Designation: D7522/D7522M – 21

Standard Test Method for Pull-Off Strength for FRP Laminate Systems Bonded to Concrete or Masonry Substrates[1]

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 adhesive-applied 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 appropriate for use with flat concrete, concrete masonry, clay masonry, and stone masonry substrates.

1.5 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.

1.6 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.

1.7 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.

1.8 Prior to the installation of some adhesively bonded FRP systems, the substrate must be patched. 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.

1.9 *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.

1.10 *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.*

1.11 *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]

C125 Terminology Relating to Concrete and Concrete Aggregates
C1232 Terminology for Masonry
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

[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.

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. Terminology C1232 defines terms related to masonry. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other standards.

3.2 *Symbols:*

D—diameter of the loading fixture.

F_p—pull-off force.

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 non-symmetric 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.

6.4 *Location of Test on Masonry Substrate*—Inclusion of a masonry joint within the cut specimen may affect the test results. Tests including a joint should not be used.

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-substrate 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 11.12.1). 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 substrate 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.

8.3 *Sampling on Masonry Substrates*—Specimens should not include joints in masonry substrates.

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, and 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 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 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.

11.3.2 Joints in masonry substrates should not be included in the specimen.

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 11.12.1) 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 11.12.1) 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-substrate 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.

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

11.12.1 *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.

11.12.2 *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.

11.12.3 *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 4—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.

11.12.4 *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.

11.12.5 *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 substrate. The failure plane in the substrate is circuitous; if it reaches the adhesive/substrate 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 substrate 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 substrate 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).

11.12.6 *Failure Mode G: Cohesive Failure in 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 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. In concrete substrates, the extent of aggregate failure (as opposed to failure through only the cement paste) is reported.

11.12.7 *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. Validation

12.1 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.

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

12.3 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. Calculations

13.1 Compute and record the pull-off bond strength or substrate strength as follows:

$$\sigma_p = \frac{4F_p}{\pi D^2} \quad (1)$$

where:

σ_p = the pull-off bond strength, MPa [psi],
F_p = the pull-off force N [lb], and
D = the diameter of the loading fixture, mm [in.].

NOTE 5—In some cases, this calculation may be automatically completed with the adhesion tester force indicator; ensure that calibration parameters are correct.

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

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

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

$$CV = 100 \times s_{n-1} / \bar{x} \quad (4)$$

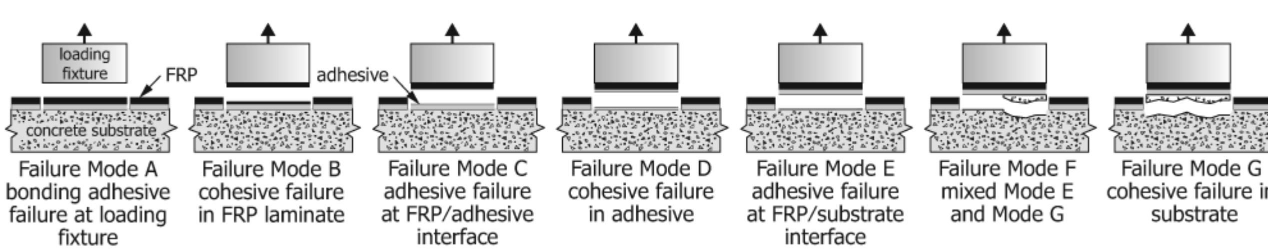

FIG. 1 Failure Modes for Pull-off Test