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Standard Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures[1]

This standard is issued under the fixed designation D7565/D7565M; 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 describes the requirements for sample preparation, tensile testing, and results calculation of flat fiber reinforced polymer (FRP) composite materials used for the strengthening of structures made of materials such as metals, timber, masonry, and reinforced concrete. The method may be used to determine the tensile properties of wet lay-up and pre-impregnated FRP composites fabricated on site or manufactured in a factory setting. The FRP composite may be of either unidirectional (0-degrees) or cross-ply (0/90 type) reinforcement. For cross-ply laminates, the construction may be achieved using multiple-layers of unidirectional fibers at either 0 or 90 degrees, or one or more layers of stitched or woven 0/90 fabrics. The composite material forms are limited to continuous fiber or discontinuous fiber-reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. The method only covers the determination of the tensile properties of the FRP composite material. Other components used to attach the FRP material to the substrate, such as the primer, putty, and adhesive in externally bonded strengthening systems, are excluded from the sample preparation and testing detailed in this document. This test method refers to Test Method D3039/D3039M for conduct of the tests.

1.2 The values stated in either SI units or inch-pound units are to be regarded 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.

1.3 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D883 Terminology Relating to Plastics

D3039/D3039M Test Method for Tensile Properties of Polymer Matrix 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

E6 Terminology Relating to Methods of Mechanical Testing

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *screed, v*—to move a flat rule along the top of a saturated laminate to level the top of the laminate and simultaneously remove excess resin.

3.2.2 *shop-manufactured FRP composite, n*—an FRP composite material manufactured under controlled conditions using an automated process in a factory, typically with tight control

[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.10 on Composites for Civil Structures.

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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.

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over the volume fractions and alignment of fibers, matrix, and voids in the material as well as the cross-sectional geometry. For strengthening applications, shop-manufactured FRP composites are typically bonded to the substrate subsequent to the fabrication of the composite reinforcement..

3.2.3 *wet lay-up FRP composite, n*—an FRP composite material fabricated by manually impregnating dry fibers with a matrix of polymeric resin. Semi-automated processes such as machine-aided wetting of fabrics before placement or vacuum-aided impregnation of laminates after placement are considered part of wet lay-up FRP. For civil infrastructure strengthening applications, the degree of control over the volume fractions of fibers, matrix, and voids as well as the overall cross-sectional geometry in wet lay-up FRP composites may be less than that for shop-manufactured composites on account of the manual process. For strengthening applications, wet lay-up FRP composites are typically applied to the substrate at the same time the dry fiber is impregnated. The impregnating resin acts as the saturant for the FRP composite and as the bonding agent between the composite reinforcement and the substrate. Wet lay-up specimens may be fabricated in either a field or a laboratory setting.

3.3 *Symbols:*

3.3.1 *CV*—sample coefficient of variation.

3.3.2 F^*—force carrying capacity of FRP laminate per unit width.

3.3.3 K^*—stiffness of FRP laminate per unit width.

3.3.4 L_g—extensometer gage length.

3.3.5 *n*—number of specimens.

3.3.6 *P*—force carried by test coupon.

3.3.7 P^{max}—maximum tensile force.

3.3.8 s_{n-1}—sample standard deviation.

3.3.9 *w*—coupon width.

3.3.10 x_I—test result for an individual coupon from the sample population for a given property.

3.3.11 $\bar{x}$—mean or average (estimate of mean) of a sample population for a given property.

3.3.12 σ—normal stress.

4. Summary of Test Method

4.1 Flat FRP specimens are prepared using a wet lay-up fabrication procedure or cut from a shop-manufactured laminate. For testing purposes, wet lay-up material may be prepared in a laboratory or field setting, as the testing objectives dictate. The testing of the specimens is carried out according to the provisions of Test Method D3039/D3039M. The ultimate force per unit width of the material is determined from the maximum force carried before failure. If the load-strain response of the material is monitored with strain gages or extensometers, then the stiffness of the material per unit width and the ultimate tensile strain of the material may be determined.

5. Significance and Use

5.1 This test method can be used to obtain the tensile force capacity and ultimate tensile strain of FRP material used for the strengthening of other structural materials such as, metals, timber, and reinforced concrete. The principal test variables could be the FRP constituents and fabrication method or the size or type of FRP laminate. The obtained tensile properties can be used for material specifications, quality control and assurance, structural design and analysis, and research and development.

5.2 This test method focuses on the FRP material itself, irrespective of the gripping method. Therefore, maximum force and strain data associated with failure or pullout at either grip are disregarded. The force capacity and maximum strain measurements are based solely on test specimens that fail in the gauge section.

6. Interferences

6.1 A summary of the interferences, specifically material and specimen preparation, gripping, system alignment, and edge effects are presented in D3039/D3039M.

6.2 Additional interferences may arise from lack of control in wet lay-up specimen preparation procedures outlined in 8.3.1. Specimen variations in resin content, ply thickness, void content and degree of cure may contribute to variability in test results.

7. Apparatus

7.1 Requirements for testing machines and instrumentation are the same as those given in D3039/D3039M, Section 7.

8. Sampling and Test Specimens

8.1 *Sampling*—Test at least five specimens per test condition 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. Report the method of sampling.

NOTE 1—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 (such as a tabbed mechanical coupon), then use another traveler coupon of the size (but without tabs) to determine when equilibrium has been reached for the specimens being conditioned.

8.2 *Geometry*—Variation in specimen width should be no greater than ±1%. Specimens width should be determined per Test Method D3039/D3039M, Section 7.1. Other dimensions shall conform to Test Method D3039/D3039M Section 8.2.1 with the exception of thickness, which is not required to be measured. Specimen thickness may however be measured as part of the general characterization of the specimen, and should be reported if measured.

NOTE 2—Calculations according to this method are based on force per unit coupon width and stiffness per unit coupon width. Specimen thickness is not required for these calculations.

8.2.1 *Specimen Width*—Minimum specimen width for unidirectional shop-manufactured and wet lay-up FRP specimens shall be 25 mm [1.0 in.]. Minimum width for cross-ply specimens shall be 25 mm [1.0 in.] for shop-manufactured composites and 38 mm [1.5 in.] for wet lay-up composites.

NOTE 3—For both unidirectional and cross-ply laminates, where fibers are used in large bundles (i.e, rovings, tows) that will be wider than 3 mm

[0.12 in.] when laid into the laminate, it is recommended that a specimen width of 38 mm [1.5 in.] or higher be used.

8.3 *Specimen Preparation:*

8.3.1 *Wet Lay-up FRP*—A polymer release film, typically 600 x 600 mm [24 x 24 in.] is placed on a smooth, flat horizontal surface. The release film should be at least 0.076 mm [0.003 in.] thick and made of a polymer that will not adhere to the resin used to impregnate the fibers. Usually, acetate and nylon are acceptable. Resin is first applied to the release film. The first ply of dry fiber preform with a minimum dimension of 300 x 300 mm [12 x 12 in.] is saturated or coated with the specified amount of resin and placed on the release film. This can be done using a properly calibrated saturator machine or using a manufacturer-specified fiber to resin weight ratio. The specified number of plies at the specified angles (0 or 90 degrees) are sequentially impregnated with resin and stacked onto the release film using the specified amount of resin per ply per unit area as in the actual installation. Using the flat edge of a small hand tool or a grooved roller, air bubbles are worked out of the material. The bubbles should be worked out in the direction of the primary fibers to ensure that no damage is caused to the fibers. A second release film is then placed over the material to provide protection. An alternative method to eliminate air bubbles is to use the flat edge of a small paddle on the outer side of the upper release film to force the entrapped air out of the material with a screeding action in the primary fiber direction. In order to ensure a smooth top surface of the FRP material, a rigid flat plate should be placed on top of the top layer of release film while the resin cures. The laminate should be placed in an area of the jobsite so as to not interfere with the installation and allowed to cure according to the manufacturer's recommendation. After the specified curing procedure is complete, the release films are removed from the panel. Specimens may be cut and tabbed after the curing procedure.

NOTE 4—The final fiber, resin, and void content of the material will depend on the method of rolling or screeding the material during fabrication. If the aim of testing is to evaluate FRP material representative of the installed strengthening material, rolling and screeding procedures used to prepare specimens should resemble those used for the installed strengthening material.

NOTE 5—Guide D5687/D5687M provides guidelines for strictly controlling the preparation of composite test specimens in the laboratory. Preparation of wet lay-up FRP should follow these guidelines to the extent that they are compatible with the intended cure and laminate consolidation regimes specified for the wet-laid FRP composite system. The lay-up and laminate consolidation steps presented in Guide D5687/D5687M are of particular relevance to this standard.

8.3.2 *Shop-Manufactured FRP*—The thickness of shop-manufactured FRP is predetermined and should not be altered. Specimen width may be altered by the agreement of the requestor and material manufacturer. Care should be taken to ensure that the specimen is flat. Testing of non-flat specimens may result in lower tensile strength due to induced moments.

8.3.3 *Machining Methods*—Specimen preparation is extremely important for this test method. If specimens are cut from plates, take precautions to avoid notches, undercuts, rough or uneven surfaces, or delaminations caused by inappropriate machining methods. Obtain final dimensions by water-lubricated precision sawing, milling, or grinding. The use of diamond tooling has been found to be extremely effective for many material systems. Edges should be flat and parallel within the tolerances specified in 8.2. See Appendix X3 of Guide D5687/D5687M for specific recommendations on specimen machining methods.

8.3.4 *Labeling*—Label the specimens so that they will be distinct from each other and traceable back to the raw material. Labeling must be unaffected by the test and must not affect the outcome of the test.

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 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 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.

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

NOTE 6—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.

11. Procedure

11.1 Follow procedures detailed in Test Method D3039/D3039M Section 11 for testing the specimens. Record the maximum failure load P^{max}. If the stiffness of the specimen is to be calculated, record the load-strain relationship and the strain at failure during the test.

12. Calculation

12.1 Calculate the maximum tensile force per unit width and report results to three significant figures.

$$F^* = \frac{P^{max}}{w} \tag{1}$$

where:

F^* = maximum tensile force per unit width, N/mm [lbf/in.],
P^{max} = maximum tensile force before failure, N [lbf], and
w = width of the specimen, mm [in.].

12.2 If the tensile stiffness is to be calculated, determine the tensile force per unit width at each required data point using Eq 2.

$$f_i = \frac{P_i}{w} \tag{2}$$

where:

f_i = force per unit width at the ith data point N/mm [lbf/in.],

P_i = force at the ith data point, N [lbf], and
w = width of the specimen, mm [in.].

12.3 Use the procedure in Test Method D3039/D3039M, Section 12.3 for calculating the tensile chord modulus of elasticity, but substitue the specimen width w for the coupon area in Test Method D3039/D3039M.

$$K^* = \frac{\Delta P/w}{\Delta \varepsilon} \tag{3}$$

where:

K^* = the chord tensile stiffness per unit width, N/mm [lbf/in.],
ΔP = difference in applied tensile force between the two strain points, N [lbf] (see Table 3 in Test Method D3039/D3039M).
w = specimen width, mm [in.], and
$\Delta \varepsilon$ = difference between two strain points in Table 3 of Test Method D3039/D3039M, nominally 0.002.

12.4 *Statistics*—For each series of tests, calculate the average value, standard deviation, and coefficient of variation (in percent) for each property determined:

$$\bar{x} = \left(\sum_{i=1}^{n} x_i \right) / n \tag{4}$$

$$S_{n-1} = \sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2 \right) / (n-1)} \tag{5}$$

$$CV = 100 \times s_{n-1}/\bar{x} \tag{6}$$

where:

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

13. Validation

13.1 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.

13.2 A significant fraction of failures in a sample population occurring within one specimen width of the tab or grip shall be cause to re-examine the means of force introduction into the material. Factors considered should include the grip pressure, grip alignment, and specimen thickness taper.

14. Report

14.1 The report shall include all information required by Test Method D3039/D3039M as well as the following:

14.1.1 Report the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

14.1.1.1 The revision level or date of issue of this test method.

14.1.1.2 The date(s) and location(s) of the test.

14.1.1.3 The name(s) of the test operator(s).

14.1.1.4 Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.

14.1.1.5 Identification of the material tested including: material specification, material type, material designation, manufacturer, manufacturer's lot or batch number, source (if not from manufacturer), date of certification, expiration of certification, filament diameter, tow or yarn filament count and twist, sizing, form or weave, fiber areal weight, matrix type, prepreg matrix content, and prepreg volatiles content.

14.1.1.6 For wet-lay up FRP, provide a description of the fabrication steps used to prepare the laminate including: fabrication, start date, fabrication end date, process specification, cure cycle, consolidation method, and a description of the equipment used.

14.1.1.7 Ply orientation stacking sequence of the laminate.

14.1.1.8 If requested, report density, volume percent reinforcement, and void content test methods.

14.1.1.9 Average ply thickness of the material and reference thickness(es) if calculated or established as part of the test.

14.1.1.10 Results of any nondestructive evaluation tests.

14.1.1.11 Method of preparing the test specimen, including specimen labeling scheme and method, specimen geometry and dimensions, sampling method, coupon cutting method, identification of tab geometry, tab material, and tab adhesive used.

14.1.1.12 Calibration dates and methods for all measurement and test equipment.

14.1.1.13 Type of test machine, grips, jaws, grip pressure, alignment results, and data acquisition sampling rate and equipment type.

14.1.1.14 Results of system alignment evaluations, if any such were done.

14.1.1.15 Dimensions of each test specimen.

14.1.1.16 Conditioning parameters and results, use of travelers and traveler geometry, and the procedure used if other than that specified in the test method.

14.1.1.17 Relative humidity and temperature of the testing laboratory.

14.1.1.18 Environment of the test machine environmental chamber (if used) and soak time at environment.

14.1.1.19 Number of specimens tested.

14.1.1.20 Speed of testing.

14.1.1.21 Transducer placement on the specimen and transducer type for each transducer used.

14.1.1.22 If strain gages were used, the type, resistance, size, gage factor, temperature compensation method, transverse sensitivity, lead-wire resistance, and any correction factors used.

14.1.1.23 Force/width-strain curves and tabulated data of load versus strain for each specimen, if obtained.

14.1.1.24 Percent bending results for each specimen so evaluated.

14.1.1.25 Individual breaking forces per unit width, recorded strains at failure, average values, standard deviation,

and coefficient of variation (in percent) for the population. Note if the failure force was less than the maximum force before failure.

14.1.1.26 Individual values of stiffness per unit width, and the average value, standard deviation, and coefficient of variation (in percent) for the population.

14.1.1.27 Failure mode and location of failure for each specimen per nomenclature provided in Test Method D3039/D3039M, Section 11.9.

15. Precision and Bias

15.1 *Precision*—The data required for the development of a precision statement is not available for this test method. Precision, defined as the degree of mutual agreement between individual measurements, cannot yet be estimated because of an insufficient amount of data.

15.2 *Bias*—Bias cannot be determined for this test method as no acceptable reference standard exists.

16. Keywords

16.1 composite materials; modulus of elasticity; pre-cured FRP system; tensile properties; tensile strength; wet lay-up FRP system

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