(2r_0^{pushrod}\right) \end{matrix}\right. \quad (2)$$

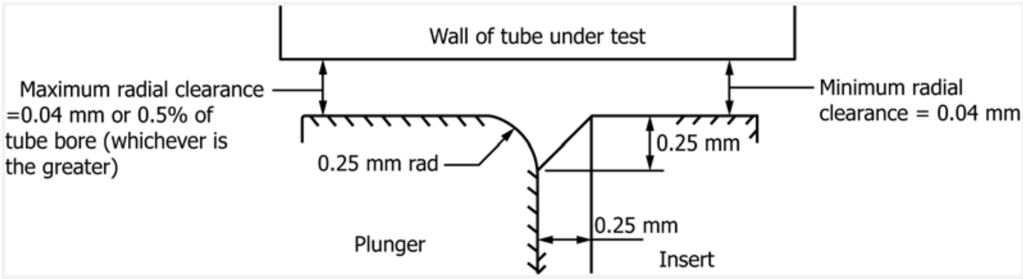


FIG. 4 Details of Interface Between Pushrod and Insert

7.2.4.2 Concentricity of the pushrod over the entire length shall 0.005 mm. Flatness of the pushrod end shall be 0.005 mm. Perpendicularity of the pushrod end shall be 0.005 mm with a run-out of 0.024 mm per 24 mm.

7.2.4.3 Length of each push rod should include the unpressurized length of the tube, plus the length of the pushrod inserted into the grip, plus the length of the tube required to take up the compression of the insert during testing. Too long of a push rod could contribute to buckling during testing. Too short of a push rod could lead to interference of the test specimen with the test machine /grip during testing. A recommended **(1)** push rod length is half minimum unpressurized length of the tubular test specimen plus the grip length of the push rod, such that:

$$L_{pushrod} \geq \; = (3.5/\beta) + grip\ length$$

and

$$X = 3.5/\beta \tag{3}$$

$$= \text{minimum unpressurized half length of tubular test specimen}$$

NOTE 3—Example of a commercial CMC (ν = 0.15) tube with outer diameter of 100 mm and wall and tube wall thickness of 2 mm. In this case $\beta = \sqrt[4]{\frac{3(1-\nu^2)}{(r_i^{tube})^2 t^2}} = \sqrt[4]{\frac{3(1-0.15^2)}{([100-2(2)]/2)^2 2^2}} = 0.133$ 1/mm such that $X = 3.5/\beta = 3.5/0.133 = 26.2$ in $L_{pushrod} = 26.2 + L_{grip}$ mm.

7.3 *Strain Measurement*—Strain should be determined by means of either a suitable diametral or circumferential extensometers, strain gages or appropriate optical methods. If Poisson's ratio is to be determined, the tubular test specimen must be instrumented to measure strain in both longitudinal and lateral directions.

7.3.1 Diametral or circumferential extensometers used for testing of CMC tubular test specimens shall satisfy Test Method E83, Class B-1 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. Extensometers shall be calibrated periodically in accordance with Test Method E83. For extensometers mechanically attached to the test specimen, the attachment should be such as to cause no damage to the specimen surface.

7.3.2 Alternatively, strain can also be determined directly from strain gages. Ideally, to eliminate the effect of misaligned uniaxial strain gages, three element rosette strain gages should be mounted to determine maximum principal strain which should be in the hoop direction. 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. Note that larger strain gages than those recommended here may be required for fabric reinforcements to average the localized strain effects of the fiber crossovers. The strain gages, surface preparation, and bonding agents should be chosen to provide adequate performance on the subject materials and suitable strain recording equipment should be employed. Note that many CMCs may exhibit high degrees of porosity and surface roughness and therefore require surface preparation including surface filling before the strain gages can be applied.

7.4 *Data Acquisition*—At the minimum, autographic record of applied load 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. Ideally, an analog chart recorder or plotter should be used 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.

7.4.1 Strain or elongation of the gage section, or both, should be recorded either similarly to the force or as independent variables of force. Cross-head displacement of the test machine may also be recorded but should not be used to define displacement or strain in the gage section.

7.5 *Dimension-Measuring Devices*—Micrometers and other devices used for measuring linear dimensions should 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, cross-sectional dimensions should be measured 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. Means for containment and retention of these fragments for later fractographic reconstruction and analysis is highly recommended.

8.2 Exposed fibers at the edges of CMC test specimens present a hazard due to the 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 *Test Specimen Geometry:*

9.1.1 *General*—The geometry of tubular test specimen is dependent on the ultimate use of the hoop tensile strength data. For example, if the hoop tensile 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 (i.e. insert length or pressurized length) will reflect the desired volume to be sampled. In addition, calculated length of the insert (i.e., pressurized length) plus the length of the pushrods (i.e., unpressurized length) will influence the final design of the test specimen geometry. Tubular test specimen geometries to maximize or minimize stresses through the wall thickness have been studied experimentally and analytically (**1**, **2**, **3**).

9.1.1.1 The following sections discuss the required hoop tensile strength tubular test specimen geometries although any geometry is acceptable if it meets requirements for pushrod and test specimen dimensions as well as those fracture location, of this test method. Deviations from the recommended geometries may be necessary depending upon the particular CMC being evaluated. Stress analyses of untried test specimens should be conducted to ensure that stress concentrations that can lead to undesired fractures outside the gage sections do not exist. It should be noted that contoured specimens by their nature contain inherent stress concentrations due to geometric transitions that are in addition to stress due to finite length elastomeric inserts. Stress analyses can indicate the magnitude of such stress concentrations while revealing the success of producing a near uniform hoop tensile stress state in the gage section of the test specimen.

9.1.2 *Test Specimen Dimensions*—Although the diameters and wall thickness of CMC tubes can vary widely depending on the application, analytical and experimental studies have shown (**1**, **2**, **3**) that successful tests can be maximized by using consistent ranges of overall tube length as follows:

$$L_t \geq 16/\beta \tag{4}$$

NOTE 4—Example of a commercial CMC (ν = 0.15) tube with outer diameter of 100 mm and wall and tube wall thickness of 2 mm. In this case $\beta = \sqrt[4]{\frac{3(1-\nu^2)}{(r_i^{tube})^2 t^2}} = \sqrt[4]{\frac{3(1-0.15^2)}{([100-2\ (2)]/2)^2 2^2}} = 0.133$ 1/mm such that $L_t \geq 16/\beta = 119.8$ mm.

9.2 *Test Specimen Preparation:*

9.2.1 Depending upon the intended application of the hoop tensile strength data, use one of the following test specimen preparation procedures. Regardless of the preparation procedure used, sufficient details regarding the procedure must be reported 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 specifications are relevant. As-processed test specimens might possess rough surface textures and nonparallel edges and as such may cause excessive misalignment or be prone to nongage section fractures, or both.

9.2.3 *Application-Matched Machining*—The tubular test specimen should have the same surface/edge preparation as that given to the component. Unless the process is proprietary, the report should be specific about the stages of material removal, wheel grits, wheel bonding, amount of material removed per pass, and type of coolant used.

9.2.4 *Customary Practices*—In instances where customary machining procedure has been developed that is completely satisfactory for a class of materials (that is, it induces no unwanted surface/subsurface damage or residual stresses), this procedure should be used.

9.2.5 *Standard Procedure*—In instances where 9.2.2 through 9.2.4 are not appropriate, 9.2.5 should apply. Studies to evaluate the machinability of CMCs have not been completed. Therefore, the standard procedure of 9.2.5 can be viewed as starting-point guidelines and a more stringent procedure may be necessary.

9.2.5.1 All grinding or cutting should be done with ample supply of appropriate filtered coolant to keep the workpiece and grinding wheel constantly flooded and particles flushed. Grinding can be done in at least two stages, ranging from coarse to fine rate of material removal. All cutting can be done in one stage appropriate for the depth of cut.

9.2.5.2 Stock removal rate should be on the order of 0.03 mm per pass using diamond tools that have between 320 and 600 grit. Remove equal stock where applicable.

NOTE 5—**Caution:** Care should be exercised in storage and handling of finished test specimens to avoid the introduction of random and severe flaws. In addition, attention should be given to pre-test storage of test specimens in controlled environments or desiccators to avoid unquantifiable environmental degradation of specimens prior to testing.

9.3 *Number of Test Specimens*—A minimum of five test specimens tested validly is required for the purposes of estimating a mean. A greater number of test specimens tested validly may be necessary if estimates regarding the form of the strength distribution are required. If material cost or test specimen availability limit the number of possible tests, fewer tests can be conducted to determine an indication of material properties.

9.4 *Valid Test*—A valid individual test is one which meets all the following requirements of this test method with final fracture in the uniformly-stressed gage section (i.e. pressurized insert length) unless those tests fracturing outside the gage section are interpreted as interrupted tests for the purpose of censored test analyses.

10. Test Procedure

10.1 *Test Specimen Dimensions*—Determine the wall thickness and outer diameter of the gage section of each test specimen to within 0.02 mm. Make measurements on at least three different cross sectional planes in the gage section. To avoid damage in the critical 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. When measuring dimensions between the woven faces of woven materials, in general, use a self-limiting (friction or ratchet mechanism) flat anvil type micrometer having anvil cross sectional dimensions of at least 5 mm. In all cases the resolution of the instrument shall be as specified in 7.5. Exercise caution to prevent damage to the test specimen gage section. Ball-tipped or sharp-anvil micrometers may be preferred when measuring small-diameter test specimens or materials with rough or uneven nonwoven surfaces. Record and report the measured dimensions and locations of the measurements for use in the calculation of the hoop tensile stress. Use the average of the multiple measurements in the stress calculations.

10.1.1 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 9.1 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 follow the procedures outlined in 9.1 for pretest measurements to assure reliable measurements.

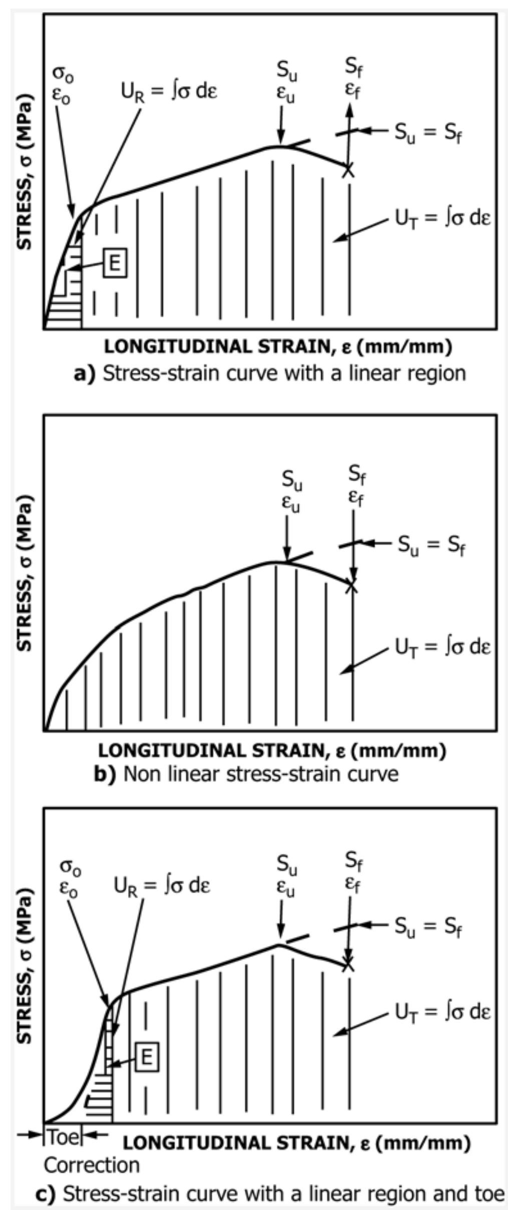
10.1.2 Conduct periodic, if not 100 %, inspection/measurements of all test specimens and test specimen dimensions to ensure compliance with the drawing specifications. Generally, high resolution optical methods (for example, an optical comparator) or high resolution digital point contact methods (for example, coordinate measurement machine) are satisfactory as long as the equipment meets the specifications in 7.5. Note that the frequency of gage section fractures and bending in the gage section are dependent on proper overall test specimen dimensions within the required tolerances.

10.1.3 In some cases it is desirable, but not required, to measure surface finish to quantify the surface condition. Such methods as contacting profilometry can be used to determine surface roughness parallel to the longitudinal axis. When quantified, surface roughness should be reported.

10.2 *Test Modes and Rates:*

10.2.1 *General*—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 hoop tensile strength at fracture of the material. However, rates other than those recommended here may be used to evaluate rate effects. In all cases the test mode and rate must be reported.

10.2.1.1 For monolithic advanced ceramics exhibiting linear elastic behavior, fracture is attributed to a weakest-link fracture mechanism generally attributed to stress-controlled fracture from Griffith-like flaws. Therefore, a force-controlled test, with force generally related directly to hoop tensile stress, is the preferred test mode. However, in CMCs the non-linear stress-strain behavior characteristic of the "graceful" fracture process of these materials indicates a cumulative damage process that is strain dependent. Generally, displacement or strain controlled tests are employed in such cumulative damage or yielding deformation processes to prevent a "run away" condition (that is, rapid uncontrolled deformation and fracture) characteristic of force- or stress-controlled tests. Thus, to elucidate the potential "toughening" mechanisms under controlled fracture of the CMC, displacement or strain control is preferred. However, for sufficiently rapid test rates, differences in the fracture process may not be noticeable and any of these test modes may be appropriate.



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).

FIG. 5 Schematic Diagrams of Stress-Strain Curves for CMCs

10.2.2 *Strain Rate*—Strain is the independent variable in non-linear analyses such as yielding. As such, strain rate is a method of controlling tests of deformation processes to avoid "run away" conditions. For the linear elastic region of CMCs, strain rate can be related to strain measurement such that:

$$\dot{\varepsilon}_L = \frac{d\varepsilon}{dT} \quad (5)$$

where:

$\dot{\varepsilon}_L$ = strain rate of the insert in units of (mm/mm)/s, and
$d\varepsilon/dT$ = slope of strain-time curve (mm/mm)/s.

Note that strain-controlled tests can be accomplished using an diametral or hoop extensometer contacting the gage section of the specimen as the primary control transducer. Strain rates on the order of 5×10^{-6} to 50×10^{-6} s^{-1} are recommended to minimize environmental effects when testing in ambient air. Alternately, strain rates shall be selected to produce final fracture in 5 to 10 s to minimize environmental effects when testing in ambient air.

10.2.3 *Displacement Rate*—The size differences of each test specimen geometry require a different testing rate for any given stress rate. Note that as the test specimen begins to fracture, the strain rate in the gage section of the specimen will change even though the rate of motion of the cross-head remains constant. For this reason displacement rate controlled tests can give only an approximate value of the imposed strain rate. Displacement mode is defined as the control of, or free-running displacement of, the test machine cross-head. Thus, the displacement rate can be calculated as follows. Displacement rates shall be selected to produce final fracture in 5 to 10 s to minimize environmental effects when testing in ambient air. Using the recommended (or desired) strain rate as detailed in 9.2.2, calculate the displacement rate for the linear elastic region of CMCs only as:

$$\dot{\delta} = \frac{d\delta}{dT} \quad (6)$$

where:

$\dot{\delta}$ = displacement rate of the cross-head in units of mm/s,
δ = cross-head displacement in units of mm, and
T = time in units of s.

10.2.4 *Force Rate*—For materials that do not experience gross changes in cross sectional area of the gage section, force rate can be directly related to stress rate and hence to the recommended (or desired) strain rate. Note that as the test specimen begins to fracture, the strain rate in the gage section of the test specimen will change even though the rate of force application remains constant. Stress rates >35 to 50 MPa/s have been used with success to minimize the influence of environmental effects and thus obtain the greatest value of ultimate hoop tensile strength. Alternately, stress or force rates should be selected to produce final fracture in 5 to 10 s to minimize environmental effects when testing in ambient air. For the linear elastic region of CMCs, force rate is calculated as:

$$\dot{F} = \frac{dF}{dT} \quad (7)$$

where:

$\dot{F}$ = the required force rate in units on N/s,
F = the applied force in units of N, and
T = time in units of s.

10.2.5 *Ramp Segments*—Normally, tests are conducted in a single ramp function at a single test rate from zero force to the maximum force at fracture. However, in some instances multiple ramp segments might be employed. In these cases a slow test rate is used to ramp from zero force to an intermediate force to allow time for removing "slack" from the test system. The final ramp segment of the test is conducted from the intermediate force to the maximum force at fracture at the required (desired) test rate. The type and time duration of the ramp should be reported.

10.3 *Conducting the Hoop Tensile Strength Test:*

10.3.1 *Mounting the Test Specimen*—The pushrods, insert and tubular test specimen must be assembled before testing can commence. Components required for each test should be identified and noted in the test report. 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 (for example, Strain Gage 1 designated SG1) coincide. Mark each pushrod to indicate the unpressurized length, X, from the end of the pushrod in contact with the insert.

10.3.2 *Preparations for Testing*—Clean and grease the insert, puhrods and bore of the tubular test specimen. Slide the insert into the tube. Slide one push rod into each end of the tubular test specimen, "sandwiching the insert between the two ends of the pushrods inside the tube. Insert the two free ends of the pushrods into the upper and lower "grips" of the test machine. Set the test mode and test rate on the test machine. Temporarily support the test specimen such that the inert is centered in the in the test specimen between the two pushrods. Preload the insert to remove the "slack" from the load train and to take up the clearance between the insert and tube wall such that the temporary supports are not necessary and can be removed. The amount of preload will depend on the insert material and clearance between the insert and tube wall therefore must be determined for each situation. Either mount the proper extensometer on the test specimen gage section and zero the output, or, attach the lead wires of the strain gages to the signal conditioner and zero the outputs. Ready the autograph data acquisition systems for data logging. Place shields into place around the test specimen.

NOTE 6—Examples of lubricants include polybutylcuprysil (PBC) (**1**), plain silicon grease, or petroleum jelly.

10.3.3 *Conducting the Test*—Initiate the data acquisition. Initiate the test mode. After test specimen fracture, disable the action of the test machine and the data collection of the data acquisition system. The breaking force should be measured within ±1.0 % of the force range and noted for the report. Carefully remove push rods (and insert if possible) from inside the test specimen. If the tube has separated into pieces, take care not to damage the fracture surfaces by preventing them from contact with each other or other objects. Place the fractured portions of the test specimen along with other fragments from the gage section into a suitable, non-metallic container for later analysis, being careful not be breath any particles or fibers.

10.3.4 Determine the relative humidity in accordance with Test Method E337.

10.3.5 *Post-Test Dimensions*—A measure of the gage section cross-sectional dimensions at the fracture location can be made and reported to 0.02 mm if the gage section has not been overly fragmented by the fracture process. If an exact measure of the cross-sectional dimensions cannot be made due to fragmentation then use the average dimensions measured in 9.1.

10.3.5.1 Measure and report the fracture location relative to the midpoint of the gage section. The convention used should be that the 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).

10.3.5.2 Note that results from test specimens fracturing outside the uniformly pressurized gage section are not recommended for use in the direct calculation of a mean hoop tensile strength for the entire test set. Results from test specimens fracturing outside the gage section of the uniformly-pressurized length are considered anomalous and can be used only as censored tests (that is, test specimens in which a tensile hoop stress at least equal to that calculated by Eq 7 was sustained in the uniformly-stressed 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, $N = 10$) for purposes of average strength, test one replacement test specimen for each test specimen that fractures outside the gage section.

10.3.5.3 Visual examination and light microscopy should be conducted to determine the mode and type of fracture (that is, brittle or fibrous). In addition, although quantitatively beyond the scope of this test method, subjective observations can be made of the length of fiber pullout, orientation of fracture plane, degree of interlaminar fracture, and other pertinent details of the fracture surface.

10.4 *Fractography*—Fractographic examination of each failed test specimen is recommended to characterize the fracture behavior of CMCs. It should be clearly noted on the test report if a fractographic analysis is not performed.

11. Calculation of Results

11.1 *General*—Various types of CMC material, due to the nature of their constituents, processing routes, and prior mechanical history, may exhibit vastly different stress-strain responses. Therefore, interpretation of the test results will depend on the type of response exhibited.

11.2 *Internal Pressure*—Calculate the internal pressure exerted on the tube by the expanding insert as follows:

$$p = \frac{F}{\pi\left(r_i^{tube}\right)^2} \tag{8}$$

where:

p = internal pressure in units of N/mm^2 = MPa,
F = axial force required by tubular test specimen along in units of N, and
r_i^{tube} = internal diameter of tube units of mm.

Note that the axial force has two components such that:

$$F = \left(1 + \frac{s}{S}\right)\left(F_t - F_r\right) \tag{9}$$

where:

s = stiffness of insert alone in units of N/mm,
S = stiffness of load train (including load fixtures and force transducer) in units of N/mm,
F_t = total force applied from the test machine in units of N, and
F_r = residual force on insert at fracture in units of N.

It should be noted that for a "soft" (i.e., compliant) insert material, $F = F_t$.

11.3 Sections 11.4 to 11.15 are Optional data reduction methods based on the assumption that stress calculations applied for assumptions of isotropic, homogeneous, linear elastic material, which may not be applicable or appropriate for CMC tubes.

11.4 *Hoop Tensile Stress*—For the assumption of isotropic, homogeneous, linear elastic material, calculate the hoop tensile stress at the inner wall as:

$$\sigma_h = \eta_m p \frac{2\left(r_i^{tube}\right)^2}{\left[\left(r_o^{tube}\right)^2 - \left(r_i^{tube}\right)^2\right]} \tag{10}$$

where:

σ_h = hoop tensile stress in units of MPa,
p = internal pressure in units of N/mm^2,
η_m = maximum stress factor (see Appendix X2),
r_i^{tube} = inner radius of tube units of mm, and
r_o^{tube} = outer radius of tube units of mm.

The stress factor, η_m, is a correction to account of differences between analytical, numerical and experimental results for hoop tensile stresses in tubes obtained from pressurization of an internal elastomer insert (**1**).

11.5 *Hoop Tensile Strain*—If strain is not obtained directly from strain gages, calculate the hoop tensile strain as:

$$\varepsilon_h = \frac{2\Delta r}{2 r_o^{tube}} \tag{11}$$

where:

ε_h = hoop tensile strain in units of mm/mm,
Δr = change in radius in units of mm, and
r_o^{tube} = outer radius of tube units of mm.

For test specimens that have been strain gaged, the appropriate strain values are obtained directly without measurement of gage section elongation.

11.5.1 Note that in some cases the initial portion of the stress-strain ($\sigma_h - \varepsilon_h$) curve shows a nonlinear region or "toe" followed by a linear region. This toe may be an artifact of the test specimen or test conditions and thus may not represent a property of the material. The ($\sigma_h - \varepsilon_h$) curve can be corrected for this toe by extending the linear region of the curve to the zero-stress point on the strain axis. 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 ($\sigma_h - \varepsilon_h$) curve is used for all subsequent calculations.

11.6 *Hoop Tensile Strength*—Calculate the hoop tensile strength as:

$$S_{hu} = \eta_m p_{\max} \frac{2(r_i^{tube})^2}{[(r_o^{tube})^2 - (r_i^{tube})^2]} \tag{12}$$

where:

S_{hu} = hoop tensile strength in units of MPa,
p_{max} = maximum internal pressure in units of N/mm^2,
η_m = maximum stress factor (see Appendix X2),
r_i^{tube} = inner radius of tube units of mm, and
r_o^{tube} = outer radius of tube units of mm.

11.7 *Strain at Hoop Tensile Strength*—Determine strain at hoop tensile strength, ε_{hu} as the strain corresponding to the hoop tensile strength measured during the test.

11.8 *Hoop Tensile Fracture Strength*—Calculate the fracture strength as:

$$S_{hf} = \eta_m P_f \frac{2(r_i^{tube})^2}{[(r_o^{tube})^2 - (r_i^{tube})^2]} \tag{13}$$

where:

S_{hf} = hoop tensile fracture strength in units of MPa,
P_f = internal pressure at fracture in units of N/mm^2,
η_m = maximum stress factor (see Appendix X2),
r_i^{tube} = inner radius of tube units of mm, and
r_o^{tube} = outer radius of tube units of mm.

In some instances, $S_{hu} = S_{hf}$.

11.9 *Strain at Hoop Tensile Fracture Strength*—Determine strain at fracture strength, ε_{hf} as the engineering strain corresponding to the fracture strength measured during the test. In some instances, $\varepsilon_{hu} = \varepsilon_{hf}$.

11.10 *Modulus of Elasticity in the Hoop Direction*—Calculate the modulus of elasticity as follows:

$$E = \frac{\Delta\sigma_h}{\Delta\varepsilon_h} \tag{14}$$

where E is the modulus of elasticity, $\Delta\sigma_h/\Delta\varepsilon_h$ is the slope of the ($\sigma_h - \varepsilon_h$) curve within the linear region. Note that the modulus of elasticity in the may not be defined for materials that exhibit entirely non-linear ($\sigma_h - \varepsilon_h$) curves.

11.11 *Poisson's Ratio*—Calculate the Poisson's ratio in hoop direction (if longitudinal strain is measured) as follows:

$$\nu = -\frac{\varepsilon_L}{\varepsilon_h} \tag{15}$$

where ν is Poisson's ratio, and $\varepsilon_L/\varepsilon_h$ is the slope of the linear region of the plot of longitudinal strain ε_L versus hoop strain, ε_h. Note that Poisson's ratio may not be defined for materials which exhibit non-linear ($\sigma_h - \varepsilon_h$) curves over the entire history (although this must be verified by plotting ε_T versus ε_L to determine whether or not a linear region exists).

11.12 *Proportional Limit Stress*—Determine the proportional limit stress, σ_{ho}, by one of the following methods. Note that by its definition the proportional limit stress, σ_{ho}, may not be defined for materials that exhibit entirely non-linear ($\sigma_h - \varepsilon_h$) curves.

11.12.1 *Offset Method*—Determine σ_{ho} by generating a line running parallel to the same part of the linear part of the $\sigma_h - \varepsilon_h$ curve used to determine the modulus of elasticity in 11.9. The line so generated should be at a strain offset of 0.0005 mm/mm. The proportional limit stress is the stress level at which the offset line intersects the ($\sigma_h - \varepsilon_h$) curve.

11.12.2 *Extension Under Force Method*—Determine σ_{ho} by noting the stress on the ($\sigma_h - \varepsilon_h$) curve that corresponds to a specified strain. The specified strain may or may not be in the linear region of the ($\sigma_h - \varepsilon_h$) but the specified strain at which

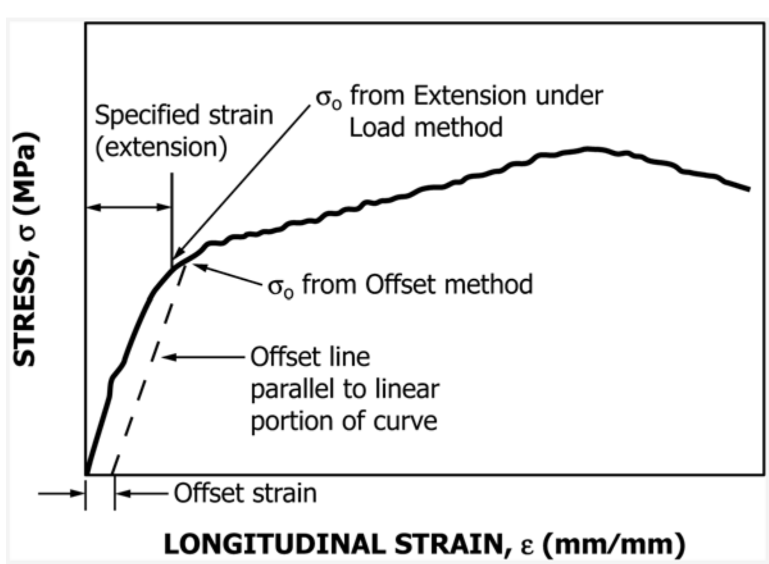


FIG. 6 Schematic Diagram of Methods for Determining Proportional Limit Stress

σ_{ho} is determined must be constant for all tests in a set with the specified strain reported.

11.12.3 *Deviation From Linearity Method*—Determine σ_{ho} by noting the stress σ_i, on the ($\sigma_h - \varepsilon_h$) curve at which there is a specified percent deviation (e.g., %dev = 10) from the stress calculated from the elastic relation, $\sigma = E_{\varepsilon i}$ such that:

$$\%dev = 100\left[\frac{(E\varepsilon_i) - \sigma_i}{\sigma_i}\right] \quad (16)$$

where:

σ_i and $_{\varepsilon i}$ = the i-th stress and corresponding strain, respectively, on the $\sigma_h - \varepsilon_h$ curve, and
E = the modulus of elasticity.

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

11.13 *Strain at Proportional Limit Stress*—Determine strain at proportional limit stress, ε_{ho}, as the strain corresponding to proportional limit stress determined for the test.

11.14 *Modulus of Resilience*—Calculate the modulus of resilience as the area under the linear part of the $\sigma_h - \varepsilon_h$ curve or alternatively estimated as:

$$U_R = \int_0^{\varepsilon_{ho}} \sigma_h d\varepsilon_h \approx \frac{1}{2}\sigma_{ho}\varepsilon_{ho} \quad (17)$$

where:

U_R = the modulus of resilience in J/m^3, and σ_{ho} and ε_{ho} as used in Eq 17 have units of Pa (that is, N/m^2) and m/m, respectively.

11.15 *Modulus of Toughness*—Calculate the modulus of toughness as the area under the entire $\sigma_h - \varepsilon_h$ curve or alternatively estimated as:

$$U_T = \int_0^{\varepsilon_{hf}} \sigma_h d\varepsilon_h \approx \frac{\sigma_{ho} + S_{hu}}{2}\varepsilon_{hf} \quad (18)$$

where U_T is the modulus of toughness in J/m^3, and σ_o and S_u as used in Eq 18 have units of Pa (that is, N/m^2) and ε_o has units of mm/mm. Note that U_T can be estimated as follows for materials for which σ_{ho} is not calculated and that have a ($\sigma_h - \varepsilon_h$) curve that can be assumed to be a parabola:

$$U_T = \int_0^{\varepsilon_{hf}} \sigma_h d\varepsilon_h \approx \frac{2}{3}S_{hu}\varepsilon_{hf} \quad (19)$$

11.15.1 Note that 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.

11.16 *Mean, Standard Deviation, and Coefficient of Variation*—For each series of tests the mean, standard deviation, and coefficient of variation for each measured value can be calculated as follows:

$$mean = \bar{x} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (20)$$

$$standard\ deviation = s.d. = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}{n-1}} \quad (21)$$

$$coefficient\ of\ variation = V = \frac{100(s.d.)}{\bar{X}} \quad (22)$$

where:

X = measured value, and
n = number of valid test.

12. Report

12.1 *Test Set*—Report the following information for the test set. Any significant deviations from the procedures and requirements of this test method should be noted in the report:

12.1.1 Date and location of testing,

12.1.2 Internal pressure test specimen geometry used (include engineering drawing),

12.1.3 Specify visco-elastic insert material and lubricant,

12.1.4 Type and configuration of the test machine (include drawing or sketch if necessary). If a commercial test machine was used, the manufacturer and model number are sufficient for describing the test machine,

12.1.5 Type, configuration, and resolution of strain measurement equipment used (include drawing or sketch if necessary). If a commercial extensometer or strain gages were used, the manufacturer and model number are sufficient for describing the strain measurement equipment,

12.1.6 Type and configuration of push rods and grip interface (include drawing or sketch if necessary). If a commercial grip interface was used, the manufacturer and model number are sufficient for describing the grip interface,

12.1.7 Number (n) of test specimens tested validity (for example, fracture in the gage section). In addition, report total of number of specimens tested (n_T) to provide an indication of the expected success rate of the particular specimen geometry and test apparatus,

12.1.8 All relevant material data including vintage data or billet identification data. (Did all test specimens come from one billet or processing run?) As a minimum, the date the material was manufactured must be reported. For commercial materials, the commercial designation must be reported. At a minimum include a short description of reinforcement (type, layup, etc.), fiber volume fraction, and bulk density,

12.1.8.1 For non-commercial materials, the major constituents and proportions should be reported as well as the primary processing route including green state and consolidation routes. Also report fiber volume fraction, matrix porosity, and bulk density. The reinforcement type, properties and reinforcement architecture should be fully described to include fiber properties (composition, diameter, source, lot number and any measured/specified properties), interface coatings (composition, thickness, morphology, source, and method of manufacture) and the reinforcement architecture (yard type/ count, thread count, weave, ply count, fiber areal weight, stacking sequence, ply orientations, etc.), 12.1.9 Description of the method of test specimen preparation including all stages of machining,

12.1.10 Heat treatments, coatings, or pre-test exposures, if any applied either to the as-processed material or to the as-fabricated specimen,

12.1.11 Test environment including relative humidity (see Test Method E337), ambient temperature, and atmosphere (for example, ambient air, dry nitrogen, silicone oil, etc.),

12.1.12 Test mode (force, pressure, or strain control) and actual test rate (force rate, pressure rate, or strain rate). Calculated strain rate should also be reported, if appropriate, in units of s^{-1},

12.1.13 Mean, standard deviation, and coefficient of variation for each test series the following measurements:

12.1.13.1 Maximum internal pressure, p_{max},

12.1.13.2 Strain at maximum internal pressure, ε_u,

12.1.13.3 Internal pressure at fracture, p_f,

12.1.13.4 Strain at hoop tensile fracture strength, ε_f,

12.1.13.5 Proportional limit internal pressure, p_o (if applicable) and method of determination,

12.1.13.6 Strain at proportional limit internal pressure, ε_o (if applicable),

12.1.14 Optional: Mean, standard deviation, and coefficient of variation for each test series the following measured properties:

12.1.14.1 Hoop tensile strength, S_u,

12.1.14.2 Strain at hoop tensile strength, ε_u,

12.1.14.3 Hoop tensile fracture strength, S_f,

12.1.14.4 Strain at hoop tensile fracture strength, ε_f,

12.1.14.5 Modulus of elasticity (hoop), E (if applicable),

12.1.14.6 Poisson's ratio, ν (if applicable),

12.1.14.7 Proportional limit hoop tensile stress, σ_o (if applicable) and method of determination,

12.1.14.8 Strain at proportional limit hoop tensile stress, ε_o (if applicable),

12.1.14.9 Modulus of resilience, U_R (if applicable), and

12.1.14.10 Modulus of toughness, U_T (if applicable).

12.2 *Individual Test Specimens*—The report should include the following information for each test specimen tested. Any significant deviations from the procedures and requirements of this test method should be noted in the report:

12.2.1 Pertinent overall specimen dimensions, if measured, such as total length, length of gage section, gripped section dimensions, etc. in units of mm,

12.2.2 Average surface roughness, if measured, of gage section measured in the longitudinal direction in units of µm,

12.2.3 Average cross sectional dimensions, in units of mm,

12.2.4 Plot of the entire internal pressure-strain curve,

12.2.4.1 Maximum internal pressure, p_{max},

12.2.4.2 Strain at maximum internal pressure, ε_u,

12.2.4.3 Internal pressure at fracture, p_f,

12.2.4.4 Strain at hoop tensile fracture strength, ε_f,

12.2.4.5 Proportional limit internal pressure, p_o (if applicable) and method of determination,

12.2.4.6 Strain at proportional limit internal pressure, ε_o (if applicable),

12.2.5 Optional: For each test series the following measured properties:

12.2.5.1 Hoop tensile strength, S_u,

12.2.5.2 Strain at hoop tensile strength, ε_u,

12.2.5.3 Hoop tensile fracture strength, S_f,

12.2.5.4 Strain at hoop tensile fracture strength, ε_f,

12.2.5.5 Modulus of elasticity (hoop), E (if applicable),

12.2.5.6 Poisson's ratio, ν (if applicable),

12.2.5.7 Proportional limit hoop tensile stress, σ_o (if applicable) and method of determination,

12.2.5.8 Strain at proportional limit hoop tensile stress, ε_o (if applicable),

12.2.5.9 Modulus of resilience, U_R (if applicable), and

12.2.5.10 Modulus of toughness, U_T (if applicable).

12.2.6 Plot of the entire hoop tensile stress-strain curve,

12.2.7 Fracture location relative to the gage section midpoint in units of mm (+ is toward the top of the specimen as marked and – is toward the bottom of the specimen as marked with 0 being the gage section midpoint), and

12.2.8 Appearance of test specimen after fracture as suggested in 10.3.5.3.

13. Precision and Bias

13.1 The hoop tensile strength behavior of a ceramic composite is not deterministic, but varies from one tubular test specimen to another. Sources of this variability are inherent variations in ceramic composites fabricated with ceramic fiber reinforcements and ceramic matrices. Variables include property variation of fibers, matrix and interphase, as well as variations in the architecture, volume fraction of reinforcement and bulk density of the composite. Such variations can occur spatially within a given test specimen, as well as between different test specimens.

13.2 Because of the nature of the materials and lack of a wide data base on a variety of advanced ceramic composite tubes subjected to internal pressure, no definitive statement can be made at this time concerning precision and bias of the test procedures of this test method.

14. Keywords

14.1 ceramic matrix composite; CMC continuous fiber composite; hoop tensile strength; internal pressure test; tubes

APPENDIXES

(Nonmandatory Information)

X1. VERIFICATION OF LOAD TRAIN ALIGNMENT

X1.1 *Purpose of Verification*—The purpose of this verification procedure is to demonstrate that the compression test setup can be used by the test operator to consistently meet the limit on percent bending. Thus, this verification procedure should involve no more care in setup than will be used in the routine testing of the actual compressive test specimen. The bending under compressive load should be measured using instrumented push rods. Conduct verification measurements *(1)* at the beginning and end of a series of tests with a measurement at the midpoint of the series recommended, *(2)* whenever the grip interfaces and load train couplers are installed on a different test machine, *(3)* whenever a different operator is conducting a series of tests, *(4)* whenever damage or misalignment is suspected.

X1.2 For simplicity, mount a minimum of four foil resistance strain gages on the verification pushrod as shown in Fig. X1.1. Note that the strain gage plane should be within 0.5 mm of the longitudinal center of the reduced or designated gage section. Avoid placing the strain gages closer than one strain gage length from geometrical features that can cause strain concentrations and inaccurate measures of the strain in the uniform gage section. Strain gages push rods composed of isotropic homogeneous materials should be as narrow as possible to minimize strain averaging. Equally space the four strain gages (90° apart) around the circumference of the gage section.

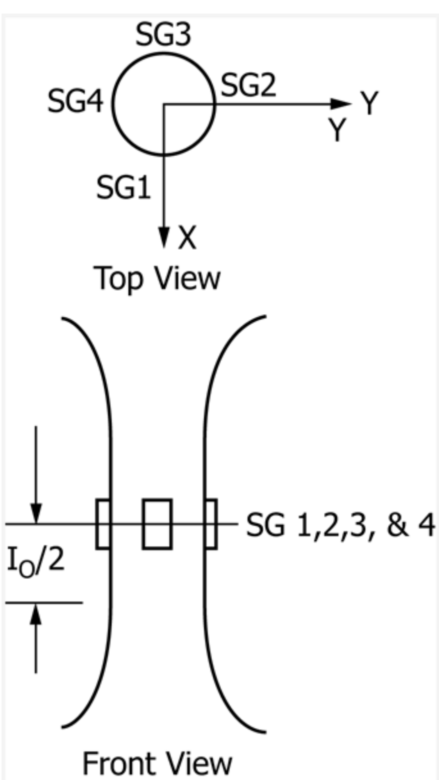


FIG. X1.1 Illustration of Strain Gage Placement on Gage Section Planes and Strain Gage Numbering (l_o = Gage Section Length, SG = Strain Gage)

X1.3 *Verification Procedure*—Procedures for verifying alignment are described in detail in Practice E1012. However, salient points for circular cross sections are described here for emphasis. The following discussion is not intended to replace Practice E1012, but rather is intended to elucidate those aspects which are directly applicable to this particular test method.

X1.3.1 Place the pushrod and test machine grips.

X1.3.2 Connect the lead wires of the 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 actual conduct of the verifications.

X1.3.3 Zero the strain gages before applying any preload to the push rod. This will allow any bending due to the compression fixture to be recorded.

X1.3.4 Apply a small preload to the push rod to stabilize it within the compression fixture.

X1.3.5 Apply a sufficient load to the push rod to achieve a mean strain equal to either one half the anticipated strain at fracture in the test material or a strain of –0.0005 (that is, –500 microstrain) whichever is greater. It is desirable to record the strain (and hence percent bending) as a function of the applied load to monitor any self-alignment of the load train.

X1.3.6 Calculate percent bending as follows referring to Fig. X1.1 for the strain gage numbers. Percent bending is calculated as follows:

$$PB = \frac{\varepsilon_b}{\varepsilon_o}100 \tag{X1.1}$$

$$\varepsilon_b = \left[\left(\frac{\varepsilon_1 - \varepsilon_3}{2}\right)^2 + \left(\frac{\varepsilon_2 - \varepsilon_4}{2}\right)^2\right]^{\frac{1}{2}} \tag{X1.2}$$

$$\varepsilon_o = \frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4}{4} \tag{X1.3}$$

where:

ε_1, ε_2, ε_3, and ε_4 = strain readings for the individual strain gages. Strain gage readings are in units of strain and compressive strains are negative.

X1.3.7 The direction of the maximum bending strain is determined as follows:

$$\theta = \arctan\left[\frac{\varepsilon_{(\text{next greatest of } 1,2,3,4)} - \varepsilon_o}{\varepsilon_{(\text{greatest of } 1,2,3,4)} - \varepsilon_o}\right] \tag{X1.4}$$

where θ is measured from the strain gage with the greatest reading in the direction of the strain gage with the next greatest reading where counter clockwise is positive as viewed from the top of the test specimen.

X1.3.8 The effect of the push rod warpage can be checked by rotating the push rod 180° about its longitudinal axis and performing the bending checks again. If similar results are obtained at each rotation, then the degree of alignment can be considered representative of the load train and not indicative of the test specimen. If load train alignment is within the specifications, the maximum percent bending should be recorded and the compression tests may be conducted. If the load train alignment is outside the specifications, then the load train must be aligned or adjusted according to the specific procedures unique to the individual testing setup. This verification procedure must then be repeated to confirm the achieved alignment.

X2. STRESS FACTORS FOR CALCULATION OF MAXIMUM HOOP STRESS

X2.1 Analysis of the pressurized overhung tube assumes the unpressurized tuber ends are infinitely long. The effects of pressurizing a tube for the central part of its length are as follows:

X2.1.1 Hoop stress varies along the pressurized length.

X2.1.2 Bending stresses occur in the axial direction.

X2.1.3 Shear stresses act at right angles to the axis.

X2.1.4 Compressive stresses due to the pressure act in the pressurized length only.

X2.2 Despite this complex stress situation, the hoop stress remains the largest of the three stress systems. The maximum hoop stress a function only of the tube diameters and Poisson's ratio of the test material for a internal pressure such that:

X2.2.1 At the outer radius in the pressurized length, hoop stress is:

$$\sigma_h = \eta_m p \frac{2\left(r_i^{tube}\right)^2}{\left[\left(r_o^{tube}\right)^2 - \left(r_i^{tube}\right)^2\right]} \tag{X2.1}$$

where:

σ_h = hoop tensile stress in units of MPa,
p = internal pressure in units of N/mm²,
η_m = maximum hoop stress factor = $[1 - 1/2\,(\theta\,(\beta\,m) + \theta\,(\beta\,n))] + \nu\sigma_x$ (see Fig. X2.1 and Ref **(1)**,
r_i^{tube} = inner radius of tube units of mm,
r_o^{tube} = outer radius of tube units of mm, and
σ_x = axial tensile tress in units of MPa.

X2.2.2 At the inner radius in the pressurized length, hoop

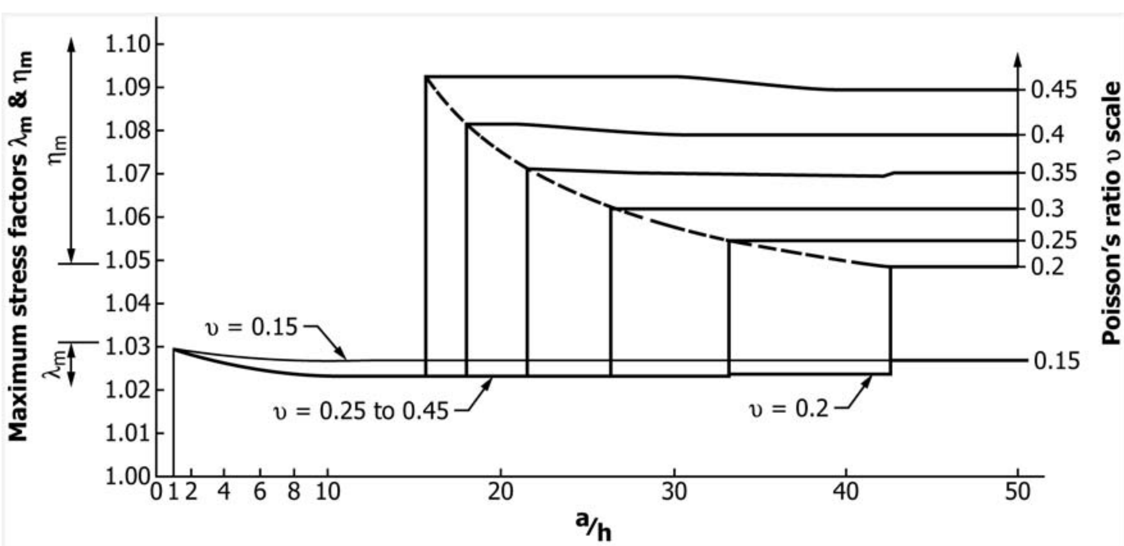


FIG. X2.1 Plot of Maximum Stress Factors λ_m and η_m for $1 \leq a/h = r_i^{tube}/t \leq 50$ with $0.15 \leq \nu \leq 0.45$ (1)

stress is:

$$\sigma_h = \lambda_m p \frac{[(r_o^{tube})^2 + (r_i^{tube})^2]}{[(r_o^{tube})^2 - (r_i^{tube})^2]} \quad (X2.2)$$

where:

σ_h = hoop tensile stress in units of MPa,
p = internal pressure in units of N/mm^2,
λ_m = maximum hoop stress factor = $[1 - 1/2\,(\theta\,(\beta\, m) + \theta\,(\beta\, n))] - p\frac{\nu}{2}(\theta\,(\beta\, m) + \theta\,(\beta\, n)) + \nu\sigma_x$ (see Fig. X2.1 and Ref **(1)**),
r_i^{tube} = inner radius of tube units of mm,
r_o^{tube} = outer radius of tube units of mm, and
σ_x = axial tensile tress in units of MPa.

X3. AXIAL FORCE TO INTERNAL PRESSURE

X3.1 The pressure generated at the inner surface of the test specimen is related to the applied stress in the test material **(2)**. The axial strain in the insert is related elastic properties of the insert material, the axial stress and the radial stress (i.e., internal pressure) such that for isotropic, linear elastic material:

$$\varepsilon_x = \frac{1}{E_{insert}}[\sigma_x - 2\nu_{insert}\,\sigma_r] \quad (X3.1)$$

where:

ε_x = axial normal strain in units of mm/mm,
E_{insert} = elastic modulus of insert material in units of MPa=N/mm^2,
σ_x = axial normal stress in units of MPa=N/mm^2,
ν_{insert} = Poisson's ratio insert material, and
σ_r = radial normal stress in units of MPa=N/mm^2.

X3.1.1 For the tubular test specimen with insert, σ_r = -p such that Eq X3.1 becomes:

$$p = \frac{E_{insert}\varepsilon_x - \sigma_x}{2\nu_{insert}} \quad (X3.2)$$

X3.1.2 For an incompressible, linear elastic material such as most elastomers, ν_{insert} = 0.5, and Eq X3.2 becomes:

$$p = E_{insert}\varepsilon_x - \sigma_x \quad (X3.3)$$

where:

σ_h = hoop tensile stress in units of MPa,
p = internal pressure in units of N/mm^2,
η_m = maximum hoop stress factor = $[1 - 1/2\,(\theta\,(\beta\, m) + \theta\,(\beta\, n))] + \nu\sigma_x$ (see Fig. X2.1 and Ref **(1)**),
r_i^{tube} = inner radius of tube units of mm,
r_o^{tube} = outer radius of tube units of mm, and
σ_x = axial tensile tress in units of MPa.

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