

ACI 440.3R-12

**Guide Test Methods for Fiber-
Reinforced Polymer (FRP)
Composites for Reinforcing or
Strengthening Concrete and
Masonry Structures**

Reported by ACI Committee 440



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Guide Test Methods for Fiber-Reinforced Polymer (FRP) Composites for Reinforcing or Strengthening Concrete and Masonry Structures

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Due to differences in the physical and mechanical behavior of fiber-reinforced polymer (FRP) materials compared to steel, unique test methods for FRP bars and laminates are required. This guide provides model test methods for the short- and long-term mechanical, thermo-mechanical, and durability testing of FRP bars and laminates. It is anticipated that these model test methods may be considered, modified, and adopted, either in whole or in part, by a U.S. national standards-writing agency such as ASTM International or AASHTO. The publication of these test methods by ACI Committee 440 is an effort to aid in this adoption. The recommended test methods are based on the knowledge gained worldwide from review of research results and literature.

Keywords: anchorage; bond; coupler; creep; fatigue; fiber-reinforced polymer composites; modulus of elasticity; shear; splice; stirrup; strength; tendon.

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PART 1—GENERAL

1.1—Introduction

Conventional concrete and masonry structures are reinforced with nonprestressed steel, prestressed steel, or both. Recently, composite materials made of fibers embedded in a

polymeric resin, also known as fiber-reinforced polymer (FRP) composites, have become an alternative to steel reinforcement. Because FRP materials are nonmetallic and noncorrosive, the problems of steel corrosion are avoided with FRP reinforcement. Additionally, FRP materials exhibit several properties, such as high tensile strength, that make them suitable for use as structural reinforcement. FRP materials are supplied as bars for reinforced and prestressing applications and in flat sheets or laminates for use as repair materials.

The mechanical behavior of FRP differs from the behavior of steel reinforcement. FRP materials, which are anisotropic due to the fiber orientation in the bars and laminates, are characterized by high tensile strength only in the direction of the reinforcing fibers. This anisotropic behavior affects the shear strength and dowel action of FRP bars and the bond performance of FRP bars to concrete.

FRP composites are available with a wide range of mechanical properties, including tensile strengths, bond strengths, and elastic moduli. Generally, FRP composites are not covered by national material standards. Instead, manufacturers of FRP composites provide test data and recommend design values based on these test data. Therefore, it is difficult to compare test results between product manufacturers. In addition, research has considered the durability of FRP reinforcement in environments containing moisture, high and low temperatures, and alkaline environments. Test methods that allow for the comparison of mechanical property retention in a wide range of standard environments are needed so that durable FRP-reinforced structures can be ensured.

1.2—Scope

This guide provides model test methods for determining the short- and long-term mechanical properties of FRP reinforcing bars, grids, tendons, and laminates—both prestressed and nonprestressed—for concrete and masonry structures. As noted in the individual methods, most of the methods for bars are also suitable for sections cut from grids. Where necessary, the tests consider the bars and laminates tested embedded in or bonded to concrete or masonry. For the most part, however, these tests are considered to be material tests and not component or structural tests.

These model test methods are intended for consideration, modification, and adoption, either in whole or in part, by a U.S. national standards-writing agency such as ASTM International or AASHTO. The publication of these test methods by ACI Committee 440 is an effort to aid in this adoption.

The guide contains only test methods and not material standards. The individual test methods contained in this guide do not specify minimum material properties that must be met for the materials to be considered acceptable for use. Guidance on deciding whether a material is acceptable based on test results is made in the material specifications and design provisions that complement these test methods (ACI 440.1R; ACI 440.2R; ACI 440.6).

The test methods presented in this guide are the recommendations of ACI Committee 440, and have not been adopted by ACI as standards. As such, they are, for the most part, written in nonmandatory language, using “should”

and “may” rather than “shall” and “must.” In keeping with the usual test method format, however, some language is imperative (“Fill a cylinder with water...” rather than “A cylinder should be filled with water...”). Although typically considered to be mandatory language, the use of imperative language in these test methods is for readability, and remains as committee recommendations only.

1.3—Existing ASTM test methods

The recommended test methods provided herein are based on the knowledge obtained worldwide from review of research results and literature. Relevant ASTM standards are referenced in the individual methods; others are listed in Table 1.3. In many cases, existing ASTM test methods are appropriate to determine material properties for FRP bars and laminates. Where such methods are completely acceptable for FRP reinforcement, no new method has been proposed. The new methods that are provided have been developed for one or more of the following reasons:

- a) To provide a test method where no current method exists
- b) To provide more detailed requirements that are specific to FRP reinforcing bars or laminates, such as details on how to grip the reinforcement in the test fixture
- c) To adapt a test method originally developed for steel reinforcing bars to work with FRP bars
- d) To provide calculated test results compatible with other ACI documents.

Table 1.3 lists specific ASTM test methods and complementary ACI 440.3R methods for various material properties. Where both ASTM and ACI 440.3R test methods exist, the differences between the methods are summarized. Hundreds of ASTM test methods are applicable to FRP composites and organic polymers. The table only describes key material properties and selected ASTM tests that can be used to determine these properties. For some properties, ASTM provides more than one test procedure. The table does not attempt to discuss the differences between various ASTM test methods.

1.4—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://terminology.concrete.org>. The definitions provided herein complement that resource.

alkaline—having a pH greater than 7 (OH^- concentration greater than 1×10^{-7} M).

anchorage—device at the ends of an FRP tendon that grips the tendon, allowing a minimum of slip and transferring prestressing load from the tendon to the abutment.

anchorage reinforcement—latticed or spiral reinforcing steel or FRP bars provided as confining reinforcement for the anchorage and arranged in front of it.

anchoring section—FRP bar section embedded in the anchorage and anchorage reinforcement, including the surrounding concrete or masonry.

aramid fiber—highly oriented organic fiber derived from polyamide incorporating into an aromatic ring structure.

average load (stress)—mean value of the maximum and minimum repeated loads (stresses).

bend capacity—ultimate tensile stress carried by the FRP stirrup, provided that failure occurs in the bend.

bend radius—inside radius of the bend.

bending angle—angle formed by the straight sections of a specimen on either side of the deflector.

bending diameter ratio—ratio of the external diameter of the deflector surface in contact with the FRP bar to the diameter of the FRP bar.

bending tensile capacity—tensile capacity at failure of a specimen within the deflected section.

bonded length—length of the test bar that is in contact with concrete.

carbon fiber—fiber produced by heating organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile (PAN), or pitch, in an inert environment.

characteristic length—for bars or tendons that have a repeating surface deformation pattern, the characteristic length is the distance, in inches (mm), of this pattern; for a spiral pattern, the characteristic length is the pitch.

coefficient of thermal expansion (CTE)—measure of the relative change in linear dimension in a material based on a unit increase in temperature of that material. Note: Due to the anisotropy of FRP composites, the CTE in the longitudinal direction of the bar is likely to be different from that measured in the transverse direction.

creep rupture—material failure due to deformation (accumulated strain) caused by creep.

creep rupture load capacity—load at which failure occurs after a specified period of time from initiation of a sustained load.

cure—to irreversibly change the properties of a thermosetting resin by chemical reaction such as condensation, ring closure, or addition. Note: Cure can be accomplished by adding curing (cross-linking) agents with or without heat and pressure.

deflected section—section of an FRP bar that is bent and maintained at the required bending angle and bending diameter ratio.

deflector—device used to maintain the position, alter the bending angle, or alleviate the stress concentrations in an FRP bar; such a device may sometimes be installed in the deflected section.

equivalent bar diameter—equivalent bar diameter is determined based on the cross-sectional area of the FRP bar (ASTM D7205/D7205M).

equivalent circumference—circumference of an assumed circle with the equivalent area determined according to ASTM D7205/D7205M.

fatigue life—number of cycles of deformation or load required to bring about failure of a material, test specimen, or structural member.

fatigue strength—maximum load (stress) range at which the specimen does not fail at a prescribed number of cycles.

fiber-volume fraction—ratio of the volume of fibers to the volume of the composite.

frequency—number of loading (stressing) cycles per second.

Table 1.3—Test methods for FRP composites used in concrete and masonry structures

Property	ASTM test method(s)	ACI 440 test method	Summary of differences
Cross-sectional area	D7205/D7205M	—	ASTM D7205/D7205M replaces ACI 440.3R-04 Method B.1.
Longitudinal tensile strength and modulus	D7205/D7205M	—	ASTM D7205/D7205M replaces ACI 440.3R-04 Method B.2.
Bond properties	A944	B.3	ASTM Pullout Test C234 (ASTM C234) has been withdrawn and, as written, did not provide adequate specimen size to prevent splitting of concrete cylinder when using FRP bars. The only remaining ASTM test method for bond of steel bars to concrete is beam-end test method (A944), which has not been modified for use with FRP bars. Ongoing work by ACI Committee 440 is expected to produce beam bond test methods.
Shear strength	D7617/D7617M	—	ASTM D7617/D7617M replaces ACI 440.3R-04 Method B.4.
Bent bar capacity	—	B.5	No existing ASTM test method available.
Durability properties	—	B.6	No existing ASTM test method available.
Fatigue properties	D3479	B.7	The ACI method provides specific information on anchoring bars in the test fixtures and on attaching elongation measuring devices to the bars. The ACI method also requires specific calculations that are not provided in the ASTM method.
Creep properties	D7337/D7337M	—	ASTM D7337/D7337M replaces ACI 440.3R-04 Method B.8.
Relaxation properties	D2990	B.9	The ACI method provides specific information on anchoring bars in the test fixtures and on attaching elongation measuring devices to the bars. The ACI method also requires specific calculations that are not provided in the ASTM method.
	E328		
Anchorage properties	—	B.10	No existing ASTM test method available.
Tensile properties of deflected bars	—	B.11	No existing ASTM test method available.
Effect of corner radius on strength	—	B.12	No existing ASTM test method available.
Flexural properties	D790	—	No ACI method developed.
	D4476		
Coefficient of thermal expansion (CTE)	E831	—	No ACI method developed.
	D696		
Glass transition temperature	E1356	—	No ACI method developed.
	E1640		
	D648		
	E2092		
Volume fraction	D3171	—	No ACI method developed.
	D2584		
Direct tension pulloff	D7522/D7522M	—	ASTM D7522/D7522M replaces ACI 440.3R-04 Method L.1.
Tensile strength and modulus	D7565/D7565M	—	ASTM D7565/D7565M replaces ACI 440.3R-04 Method L.2.
Lap shear strength	D7616/D7616M	—	ASTM D7616/D7616M replaces ACI 440.3R-04 Method L3.
Bond strength	D4551	—	No ACI method developed.
	C882		

FRP bar—composite material formed into a long, slender, structural shape suitable for the internal reinforcement of concrete and consisting of primarily longitudinal unidirectional fibers bound and shaped by a rigid polymer resin material. The bar may have a cross section of variable shape, commonly circular or rectangular, and may have a deformed or roughened surface to enhance bonding with concrete.

FRP laminates—two or more layers of fiber reinforcements, such as, glass, carbon, and aramid arranged in one or more orientations—for example, 0, 90, +45, –45 degrees—and held together by a polymer matrix. Laminates come in the physical form of dry, prepreg, and precured materials.

FRP tendon—FRP element, such as a bar or strand, or a bundle of such elements primarily used in tension to impart compressive stress to concrete or masonry.

gauge length—distance between two gauge points on the test section, over which the percentage of elongation is determined.

glass fiber—fiber drawn from an inorganic fusion of silica (SiO₂) and other compounds that has cooled without crystallization.

grid—two-dimensional (planar) or three-dimensional (spatial) rigid array of interconnected FRP bars that form a contiguous lattice that can be used to reinforce concrete.

Note: The lattice can be manufactured with integrally

connected bars or made of mechanically connected individual bars.

impregnate—in the case of FRP composites, to saturate the fibers with resin.

load (stress) amplitude—one-half of the load (stress) range.

load (stress) range—difference between the maximum and minimum repeated loads (stress).

load (stress) ratio—minimum load (stress) divided by maximum load (stress).

maximum repeated load (stress)—maximum load (stress) during repeated loading (stressing).

minimum repeated load (stress)—minimum load (stress) during repeated loading (stressing).

number of cycles—number of times the repeated load (stress) is applied to the test specimen.

pitch—black residue from the distillation of petroleum, used as a precursor for the production of carbon fibers; the other precursor for polymer fibers is polyacrylonitrile.

polyacrylonitrile (PAN)—polymeric precursor for the production of carbon fibers; the other precursor for carbon fibers is pitch.

precured FRP—fully cured FRP that is usually made in a factory and brought to the site as a rigid solid; if used as a repair material for concrete, a precured FRP should be bonded to the surface of the concrete with an adhesive.

precursor—rayon, polyacrylonitrile, or pitch fibers from which carbon fibers are derived.

prepreg FRP—reinforcement fabrics for FRP laminates that have been preimpregnated with a resin; usually this resin is cured to an intermediate stage (B-staged) and the resulting prepreg is stored at cold temperatures; the cure restarts once the prepreg is brought to room temperature.

relaxation—reduction of stress (or load) in a material under a constant state of strain (or deformation).

relaxation rate—absolute value of the slope of the relaxation curve at a given time. In particular, the relaxation value after 1 million hours is referred to as the million-hour relaxation rate.

repeated load (stress)—load (stress) alternating cyclically between fixed maximum and minimum values.

S-N curve—graphical plot of the repeated load (stress) along a vertical axis versus the number of cycles to fatigue failure on the horizontal axis.

stress—load divided by the cross-sectional area of a lot of specimens. Refer to ASTM D7205/D7205M for the calculation of cross-sectional area.

tail length—length provided beyond the bend portion.

tensile capacity—maximum tensile load carried by test specimen before failure.

tensile strength—ultimate tensile strength of FRP bars in the direction parallel to the fibers.

test section—portion of a specimen between the anchoring sections of the test specimen.

thermoset—resin that is formed by cross-linking polymer chains. Note: A thermoset cannot be melted and reshaped because the polymer chains form a three-dimensional network.

ultimate strain—change in length per unit length corresponding to the tensile capacity.

1.5—Notation

A	= cross-sectional area of FRP bar (according to ASTM D7205/D7205M), mm ²
a_1	= empirical constant
b_1	= empirical constant
C_b	= equivalent circumference of FRP bar, mm
D	= external diameter at deflector surface position, mm
d_b	= equivalent diameter of reinforcing bar, mm
E_L	= axial (longitudinal) modulus of elasticity of FRP bar, MPa
F	= tensile load, N
F_{u1}	= tensile capacity before immersion, N
F_{u2}	= tensile capacity after immersion, N
F_{ub}	= ultimate load capacity according to bend test of FRP bars, N
f_u	= ultimate tensile strength parallel to the fibers (according to ASTM D7205/D7205M), MPa
f_{ub}	= bend capacity of the FRP stirrup, MPa
ℓ	= bonded or overlap length, mm
L_c	= length from the top of the embedded bar to the point of attachment of the measuring device, mm
L_t	= tail length of bend bar, mm
P	= tensile failure load of specimen, N
R_{et}	= tensile capacity retention rate, percent
r_t	= radius of bend in FRP reinforcement, mm
S	= reduced tensile strength of specimen corresponding to a specific corner radius, MPa
S_c	= elastic elongation, mm
T	= time, h
W_0	= initial mass of the specimen before immersion, g
W_1	= mass of the specimen after immersion for a period (Time 1), g
Y_r	= relaxation rate, percent
α	= bending angle, degrees
χ	= strength reduction factor due to bend effect
$\Delta\epsilon$	= strain increment
ΔP	= tensile load increment, N
τ	= bond or shear stress, MPa

PART 2—TEST METHODS FOR FRP BARS

B.1—Test method for cross-sectional properties of FRP bars

This test method has been replaced by ASTM D7205/D7205M, Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars.

B.2—Test method for longitudinal tensile properties of FRP bars

This test method has been replaced by ASTM D7205/D7205M, Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars.

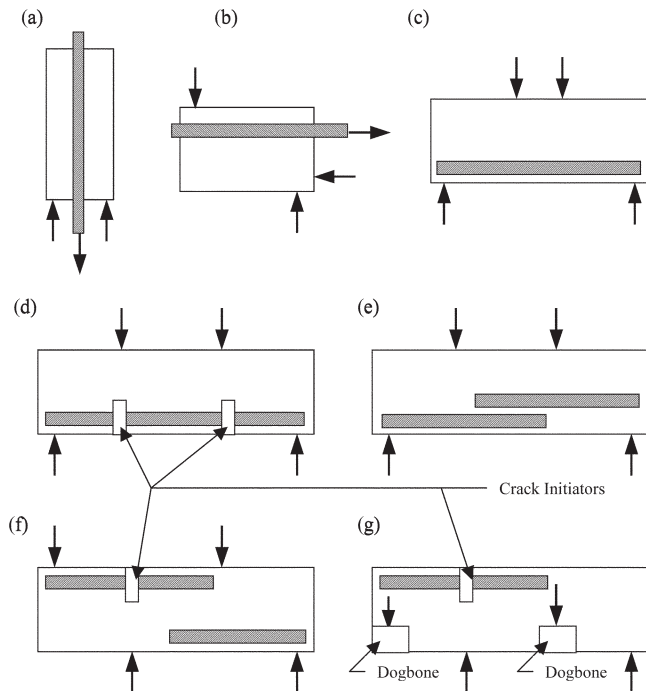


Fig. B.3.1a—Types of test methods for different bond values of FRP reinforcement in concrete: (a) pullout specimen; (b) beam-end specimen; (c) simple beam specimen; (d) hinged beam-end specimen; (e) splice specimen; (f) cantilever beam specimen (without dogbones); and (g) cantilever beam specimen (with dogbones).

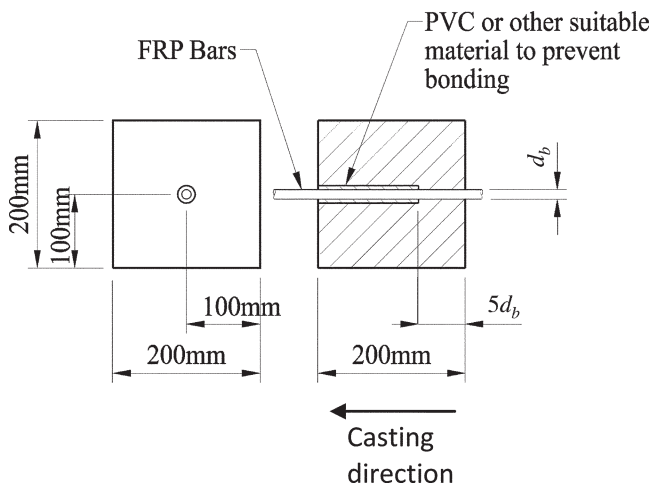


Fig. B.3.1b—Vertical bond test specimen.

B.3—Test method for bond strength of FRP bars by pullout testing

The following references are provided for historical and informational purposes only—Al-Zahrani et al. (1996); Benmokrane et al. (2002); Chaallal and Benmokrane (1993); and Freimanis et al. (1998).

B.3.1 Scope—This test method specifies the test requirements for determining the bond strength of FRP bars used as reinforcing bars or prestressing tendons in concrete by pullout testing. Various types of test methods are available for the determination of different bond values of FRP rein-

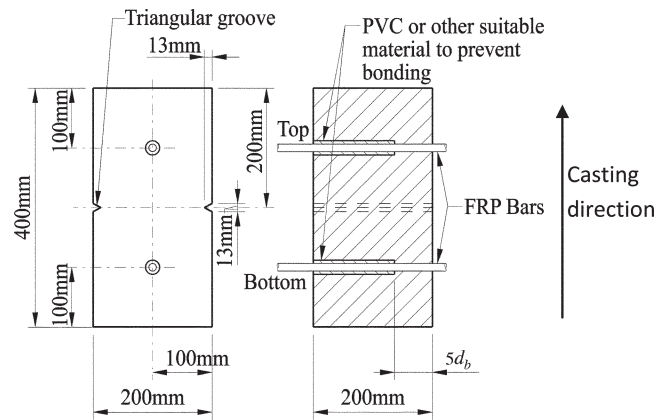


Fig. B.3.1c—Horizontal bond test.

forcement in concrete structures, as shown schematically in Fig. B.3.1a. This test method describes the pullout test specimen to determine the bond strength.

Two methods for casting test specimens are provided. The first method aligns the bar with the concrete casting direction, similar to that of a longitudinal bar in a reinforced concrete column (Fig. B.3.1b). The second method aligns the bars transverse to the concrete casting direction, similar to that of the longitudinal bar in a reinforced concrete beam or slab (Fig. B.3.1c).

B.3.2 Referenced documents

ASTM A944-10—Standard Test Method for Comparing
Bond Strength of Steel Reinforcing Bars to Concrete Using
Beam End Specimens

ASTM C39/C39M-12—Standard Test Method for
Compressive Strength of Cylindrical Concrete Specimens

ASTM C143/C143M-10—Standard Test Method for
Slump of Hydraulic Cement Concrete

ASTM C192/C192M-07—Standard Practice for Making
and Curing Concrete Test Specimens in the Laboratory

ASTM C293/C293M-10—Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center Point Loading)

ASTM C511-09—Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes

ASTM C617/C617M-11 Standard Practice for Capping
Cylindrical Concrete Specimens

ASTM D618-08—Standard Practice for Conditioning
Plastics for Testing

ASTM D7205/D7205M-06(2001)—Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars

ASTM E4-10—Standard Practices for Force Verification
of Testing Machines

B.3.3 Significance and use

B.3.3.1 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. The test method should not be used to establish design bond

values and development lengths for FRP bars embedded in concrete.

B.3.3.2 This test method is intended to determine the bond behavior for material specifications, research and development, and quality assurance. 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 normalweight concrete, which is an important factor to consider in the use of FRP bars as reinforcing bars or tendons.

B.3.3.3 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 to establish long-term environmental effects on bond to concrete, including environmental reduction factors for FRP bars embedded in concrete.

B.3.4 Test equipment and requirements

B.3.4.1 Use a testing machine with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM E4. A testing machine with either loading-rate or displacement-rate control is preferred. The load should be applied to the reinforcing bar at a rate no greater than 20 kN/minute or at the no-load speed of the testing machine head of not greater than 1.3 mm/minute, depending on the type of testing machine used and the means provided for ascertaining or controlling testing speed.

B.3.4.2 The loading plate (Fig. B.3.4.2) should be a machined steel plate at least 200 mm square and 20 mm thick, and have a hole drilled through its center of sufficient diameter to accommodate the FRP bar.

B.3.4.3 The loading end of the FRP bar should be fitted with an anchor capable of transmitting loads until the bar is pulled out of the concrete by a bond failure. The load transmission device should only transmit axial loads to the FRP bars, without applying either torsion or bending.

B.3.4.4 The displacement measuring devices fitted to both the free end and loaded end of the FRP bars should be displacement measuring devices (LVDTs) or similar apparatuses, reading accurately to 0.01 mm. Three LVDTs at 120-degree intervals at the loaded end and either one concentric gauge or two gauges at 180-degree intervals at the free end of the bar are recommended (Fig. B.3.4.4).

B.3.4.5 Two types of molds for bond test specimens are required:

1. For 200 mm concrete cubes, each containing a vertically embedded bar
2. For 200 x 200 x 400 mm prisms, each containing two horizontally embedded bars

Preferably, the molds should be made of metal no less than 6 mm thick. The molds should be watertight and constructed for easy removal without disturbing the embedded bars.

B.3.5 Specimen preparation

B.3.5.1 FRP bar specimens should be representative of the lot or batch being tested. Each specimen should be cut into 1200 mm long sections and assembled with an anchor

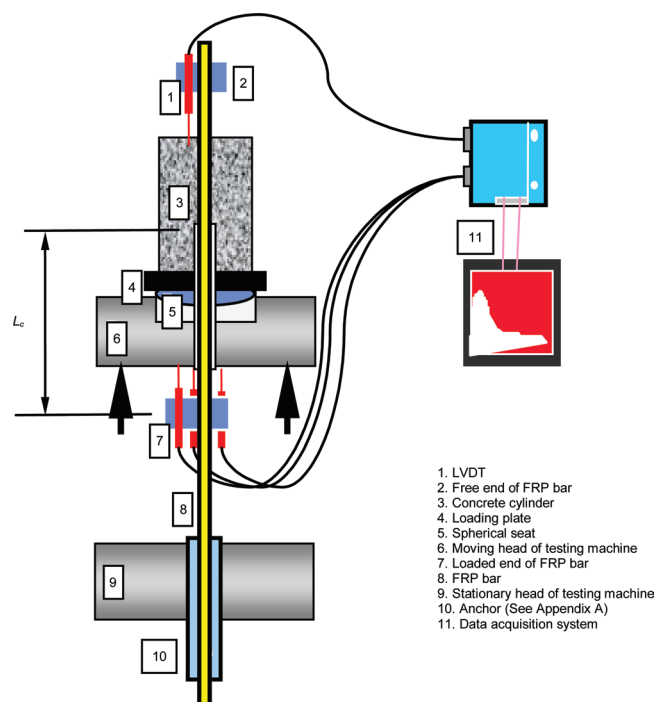


Fig. B.3.4.2—Schematic details of pullout bond test setup.

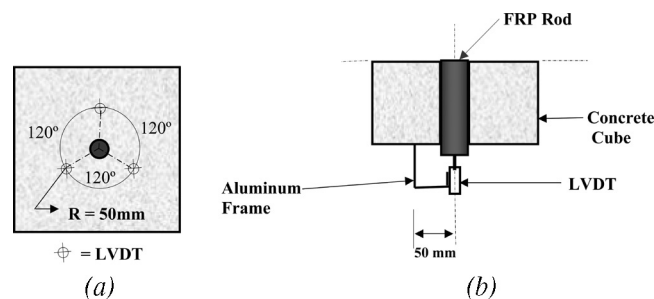


Fig. B.3.4.4—Positions of LVDTs at surface of concrete cube: (a) plan view of three LVDTs at loaded end; and (b) one LVDT at free end.

(ASTM D7205/D7205M) at one end. The test specimens should contain either one FRP bar embedded parallel to the direction of casting of the concrete (Fig. B.3.1b), or two FRP bars embedded perpendicular to the direction of casting of the concrete (Fig. B.3.1c). Five specimens of each type should constitute a set of test specimens. If a specimen has failed or slipped at the anchoring section, or split the concrete cover, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

B.3.5.1.1 Specimens for parallel embedded bar (Fig. B.3.1b)—These specimens should consist of concrete cubes, 200 mm on each edge, with a single FRP bar embedded vertically along the central axis in each specimen. 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 load. If splitting occurs at the concrete