

Designation: D7522/D7522M - 15

Standard Test Method for Pull-Off Strength for FRP Laminate Systems Bonded to Concrete Substrate¹

This standard is issued under the fixed designation D7522/D7522M; 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 apparatus and procedure for evaluating the pull-off strength of wet lay-up or pultruded (shop-fabricated) Fiber Reinforced Polymer (FRP) laminate systems adhesively bonded to a flat concrete substrate. The test determines the greatest perpendicular force (in tension) that an FRP system can bear before a plug of material is detached. Failure will occur along the weakest plane within the system comprised of the test fixture, FRP laminate, adhesive and substrate.

1.2 This test method is primarily used for quality control and assessment of field repairs of structures using adhesiveapplied composite materials.

1.3 This test method is appropriate for use with FRP systems having any fiber orientation or combination of ply orientations comprising the FRP laminate.

1.4 This test method is not appropriate for use as an "acceptance" or "proof" wherein the FRP system remaining intact at a prescribed force is an acceptable result.

1.5 Pull-off strength measurements depend upon both material and instrumental parameters. Different adhesion test devices and procedures will give different results and cannot be directly compared.

1.6 This test method can be destructive. Spot repairs may be necessary. The test method will result in an exposed cut FRP section; repair methods must consider the potential for moisture uptake through this cut section.

1.7 Prior to the installation of some adhesively bonded FRP systems, the substrate concrete must be patched (often to replace lost concrete volume). This test method is not appropriate for determining the pull-off strength of the FRP from the patch material. An additional test method is required to determine the pull-off strength of the patch from the substrate

concrete. Throughout this standard, "substrate" is understood to mean the concrete or concrete patch material to which the FRP is adhered.

1.8 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.

1.9 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
- C125 Terminology Relating to Concrete and Concrete Aggregates
- D883 Terminology Relating to Plastics
- D3878 Terminology for Composite Materials
- D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
- 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

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 C125 defines terms relating to concrete. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other standards.

¹This 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.

Current edition approved April 15, 2015. Published May 2015. Originally approved in 2009. Last previous edition approved in 2009 as D7522/D7522M-09. DOI: 10.1520/D7522_D7522M-15.

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.



3.2 Symbols:

3.2.1 *D*—diameter of the loading fixture.

3.2.2 F_p —pull-off force.

3.2.3 σ_p —pull-off bond stress.

4. Summary of Test Method

4.1 The pull-off test is performed by securing a circular loading fixture (dolly) normal (perpendicular) to the flat surface of the FRP laminate with an affixing adhesive. An adhesion testing device is attached to the loading fixture and aligned to apply tension normal to the test surface. The force applied to the loading fixture is gradually increased and monitored until a plug of material is detached exposing the plane of limiting strength within the system. The nature of the failure is qualified in accordance with the percent of adhesive and cohesive failures, and the actual interfaces and layers involved. The pull-off strength is computed based on the maximum indicated force, the instrument calibration data, and the original surface area stressed. Pull-off strength results using different devices may vary, as results are sensitive to test device parameters.

5. Significance and Use

5.1 The pull-off strength of a bonded FRP system is an important performance property that has been used in specifications, particularly those for assessing the quality of an application. This test method serves as a means for uniformly preparing and testing bonded FRP systems, and evaluating and reporting the results.

5.2 Variations in results obtained using different devices are possible. Therefore, it is recommended that the type of adhesion test device (including manufacturer and model) be mutually agreed upon between the interested parties.

5.3 This test method is intended for use in both the field and the laboratory.

5.4 The basic material properties obtained from this test method can be used in the control of the quality of adhesives and in the theoretical equations for designing FRP systems for external reinforcement to strengthen existing structures.

6. Interferences

6.1 Material and Specimen Preparation-Improper preparation of the surface of the composite material before bonding the circular loading fixture is known to cause premature failures at this interface. Improper curing of the bonding adhesive can also cause failure at this interface. Non-uniform FRP or FRP-to-substrate adhesive thickness in one specimen can affect an individual test result and lead to non-symmetric or mixed-mode failure pattern. Variation in FRP or adhesive thickness between specimens can cause biased or scattered test results. Improper fixturing of the hole cutter relative to the specimen can lead to a non-circular hole or damage to the FRP composite/substrate interface around the perimeter of the hole. This can cause biased or scattered test results and nonsymmetric or mixed-mode failure patterns. Misalignment between the circular test fixture and the drilled circle can also lead to biased or scattered test results and non-symmetric or mixed-mode failure patterns.

6.2 Adhesion Testing Device—Improper alignment of the adhesion tester grip (see 7.1.3) can lead to biased or scattered test results and non-symmetric or mixed-mode failure patterns. Variation in the rate of loading between specimens can cause biased or scattered test results.

6.3 *Environmental Conditions at Time of Testing*—Testing at non-standard temperature or relative humidity may affect the test results. Specimens tested in field conditions should be noted as such.

7. Apparatus

7.1 *Adhesion Test Device*, commercially available, or comparable apparatus conforming to the following specifications. A specific example of an appropriate commercially available tester is provided in Annex A1.

7.1.1 The tester is comprised of detachable circular loading fixtures, screws with spherical heads that are screwed into the center of a fixture, a socket in the testing assembly that holds the head of the screw, pressure gage or dynamometer, and a mechanical or hydraulic means of applying the force in a controlled manner.

7.1.2 *Loading Fixtures*, having a minimum diameter of 50 mm [2.0 in.], a flat surface on one end that can be adhered to the FRP surface and a means of attachment to the tester on the other end.

7.1.3 *Adhesion Tester Grip*, having a central grip for engaging the loading fixture in a manner such that the resultant force is normal to the FRP surface (typically achieved with a spherical head bearing).

7.1.4 *Adhesion Tester Base*, permitting a uniform bearing against the FRP surface to react the test force.

7.1.5 Means of moving the grip away from the base in as smooth and continuous a manner as possible so that a torsion-free, co-axial (opposing pull of the grip and push of the base along the same axis) force results between them.

7.1.6 *Timer*, or means of limiting the rate of stress applied to the FRP-concrete interface being tested to less than or equal to 1 MPa/min. [150 psi/min.]. A timer is the minimum equipment when used by the operator along with the force indicator in 7.1.7.

7.1.7 *Force Indicator and Calibration Information*, for determining the actual force delivered to the loading fixture.

7.2 Loading Fixture Bonding Adhesive, for securing the fixture to the FRP laminate such that laminate properties are not affected. The bonding adhesive must have a tensile capacity greater than the expected tensile capacity of the FRP system and the concrete substrate and be sufficient to mitigate a Failure Mode A (see 12.2.1). Two component epoxies have been found to be appropriate.

7.3 *Circular Hole Cutter*, having an inside diameter equal to that of the loading fixture to score through the FRP laminate into the substrate around the loading fixture. The hole cutter must not damage the FRP laminate while scoring through it; therefore a thin-walled diamond grit hole saw is appropriate. In most cases a center drill arbor may be used to facilitate the scoring operation without affecting test results.



8. Test Specimen Preparation and Sampling

8.1 The FRP system is applied to the concrete surface in accordance with the manufacturer's recommended procedure. The manufacturer's instructions should be followed as to the elapsed time between FRP application and pull-off testing.

8.2 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. The method of sampling shall be reported.

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 This testing may be completed to assess a variety of effects including concrete surface preparation, adhesive curing conditions, hygrothermal exposure, environmental exposure (for example, alkaline solution, etc.). In such cases, test specimens should be conditioned as specified in the experimental protocol.

10.2 If not otherwise specified, 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.

10.3 If pre-conditioning is completed, the pre-test specimen conditioning process, to include specified environmental exposure levels shall be reported with the test data.

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

NOTE 1-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 Select a flat measurement site in accordance with the sampling schedule.

11.2 Select a circular loading fixture having a diameter not less than 50 mm [2.0 in.]. For FRP bonded to concrete substrates which are known to contain large aggregate sizes, a larger fixture may be used.

NOTE 2-The loading fixture diameter is limited by the test device dimensions and capacity. Little data is available for diameters greater than 50 mm regardless of aggregate size; generally a 50 mm diameter test fixture will be adequate.

11.3 Score through the FRP laminate into the substrate concrete using a core drill apparatus. The remaining scribed circle (that is, the inside diameter of the core drill) should be the same diameter as the loading fixture used. The core shall be drilled through the bonded FRP and adhesive layers and into the concrete substrate a depth of between 6 mm [0.25 in.] and 12 mm [0.50 in.].

11.3.1 The operator must be aware of existing internal reinforcement ("rebar"). Under no circumstances should the drilled core cut through existing reinforcement.

11.4 Prepare the FRP surface for bonding the loading fixture. Generally, the FRP surface should be cleaned with solvent, sanded with medium-grit sandpaper, rinsed with solvent, and allowed to dry.

NOTE 3-Generally, any surface preparation of the FRP that results in test fixture adhesion sufficient to avoid occurrence of Failure Mode A (see 12.2.1) is adequate.

11.5 Attach the loading fixture with the designated bonding adhesive following the manufacturer's instructions. The bonding adhesive must be permitted to cure sufficiently so that Failure Mode A (see 12.2.1) does not occur.

11.6 Carefully connect the central grip of the adhesion tester to the loading fixture without bumping, bending, or otherwise stressing the sample and connect the assembly to its control mechanism. For non-horizontal surfaces, support the adhesion tester assembly so that its weight does not contribute to the force exerted in the test.

11.7 Align the device according to the manufacturer's instructions and set the force indicator to zero.

11.8 Apply manual or mechanized loading so that the continuous grip assembly motion results in a rate of applied normal stress at the FRP-concrete interface of less than or equal to 1 MPa/min. [150 psi/min.] until rupture occurs.

11.9 Record pull-off force measurement and nature of failure plane.

11.10 If a plug of material is detached, label and store the test specimen including the attached loading fixture for qualification of the failed surface in accordance with the experiment protocol.

11.11 Report any departures from the procedure such as possible misalignment, hesitations in the force application, etc.

12. Calculation and Interpretation of Results

12.1 Calculations-Compute and record the pull-off bond strength or concrete strength as follows:

$$\sigma_p = \frac{4F_p}{\pi D^2} \tag{1}$$

where:

 σ_p = the pull-off bond strength, MPa [psi],

 F_p^P = the pull-off force N [lb], and D = the diameter of the loading fixture, mm [in.].

Note 4-In some cases, this calculation may be automatically completed with the adhesion tester force indicator; ensure that calibration parameters are correct.

12.1.1 Statistics-For each series of tests calculate the average, standard deviation and coefficient of variation (in percent) of the pull-off strength as follows:

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

$$s_{n-1} = \sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right)/(n-1)}$$
 (3)

協学 D7522/D7522M – 15

(4)

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

where:

 \bar{x} = sample mean (average),

 s_{n-1} = sample standard deviation,

V = sample coefficient of variation, in percent,

n = number of specimens, and x_i = measured or derived property.

12.2 *Interpretation of Results*—The adhesion of the FRP laminate to the concrete surface is necessary for the concrete member to be able to transfer force into the FRP. The interface bond and the strength (quality) of the concrete itself are critical. Possible failure modes in this tension test are shown in Fig. 1 and described below:

12.2.1 Failure Mode A: bonding adhesive failure at loading fixture is not an acceptable failure mode for this test and is an indication of the use of an inappropriate bonding adhesive system for affixing the loading fixture.

12.2.2 Failure Mode B: cohesive failure in FRP laminate (Fig. 2(a)) is an indication of poor through-thickness properties of the FRP. Such failures may be due to incomplete wet-out of the fibers or plies comprising the laminate. Such failures may also result from environmental degradation of the FRP material itself.

12.2.3 Failure Modes C and E: adhesive failure at either adhesive interface is an indication of poor adhesion properties which may result from (a) improper selection (matching) of adhesive for adherend materials; (b) contamination of adhesive; (c) improper or incomplete cure of adhesive; (d) contamination or improper preparation or cleaning of adherend surfaces; or (e) environmental degradation.

NOTE 5—Mode E is more common that Mode C; this is believed to reflect greater variability in concrete surface preparation and the greater likelihood of contamination of this interface during installation.

12.2.4 Failure Mode D: cohesive failure in adhesive is unlikely to be observed in conventional FRP applications. If observed, Mode D is an indication of poor adhesive properties likely resulting from contamination, incomplete cure or environmental degradation. In these cases, however, Modes C or E are more likely.

12.2.5 Failure Mode F: mixed cohesive failure in substrate and adhesive failure at the adhesive/substrate interface is commonly observed in FRP pull-off tests. It is believed that this failure initiates in the concrete substrate. The failure plane in concrete is circuitous; if it reaches the adhesive/concrete interface, the failure plane is likely to follow the interface plane resulting in a mixed mode failure. It is typically observed that such a failure propagates through the concrete on one "side" of the disk and through the interface on the other (Fig. 2(b)), supporting the described behavior. It is rare to have a mixed mode failure with the concrete failure interspersed with the interface failure across the area of the disk. Mode F failures are reported with their proportions of each failure mode (G and E).

12.2.6 Failure Mode G: cohesive failure in concrete substrate (Fig. 2(c)) is the desired failure mode, representing a sound FRP-adhesive system. Note that obtaining a Mode G failure does not automatically mean that the test result will meet an acceptance criteria; this failure mode is desired since the concrete substrate – as the least controllable constituent – should be the "weak link" in the bonded FRP system. An initially degraded substrate or poor surface preparation will lead to low Mode G pull-off strength values. The extent of aggregate failure (as opposed to failure through only the cement paste) is reported.

12.3 *Multiple Layer Laminate Applications* have multiple planes at which Failure Modes B, C, D or E may occur. In this case, the layer at which the failure occurs is reported. Typically the layer closest to the concrete is the designated layer (or ply) number 1.

12.4 *Validation*—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.

12.4.1 Reattaching a dolly that has been damaged or exhibited Failure Mode A shall not be permitted for any specimen.

12.4.2 A significant fraction of failures in a sample population exhibiting undesirable failure modes shall be cause to re-examine the means of force introduction into the material.

13. Report

13.1 Report the following information:

13.1.1 A description of the test including the date, time and test operator; the nature of the test: field or laboratory; the characteristics of the FRP system (including both FRP materials and adhesive); characteristics and condition of the substrate concrete.

13.1.2 Temperature and relative humidity and any other pertinent environment conditions during the test period and during the conditioning phase if specimens are conditioned.

13.1.3 Description of the adhesion tester indicating manufacturer, capacity and serial number.

13.1.4 Measurements of loading fixture: diameter and height.

13.1.5 Diameter of scored core and depth of penetration of scoring into concrete substrate.



FIG. 1 Failure Modes for Pull-off Test

(III) D7522/D7522M – 15



FIG. 2 Failure Modes (a) Mode B, (b) Mode F and (c) Mode G

13.1.6 Sampling method and sample identification and test location.

13.1.7 Sample failure stress (12.1) and failure mode (12.2).

13.1.8 Average failure stress and statistics for sample population.

13.1.9 Corrections made to data including test values omitted from calculated average and basis for omitting test values (such as failure mode). Note any other deviations from the procedure.

14. Precision and Bias

14.1 *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.

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

15. Keywords

15.1 bond strength; composite materials; concrete repair and rehabilitation; pull-off strength; pultruded (shopfabricated) FRP; wet lay-up FRP

ANNEX

(Mandatory Information)

A1. FIXED ALIGNMENT ADHESION TEST DEVICE

A1.1 Apparatus

A1.1.1 A fixed-alignment portable tester meeting the requirements of this test method as shown in Fig. A1.1.³

A1.1.2 The tester is comprised of detachable aluminum loading fixtures, 50 mm [2.0 in.] in diameter, screws with spherical heads that are screwed into the center of a fixture, a socket in the testing assembly that holds the head of the screw, dynamometer, wheel and crank.

A1.1.3 Currently, the testers are available in four models, with maximum tensile forces of 6, 16, 25, and 50 kN [1350, 3600, 5625, and 11250 lb] respectively. Versions having digital manometers or separate indicating devices are available. For a fixture having a 50 mm [2.0 in.] diameter, a 16 kN device corresponds to a pull-off bond strength range of 0 to 8.15 MPa [0 to 1180 psi].

A1.1.4 Other devices capable of pulling 50 mm [2.0 in.] diameter aluminum loading fixtures from the surface, as described in Section 11, may also be appropriate for use with this method.

A1.2 Procedure:

A1.2.1 Follow the general procedure described in Section 11. Procedures specific to this instrument are described in this section.

A1.2.2 Set the zero as described in the operation instructions of the respective instrument.

A1.2.3 After fixing a loading fixture to a substrate, insert a screw with a spherical head into the center of the fixture. Position the testing equipment on the metal disc. Then by means of the notched wheel, fix the head of the spherical screw into the socket at the base of the equipment. For the first mechanical approach, stop screwing down the wheel when a slight resistance is encountered. Tests are completed by turning the crank steadily clockwise, with loading rates as specified in 11.8. After each test, turn the crank in the counterclockwise direction until the socket returns to the starting position.

³ The sole source of supply of the Dyna Z-series testers known to the committee at this time is Proceq USA Inc., 4217 Grove Avenue, Gurnee IL 60031. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,¹ which you may attend.

🖽 D7522/D7522M – 15



ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/