Designation: D 6415 – 99$^{\epsilon 1}$

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 D 6415; 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.

ϵ^1 NOTE—Equation 5 was editorially corrected in December 2000.

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). The curved beam consists of two straight legs connected by a 90° bend with a 6.4-mm inner radius. An out-of-plane (through-the-thickness) tensile stress is produced in the curved region of the specimen when load 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 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.*

1.4 The values stated in SI units are to be regarded as standard. The values given in parentheses are provided for information purposes only.

2. Referenced Documents

2.1 *ASTM Standards:*

D 883 Terminology Relating to Plastics[2]

D 2734 Test Methods for Void Content of Reinforced Plastics[3]

D 3171 Test Method for Fiber Content of Resin Matrix Composites by Matrix Digestion[4]

D 3878 Terminology of High-Modulus Reinforcing Fibers and Their Composites[4]

D 5229/D 5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials[4]

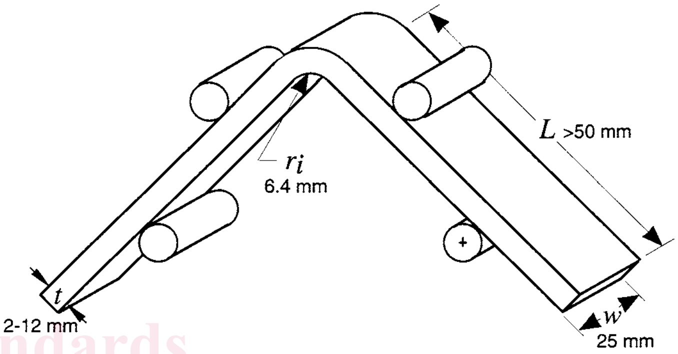

FIG. 1 Test Specimen Geometry

D 5687/D 5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation[4]

E 4 Practices for Force Verification of Testing Machines[5]

E 6 Terminology Relating to Methods of Mechanical Testing[5]

E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[6]

3. Terminology

3.1 *Definitions*—Terminology D 3878 defines terms relating to high-modulus fibers and their composites. Terminology D 883 defines terms relating to plastics. Terminology E 6 defines terms relating to mechanical testing. In the event of a conflict between terms, Terminology D 3878 shall have precedence over the other 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.

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[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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[2] *Annual Book of ASTM Standards*, Vol 08.01.

[3] *Annual Book of ASTM Standards*, Vol 08.02.

[4] *Annual Book of ASTM Standards*, Vol 15.03.

[5] *Annual Book of ASTM Standards*, Vol 03.01.

[6] *Annual Book of ASTM Standards*, Vol 14.02.

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

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

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

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

3.3.6 g = parameter used in strength calculation.

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

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

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

3.3.10 M = applied moment (see 3.2.1).

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

3.3.12 $P^{\max}$ = maximum force applied to the four-point-bending fixture before failure.

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

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

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

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

3.3.17 t = average thickness of specimen.

3.3.18 w = width of the specimen.

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

3.3.20 κ = parameter used in strength calculation.

3.3.21 ρ = parameter used in strength calculation.

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

3.3.23 ϕ_i = angle from horizontal of the specimen legs at the start of the test in degrees (0.5 × angle between the legs).

3.3.24 σ_r = radial stress component in curved segment.

4. Summary of Test Method

4.1 A 90° curved-beam test specimen is used to measure the curved beam strength of a continuous-fiber-reinforced composite material (Fig. 1). The curved beam strength represents the moment per unit width which causes a delamination(s) to form. 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 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 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.

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 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, Fabrication, 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. The curved beam and interlaminar strengths measured using this test method are extremely sensitive to fiber volume and void content. Consequently, the test results may reflect manufacturing quality as much as material properties.

7. Apparatus

7.1 *Testing Machine*—The testing machine shall be in conformance with Practices E 4, and shall satisfy the following requirements:

7.1.1 *Testing Machine Heads*—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 11.6.

7.1.3 *Load Indicator*—The testing machine load-sensing device shall be capable of indicating the total load 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 load with an accuracy over the load 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. 2 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. D, between 6 and 10 mm and be mounted on roller bearings. The horizontal distance between the centers of the loading bars shall be 100 ± 2 mm (l_b) for the bottom fixture and 75 ± 2 mm (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 *Load Versus Displacement (P Versus Δ) Record*—An *X-Y* plotter, or similar device, shall be used to make a permanent record during the test of load versus displacement. Alternatively, the data may be stored digitally and postprocessed.

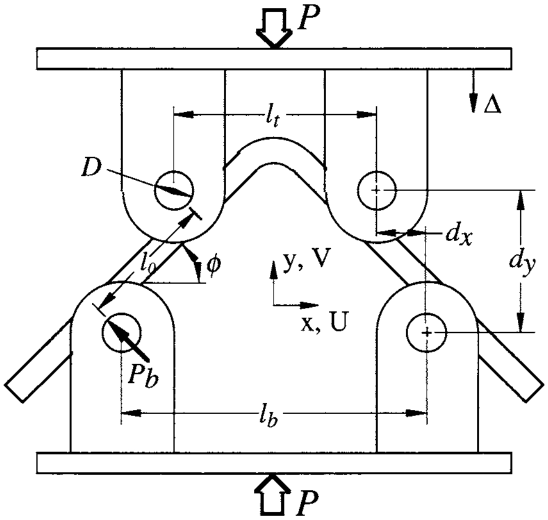

FIG. 2 Curved Beam in Four-Point Bending

7.5 *Micrometers*—The micrometer(s) shall use a suitable-size diameter 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.

7.6 *Calipers*—The caliper(s) shall use a knife-edge interface on the curved surfaces of the specimen 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.

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 E 122 should be consulted. Report the method of sampling.

8.2 *Specimen Lay-up*—The laminate shall have a cross section of constant thickness. The thickness shall be in the range from 2 to 12 mm.

8.2.1 *Lay-up to Measure Curved Beam Strength*—Any lay-up that can be manufactured to the specified dimensions may be used.

8.2.2 *Lay-up to Measure Interlaminar Strength*—Specimens shall have a unidirectional lay-up 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 is suggested.

8.3 *Specimen Manufacturing*—It is suggested that a male tool be used 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.

8.4 *Specimen Dimensions*—Specimen geometry is shown in Fig. 1. The specimen shall be 25 ± 1 mm wide with an inner radius of 6.4 ± 0.2 mm (0.25 ± 0.01 in.) at the bend. The loading legs shall be a minimum of 50 mm in length 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.

8.5 *Specimen Preparation*—Fabricate and machine panels in accordance with Guide D 5687/D 5687M. 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. Label the coupons so that they will be distinct from each other and traceable back to the raw material, and in a manner that will both be unaffected by the test and not influence the test.

8.6 *Void Content and Fiber Volume*—Curved beam strength is very sensitive to void content and fiber volume fraction. Consequently, the void content and fiber volume shall be reported. Void content may be determined using the equations of Test Methods D 2734. The fiber volume fraction may be determined using matrix digestion in accordance with Test Method D 3171. The samples for testing shall be removed from the curved region of the specimen.

9. Calibration

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

10. Conditioning

10.1 *Standard Conditioning Procedure*—Condition the specimen in accordance with Procedure C of D 5229/D 5229M unless other conditioning is specified as part of the experiment. Store and test specimens at standard laboratory atmosphere (23 ± 3°C [73 ± 5°F] and 50 ± 10 % relative humidity). Report nonstandard conditioning and nonstandard test environments.

10.2 *Oven Drying*—If strength measurements are desired for laminates in an oven-dried condition, use Procedure D of Test Method D 5229/D 5229M.

11. Procedure

11.1 Mount the four-point-bending fixture in the testing machine. Align the fixture halves such that all loading bars are parallel to each another. The distance between centerlines of the upper and lower loading bars on the right side must be equal to the distance between the centerlines on the left side, initially and during the test. Report any deviations from this test method, whether intentional or inadvertent.

11.2 Obtain samples to measure fiber volume and void content from the curved region of the specimen panel.

11.3 Measure the thickness of each specimen to the nearest 0.05 mm (0.002 in.) at several points around the curved region and along each leg. A knife-edge caliper must be used to measure the thickness in the curved region. The variation in thickness shall not exceed 5 % of the nominal thickness. Record the average thickness for each leg and for the curved region.

11.4 Measure the angle between the inside surface of the two legs to calculate ϕ_i (0.5× angle between the legs).

11.5 Place the specimen in the fixture making sure that the specimen is roughly centered between the loading bars. The specimen edges shall be perpendicular to the loading bars so that each of the four loading bars makes contact across the entire width of the specimen. Because of the geometry of the fixture and specimen, the specimen will center itself between the loading bars when load is applied.

11.6 Apply load to the specimen in displacement control at a constant crosshead (or servo-hydraulic ram) displacement rate. The displacement rate should be selected so as to produce a failure within 1 to 10 min. Record the load versus displacement trace digitally or on an *X-Y* chart recorder or other appropriate recording device.

11.7 As load is increased, the specimen will begin to flex open. Monitor the edges to determine when delaminations form. A brittle white paint may be applied to the specimen edges to aid in detecting matrix cracks or delaminations. Delamination formation is typically accompanied by a sharp decrease in load. Typical P/Δ curves are shown for a unidirectional specimen (for use in calculating interlaminar strength) and for a multidirectional specimen (for use in calculating *CBS*) in Figs. 3 and 4, respectively.

11.8 Terminate the test after the load has decreased to less than half of the peak load. Record the load and displacement for the duration of the test to capture any secondary delaminations.

12. Calculation

12.1 Calculate the curved beam strength (moment/width) from the total load, P, at the first load drop (corresponding to the initial delamination). The interlaminar strength must be determined from elasticity equations for a curved beam segment with cylindrical anisotropy. Since a force couple acts on each leg, the test section is in pure bending (that is, force resultant is zero). Consequently, the moment is the only required loading input for the stress equations.

NOTE 2—For multidirectional laminated specimens, the use of peak rather than the total load, P, at the first load drop may be of engineering interest in calculating *CBS* from Eq 1, but this deviation should be clearly noted in the test report.

12.2 *Curved Beam Strength*—Referring to Figs. 1 and 2, the applied moment on the curved section of the specimen is the product of the force exerted by one of the cylindrical loading bars, P_b, and the distance, l_0, between two bars along a leg (Eq 1). Calculate the bar force and distance from the total load, P, at the first load drop (corresponding to the initial delamination) and the geometries of the loading fixture and test specimen.

$$CBS = \frac{M}{w} = \frac{P_b l_0}{w} = \left(\frac{P}{2w\cos(\phi)}\right)\left(\frac{d_x}{\cos(\phi)} + (D+t)\tan(\phi)\right) \quad (1)$$

The curved beam strength is given in Eq 1 where ϕ is the angle in degrees of the loading arm from horizontal, d_x is the horizontal distance between the centerlines of two top and bottom adjacent rollers $(l_b - l_t)/2$, D is the diameter of the cylindrical loading bars, and t is the specimen thickness.

12.2.1 Since ϕ can change significantly during loading, the value of ϕ at failure can be used to obtain a more accurate value of the applied moment. To calculate ϕ during loading, the vertical distance, d_y, between the cylindrical loading bars is calculated by subtracting the vertical displacement, Δ, of the loading fixture from the initial value of d_y (Eq 2).

$$d_y = d_x \tan(\phi_i) + \frac{D+t}{\cos(\phi_i)} - \Delta \quad (2)$$

The vertical displacement, Δ, is obtained from the stroke output of the test stand or a displacement gage. The initial value of d_y is calculated from the initial angle, ϕ_i, and the loading geometry. The initial angle, ϕ_i, is half the overall angle