Designation: 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 (Figs. 1 and 2). The curved beam consists of two straight legs connected by a 90° bend with a 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

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.*

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

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 the other terminology standards.

[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] 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.

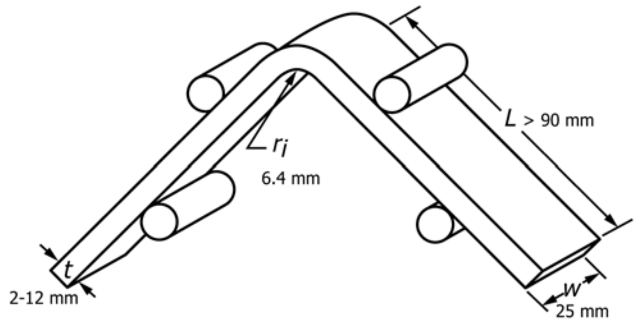

FIG. 1 Test Specimen Geometry (SI units)

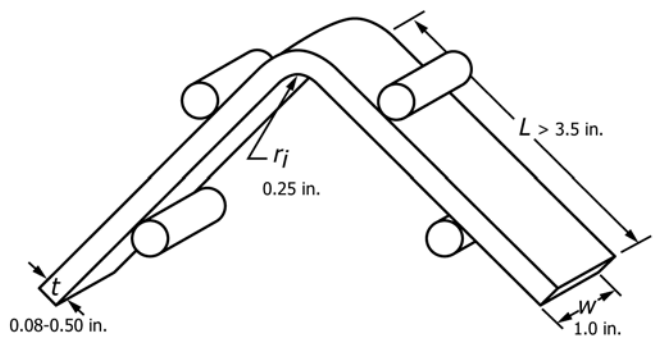

FIG. 2 Test Specimen Geometry (inch-pound)

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_i= test result for an individual specimen from the sample population for a given property.

3.3.22 $\bar{x}$ = 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 (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 A record of the applied force versus stroke is obtained digitally or through the use of an x-y recorder or equivalent real-time plotting device. The curved beam strength represents the moment per unit width that causes a delamination(s) to 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.

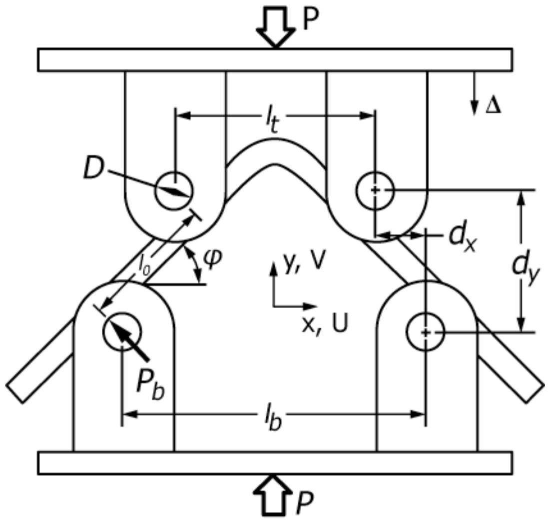

FIG. 3 Curved Beam in Four-Point Bending

5. Significance and Use

5.1 Susceptibility to delamination is one of the major design concerns for many advanced laminated composite structures. 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 This test method 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 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 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 11.4.