INTERNATIONAL

Designation: ~~D6415/D6415M – 06a (Reapproved 2013)~~ D6415/D6415M – 22

Standard Test Method for Measuring the Curved Beam Strength of a Fiber-Reinforced Polymer-Matrix Composite[1]

This standard is issued under the fixed designation D6415/D6415M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method determines the curved beam strength of a continuous fiber-reinforced composite material using a 90° curved beam specimen (~~Fig. 1~~Figs. 1 and 2~~ and Fig. 2~~). The curved beam consists of two straight legs connected by a 90° bend with a ~~6.4-mm~~6.4 mm [0.25 in.] inner radius. An out-of-plane (through-the-thickness) tensile stress is produced in the curved region of the specimen when force is applied. This test method is limited to use with composites consisting of layers of fabric or layers of unidirectional fibers.

1.2 This test method may also be used to measure the interlaminar tensile strength if a unidirectional specimen is used where the fibers run continuously along the legs and around the bend.

1.3 This test method is limited to use with composites consisting of layers of fabric or layers of unidirectional fibers.

1.4 *Units*—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 necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

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

1.5 *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~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

~~1.4 The values stated in either SI units or inch-pound units are to be regarded separately as standard. Within the text the inch-pound units are shown in brackets. 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.~~

1.6 *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.*

[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of D30.06 on Interlaminar Properties.

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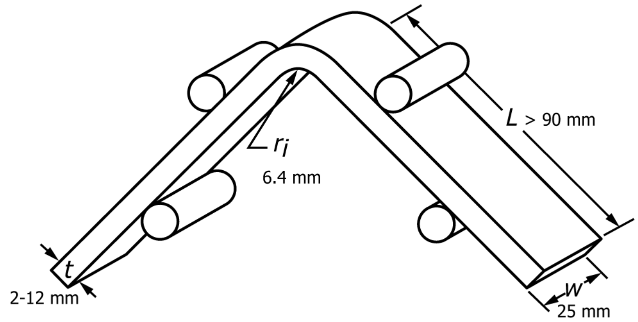

FIG. 1 Test Specimen Geometry (SI units)

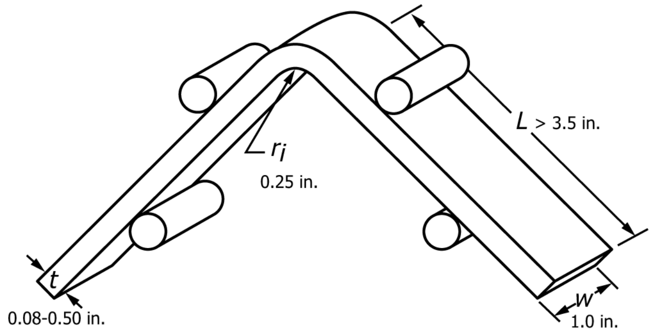

FIG. 2 Test Specimen Geometry (inch-pound)

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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
D5687/D5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation
E4 Practices for Force Calibration and Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E18 Test Methods for Rockwell Hardness of Metallic Materials
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E456 Terminology Relating to Quality and Statistics
~~E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases (Withdrawn 2015)[3]~~
~~E1434 Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases (Withdrawn 2015)[3]~~
~~E1471 Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases (Withdrawn 2015)[3]~~

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

[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.

E177 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other ~~terminologies.~~ terminology standards.

3.2 *Definitions of Terms Specific to This Standard:*

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 nondimensional 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.

3.2.1 *applied moment, M* $[ML^2T^{-2}]$, *n*—the moment applied to the curved test section of the specimen.

3.2.2 *curved beam strength, CBS* $[ML^1T^{-2}]$, *n*—the moment per unit width, *M/w*, applied to the curved test section which causes a sharp decrease in applied load or delamination(s) to form.

3.2.3 *interlaminar tensile strength,* F^{3u} $[ML^{-1}T^{-2}]$, *n*—the strength of the composite material in the out-of-plane (through-the-thickness) direction.

3.3 *Symbols:*

3.3.1 *CBS* = curved beam strength (see 3.2.2).

3.3.2 *CV* = coefficient of variation statistic of a sample population for a given property (in percent).

3.3.3 d_x, d_y= horizontal and vertical distances between two adjacent top and bottom loading bars, respectively.

3.3.4 *D* = diameter of the cylindrical loading bars on the four-point-bending fixture.

3.3.5 E_r, E_θ= moduli in the radial and tangential directions, respectively.

3.3.6 F^{3u}= interlaminar tensile strength (see 3.2.3).

3.3.7 *g* = parameter used in strength calculation.

3.3.8 l_b= distance between the centerlines of the bottom loading bars on the four-point-bending fixture.

3.3.9 l_0= distance along the specimen's leg between the centerlines of a top and bottom loading bar.

3.3.10 l_t= distance between the centerlines of the top loading bars on the four-point-bending fixture.

3.3.11 *M* = applied moment (see 3.2.1).

3.3.12 *P* = total force applied to the four-point-bending fixture.

3.3.13 P^{max}= maximum force applied to the four-point-bending fixture before failure.

3.3.14 P_b= force applied to the specimen by a single loading bar.

3.3.15 r, θ = cylindrical coordinates of any point in the curved segment.

3.3.16 r_i, r_o= inner and outer radii of curved segment.

3.3.17 r_m= radial position of the maximum interlaminar (radial) tensile stress.

3.3.18 S_{n-1}= standard deviation statistic of a sample population for a given property.

3.3.19 *t* = average thickness of specimen.

3.3.20 *w* = width of the specimen.

3.3.21 ~~x_1~~x_i= test result for an individual specimen from the sample population for a given property.

3.3.22 ~~$\bar{x}$~~ $\bar{x}$ = mean or average (estimate of mean) of a sample population for a given property.

3.3.23 Δ = relative displacement between the top and bottom halves of the four-point-bending fixture.

3.3.24 κ = parameter used in strength calculation.

3.3.25 ρ = parameter used in strength calculation.

3.3.26 φ = angle from horizontal of the specimen legs in degrees.

3.3.27 φ_i= angle from horizontal of the specimen legs at the start of the test in degrees ~~(0.5~~ (90° - 0.5 × angle between the legs).

3.3.28 σ_r= radial stress component in curved segment.

4. Summary of Test Method

4.1 The curved-beam test specimen consists of two straight legs connected by a 90° bend with a 6.4 mm [0.25 in.] inner radius (Figs. 1 and 2). The specimen has uniform thickness that is composed of layers of continuous-fiber-reinforced composite material.

4.2 The curved beam is loaded in four-point bending (Fig. 3) such that a constant bending moment is applied across the curved test section. The bending moment produces an out-of-plane tensile stress in the curved region of the specimen that causes an abrupt failure. The failure typically consists of one or more delaminations between the composite layers in the curved region.

4.3 ~~A90° curved-beam test specimen is used to measure the curved beam strength of a continuous-fiber-reinforced composite material (~~A record of the applied force versus stroke is obtained digitally or through the use of an x-y recorder or equivalent~~Fig. 1 and~~real-time ~~Fig. 2).~~ plotting device. The curved beam strength represents the moment per unit width ~~which~~that causes a delamination(s) to ~~form.~~ form and is calculated from the force corresponding to delamination formation. If the curved beam is unidirectional with all fibers running continuously along the legs and around the bend and an appropriate failure mode is observed, an interlaminar (through-the-thickness) tensile strength may also be calculated. ~~The curved beam is uniform thickness and consists of two straight legs connected by a 90° bend with a 6.4-mm [0.25-in.] inner radius. The curved beam is loaded in four-point bending to apply a constant bending moment across the curved test section. An out-of-plane tensile stress is produced in the curved region of the specimen to cause the failure.~~

5. Significance and Use

5.1 Susceptibility to delamination is one of the major design concerns for many advanced laminated composite structures.

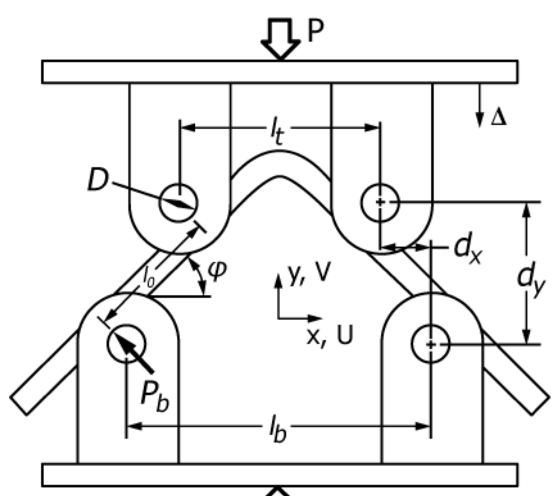

FIG. 3 Curved Beam in Four-Point Bending

Complex structural geometries can result in out-of-plane stresses, which may be difficult to analyze. When curved structural details are loaded such that the deformation results in an increase in the radius of curvature, interlaminar tensile stress and delaminations can result. Knowledge of a laminated composite material's resistance to interlaminar fracture is useful for product development and material selection. Failure criteria and design allowables involving out-of-plane stresses may not be readily available or may be poorly validated, requiring additional experimental data.

5.2 ~~Out-of-plane stress analyses are not easily performed. Failure criteria are varied and poorly validated. Interlaminar allowables are not readily available. However, stress analysts routinely encounter structural details in which they cannot ignore the out-of-plane loads.~~ This test method ~~is designed to produce out-of-plane structural failure data for structural design and analysis, quality assurance, and research and development. For unidirectional specimens, this test method is designed to produce interlaminar tensile strength data. Factors that influence the curved beam strength and should therefore be reported include the following: material, methods of material preparation, methods of processing and specimen fabrication, specimen preparation, specimen conditioning, environment of testing, speed of testing, time at temperature, void content, and volume percent reinforcement.~~can serve the following purposes:

5.2.1 To measure a curved-beam strength;

5.2.2 To measure an interlaminar strength when using a unidirectional specimen where all fibers are oriented 0° relative to the long straight edges of the specimen;

5.2.3 To establish quantitatively the effect of fiber surface treatment, local variations in fiber volume fraction, and processing and environmental variables on the curved beam strength or the interlaminar (through-the-thickness) tensile strength of a particular composite material;

5.2.4 To compare quantitatively the relative curved-beam strength or interlaminar tensile strengths of composite materials with different constituents;

5.2.5 To compare quantitatively the values of the curved-beam strength or interlaminar tensile strengths obtained from different batches of a specific composite material, for example, to use as a material screening criterion, to use for quality assurance, or to develop a design allowable;

5.2.6 To produce out-of-plane structural failure data for structural design and analysis; and

5.2.7 To develop failure criteria for predicting failures caused by out-of-plane stresses.

6. Interferences

6.1 Failure in non-unidirectional specimens may be initiated from matrix cracks or free edge stresses. Consequently, the interlaminar strength calculated from non-unidirectional specimens (for example, multidirectional or fabric layups) may be in error.

6.2 The stress state of a curved beam in four-point bending is complex. Circumferential tensile stresses are produced along the inner surface, and circumferential compressive stresses are produced on the outer surface. The radial tensile stress ranges from zero at the inner and outer surfaces to a peak in the middle third of the thickness. Consequently, the failure should be carefully observed to ensure that a delamination(s) is produced across the width before the failure data are used.

6.3 Since stresses are nonuniform and the critical stress state occurs in a small region, the location of architectural characteristics of the specimen (for example, fabric weave, and tow intersections) may affect the curved beam strength.

6.4 Nonlaminated, 3-D reinforced, or textile composites may fail by different mechanisms than laminates. The most critical damage may be in the form of matrix cracking or fiber failure, or both, rather than delaminations.

6.5 *Material and Specimen Preparation*—Poor material fabrication practices, lack of control of fiber alignment, and damage induced by improper coupon machining are known causes of high material data scatter in composites in general. Important aspects of specimen preparation that contribute to data scatter include thickness variation, curve geometry, surface roughness, and failure to maintain the dimensions specified in ~~section~~ 8.2.

6.6 The curved beam and interlaminar strengths measured using this test method are extremely sensitive to reinforcement volume and void content. Consequently, the test results may reflect manufacturing quality as much as material properties. Both reinforcement volume and void content shall be reported.

6.7 Specimens with low bending stiffness, or high values of interlaminar strength, or both, may exhibit excessive bending of the specimen legs during flexural loading. This can create large errors in the calculated bending moment, resulting in unconservative strength calculations. A recommended limitation on crosshead displacement is provided in Section 12. Although outside of the scope of this test method, a doubler may be added to the legs to reduce the flexure.

7. Apparatus

7.1 *Testing Machine*—A properly calibrated test machine shall be used which can be operated in a displacement control mode with a constant displacement rate. The testing machine ~~shall be in conformance with~~ will conform to the requirements of Practices E4, and shall satisfy the following requirements:

7.1.1 *Testing Machine Configuration*—The testing machine shall have both an essentially stationary head and a movable head.

7.1.2 *Drive Mechanism*—The testing machine drive mechanism shall be capable of imparting to the movable head a controlled velocity with respect to the stationary head. The velocity of the movable head shall be capable of being regulated in accordance with ~~11.3~~11.4.

7.1.3 *Force Indicator*—The testing machine force-sensing device shall be capable of indicating the total force being carried by the test specimen. This device shall be essentially free from inertia lag at the specified rate of testing and shall indicate the force with an accuracy over the force range(s) of interest of within ±1 % of the indicated value.

7.1.4 *Grips*—Each head of the testing machine shall have a means to hold half of the four-point-bending fixture firmly in place. A convenient means of providing an attachment point for each fixture half is through the use of a metal "T" in each grip. The lower part of the "T" is clamped in the grips, and the top part of the "T" provides a flat attachment surface for each fixture half.

7.2 *Four-Point-Bending Fixture*—A four-point-bending test apparatus as shown in Fig. 3 shall be used to load the specimen. Machine drawings, for example, fixtures are shown in the appendix. Other designs that perform the necessary functions are acceptable. The cylindrical loading bars shall have ~~diameters.~~diameters, D, of ~~6 to 10 mm [0.25 to 0.40 in.]~~ 6.0 to 12.8 mm [0.23 to 0.50 in.] and be mounted on roller bearings. All loading bars shall have diameters within ±0.1 mm [±0.004 in.] and shall have finely ground surfaces free of indentations and burrs with a hardness greater than or equal to 55 HRC as specified in Test Methods E18. The distance between the bar centers shall be 100 ± ~~2 mm~~ 2 mm [4.00 ± ~~0.05 in.]~~ 0.05 in.] (l_b) for the bottom fixture and 75 ± ~~2 mm~~ 2 mm [3.00 ± ~~0.05 in.]~~ 0.05 in.] (l_t) for the top fixture.

7.3 *Displacement Indicator*—The relative axial displacement between the upper and lower fixtures may be estimated as the crosshead travel, provided the deformation of the testing machine and support fixture is less than 2 % of the crosshead travel. If not, this displacement shall be obtained from a properly calibrated external gage or transducer located between the two fixtures. The displacement indicator shall indicate the displacement with an accuracy of ±1 % of the thickness of the specimen.

7.4 *Force Versus Displacement (P Versus Δ) Record*—~~An~~ A digital record of force versus load point displacement shall be stored for subsequent post-processing. Alternatively, an *X-Y* plotter, or similar device, ~~shall~~may be used to make a permanent record during the test of force versus displacement. ~~Alternatively, the data may be stored digitally and postprocessed.~~

~~7.5 *Micrometers*—The micrometer(s) shall use a 4 to 6 mm [0.16 to 0.25 in.] ball-interface on irregular surfaces such as the bag-side of a laminate, and a flat anvil interface on machined or very-smooth tooled surfaces. The accuracy of the instruments shall be suitable for reading to within 1 % of the sample width and thickness. For typical specimen geometries, an instrument with an accuracy of ±25 μm [±0.001 in.] is desirable for both thickness and width measurements.~~

7.5 *Micrometers and Calipers*—~~The caliper(s) shall use a knife-edge interface on the curved surfaces of the specimen and~~A micrometer with a 4 to 8 mm [0.16 to 0.32 in.] nominal diameter ball-interface or a flat anvil interface ~~on machined or very-smooth tooled surfaces. The~~ shall be used to measure the specimen thickness. A ball interface is recommended for thickness measurements when at least one surface is irregular (for example, a coarse peel ply surface which is neither smooth nor flat). A micrometer or caliper with a flat anvil interface shall be used for measuring length, width, and other machined surface dimensions. A knife-edge caliper shall be used to measure the specimen thickness in the radius section. 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 instrumentsinstrument(s) shall be suitable for reading to within 1 % 1 % of the sample width and thickness. specimen dimensions. For typical specimen geometries, an instrument with an accuracy of ±25 µm [±0.001 in.] is desirable for both thickness and width measurements. ±0.0025 mm [±0.0001 in.] is adequate for thickness measurements, while an instrument with an accuracy of ±0.025 mm [±0.001 in.] is adequate for measurement of length, width, other machined surface dimensions.

7.7 *Conditioning Chamber*—When conditioning materials at non-laboratory environments, a temperature/vapor-level controlled environmental conditioning chamber is required that shall be capable of maintaining the required temperature to within ± 3°C [± 5°CF] and the required relative humidity level to be within ± 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 environments other than ambient testing laboratory conditions. This chamber shall be capable of maintaining the gage section of the test specimen and fixture at the required test environment during the mechanical test. The test temperature shall be maintained within ±3 °C [±5 °F] of the required temperature, and the relative humidity level shall be maintained to within ±3 % RH of the required humidity level.

8. Sampling and Test Specimens

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

8.2 *Geometry*

8.2.1 *Dimensions*—Specimen geometry is shown in Fig. 1Figs. 1 and 2 and Fig. 2. The laminate shall have a cross section of constant thickness. The thickness shall be 2 to 12 mm [0.08 to 0.50 in.] The width shall be 25 ± 1 mm [1.00 ± 0.04 in.] wide with an inner radius of 6.4 ± 0.2 mm [0.25 ± 0.01 in.] at the bend. The loading leg length shall be a minimum of 90 mm [3.5 in.] and short enough to prevent contact with the fixture base. The variation in thickness for any given specimen shall not exceed 5 % of the nominal thickness. The angle between the two loading legs shall be 90 ± 3°. This angle is often different from 90° because of specimen "spring back" upon removal from the tool after curing.

8.2.2 *Stacking Sequence*

8.2.2.1 *Curved Beam Strength Measurement*—Any stacking sequence that can be manufactured to the specified dimensions may be used.

8.2.2.2 *Interlaminar Strength Measurement*—Specimens shall have a unidirectional stacking sequence with the fibers running circumferentially around the curved region. For comparison screening of interlaminar strength, a specimen with an appropriate number of plies to produce a thickness of 4.2 ± 0.2 mm 0.2 mm [0.17 ± 0.008 in.] 0.008 in.] is suggested.

8.3 *Specimen Preparation*—Guide D5687/D5687M provides recommended specimen preparation practices and should be followed where practical. Special care should be taken to ensure that specimen edges are sufficiently free of obvious flaws as determined by visual inspection.

8.3.1 A male tool is recommended for lay-up and cure to obtain a more precise inner radius. A male/female tool combination or a completely enclosed mold can also be used. Control of fiber alignment is critical. Improper fiber alignment will affect the measured properties. Erratic fiber alignment will also increase the coefficient of variation. Report the panel fabrication method.

8.3.2 *Machining*—Specimen preparation is extremely important for this specimen. Take precautions when cutting specimens from large panels to avoid notches, undercuts, rough or uneven surfaces, or delaminations due to inappropriate machining methods. Obtain final dimensions by water-lubricated precisions sawing, milling, or grinding. The use of diamond-tipped tooling (as well as water-jet cutting) has been found to be extremely effective for many material systems. Edges should be flat and parallel within the specified tolerances. Record and report the specimen cutting methods. The machined edges of the specimens may be polished as necessary to provide smooth surfaces to aid visually detecting delaminations during the test. Alternatively, the edges in the curved region may be coated with a thin white layer such as water-soluble typewriter correction fluid to aid delamination detection.