Designation: C1863 − 18

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

This standard is issued under the fixed designation C1863; 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 direct internal pressurization that is applied monotonically at ambient temperature. This type of test configuration is sometimes referred to as "tube burst test." This test method is specific to tube geometries, because flaw populations, fiber architecture, material fabrication, and test 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 a pressurized fluid applied either directly to the material or through a secondary bladder inserted into the tube. The monotonically applied uniform radial pressure on the inside of the tube results in hoop stress-strain response of the composite tube that 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 introduction of a monotonically applied internal pressure 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: unidirectional (1D, filament wound and tape lay-up), bidirectional (2D, fabric/tape lay-up and weave), and tridirectional (3D, braid and weave). These types of ceramic matrix composites can be composed of a wide range of ceramic fibers (oxide, graphite, carbide, nitride, and other compositions) in a wide range of crystalline and amorphous ceramic matrix compositions (oxide, carbide, nitride, carbon, graphite, and other compositions).

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 the intended application that includes composite material property and tube radius. Lengths of the composite tube, length of the pressurized section, and length of tube overhang are determined 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 lengths of pressurized section are possible.

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

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

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

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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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1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* Specific hazard statements are given in Section 8.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C1145 Terminology of Advanced Ceramics

C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics

D3878 Terminology for Composite Materials

E4 Practices for Force Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

E83 Practice for Verification and Classification of Extensometer Systems

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

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

IEEE/ASTM SI 10 American National Standard for Metric Practice

3. Terminology

3.1 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 and Terminologies C1145, D3878, and E6 are shown in the following with the appropriate source given in parentheses. Additional terms used in conjunction with this test method are defined in the following:

3.2 *Definitions:*

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

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

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

3.2.4 *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**

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

3.2.6 *hoop fracture strength* (FL^{-2})*, n*—the tensile component of hoop stress at the point when the structural integrity of the material is compromised and the tubular test specimen ruptures. Hoop fracture strength is calculated from the internal pressure induced at rupture of the tubular test specimen.

3.2.7 *hoop stress* (FL^{-2})*, n*—the tensile stress in the circumferential direction of a tube or pipe due to internal hydrostatic pressure.

3.2.8 *hoop tensile strength* (FL^{-2})*, 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.

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

3.2.9.1 *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).

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

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

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

3.2.12.1 *Discussion*—The modulus of toughness can also be referred to as the "cumulative damage energy" and as such is regarded as an indication of the ability of the material to sustain damage rather than as a material property. Fracture mechanics methods for the characterization of CMCs have not been developed. The determination of the modulus of toughness as provided in this test method for the characterization of the

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

cumulative damage process in CMCs may become obsolete when fracture mechanics methods for CMCs become available.

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

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

3.2.14 *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**

4. Summary of Test Method

4.1 In this test method, a composite tube/cylinder with a defined gage section and a known wall thickness is loaded via internal pressurization from a pressurized fluid applied either directly to the material or through a secondary bladder inserted into the tube. The monotonically applied uniform radial pressure on the inside of the tube results in hoop stress-strain response of the composite tube that 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.

4.2 Hoop tensile strength as used in this test method refers to the tensile strength in the hoop direction from the introduction of a monotonically applied internal pressure where 'monotonic' refers to a continuous nonstop test rate without reversals from test initiation to final fracture.

4.3 The test method is applicable to a range of test specimen tube geometries based on a nondimensional parameter that includes composite material property and tube radius. Lengths of the composite tube and other test specimen parameters are determined so as to provide a gage length with uniform internal radial pressure that results in only a hoop stress in the gage section. A wide range of combinations of material properties, tube radii, wall thicknesses, tube lengths, pressurized lengths, and overhang (that is, unpressurized) lengths are possible.

5. Significance and Use

5.1 This test method (also known as "tube burst test") may be used for material development, material comparison, material screening, material down selection, and quality assurance. This test method can also be used for material characterization, design data generation, material model verification/validation, or combinations thereof.

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.

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

5.4 Unlike monolithic advanced ceramics that fracture catastrophically from a single dominant flaw, CMCs generally experience "graceful" fracture from a cumulative damage process. Therefore, while the volume of material subjected to a 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 stresses induced from internal pressurization of tubes. Nonuniform stress states may be inherent in these types of tests and subsequent evaluation of any nonlinear stress-strain behavior must take into account the asymmetric behavior of the CMC under multiaxial stressing. This nonlinear behavior may develop as the result of cumulative damage processes (for example, matrix cracking, matrix/fiber de-bonding, 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. Conduct testing to evaluate the maximum strength potential of a material in inert environments or at sufficiently rapid testing rates, or both, so as to minimize slow crack growth effects. Conversely, testing can be conducted in environments and testing modes and rates representative of service conditions to evaluate material performance under use conditions. When testing is conducted in uncontrolled ambient air with the intent of evaluating maximum strength potential, monitor and report relative humidity and temperature. Test at humidity levels >65 % relative humidity (RH). Report any deviations from this recommendation.

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 (that is, increased frequency of surface-initiated fractures compared to volume-initiated fractures), or an inherent part of the strength characteristics to be measured. Surface preparation can also lead to the introduction of residual stresses. Universal or standardized test methods of surface preparation do not exist. It should be understood that final machining steps may or may not negate machining damage introduced during the initial machining. Thus, test specimen fabrication history may play an important role in the measured strength distributions and should be reported. In addition, the nature of fabrication used for certain composites (for example, chemical vapor infiltration or hot pressing) may require the testing of test specimens in the as-processed condition (that is, it may not be possible to machine the test specimen faces).

6.3 Internally pressurized tests of CMC tubes can produce multiaxial stress distributions with maximum and minimum stresses occurring at the surface of the test specimen, leading to fractures originating at surfaces or near geometrical transitions. In addition, 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 nonuniform stresses caused by bending.

6.4 If an internal bladder is used to transfer the pressure to the tubular test specimen, friction between the insert and the rough or unlubricated (or both) inner surface of test specimen can produce axial stresses on the inner bore of the tube that will affect hoop stress in the tube if the wall thickness of the bladder is large. In addition, this friction can 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. Because such non-gage section fractures will usually constitute invalid tests, provide an explanation when differentiating between valid and invalid tests.

7. Apparatus

7.1 Various methods can be used to produce direct pressure in the CMC tube. An overview of some of these methods is provided in Appendix X1. Specifics regarding test apparatus are provided in the following sections.

7.2 *Testing Machines*—Various methods can be used to produce pressure in the tube. If uniaxial test machines are used to apply uniaxial force to a chamber to produce internal pressurization to the tubular test specimen, then this machine shall conform to the requirements of Practices E4. The axial force used in inducing the internal pressure shall be accurate to within ±1 % at any force within the selected force range of the testing machine as defined in Practices E4. A schematic showing pertinent features of such a hoop tensile strength testing apparatus is shown in Fig. 1 (**1, 2**).[3]

7.3 *Fixtures:*

7.3.1 *General*—In general, two types of test setups and related fixtures as detailed in the following subsections have been used for hoop tensile strength testing of tubes: compression pressurization and direct pressurization.

7.3.2 *Compression Pressurization*—Compression loading fixtures (**1-4**) used in combination with universal testing machines to produce the internal pressure for the tubular test specimens are generally composed of two parts: (*1*) hydraulic piston assembly attached to the test machine, and (*2*) pressurization test fixture in which the tubular test specimen is mounted and tested under pressure. A schematic drawing of such a setup is shown in Fig. 1.

7.3.3 *Direct Pressurization*—Direct pressurization of the tubular test specimen is obtained from an external source such

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

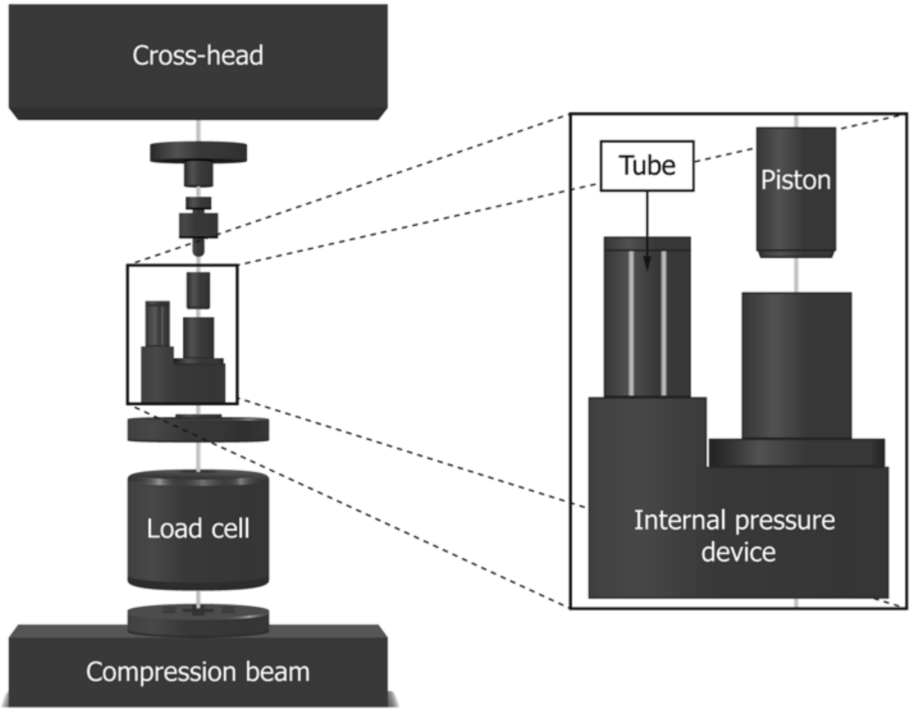


FIG. 1 Schematic of an Internal Pressure Device Using a Universal Test Machine for Pressurization (2)

as a hydraulic pump or pressure reservoir (5-12). Inlet pressure to the tubular test specimen is controlled directly as shown in Figs. 2 and 3.

7.3.3.1 Studies (13) have shown that the pressurized length of the tube, L, and hence minimum length of the tubular specimen or bladder (or both) can be calculated as:

$$L \geq 9/\beta$$

and

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

where:

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

NOTE 1—Example of a commercial CMC ($\nu = 0.15$ in the hoop direction) 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 $L = 9/\beta = 9/0.133 = 67.38$ mm.

7.4 *Strain Measurement*—Determine strain by means of suitable diametral or circumferential extensometers, strain gages, or appropriate whole-field methods. If Poisson's ratio is to be determined, instrument the tubular test specimen to measure strain in both axial and circumferential directions.

7.4.1 *Extensometry*—Diametral or circumferential extensometers used for testing of CMC tubular test specimens shall satisfy Practice 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.

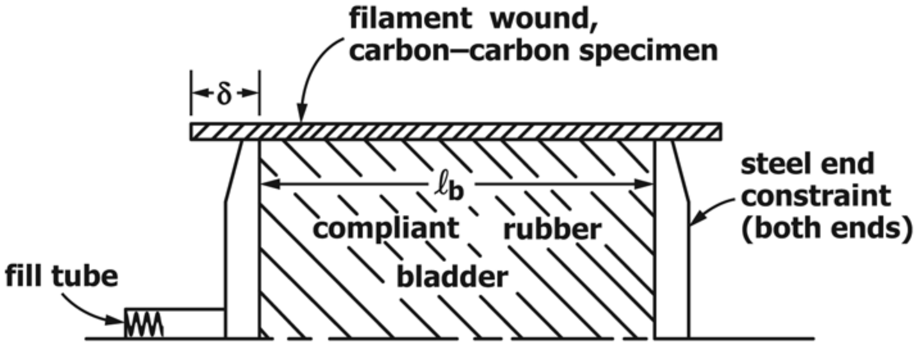
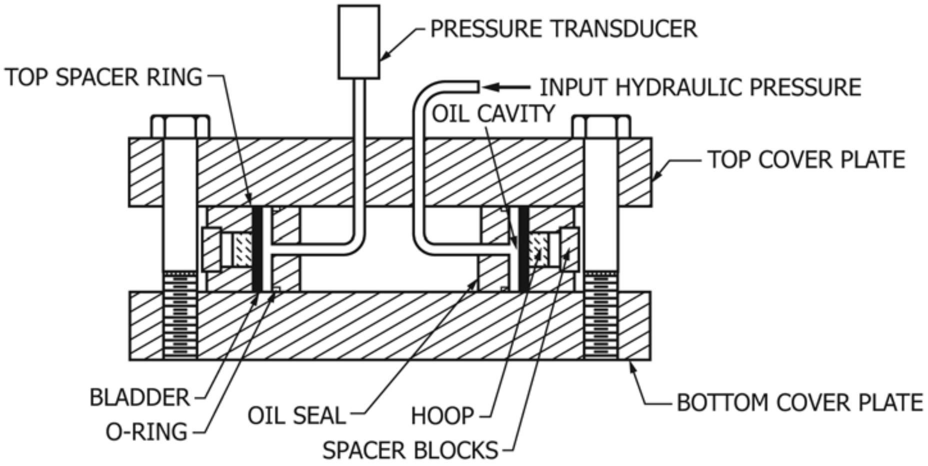


FIG. 2 Schematic Diagram of Burst Tube Arrangement Showing Internal Bladder Length (Gage Length), lb, and Overhang Length of Tube, σ (4)



NOTE 1—Caution is advised regarding imposing an axial compressive force.

FIG. 3 Schematic of Room Temperature Hydrostatic Test Facility (8)

Calibrate extensometers periodically in accordance with Practice E83. For extensometers mechanically attached to the test specimen, make the attachment so as to cause no damage to the specimen surface.

7.4.2 *Strain Gages*—Alternatively, strain can also be determined directly from strain gages. Ideally, to eliminate the effect of misaligned uniaxial strain gages, mount three-element rosette strain gages on the test specimen 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, use strain gage lengths greater than three unit cells of the fiber architecture but not less than 9 to 12 mm for the longitudinal direction and greater than three unit cells of the fiber architecture or not less than 6 mm for the transverse direction. Note that larger strain gages may be required for fabric reinforcements to average the localized strain effects of the fiber crossovers. However, larger strain gages adhered to the curved surfaces of the tubular test specimens may have an initial strain due to tube curvature that may render the strain reading unusable. Choose strain gages, surface preparation, and bonding agents so as to provide adequate performance on the subject materials. Employ suitable strain recording equipment. Note that many CMCs exhibit high degrees of porosity and surface roughness and therefore require surface preparation, including surface filling, before the strain gages can be applied.

7.4.3 *Circumferential Displacement*—In this method (**8**), a "string" is wrapped around the circumference of the gage section of the tubular test specimen and is attached to spring-loaded linear variable differential transformers (LVDTs) mounted on a rigid frame (see Fig. 4). The arrangement monitors the circumferential change in displacement with increasing pressure. The change in circumference, ΔC, can be transformed into the outer diameter circumferential strain as $\Delta C/C_o$ where C_o is the original circumference.

7.4.4 *Whole-Field Strain Measurement*—Digital image correlation (DIC) is a whole-field, optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images (**14, 15**). The resulting image shows the strain distribution over the surface of the tube.

NOTE 2—Several methods can be used to measure the whole-field displacement distribution using DIC. Typically, an image is recorded before deformation at a particular brightness distribution and then a similar brightness distribution is searched for in the image after deformation. The displacement components of a pixel located at the center of the subset are determined, and the displacement distributions are obtained by

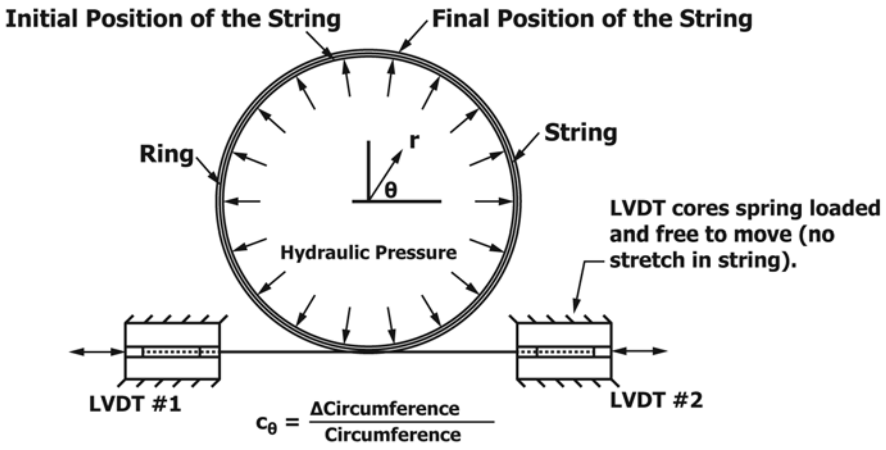


FIG. 4 LVDT/String Arrangements for Measuring Hoop (8)