



# Standard Test Method for Transverse Tensile Properties of Hoop Wound Polymer Matrix Composite Cylinders<sup>1</sup>

This standard is issued under the fixed designation D5450/D5450M; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

*This standard has been approved for use by agencies of the U.S. Department of Defense.*

## 1. Scope

1.1 This test method determines the transverse tensile properties of wound polymer matrix composites reinforced by high-modulus continuous fibers. It describes testing of hoop wound (90°) cylinders in axial tension for determination of transverse tensile properties.

1.2 The technical content of this standard has been stable since 1993 without significant objection from its stakeholders. As there is limited technical support for the maintenance of this standard, changes since that date have been limited to items required to retain consistency with other ASTM D30 Committee standards, including editorial changes and incorporation of updated guidance on specimen preconditioning and environmental testing. The standard, therefore, should not be considered to include any significant changes in approach and practice since 1993. Future maintenance of the standard will only be in response to specific requests and performed only as technical support allows.

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

1.3.1 Within the text, the inch-pound units are shown in brackets.

1.4 *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.*

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.04 on Lamina and Laminate Test Methods.

Current edition approved July 1, 2016. Published July 2016. Originally approved in 1993. Last previous edition approved in 2012 as D5450/D5450M – 12. DOI: 10.1520/D5450\_D5450M-16.

## 2. Referenced Documents

### 2.1 ASTM Standards:<sup>2</sup>

- D792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
- D883 Terminology Relating to Plastics
- D2584 Test Method for Ignition Loss of Cured Reinforced Resins
- D2734 Test Methods for Void Content of Reinforced Plastics
- D3171 Test Methods for Constituent Content of Composite Materials
- D3878 Terminology for Composite Materials
- D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
- D5448/D5448M Test Method for Inplane Shear Properties of Hoop Wound Polymer Matrix Composite Cylinders
- D5449/D5449M Test Method for Transverse Compressive Properties of Hoop Wound Polymer Matrix Composite Cylinders
- E4 Practices for Force Verification of Testing Machines
- E6 Terminology Relating to Methods of Mechanical Testing
- E111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
- E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
- E132 Test Method for Poisson's Ratio at Room Temperature
- E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
- E251 Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages
- E456 Terminology Relating to Quality and Statistics
- E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
- E1237 Guide for Installing Bonded Resistance Strain Gages

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

### 3. Terminology

3.1 *Definitions*—Terminology **D3878** defines terms relating to high-modulus fibers and their composites. Terminology **D883** defines terms relating to plastics. Terminology **E6** defines terms relating to mechanical testing. Terminology **E456** and Practice **E177** define terms relating to statistics. In the event of a conflict between terms, Terminology **D3878** shall have precedence over other standards.

NOTE 1—If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [M] for mass, [L] for length, [T] for time, [θ] for thermodynamic temperature, and [nd] for non-dimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

#### 3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *hoop wound, n*—a winding of a cylindrical component where the filaments are circumferentially oriented.

3.2.2 *specimen, n*—a single part cut from a winding. Each winding may yield several specimens.

3.2.3 *transverse tensile elastic modulus,  $E_{22}$  [ $ML^{-1}T^{-2}$ ]*, *n*—the tensile elastic modulus of a unidirectional material in the direction perpendicular to the reinforcing fibers.

3.2.4 *transverse tensile strain at failure,  $\epsilon_{22}^u$  [nd]*, *n*—the value of strain, perpendicular to the reinforcing fibers in a unidirectional material, at failure when a tensile force is applied in the direction perpendicular to the reinforcing fibers.

3.2.5 *transverse tensile strength,  $\sigma_{22}^u$  [ $ML^{-1}T^{-2}$ ]*, *n*—the strength of a unidirectional material when a tensile force is applied in the direction perpendicular to the reinforcing fibers.

3.2.6 *winding, n*—an entire part completed by one winding operation and then cured.

### 4. Summary of Test Method

4.1 A thin walled hoop wound cylinder nominally 100 mm [4 in.] in diameter and 140 mm [5.5 in.] in length is bonded into two end fixtures. The specimen/fixture assembly is mounted in the testing machine and monotonically loaded in tension while recording force. The transverse tensile strength can be determined from the maximum force carried prior to failure. If the cylinder strain is monitored with strain gauges, then the stress-strain response of the material can be determined. From the stress-strain response the transverse tensile strain at failure, transverse tensile modulus of elasticity, and Poisson's ratio can be derived.

### 5. Significance and Use

5.1 This test method is used to produce transverse tensile property data for material specifications, research and development, quality assurance, and structural design and analysis. Factors which influence the transverse tensile response and should, therefore, be reported are: material, methods of material preparation, specimen preparation, specimen conditioning, environment of testing, specimen alignment and gripping, speed of testing, void content, and fiber volume

fraction. Properties, in the test direction, which may be obtained from this test method include:

5.1.1 *Transverse Tensile Strength,  $\sigma_{22}^u$ ,*

5.1.2 *Transverse Tensile Strain at Failure,  $\epsilon_{22}^u$ ,*

5.1.3 *Transverse Tensile Modulus of Elasticity,  $E_{22}$ , and*

5.1.4 *Poisson's Ratio,  $\nu_{21}$ .*

### 6. Interference

6.1 *Material and Specimen Preparation*—Poor material fabrication practices, lack of control of fiber alignment, and damage induced by improper specimen machining are known causes of high material data scatter in composites.

6.2 *Bonding Specimens to Test Fixtures*—A high percentage of failures in or near the bond between the test specimen and the test fixtures, especially when combined with high material data scatter, is an indicator of specimen bonding problems. Specimen to fixture bonding is discussed in **11.5**.

6.3 *System Alignment*—Excessive bending may cause premature failure, as well as highly inaccurate modulus of elasticity determination. Every effort should be made to eliminate excess bending from the test system. Bending may occur due to misaligned grips, misaligned specimens in the test fixtures, or from departures of the specimen from tolerance requirements. The alignment should always be checked as discussed in **13.2**.

### 7. Apparatus

7.1 *Micrometers and Calipers*—A micrometer with a 4 to 7 mm [0.16 to 0.28 in.] nominal diameter ball-interface or a flat anvil interface shall be used to measure the specimen wall thickness, inner diameter, and outer diameter. A ball interface is recommended for these measurements when at least one surface is irregular (e.g. a course peel ply surface, which is neither smooth nor flat). A micrometer or caliper with a flat anvil interface shall be used for measuring the overall specimen length, the gauge length (the free length between the fixtures) and other machined surface dimensions. The use of alternative measurement devices is permitted if specified (or agreed to) by the test requestor and reported by the testing laboratory. The accuracy of the instruments shall be suitable for reading to within 1 % of the sample dimensions. For typical specimen geometries, an instrument with an accuracy of  $\pm 0.0025$  mm [ $\pm 0.0001$  in.] is adequate for wall thickness measurements, while an instrument with an accuracy of  $\pm 0.025$  mm [ $\pm 0.001$  in.] is adequate for measurement of the inner diameter, outer diameter, overall specimen length, gauge length, and other machined surface dimensions.

7.2 *Tension Fixture*—The tension fixture consists of a steel outer shell, insert, load rod, and spherical washer. An assembly drawing for these components and the test fixture is seen in **Fig. 1**.

7.2.1 *Outer Shell*—The outer shell (metric units **Fig. 2**, english units **Fig. 3**) is circular with a concentric circular hollow in one face, a groove along the diameter of the other face, and a center hole through the thickness. Along the diameter perpendicular to the groove, three pairs of small eccentric holes are placed at three radial distances. The two

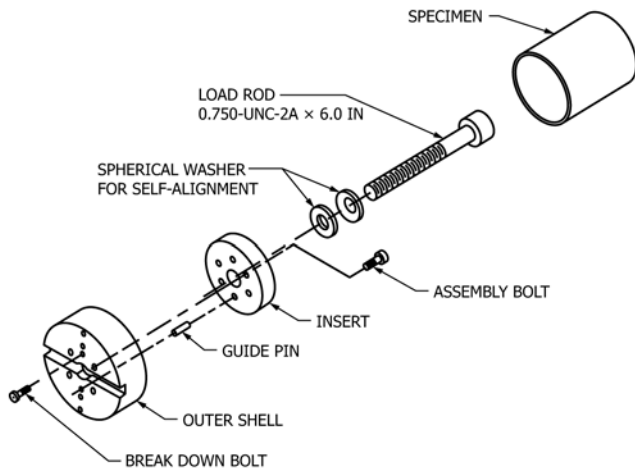


FIG. 1 Assembly Drawing for Tension Fixture and Specimen

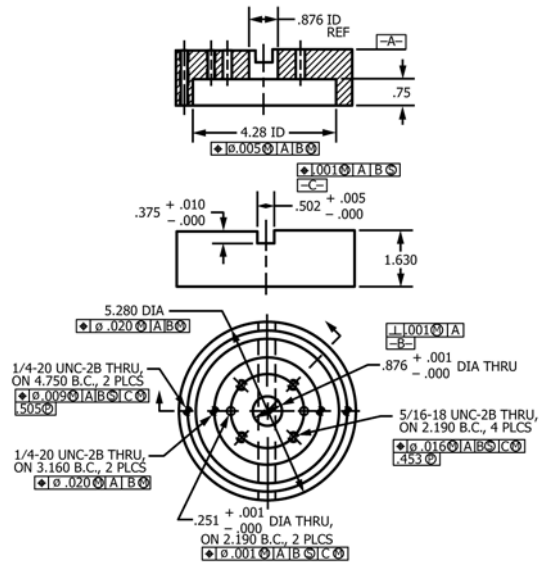


FIG. 3 The Outer Shell of the Tension Fixture in English Units

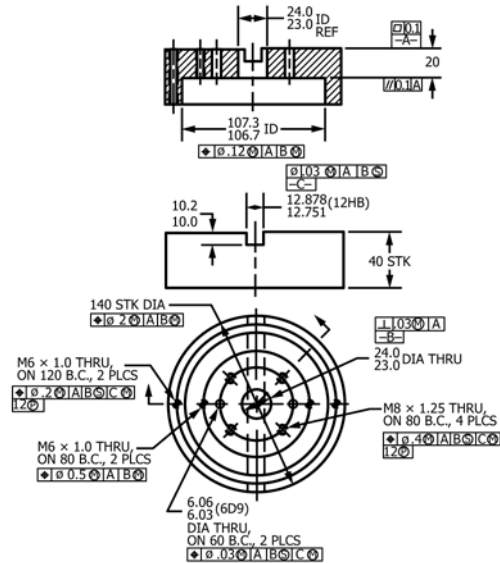


FIG. 2 The Outer Shell of the Tension Fixture in Metric Units

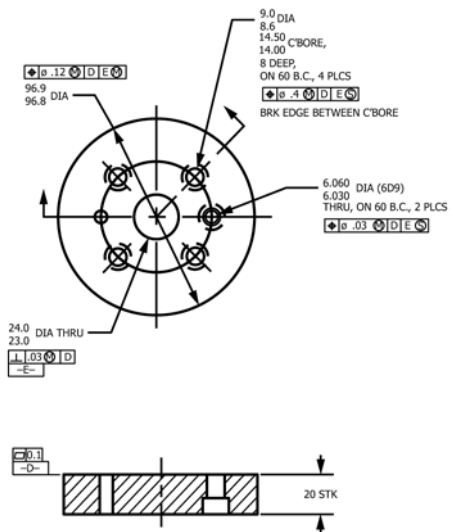


FIG. 4 The Insert of the Tensile Fixture in Metric Units

outer pairs of holes are threaded. Four additional threaded holes are placed at the same radial distance as the innermost pair of holes, at ninety degree intervals starting forty-five degrees from the diameter that passes through the center groove.

7.2.2 *Insert*—The fixture insert is circular with a center hole through the thickness (metric units Fig. 4, english units Fig. 5). Two sets of holes are placed along a concentric centerline. These holes align with the innermost set of holes in the outer shell. The set of four holes at ninety degree intervals are counterbored. The insert is fastened inside the hollow of the outer shell to form the concentric groove used to put the specimen in the fixture (Fig. 1).

7.2.3 *Load Rod and Spherical Washers*—Two spherical washers for self alignment are placed over a 0.750-UNC-2A x 6.0 inch load rod. The load rod is then slid through the center hole of the outer shell and insert assembly as illustrated in Fig. 1.

7.2.4 The outer shell and insert for the tension fixture are the same outer shell and insert used for the fixtures in Test Methods D5448/D5448M and D5449/D5449M.

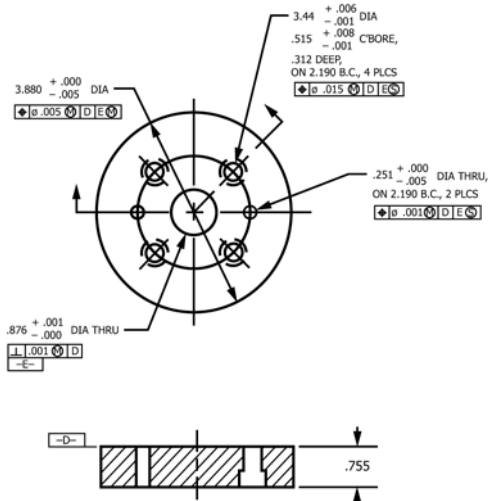
7.3 *Testing Machine*, comprised of the following:

7.3.1 *Fixed Member*—A fixed or essentially stationary member to which one end of the tension specimen/fixture assembly, shown in Fig. 1, can be attached.

7.3.2 *Movable Member*—A movable member to which the opposite end of the tension specimen/fixture assembly, shown in Fig. 1, can be attached.

7.3.3 *Drive Mechanism*, for imparting to the movable member a uniform controlled velocity with respect to the fixed member, this velocity to be regulated as specified in 11.6.

7.3.4 *Force Indicator*—A suitable force-indicating mechanism capable of showing the total tensile force carried by the test specimen. This mechanism shall be essentially free of inertia-lag at the specified rate of testing and shall indicate the force within an accuracy of  $\pm 1\%$  of the actual value, or better. The accuracy of the testing machine shall be verified in accordance with Practice E4.



**FIG. 5 The Insert of the Tensile Fixture in English Units**

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

**7.4 Strain-Indicating Device**—Force versus strain data shall be determined by means of bonded resistance strain gauges. Each strain gauge shall be 6.3 mm [0.25 in.] in length. The specimen shall be instrumented to measure strain in both the axial and circumferential directions to determine Poisson’s ratio. Strain gauge rosettes (0°/45°/90°) shall be used to correct for gauge misalignment. Gauge calibration certification shall comply with Test Method **E251**. Some guidelines on the use of strain gauges on composites are as follows. A general reference on the subject is Tuttle and Brinson.<sup>3</sup>

**7.4.1 Surface Preparation**—The surface preparation of fiber-reinforced composites, discussed in Practice **E1237**, can penetrate the matrix material and cause damage to the reinforcing fibers, resulting in improper specimen failures. Reinforcing fibers should not be exposed or damaged during the surface preparation process. The strain gauge manufacturer should be consulted regarding surface preparation guidelines and recommended bonding agents for composites, pending the development of a set of standard practices for strain gauge installation surface preparation of fiber-reinforced composite materials.

**7.4.2 Gauge Resistance**—Consideration should be given to the selection of gauges having larger resistance to reduce heating effects on low-conductivity materials. Resistances of 350Ω or higher are preferred. Additional considerations should be given to the use of the minimum possible gauge excitation voltage consistent with the desired accuracy (1 to 2 volts is recommended) to further reduce the power consumed by the gauge. Heating of the specimen by the gauge may affect the performance of the material directly, or it may affect the

<sup>3</sup> Tuttle, M. E., and Brinson, H. F., “Resistance-Foil Strain-Gauge Technology as Applied to Composite Materials,” *Experimental Mechanics*, Vol 24, No. 1, March 1984; pp. 54–64; errata noted in Vol 26, No. 2, Jan. 1986, pp. 153–154.

indicated strain due to a difference between the gauge temperature compensation factor and the coefficient of thermal expansion of the specimen material.

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

**7.4.4 Transverse Sensitivity**—Consideration should be given to the transverse sensitivity of the selected strain gauge. The strain gauge manufacturer should be consulted for recommendations on transverse sensitivity corrections and effects on composites. This is particularly important for a transversely mounted gauge used to determine Poisson’s ratio.

**7.5 Conditioning Chamber**—When conditioning materials at nonlaboratory environments, a temperature/vapor-level controlled environment conditioning chamber is required, which shall be capable of maintaining the required temperature to within  $\pm 3^{\circ}\text{C}$  [ $\pm 5^{\circ}\text{F}$ ] and the required relative vapor level to within  $\pm 3\%$ . Chamber conditions shall be monitored either on an automated continuous basis or on a manual basis at regular intervals.

**7.6 Environmental Test Chamber**—An environmental test chamber is required for test environment other than ambient testing laboratory conditions. This chamber shall be capable of maintaining the gauge section of the test specimen at the required test environment during the mechanical test.

## 8. Sampling and Test Specimens

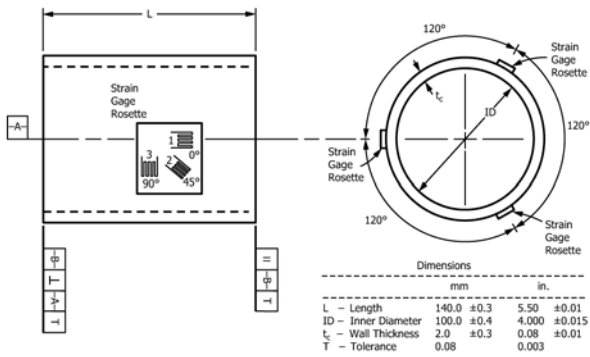
**8.1 Sampling**—At least five specimens per test condition should be tested unless valid results can be gained through the use of fewer specimens, such as in the case of a designed experiment. For statistically significant data, the procedures outlined in Practice **E122** should be consulted. The method of sampling shall be reported.

**NOTE 2**—If specimens are to undergo environmental conditioning to equilibrium, and are of such type or geometry that the weight change of the material cannot be properly measured by weighing the specimen itself, then another traveler of the same nominal thickness and appropriate size shall be used to determine when equilibrium has been reached for the specimens being conditioned.

**8.2 Geometry**—The test specimen shall be as shown in **Fig. 6**. The length of all specimens shall be 140 mm [5.5 in.]. This provides a gauge length of 102 mm [4.0 in.]. The inner diameter of all specimens shall be  $102 \pm 4$  mm [ $4.000 \pm 0.015$  in.]. Specimens may be fabricated on a tapered mandrel yielding a maximum taper over the specimen length of 0.0005 mm/mm [in./in.] on the diameter. The specimens shall have a nominal wall thickness of 2 mm [0.08 in.], the actual thickness to be specified by the winding parameters and shall be maintained as the test specimen is wound and cured.

**8.3 Winding**—All specimens shall be hoop wound (approximately 90°) with a single tow and enough layers to meet the thickness criterion previously described.





NOTE 1—Tube may be fabricated on a tapered mandrel with maximum taper of 0.0005 in./in. (0.0005 mm/mm) on the diameter.

NOTE 2—Actual measure of inner diameter will depend on specimen placement along tapered mandrel during fabrication.

FIG. 6 Test Specimen Shown with Strain Gauge Configuration

## 9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time the equipment is used.

## 10. Conditioning

10.1 The recommended pre-test condition is effective moisture equilibrium at a specific relative humidity as established by Test Method D5229/D5229M; however, if the test requestor does not explicitly specify a pre-test conditioning environment, no conditioning is required and the test specimens may be tested as prepared.

10.2 The pre-test specimen conditioning process, to include specified environmental exposure levels and resulting moisture content, shall be reported with the test data.

NOTE 3—The term moisture, as used in Test Method D5229/D5229M, includes not only the vapor of a liquid and its condensate, but the liquid itself in large quantities, as for immersion.

10.3 If no explicit conditioning process is performed, the specimen conditioning process shall be reported as “unconditioned” and the moisture content as “unknown.”

## 11. Procedure

### 11.1 Parameters to be Specified Prior to Test:

11.1.1 The sampling method, specimen geometry, and test parameters used to determine density and reinforcement volume,

11.1.2 The tension specimen sampling method,

11.1.3 The environmental conditioning test parameters, and

11.1.4 The tensile property and data reporting format desired.

NOTE 4—Specific material property, accuracy, and data reporting requirements should be determined prior to test for proper selection of instrumentation and data recording equipment. Estimates of operating stress and strain levels should also be made to aid in transducer selection, calibration of equipment, and determination of equipment settings.

### 11.2 General Instructions:

11.2.1 Any deviation from this test method shall be reported.

11.2.2 Unless otherwise directed, determine specific gravity and reinforcement and void volume percentages for each winding. Extract the material used for the determination of these properties from the center of the winding if multiple specimens are extracted from one winding or from one of the ends of the winding if only one specimen is extracted from the winding. Determine and report specific gravity and density as specified in Test Method D792. Determine and report volume percent of the constituents by one of the matrix digestion procedures of Test Method D3171, or, for certain reinforcement materials such as glass and ceramic, by the matrix burn-off technique of Test Method D2584. The void content equations of Test Methods D2734 are applicable to both Test Method D2584 and the matrix digestion procedures.

11.2.3 Following any conditioning, but before the tension testing, measure and report the specimen’s outer diameter (OD), inner diameter (ID), and length. The specimens are measured by first marking two randomly selected locations within the middle two-thirds of the specimen length. At each of the points, average four measurements of the outer diameter on an axis that passes through the point and then repeat the procedure on an axis perpendicular to the initial axis. Repeat the procedure for the inner diameter using the same axes. Subtract the average inner diameter from the average outer diameter and divide the remainder by two. This value will be used as the composite wall thickness,  $t_c$ . Also, obtain four length measurements, made at 90° intervals around the specimen circumference, and compute their average. This value will be used as the specimen length.

11.3 *Strain Gauge Installation*—Attach strain gauges to the center of the specimen’s gauge section. Three strain gauge rosettes (oriented as 0°/45°/90°, where 0° is parallel to the specimen axis), mounted 120° around the specimen outer circumference from each other as shown in Fig. 6, are recommended in order to ascertain that only tensile loading is being applied. Non-tensile loading may be detected if the strain measured on one of the rosettes is greatly different from the strain on one or both of the other rosettes. For an accurate assessment of Poisson’s ratio, strain gauges may be optionally attached to the inside of the specimen, directly opposite the gauges on the outside, to measure circumferential strain.

11.4 *Fixture Assembly*—Assembly of tension fixture is illustrated in Fig. 1. Place two guide pins into the guide pin holes of the insert so that approximately half of the pins length are protruding from the insert. Place the insert inside the concentric circular hollow of the outer shell so that the protruding guide pins enter the outer shell guide pin holes. Secure the insert to the outer shell using four assembly bolts. Place spherical washers over load rod and insert load rod through the center hole of the outer shell and insert assembly.

11.5 *Securing Specimen*—Secure the test specimen within two fixtures, as shown in Fig. 7, by filling the fixtures cavities with potting material and inserting the specimen ends firmly to the bottom of the cavities while allowing the potting material to form a bead (see Note 5). Cure according to the manufacturer’s specifications, but the cure temperature should not jeopardize the specimen. Obtain four measurements of the free length between the fixtures, made at 90° intervals around the

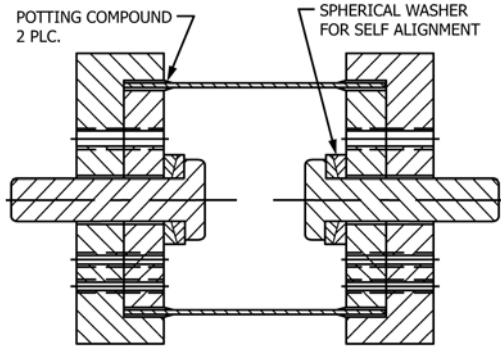


FIG. 7 Illustration of Assembled Tension Fixture and Specimen

specimen/fixture circumference, and compute their average. This value will be used as the gauge length.

NOTE 5—Select the potting material so that it can be cured at a temperature,  $T_c$ , no greater than 28°C [50°F] lower than the glass transition temperature  $T_g$  of the specimen,  $T_c < T_g - 28^\circ\text{C}$  [ $T_c < T_g - 50^\circ\text{F}$ ]. It is helpful if the potting material can be removed without a great deal of difficulty upon completion of the test. Select a potting material to have properties sufficient to avoid failure of the potting material and failure of the specimen near the potting material during the test.

11.6 *Speed of Testing*—Set the speed of testing to effect a nearly constant strain rate in the gauge section. If strain control is not available on the testing machine, this may be approximated by repeated monitoring and adjusting of the rate of force application to maintain a nearly constant strain rate, as measured by strain transducer response versus time. The strain rate should be selected so as to produce failure within 1 to 10 min. If the ultimate strain of the material cannot be reasonably estimated, conduct initial trials using standard speeds until the ultimate strain of the material and the compliance of the system are known, and the strain rate can be adjusted. The suggested standard speeds are as follows:

11.6.1 *Strain Control Machines*—A standard strain rate of  $0.0125 \text{ min}^{-1}$ .

11.6.2 *Constant Crosshead Speed Machine*— A standard crosshead displacement of 1.3 mm [0.05 in.] per min.

NOTE 6—Use of a fixed crosshead speed in testing machine systems with a high compliance will result in a strain rate which is much lower than required.

11.7 *Test Environment*—Condition the specimen to the desired moisture profile and test under the same conditioning fluid exposure level. However, cases such as elevated temperature testing of a moist specimen place unrealistic requirements on the capabilities of common testing machine environmental chambers. In such cases, the mechanical test environment may need to be modified, for example, by testing at elevated temperature with no fluid exposure control, but with a specified limit on time to failure from withdrawal from the conditioning chamber. Record modifications to the test environment.

NOTE 7—When testing a conditioned specimen at elevated temperature with no fluid exposure control, the percentage moisture loss of the specimen prior to test completion may be estimated by placing a conditioned traveler of known weight within the test chamber at the same time the specimen is placed in the chamber. The traveler should be configured to mimic the specimen, such that moisture evaporation is

comparable to that of the test specimen. Upon completion of the test, the traveler is removed from the chamber, weighed, and the percentage weight calculated and reported.

11.7.1 If the testing area environment is different than the specimen conditioning environment, then store the specimen in the conditioned environment until test time.

11.8 *Data Recording Instrumentation*— Attach the data recording instrumentation to the strain gauges on the specimen and to the load cell.

11.9 *Loading*—Apply force to the specimen at the specified rate until failure, while recording data.

11.10 *Data Recording*—Record force versus strain (or displacement) continuously, or at frequent regular intervals; for this test method, a sampling rate of 2 to 3 data recordings per second, and a target minimum of 100 data points per test are recommended. If the specimen is to be failed, record the maximum force, the failure force, and the strain (or displacement) at, or as near as possible to where the force drops off significantly. Typically, a 10 % drop off in force is considered significant.

11.11 *Failure Mode*—Record the mode and location of failure of the specimen. Choose, if possible, a standard description from the sketches of common test failure modes which are shown in Fig. 8. Failure in a specimen occurring within one specimen thickness of the bond between the specimen and the test fixture is considered a grip (GR) failure. Typically, a grip failure is precipitated by an anomalous condition; therefore, the grip failure mode is considered inappropriate.

11.12 *Fixture Disassembly*—This is only an advised procedure for disassembling the test fixture. Cut each end of the specimen at the base of the fixture. Remove the load rod and spherical washers from the outer shell and insert assembly. Remove the four assembly bolts from the insert. Place the outer shell and insert assembly into an oven at a temperature that will degrade the potting compound. After a sufficient period of time, remove the fixtures from the oven and allow them to cool.

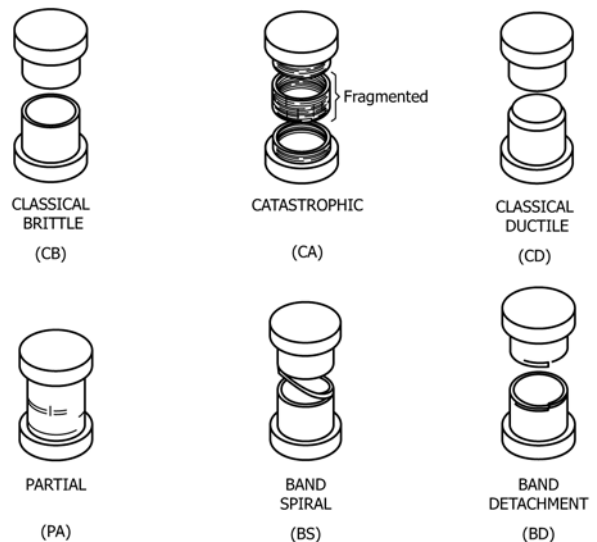


FIG. 8 Failure Modes for Hoop Wound Tubes in Tension

Insert two break down bolts into outer shell (see Fig. 1). Turn break down bolts to force insert out of the concentric circular hollow of the outer shell. Remove guide pins from insert and outer shell. Wire brush insert and outer shell to remove specimen debris.

## 12. Validation

12.1 Values for ultimate properties shall not be calculated for any specimen that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

$$\varepsilon_1^i = \frac{\hat{\varepsilon}_1^i (1 - \nu_o K_{t_1}) - K_{t_1} \hat{\varepsilon}_3^i (1 - \nu_o K_{t_3})}{1 - K_{t_1} K_{t_3}} \quad (1)$$

$$\varepsilon_2^i = \frac{\hat{\varepsilon}_2^i (1 - \nu_o K_{t_2})}{1 - K_{t_2}} - \frac{K_{t_2} [\hat{\varepsilon}_1^i (1 - \nu_o K_{t_1}) (1 - K_{t_3}) + \hat{\varepsilon}_3^i (1 - \nu_o K_{t_3}) (1 - K_{t_1})]}{(1 - K_{t_1} K_{t_3}) (1 - K_{t_2})} \quad (2)$$

$$\varepsilon_3^i = \frac{\hat{\varepsilon}_3^i (1 - \nu_o K_{t_3}) - K_{t_3} \hat{\varepsilon}_1^i (1 - \nu_o K_{t_1})}{1 - K_{t_1} K_{t_3}} \quad (3)$$

where:

$\nu_o$  = Poisson's ratio for the material used in calibration by the strain gauge manufacturer (usually 0.285),

$K_{t_1}, K_{t_2}, K_{t_3}$  = transverse sensitivity coefficients for gauges (1), (2), and (3) (these values are typically reported by the manufacturers in percentages and must be converted for use in the above equations, for example,  $K_t = 0.7\% = 0.007$ ),

$\hat{\varepsilon}_1^i, \hat{\varepsilon}_2^i, \hat{\varepsilon}_3^i$  = indicated (uncorrected) strains from gauges (1), (2), and (3) for the  $i^{\text{th}}$  rosette, and

$\varepsilon_1^i, \varepsilon_2^i, \varepsilon_3^i$  = corrected strains for gauges (1), (2), and (3) for the  $i^{\text{th}}$  rosette.

13.2 *Principal Strain Calculation*—Calculate separately for each rosette the principal strains in the material that result from the applied force using the corrected strain gauge readings.

$$\varepsilon_{11}^i = \frac{\varepsilon_1^i + \varepsilon_3^i}{2} + \frac{1}{2} ((\varepsilon_1^i - \varepsilon_3^i)^2 + (2\varepsilon_2^i - \varepsilon_1^i - \varepsilon_3^i)^2)^{1/2}$$

$$\varepsilon_{22}^i = \frac{\varepsilon_1^i + \varepsilon_3^i}{2} - \frac{1}{2} ((\varepsilon_1^i - \varepsilon_3^i)^2 + (2\varepsilon_2^i - \varepsilon_1^i - \varepsilon_3^i)^2)^{1/2}$$

where:

$\varepsilon_{11}^i$  = strain in the direction of the fiber (circumferential) for the  $i^{\text{th}}$  rosette, and

$\varepsilon_{22}^i$  = strain in the direction perpendicular to the fiber (axial) for the  $i^{\text{th}}$  rosette.

If  $\varepsilon_{11}^i$  or  $\varepsilon_{22}^i$  varies by more than 5% with location of rosette around the cylinder, within the strain range used to calculate the transverse elastic modulus (see 13.6), the strain field is not uniform and the test is invalid.

13.3 *Calculation of Angle of Rotation from Principal Plane*—Calculate separately for each rosette the angle of rotation of the rosette from the principal plane using the corrected strain gauge readings.

12.2 A significant fraction of failures in a sample population occurring within one specimen thickness of the bond between the specimen and test fixture shall be cause to reexamine the means of force introduction into the material. Factors considered should include alignment of the specimen in the fixture, alignment of the fixtures in the grips, and material used to bond the specimen to the fixture.

## 13. Calculation

13.1 *Transverse Sensitivity Correction*—Correct the strain gauge readings for transverse sensitivity separately for each rosette.

$$\theta^i = \frac{1}{2} \tan^{-1} \left( \frac{2\varepsilon_2^i - \varepsilon_1^i - \varepsilon_3^i}{\varepsilon_3^i - \varepsilon_1^i} \right) \quad (4)$$

where  $\theta^i$  = angle of rotation of the  $i^{\text{th}}$  rosette from the principal plane.

If  $\theta_i$  for any of the rosettes around the cylinder is greater than  $\pm 10^\circ$ , the calculation of the principal strains (axial and circumferential strains for the cylindrical specimens) is not considered reliable and the test is invalid.

NOTE 8—The preceding equations used to calculate the principal strain and angle of rotation from the principal plane are developed specifically for gauges configured as illustrated in Fig. 6.

13.4 *Average Principal Strain*—Calculate the average principal strains in the material using the following equation:

$$\bar{\varepsilon}_{11} = \sum_{i=1}^n \varepsilon_{11}^i / n$$

$$\bar{\varepsilon}_{22} = \sum_{i=1}^n \varepsilon_{22}^i / n$$

where:

$\bar{\varepsilon}_{11}$  = average  $\varepsilon_{11}$  for the rosettes,

$\bar{\varepsilon}_{22}$  = average  $\varepsilon_{22}$  for the rosettes, and

$n$  = number of rosettes on the test specimen (usually three).

Record the average strain in the axial ( $\bar{\varepsilon}_{22}$ ) and circumferential directions at failure.

13.5 *Tensile Strength*—Calculate the transverse tensile strength,  $\sigma_{22}^m$ , using the following equations:

$$\sigma_{22}^m = P_{max} / A$$

where:  $A$  = the cross-sectional area,

$$A = \frac{\pi}{4} (OD^2 - ID^2),$$

and *ID* and *OD* are the average inner and outer diameters, respectively.

13.6 *Tensile Modulus of Elasticity*— Select the appropriate chord modulus strain range from **Table 1**. Calculate the tensile modulus of elasticity using the following equation:

$$E_{22} = \Delta\sigma_{22}/\Delta\bar{\epsilon}_{22}$$

where:

- $E_{22}$  = transverse elastic modulus, MPa [psi],
- $\Delta\sigma_{22}$  = difference in applied tensile stress between the two strain points of **Table 1**, MPa [psi], and
- $\Delta\bar{\epsilon}_{22}$  = difference between the two strain points of **Table 1** (nominally either 0.001, 0.002, or 0.005).

If data is not available at the exact strain range end points (as often occurs with digital data), use the closest available data point. Report the tensile modulus of elasticity to three significant figures. Also report the strain range used in the calculation.

13.6.1 The tabulated strain ranges should only be used for materials which do not exhibit a transition region (a significant change in the slope of the stress-strain curve) within the given strain range. If a transition region occurs within the recommended strain range, then a more suitable strain range shall be used and reported.

13.6.2 *Tensile Modulus of Elasticity (Other Definitions)*— Other definitions of elastic modulus may be evaluated and reported at the user’s discretion. If such data is generated and reported, report also the definition used, the strain range used, and the results to three significant figures. Test Method **E111** provides additional guidance in the determination of modulus of elasticity.

13.7 *Poisson’s Ratio*—Select the appropriate elastic modulus strain range from **Table 1**. Determine the average circumferential strain,  $\bar{\epsilon}_{11}$ , at each of the two average axial strains,  $\bar{\epsilon}_{22}$ , strain range end points. Calculate Poisson’s ratio using the following equation:

$$\nu_{21} = -\Delta\bar{\epsilon}_{11}/\Delta\bar{\epsilon}_{22}$$

where:

- $\nu_{21}$  = Poisson’s ratio,
- $\Delta\bar{\epsilon}_{11}$  = difference in average circumferential strain between the two strain points of **Table 1**, and
- $\Delta\bar{\epsilon}_{22}$  = difference between the two axial strain points in **Table 1** (nominally either 0.001, 0.002, or 0.005).

If data is not available at the exact strain range end points (as often occurs with digital data), use the closest available data point. Report the tensile modulus of elasticity to three significant figures. Also report the strain range used in the calculation.

13.7.1 *Tensile Poisson’s Ratio (Other Definitions)*—Other definitions of Poisson’s ratio may be evaluated and reported at

the user’s discretion. If such data is generated and reported, report also the definition used, the strain range used, and the results to three significant figures. Test Method **E132** provides additional guidance in the determination of Poisson’s ratio.

13.8 *Statistical Requirements*—For each series of valid tests calculate the average value ( $\bar{x}$ ), standard deviation (*s*), and coefficient of variation (*cv*) for each strength, strain at failure, modulus, and Poisson’s ratio.

$$\bar{x} = \left( \sum_{i=1}^n x_i \right) / n \quad (5)$$

$$S_{n-1} = \sqrt{\left( \sum_{i=1}^n x_i^2 - n \bar{x}^2 \right) / (n - 1)} \quad (6)$$

$$CV = 100 \times S_{n-1} / \bar{x} \quad (7)$$

where:

- $\bar{x}$  = sample mean (average),
- $S_{n-1}$  = sample standard deviation,
- CV* = sample coefficient of variation, %,
- n* = number of specimens, and
- $x_i$  = measured or derived property,

## 14. Report

14.1 The report shall include the following data:

14.1.1 Complete identification of the material tested, including type, source, manufacturer’s code number, form, fiber volume fraction, void content, filament count, ply sequence and wind angle, fiber and resin lot number, and any previous history.

14.1.2 Complete description of the method of fabricating the specimens, including processing details.

14.1.3 Density, fiber volume fraction, and void content for each winding.

14.1.4 Complete description of the testing equipment used including the test machine, load cell, strain gauges, data acquisition system, and estimates of error for each parameter measured. Identification of potting material, radius of bead, and cure temperature.

14.1.5 Conditioning procedures used if other than specified in test method.

14.1.6 Relative humidity and temperature conditions in the test room.

14.1.7 Test method used, including type and rate of loading.

14.1.8 Number of specimens tested and identification number for each specimen.

14.1.9 *Test Specimen Dimensions*: The outer diameter, inner diameter, wall thickness  $t_c$ , total length, and gauge length for each specimen, average values, standard deviations, and coefficients of variation.

14.1.10 Tensile strength for each specimen, average value, standard deviation, and coefficient of variation for valid tests.

14.1.11 Strain at failure for each specimen (axial and circumferential), average values, standard deviations, and coefficients of variation for valid tests.

14.1.12 Transverse elastic modulus for each specimen, average value, standard deviation, and coefficient of variation for valid tests. Include how the modulus was determined and at

**TABLE 1 Specimen Elastic Modulus Calculation Strain Ranges**

Ultimate Tensile Strain Capability of Material, $\mu\epsilon^A$	Tensile Elastic Modulus Calculations Axial Strain Range	
	Start Point, $\mu\epsilon$	End Point, $\mu\epsilon$
<6000	500	1500
$\geq 6000$ but <12 000	1000	3000
$\geq 12 000$	1000	6000

<sup>A</sup> 1000  $\mu\epsilon$  = 0.001 absolute strain.



what point or between what points on the force versus strain or stress versus strain curve.

14.1.13 Poisson's ratio for each specimen, average value, standard deviation, and coefficient of variation for valid tests.

14.1.14 Full force versus strain or stress versus strain curves for the averages in the axial and circumferential directions. If average curves cannot be calculated, the individual force versus strain or stress versus strain curves corresponding to each strain gauge should be reported.

14.1.15 Mode of failure and failure location in specimen. Use Fig. 8 to describe the gauge section failure modes. Multiple failure modes can occur in a specimen. Any failure that involves the portion of the specimen bonded to the grips is considered a grip failure (GR).

14.1.16 Date of test.

14.1.17 Quality assessment of the test data (for example, acceptable, questionable), deviations from this test method, and any explanation.

## 15. Precision and Bias

15.1 *Interlaboratory Test Program*—An interlaboratory study was run in which randomly drawn test specimens of one material (Graphite/Epoxy) were tested for tensile strength, modulus, Poisson's ratio, and strain to failure in each of six

laboratories (five laboratories where noted), with each laboratory testing twelve specimens of the material. Except for the use of only one material and five laboratories where noted, Practice E691 was followed for the design and analysis of the data.

15.2 *Test Result*—The precision information is given in percentage of the average tensile strength, modulus, Poisson's ratio, and strain to failure (CV %) for the comparison of two test results, each of which is the average of five test determinations.

### 15.3 Precision:

	$\sigma_{22}^{ur}$	$E_{22}^t$	$\nu_{21}^t$	$\epsilon_{22}^{ur}$
Repeatability Coefficient of Variation	13.6 %	3.9 %	12.7 %	16.2 %
Reproducibility Coefficient of Variation	15.2 %	4.4 %	13.6 %	16.9 %

NOTE 9—The precision estimates for modulus ( $E_{22}^t$ ), Poisson's ratio ( $\nu_{21}^t$ ), and strain to failure ( $\epsilon_{ur}^{22}$ ) are based on data from five laboratories.

15.4 *Bias*—Bias cannot be determined for this test method because an acceptable reference standard does not exist.

## 16. Keywords

16.1 composite materials; filament winding; Poisson's ratio; transverse modulus of elasticity; transverse tensile properties; transverse tensile strength; tubes

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