**ACI 440.3R-04**

# Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures

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*Fiber-reinforced polymer (FRP) materials have emerged as a practical material for producing reinforcing bars and laminates for concrete structures. FRP reinforcing bars and laminates offer advantages over steel reinforcement in that FRP is noncorrosive and nonconductive. FRP reinforcing bars, grids, and tendons are being used for nonprestressed and prestressed concrete structures. FRP laminates are being used as external reinforcement for strengthening of existing concrete and masonry structures. Due to differences in the physical and mechanical behavior of FRP materials compared to steel, unique test methods for FRP bars and laminates are required.*

*This document provides model test methods for the short-term 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 from research results and literature worldwide. Many of the proposed test methods for reinforcing rods are based on those found in "Recommendation for Design and Construction of Concrete Structures using Continuous Fiber Reinforcing Materials" published in 1997 by the Japan Society for Civil Engineers (JSCE). The JSCE test methods have been modified extensively to add details and to adapt the test methods to U.S. practice.*

**Keywords:** anchorage; bond; concrete; coupler; creep; fatigue; fiber-reinforced polymers (FRP); modulus of elasticity; reinforced concrete; shear; splice; stirrup; strength; tendon.

## CONTENTS

## PART 1—GENERAL

### 1.1—Introduction

Conventional concrete 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 polymers (FRPs), have become alternatives to steel reinforcement for concrete structures. 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 for concrete structures.

The mechanical behavior of FRP differs from the behavior of steel reinforcement. FRP materials are anisotropic due to the fiber orientation in the bars and laminates and 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.

FRPs are available with a wide range of mechanical properties (tensile strengths, bond strengths, and elastic moduli). Generally, FRP concrete reinforcements are not covered by national material standards, as few such standards exist. Instead, manufacturers of FRP provide test data and recommend design values based on these test data. Unfortunately, also due to the lack of material standards, few standard test methods exist for FRP concrete reinforcements. Therefore, it is difficult to compare test results between product manufacturers. In addition, research has considered the durability of FRP concrete reinforcements 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 concrete structures can be ensured.

### 1.2—Scope

This document provides model test methods for determining the short-term and long-term mechanical properties of FRP reinforcing bars, grids, and tendons for concrete, both prestressed and nonprestressed, and for FRP laminates as external reinforcement for concrete structures. As noted in the individual methods, most of the methods for bars are also suitable for tendons and sections cut from grids. Where necessary, the tests consider the bars and laminates acting in concert with concrete. 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 to 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 document contains only test methods and not material standards. The individual test methods contained in this document 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).

The test methods presented in this document 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 remain as committee recommendations only. If an architect or engineer desires one of the test methods to be part of the contract documents, all of the nonmandatory language would need to be restated into mandatory language.

## 1.3—Existing ASTM test methods

The recommended test methods provided herein are based on the knowledge obtained from research results and literature worldwide. Relevant ASTM standards are referenced in the individual methods; others are listed in Table 1.1. 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 reinforcements, no new method has been proposed. The new methods that are provided have been developed for one or more of the following reasons:

1. To provide a test method where no current method exists;

2. To provide more detailed requirements that are specific to FRP concrete reinforcing bars or laminates, such as details on how to grip the reinforcements in the test fixture;

3. To adapt a test method originally developed for steel reinforcing bars to work with FRP bars; or

4. To provide calculated test results that are compatible with other ACI documents.

Table 1.1 lists specific ASTM test methods and complementary ACI 440 methods for various material properties. Where both ASTM and ACI 440 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

The following definitions clarify terms that are not commonly used in reinforced concrete practice.

### -A-

**AFRP**—aramid fiber-reinforced polymer.

**aging**—the process of exposing materials to an environment for an interval of time.

**alkaline**—having a pH greater than 7 (OH⁻ concentration greater than $1 \times 10^{-7}$ M).

**anchorage**—a device at the ends of an FRP bar that grips the bar, allowing a minimum of slip and transfers prestressing load from the tendon to the concrete members.

**anchorage reinforcement**—the latticed or spiral reinforcing steel or FRP bars as confining reinforcement connected with the anchorage and arranged behind it.

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

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

### -B-

**bar, FRP**—a 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.

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

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

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

**braiding**—intertwining fibers in an organized fashion.

### -C-

**CFRP**—carbon fiber-reinforced polymer.

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

**coefficient of thermal expansion (CTE)**—a 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 FRPs, the CTE in the longitudinal direction of the rod is likely to be different from that measured in the transverse direction.

**composite**—a combination of one or more materials differing in form or composition on a macroscale. Note: The constituents retain their identities; that is, they do not dissolve or merge completely into one another, although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

**creep**—time-dependent deformation (or strain) under sustained load (or stress).

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

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

**creep rupture strength**—the stress causing failure after a specified period of time from initiation of a sustained load.

**creep rupture time**—the lapsed time between the start of a sustained load and failure of the test specimen.

**creep strain**—the differential change in length per unit length occurring in a specimen due to creep.

**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.

## Table 1.1—Test methods for bars used for reinforcing or prestressing concrete

| Property | ASTM test method(s) | ACI 440 test method | Summary of differences |
|---|---|---|---|
| Cross-sectional area | — | B.1 | No existing ASTM test method available. |
| Longitudinal tensile strength and modulus | D 3916 | B.2 | ACI method provides detailed information on anchoring bars in the test fixture. ACI method also provides procedural requirements for attachment of elongation reading devices on bar with various deformation patterns. |
| Bond properties | A 944 | B.3 | ASTM Pullout Test C 234 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 (A 944), 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 | D 5379 | B.4 | The ACI method focuses on dowel action of bars and does not overlap with existing ASTM methods that focus mainly on beam shearing failure modes. Bar shear strength is of specific concern for applications where FRP rods are used to cross construction joints in concrete pavements. |
| | D 3846 | | |
| | D 2344 | | |
| | D 4475 | | |
| Bent bar capacity | — | B.5 | No existing ASTM test methods available. |
| Durability properties | — | B.6 | No existing ASTM test method available. |
| Fatigue properties | D 3479 | B.7 | ACI methods provide specific information on anchoring bars in the test fixtures and on attaching elongation measuring devices to the bars. The ACI methods also require specific calculations that are not provided in the ASTM methods. |
| Creep properties | D 2990 | B.8 | |
| Relaxation properties | D 2990 | B.9 | |
| | E 328 | | |
| Anchorage properties | — | B.10 | No existing ASTM test methods available. |
| Tensile properties of deflected bars | — | B.11 | No existing ASTM test methods available. |
| Effect of corner radius on strength | — | B.12 | No existing ASTM test method available. |
| Flexural properties | D 790 | — | No ACI methods developed. |
| | D 4476 | | |
| Coefficient of thermal expansion | E 831 | — | No ACI methods developed. |
| | D 696 | | |
| Glass transition temperature | E 1356 | — | No ACI methods developed. |
| | E 1640 | | |
| | D 648 | | |
| | E 2092 | | |
| Volume fraction | D 3171 | — | No ACI methods developed. |
| | D 2584 | | |
| **Test methods for laminates used as strengthening and repair materials** | | | |
| Direct tension pulloff | D 4551 | L.1 | ACI method provides specific requirements for specimen preparation not found in the ASTM test method. |
| Tensile strength and modulus | D 3039 | L.2 | ACI method provides for calculating tensile strength and modulus on gross cross-sectional and equivalent, fiber area basis. |
| Lap shear strength | D 3165 | L.3 | ACI method provides specific requirements for specimen preparation. |
| | D 3528 | | |
| Bond strength | D 4551 | — | No ACI methods developed. |
| | C 882 | | |

### -D-

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

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

**deformability**—the ratio of energy absorption (area under the moment-curvature curve) at ultimate strength level to the energy absorption at service level.

**degradation**—a decline in the quality of the mechanical properties of a material.

**development length**—length of embedded reinforcement required to develop the tensile capacity.

### -E-

**E-glass**—a general-purpose fiber that is used in reinforced polymers; a family of glass with a calcium, alumina, and borosilicate composition and a maximum alkali content of 2%.

**equivalent area**—area determined according to Test Method B.1.

**equivalent circumference**—circumference of an assumed circle with the equivalent area determined according to Test Method B.1.

## -F-

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

**fatigue strength**—the greatest stress that can be sustained for a given number of load cycles without failure.

**fiber**—any fine thread-like natural or synthetic object of mineral or organic origin. Note: This term is generally used for materials whose length is at least 100 times its diameter.

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

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

**fiber, glass**—fiber drawn from an inorganic fusion of silica ($SiO_2$) and other compounds that has cooled without crystallization.

**fiber content**—the amount of fiber present in a composite. Note: This is usually expressed as a percentage volume fraction or weight fraction of the composite. Due to differing constituent densities, weight fractions and volume fractions of fibers are not the same.

**fiber-reinforced polymer (FRP)**—composite material consisting of continuous fibers impregnated with a fiber-binding polymer then molded and hardened in the intended shape.

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

**fiber-weight fraction**—the ratio of the weight of fibers to the weight of the composite.

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

## -G-

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

**GFRP**—glass fiber-reinforced polymer.

**glass-transition temperature $T_g$**—the midpoint of the temperature range over which an amorphous material changes from (or to) a brittle, vitreous state to (or from) a plastic state.

**grid**—a 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.

## -H-

**hybrid**—an FRP that is reinforced with a combination of two or more different fibers, such as carbon and glass.

## -I-

**impregnate**—in the case of fiber-reinforced polymers, to saturate the fibers with resin.

## -L-

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

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

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

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

## -M-

**matrix**—in the case of FRP, the polymeric materials that serve to bind the fibers together, transfer load to the fibers, and protect them against environmental attack and damage due to handling.

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

**microstrain**—strain $\times 10^6$.

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

## -N-

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

## -P-

**PAN**—polyacrylonitrile, a polymeric precursor for the production of carbon fibers. The other precursor for carbon fibers is pitch.

**pitch**—a black residue from the distillation of petroleum. Used as a precursor for the production of carbon fibers. The other precursor for polymer fibers is PAN.

**polymer**—a high-molecular-weight organic compound, natural or synthetic, containing repeating units.

**precured FRP**—a 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**—the rayon, PAN, 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.

**pultrusion**—a continuous process for manufacturing composites that have a uniform cross-sectional shape. Note: The process consists of continuously pulling impregnated, formable fiber-reinforcing material through a shaping die where the material is heated and subsequently cured or hardened.

## -R-

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

**relaxation rate**—the 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.

**resin**—polymeric material that is rigid or semirigid at room temperature, usually with a melting point or glass-transition temperature above room temperature.

**rod, FRP**—resin-bound construction mostly made of continuous fibers in the shape of a bar or tendon used to reinforce concrete uniaxially.

### -S-

**S-N curve**—the 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. Refer to Test Method B.1 for the calculation of cross-sectional area.

**stress concentration**—the magnification of stress in a region due to the presence of a bend, notch, void, hole, or inclusion. Stress concentrations (nonuniform stresses) occur in regions where St. Venant's principle does not apply.

### -T-

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

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

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

**thermoplastic**—resin that is not cross-linked; it generally can be repeatedly remelted and reshaped by the application of heat.

**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.

### -U-

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

### -V-

**vinyl esters**—a class of thermosetting resins containing ester of acrylic, methacrylic acids, or both, many of which have been made from epoxy resin.

### -W-

**wet lay-up FRP**—a method of forming an FRP laminate, often on a substrate such as concrete, using dry FRP fabrics that are saturated with resin in-place. Once cured, the resin system acts as the matrix of the FRP laminate and acts to adhere the laminate to the substrate.

## 1.5—Notation

$A$ = cross-sectional area of FRP bar, mm$^2$

$A_1$ = empirical constant

$A_a$ = adhesion fixture contact area, mm$^2$

$B$ = width of specimen, mm

$B_1$ = 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

$E_f$ = modulus of elasticity of FRP laminate based on specimen area, MPa

$E_f'$ = modulus of elasticity of FRP laminate based on fiber area, MPa

$E_L$ = axial (longitudinal) modulus of elasticity of FRP bar, MPa

$F$ = tensile load, N

$F_1$ = tensile load at approximately 50% of the ultimate load capacity or of guaranteed tensile capacity of FRP bar, N

$F_2$ = tensile load at approximately 20% of the ultimate load capacity or of guaranteed tensile capacity of FRP bar, N

$F_{max}$ = maximum tensile load, N

$F_p$ = pull-off force, N

$F_r$ = million-hour creep rupture capacity of FRP, N

$F_u$ = tensile capacity of FRP bar, 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

$f_{fu}$ = tensile strength of FRP based on specimen area, MPa

$f_{fu}'$ = tensile strength of FRP based on fiber area, MPa

$f_r$ = million hour creep rupture strength of FRP bar, MPa

$f_u$ = ultimate tensile strength parallel to the fibers, MPa

$f_{ub}$ = bend capacity of the FRP stirrup, MPa

$L$ = specimen length, mm

$L$ = bonded or embedded or overlap length, mm

$L_a$ = length of anchor cylinder, mm

$L_c$ = length from the top of the embedded bar to the point of the attachment of the measuring device, mm

$L_g$ = gauge length of measuring instrument, mm

$L_t$ = tail length of bend bar, mm

$P$ = tensile failure load of specimen, N

$P_S$ = maximum failure load, N

$P_u$ = maximum tensile load, N

$R$ = stress ratio

$R_{et}$ = tensile capacity retention rate, %

$r_t$ = 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

$T$ = specimen thickness, mm

$T$ = time, h

$T'$ = equivalent fiber thickness, mm

$T_g$ = glass-transition temperature, °C

$V_0$ = volume of water or ethanol in the cylinder before immersion of the specimen, mL

$V_1$ = volume of water or ethanol after the specimen is immersed, mL

$v_{su}$ = average tensile shear strength, MPa

$W_0$ = initial mass of the specimen before immersion, g

$W_1$ = mass of the specimen after immersion for a period of time 1, g

$Y_c$ = creep load ratio

$Y_r$ = relaxation rate, %

$\alpha$ = bending angle, degrees

$\varepsilon_1$ = tensile strain at approximately 60% of the ultimate load capacity or guaranteed tensile capacity of FRP bars

$\varepsilon_2$ = tensile strain at approximately 20% of the ultimate load capacity or guaranteed tensile capacity of FRP bars

$\varepsilon_f$ = strain in FRP reinforcement due to load

$\varepsilon_{fu}$ = design rupture strain of FRP reinforcement

$\varepsilon_{fu}^*$ = rupture strain of FRP reinforcement as reported by the manufacturer

$\varepsilon_u$ = ultimate strain of FRP bar

$\chi$ = strength-reduction factor due to bend effect

$\tau$ = bond or shear stress, MPa

$\tau_{max}$ = bond strength, MPa

$\tau_{su}$ = tensile shear strength, MPa

$\tau_u$ = shear strength, MPa

$\sigma_p$ = pull-off bond strength, MPa

$\Delta P$ = tensile load increment, N

$\Delta V$ = the increase in the cylinder volume reading when specimen is immersed in the water or ethanol, mL

$\Delta\varepsilon$ = strain increment

$dP/dl$ = slope of the chord between 1000 and 3000 microstrain of the load-deformation curve

## PART 2—TEST METHODS FOR FRP BARS FOR CONCRETE STRUCTURES
### B.1—Test method for cross-sectional properties of FRP bars

**1** *Scope*

**1.1**—This test method is used to determine the cross-sectional area, equivalent diameter, and equivalent circumference of an FRP bar.

**1.2**—For a grid, the method is used to determine the cross-sectional area of a single segment of the grid.

**2** *Referenced documents*

**2.1**—*ASTM standards*

D 618    Standard Practice for Conditioning Plastics for Testing

**3** *Significance and use*

**3.1**—FRP bars are made in varying forms, including deformed, sand coated, and ribbed, and multistrand cables and braided shapes. A methodology is required to determine the cross-sectional area, equivalent diameter, and equivalent circumference of the various shapes.

**3.2**—This test method is intended to determine the actual average cross-sectional area, equivalent diameter, and equivalent circumference of an FRP bar for material specifications, quality control, and structural design and analysis.

**3.3**—Cross-sectional properties of FRP bar are important factors to be considered in the design of FRP bars as concrete reinforcement. The cross-sectional properties are measured according to the method given herein, in keeping with the intended purposes.

**3.4**—This test method is not appropriate for bar geometries that will trap air when submerged in the graduated cylinder.

**4** *Terminology*

**4.1**—No new terminology introduced.

**5** *Test equipment and requirements*

**5.1**—A graduated measuring cylinder with a maximum gradient of 10 mL and of sufficient height and diameter to contain the specimen is used to measure the volume of the specimen.

**5.2**—Water or ethanol is used if air bubbles are present on the surface of the specimen.

**5.3**—Calipers with precision of 0.025 mm are used to measure the dimensions of the specimens.

**6** *Specimen preparation*

**6.1**—Specimens should be representative of the lot or batch being tested. Test specimens, as a rule, should not be subjected to any processing.

**6.2**—During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other environmental conditions causing changes to the material properties of the specimen should be avoided.

**6.3**—Five bar specimens, approximately 200 mm long, should be used. If the bars have a repeating surface deformation pattern, then at least on characteristic length should occur over the length of the sample. For FRP grids, the specimen length will be the space of the grid. When cutting the specimens, care should be taken to ensure the perpendicularity of the cutting face to the longitudinal direction of the specimen. Burrs on the cut face should be removed.

**6.4**—The cut surface of the specimen may be coated with a thin layer of paraffin wax if moisture uptake into the solid FRP material is considered to be an issue.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Condition specimens in accordance with Procedure A of ASTM D 618, store and test at the standard laboratory atmosphere ($23 \pm 3$ °C and $50 \pm 10\%$ relative humidity).

**8** *Test method*

**8.1**—The specimens should be kept in the test environment for at least 24 h before testing.

**8.2**—Fill a dried graduated cylinder with water or ethanol to an appropriate height such that the fluid will not overflow upon insertion of the specimen into the cylinder.

**8.3**—Measure the length of each specimen three times, rotating the specimens by 120 degrees for each measurement. The average of the three measurements, rounded to the nearest 0.1 mm, is used as the specimen length.

**8.4**—Measure the volume of water or ethanol in the cylinder before immersing the specimen. Immerse the specimen in the water or ethanol in the graduated cylinder with no part protruding above the brim. Care should be taken to avoid entrapping air along the specimen when it is immersed. Determine the volume increase.

**9** *Calculations*

**9.1**—When the volume and length of each of the five specimens have been determined, the cross-sectional area $A$ is determined and rounded to the nearest 1 mm$^2$ as the volume of the specimen is divided by the length $L$

$$A = \frac{\Delta V}{L} \times 1000 = \frac{V_1 - V_0}{L} \times 1000 \qquad (1)$$

where

$\Delta V$ = the increase in the cylinder volume reading when specimen is immersed in the water or ethanol, mL;

$V_0$ = volume of water or ethanol in the cylinder before immersing the specimen, mL;

$V_1$ = volume of water or ethanol when the specimen is immersed in the water or ethanol, mL; and

$L$ = length of the specimen, mm.

**9.2**—The equivalent diameter $d_b$ of each specimen should be calculated by assuming the cross section to be a circle

$$d_b = 2\sqrt{\frac{A}{\pi}} \ (\text{mm}) \qquad (2)$$

**9.3**—The equivalent circumference $C_b$ should be calculated as

$$C_b = 2\sqrt{\pi \cdot A} \ (\text{mm}) \qquad (3)$$

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer and fiber volume fraction.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Designation and surface modification of FRP bar.

**10.5**—Type of liquid used for the test (water or ethanol).

**10.6**—Date of test and test temperature and relative humidity.

**10.7**—Length, volume, and average cross-sectional area, equivalent diameter, and equivalent circumference for each specimen.

**10.8**—Mean and standard deviation of cross-sectional area, equivalent diameter, and equivalent circumference for each set of test specimens.

**10.9**—Details of specimen conditioning before test.

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

**1** *Scope*

**1.1**—This test method specifies the test requirements for tensile strength, modulus of elasticity, and ultimate elongation of FRP bars used as reinforcing bars or prestressing tendons in concrete.

**2** *Referenced documents*

**2.1** *ASTM standards*—

D 618     Standard Practice for Conditioning Plastics for Testing

D 3916    Standard Test Method for Tensile Properties of Pultruded Glass-Fiber Reinforced Plastic Rod

E 4        Standard Practices for Force Verification of Testing Machines

**3** *Significance and use*

**3.1**—This test method for obtaining the tensile strength, modulus of elasticity, and ultimate strain is intended for use in laboratory tests in which the principal variable is the size or type of FRP bar.

**3.2**—This test method focuses on the FRP bar itself, excluding the performance of the anchorage. Therefore, failure or pullout at an anchoring section should be disregarded, and the test findings should be based solely on test specimens that fail in the test section.

**4** *Terminology*

**4.1** *Test section*—The portion of a specimen between the anchoring sections of the test specimen.

**4.2** *Anchoring section*—The end parts of the specimen where an anchorage is fitted to transmit the loads from the testing machine to the test section.

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

**4.4** *Anchorage*—Device fitted to the anchoring section of a specimen to transmit loads from the testing machine to the test specimen. Refer to Appendix A.

**4.5** *Tensile capacity*—The maximum tensile load carried by test specimen before failure.

**4.6** *Guaranteed tensile capacity*—The average maximum tensile load minus three standard deviations. The tensile capacity which an FRP manufacturer guarantees it will meet.

**4.7** *Ultimate strain*—The change in length per unit length corresponding to the tensile capacity.

**5** *Test equipment and requirements*

**5.1** *Test machine*—Use a testing machine with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading rate or displacement rate control is preferred.

**5.2** *Strain measuring devices*—Extensometers or LVDTs used should be capable of recording specimen elongation during testing with an accuracy of not less than 0.002% of the gauge length.

**5.3** *Gauge section length*—To determine the modulus of elasticity and ultimate strain of the test specimen, the extensometer or LVDT should be mounted in the center of the test section at a distance from the anchorage of at least eight times the diameter of the FRP bar. The extensometer or LVDT should be properly aligned with the direction of tension. The gauge length should not be less than eight times the diameter of the FRP bar, nor less than the characteristic length.

**5.4** *Data acquisition system*—The system should be capable of continuously reading load, strain, and displacement at a minimum rate of two readings per second. The minimum resolutions should be 100 N for load, $10^{-5}$ for strain, and 0.001 mm for displacement.

**6** *Specimen preparation*

**6.1**—Specimens should be representative of the lot or batch being tested. For grid-type FRP specimens, linear test specimens may be prepared by cutting away extraneous material in such a way as not to affect the performance of the part to be used. Leaving a 2 mm projection of the cross bars

is recommended. In the gauge length of the specimen, no post-production machining, abrading, or other such processing is permitted. Such processing may be used in the anchoring sections to promote bond of the rod to the anchoring device.

**6.2**—During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other factors possibly causing changes to the material properties of the specimen should be avoided.

**6.3**—The length of the specimen should be the sum of the length of the test section and the lengths of the anchoring sections. The length of the test section should not be less than 100 mm, nor should it be less than 40 times the diameter of the FRP bar. For FRP bars in twisted strand form, the length should also be greater than two times the strand pitch.

**6.4**—The number of test specimens should not be less than five. If the specimen fails at or slips out of an anchoring section, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Conditioning according to Procedure A of ASTM D 618 is recommended. Store and test specimens at the standard laboratory atmosphere (23 ± 3 °C and 50 ± 10% relative humidity).

**8** *Test method*

**8.1**—When mounting the specimen on the testing machine, care should be taken to ensure that the longitudinal axis of the specimen coincides with the line joining the two anchorages fitted to the testing machine.

**8.2**—The data acquisition system should be started a few seconds before starting the loading. The rate of loading (displacement rate or load rate) should be constant during a test, and should be such that the specimen fails in 1 to 10 min.

**8.3**—The load should be increased until tensile failure occurs. Strain measurements should be recorded until the load reaches at least 50% of the tensile capacity or the guaranteed tensile capacity, whichever is higher.

**9** *Calculations*

**9.1**—A load (stress)-strain curve should be generated from the load (stress) and strain measurements recorded from the extensometer or strain gauge readings.

**9.2**—The tensile strength should be calculated according to Eq. (1), with a precision to three significant digits.

$$f_u = F_u/A \qquad (1)$$

where
$f_u$ = tensile strength, MPa;
$F_u$ = tensile capacity, N; and
$A$ = cross-sectional area of specimen, mm$^2$.

Note: The cross-sectional area $A$ is as defined in Test Method B.1. For use in design guides, the load from the test may be divided by the area of standard reinforcing steel of the same nominal diameter. The test report should indicate whether the actual area or standard area is used.

**9.3**—The tensile modulus of elasticity should be taken as a linear regression of the data points from 20 to 50% of the tensile strength of the bar. It may be calculated from the differ-

ence between the load (stress)-strain curve values at 20 and 50% of the tensile capacity, according to Eq. (2), with a precision to three significant digits, provided that the load (stress)-strain curve is linear during this load range. For FRP bars where a guaranteed tensile capacity is given, the values at 20 and 50% of the guaranteed tensile capacity may be used.

$$E_L = \frac{F_1 - F_2}{(\varepsilon_1 - \varepsilon_2)A} \qquad (2)$$

where
$E_L$ = axial (longitudinal) modulus of elasticity, MPa;
$A$ = cross-sectional area, mm$^2$;
$F_1$ and $\varepsilon_1$ = load and corresponding strain, respectively, at approximately 50% of the ultimate tensile capacity or guaranteed tensile capacity, N and dimensionless, respectively; and
$F_2$ and $\varepsilon_2$ = load and corresponding strain, respectively, at approximately 20% of the ultimate tensile capacity or guaranteed tensile capacity, N and dimensionless, respectively.

**9.5**—Ultimate strain should be the strain corresponding to the ultimate tensile capacity when the strain-gauge measurements of the specimen are available up to failure. If extensometer or strain-gauge measurements are not available up to failure, the ultimate strain should be calculated from the ultimate tensile capacity and modulus of elasticity according to Eq. (3), with a precision to three significant figures.

$$\varepsilon_u = \frac{F_u}{E_L A} \qquad (3)$$

where $\varepsilon_u$ = ultimate strain of FRP bar, dimensionless.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer, and volume ratio of fiber.

**10.3**—Numbers or identification marks of test specimens date of test, test temperature, and loading rate.

**10.4**—Designation, equivalent diameter, and cross-sectional area as determined according to Test Method B.1.

**10.5**—A brief description of the anchorage device, drawings or photographs of the anchorage device describing dimensions, and materials used.

**10.6**—Details of specimen conditioning including: environment, temperature, humidity, and duration.

**10.7**—Ultimate tensile capacity for each test specimen, means and standard deviations for ultimate tensile capacity, and tensile strength.

**10.8**—Tensile modulus of elasticity for each test specimen, and means and standard deviations.

**10.9**—Ultimate strain for each test specimen, means, and standard deviations, if measured.

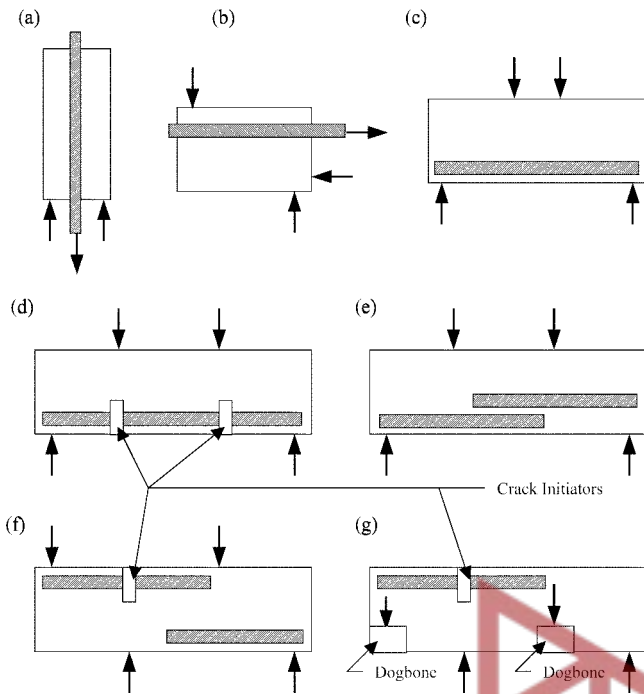**10.10**—Stress (load)-strain curve for each test specimen.

Fig. B.3.1—*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).*
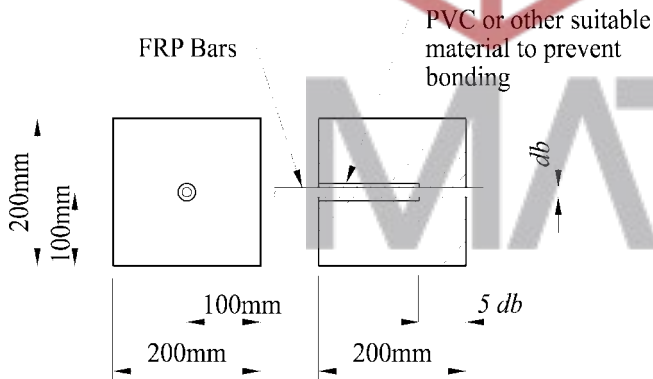


Fig. B.3.2—*Vertical bond test specimen.*

**10.11**—A brief description, with photographs and sketches if necessary, of the post-failure appearance of each specimen. Report anomalous failure modes observed during testing or anomalous post-failure appearances of any specimens.

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

**1** *Scope*

**1.1**—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.

**1.2**—Various types of test methods are available for the determination of different bond values of FRP reinforcement in concrete structures, as shown schematically in Fig. B.3.1.
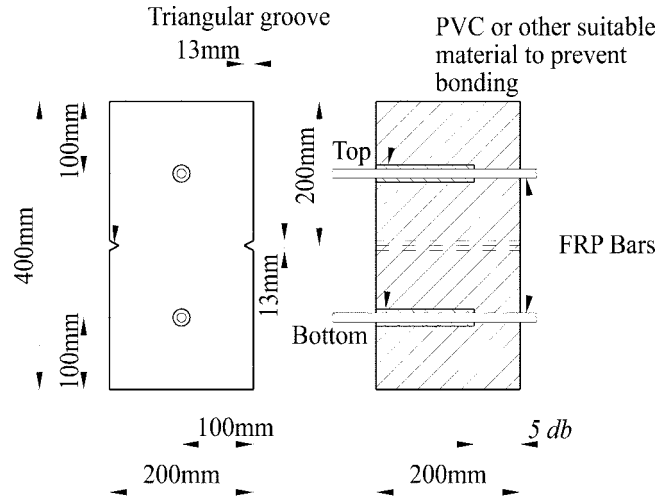


Fig. B.3.3—*Horizontal bond test.*

This test method describes the pullout test specimen to determine the bond strength.

**1.3**—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.3.2). 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.3.3).

**2** *Referenced documents*

**2.1** *ASTM standards—*

A 944    Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens

C 39    Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C 143    Standard Test Method for Slump of Hydraulic Cement Concrete

C 192    Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

C 293    Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)

C 511    Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concrete

C 617    Standard Practice for Capping Cylindrical Concrete Specimens

D 618    Standard Practice for Conditioning Plastics for Testing

E 4    Standard Practices for Force Verification of Testing Machines.

**3** *Significance and use*

**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.

**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 be considered in the use of FRP bars as reinforcing bars or tendons.

**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.

**4** *Terminology*

**4.1 *Bonded length*—**The length of the test rod that is in contact with concrete.

**5** *Test equipment and requirements*

**5.1**—Use a testing machine with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading-rate or displacement-rate control is preferred. The load should be applied to the reinforcement bar at a rate not greater than 20 kN/min or at the no-load speed of the testing machine head of not greater than 1.3 mm/min, depending on the type of testing machine used and the means provided for ascertaining or controlling testing speed.

**5.2**—The loading plate (Fig. B.3.4) 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.

**5.3**—The loading end of the FRP bar should be fitted with an anchor capable of transmitting loads until the rod 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.

**5.4**—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.3.5).

**5.5**—Two types of molds for bond test specimens will be required: for 200 mm concrete cubes, each containing a vertically embedded bar, and 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.

**6** *Specimen preparation*

**6.1**—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 (refer to Appendix A) at one end. The test specimens should contain



1. LVDT
2. Free end of FRP bar
3. Concrete cylinder
4. Loading plate
5. Spherical seat
6. Moving head of testing machine
7. Loaded end of FRP bar
8. FRP bar
9. Stationary head of testing machine
10. Anchor (See Appendix A)
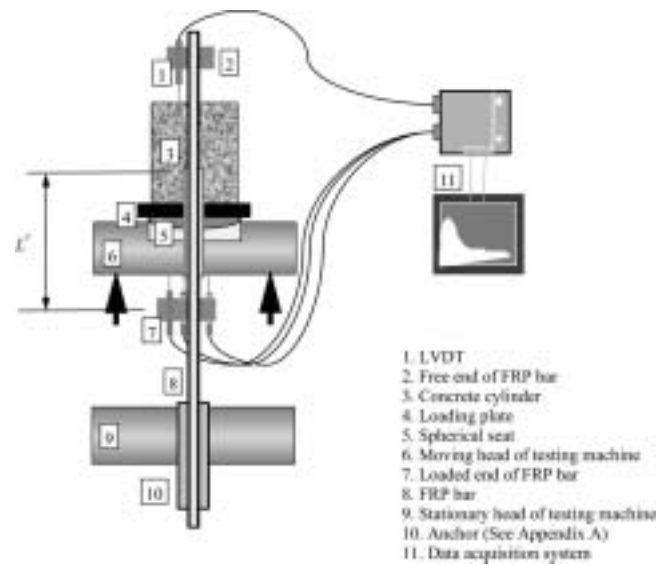11. Data acquisition system

*Fig. B.3.4—Schematic details of pullout bond test setup.*
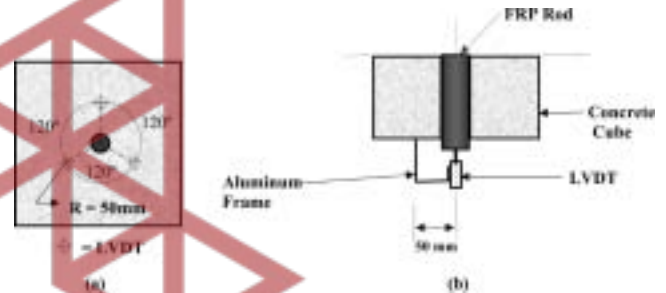


*Fig. B.3.5—Positions of LVDTs at surface of concrete cube: (a) plan view of three LVDTs at loaded end; and (b) one LVDT at free end.*

either one FRP bar embedded perpendicularly to the direction of casting of the concrete (Fig. B.3.2), or two FRP bars embedded parallel to the casting of the concrete (Fig. B.3.3). 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.

**6.1.1** *Specimens for perpendicularly embedded bar (Fig. B.3.2)*—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 failure of concrete occurs, a 300 mm cube is required and new tests should be performed.

**6.1.2** *Specimens for parallel embedded bar (Fig. B.3.3)*—These specimens should consist of concrete prisms 200 x 200 x 400 mm, with the longer axes in the vertical direction. Two bars should be embedded 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 from the bottom of the prism

and the other with its axis 300 mm 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 load. A triangular groove should be formed on each of the two opposite sides of the prism parallel to the bars and at the midheight of the prism. These grooves should be at least 13 mm deep, measured perpendicular to the surface of the concrete. The grooves should facilitate breaking of the prism into two test specimens at the weakened plane before performing the bond tests.

The bonded length of the FRP bar should be five times the diameter of the FRP bar. If the bonded length, as defined previously, does not represent the bonding characteristics of the FRP bar, the bonded length may be extended as appropriate. Outside of the bonded section, the embedded bar should be sheathed with polyvinyl chloride (PVC) or other suitable material to prevent bonding. At the free end, bars should protrude from the concrete slightly so that the end of the LVDT(s) will bear on the bar (Fig. B.3.5).

**6.2**—The bars shall be placed into the molds as follows:

**6.2.1**—The opening in the form through which the FRP bar is inserted should be sealed using oil, putty, or similar materials to prevent ingress of water and other substances.

**6.2.2**—The orientation of the specimen should not be changed until the form is removed.

**6.3**—Before casting the test specimens, coat the inside surface of the molds with a thin film of mineral oil, petroleum jelly, or stearic acid paste. The following procedures are recommended for placement of concrete in the molds unless another well-established method is used:

**6.3.1**—For 200 x 200 x 400 mm prisms, place the concrete in four layers of approximately equal thickness and rod each layer 25 times with a 16 mm-diameter tamping rod.

**6.3.2**—For 200 mm cubes, place the concrete in four layers of approximately equal thickness and rod each layer 25 times with a 16 mm-diameter tamping bar.

**6.3.3**—After the top layer has been consolidated, strike off the surface with a trowel and protect against moisture evaporation by one of the acceptable methods described in Paragraph 7.1 of ASTM C 192. Care should be taken that evaporation does not take place in the area adjacent to the protruding FRP bar for vertically cast specimens.

**6.4**—The concrete should be a standard mixture, with coarse aggregates having a maximum dimension of 20 to 25 mm. It should be batched and mixed in accordance with the applicable portions of ASTM C 192. The concrete should have slump of $100 \pm 20$ mm in accordance with ASTM C 143, and the compressive strength at 28 days should be $30 \pm 3$ MPa in accordance with ASTM C 39. A minimum of five standard 150 x 300 mm or 100 x 200 mm control cylinders should be made for determining compressive strength from each batch of concrete.

**6.5**—Molds should not be removed from the specimens earlier than 20 h 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 ASTM C 192 until the time of testing. Specimens should be tested at an age of 28 days.

**6.6**—When the specimens are between 7 and 14 days old, the 200 x 200 x 400 mm prisms should be broken in half in flexure to form two 200 mm cubes. Specimens should be broken as simple beams with center-point loading in accordance with ASTM C 293. The two triangular grooves in the upper and lower faces of the prisms should be located at midspan. The load should be applied to a 19 mm-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.

**6.7**—The surface of the 200 mm cube containing the vertically embedded bar should be capped so as to utilize it as the bearing surface in the pullout test. The applicable portions of ASTM C 617, relative to capping materials and procedures, should be followed.

**7** *Conditioning*

**7.1**—Unless a different testing environment is specified, the pullout tests should be conducted at the standard laboratory atmosphere ($23 \pm 3$ °C and $50 \pm 10\%$ relative humidity).

**7.2**—Preconditioning of FRP bar specimens before casting in concrete, such as post-production machining, abrading, or other such processing, is permitted but should be reported.

**8** *Test method*

**8.1**—The specimen should be mounted in the testing machine in one of the following two test setups:

**8.1.1**—The capped or bearing surface of the cube from which the long end of the bar projects should be in contact with the bearing block (or plaster pad) assembly. The spherically seated bearing block should rest on a support that transfers the reaction from this block to the load cell of the testing machine. The projecting FRP bar should extend through the bearing block assembly and the support, and the anchor should be gripped for tension by the jaws of the testing machine (Fig. B.3.4). The free end of the bar may also be potted in an anchor as described in Appendix A.

**8.1.2**—The concrete cube should be fixed on the stationary head of the testing machine. LVDTs at the loaded end and free end are attached to measure the slips of the FRP bar, as shown in Fig. B.3.5. The anchor is then threaded or gripped by the moving head of the testing machine.

**8.2**—Assemble the testing apparatus on the specimen. Carefully measure and record, to the nearest 0.5 mm, the distance between the top surface of the bonded length and the point of attachment of the measuring device on the FRP bar. The elongation of the FRP bar over this distance may be calculated and subtracted from the measured slip plus elongation to obtain the loaded-end slip. Moreover, free-end slip shall be measured to the nearest 0.5 mm.

**8.3**—Apply load to the FRP bar at a load rate no greater than 20 kN/min, or at a testing machine head speed not greater than 1.3 mm/min.

**8.4**—Read and record the applied load and the LVDT readings at a sufficient number of intervals throughout the test to provide at least 15 readings by the time a slip of 0.25 mm has occurred at the loaded end of the FRP bar. The slippage

of the free end should be recorded in increments of 0.01 mm, together with the corresponding applied load.

**8.5**—Continue the loading and readings at appropriate intervals until rupture of the FRP bar occurs, the enclosing concrete splits, or slippage of at least 2.5 mm occurs at the loaded end of the embedded length.

**8.6**—In cases where a specimen is judged to have undergone a tensile failure at an anchoring section, to have slipped out of an anchoring section before the FRP bar has slipped from the concrete, or where the load 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.

**9** *Calculations*

**9.1**—The average bond stress should be calculated according to Eq. (1) and reported with a precision to three significant digits, and the curves for the pullout or bond stress versus slippage at both free-end and loaded-end displacement for each specimen should be plotted.

$$\tau = \frac{F}{C_b \cdot l} \qquad (1)$$

where
$\tau$ = average bond stress, MPa;
$F$ = tensile load, N;
$C_b$ = equivalent circumference of FRP bar, mm; and
$l$ = bonded length, mm.

**9.2**—Average bond stresses causing slippage at the free end and the loaded end of 0.05, 0.10, and 0.25 mm, and the maximum bond stress (the bond strength) at failure, should be calculated.

**9.3**—At each load level, the slip at the loaded end should be calculated as the average of the readings of the LVDTs, 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 device on the FRP bar, the latter being calculated as follows

$$S_c = \frac{FL_c}{E_L A} \qquad (2)$$

where
$S_c$ = elastic elongation, mm;
$F$ = tensile load, N;
$L_c$ = length from the top of the embedded bar to the point of the attachment of the measuring device (Fig. B.3.4), mm;
$E_L$ = longitudinal modulus of elasticity of FRP bar, MPa; and
$A$ = cross-sectional area, mm$^2$.

**10** *Report*

The test report should include the following items:

**10.1** *Properties of the concrete—*

**10.1.1**—The mixture proportions of cement, fine aggregate, coarse aggregate, admixture (if any used), and the *w/c*.

**10.1.2**—Slump of freshly mixed concrete as determined in accordance with ASTM C 143.

**10.1.3**—Twenty-eight day strength of control cylinders as determined in accordance with ASTM C 39.

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

**10.2** *Properties of the FRP bar—*

**10.2.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2.2**—Type of fiber and fiber binding material, as reported by the manufacturer, fiber volume fraction, surface treatment, and preconditioning of FRP bar.

**10.2.3**—Designation, equivalent diameter, and cross-sectional area, as determined according to Test Method B.1.

**10.2.4**—Modulus of elasticity and ultimate tensile strength, as determined in accordance with Test Method B.2.

**10.2.5**—A close-up photograph of the rods showing surface deformations and characteristics.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Date of test, test temperature, and loading rate.

**10.5**—Dimensions of test specimens, bonded length of FRP bar.

**10.6**—A brief description of the gripping device.

**10.7**—Average bond stress causing slippage at the free end of 0.05, 0.10, and 0.25 mm for each specimen.

**10.8**—Average bond stress causing slippage at the loaded end at intervals of values from 0 to 0.25 mm for each test specimen.

**10.9**—Maximum bond stress, failure mode, and averages for each test specimen.

**10.10**—Bond stress-slippage displacement (free-end and loaded-end) curves for each test specimen.

## B.4—Test method for transverse shear strength of FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for FRP round bars used as reinforcing bars or prestressing tendons in concrete for determining the transverse shear (dowel) strength by direct application of double shear.

**2** *Referenced documents*

**2.1** *ASTM standards—*

D 618    Standard Practice for Conditioning Plastics for Testing

E 4    Standard Practices for Force Verification of Testing Machines

**3** *Significance and use*

**3.1**—This test method for transverse shear strength is intended for use in laboratory tests in which the principal variable is the size or type of FRP round bars. This test method establishes values of shear strength for material specifications, quality control, quality assurance, research and development, and may also be used for structural design purposes.

**3.2**—The transverse shear strength should be measured according to the method given herein, in keeping with the intended purposes.

**4** *Terminology*

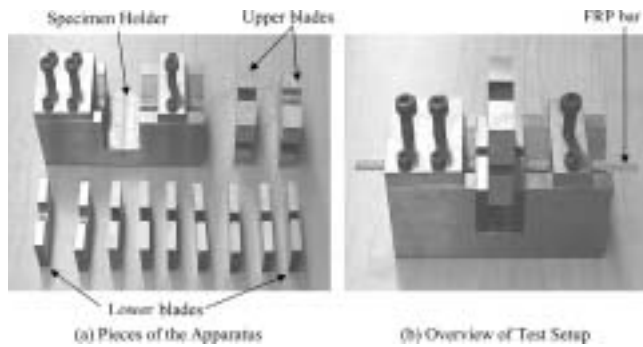**4.1**—No new terminology introduced.

*Fig. B.4.1—Double shear testing devices: (a) pieces of apparatus; and (b) overview of test setup.*
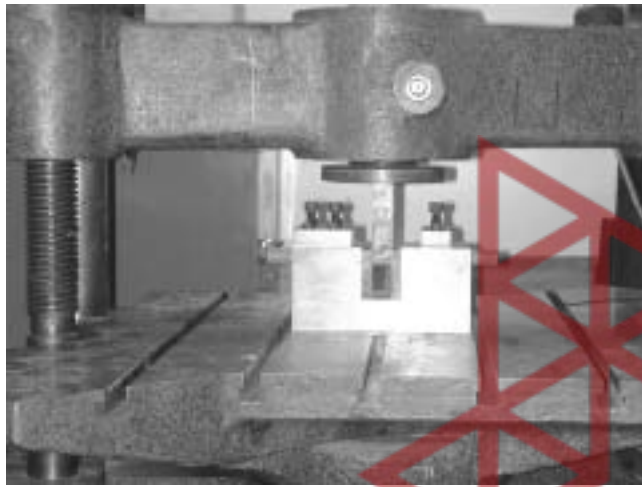


*Fig. B.4.2—Test setup.*

**5** *Test equipment and requirements*

**5.1**—Use a testing machine with a loading capacity in excess of the shear capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading-rate or displacement-rate control is preferred. The testing machine should also be capable of giving readings of loading accurate to within 1% throughout the test.

**5.2**—Figures B.4.1 and B.4.2 show a typical test setup. It consists of sample holder, one upper blade, and two lower blades. The sample holder is 230 mm long x 100 mm wide x 110 mm high, and has a longitudinal V-shape cut for placing FRP samples and a rectangle cut for holding upper and lower blades in the center of its top part. Detailed dimensions of the fixture and its components are given in Fig. B.4.3(a) through (e). There are several sets of blades with different sizes of half-ring cuts for different diameters of FRP bars.

**5.3**—The shear testing apparatus should be made of steel (mild, nonhardened steel is acceptable) and constructed so that a rod-shaped specimen is sheared on two planes simultaneously by the blades (edges) converging along faces perpendicular to the axis of the test specimen. The sum of the two gaps between the one upper blade and two lower blades should be less than 0.25 mm. Faces of the blades should be ground and polished to reduce friction during the test. A light coat of machine oil may be used on the faces of the blades to reduce friction.

**6** *Specimen preparation*

**6.1**—Test specimens should be representative of the lot or batch being tested and, as a rule, should not be subjected to any processing.

**6.2**—During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions possibly causing changes to material properties of the test specimen should be avoided.

**6.3**—Test specimens should be 300 mm long, regardless of the diameters of the FRP bars.

**6.4**—The number of test specimens should not be less than five.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Condition specimens in accordance with Procedure A of ASTM D 618; store and test at the standard laboratory atmosphere ($23 \pm 3$ °C and $50 \pm 10\%$ relative humidity), unless a different environment is specified as part of the experiment.

**8** *Test method*

**8.1**—The specimen should be mounted in the center of the shear apparatus, touching the upper loading device. No gap should be visible between the contact surface of the loading device and the test specimen.

**8.2**—The specified loading rate should be such that the shearing stress increases at a rate of 30 to 60 MPa per min. Load should be applied uniformly without subjecting the specimen to shock.

**8.3**—Loading should be continued until the specimen fails. The failure load should be recorded with a precision to three significant digits. Loading may decrease temporarily due to the presence of two rupture faces.

**9** *Calculations*

**9.1**—Failure, whether it is due to shear or not, should be determined by visual inspection.

**9.2**—Shear strength should be calculated according to Eq. (1), with a precision to three significant digits

$$\tau_u = \frac{P_s}{2A} \qquad (1)$$

where
$\tau_u$ = shear strength, MPa;
$P_s$ = maximum failure load, N; and
$A$ = cross-sectional area of specimen, mm$^2$.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer and fiber volume fraction.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Designation, diameter, and cross-sectional area.

**10.5**—Conditioning of specimens before testing.

**10.6**—Date of test, test temperature, and loading rate.

**10.7**—Maximum failure load for each test specimen, average of maximum failure loads and shear strength.
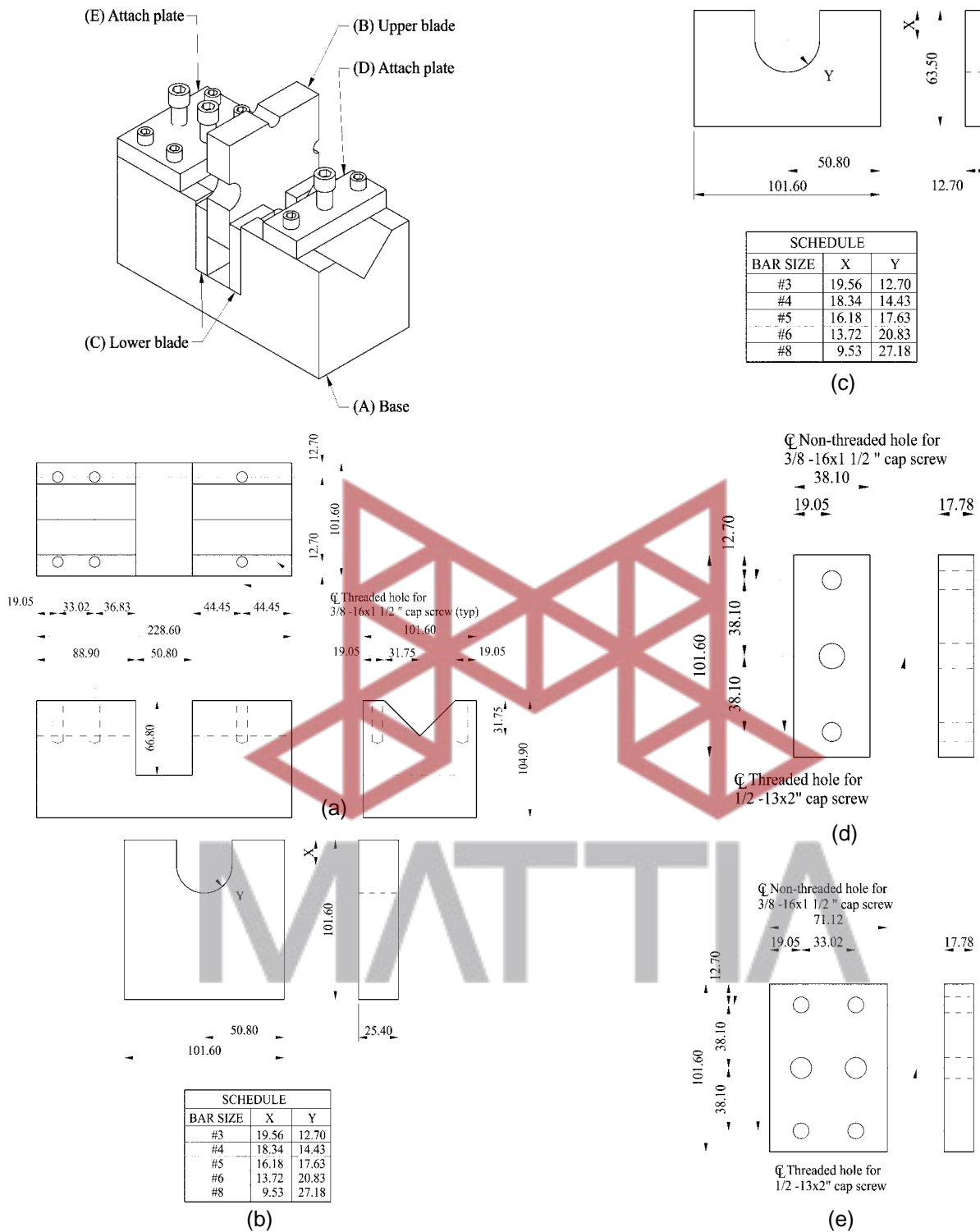
*Fig. B.4.3—Detailed drawings of double shear testing devices (full assembly upper left): (a) base; (b) upper blade; (c) lower blade; (d) attach plate; and (e) attach plate (in mm).*

**10.8**—Failure mode of each test specimen. Failure modes are generally described as being shear, fiber debonding, or a combination of both. Typical specimens that have failed in the shearing mode are shown in Fig. B.4.4.

**B.5—Test method for strength of FRP bent bars and stirrups at bend locations**

**1** *Scope*

**1.1**—This test method specifies the test requirements for strength capacity of FRP bent bars used as an anchorage for stirrups in concrete structures.

**2** *Referenced documents*

**2.1** *ASTM standards—*

C 39    Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

Fig. B.4.4—Test specimen: (a) before test; and (b) after test.



Fig. B.5.1—Configuration of specimen.

C 143 Standard Test Method for Slump of Hydraulic Cement Concrete

C 192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

E 4 Standard Practices for Force Verification of Testing Machines

### 3 Significance and use

**3.1**—This test method is intended for use in laboratory tests to determine the strength capacity of the bent portion provided as an anchorage in which the principal variable is the size, bend radius, or type of FRP stirrup.

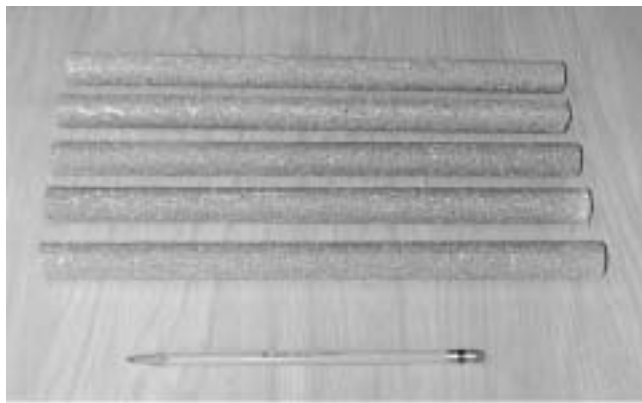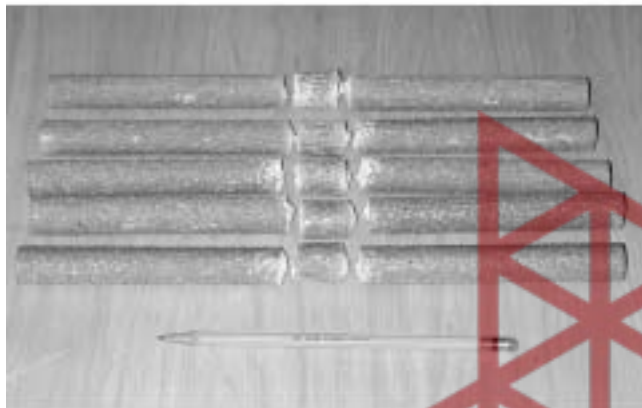**3.2**—Bending of FRP stirrups to develop anchorage leads to a significant reduction in the strength capacity of the stirrups. The bend radius and tail length beyond the bend are important factors affecting the bend capacity.

**3.3**—This test method measures the ultimate load capacity of a single FRP stirrup subjected to tensile forces in the direction of the straight portion.

**3.4**—This test method is intended to determine the bend capacity and strength reduction for material specifications, research and development, quality assurance, and structural design and analysis. The behavior of bent bars and stirrups should be measured according to the method given herein, in keeping with the intended purposes.
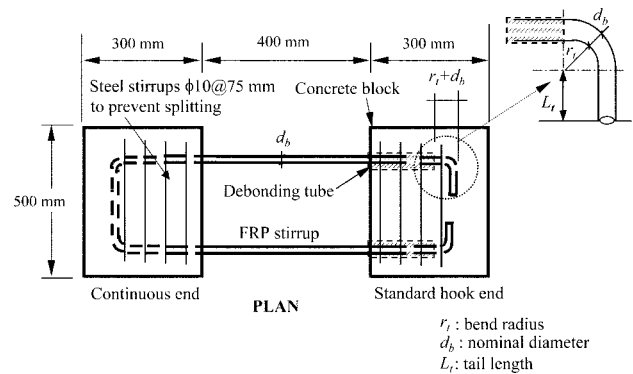
### 4 Terminology

**4.1 Bend capacity**—Ultimate tensile stress that can be carried by the FRP stirrup provided that failure occurred at the bend.

**4.2 Tensile strength**—Ultimate tensile strength of FRP bars in the direction parallel to the fibers.

**4.3 Bend radius**—Inside radius of the bend, as illustrated in Fig. B.5.1.

**4.4 Tail length**—The length provided beyond the bend portion, as illustrated in Fig. B.5.1.

**4.5 Equivalent bar diameter**—The equivalent bar diameter is determined based on the cross-sectional area of the FRP bar (refer to Test Method B.1).

### 5 Test equipment and requirements

**5.1**—The hydraulic cylinder and load cell should be calibrated according to ASTM Practices E 4, have a loading capacity in excess of the capacity of the specimen, and be capable of applying load at the required loading rate. The load cell should also be capable of giving readings of loading accurate to within 1% throughout the test.

### 6 Specimen preparation

**6.1**—The configuration of a typical specimen is shown in Fig. B.5.1. The dimensions of each concrete block used to anchor the FRP stirrup may be varied according to the dimensions of the stirrup used. The free length of the stirrup between the two blocks, however, should not be less than 200 mm (400 mm is suggested). The concrete block should be reinforced using steel stirrups, as shown in Fig. B.5.1, to prevent splitting of the concrete block before rupture of the stirrup at the bend. The dimensions of the stirrups might be variable, therefore, the tail length $l_t$ of the FRP stirrup tested to evaluate the bend capacity should not exceed 150 mm. The debonding tube is used to eliminate the straight-bar development of the hooked bar. The debonding tube should slip fit over the reinforcing bar. Fill the ends of the debonding tube with caulk to prevent the tubes from filling with concrete during casting.

**6.2**—The concrete should be a standard mixture, with coarse aggregates having a maximum dimension of 20 to 25 mm. It should be batched and mixed in accordance with the applicable portions of ASTM C 192. The concrete should have slump of 100 ± 20 mm in accordance with ASTM C 143, and the compressive strength at 28 days should be 30 ± 3 MPa in accordance with ASTM C 39. A minimum of five

standard 150 x 300 mm or 100 x 200 mm control cylinders should be made for determining compressive strength from each batch of concrete.

**6.3**—The number of test specimens for each test condition should not be less than five. If a specimen fails by splitting of the concrete block, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

**6.4**—If test specimens fail due to pullout of the bent bar from the concrete, this is an indication that the bend radius and tail length are inadequate for the bar being tested. It will be necessary to adjust these parameters, and perhaps the size of the test blocks as well, and retest.

**7** *Conditioning*

**7.1**—Unless a different testing environment is specified as part of the experiment, the tests should be conducted at the standard laboratory atmosphere (23 ± 3 °C and 50 ± 10% relative humidity).

**7.2**—Preconditioning of FRP bars before casting in concrete is permissible but must be reported.

**8** *Test method*

**8.1**—The test setup, shown in Fig. B.5.2, consists of a hydraulic jack to apply the relative displacement between the two concrete blocks and a load cell to measure the applied load. Steel plates and plaster bags should be placed in front of the load cell and the hydraulic jack to distribute the applied load to the surface of the concrete. A spherical washer may also be used at the end of the ram. The two blocks should be placed on top of steel rollers to minimize the friction forces between the blocks and testing bed.

**8.2**—Tensile strength of straight FRP bars with the same diameter as the FRP stirrups should be evaluated according to Test Method B.2.

**8.3**—The test specimens should not be subjected to any shock, vibration, or torsion during the test. Increase the force in the jack in a smooth, continuous manner until the specimen fails. Do not pause the application of load during the test. The loading rate should be selected so that the specimen fails at a time of between 1 and 10 min from the start of the test.

**8.4**—Record the failure load and failure mode for the specimen.

**9** *Calculations*

**9.1**—The bend capacity of the FRP stirrup should only be assessed on the basis of the specimen undergoing failure at the bend. In cases where block splitting has clearly taken place, the data should be disregarded, and additional tests should be performed until the number of the test specimens failing at the bend is not less than five.

**9.2**—The bend capacity of the FRP stirrup should be calculated according to Eq. (1), and rounded to three significant digits

$$f_{ub} = \frac{F_{ub}}{2A} \qquad (1)$$

where

$f_{ub}$ = bend capacity of the FRP stirrup, MPa;
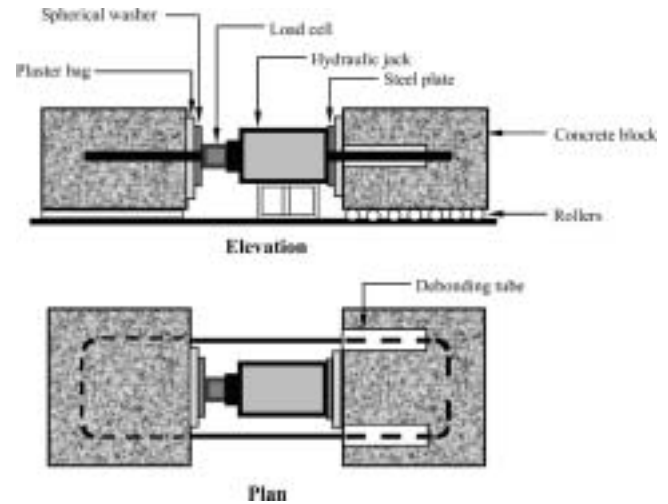


*Fig. B.5.2—Test setup.*

$F_{ub}$ = ultimate load capacity according to bend tests, N; and
$A$ = cross-sectional area of single leg of the FRP stirrup, $mm^2$.

**9.3**—The strength-reduction factor is calculated according to Eq. (2)

$$\chi = \frac{f_{ub}}{f_u} \qquad (2)$$

where

$\chi$ = strength-reduction factor due to bend effect; and
$f_u$ = ultimate tensile strength parallel to the fibers determined according to Test Method B.2 (MPa).

**10** *Report*

The test report should include the following items:

**10.1** *Properties of concrete—*

**10.1.1**—The mixture proportions of cement, fine aggregate, coarse aggregate, admixture (if any used), and the *w/c* ratio.

**10.1.2**—Slump of freshly mixed concrete as determined in accordance with ASTM C 143.

**10.1.3**—Twenty-eight day strength of control cylinders as determined in accordance with ASTM C 39.

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

**10.2**—Trade name, shape, and date of manufacture, if available, and lot number of FRP bar tested for stirrups.

**10.3**—Type of fiber and matrix used in the FRP stirrup, and fiber volume fraction.

**10.4**—Process used to fabricate the stirrups, as reported by the manufacturer.

**10.5**—Numbers or identification marks of test stirrups.

**10.6**—Designation, diameter, and cross-sectional area.

**10.7**—Dimensions of concrete block, configuration (diameter and space) of steel stirrup confinement, debonded length, bend radius, and tail length of the bent bar.

**10.8**—Preconditioning of FRP bars before casting.

**10.9**—Date of test and test temperature.

**10.10**—Type and capacity of load cell.

**10.11**—Bend capacity and strength-reduction factor for each test stirrup.

**10.12**—Average bend capacity and strength-reduction factor for all specimens that failed at the bend as intended.

## B.6—Accelerated test method for alkali resistance of FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for evaluating alkali resistance of FRP bars used as reinforcing bars in concrete by immersion in aqueous alkaline solution. Alkali resistance is measured by subjecting the FRP bars to an alkali environment, with or without stress, and then testing them in tension according to Test Method B.2.

**1.2**—This test method presents three procedures conducted at a temperature of 60 °C, each defining different loading conditions.

**1.2.1** *Procedure A*—A system in which FRP specimens are immersed in the alkaline solution with no tensile load applied. The test control parameters are the pH value and temperature of the alkaline solution and immersion time.

**1.2.2** *Procedure B*—A system in which FRP specimens are immersed in the alkaline solution under sustained tensile load. The test parameters are the sustained load level, the pH value, and temperature of the alkaline solution and immersion time.

**1.2.3** *Procedure C*—A system in which FRP specimens, surrounded by moist concrete, are subjected to a sustained tensile load. The test parameters are the sustained load level, the pH value, and temperature of concrete and embedded time.

**2** *Referenced documents*

**2.1** *ASTM standards—*

C 192    Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

C 511    Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concrete

D 618    Standard Practice for Conditioning Plastics for Testing

D 5229M Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

**3** *Significance and use*

**3.1**—This test method for investigating the alkali resistance of FRP bars is intended for use in laboratory tests in which the principal variables are the temperature and concentration of alkaline solution, the type of FRP bars, and the sustained load level.

**3.2**—This test method measures the mass change and tensile capacity after immersion of FRP bars in alkaline solution without stressing (Procedure A), and the tensile capacity after immersion of FRP bars in an alkaline solution and embedment of FRP bars in moist concrete under sustained load condition (Procedures B and C).

**3.3**—This test method is intended to determine the alkaline-resistant data for material specifications, research and development, quality assurance, and structural design and analysis. The alkaline resistance should be measured according to the method given herein. The primary test result is the mass change and tensile capacity retention of the test specimen, which are important factors to be considered in the use of FRP bars.

**3.4**—The level of sustained loading (for Procedures B and C) is not specified as part of the test method. Typically, the stress in the sustained load tests should be equal to the stress caused by the dead loads, and any part of the live loads that is sustained. If service load conditions are not known, the sustained tensile stress in glass FRP bars should be set to induce a tensile strain equal to 2000 microstrain. Higher levels of sustained stress can be used as an accelerating condition. The level of sustained stress should be reported.

**4** *Terminology*

**4.1**—No new terminology introduced.

**5** *Test equipment and requirements*

**5.1** *Balance*—An analytical balance capable of the appropriate accuracy in accordance with Procedure A of ASTM D 618.

**5.2**—The testing machine and devices should be used in accordance with Test Method B.2.

**6** *Specimen preparation*

**6.1**—FRP bar specimens should be representative of the lot or batch being tested. In general, test specimens should not be subjected to any processing beyond manufacturing. For grid-type FRP bars, linear test specimens may be prepared by cutting away extraneous material in such a way as not to affect the performance of the tested part.

**6.2**—During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions possibly causing changes to material properties of the specimen should be avoided.

**6.3**—The length of the specimen should be the sum of the length of the test section and the lengths of the anchoring sections. The length of the test section should not be less than 40 times the diameter of the FRP bar. For FRP bar in twisted strand form, the length should also be greater than two times the strand pitch.

**6.4**—The number of test specimens for pre- and post-immersion testing should not be less than five. Each specimen should be clearly labeled with identifying markings.

**6.5**—Coat the ends of bars and the ends and transverse elements of grids with epoxy resin to prevent the infiltration of solution via these cuts. Allow resin to cure completely before immersion.

**6.6**—The alkaline solution in Procedures A and B should be a composition representative of the porewater inside portland-cement concrete. The suggested composition of alkaline solution consists of 118.5 g of $Ca(OH)_2$, 0.9 g of NaOH, and 4.2 g of KOH in 1 L of deionized water. The solution should have a pH value of 12.6 to 13, a representative pH value of mature concrete pore solution. The alkaline solution should be covered before and during test to prevent interaction with atmospheric $CO_2$ and to prevent evaporation.

**7** *Conditioning*

**7.1**—Samples for Procedure A should be immersed in the alkaline solution at 60 ± 3 °C for exposure times of 1, 2, 3, 4, and 6 months, unless longer exposure periods are

specified. After the allotted times, the samples should be removed from the alkaline solution, thoroughly washed in deionized water, towel dried, weighed, and tested in tension to failure.

**7.2**—Samples for Procedure B should be installed in anchoring devices at both ends in accordance with Appendix A. The test section of the specimen should be immersed in the alkaline solution inside an environmental cabinet or container holding the alkaline solutions and having a constant temperature of 60 ± 3 °C. The specimen should be held in a loading fixture to subject to a constant tensile sustained load for exposure times of 1, 2, 3, 4, and 6 months, unless longer exposure periods are specified.

**7.3**—Samples for Procedure C should be performed by embedding the test section of the specimens in a moist concrete. Typical dimensions of the concrete cylinder are shown in Fig. B.6.1. The 150 mm dimension of the specimens may be increased if larger-diameter bars are used. The concrete should be a standard mixture, specified in Test Method B.3. The concrete mixture should be batched and mixed in accordance with the applicable portions of ASTM C 192, and the curing procedure should conform to the ASTM C 511. After 28 days of curing in water, the samples should have installed anchors at both their ends in accordance with Appendix A, and then positioned in the conditioning fixture for subjecting to a sustained tensile load for exposure times of 1, 2, 3, 4, and 6 months, unless longer exposure periods are specified. The concrete cylinder should be kept moist and inside an environmental cabinet having a constant temperature of 60 ± 3 °C during the testing. The FRP specimens should be tested with the concrete cylinder still attached.

**8** *Test method*

**8.1**—The pH value of the alkaline solution should be measured at the beginning of the test and after the alkali-resistance test. During immersion of the test specimens, the pH value of the alkaline solution should be monitored at least every 5 days and adjusted, if necessary, to keep the same constituents and pH value as the beginning of the test.

**8.2**—The external appearance of the specimen should be examined before and after the alkali resistance test for comparison of color, surface condition, and change of shape. If necessary, the specimen may be sectioned and polished, and the condition of the cross section examined under a microscope.

**8.3** *Mass change testing of specimens for Procedure A*— Before immersion, the specimen should be dried until its mass is unchanged, according to Procedure D of ASTM D 5229/D 5229M (this is the initial mass $W_0$). After immersion for the prescribed period of time, the specimen should be removed from the alkaline solution, quickly washed with deionized water, dried with tissue paper, and then immediately weighed (this is the mass at Time 1, denoted as $W_1$). Then the specimen should have anchors installed at both ends for tensile capacity retention testing.

**8.4** *Tensile capacity retention testing of specimens for Procedures A, B, and C*—Specimens should be tested in tension to failure within 24 h after removal from the condi-
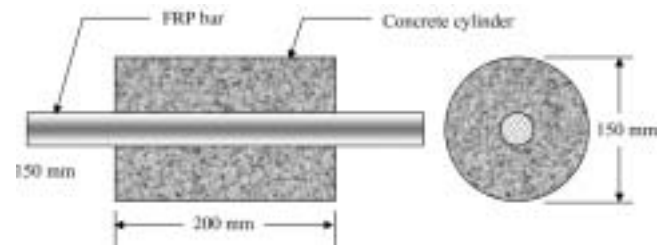


*Fig. B.6.1—Dimensions of concrete cylinder.*

tioning environment at the prescribed exposure length of time. The tensile test method should follow Test Method B.2.

**9** *Calculations*

**9.1**—The mass change of FRP bars should be calculated according to Eq. (1) and (2).

$$\text{Mass gain (\%)} = \frac{W_1 - W_0}{W_0} \times 100 \qquad (1)$$

$$\text{Mass loss (\%)} = \frac{W_0 - W_1}{W_0} \times 100 \qquad (2)$$

where
$W_1$ = mass of the specimen after immersion for a period of time 1, g and
$W_0$ = initial mass of the specimen before immersion, g.

**9.2**—The material properties of FRP bars should be assessed only for those test specimens undergoing failure in the test section. In cases where tensile failure or slippage has occurred at an anchoring section, the data should be disregarded and additional tests should be performed from the same conditioning lot as the failed specimen. The tensile capacity retention should be calculated according to Eq. (3), with a precision to two significant digits.

$$R_{et} = \frac{F_{u2}}{F_{u1}} \times 100 \qquad (3)$$

where
$R_{et}$ = tensile capacity retention, %;
$F_{u1}$ = tensile capacity before immersion, N; and
$F_{u2}$ = tensile capacity after immersion, N.

**10** *Report*

The test report should include the following items:

**10.1** *Common items*—

**10.1.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.1.2**—Type of fiber and fiber binding material, as reported by the manufacturer, and fiber volume fraction.

**10.1.3**—Numbers or identification marks of test specimens.

**10.1.4**—Designation, diameter, and cross-sectional area.

**10.1.5**—Date of start and end of immersion.

**10.2**—Items related to alkaline solution immersion:

**10.2.1**—Composition of alkaline solution, pH, temperature, immersion period, and time.

**10.2.2**—Sustained load level, time, and procedure of solution monitoring and adjusting.

**10.2.3**—Record of observation of external appearance and mass change.

**10.2.4**—Specimen mass at each time interval.

**10.2.5**—Plots of percent mass change versus time, calculated by Eq. (1) or (2).

**10.3**—Items related to tensile testing:

**10.3.1**—Test temperature and loading.

**10.3.2**—Tensile capacities for immersed and non-immersed test specimens at the 1-, 2-, 3-, 4-, and 6-month intervals, with averages and standard deviations of tensile capacities and tensile strength.

**10.3.3**—Modulus of elasticity and the average for all immersed and nonimmersed test specimens, respectively.

**10.3.4**—Ultimate strain for all immersed and nonimmersed test specimens and average ultimate strain.

**10.3.5**—Tensile capacity retention.

**10.3.6**—Stress-strain curves for all immersed and nonimmersed test specimens.

**10.3.7**—Plot of tensile capacity retention versus time of exposure.

## B.7—Test method for tensile fatigue of FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for tensile fatigue under a constant tensile load range for FRP bars used as reinforcing bars or prestressing tendons in concrete.

**1.2**—The specimens should be linear or grid FRP formed from continuous fibers in such a manner as to act mechanically as a monolithic body.

**1.3**—Various types of fatigue testing, such as tension-tension; tension-compression; compression-compression; and various combinations of tension, compression, and shear are possible. The tension-tension test method given herein is considered to be the most basic for evaluating material characteristics. The test control parameter is the load, and the loading machine is controlled so that the specimen is subjected to repetitive constant load range. In this procedure, the test control parameter may be described using either stress or applied load as a constant amplitude fatigue variable.

**2** *Referenced documents*

**2.1** *ASTM standards—*

| | |
|---|---|
| D 618 | Standard Practice for Conditioning Plastics for Testing |
| D 3039/D 3039M | Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials |
| D 3479/D 3479M | Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials |
| E 4 | Standard Practices for Force Verification of Testing Machines |
| E 739 | Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data |

**3** *Significance and use*

**3.1**—This test method is intended for use in laboratory tests in which the principal variable is the maximum value of the repeated load.

**3.2**—This test method is intended to develop the tensile fatigue data for material specifications, research and development, quality assurance, and structural design and analysis. The primary test result is the fatigue life of the specimen under a specific loading and environmental condition. Guidance in statistical analysis of fatigue life data, such as determination of linear or linearized stress life (*S-N*), can be found in ASTM Practice E 739.

**3.3**—Fatigue properties of reinforced or prestressed concrete structures are important factors to be considered in design. For FRP bars used as reinforcing bars or tendons, the fatigue behavior should be measured according to the method given herein, in keeping with the intended purposes. Factors that can affect the fatigue lifetime of an FRP bar include the maximum load, the load ratio (minimum load divided by maximum load), the wave shape (sinusoidal, triangular, square, and so on), the rate of loading (Hz), the environment (such as moisture and temperature), and the method of material conditioning and specimen preparation. These factors should be reported.

**3.4**—This test method determines the number of repeated loading cycles required to fail an FRP bar. Such data can be used to create *S-N* curves for a particular set of testing conditions where the principal variable is the maximum value of the repeated load. Because FRP bars often have slight variations in cross-sectional area from one axial position to another, the area of a particular lot of rods is used to compute the stress in those specimens.

**3.5**—This test method can be used in the study of fatigue damage in an FRP bar, such as the occurrence of microscopic cracks, fiber fractures, or delaminations. The specimen's residual strength, stiffness, or both, may change due to these damage mechanisms. The loss in strength associated with fatigue damage may be determined by discontinuing cyclic loading to obtain the quasistatic tensile strength using Test Method B.2. The loss in stiffness may be quantified by discontinuing cyclic loading at selected cycle intervals to obtain the quasistatic axial tensile stress-strain using modulus determination described in Test Method B.2.

**4** *Terminology*

**4.1** *Repeated load (stress)*—Load (stress) alternating cyclically between fixed maximum and minimum values.

**4.2** *Maximum repeated load (stress)*—The maximum load (stress) during repeated loading (stressing).

**4.3** *Minimum repeated load (stress)*—The minimum load (stress) during repeated loading (stressing).

**4.4** *Load (stress) range*—The difference between the maximum and minimum repeated loads (stresses).

**4.5** *Load (stress) amplitude*—One-half of the load (stress) range.

**4.6** *Load (stress) ratio*—The minimum load (stress) divided by maximum load (stress).

**4.7** *Average load (stress)*—The mean value of the maximum and minimum repeated loads (stresses).

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

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

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

**4.11** *Frequency*—The number of loading (stressing) cycles per second.

**4.12** *Characteristic length*—A length of specimen that contains one repeating unit of microstructure, deformation pattern, or other heterogeneity.

**4.13** *Stress*—Load divided by the cross-sectional area of a lot of specimens. Refer to Test Method B.1 for the calculation of cross-sectional area.

**5** *Test equipment and requirements*

**5.1**—The testing machine should generally conform to ASTM Practices E 4 and be capable of maintaining constant load amplitude, maximum and minimum repeated load, and frequency. The testing machine should be fitted with a counter capable of recording the number of cycles to failure of the specimen. The load indicator should be capable of measuring loads with an accuracy of not less than 1% of the load range.

**5.2**—Anchorages should be in accordance with Appendix A. Ideally, the same type of anchorage should be used for all specimens in a given series of tests.

**5.3**—If strain measurements are required as the result of the fatigue tests, an extensometer capable of maintaining an accuracy of ±1% of the indicated value should be used. The extensometer should allow a gage length that includes an integer number of characteristic lengths of the specimen. The integer should be at least two, but possibly greater than two to obtain a gage length of at least 50 mm.

**6** *Specimen preparation*

**6.1**—Specimens should be representative of the lot or batch being tested. During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions possibly causing changes to the material properties of the specimen should be avoided.

**6.2**—The specimen should be prepared and handled in accordance with Test Method B.2.

**6.3**—There should be a minimum of five test specimens for each load (stress) level. At least five loading levels should be used to construct a plot of stress versus load cycles to failure. If a specimen fails at or slips out of an anchoring section, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

**6.4**—The total length of the specimen should be 40 bar diameters plus the total gripped length of bar. The bar diameter is found by referring to Test Method B.1.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Condition specimens in accordance with Procedure A of ASTM D 618; store and test at the standard laboratory atmosphere ($23 \pm 3$ °C and $50 \pm 10\%$ relative humidity), unless a different environ-ment, such as temperature or alkaline solution, is specified as part of the experiment.

**7.2**—If another preconditioning procedure is used, the sequence of that preconditioning during specimen preparation can be important. Report if the specimen was preconditioned before or after anchors were applied.

**8** *Test method*

**8.1**—The mounting of test specimens should be in accordance with Test Method B.2.

**8.2**—For purposes of determining an *S-N* curve, the maximum and minimum loads may be set by one of the following three methods:

1. Fix the average load and vary the load amplitude;

2. Fix the minimum load and vary the maximum load; or

3. Fix the load ratio and vary the maximum and minimum load according to this fixed ratio.

The method adopted should be determined according to the purpose of the test. In any cases, a minimum of five load (stress) levels should be chosen such that the range of the number of cycles to failure is between $10^3$ and $2 \times 10^6$. Typical *S-N* curves for FRP materials are generated using Method C and use a fixed load (stress) ratio *R* of 0.1.

**8.3**—The following procedure may be used where the maximum stress level for the initial test is difficult to determine:

1. Select an appropriate maximum stress in the range 20 to 60% of the quasistatic tensile strength, and commence fatigue testing with this value as the repeated maximum load;

2. If the specimen does not fail after $10^4$ cycles at this repeated maximum stress, add 5% of the quasistatic tensile strength and perform the test uninterrupted using the same specimen;

3. If failure does not occur after $10^4$ cycles following Step 2, a further 5% should be added to the repeated maximum load;

4. Repeat Step 3 until the specimen fails; and

5. The initial maximum stress applied to an untested specimen can be set at the previously found maximum load minus 5% of the quasistatic tensile strength.

For tendons for prestressing applications, the stress levels of interest can be in the range of 50 to 75% of the quasistatic tensile strength. For bars for reinforced concrete, however, the stress levels of interest may be 15 to 30% of the quasistatic tensile strength.

**8.4**—The loading frequency should be within the range of 1 to 10 Hz, preferably 4 Hz. Temperature of the bar can increase due to internal damping. Such temperature changes can affect the fatigue performance of the bar. Thus, if temperature changes are likely to occur or if any doubts about temperature exist, temperature should be monitored with a suitable device or indicator, such as a contact thermocouple or infrared thermocouple. The temperature should be monitored for newly developed FRP materials and in any case where the loading frequency exceeds 4 Hz. If measured, temperature changes should be reported. The wave-form of the load signal (sinusoidal, triangular, square, and so on) should be held constant in any series of fatigue tests that are to be compared to each other in an *S-N* curve, unless the purpose of the tests are specifically to evaluate the effects of wave-form.

**8.5**—Static load should be applied up to the average load, after which repeated loading should begin at the prescribed frequency. The prescribed load should be introduced as rapidly as possible without dynamic effects. The maximum and minimum repeated loads should not change for the duration of the test. Counting the number of cycles should normally commence when the load on the specimen has reached the prescribed maximum load.

**8.6**—Complete separation (breaking) of the specimen should be deemed to constitute failure. The number of cycles to failure should be recorded. If the specimen does not fail after $4 \times 10^6$ cycles, the test may be discontinued. A specimen that does not fail should not be reused.

**8.7**—Tests for each specimen should normally be conducted without interruption from the start of the test to the end of the test. When a test is interrupted, the number of cycles up to the time of interruption and the period of the interruption should be recorded.

**9** *Calculations*

**9.1**—Five valid test specimens are required at each load level. A valid specimen is one that does not fail in the anchor, fails in the gage length at a cycle count of between 1000 and $2 \times 10^6$ cycles, or not fail after $2 \times 10^6$ cycles.

**9.2**—If an *S-N* curve is desired, the curve should be plotted in accordance with ASTM Practice E 739 with maximum repeated stress, stress range, or stress amplitude represented on a linear scale on the vertical axis, and the number of cycles to failure represented on a logarithmic scale on the horizontal axis. Where measurement points coincide, the number of coinciding points should be noted. Right-facing arrows should be added to indicate points from test results for test specimens that do not fail.

**9.3**—If a fatigue strength is desired, the fatigue strength at $2 \times 10^6$ cycles should be derived by interpolation on an *S-N* curve obtained by one of the three load selection methods (A, B, C). The fatigue strength should be reported with a precision of three significant digits.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer, and fiber volume content.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Designation, diameter, and cross-sectional area for the lot from which the specimens are taken.

**10.5**—Length of specimens (total and between anchors).

**10.6**—Description of preconditioning applied to specimens, including the sequence of preconditioning during specimen preparation.

**10.7**—Date of test, test temperature and humidity (from start to end of test), and type of testing machine.

**10.8**—Description of anchorage.

**10.9**—Description of extensometer(s) and extensometer gage length.

**10.10**—Method of selecting maximum and minimum loads for a series of tests to construct an *S-N* curve (Method A, B, or C).

**10.11**—Maximum load (stress), minimum load (stress), load (stress) range, number of cycles to failure, loading waveform, and frequency for each test specimen.

**10.12**—Record of observed failure mode for each test specimen.

**10.13**—*S-N* curve, if obtained in a series of tests.

**10.14**—Fatigue strength at $2 \times 10^6$ cycles, if obtained from an *S-N* curve.

## B.8—Test method for creep rupture of FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for creep rupture of FRP bars used as reinforcing bars or prestressing tendons in concrete.

**2** *Referenced documents*

**2.1** *ASTM standards—*

D 618    Standard Practice for Conditioning Plastics for Testing

D 2990   Standard Test methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

**3** *Significance and use*

**3.1**—This test method for investigating creep rupture to compare the creep behavior of different FRP bars is intended for use in laboratory tests in which the principal variable is the size or type of FRP bars, magnitude of applied stress, and duration of load application.

**3.2**—Unlike steel reinforcing bars or prestressing tendons subjected to significant sustained stress for long time periods, creep rupture of FRP bars may take place below the static tensile strength. Therefore, the creep strength should be evaluated when determining acceptable stress levels in FRP bars used as reinforcement or tendons in concrete members to resist sustained loads such as self-weight of a member or other forms of dead loads. Creep rupture strength varies according to the type of FRP bars used.

**3.3**—This test method measures the load-induced, time-dependent tensile strain at selected ages for FRP bars, under an arbitrary set of controlled environmental conditions, and the corresponding load ratio.

**3.4**—This test method is intended to determine the creep rupture data for material specifications, research and development, quality assurance, and structural design and analysis. The primary test result is the million-hour creep rupture strength of the specimen under a specific loading and environmental condition.

**3.5**—Creep properties of reinforced or prestressed concrete structures are important to be considered in design. For FRP bars used as reinforcing bars or tendons, the creep rupture should be measured according to the method given herein.

**4** *Terminology*

**4.1** *Creep*—Time-dependent deformation (or strain) under sustained load (or stress).

**4.2** *Creep rupture*—Material failure due to deformation (accumulated strain) caused by creep.

**4.3** *Creep rupture capacity*—The load at which failure occurs after a specified period of time from initiation of a sustained load. In particular, the predicted stress causing

failure after 1 million hours is referred to as the million-hour creep rupture capacity. This capacity is determined by the method described in Section 9.

**4.4 *Creep rupture time***—The lapsed time between the start of a sustained load and failure of the test specimen.

**4.5 *Creep rupture strength***—The stress causing failure after a specified period of time from initiation of a sustained load.

**4.6 *Creep strain***—The differential change in length per unit length occurring in a specimen due to creep.

**4.7 *Load ratio***—The ratio of a constant sustained load applied to a specimen to its tensile capacity.

**5** *Test equipment and requirements*

**5.1**—The testing machine should be capable of maintaining constant, sustained loading during deformation of the test specimen.

**5.2**—The anchorage should be in accordance with Appendix A.

**5.3**—The extensometer or strain gage used should be in accordance with Test Method B.2.

**6** *Specimen preparation*

**6.1**—Specimens should be representative of the lot or batch being tested. During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions possibly causing changes to the material properties of the specimen should be avoided.

**6.2**—Test specimens should be prepared and handled in accordance with Test Method B.2. The number of test specimens for each test condition should not be less than five. If a specimen fails at or slips out of an anchoring section, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Condition specimens in accordance with Procedure A of ASTM D 618; store and test at the standard laboratory atmosphere ($23 \pm 3$ °C and $50 \pm 10\%$ relative humidity), unless a different environment is specified as part of the experiment.

**8** *Test method*

**8.1**—The mounting of the specimen and gage length should be in accordance with Test Method B.2.

**8.2**—Test specimens should not be subjected to any dynamic effects, vibration, or torsion.

**8.3**—Creep test measurement is considered to start at the moment when the specimen has attained the prescribed load.

**8.4**—Creep tests should be conducted for not less than five values of load. The load should be chosen between 0.2 and 0.8 of the tensile capacity measured according to Test Method B.2. Data from test specimens that break before the load is fully applied to the specimen should be disregarded. If five valid tests cannot be achieved at a given load level, then the load level should be reduced.

**8.5**—The times to rupture should span at least three decades of time (such as 1, 10, 100, and 1000 h) to allow construction of a regression line through reasonably spread data. The linear regression should have an acceptable regression coefficient ($r^2 > 0.98$).

**8.6**—Preferably, creep strain should be recorded automatically by a recorder attached to the testing machine. If a recorder is not attached to the testing machine, creep strain should be measured and recorded at the following times after the prescribed load is attained: 1, 3, 6, 9, 15, 30, 45 min; and 1, 1.5, 2, 4, 10, 24, 48, 72, 96, and 120 h. Subsequent measurements should be at least once every 120 h.

**9** *Calculations*

**9.1**—The material properties of the FRP bar should only be assessed on the basis of the specimens that fail in the test section. In cases where tensile failure or slippage occurs at an anchoring section, the data should be disregarded, and additional tests should be performed until the number of test specimens failing in the test section is not less than five.

**9.2**—The load ratio-creep rupture time curve should be plotted on a semi-logarithmic graph where the load ratio is represented on an arithmetic scale along the vertical axis and creep rupture time in hours is represented on a logarithmic scale along the horizontal axis.

**9.3**—A creep rupture line chart should be prepared by calculating an approximation line from the graph data by means of the least-square method according to Eq. (1)

$$Y_c = a_1 - b_1 \log T \qquad (1)$$

where
$Y_c$ = creep load ratio;
$a_1, b_1$ = empirical constants; and
$T$ = time, h.

**9.4**—The load ratio at 1 million hours, as determined from the calculated approximation line, is the creep rupture load ratio. The load and stress corresponding to this creep rupture load ratio are the million-hour creep rupture capacity and the million-hour creep rupture strength, respectively. The million-hour creep rupture strength is calculated according to Eq. (2), with a precision to three significant digits

$$f_r = F_r / A \qquad (2)$$

where
$f_r$ = million-hour creep rupture strength of FRP bar, MPa;
$F_r$ = million-hour creep rupture capacity, N; and
$A$ = cross-sectional area of specimen, mm$^2$.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Designation, diameter, and cross-sectional area.

**10.5**—Date of test and test environmental conditions (humidity and temperature).

**10.6**—Type and manufacturer of testing machine.

**10.7**—Type and name of anchorage.

**10.8**—Tensile capacity, average tensile capacity, and tensile strength of test specimens.

**10.9**—Load ratios and creep rupture time curve of test specimens.

**10.10**—Formula for derivation of approximation line.

**10.11**—Creep rupture load ratio, million-hour creep rupture capacity, and million-hour creep rupture strength.

## B.9—Test method for long-term relaxation of FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for evaluating the long-term relaxation behavior of FRP bars used as prestressing tendons in concrete under a given constant temperature and strain.

**2** *Referenced documents*

  **2.1** *ASTM standards*—

D 618      Standard Practice for Conditioning Plastics for Testing

E 4         Standard Practices for Force Verification of Testing Machines

**3** *Significance and use*

**3.1**—This test method for investigating long-term relaxation of FRP bars is intended for use in laboratory tests in which the principal variables are the size or type of FRP bars, magnitude of applied stress, and duration of load application.

**3.2**—This test method measures the load-induced, time-dependent tensile strain at selected ages for FRP bars under an arbitrary set of controlled environmental conditions and a corresponding load ratio.

**3.3**—This test method is intended to determine the relaxation data for material specifications, research and development, quality assurance, and structural design and analysis. The primary test result is the relaxation rate of the specimen under a specific loading and environmental condition.

**3.4**—Relaxation properties of prestressed concrete structures are important to be considered in design. For FRP bars used as prestressing tendons, the relaxation behavior should be measured according to the method given herein, in keeping with the intended purposes.

**4** *Terminology*

**4.1** *Relaxation*—The reduction of stress (or load) in a material under a constant state of strain (or deformation).

**4.2** *Relaxation rate*—The 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.

**4.3** *Tensile capacity*—The average of the tensile failure loads determined based on tests conducted in accordance with Test Method B.2.

**5** *Test equipment and requirements*

**5.1**—Use a testing machine with a loading capacity in excess of the relaxation load of the test specimen and calibrated according to ASTM Practices E 4. The testing machine should be capable of loading at a rate of $200 \pm 50$ MPa per min. and sustaining load while maintaining a constant strain.

**5.2**—The anchorage should be in accordance with Appendix A.

**5.3**—The accuracy of the initial load applied to the specimen should be as follows:

- Testing machines with loading capacity equal to or less than 1 kN: $\pm 1.0\%$ of set load; and
- Testing machines with loading capacity of more than 1 kN: $\pm 2.0\%$ of set load.

**5.4**—The accuracy of readings or automatic recording of loads should be within 0.1% of the initial load.

**5.5**—The testing machine should control strain fluctuations to no greater than $\pm 25 \times 10^{-6}$ in the specimen throughout the test period once the strain in the specimen has been fixed. If the FRP bar slips from an anchoring section, the slippage distance should be compensated so as not to affect the test results.

**5.6**—If an extensometer or strain gage is to be fitted to the test specimen, the extensometer or strain gage should be in accordance with Test Method B.2.

**6** *Specimen preparation*

**6.1**—Specimens should be representative of the lot or batch being tested. During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions possibly causing changes to the material properties of the specimen should be avoided.

**6.2**—Test specimens should be prepared and handled in accordance with Test Method B.2.

**6.3**—The number of test specimens for each test condition should not be less than five. If a specimen fails at or slips out of an anchoring section, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Condition specimens in accordance with Procedure A of ASTM D 618; store and test at the standard laboratory atmosphere ($23 \pm 3$ °C and $50 \pm 10\%$ relative humidity), unless a different environment is specified as part of the experiment.

**8** *Test method*

**8.1**—Mounting of the specimen and gage length should be in accordance with Test Tethod B.2.

**8.2**—If a strain gage is to be attached to the test specimen, the specimen should be preloaded by applying a load of 10 to 40% of the prescribed initial load, after which the strain gage should be attached and correctly calibrated.

**8.3**—The initial load should be either 70% of the guaranteed tensile capacity or 80% of the million-hour creep rupture capacity, whichever is smaller. In some cases, these conditions may result in a load that causes creep rupture but not failure due to relaxation; in such cases, it should be confirmed under actual loading conditions that the load does not result in creep rupture of the FRP specimens, by increasing the initial load as necessary.

**8.4**—The initial load should be applied without subjecting the specimen to shock or vibration. The specified rate of loading should be $200 \pm 50$ MPa per min. The strain on the specimen should be kept constant after the initial load has been applied and maintained for $120 \pm 2$ s. This time should be deemed to be the test start time.

**8.5**—Load reduction should generally be measured over a period of at least 1000 h. Preferably, load reduction should be recorded automatically by a recorder attached to the

testing machine. If no recorder is attached to the testing machine, stress relaxation should be measured and recorded at the following times: 1, 3, 6, 9, 15, 30, and 45 min; and 1, 1.5, 2, 4, 10, 24, 48, 72, 96, and 120 h. Subsequent measurements should be taken at least once every 120 h.

**9** *Calculations*

**9.1**—The relaxation value should be calculated by dividing the load measured in the relaxation test by the initial load.

**9.2**—The relaxation curve should be plotted on a semi-logarithmic graph where the relaxation value, in percent, is represented on an arithmetic scale along the vertical axis, and test time in hours is represented on a logarithmic scale along the horizontal axis. An approximation line should be derived from the graph data by means of the least-squares method according to Eq. (1)

$$Y_r = a_1 - b_1 \log T \qquad (1)$$

where
$Y_r$ = relaxation rate, %;
$a_1, b_1$ = empirical constants; and
$T$ = test time, h.

**9.3**—The relaxation rate after 1 million hours should be determined from the approximation line; this value represents the million-hour relaxation rate. Where the service life of the structure in which the FRP bars are to be used is determined in advance, the relaxation rate for the number of years of service life ("service life relaxation rate") should also be determined.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Designation, diameter, and cross-sectional area.

**10.5**—Date of test and test environmental conditions (humidity and temperature and their fluctuations).

**10.6**—Type and manufacturer of testing machine.

**10.7**—Initial load and loading rate of initial load.

**10.8**—Guaranteed tensile capacity and ratio of initial load to guaranteed tensile capacity.

**10.9**—Relaxation curve for each test specimen.

**10.10**—Average relaxation rates at 10, 120, and 1000 h.

**10.11**—Formula for determining the approximation line.

**10.12**—Million hour relaxation rate.

**10.13**—Relaxation rate corresponding to design service life ("service life relaxation rate"), where applicable.

## B.10—Test method for performance of anchorages of FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for the performance of the anchorage of FRP bars used as pretensioned prestressing tendons in concrete. In this application, the anchorage is used only for a short period, to transfer tension into the tendons. The long-term anchorage is via bond of the tendon to concrete.

**1.2**—The anchorage performance over extended periods of use (for instance, fatigue performance) is not covered in this test.

**2** *Referenced documents*

**2.1** *ASTM standards*—
E 4 Standard Practices for Force Verification of Testing Machines

**3** *Significance and use*

**3.1**—This test method for investigating the performance of anchorage is intended for use in laboratory tests in which the principal variable is the size or type of FRP tendons used in pretensioned prestressing of tendons. This test method should not be used to develop tendon design values.

**4** *Terminology*

**4.1** *Anchorage*—A 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.

**5** *Test equipment and requirements*

**5.1**—Use a testing machine or hydraulic jack and load cell with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading-rate or displacement-rate control is preferred. Tendons may be tested vertically or horizontally using a hydraulic jack.

**5.2**—FRP tendon should be loaded at a rate of 100 to 500 MPa/min, and the test should finish in 1 to 10 min.

**6** *Specimen preparation*

**6.1**—A specimen should be prepared by attaching the prestressing anchorage to be assessed to one end of the FRP tendon. The other end of the tendon should be anchored according to Appendix A (refer to Fig. A.1, A.2, and A.3).

**6.2**—The length of the specimen should be the sum of the length of the tendon and the lengths of the anchoring sections at each end. The length of the tendon should not be less than 100 mm, nor should it be less than 40 times the diameter of the FRP tendon. For FRP tendons in twisted strand form, the length should also be greater than two times the strand pitch.

**6.3**—The number of test specimens should be no less than five.

**7** *Test conditions*

**7.1**—Unless a different testing environment is specified as part of the experiment, the pullout anchorage tests should be conducted at the standard laboratory atmosphere of a 23 ± 3 °C and 50 ± 10% relative humidity.

**7.2**—Preconditioning of FRP tendons is permissible. Preconditioning may include abrasion of the surface of the tendon, environmental conditioning of the tendon, and post-curing of the tendon.

**8** *Test method*

**8.1**—Test specimens should be mounted and supported by a tensile testing machine. The area and geometry of the surface supporting the anchorage and the manner of application of force should approximate the actual conditions within the prestressed concrete structure as closely as possible. The anchorage end of the tendon should be supported on a platen
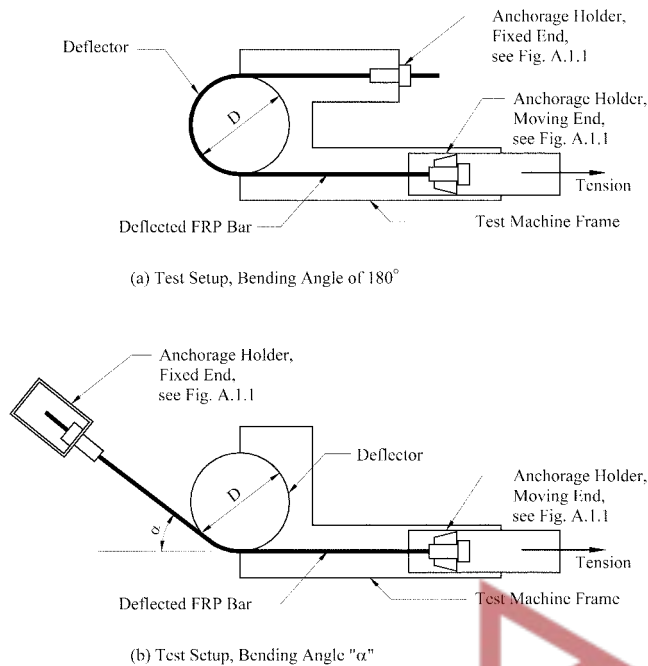
(a) Test Setup, Bending Angle of 180°



(b) Test Setup, Bending Angle "α"

*Fig. B.11.1—Typical bending tensile test setups.*

in a manner similar to that in the pullout specimen shown in Fig. A.3.

**8.2**—Loading should be continued up to tensile failure, as determined by either failure of the FRP tendon or excessive deformation of the anchoring device.

**9** *Calculations*

**9.1**—The tensile capacity for each specimen and average tensile capacity should be calculated. The modes of failure should also be recorded, noting any deformation or damage of the anchorage.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of testing machine.

**10.3**—Type of fiber and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.4**—Numbers or identification marks of test specimens.

**10.5**—Designation, diameter, and cross-sectional area.

**10.6**—Preconditioning of tendons, if any.

**10.7**—Date of test, test temperature, and loading rate.

**10.8**—Dimensions of test specimens and description of anchorage.

**10.9**—Tensile failure capacity for each test specimen, average tensile capacity, location of failure, and failure modes.

**10.10**—Records of any deformation or damage to anchorage.

## B.11—Test method for tensile properties of deflected FRP bars

**1** *Scope*

**1.1**—This test method specifies the test requirements for tensile properties of deflected FRP bars used as prestressing tendons in concrete.

**2** *Referenced documents*

**2.1** *ASTM standards—*

D 618    Standard Practice for Conditioning Plastics for Testing

E 4    Standard Practices for Force Verification of Testing Machines

**3** *Significance and use*

**3.1**—This test method for obtaining the tensile properties of deflected FRP bars is intended for use in laboratory tests in which the principal variable is the size or type of FRP bars.

**3.2**—When FRP bars manufactured as straight bars are tensioned after being bent, the bending stress or added lateral pressure may cause strength reduction. This test method is developed for FRP bars bent as external prestressing or arranged in a curved layout as internal prestressing.

**3.3**—This test method is intended to determine the flexural tensile data of bent FRP bars for material specifications, research and development, quality assurance, and structural design and analysis. The primary test result is the bent tensile capacity of the specimen under a specific loading and environmental condition.

**3.4**—Flexural tensile properties of prestressed concrete structures are important factors to be considered in design. For FRP bars used as tendons, the flexural tensile behavior should be measured according to the method given herein.

**4** *Terminology*

**4.1** *Deflected section*—The section of an FRP bar that is bent and maintained at the required bending angle and bending diameter ratio.

**4.2** *Deflector*—A device used to maintain the position, alter the bending angle, or alleviate the stress concentrations in the FRP bar (Fig. B.11.1). The deflector is used in the test method to introduce a bending stress into the tendon. The deflector is used in internal pretensioned prestressed concrete or externally post-tensioned concrete to direct the tendon layout.

**4.3** *Bending angle*—The angle formed by the straight sections of a specimen on either side of the deflector (refer to Fig. B.11.1).

**4.4** *Bending diameter ratio*—The ratio of the external diameter of the deflector surface in contact with the FRP bar to the diameter of the FRP bar.

**4.5** *Bending tensile capacity*—The tensile capacity at failure of a specimen within the deflected section.

**5** *Test equipment and requirements*

**5.1**—Use a testing machine with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading- or displacement-rate control is preferred. The test fixture should include a loading device, load indicator, anchorage holder, and deflector.

**5.2**—The loading device should have a loading capacity in excess of the tensile capacity of the test specimen and should be capable of applying load at the required loading rate.

**5.3**—The load indicator should be capable of displaying loads with an accuracy of not less than 1% of the failure load.

**5.4**—The anchorage holder should be suitable for the geometry of the test specimen and should be capable of

accurately transmitting loads from the testing machine to the test specimen. The anchorage should be constructed so as to transmit only axial loads to the test specimen, without transmitting either torsion or flexural force.

**5.5**—The deflector should be capable of maintaining the required bending angle and bending diameter during the test until failure of the test specimen. The deflector surface in contact with the specimen should be suitable for contact with the bar's outer surface. For a round bar, a smooth rigid deflector surface may be used. For bars that are stranded or spiraled, it may be appropriate to use a deflector machined to match the surface of the bar.

**6** *Specimen preparation*

**6.1**—Specimens should be representative of the lot or batch being tested. During the sampling and preparation of test specimens, all deformation, heating, outdoor exposure to ultraviolet light, or other conditions possibly causing changes to the material properties of the specimen should be avoided.

**6.2**—Test specimens should be prepared and handled in accordance with Test Method B.2.

**6.3**—The length of the specimen should be the sum of the length of the test section and the lengths of the anchoring sections. The length of the test section should be such that the distance from an anchorage to the deflected section should not be less than 100 mm, nor less than 40 times the diameter of the FRP bar. For FRP bars in strand form, the distance from an anchorage to the deflected section should not be less than two times the strand pitch.

**6.4**—The number of test specimens for each test condition (combination of bending diameters and bending angles) should not be less than five. If a specimen fails at an anchoring section, or slips out of an anchoring section, an additional test should be performed on a separate specimen taken from the same lot as the failed specimen.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Condition specimens in accordance with Procedure A of ASTM D 618; store and test at the standard laboratory atmosphere of a 23 ± 3 °C and 50 ± 10% relative humidity, unless a different environment (such as temperature or alkaline solution) is specified as part of the experiment.

**8** *Test method*

**8.1**—The bending diameter and bending angle should be set appropriately for the test (Fig. B.11.1). This combination forms a single test condition. Each specimen should have only one deflected section.

**8.2**—Care should be taken when mounting the specimen in the testing machine to maintain the required bending angle and bending diameter at the deflected section during the test.

**8.3**—The specified rate of loading should be between 100 and 500 MPa/min and the test should finish in 1 to 10 min. The deflected bar should exit the deflector on a tangent and not bend over the corner of the deflector.

**8.4**—Loading should be continued until failure of the test specimen. Failure load and failure location should be measured and recorded.

**9** *Calculations*

**9.1**—The material properties of FRP bars should only be assessed on the basis of the specimen undergoing failure in the test section. In cases where tensile failure or slippage has occurred at an anchoring section, the data should be disregarded and additional tests should be performed until the number of test specimens failing in the test section is no less than five.

**9.2**—The maximum, minimum, average, and standard deviation of the bending tensile capacity for each set of test conditions should be calculated in accordance with Test Method B.2.

**9.3**—The location and mode of failure should be observed and recorded for each test specimen.

**10** *Report*

The test report should include the following items:

**10.1**—The trade name, shape and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.3**—Numbers or identification marks of test specimens.

**10.4**—Designation, diameter, and cross-sectional area.

**10.5**—Condition of surface of FRP bar (material, thickness, configuration of any coating, and so on).

**10.6**—Date of test, test temperature, loading rate, and type and manufacturer of test machine.

**10.7**—Type of anchor device.

**10.8**—Bending angle, external diameter of deflector surface in contact with FRP bar, bending diameter ratio, and material and surface configuration.

**10.9**—Bending tensile capacity for each test specimen.

**10.10**—Location and mode of failure for each test specimen.

**10.11**—Numbers of test specimens for each set of conditions, and maximum, minimum, average and standard deviation of the bending tensile capacity.

## B.12—Test method for determining the effect of corner radius on tensile strength of FRP bars

**1** *Scope*

**1.1**—This method determines the effect of corner radius on the tensile properties of fiber reinforced polymer (FRP) bars used as reinforcing bars or prestressing tendons in concrete where bars are subject to tensile stresses. Tension tests are conducted using a three-component test fixture.

**2** *Referenced documents*

**2.1** *ASTM standards*—

| | |
|---|---|
| D 883 | Terminology Relating to Plastics |
| D 3039/D 3039M | Test Method for Tensile Properties of Polymer Matrix Composite Materials |
| E 4 | Practices for Force Verification of Testing Machines |
| E 6 | Terminology Relating to Methods of Mechanical Testing |

**3** *Significance and use*

**3.1**—Tension tests are conducted using a unique test fixture. The testing fixture consists of three components: upper and lower parts and interchangeable corner inserts made of any suitable metal (such as aluminum or steel) (Fig. B.12.1). Detailed dimensions are shown in Fig. B.12.2,
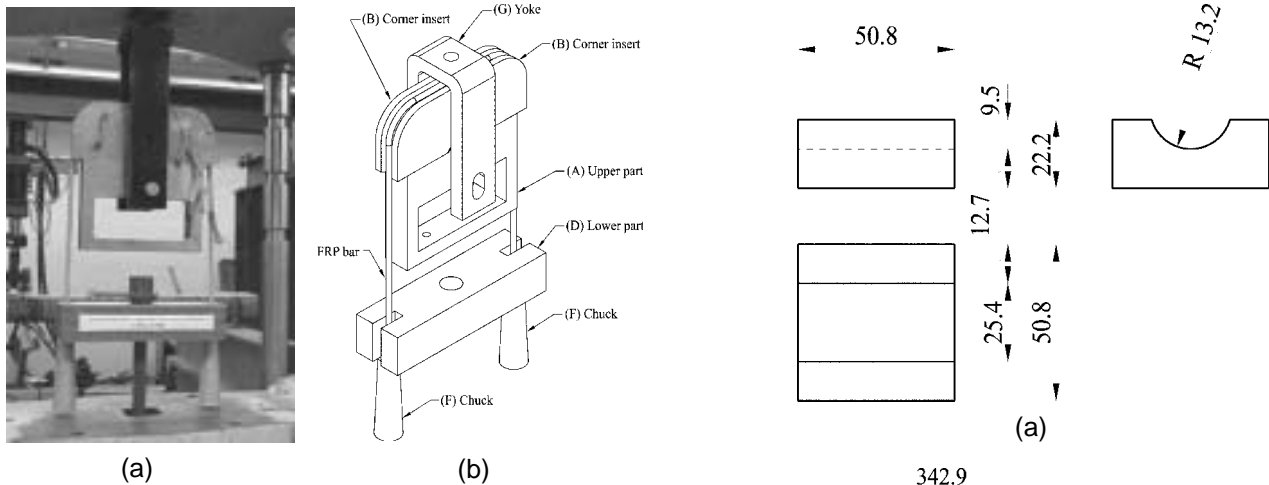
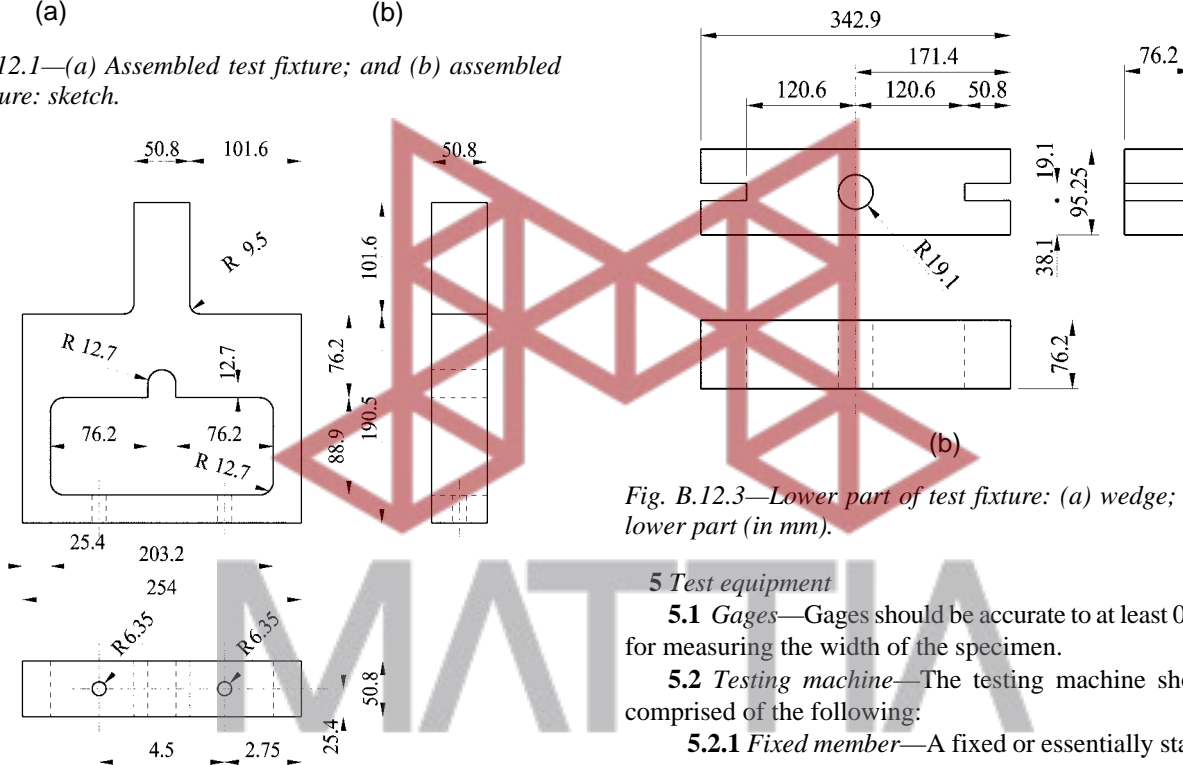Fig. B.12.1—(a) Assembled test fixture; and (b) assembled test fixture: sketch.



Fig. B.12.2—Upper part of test fixture (in mm).



Fig. B.12.3—Lower part of test fixture: (a) wedge; and (b) lower part (in mm).

B.12.3, B.12.4, B.12.5, and B.12.6. The FRP specimen in the form of a bent bar is placed in the groove that runs along the sides and the top of the test fixture and corner inserts. Instrumentation is mounted depending on the variables being monitored. If modulus and strain distribution are required, strain gages can be mounted around the corner areas. The load is applied until failure of the FRP specimen.

**3.2**—This tension test can provide accurate information with regard to the effect of corner radius on the tensile properties of FRP bent bars when applied under conditions with similar interaction mechanisms to those of the test method.

**3.3**—The method can be used for testing FRP bent bars with any fiber or resin type in rectangular or round solid shape.

**3.4**—The data provided by this test can be used for research and development, design, and acceptance/rejection criteria.

**4** *Terminology*

**4.1**—No new terminology introduced.

**5** *Test equipment*

**5.1** *Gages*—Gages should be accurate to at least 0.01 mm for measuring the width of the specimen.

**5.2** *Testing machine*—The testing machine should be comprised of the following:

**5.2.1** *Fixed member*—A fixed or essentially stationary member supporting the load fixture.

**5.2.2** *Movable member*—A member capable of applying a tensile load to the tensile loading fixture and transfer the load to the test fixture.

**5.2.3** *Drive mechanism*—A drive for imparting to the movable member a controlled speed with respect to the stationary member.

**5.2.4** *Load indicator*—A suitable load-indicating mechanism capable of showing the total tensile load carried by the test fixture. This mechanism should indicate the load with an accuracy of 1% or better of the actual value. The accuracy should be verified in accordance with ASTM Practice E 4.

**5.3** *Strain recording*—A suitable strain-recording system is required for modulus determination and strain distribution.

**5.4** *Test fixture*—The test fixture consists of the upper and lower parts around which the FRP bar is placed. The upper part is used as the testing area with interchangeable corner inserts located at its two corners. The lower part is
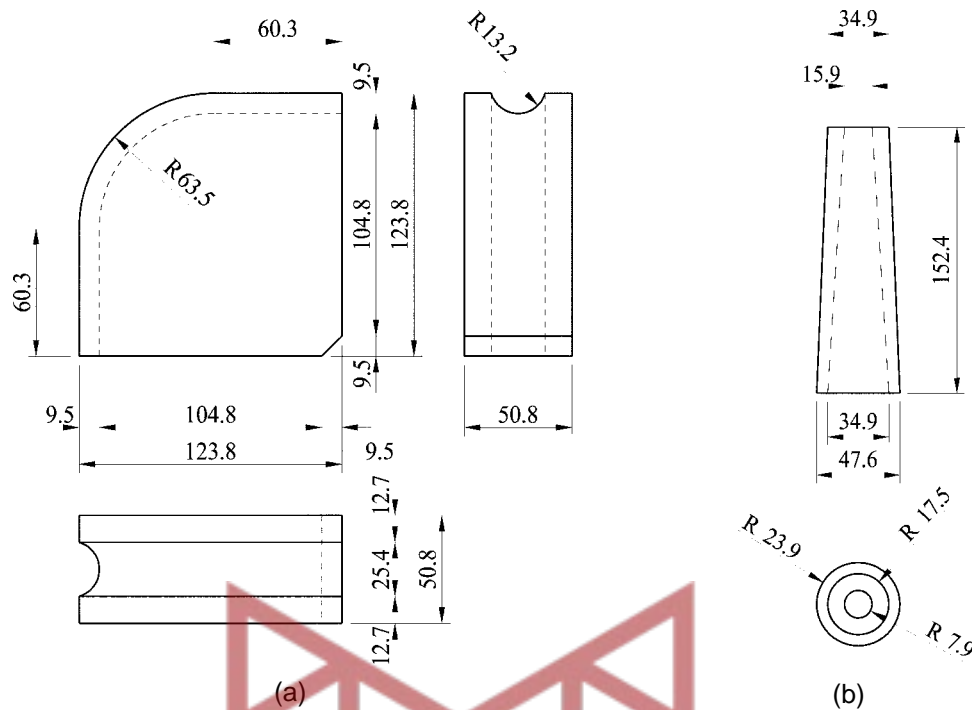
*Fig. B.12.4—Interchangeable corner inserts and wedge: (a) corner insert; and (b) chuck (in mm).*

used to anchor the specimen through anchors. Two bolts and two steel rods are used to hold the upper and lower fixture sections together during specimen installation.

**5.5** *Tensile loading fixture*—The fixture is used to transfer the load from the testing machine to the test fixture (Fig. B.12.5). All drilled holes in the tensile loading fixture and test fixture should be oversized to avoid any twisting and tightening when the rods and nuts are installed. All holes should be drilled 1.60 mm larger than nominal value.

**6** *Specimen preparation*

**6.1** *Geometry*—The FRP test specimen should conform to the dimensions of the test fixture shown in Fig. B.12.2 and B.12.3.

**6.1.1** *Anchorage*—An anchorage system at the ends of the test bar should be provided with a sufficient length and size in accordance with Appendix A, so that failure occurs at the bent portion.

**6.1.2** *Alignment*—The specimen should be installed with its center-line parallel to that of the side surface of the test fixture. A convenient method is to have two lines marked on the side surface of the test fixture between which the FRP sheets are applied.

**6.2** *Strain*—Where load-strain data are desired, the specimen may be instrumented with strain gages. The strain gages should be located at the center of the specimen in the width direction and parallel to the fiber direction. Strain gages should be mounted on both the flat surfaces in and outside the corner area. A recommended strain gage arrangement is shown in Fig. B.12.6.

**6.3** *Number of specimens*—A minimum of five specimens is recommended for each material.

**7** *Conditioning*
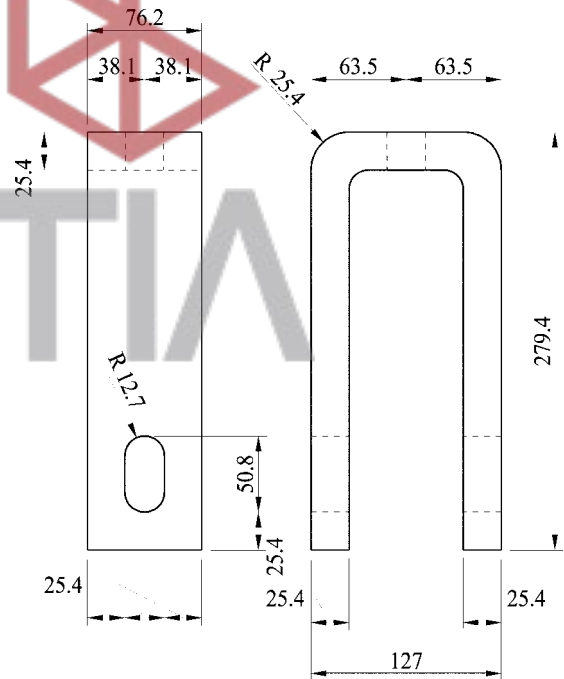


*Fig. B.12.5—Tensile fixture (two sets needed) (yoke) (in mm).*

**7.1**—Store and test at the standard laboratory conditions of 23 ± 3 °C and 50 ± 10% relative humidity, unless a different environment (such as temperature or alkaline solution) is specified as part of the experiment.

**8** *Test method*

**8.1** *Assembling test fixture*—The tensile loading fixture is placed onto the upper cross-head of the testing machine, and the upper test fixture is connected to the tensile loading

*Fig. B.12.6—Installation of specimen and possible strain gauge arrangement (in mm).*

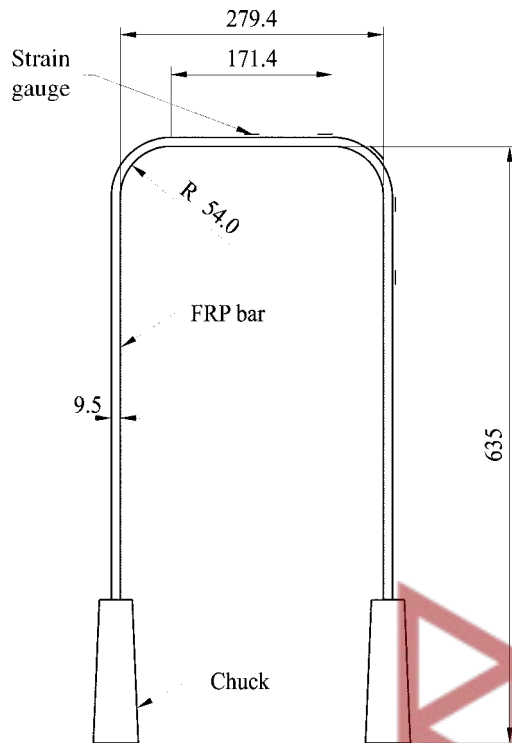fixture using a short plain steel rod through the holes on the upper part. The lower part of the test fixture is placed onto the lower plate of the testing machine using a threaded steel bar and two nuts. The steel bar should be long enough to provide sufficient space for the anchor of the test bar when placed between the lower part and the lower cross-head.

**8.2**—There should be no misalignment between the test fixture and tensile loading frame. No twisting should be produced in the test fixture and specimen.

**8.3**—Connect data recording equipment.

**8.4**—Apply and release a small load on the specimen (less than 5% of expected failure load) to realign the test fixture. The strain gauges are zeroed in this step.

**8.5**—Set the recommended speed of testing. Speed of testing shall be determined by the specifications for the material being tested or by the client. When the speed of testing is not specified, however, a speed of 1.0 to 2.0 mm/min is recommended.

**8.6**—Record the strain and load values continuously.

**8.7**—Record the maximum load from the load indicator of the testing machine.

**8.8**—Record the failure mode of the specimen. The failure zone is normally located around the corner.

**9** *Calculations*

**9.1** *Reduced tensile strength*—Calculate the reduced tensile strength using Eq. (1). Report the results to three significant figures

$$S = P/(2A) \qquad (1)$$

where
$S$ = reduced tensile strength of specimen corresponding to a specific corner radius, MPa;
$P$ = tensile failure load of specimen, N; and
$A$ = cross-sectional area of the test bar, mm$^2$.

**9.2** *Tensile modulus*—Calculate the tensile modulus of different points using Eq. (2). Report the results to three significant figures. The modulus should be calculated using the load and strain values corresponding to 20 and 50% of the reduced tensile strength $S$.

$$E_L = \Delta P/(2A\Delta\varepsilon) \qquad (2)$$

where
$E_L$ = axial (longitudinal) elasticity modulus of specimen, MPa;
$\Delta P$ = tensile load increment, N;
$A$ = cross-sectional area of the FRP bar, mm$^2$; and
$\Delta\varepsilon$ = strain increment.

**10** *Report*

The test report should include the following items:

**10.1**—Complete identification of the material tested, including, source, manufacturer's code number, form, previous history, resin type, processing details, specimen quality control, description of equipment used, deviations from this standard test method, and description of the fabrication process of the specimen compared with the specified one provided by the manufacturer.

**10.2**—Method of preparing test specimen and verification of quality.

**10.3**—Test specimen dimensions and corner radius.

**10.4**—Number of specimens tested.

**10.5**—Speed of testing.

**10.6**—Failure load.

**10.7**—Individual specimen strength and average values.

**10.8**—Individual specimen modulus and average values.

**10.9**—Date of tests.

## PART 3—TEST METHODS FOR FRP LAMINATES FOR CONCRETE AND MASONRY
### L.1—Test method for direct tension pull-off test
**1** *Scope*

**1.1**—This test method specifies the test requirements to uniformly prepare and test the tensile bond strength of an FRP laminate bonded to the surface of a concrete member, test the tensile strength of the substrate concrete, or both.

**2** *Referenced documents*

**2.1** *ASTM standards*—

D 4541    Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Tester

**3** *Significance and use*

**3.1**—The pull-off test is performed by securing a 25 to 40 mm square or circular plate area adhered to the surface of the FRP or concrete with a bonding agent. After the bonding agent is cured, a test apparatus is attached to the loading fixture and aligned to apply tension perpendicular to the concrete. The specimen is loaded until the adhesion fixture detaches from the surface. The pull-off strength is computed

based on the maximum indicated load, the instrument calibration data, and the original stressed surface area. Debonding of the adhered plate from the FRP is an indication of improper surface preparation or an under-strength adhesive. This mode of failure yields an invalid test result. Figure L.1.1 is a schematic of a portable adhesion tester.

**3.2**—This test method is intended for use in both the field and the laboratory. Due to the increased use of adhesively bonded FRP laminates to externally strengthen existing concrete structures, there is a need for evaluating direct tension pull-off behavior. This method is intended to meet such a need.

**3.3**—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 laminates as external reinforcement to strengthen existing structures.

**4** *Terminology*

**4.1**—No new terminology introduced.

**5** *Test equipment*

**5.1**—The portable adhesion test apparatus should conform to ASTM D 4541.

**5.1.1**—Use a 25 to 40 mm square or circular plate adhesion fixture. Both square and circular plates are acceptable.

**5.1.2**—Use a manual or mechanized device for applying a uniform cross-head speed.

**5.1.3**—Have a method for recording peak-load.

**5.1.4**—Be adjustable for loading perpendicular to the sample and applying tensile force without torque.

**5.2**—The portable adhesion tester (shown in Fig. L.1.1) illustrates the mandatory components.

**5.2.1** *Adhesion fixture*—The adhesion fixture should have a flat surface on one end and have a pinned or otherwise freely rotating attachment on the other end.

**5.2.2** *Detaching assembly*—The detaching assembly should have a stand-off support centered on the central attachment grip and a self-aligning device for engaging the adhesion fixture.

**5.2.3** *Detaching assembly base*—The detaching assembly base should provide firm and perpendicular contact with the surface.

**5.2.4** *Loading device*—The manual or mechanized device for pulling the adhesion fixture should apply a uniform cross-head speed until rupture occurs so that the maximum stress is obtained in less than 100 s.

**5.2.5** *Force indicator*—The force indicator should have calibration information and a maximum scale indicator greater than 4450 N.

**5.2.6** *Bonding agent*—An adhesive material that will provide more than 5.5 MPa tensile stress should be used. The bonding agent should be applied in accordance with manufacturer's instructions.

**6** *Specimen preparation*

**6.1**—Apply the FRP to the surface of the concrete following manufacturer's recommended procedures. The manufacturer's instructions should be followed as to elapsed time between application of FRP and testing. The following procedure, when in keeping with the manufacturer's instructions, should be followed for making the adhesion measurement.
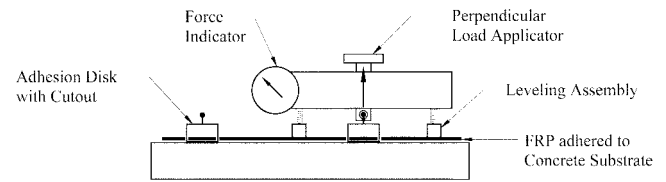


*Fig. L.1.1—Direct tension pulloff test setup.*

**7** *Conditioning*

**7.1**—Store and test at the standard laboratory atmosphere of 23 ± 3 °C and 50 ± 10% relative humidity, unless a different environment (such as temperature or alkaline solution) is specified as part of the experiment.

**8** *Test method*

**8.1**—Select a flat measurement site in accordance with the sampling schedule.

**8.2**—Prepare the FRP surface for bonding the fixture. The FRP surface should be cleaned with solvent, sanded with medium-grit sandpaper, rinsed with solvent, and allowed to dry.

**8.3**—Core drill or square cut through the FRP laminate into the substrate concrete, according to the size and shape of the adhesion fixture, using a carbide tipped or diamond core bit or cutting wheel. Cut into the concrete to a depth of 6 to 12 mm.

**8.4**—Attach the adhesion fixture with the designated bonding agent. Cure in accordance with the bonding agent manufacturer's instructions.

**8.5**—Position the detaching assembly over the adhesion fixture and attach the adhesion fixture to the detaching assembly. Align the load applicator perpendicularly. Adjust the detaching-assembly legs as required.

**8.6**—Take up the slack in the adhesion tester by screwing down the adjustment knob.

**8.7**—Set the force indicator to the zero mark.

**8.8**—Apply manual or mechanized loading so that it provides a continuous cross-head motion at a rate of less than 1 MPa/s until rupture occurs. The maximum load should be obtained in less than 100 s. Record pull-off force measurement.

**9** *Calculations*

**9.1**—Compute and record the pull-off bond strength or concrete strength, whichever is applicable.

$$\sigma_p = \frac{F_p}{A_a} \qquad (1)$$

where

$\sigma_p$ = the pull-off bond strength, MPa;
$F_p$ = the pull-off force, N; and
$A_a$ = the adhesion fixture contact area, mm$^2$.

**9.2**—*Interpretation of results*

**9.2.1**—The adhesion of the FRP laminate to the concrete surface is necessary for the concrete member to be able to transfer load into the FRP laminate. The interface bond and the strength (quality) of the concrete itself are critical. Possible failure modes in this tension test are:

**9.2.2**—Adhesive failure occurring at the interface of the FRP laminate or the concrete.

**9.2.3**—Cohesive failure within the FRP laminate.

**9.2.4**—Cohesive failure within the concrete.

**9.2.5**—Combinations of 8.1.1, 8.1.2, and 8.1.3 above.

**9.2.6**—Bonding agent failure is not an acceptable failure mode.

**10** *Report*

The test report should include the following:

**10.1**—The trade name, size, and date of manufacture, if available, and lot number of product tested.

**10.2**—Type of fiber and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.3**—Description of the FRP systems.

**10.4**—Measurements of adhesive fixture.

**10.5**—Identification of commercial test device.

**10.6**—Sample identification and test location.

**10.7**—Sample failure stress and mode of failure.

**10.8**—Average failure stress for sample population.

**10.9**—Test temperature and relative humidity, date of test, and test operator.

## L.2—Test method for tension test of flat specimen

**1** *Scope*

**1.1**—This test method describes the requirements for sample preparation and tensile testing of unidirectional and bidirectional externally bonded FRP systems for strengthening concrete structures. The method may be used to determine the tensile properties of wet lay-up FRP systems, prepreg FRP systems, and precured FRP flat laminates. The method only covers the determination of the tensile properties of the continuous fibers reinforcing the saturated resin. Other components comprising the FRP system, such as the primer and putty, are ordinarily excluded from the sample preparation and testing detailed in this document.

**2** *Referenced documents*

**2.1** *ASTM standards*—

| | |
|---|---|
| D 618 | Standard Practice for Conditioning Plastics for Testing |
| D 3039/D 3039M | Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials |
| E 4 | Standard Practices for Force Verification of Testing Machines |

**3** *Significance and use*

**3.1**—This test method for obtaining the tensile strength, modulus of elasticity, and ultimate elongation is intended for use in laboratory and field tests in which the principal variable is the size or type of FRP laminates. The obtained tensile properties can be used for material specifications, research and development, quality control and assurance, and structural design and analysis. The methods specifying the calculation to determine the tensile properties of the samples are described in Appendix B.

**3.2**—This test method focuses on the FRP laminate itself, excluding the performance of the tab. Therefore, failure or pullout at an anchoring section should be disregarded,

and the test findings should be based solely on test specimens that fail in the gauge section.

**3.3**—Tensile properties of FRP laminates are important factors to be considered in the design of FRP laminates as external concrete reinforcement. The tensile behavior should be measured according to the method given herein.

**4** *Terminology*

**4.1** *Gauge length*—The gauge length is the length of the specimen between end tabs, measured from points one specimen width from each tab.

**5** *Test equipment and requirements*

**5.1** *Testing machine*—Use a testing machine with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading-rate or displacement-rate control is preferred.

**5.2** *Micrometers*—Micrometers should be suitable for reading to 0.025 mm of the specimen thickness and width.

**5.3** *Strain measurements*—Strain may be determined by means of an extension indicator or strain indicator attached mechanically or bonded directly to the sample. Cross-head motion is not a suitable indication of strain. If Poisson's ratio is to be determined, the specimen should be instrumented to measure strain in both longitudinal and lateral directions.

**5.4** *Data acquisition system*—The data-acquisition system should be capable of continuously logging load, strain, and displacement at a minimum rate of two readings per second. The minimum resolution should be 100 N for load, one microstrain for strain, and 0.01 mm for displacement.

**6** *Specimen preparation*

**6.1** *Field preparation of wet lay-up materials*—Make field specimens in a manner similar to the actual field installation of the material. A plastic sheet should be placed on a smooth, flat horizontal surface. The specified number of plies at the specified angles should be sequentially resin coated and stacked on the plastic surface using the same amount of resin per unit area as would be applied in the actual installation. Grooved rollers or flat spatulas may be used to work out the trapped air in the laminate. A second plastic sheet is placed over the laminate and a smooth rigid flat plate placed on top of the plastic. After cure, the panel is sent to the test lab.

**6.2** *Laboratory preparation of wet lay-up materials*—A plastic sheet should be placed on a smooth, flat horizontal surface. Resin should be coated onto the film, and the FRP fabric or sheet material should be placed into the resin. Additional resin should be overcoated. This process should be repeated for multiple plies. A grooved roller may be used to work out trapped air. A second plastic sheet should be placed over the assembly. Using the flat edge of a small paddle, excess resin is forcibly pushed out of the laminate with a screeding action in the fiber direction. The laminate should be cured without removing the plastic. Specimens may be cut and tabbed after cure. Alternatively, specimens may be cut with a steel rule and utility knife after gelation but before full cure. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the

**Table 1—Width and gauge lengths of specimens**

| Fiber orientation | Minimum specimen width, mm | Minimum gauge length, mm |
|---|---|---|
| 0 degree | 12.7 | 127 |
| 0/90 degree | 25.4 | 127 |

engineer and material supplier should agree on a representative specimen fabrication process.

**6.3** *Field/laboratory preparation of precured FRP laminates*—Specimens should be cut to size using an appropriate table saw. Because thickness is predetermined, specimen width and length may be altered by the agreement of the engineer and laminate manufacturer. Care should be taken to ensure that the specimen is flat. Testing of nonflat specimens may result in lower tensile values due to induced moments.

**6.4** *Geometry*—The specimen should be as shown in Fig. L.2.1, where the specimen has a constant cross section with tabs bonded to the ends. Table 1 gives the width and gauge length of specimens used for different fiber orientations. Tabs need not always be bonded to the specimen to be effective in transferring the load into the specimen. Friction tabs, often used with emery cloth, can be employed. Variation in specimen width should be no greater than ±1%. Variation in laboratory prepared specimen thickness should be no greater than ±2%. Variation in field prepared specimen thickness should be no greater than ±10%.

**6.5** *Tabs*—Molded fiberglass or aluminum tabs should be acceptable. The tabs should be strain compatible with the composite being tested. The tabs should be bonded to the surface of the specimen using a high-elongation (tough) adhesive system that will meet the temperature requirements of the test. The width of the tab should be the same as the width of the specimen. The length of the tabs should be determined by the shear strength of the adhesive, the specimen, or the tabs (whichever is lower), thickness of the specimen, and estimated strength of the composite. Note that a significant proportion of failures within one specimen width of the tab should be cause to reexamine the tab material and configuration, gripping method and adhesive, and to make necessary adjustments to promote failure within the gauge length section.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Unless a different environment is specified as part of the experiment in laboratory, condition the test specimens in accordance with Procedure A of ASTM D 618 and store and test at the standard laboratory atmosphere (23 ± 3 °C and 50 ± 10% relative humidity).

**8** *Test method*

**8.1**—At least five specimens should be tested for each test condition.

**8.2**—Measure the width and thickness of the specimen in accordance with the ASTM D 3039. Record the average value of cross-sectional area.

**8.3**—Place the specimen in the grips of the testing machine, taking care to align the long axis of the specimen and the grips with a line joining the points of attachment of the grips to the machine. The speed of testing should be set
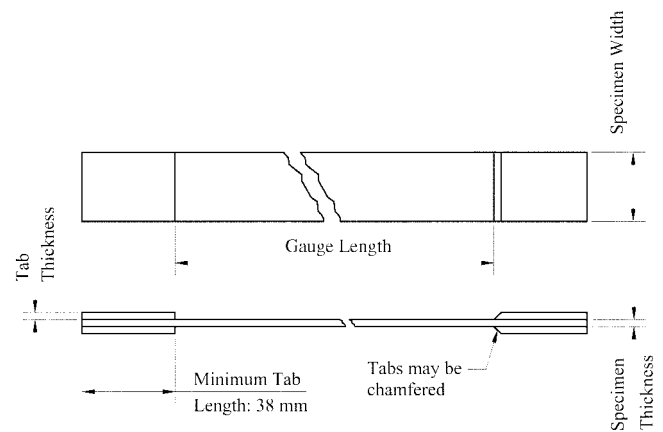


*Fig. L.2.1—Tension test of FRP laminate specimens.*

to give the recommended strain rates in the specimen gage section. The loading rate should be set to affect a constant strain rate in the gage length. Standard strain rates between $0.17 \times 10^{-3}$ s$^{-1}$ to $0.33 \times 10^{-3}$ s$^{-1}$ are recommended. A constant cross-head speed may also be used. The cross-head speed should be determined by multiplying the recommended strain rate by the distance between tabs, in millimeters. If strain is to be determined, attach the extensometer or strain gage to the specimen.

**8.4**—Record load and strain (or deformation) continuously, if possible, or, alternatively record load and deformation at uniform intervals of strain. Record the maximum load sustained by the specimen during the test. Record the strain at rupture.

**9** *Calculations*

**9.1**—Calculate tensile strength and modulus of elasticity per either Method 1 or Method 2 as given in Appendix B.

**10** *Report*

The report should include the following:

**10.1**—Identification of the material tested including the trade name, date of manufacture, if available, and lot number of product tested, type of fiber, and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.2**—Description of fabrication method and stacking sequence.

**10.3**—Specimen dimensions.

**10.4**—Conditioning procedure used.

**10.5**—Number of specimens tested.

**10.6**—Speed of testing, if other than specified.

**10.7**—Breaking load and failure strain including average value, standard deviation, and coefficient of variation.

**10.8**—Basis for calculation of tensile strength and modulus of elasticity (composite area, Method 1 or equivalent thickness method, Method 2; refer to Appendix B).

**10.9**—Ultimate tensile strength for each test specimen, means, and standard deviations.

**10.10**—Modulus of elasticity for each test specimen, means, and standard deviations.

**10.11**—Date of test.

**10.12**—Test operator.

## L.3—Test method for overlap splice tension test

**1** *Scope*

**1.1**—This test method describes the requirements for sample preparation and tensile testing of overlap splices to determine the splice tensile properties of unidirectional and bidirectional externally bonded FRP systems for strengthening concrete structures. The method only covers the determination of the tensile splice properties of the continuous fibers reinforcing the saturated resin. Other components comprising the FRP system, such as the primer and putty, are ordinarily excluded from the sample preparation and testing detailed in this document.

**2** *Referenced documents*

**2.1** *ASTM standards*—

| | |
|---|---|
| D 618 | Standard Practice for Conditioning Plastics for Testing |
| D 3039/D 3039M | Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials |
| D 3165 | Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single Lap Joint Laminated Assemblies |
| D 3528 | Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading |
| E 4 | Standard Practices for Force Verification of Testing Machines |

**3** *Significance and use*

**3.1**—This test method is intended for use in both the field and the laboratory. Due to the increased use of adhesively bonded FRP laminates as a result of the inherent advantages afforded by bonded joints (particularly the alleviation of stress risers and stress cracking), there is a need for tests by which joints of various FRP substrates and adhesives may be compared. This method is intended to meet such a need.

**3.2**—The basic material properties obtained from this test method can be used in the control of the quality of adhesives, in the theoretical equations for designing FRP laminates as reinforcement for externally strengthening existing structures, and in the evaluation of new adhesives.

**4** *Terminology*

**4.1**—No new terminology introduced.

**5** *Test equipment and requirements*

**5.1** *Testing machine*—Use a testing machine with a loading capacity in excess of the tensile capacity of the test specimen and calibrated according to ASTM Practices E 4. A testing machine with either loading-rate or displacement-rate control is preferred.

**6** *Specimen preparation*

**6.1** *Field preparation of wet lay-up materials*—Make field specimens in a manner similar to the actual field installation of the material. A plastic sheet should be placed on a smooth, flat horizontal surface. The specified number of plies at the specified angles should be sequentially resin coated and stacked on the plastic surface using the same amount of resin per unit area as applied in the actual installation. The overlap splice should be constructed by carefully measuring the specified overlap length and placing the material accordingly. Grooved rollers or flat spatulas may be used to work out the trapped air in the laminate. Care should be taken to ensure that the overlap ply does not slide during the rolling or screeding process. A second plastic sheet should be placed over the laminate and a smooth rigid flat plate placed on top of the plastic. A weight should be placed on top of the plate. The weight should be sufficient to produce a smooth surface upon cure, but should not cause significant flow of resin. After cure, the panel should be cut and tabbed. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the engineer and material supplier should agree on a representative specimen fabrication process.

**6.2** *Laboratory preparation of wet lay-up materials*—A plastic sheet is placed on a smooth, flat horizontal surface. Resin is coated onto the film, and the FRP fabric or sheet material is placed into the resin. Construct the overlap splice by carefully measuring the specified overlap length and placing the material accordingly. Additional resin should be applied in a thin layer once the fabric is in place. The process can be repeated for multiple plies, if needed, and a grooved roller may be used to work out trapped air. A second plastic sheet is placed over the assembly. Using the flat edge of a small paddle, excess resin is (with a screeding action) forcibly pushed out of the laminate in the fiber direction. Care should be taken to ensure that the overlap ply does not slide during the rolling or screeding process. The laminate should be cured without removing the plastic. Specimens should be cut and tabbed after cure. Alternatively, specimens may be cut with a steel rule and utility knife after gelation but before full cure. For FRP systems requiring heat, pressure, or other mechanical/physical processing for cure, the engineer and material supplier should agree on a representative specimen fabrication process.

**6.3** *Field/laboratory preparation of precured FRP laminates*—Laminates should be cut to size using an appropriate table saw. The mating surfaces of the lap joint should be cleaned in accordance with the FRP manufacturer directions. Resin/adhesive should be applied to the mating surfaces, and the lap joint should be measured, formed, and cured. Because laminate thickness is predetermined, specimen width and length may be altered by agreement of the engineer and laminate manufacturer. Care should be taken to ensure that the specimen is flat. Testing of nonflat specimens may result in lower tensile values due to induced moments.

**6.4** *Geometry*—The specimen should be as shown in Fig. L.3.1, with tabs bonded to the ends. Tabs need not be bonded to the material under test to be effective in transferring load into the specimen. Friction tabs, often used with emery cloth, can be employed. Single-lap and double-lap geometry are permitted. Chamfering of the lap ends is not permitted unless similar configurations are used in the field. Table 1 shows nominal specimen geometry for various overlap lengths. Variations in specimen width and thickness should not be greater than ±1%.

**6.5** *Tabs*—Molded fiberglass or aluminum tabs should be acceptable. The tab should be strain compatible with the composite being tested. The tabs should be bonded to the

**Table 1—Width and gauge lengths of specimens**

| Overlap length, mm | Specimen length, mm | Specimen width, mm |
|---|---|---|
| 25 | > 230 | 25 |
| 50 | > 254 | 25 |
| 76 | > 279 | 25 |
| 102 | > 305 | 25 |
| 152 | > 356 | 25 |
| 203 | > 406 | 25 |

surface of the specimen using a high-elongation (tough) adhesive system that will meet the temperature requirements of the test. The width of the tab should be the same as the width of the specimen. The length of the tab should be determined by the shear strength of the adhesive, the specimen, or the tabs (whichever is lower), thickness of the specimen, and estimated strength of the composite. If a significant proportion of failure occurs within one specimen width of the tab, there should be a re-examination of the tab material and configuration, gripping method, and adhesive, and necessary adjustments should be made to promote failure within the gage length section.

**7** *Conditioning*

**7.1** *Standard conditioning procedure*—Unless a different environment is specified as part of the experiment in a laboratory, condition the test specimens in accordance with Procedure A of ASTM D 618 and store and test at the standard laboratory atmosphere (23 ± 3 °C and 50 ± 10% relative humidity).

**8** *Test method*

**8.1**—At least five specimens should be tested for each test condition.

**8.2**—Measure the width and length of the overlap joint. Record the surface area of the joint.

**8.3**—Place the specimen in the grips of the testing machine, taking care to align the long axis of the specimen and the grips with a line joining the points of attachment of the grips to the machine. The loading rate should be set to give the recommended strain rates in the specimen gage section. Speed of testing should be set to affect a constant strain rate in the gage section. Standard strain rates between $0.17 \times 10^{-3}$ s$^{-1}$ to $0.33 \times 10^{-3}$ s$^{-1}$ are recommended. A constant cross-head speed may also be used. The cross-head speed should be determined by multiplying the recommended strain rate by the distance between tabs, in millimeters. If strain is to be determined, attach the extensometer or strain gage to the specimen.

**8.4**—Record the maximum load sustained by the specimen during the test and the failure mode of the specimen, according to the following definitions.

**8.4.1** *Delamination/debond*—The failure is a generally clean separation at the overlap interface.

**8.4.2** *Tension failure*—Specimen fails outside of overlap splice at representative single laminate strength and not within or adjacent to either of the grips.

**8.4.3** *Splitting*—Specimen fails along entire length, leaving portions of overlap bond intact.

**8.4.4** *Tab failure*—A significant proportion of failures within one specimen width of the tab should be cause to
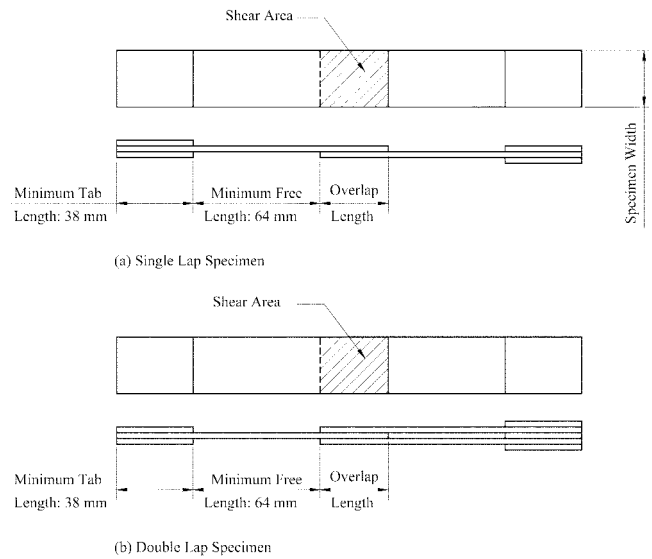


*Fig. L.3.1—Overlap tension specimen.*

re-examine the tab material and configuration, gripping method and adhesive, and to make necessary adjustments to promote failure within gage length of specimen.

**8.4.5**—Combinations of the above failure modes.

**8.5** *Statistics*—For each series of tests, calculate the average value, standard deviation, and coefficient of variation.

**9** *Calculations*

**9.1**—Calculate the average shear strength using the following equations, and report results with a precision to two significant figures

$$\text{for single lap: } v_{su} = \frac{F_{max}}{bl} \quad (1)$$

$$\text{for double lap: } v_{su} = \frac{F_{max}}{2bl} \quad (2)$$

where
$v_{su}$ = average tensile shear strength, MPa;
$F_{max}$ = maximum tensile load, N;
$b$ = specimen width, mm; and
$l$ = overlap length, mm.

**10** *Report*

The report should include the following:

**10.1**—Identification of the material tested, including the trade name, date of manufacture, if available, and lot number of product tested, type of fiber and fiber binding material as reported by the manufacturer, and fiber volume fraction.

**10.2**—Description of fabrication method and stacking sequence, including method of surface preparation before bonding.

**10.3**—Specimen dimensions and overlap length.

**10.4**—Complete identification of the adhesive tested.

**10.5**—Cure schedule time and temperature for bonding samples and conditioning procedure used.

**10.6**—Number of specimens tested.

**10.7**—Speed of testing if other than specified.

**10.8**—Tensile shear strength, including average value, standard deviation, and coefficient of variation.

**10.9**—Test temperature and conditions, date of test, and test operator.

**10.10**—Type of failure.

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**B.9** *Test method for long-term relaxation of FRP bars*

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## APPENDIX A—ANCHOR FOR TESTING FRP BARS UNDER MONOTONIC, SUSTAINED, AND CYCLIC TENSION

**1** *Scope*

**1.1**—This procedure specifies an anchor for FRP specimens to facilitate gripping of specimens for various types of tests performed under tensile loading. It also specifies preparation of the specimens.

**2** *Referenced documents*

**2.1** *ASTM standards—*

D 3916     Standard Test Method for Tensile Properties of Pultruded Glass-Fiber Reinforced Plastic Rod

**3** *Significance and use*

**3.1**—This anchor is recommended for performing tests for monotonic tension, creep, relaxation, fatigue, and pull-out bond strength of FRP bars.

**3.2**—This anchor is not recommended for testing FRP bars that require more than $400 \times 10^3$ N of load to fail the specimen.

**4** *Description of anchor*

**4.1** *Geometry*—The geometric dimensions of the anchor are shown in Fig. A.1. The PVC cap has a concentric hole of
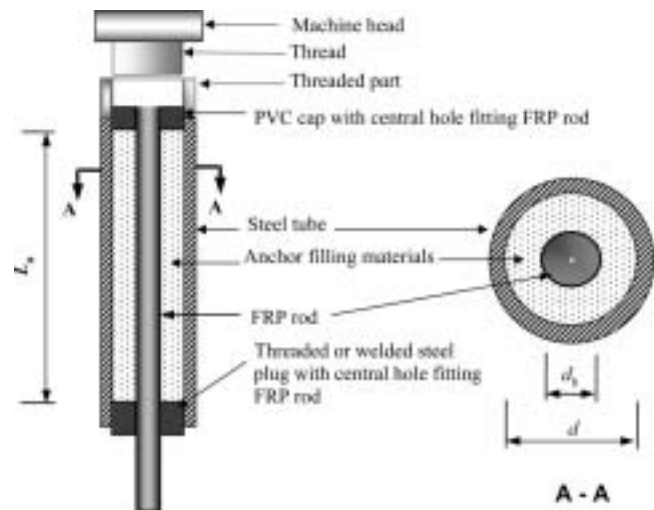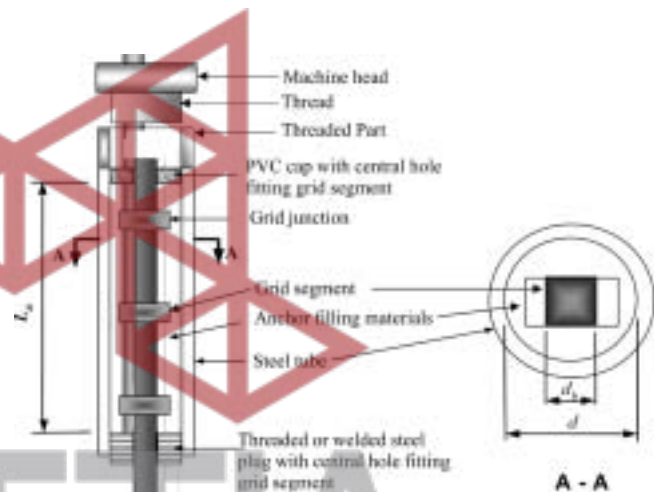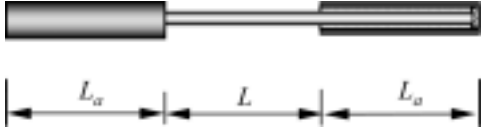


*Fig. A.1—Anchor details.*



*Fig. A.2—Anchor details for test on grid segments.*

the appropriate diameter used to center FRP bars inside the steel tube. The steel plug with a concentric hole fitting FRP bars may be either threaded or welded to the steel tube. Recommended details of the steel tubes are given in Table A1.1. Tube lengths shorter than those recommended in Table A1.1 may be used if no excessive slip is observed and the specimen fails within the gage length as required. For segments cut from FRP grids, the same gripping fixture is suggested; however, three grid junctions are suggested to be included in embedment, as shown in Fig. A.2.

**4.2** *Attachment to testing machine*—The anchor may be adapted to fit into the grips of any testing machine or frame as shown in Fig. A.3.

**4.3** *Anchor filler materials*—The tube may be filled with either pure polymer resin or a 1:1 mixture by weight of resin and clean sand or an expansive cement grout. A filler material compatible with the resin of which the specimen is made should be used. The strength of the filler should be such that the maximum tensile load occurring during a test does not cause slip throughout the entire bonded length of the specimen.

## Table A1.1—Recommended dimensions of test specimens and steel tubes

| FRP bar type | Diameter of the FRP bar $d_b$, mm | Outside diameter of the steel tube, mm | Nominal wall thickness of the steel tube, mm | Minimal length of the steel tube $L_aT$, mm |
|---|---|---|---|---|
| GFRP[*] | 6.4 | 35 | 4.8 | 300 |
| GFRP | 9.5 | 35 | 4.8 | 300 |
| GFRP | 13 | 42 | 4.8 | 380 |
| GFRP | 16 | 42 | 4.8 | 380 |
| GFRP | 19 | 48 | 4.8 | 460 |
| GFRP | 22 | 48 | 4.8 | 460 |
| CFRP[†] | 9.5 | 35 | 4.8 | 460 |

[*]GFRP: FRP bars made with glass fibers.
[†]CFRP: FRP bars made with carbon fibers.

**5** *Specimen preparation*

**5.1** *Cutting specimen*—Specimens of the required length should be cut from the bars supplied. To obtain specimens from grids and cages, cutting the crossbars too close to the rod should be avoided. Leaving a 2 mm projection of the crossbars may enhance gripping.

**5.2** *Specimen length*—The total length of the specimen should be the free length plus two times the anchor length $L_a$, in mm. The free length should be $40d_b$ or greater where $d_b$ is the rod diameter.

**5.3** *Surface preparation*—Mechanical or chemical treatment of the inner surface of the tube to promote adhesion of the specimen with the casting resin is recommended, provided that it does not affect the tensile properties of the specimen in the gage length portion and that failure still occurs outside the anchors.

**6** *Anchor casting procedure*

**6.1** *Assembly and preparation*—The steel plug should be threaded to the steel pipe. The specimen should go through the concentric hole of the PVC cap and steel plug and be held axially aligned inside the tube. Silicon caulking should be applied at the bottom of the plug so as to prevent any possible leakage of resin. If the specimen requires anchors at both ends, a suitable jig should be used to hold both tubes and the specimen axially aligned (Fig. A.4).

**6.2** *Mixing and handling polymer resin*—The resin should be mixed and handled following the manufacturer's instructions, paying particular attention to safety.

**6.3** *Casting*—Whenever possible, the anchor should be cast in a vertical position as shown in Fig. A.1. The resin should be poured to the required level directly from a beaker with a narrow spout, or by means of a funnel with a suitable stem. Lightly tap the outside of the tube to remove any entrapped air pocket inside, and then slide the PVC cap on the rod down and tap onto the top of the tube immediately. If the specimen needs anchors at both ends, at least 12 h should elapse before the first anchor is flipped to cast the other anchor.
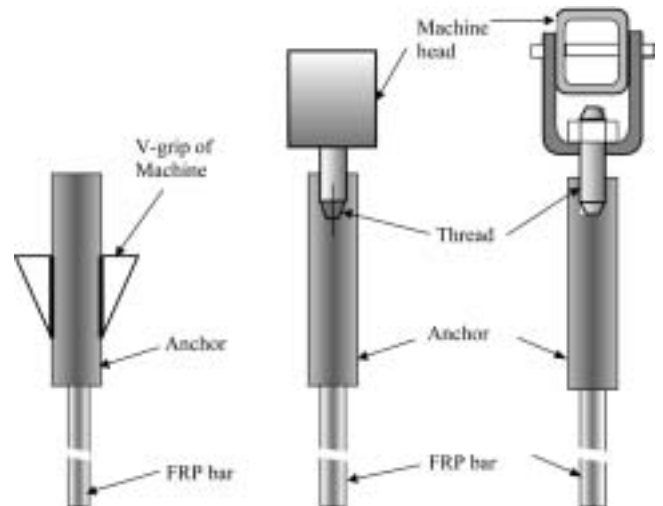


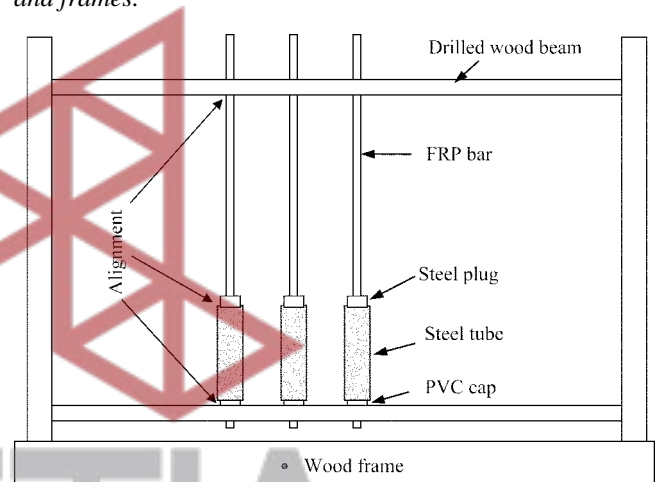*Fig. A.3—Attachment of anchor to various testing machines and frames.*



*Fig. A.4—Jig to align specimen and anchors.*

**6.4** *Curing*—The curing schedule recommended by the manufacturer of the filler material should be allowed before testing to allow the resin to set inside the tube.

**6.5** *Handling*—When not held vertically, the anchored specimen should be handled by holding both grips to avoid bending or twisting of the specimen.

## APPENDIX B—METHODS FOR CALCULATING TENSILE PROPERTIES OF FLAT SPECIMEN

**1** *Scope*

**1.1**—These methods specify the calculation to determine the tensile properties of unidirectional and bidirectional externally bonded FRP systems for strengthening concrete structures. The requirements for sample preparation and tensile testing are described in Test Method L.2. Two methods of calculation are provided.

**1.2**—Method 1 is based on composite area and uses the measured width and thickness of the specimen to determine the cross-sectional area of the specimen for calculation of the tensile strength and modulus of elasticity.

**1.3**—Method 2 is based on equivalent fiber area and uses the equivalent thickness of a fiber layer without resin, $t'$, and

the measured width for calculation of the tensile strength and modulus of elasticity.

**2** *Referenced documents*

**2.1** *ASTM standards—*

D 3039/D 3039M Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

**3** *Significance and use*

**3.1**—The methods for calculating the tensile strength, modulus of elasticity, and ultimate elongation are intended for use in laboratory and field tests in which the principal variable is the size or type of FRP laminates. The obtained tensile properties can be used for material specifications, research and development, quality control and assurance, and structural design and analysis.

**3.2**—The methods given herein focus on the FRP laminate itself, excluding the performance of the tab. Therefore, failure or pullout at an anchoring section should be disregarded, and the test findings should be based solely on test specimens that fail in the test section.

**3.3**—Tensile properties of FRP laminates are an important factor to be considered in the design of FRP laminates as external concrete reinforcement. The tensile behavior should be measured according to the method given herein, in keeping with the intended purposes.

**4** *Calculations*

**4.1** *Method 1 (based on composite area)*—Calculate the tensile strength and modulus using Eq. (1) and (2), and report results with a precision to three significant figures. For calculating modulus, the strain range should not exceed 50% of the ultimate strain of the specimen in accordance with ASTM D 3039. For most cases, such as glass and carbon composite materials, the range is 1000 to 3000 microstrain.

$$f_{fu} = \frac{P_u}{bt} \tag{1}$$

$$E_f = \frac{dP}{dl}\frac{L_g}{bt} \tag{2}$$

where

$f_{fu}$ = tensile strength of FRP laminate based on specimen area, MPa;

$P_u$ = maximum tensile load, N;

$b, t$ = width and thickness, respectively, mm;

$L_g$ = gage length of measuring instrument, mm;

$E_f$ = modulus of elasticity of FRP laminate based on specimen area, MPa; and

$dP/dl$ = slope of chord between 1000 and 3000 microstrain of the load-deformation curve.

**4.2** *Method 2 (based on equivalent fiber area)*—Calculate the tensile strength and elastic modulus using Eq. (3) and (4) and report results with a precision to three significant figures

$$f_{fu}' = \frac{P_u}{bt'} \tag{3}$$

$$E_f' = \frac{dP}{dl}\frac{L_g}{bt'} \tag{4}$$

where

$P$, $b$, $L_g$, and $dP/dl$ = the same as defined in Eq. (1) and (2);

$t'$ = the equivalent thickness of a fiber layer without resin, mm;

$f_{fu}'$ = the equivalent tensile strength of a fiber layer without resin, MPa; and

$E_f'$ = the equivalent elastic modulus of a fiber layer without resin, MPa.

The equivalent thickness $t'$ is provided by the manufacturer of the fiber reinforcement fabric. For biaxial fabrics, the manufacturer should provide a measurement of $t'$ in each fiber direction. If more than one ply of the same fabric is used in a laminate, then $t'$ represents the equivalent fiber thickness of the sum of the plies.

*Statistics*—For each series of tests, calculate the average value, standard deviation, and coefficient of variation for the tensile strength, failure strain, and elastic modulus.