Designation: D7913/D7913M – 14

Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing[1]

This standard is issued under the fixed designation D7913/D7913M; 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 covers the determination of the bond strength of fiber-reinforced polymer (FRP) composite bars used as reinforcing bars or pre-stressing tendons in concrete.

1.2 Two procedures for casting test specimens are provided. The first procedure aligns the bar with the concrete casting direction. The second procedure aligns the bar's transverse to the concrete casting direction.

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 *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]

A944 Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens
C33/C33M Specification for Concrete Aggregates
C39/C39M Test Method for Compressive Strength of Cylindrical Concrete Specimens
C143/C143M Test Method for Slump of Hydraulic-Cement Concrete
C150/C150M Specification for Portland Cement
C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory
C293/C293M Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)
C511 Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C617/C617M Practice for Capping Cylindrical Concrete Specimens
D792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
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
D7205/D7205M Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars
D7705 Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E83 Practice for Verification and Classification of Extensometer Systems
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E456 Terminology Relating to Quality and Statistics
E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
F2203 Test Method for Linear Measurement Using Precision Steel Rule

3. Terminology

3.1 Terminology in D3878 defines terms relating to high modulus fibers and their composites. Terminology in D883 defines terms relating to plastics. Terminology in E6 defines terms relating to mechanical testing. Terminology in E456 and in Practice E122 define terms relating to statistics and the selection of sample sizes. In the event of a conflict between terms, Terminology in D3878 shall have precedence over the other terminology standards.

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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 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.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *anchor, n*—a protective device placed on one end of a bar, between the bar and the grips of the tensile testing machine, to prevent grip-induced damage. Usually used on bars with irregular surfaces. **D7205/D7205M**

3.2.2 *bar, n*—a linear element, often with surface undulations or a coating of particles that promote mechanical interlock with concrete.

3.2.3 *bonded length, n*—the length of the test bar that is in contact with concrete.

3.2.4 *effective circumference, n*—a geometric value representing the circumference of a circle which has an enclosed area equal to the nominal cross-sectional area of a bar.

3.2.5 *effective diameter, n*—a geometric value representing the diameter of a circle which has an enclosed area equal to the nominal cross-sectional area of a bar.

3.2.6 *nominal cross-sectional area, n*—a measure of cross-sectional area of a bar, determined over at least one representative length, used to calculate stress.

3.2.7 *nominal value, n*—a value, existing in name only, assigned to a measurable property for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the property.

3.2.8 *representative length, n*—the minimum length of a bar that contains a repeating geometric pattern that, placed end-to-end, reproduces the geometric pattern of a continuous bar (usually used in reference to bars having surface undulations for enhancing interlock with concrete).

3.2.9 *surface undulation, n*—variation in the area, orientation, or shape of the cross-section of a bar along its length, intended to enhance mechanical interlock between a bar and concrete, made by any of a number of processes such as, for example, indentation, addition of extra materials, and twisting.

3.3 *Symbols:*

3.3.1 A—nominal cross-sectional area of a bar

3.3.2 d_b—effective bar diameter per Test Method D7205/D7205M

3.3.3 C_b—effective circumference of FRP bar

3.3.4 CV—sample coefficient of variation

3.3.5 E_{CHORD}—tensile chord modulus of elasticity in the test direction per Test Method D7205/D7205M

3.3.6 F—tensile force in bar

3.3.7 f_c'—compressive strength of concrete

3.3.8 l—bonded length

3.3.9 L—free length of the loaded-end of the bar

3.3.10 L_c—length from the top of the embedded bar to the point of attachment of the slip measuring device

3.3.11 n—number of specimens

3.3.12 r—repeatability limit, the value below which the absolute difference between two individual test results obtained under repeatability conditions may be expected to occur with a probability of approximately 0.95 (95 %)

3.3.13 Sc—elastic elongation

3.3.14 s_{n-1}—sample standard deviation

3.3.15 $\bar{x}$—sample mean

3.3.16 x_i—measured or derived property

3.3.17 w/c—water to cement ratio

3.3.18 τ—average bond stress

4. Summary of Test Method

4.1 FRP bars are cast in concrete prisms in one of two orientations and the concrete is allowed to cure for 28 days. Cured specimens are placed in a test fixture consisting of a compression platen at one end. The loaded-end of the bar is gripped in a tension anchor and loaded in tension until failure. The average bond stress is calculated as the maximum force observed during the test divided by the surface area of the bar bonded to the concrete prism.

5. Significance and Use

5.1 The behavior of the bond between concrete and FRP reinforcing bars is an important performance aspect that has been used in material specifications and design standards. This test method serves as a means for uniformly preparing specimens and testing FRP bar-to-concrete bond, and for providing a standard method to calculate, evaluate and report bond strength.

5.2 This test method for measuring bond strength by pullout testing is intended for use in laboratory tests in which the principal variable is the size or type of FRP bars.

NOTE 1—This test method should not be used to establish design bond values and development lengths for FRP bars embedded in concrete, as it does not represent the state of bond stress observed in concrete flexural members reinforced with FRP bars. See Test Method A944 for a beam-end test configuration, used for determining bond stress in steel bars.

5.3 This test method is intended to determine the bond behavior for material specifications, research and development. The bond behavior will be specimen-configuration dependent, which may affect both analysis and design. The primary test result is the bond strength of the specimen to normal weight concrete.

5.4 This test method may also be used to determine the conformance of a product or a treatment to a requirement relating to its effect on the bond developed between FRP bar and concrete. The result obtained from this test method should be used only for comparative purposes to compare parameters or variables of bond strength. The method may be used as part of a protocol to establish long-term environmental effects on bond to concrete, including environmental reduction factors for FRP bars embedded in concrete.

6. Interferences

6.1 The results from the procedures presented are limited to the material and test factors listed in Section 5.

6.2 *Gripping*—The method of gripping has been known to cause premature tensile failures in bars. Anchors, if used, should be designed in such a way that the required tensile capacity can be achieved without slip throughout the length of the anchor during the test.

6.3 *Concrete Cover Splitting*—The concrete prism may split during the test, an indication that the force in the bar is too high for the given specimen configuration. It may be necessary to decrease the bonded length or increase the prism size for bars with unusually high bond strength. A prism dimension of 300 mm [12 in.] is suggested in situations where prism splitting occurs.

6.4 *Bar Surface Characteristics*—The average bond strength is related to the surface characteristics of the bar. Modifications to this texture are likely to affect bond strength and any such modifications made during specimen preparation should be reported. If the bar has a representative length that is greater than the bonded length, the bond strength may vary depending on the location of the bonded section in relation to the representative length.

6.5 *Concrete Prism Flatness*—Flatness of the bearing surface of the concrete prism where it meets the steel loading plate (Fig. 1) should be ensured. Non-flat surfaces or lack of perpendicularity between the concrete surface and the FRP bar may lead to premature fracture of the concrete prism due to stress concentrations and may increase the displacement readings at the loaded-end of the bars due to deformation of the concrete prism. For horizontally cast specimens, a rigid mold with smooth interior surfaces should be used. A compliant plate such as a sheet of plywood or a thin overlay of high-strength cement or plaster material may be used to accommodate uneven surfaces, see Section 8.6.7.

6.6 *Concrete Strength*—The bond strength is related to the concrete compressive strength. Therefore the concrete must be composed of known constituents and the specimens must be cured in a controlled environment.

6.7 *System Alignment*—Excessive bending may cause premature failure, as well as a highly inaccurate bond stress determination. Every effort should be made to eliminate bending from the test system. Bending may occur due to misalignment of the bar within the anchor or grips or due to

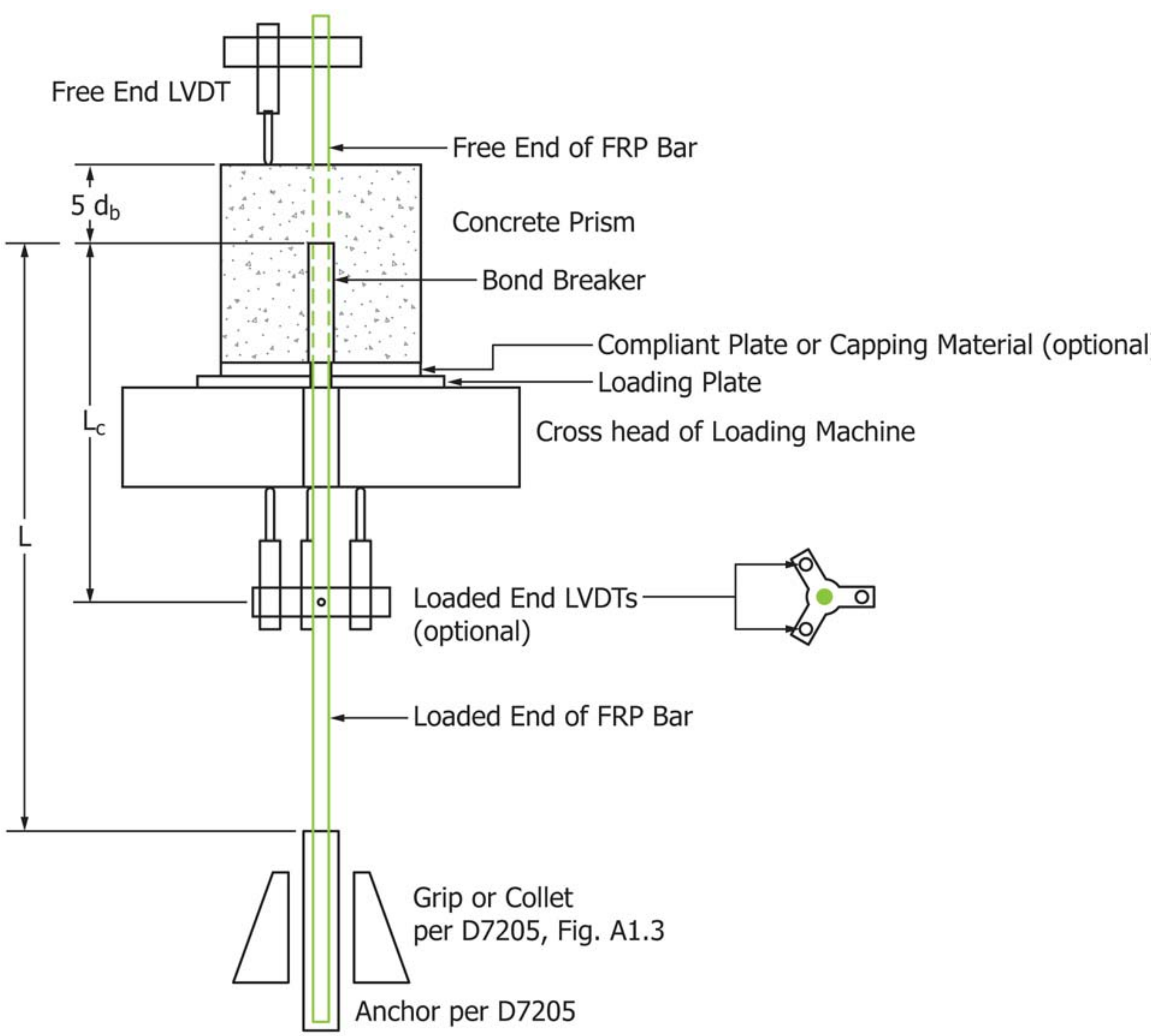

FIG. 1

lack of perpendicularity between the face of the compression platen, the cast face of the prism that mates with the compression platen, and the bar. See Practice E1012 for verification of specimen alignment under tensile loading.

6.8 *Measurement of Cross-Sectional Area*—The nominal cross-sectional area of the bar is measured by immersing a prescribed length of the specimen in water to determine its buoyant weight per Test Methods D792 and D7205/D7205M. Bar configurations that trap air during immersion (aside from minor porosity) cannot be assessed using this method. This method may not be appropriate for bars that have large variations in cross-sectional area along the length of the bar.

6.9 *Environmental Conditions at Time of Testing*—Test results may be affected by the laboratory conditions. Test conditions shall be reported.

7. Apparatus

7.1 *Testing Machine*—The testing machine used shall conform to the requirements of the sections on Basis of Verification, Corrections, and Time Interval Between Verifications of Practices E4. Motorized pumps or hand operated positive displacement pumps shall be capable of applying forces at a uniform rate without shock or interruption. The testing machine shall have a force capacity in excess of the bond capacity of the test specimen.

7.1.1 The force indicator on the testing machine shall be calibrated to a range of not greater than 10 times the observed failure force of the specimen.

7.2 *Steel Rule*—Linear measuring device for measuring bonded length per Test Method F2203.

7.3 *Drive Mechanism*—The testing machine with either loading-rate or displacement-rate control. The testing machine drive mechanism shall be capable of imparting to the movable head a controlled force or displacement rate with respect to the stationary head. The rate of the movable head shall be capable of being regulated as specified in 11.2.4.

7.4 *Test Fixture*—The test fixture consists of a loading plate, anchor, free-end LVDT (linear variable differential transformer) clamp and optional loaded-end LVDT clamp (see Fig. 1). The loading plate should rest on a support that transfers the reaction from this block to the force indicator of the testing machine. As an alternative, the force indicator of the testing machine can be attached to the tension grip at the loaded-end of the bar.

7.4.1 *Loading Plate*—The loading plate should be a machined steel plate at least 200 mm [8 in.] square and the surface dimensions of the plate must be larger than the mating dimensions on the specimen. The plate shall be at least 20 mm [0.75 in.] thick with a surface finish of 1.6 µm [64 µin.] or better. The hole drilled through the loading plate should be 10 mm ± 5 mm [0.4 in. ± 0.2 in.] larger in diameter than the maximum transverse dimension of the FRP bar. The loading plate may be fabricated in two parts to accommodate the testing of specimens fitted with end anchors.

7.4.2 If used, the anchor on the loaded-end of the FRP bar shall conform to Test Method D7205/D7205M, and may be attached to a tension grip body, to a collet, or to the second head of the testing machine, if so equipped.

NOTE 2—The tensile forces transmitted through the anchor will be below those required to rupture the FRP bar in tension. Therefore, it may be appropriate to use v-groove tension wedge grips, instead of the anchor as recommended in Test Method D7205/D7205M. If excessive slip or rupture at the grip body occurs, then a suitable anchor should be used.

7.4.3 The free-end LVDT clamp shall accommodate one LVDT to measure the free-end slip of the FRP bar, relative to the end of the concrete prism, during the test.

7.4.4 The optional loaded-end LVDT fixture shall accommodate one or more LVDTs. An arrangement of three LVDTs arranged 120° apart is suggested to measure the loaded-end slip plus elastic elongation over the distance Lc and to characterize and account for bending in the specimen.

7.5 *Displacement Devices*—The displacement measuring devices fitted to both the free end and optionally at the loaded-end of the FRP bars shall be LVDTs or similar devices, reading accurately to 0.01 mm [0.0004 in.]. An extensometer corresponding to Type 2, Class B-2 of Practice E83 may be used to measure free-end slip.

7.6 *Concrete Molds*—Two types of molds for bond test specimens are described: for 200 mm [8 in.] concrete prisms, containing either a vertically or horizontally embedded bar; and for 200 × 200 × 400 mm [8 × 8 × 16 in.] prisms, containing two horizontally embedded bars.

7.6.1 The molds should be made of metal no less than 6 mm [0.25 in.] or rigid plastic or wood no less than 12 mm [0.5 in.] thick. The molds should be watertight and constructed for easy removal without disturbing the embedded bars. Mold surface treatments and oiling of surfaces to promote easy removal of the specimens from the molds are acceptable.

7.7 *Concrete Curing Apparatus or Chamber*—The pullout specimens and the concrete compression specimens should be cured according to Practice C192/C192M in a moist cabinet or water storage tank according to Specification C511.

8. Specimen Preparation and Sampling

8.1 Each FRP bar should be cut into lengths so that the loaded-end of the specimen, L, is 1200 mm ± 5 mm [47 in. ± 0.2 in.] (see Fig. 1). An anchor meeting the requirements of Test Method D7205/D7205M, Annex A, may be fitted to the loaded-end of the bar.

8.2 The test specimens should contain either one FRP bar embedded parallel or perpendicular to the direction of casting of the concrete (Fig. 2), or two FRP bars embedded perpendicular to the direction of casting of the concrete (Fig. 3). Five specimens of a given type providing valid test results constitute a minimum set of test specimens. If a specimen ruptures in tension, or slips at the anchoring section, or splits the concrete cover, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen. It is suggested that additional specimens be prepared with the same batch of concrete, to ensure that five valid tests will be recorded.

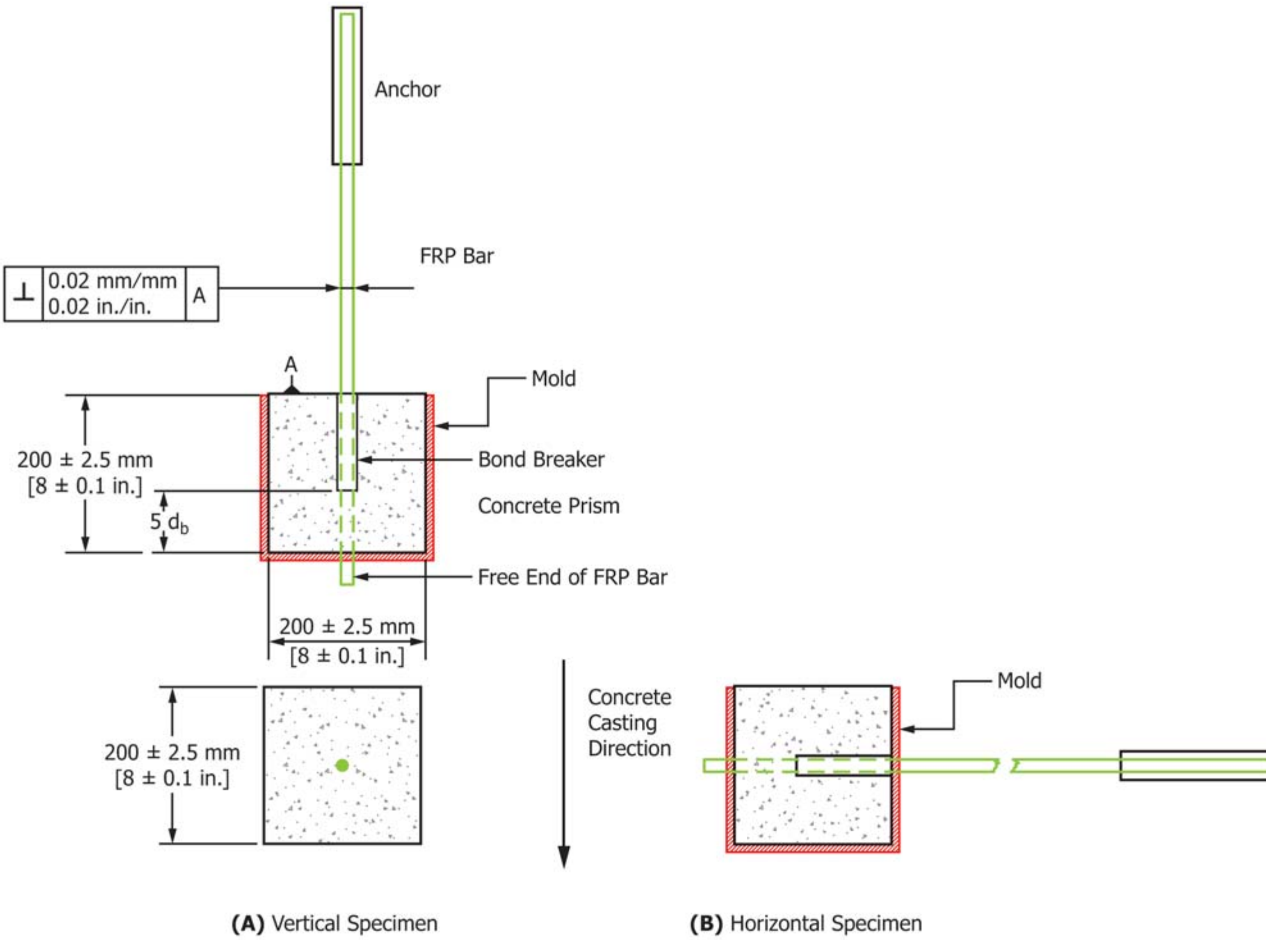

FIG. 2 Dimensions of Singly-Cast Specimens

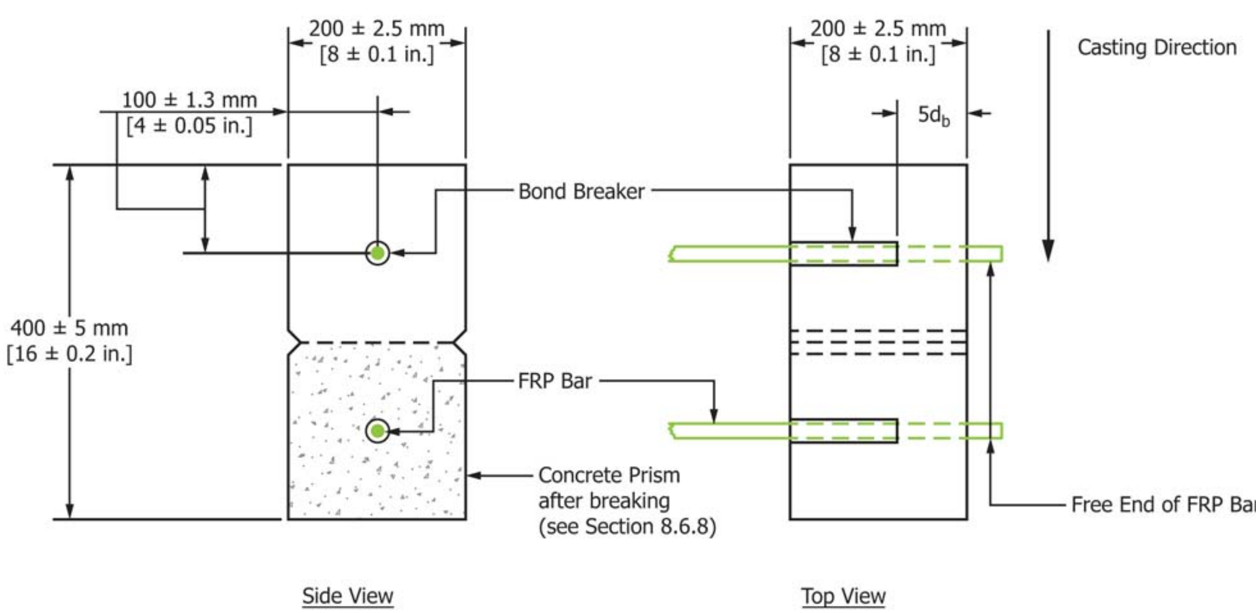

FIG. 3 Ganged Horizontal Specimens

8.3 *Specimens for Vertical Embedded Bar (*Fig. 2*(A))*—These specimens should consist of concrete prisms, 200 mm [8 in.] on each edge, with a single FRP bar embedded vertically along the central axis in each specimen. Specimens may be cast individually in separate molds or in a multi-specimen ganged form with dividers. The bar should project upward from the top face a sufficient length to extend through the bearing blocks and the support of the testing machine, and provide an adequate length to be gripped for application of force.

8.3.1 These specimens are referred to as "vertical specimens."

8.4 Specimens for horizontal embedded bar:

8.4.1 Horizontal specimens may be cast as individual specimens in individual molds or in combined molds using a form divider, as shown in Fig. 2(B).

8.4.2 *Ganged Horizontal Specimens (*Fig. 3*)*—Ganged specimens should consist of concrete prisms 200 × 200 × 400 mm [8 × 8 × 16 in.]. Two bars should be embedded horizontally in each specimen, perpendicular to the longer axis and parallel to and equidistant from the sides of the prism. In the vertical direction, one bar should be located with its axis 100 mm [4 in.] from the bottom of the prism and the other with its axis 300 mm [12 in.] from the bottom. The bar should project from the concrete face a sufficient length to extend through the bearing blocks and the support of the testing machine, and provide an adequate length to be gripped for application of force. A triangular groove should be formed on each of the two opposite sides of the prism parallel to the bars and at the mid-height of the prism. These grooves should be at least 13 mm [0.5 in.] deep, measured perpendicular to the surface of the concrete. The grooves facilitate breaking of the prism into two test specimens at the weakened plane before performing the bond tests.

NOTE 3—The provision for casting two bars into one horizontal prism, and the subsequent separation of the prism into two halves before testing is primarily to investigate the so-called "top bar effect" which occurs due to moisture migration in curing concrete and which can negatively affect bond strength in concrete reinforcing bars. It is recommended that individual specimens be cast in all situations except when the "top bar effect" is being investigated.

8.4.3 These specimens are referred to as "horizontal specimens."

8.5 The bonded length of the FRP bar shall be five times the effective diameter of the FRP bar. Outside of the bonded section, the embedded bar should be sheathed with polyvinyl chloride (PVC) pipe or other suitable material to prevent bonding. At the free end, bars should protrude from the concrete slightly, so that the end of the free-end LVDT will bear on the bar (Fig. 1).

8.6 The bars shall be placed into the molds as follows:

8.6.1 The opening in the form through which the FRP bar is inserted should be sealed using caulk, putty, or similar materials to prevent egress of water and other substances.

8.6.2 The orientation of the specimen should not be changed until the form is removed.

8.6.3 Before casting the concrete, it is acceptable to coat the inside surface of the molds with a form release agent. Release agent shall not come into contact with the FRP bar.

8.6.4 Before placing the concrete, measure the bonded length with a steel ruler per Test Method F2203 and record the bonded length to the nearest 1.0 mm [0.5 in.].

8.6.5 Place and consolidate concrete per Section 7 of Practice C192/C192M. Strike off the free surface adjacent to the loaded end of the bar with a trowel and protect against moisture evaporation by one of the acceptable methods as described in subsection 7.1 of Practice C192/C192M. Care should be taken that evaporation does not take place in the area adjacent to the protruding FRP bar for vertically cast specimens.

8.6.6 *Concrete Mix*—The concrete mix described below is recommended. Specimens may be constructed with other concrete mixes, but the concrete mix design and curing regime must be reported.

8.6.6.1 The concrete should be a standard mixture, with coarse aggregates having a maximum dimension of 20 to 25 mm [0.8 to 1.0 in.]. Aggregates shall conform to C33/C33M. The concrete should be batched and mixed in accordance with the applicable portions of Practice C192/C192M. The concrete should have slump of 100 ± 20 mm [4 ± ¾ in.] in accordance with Test Method C143/C143M, and the compressive strength at 28 days should be 30 ± 3 MPa [4350 ± 400 psi] in accordance with Test Method C39/C39M. A minimum of five standard (150 × 300 mm [6 × 12 in.]) or 100 × 200 mm [4 × 8 in.] control cylinders should be made for determining compressive strength from each batch of concrete.

8.6.6.2 *Cement*—Use Type I/II portland cement conforming to Specification C150/C150M. The concrete mixture shall not include any other cementitious materials (for example, slag, fly ash, silica fume, or limestone powder) or chemical admixtures (for example, air-entraining agents, water reducers, high-range water reducers, shrinkage-compensating admixtures, corrosion inhibitors, set retarders, and set accelerators) unless the evaluation of these constituents is an objective of the test program.

8.6.7 Molds should not be removed from the specimens earlier than 20 hours after casting. Extreme care should be taken to prevent striking or otherwise disturbing the FRP bars. Immediately after removing the molds, specimens should be cured in accordance with Practice C192/C192M until the time of testing. Specimens should be tested at an age of 28 days.

8.6.8 When ganged horizontal specimens, cast to assess the top bar effect, are between 7 and 14 days old, the 200 × 200 × 400 mm prisms should be broken in half in flexure to form two 200 mm [8 in.] cubes. Specimens should be broken as simple beams with center-point loading in accordance with Test Method C293/C293M. The two triangular grooves in the upper and lower faces of the prisms should be located at mid-span. The force should be applied to a 20 mm [0.75 in.] diameter bar laid in the upper groove until fracture occurs. Care should be taken not to strike or otherwise disturb the FRP bars during the operation.

8.7 The surface of the specimens from which the loaded end of the bar projects may be capped to prepare the bearing surface prior to the pullout test. The applicable portions of Practice C617/C617M, relative to capping materials and procedures, should be followed.

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 FRP bar surface treatments, concrete curing regimes, hygrothermal exposure, and environmental exposure (see, for example, D7705 Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction). 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 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 4—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 Parameters to be specified prior to test:

11.1.1 *Laboratory Conditions*—Unless otherwise specified, testing should take place in standard laboratory conditions (23 ± 3°C [73 ± 5°F] and 50 ± 10% relative humidity). Testing conditions shall be reported.

11.2 General Instructions:

11.2.1 The bearing surface of the prism from which the long end of the bar projects should be placed in contact with the loading plate. The projecting FRP bar should extend through the bearing block assembly and the support. The anchor should be gripped for tension by the jaws of the testing machine or otherwise attached to the other end of the loading machine.

11.2.2 The LVDT at the free end and, optionally, LVDTs at the loaded-end should be attached to measure the slip of the FRP bar, as shown in Fig. 1.

11.2.3 If loaded-end LVDTs are used, measure and record, to the nearest 0.5 mm [0.020 in.], the distance between the top end of the un-bonded length and the point of attachment of the measuring device on the FRP bar (distance L_c in Fig. 1). The elongation of the FRP bar over this distance should be calculated and subtracted from the measured slip plus elongation to obtain the loaded-end slip.

11.2.4 Apply force to the FRP bar at a rate no greater than 20 kN/min [4500 lbf/min], or at a testing machine head speed not greater than 1.3 mm/min [0.050 in./min].

11.2.5 The data acquisition rate should be set so as to measure and record the slippage of the free end of the bar in increments of no more than 0.01 mm [0.0004 in.], together with the corresponding applied force and the measurement from the loaded-end LVDT(s), if used.

11.2.6 Continue the loading and readings at appropriate intervals until the measured force is decreasing and slippage of at least 2.5 mm [0.10 in.] occurs at the free end of the bar.

12. Validation

12.1 For cases where a specimen separates into two parts at the anchoring section or along the free length, or slips out of the anchoring section or grip, or where the force is significantly reduced due to splitting or cracking of the concrete, the data should be disregarded and additional tests should be performed until the number of valid tests is not less than five.

13. Calculations

13.1 The average bond stress shall be calculated according to Eq 1 and reported with a precision to three significant digits for each force reading taken during the test.

$$\tau = \frac{F}{C_b l} \tag{1}$$

where:

τ = average bond stress, MPa [psi];
F = tensile force, N [lbf];
C_b = effective circumference of FRP bar, calculated as 3.1416 d_b, where d_b is the effective bar diameter of the bar, calculated according to Test Method D7205/D7205M, Section 11.2.5.1, mm [in.]; and
l = bonded length, mm [in.].

13.2 *Optional if loaded-end slip is measured*—At each force level, the slip at the loaded-end should be calculated as the average of the readings of the LVDT(s), minus the elongation, S_c, of the FRP bar in the length, L_c, between the top surface of bonded length and the point of attachment of the measuring devices on the FRP bar, the latter being calculated using Eq 2.

$$S_c = \frac{F L_c}{E_{CHORD} A} \tag{2}$$

where:

S_c = elastic elongation, mm [in.];
F = tensile force, N [lbf];
L_c = length from the top of the embedded bar to the point of the attachment of the measuring device (Fig. 1), mm [in.];
E_{CHORD} = modulus of elasticity of FRP bar, MPa [psi] according to Test Method D7205/D7205M; and
A = nominal cross-sectional area calculated according to Test Method D7205/D7205M, Section 11.2.5.1, mm [in.].

13.3 Calculate and record the average bond stress causing slippage of 0.05 mm [0.002 in.], 0.10 mm [0.004 in.] and 0.25 mm [0.010 in.] at the free end and at the loaded-end (if measured). Using the peak force identified from the data taken per Section 11, calculate and record the maximum bond stress (bond strength) and both the free and loaded-end slippage (if measured) at which the bond strength occurs.

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

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

$$S_{n-1} = \sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\,\bar{x}^2 \right) / (n-1)} \quad (4)$$

$$CV = 100 S_{n-1} / \bar{x} \quad (5)$$

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.

14. Report

14.1 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 bar fabrication parameters, shall be the responsibility of the requestor):

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

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

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

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

14.2 *Properties of the FRP Bars:*

14.2.1 Identification of the material tested including (if available): 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, and matrix type.

14.2.2 If available, description of the fabrication steps used to prepare the bar, including fabrication start date, fabrication end date, process specification, cure cycle, consolidation method, and a description of the equipment used.

14.2.3 Description of the size and surface characteristics of the bar and any modifications of the as-received surface texture made as part of specimen preparation.

14.2.4 Representative length of the bar, if applicable.

14.2.5 If requested, report density, volume percent reinforcement, and void content test methods, specimen sampling method and geometries, test parameters, and test results.

14.2.6 Average value of the nominal area of the bar and the effective bar diameter and circumference.

14.2.7 Modulus of elasticity and ultimate tensile strength as determined according to Test Method D7205/D7205M.

14.2.8 A close-up photograph of the bars showing surface deformations and characteristics.

14.2.9 Environmental conditioning protocol for the bar before casting, if any.

14.3 *Properties of the concrete:*

14.3.1 The mixture proportions of cement, fine aggregate, coarse aggregate, admixtures if used, and the *w/c* ratio.

14.3.2 Slump of freshly mixed concrete as determined in accordance with Test Method C143/C143M.

14.3.3 Twenty-eight day strength of control cylinders as determined in accordance with Test Method C39/C39M.

14.3.4 Any deviation from the stipulated standards in such aspects as mixing, curing, dates of demolding, and testing of control cylinders.

14.4 *Test Parameters:*

14.4.1 Date of test, test temperature and relative humidity, method of test machine control, loading rate.

14.4.2 Dimensions of test specimens and bonded length of FRP bar.

14.4.3 Description of anchoring device or method of gripping the loaded-end of the bar.

14.4.4 Description of instrumentation used for displacement measurements at the free and loaded ends (if used).

14.4.5 Description of preparation of concrete surface from which bar projects.

14.5 *Calculated Results*—Provide results for each test and average, and statistics for sample population.

14.5.1 Bond stress causing slippage at the free end and at the loaded-end (if measured) at slippages of 0.05 mm [0.002 in.], 0.10 mm [0.004 in.] and 0.25 mm [0.010 in.].

14.5.2 Maximum bond stress (bond strength) and the free and loaded-end slippage (if measured) at which the bond strength occurs.

14.5.3 Bond stress-slippage displacement (free-end and loaded-end) plots.

14.6 Description and close-up photography of the failed surface of the FRP bar in the location of the bonded section. Note location of failure surface and FRP material remaining adhered to concrete prism.

15. Precision and Bias

15.1 *Precision*—The single lab repeatability has been determined for commercially-available FRP bars in three sizes, with eight specimens of each size tested with a bonded length *l/db=5* as recommended by the standard. These results are shown in Table 1. The data in Table 1 was developed using the inch-pound version of this test method. The indices shown in SI units are exact conversions of the values in inch-pound units. Attempts to develop a full precision statement have been unsuccessful. For this reason, full data on precision cannot be given. Anyone wishing to participate in the development of precision data should contact the Chairman, D30.10, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

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

TABLE 1 Single Lab Repeatability Data for Bond Strength (τ maximum)

Bar Size and Diameter[A]			Concrete Strength[B]		Bond Strength					
					$\bar{x}$		S_{n-1}		r	
Size	mm	in.	MPa	psi	MPa	psi	MPa	psi	MPa	psi
5	15.9	0.63	44.5	6460	15.3	2220	0.819	119	2.29	333
6	19.1	0.75	37.0	5360	15.4	2230	0.810	118	2.27	329
8	25.4	1.00	44.5	6460	13.5	1960	1.913	277	5.36	777

[A] Diameter was not measured in this experiment but rather taken as the trade size diameter reported by the manufacturer, to the nearest one-eighth of an inch.
[B] Concrete compressive strength is reported here, as bond strength is related to concrete compressive strength.

16. Keywords

16.1 bond; FRP composite reinforcement; reinforced concrete