Designation: D8337/D8337M – 21

Standard Test Method for
Evaluation of Bond Properties of FRP Composite Applied to Concrete Substrate using Single-Lap Shear Test[1]

This standard is issued under the fixed designation D8337/D8337M; 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 to evaluate the lap shear bond properties of wet lay-up or shop-fabricated (for example, pultruded) fiber-reinforced polymer (FRP) composite systems adhesively applied to a flat concrete substrate. The test determines the plateau force that an FRP system can bear before complete debonding from a concrete prism tested using a direct single-lap shear test. This plateau force is reported as bond capacity and may be different from the maximum applied force. The plateau force is then used to determine the interfacial fracture energy and the cohesive material law.

1.2 This test method is not intended for job approval or for product qualification purposes unless an external agency adopts the test method for those purposes.

1.3 This test method is intended for use with adhesive-applied or wet lay-up FRP systems and is appropriate for use with FRP systems having any fiber orientation or combination of ply orientations comprising the FRP composite, although the test condition only considers forces in the direction parallel to the prism longitudinal axis.

1.4 *Units*—The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

1.4.1 Within the text, the inch-pound units are shown in brackets.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C31/C31M Practice for Making and Curing Concrete Test Specimens in the Field
C33/C33M Specification for Concrete Aggregates
C39/C39M Test Method for Compressive Strength of Cylindrical Concrete Specimens
C42/C42M Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C125 Terminology Relating to Concrete and Concrete Aggregates
C150/C150M Specification for Portland Cement
C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory
C496/C496M Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
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
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
D7565/D7565M Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures
D7958/D7958M Test Method for Evaluation of Performance

[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.

for FRP Composite Bonded to Concrete Substrate using Beam Test

E4 Practices for Force Verification of Testing Machines

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

E251 Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages

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 C125 defines terms relating to concrete. Terminology E456 and Practice E122 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other standards.

3.2 *Symbols:*

a—distance between the top plate and the edge of the concrete prism

c—width of the top flange of the Ω-shaped plate

c_1—length of the web of the Ω-shaped plate

c_2—width of the bottom flange of the Ω-shaped plate

b—width of test concrete prism

b_f—bonded width of FRP

CV—sample coefficient of variation

d—overall depth of test concrete prism

d_f —bond break, that is, distance between the beginning of the bonded area and the top edge (at loaded end of the composite strip) of the concrete prism

E_c—modulus of elasticity of concrete

E^{chord}—tensile chord modulus of elasticity of pultruded FRP (Test Method D3039/D3039M)

f'_c—compressive strength of concrete

f'_t—splitting tensile strength of concrete

g—global slip (or loaded end slip) as measured by LVDTs

$g_{15\%}$—global slip corresponding to $P_{15\%}$ in the load response

$g_{35\%}$—global slip corresponding to $P_{35\%}$ in the load response

G_F—interfacial fracture energy

h—thickness of pultruded FRP

k—slope of the linear ascending branch of the cohesive material law

K^*—chord tensile stiffness of wet-layup composite (Test Method D7565/D7565M)

ℓ—bonded length of FRP

L—length of test concrete prism

L_f—total length of the FRP composite strip

l_{eff}—effective bond length

N—number of specimens

n—number of plies (that is, number of layers of fibers)

P_{max}—maximum applied force indicated by testing machine

P_{pl}—plateau force, named also bond capacity, associated with propagation of the debonding until complete separation

$P_{15\%}$—applied force corresponding to 15 % of P_{pl}

$P_{35\%}$—applied force corresponding to 35 % of P_{pl}

s—slip between the faces of the interfacial crack

s_f—slip s corresponding to the complete separation of the faces of the interfacial crack

s_m—slip s corresponding to the maximum shear stress τ_{max}

S_{N-1}—sample standard deviation

t—machine stroke

v—distance between the axis of LVDT A or LVDT B and the edge of the FRP strip

w_c—displacement measured by LVDT C

w_d—displacement measured by LVDT D

x_i—measured or derived property

z—horizontal distance between LVDT C and LVDT D

z_1—distance between point of reaction of LVDT C and LVDT D and the bottom plate

ε_{pl}—debonding strain in the FRP corresponding to P_{pl}

ε_{yy}—longitudinal strain component in the FRP strip (in the direction of the axis of the prism)

τ—interfacial shear stress

τ_{max}—maximum interfacial shear stress

4. Summary of Test Method

4.1 The direct single-lap shear test is conducted using a push-pull configuration, where the concrete prism with square or rectangular cross-section is restrained while the composite strip is pulled until failure. FRP reinforcement is bonded to one face of the concrete prism. Because the formed faces of the concrete prism might have a different amount of aggregates near the surface, the face to which the FRP composite is applied with respect to the casting orientation shall be clearly identified in the report. Neither the troweled (Practice C192/C192M) longitudinal face nor the square (or rectangular) ends of the concrete prism shall be used to bond the FRP reinforcement.

5. Significance and Use

5.1 This test method is intended for use in a laboratory setting.

5.2 This test method is used to evaluate the plateau force P_{pl} that an FRP composite can bear before complete debonding from a concrete prism.

5.3 The evaluation of the plateau force is intended to be made under consistent environmental conditioning and the tests conducted in ambient laboratory or otherwise consistent environmental conditions.

5.4 This test can be used to determine the effective bond length l_{eff} of the FRP composite if different bonded lengths are tested with constant bonded width. The effective bond length l_{eff} is defined as the minimum bonded length ℓ necessary to achieve the bond capacity P_{pl} for the width of FRP tested.

5.5 This test can be used to determine the variation of the bond capacity with the bonded width b_f if different bonded widths are tested while the bonded length ℓ is constant and greater than the effective bond length l_{eff}.

5.6 This test is used to obtain the plot of the applied force versus loaded end (or global) slip of the composite with respect to the substrate. The loaded end slip is the average of two linear variable differential transformer (LVDT) readings, as described in 7.6. The plot obtained is used to determine the bond properties of the system.

5.7 This test method can also serve as a means for uniformly preparing and testing standard specimens suitable for being subject to environmental conditioning and subsequently used to evaluate FRP-bonded-to-concrete system performance, and evaluating and reporting the results. The comparison of results from this test method conducted on identical specimens subject to different environmental conditioning protocols can be used to evaluate the effects of environmental exposure on the bond performance of FRP systems.

6. Interferences

6.1 *Material and Specimen Preparation*—Non-uniform FRP thickness or FRP-to-substrate adhesive thickness can affect an individual test result and introduce biased or scattered test results.

6.1.1 *Surface Preparation*—Concrete surface may be sandblasted or abraded as per the FRP manufacturer's recommendation. Variation of roughness of the concrete surface between specimens can cause biased or scattered results

6.1.2 Specimen aging and conditioning affect the concrete strength and modulus as well as the epoxy strength and modulus, which may affect the stress transfer at the FRP-concrete interface and therefore the plateau force.

6.2 *Specimen Dimensions*—This method calculates a value of force required to debond completely the FRP composite from the concrete substrate; as such, results are dependent on the specimen dimensions. Unless this test is used to determine the effective bond length or the effect of the bonded width, comparing values calculated using specimens having different dimensions should not be done.

6.3 *FRP Reinforcement*—A bonded area of the composite that is wider than two thirds of the prism width or longer than four fifths of the length of the concrete prism can be sufficient to cause spalling of the concrete prism because of the unrestrained shear deformation near the edges of the prism (see 11.10.3). Testing widths larger than two thirds of the prism width might be of interest, as it could identify effects relevant to retrofit of thin-stemmed beams; however, if spalling occurs prior to debonding of the FRP strip, it will result in an invalid test as per the scope of this standard. The number of plies may cause a different failure mode independent of the dimensions of the bonded area

6.4 Splitting of the FRP strip lengthwise prior to bond failure should be considered an interference, which invalidates the results.

6.5 *Test Rate*—A change of the test rate among specimens may invalidate the results, as the interfacial properties can be rate dependent.

6.6 Adhesive failure (see 11.10.1.2), cohesive failure in either adhesive or FRP material (see 11.10.1.3), and FRP rupture failure (see 11.10.2) should be considered interferences, which invalidate the results.

7. Apparatus

7.1 *Micrometers and Calipers*—Micrometers used to determine specimen dimensions shall use a suitable size diameter ball-interface on irregular surfaces and a flat anvil interface on machined edges or very-smooth tooled surfaces. For typical specimen geometries, the accuracy of the instrument(s) shall be suitable for reading to within 1 % of the intended measurement. The use of alternative measurement devices is permitted if specified (or agreed to) by the test requestor and reported by the testing laboratory.

7.2 *Dimensional Tolerances*—Dimensional tolerances for the components of the test fixture produced in U.S. customary units shall be standard tolerances as follows: Unless noted otherwise on the drawings, dimensions given to one decimal place (0.X in.) shall be ±0.05 in., dimensions given to two decimal places (0.0X in.) shall be ±0.01 in., and dimensions given to three decimal places (0.00X in.) shall be ±0.005 in. For components produced in SI units, standard tolerances for dimensions given to zero decimal places (X mm) shall be ±1 mm, dimensions given to one decimal place (0.X mm) shall be ±0.25 mm, dimensions given to two decimal places (0.0X mm) shall be ±0.1 mm.

7.3 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. Hand operated testing machines having pumps that do not provide a continuous loading in one stroke are not permitted. Motorized pumps or hand operated positive displacement pumps having sufficient volume in one continuous stroke to complete a test without requiring replenishment are permitted and shall be capable of applying loads at a uniform rate without shock or interruption.

7.4 *Loading Apparatus*—Tests are conducted using a direct single-lap shear test set-up.

7.4.1 The concrete prism is restrained against movement by two steel plates placed against the square (or rectangular) end cross-sections of the concrete prism (Fig. 1). The centroid of the bottom plate must be aligned with the axis of the machine. The top plate is connected to the bottom plate through four threaded steel bars bolted to the two plates. In order to ensure adequate stiffness, an additional plate (stiffener) could be welded perpendicularly to the top plate. Appendix X1 provides recommended dimensions that can be considered as a reference when one ply of FRP is applied and the 28-day compressive strength f'_c of the cylinders falls between 22 to 55 MPa [3200 to 8000 psi] (see 8.4.3). It is recommended that the top plate has a distance a from the edge of the concrete prism equal to or greater than 25 mm [1 in.] to avoid high compressive stresses close to the FRP-concrete interface.

7.5 The stroke of the testing machine and the applied force shall be recorded continuously during the test.

7.6 *Slip Measurement*—Two linear variable differential transformers (LVDTs) shall be mounted on the concrete surface by means of two aluminum holders that are placed on each side of the FRP strip at the top edge of the bonded region. The holder is a prismatic aluminum block with a central hole to fit

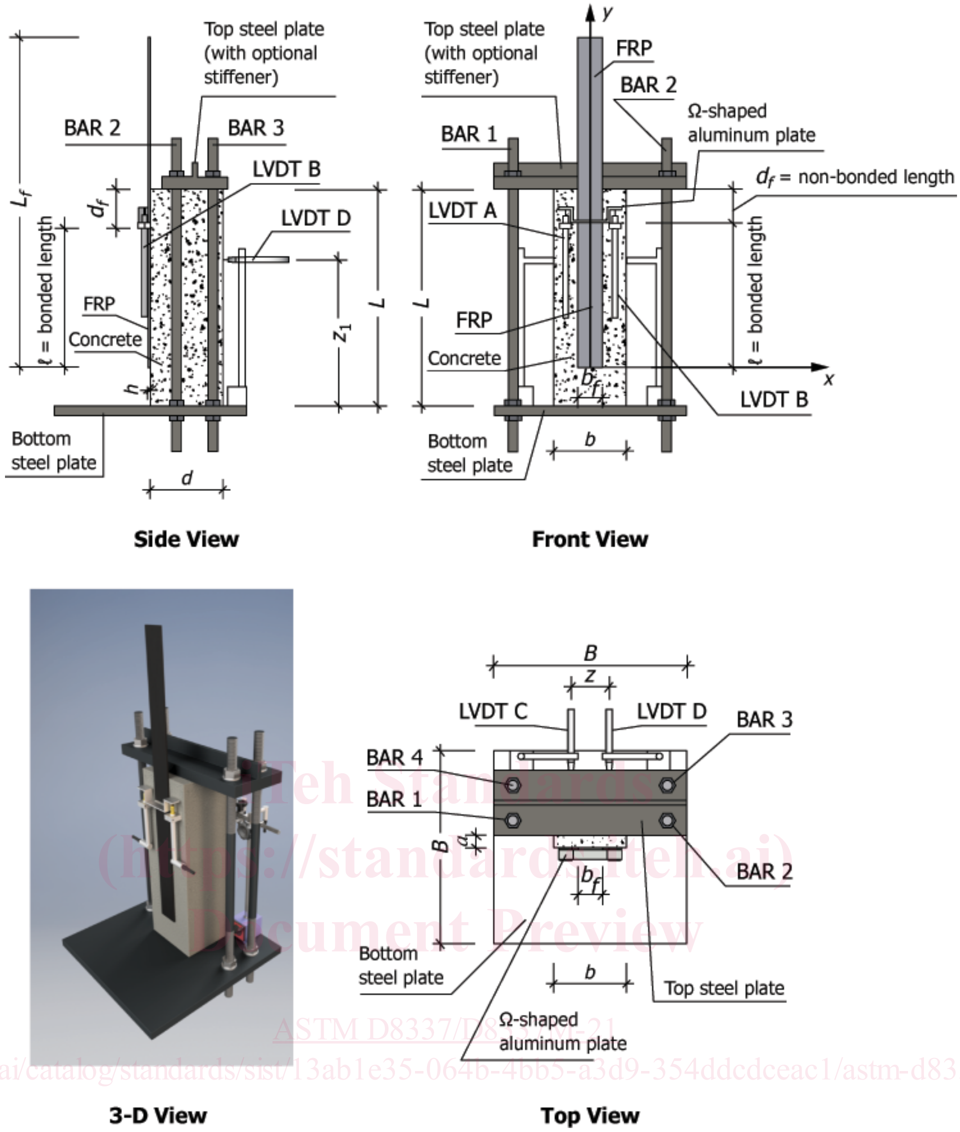

FIG. 1 Schematic of Suitable Apparatus for Direct Single-Lap Shear Test

the LVDT (Fig. 2). A cut-through discontinuity of the hole is used to accommodate LVDTs of different sizes. An additional threaded hole is used to insert a screw to tighten the LVDT. The holder can be glued to the surface of the concrete prism. Fig. 2 shows additional details of the portion of the test setup where the LVDTs are mounted. The recommended distance v between the axis of the LVDT and the edge of the composite strip should be equal to 20 mm [0.8 in.]. The LVDTs (named LVDT A and B in Fig. 1) react off of a thin aluminum Ω-shaped plate that should be attached to the composite surface adjacent to the beginning of the bonded area. The epoxy used for the FRP system should be used to apply the Ω-shaped plate to the surface of the FRP composite. As shown in Fig. 2, epoxy is used to create two weld bead-like strips that firmly attach the Ω-shaped plate to the FRP strip. The bottom epoxy strip should not overlap with the bonded area. The flanges of the Ω-shaped plate overhang from the FRP strip. Therefore, cardboard can be used as a temporary support of the aluminum plate until the epoxy used to attach the plate itself is cured. The thickness of the Ω-shaped plate should be between 1 mm [0.04 in.] and 2 mm [0.08 in.]. The other recommended dimensions c, c_1, and c_2 of the Ω-shaped plate are provided in Appendix X1 and are based on the recommended dimensions of the specimen shown in Fig. X1.1.

7.7 *Optional Out-of-Plane Displacement Measurement*—Two optional LVDTs (named LVDT C and D in Fig. 1) can be used to monitor the out-of-plane displacement of the concrete prism, that is, the displacement in the direction perpendicular to the face of the composite strip. Two LVDT holders should be mounted onto the bottom plate using two magnets. The LVDT C and D react off of the face of concrete prism parallel to the one to which the composite is applied. The distance z_1 of the measurement point should be provided in the report. The distance on center z between LVDT C and LVDT D should be 80 mm [3 in.] if the dimensions of the prism provided in 8.3 are used. The use of LVDT C and D, although optional, is highly recommended to monitor the out-of-plane displacement.

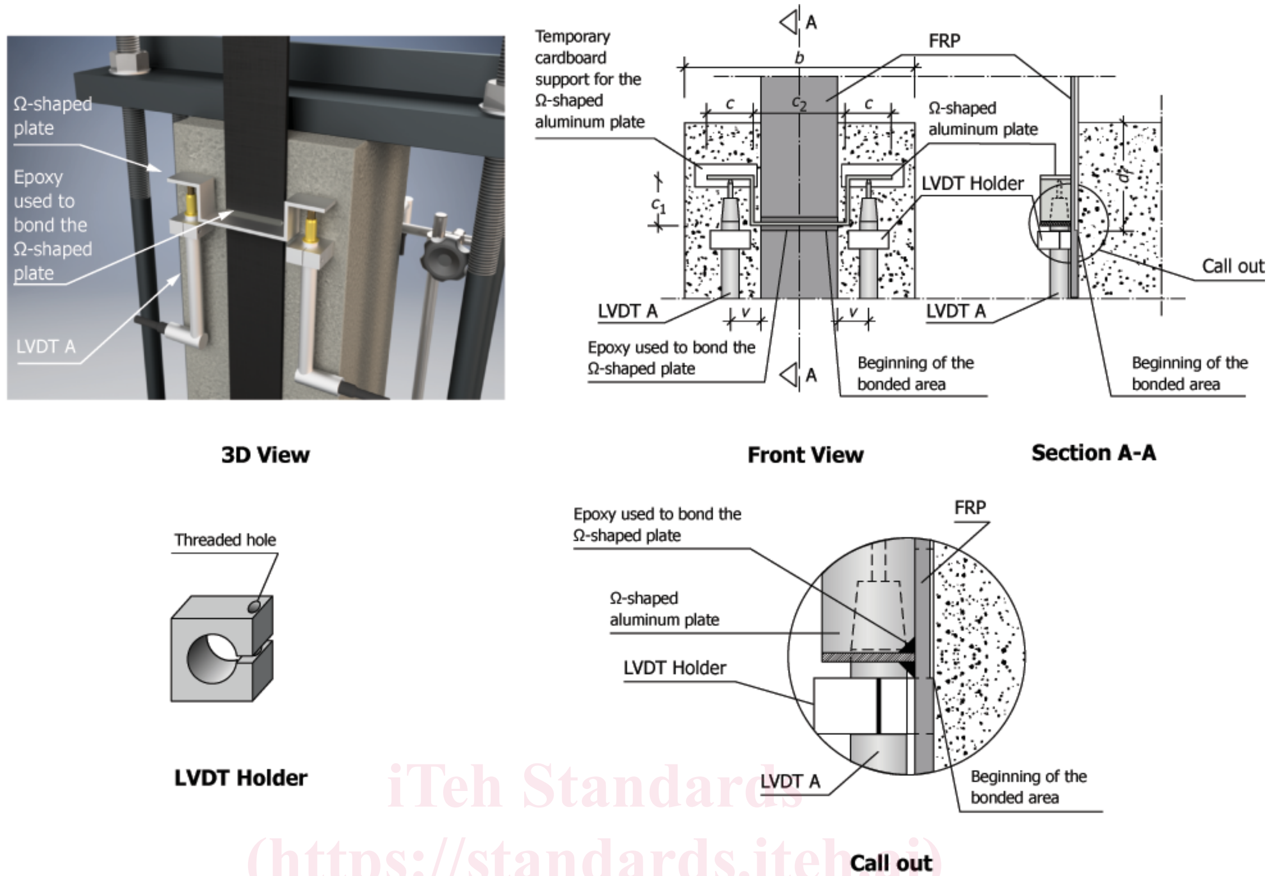

FIG. 2 Details of the Ω-Shaped Plate

7.8 *Optional Strain Measurements on the FRP Surface*—Strain gages could be applied along the centerline of the FRP strip (that is, along the direction of the fibers) to obtain the profile(s) of the longitudinal strain component ε_{yy} (reference system in Fig. 1) corresponding to one (or more) point(s) of the load response within the interval of global slip (g_1, g_2) defined in 11.8. An active gage length of 6 mm [0.25 in.] is recommended for most materials. Active gage lengths should not be less than 3 mm [0.125 in.]. Gage calibration certification shall comply with Test Methods E251. It is recommended that at least 6 strain gages are applied along the bonded length to obtain a reliable strain profile. It is recommended that, if available, digital image correlation (DIC) is used instead of strain gages to obtain the strain profile(s) along the centerline of the FRP strip. For each value of y (reference system in Fig. 1), the longitudinal strain component ε_{yy} should be averaged over a strip centered with respect to the width of the FRP strip and corresponding to the interval -5 mm [-0.2 in.] ≤ x ≤ 5 mm [0.2 in].

NOTE 1— If the overall width of the FRP strip is smaller than 20 mm [0.8 in.], the interval of x to average the values of the strain component ε_{yy} obtained from DIC should be equal to half of the width of the FRP strip.

8. Sampling and Test Specimen

8.1 *Dimensional Tolerances*—Dimensional tolerances described in 7.2 are applied to the concrete prism and FRP strip dimensions.

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 The concrete test specimen shall conform to all requirements of Test Method C42/C42M or Practices C31/C31M or C192/C192M. The recommended dimensions of the concrete prism are b = 150 mm [6 in.] width × d = 150 mm [6 in.] depth × L = 450 mm [18 in.] length (Fig. 3). Dimensions b, d, L of the prism can be varied as long as they are kept constant within the same experimental protocol. Dimensions b and d could be varied independently (as long as constant for the same experimental protocol) since rectangular cross-sections of the concrete prism are allowed. The sides of the specimen shall be at right angles with the top and bottom. All surfaces, except for

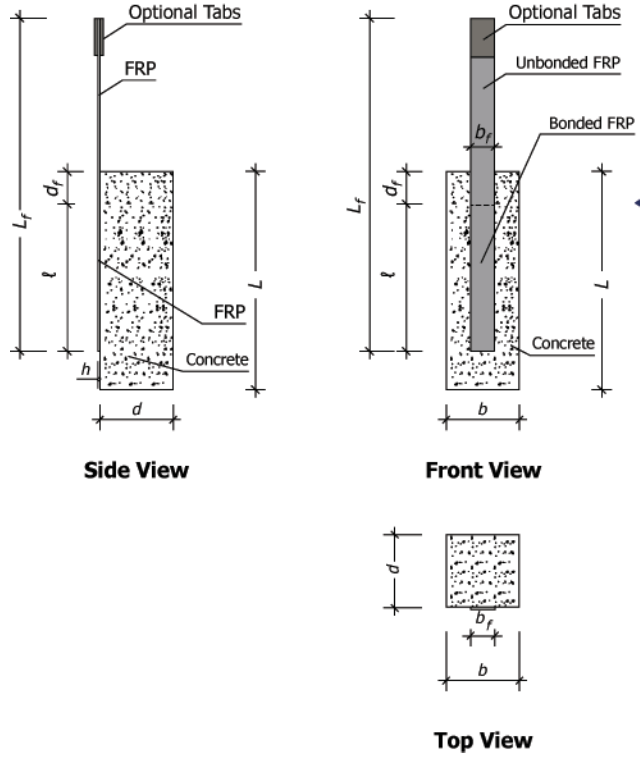

FIG. 3 Specimen Dimensions and Details of Bonded FRP System

the troweled face, shall be smooth and free of scars, indentations, holes, or inscribed identification marks.

8.4 *Cast Specimens (Practices C31/C31M or C192/C192M)*—Cast specimen concrete mixture shall meet the following requirements:

8.4.1 *Aggregates*—Aggregates shall conform to Specification C33/C33M, and the maximum aggregate size should be 10 mm [3⁄8 in.] or 15 mm [5⁄8 in.], unless the effect of the aggregate size on the bond capacity is an objective of a test program.

8.4.2 *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 is an objective of the test program.

8.4.3 *Concrete Strength*—Cylinders should be cast and tested in accordance with Practice C31/C31M, Test Method C39/C39M, Test Method C496/C496M, and Practice C617/C617M. The 28-day compressive strength f'_c of the cylinders should fall between 22 to 55 MPa [3200 to 8000 psi]. The 28-day splitting tensile strength f'_t should fall between 2 MPa [300 psi] and 10 MPa [1500 psi]. The ranges provided for f'_c and f'_t do not need to be considered if the test is used to determine the effect of mechanical properties of concrete on the bond capacity of the FRP composite strip.

8.4.4 *Curing*—Cure cylinders and concrete specimens for 28 days in water in accordance with Specification C511.

8.5 Surface preparation of the specimen face that will receive the FRP system shall be in accordance with the FRP manufacturer's requirements of the FRP system being tested. Details of the surface preparation shall be recorded with the test data.

8.5.1 The bond break d_f, that is, the distance between the beginning of the bonded area and the top edge (at loaded end of the composite strip) of the concrete prism (Fig. 1), should be 70 mm [2.75 in.] minimum to avoid spalling of concrete.

NOTE 2—Bond breaking is easily accomplished using masking tape that covers the concrete surface from the top edge to the beginning of the bonded area. For additional details, refer to 8.6.4 and Fig. 4.

8.6 The FRP system applied to one face of the specimen should meet the following requirements as shown in Fig. 3:

8.6.1 The FRP system shall be applied in accordance with the FRP manufacturer's recommended procedure. The FRP manufacturer's instructions should be followed as to the elapsed time between FRP system application and testing.

8.6.2 The width of the applied FRP system should be equal to 50 mm [2 in.] if the width of the concrete prism is 150 mm [6 in.]. The FRP system shall be centered on the strengthened face of the prism. A different width of the composite strip is allowed.

8.6.3 The bonded length ℓ of the applied FRP system should be equal to 300 mm [12 in.]. A different bonded length of the composite strip is allowed.

8.6.4 The composite strip will be longer than the bonded length ℓ. If a wet layup procedure is used (Test Method D7565/D7565M), a support for the FRP strip, which overhangs

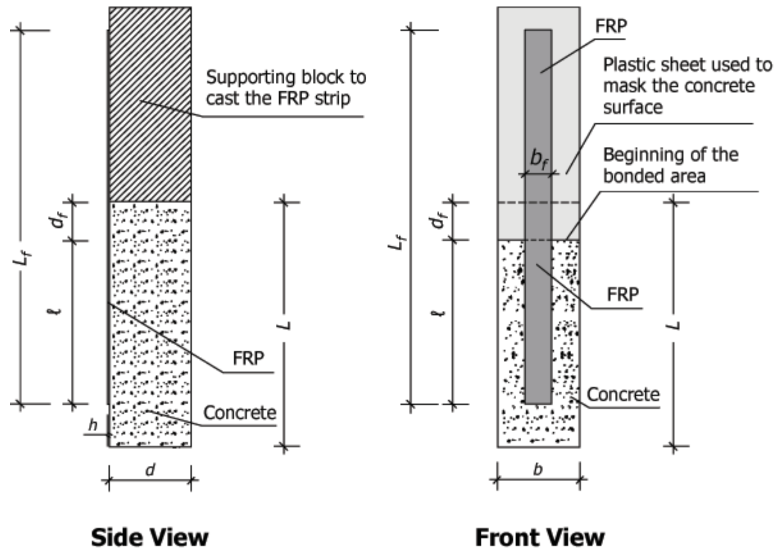

FIG. 4 Details of the Supporting Block Used to Apply the FRP Strip

from the concrete prism (Fig. 4), should be provided in order to cast the composite with all the fibers parallel to the concrete surface. Tape and plastic sheet can be used to mask the remaining surface of concrete in order to avoid resin bonding to concrete outside the bonded area (Fig. 4).

8.6.4.1 The total length L_f (Fig. 1 and Fig. 3) of the FRP composite should be computed in accordance with Eq 1 and Eq 2:

$$L_f = \ell + d_f + 300 \text{ mm} \quad (1)$$

$$[L_f = \ell + d_f + 12 \text{ in.}] \quad (2)$$

NOTE 3—The total length L_f can be reduced if the testing machine vertical clearance does not allow for fitting long FRP strips.

8.6.5 Optional aluminum, steel, or composite tabs can be placed at the end of the composite strip and used to improve gripping with the clamping wedges during testing. A visual inspection of the tabs can provide information on whether slippage between the tabs and the clamping wedges occurred. If the marks on the tabs caused by the force applied by the wedges are elongated, slippage of the tabs might have occurred. Slippage of the tabs does not invalidate the test unless the force cannot be transferred to the FRP strip. However, slippage of the tabs will alter the values of the stroke.

NOTE 4—Tabs are not represented in Fig. 4 because they are applied after the FRP is cured and prior to testing. Similarly, the plastic sheet is not shown in Fig. 3.

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 conducted to assess variation of bond performance associated with a variety of effects, including 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 for control or other specimens not otherwise subject to environmental conditioning 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.

NOTE 5—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.

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.

11. Procedure

11.1 Center the specimen in order to have the composite strip perfectly aligned with the clamping wedge.

11.2 Apply an initial pre-compression to the concrete prism by tightening the bolts of the four steel bars used to connect the top and bottom plates. The total pre-compression force applied to the four steel bars should be measured using a torque wrench. The total pre-compression should be not greater than one fourth of the maximum applied force (P_{max}) expected. In addition, the total force applied to the four steel bars divided by the cross-sectional area of the prism should provide a stress that is lower or equal to one tenth of the compressive strength f'_c of concrete (Test Method C39/C39M).

11.3 Clamp the loaded end of the composite strip within the wedges of the testing machine. Slowly adjust the position of