Designation: D7914/D7914M – 14

Standard Test Method for Strength of Fiber Reinforced Polymer (FRP) Bent Bars in Bend Locations[1]

This standard is issued under the fixed designation D7914/D7914M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method determines the quasi-static ultimate strength of fiber reinforced polymer (FRP) composite bent bars commonly used as anchorages for stirrups in reinforced, prestressed, or post-tensioned concrete structures. This test method only applies to bars with a solid cross section.

1.2 FRP bent bars are often used in reinforced concrete applications to shorten the development length of the bar or to act as a tie or a stirrup to resist shear forces. Bent bars can be produced with varying angles of bend in order to fit their intended purpose.

1.3 For this test method, the FRP bars are bent at a 90 degree angle. In general, bars have a regular pattern of surface undulations, a coating of bonded particles, or both, that promote mechanical interlock between the bar and concrete.

1.4 The strength values provided by this method are short-term, quasi-static tensile strengths that do not account for sustained static or cyclic loading. If bars are to be used under high levels of sustained or repeated loading, additional material characterization may be required.

1.5 The characteristic values obtained from this test method are intended to represent the quasi-static ultimate strength of FRP bent bars with a tail length of twelve bar diameters.

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

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

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A615/A615M Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement
C39/C39M Test Method for Compressive Strength of Cylindrical Concrete Specimens
C143/C143M Test Method for Slump of Hydraulic-Cement Concrete
C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory
D792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
D883 Terminology Relating to Plastics
D3171 Test Methods for Constituent Content of Composite Materials
D3878 Terminology for Composite Materials
D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
D7205/D7205M Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E456 Terminology Relating to Quality and Statistics

3. Terminology

3.1 Terminology in D3878 defines terms relating to high-modulus fibers and their composites. Terminology in D883 defines terms relating to plastics. Terminology in E6 defines terms relating to mechanical testing. Terminology in E456 and in Practice E122 define terms relating to statistics and the selection of sample sizes. In the event of a conflict between

[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.10 on Composites for Civil Structures.

Current edition approved Aug. 1, 2014. Published December 2014. DOI: 10.1520/D7914_D7914M-14.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

terms, Terminology in D3878 shall have precedence over the other terminology standards.

3.2 *Definitions:*

3.2.1 *bar, n*—a linear element, with a substantially round cross-section, often with surface undulations or a coating of particles that promote mechanical interlock with concrete.

3.2.2 *bend radius, n*—inside radius of the bend.

3.2.3 *bend strength, n*—ultimate tensile stress that can be carried by the FRP bent bar provided that failure occurs in the bend.

3.2.4 *bent bar, n*—a bar with a section formed in such a manner as to deviate from its primary axis.

3.2.5 *equivalent bar diameter, n*—the equivalent bar diameter is determined according to Test Method D7205/D7205M and is based upon the standard cross-sectional area of the FRP bar.

3.2.6 *quasi-static, adj*—loading where inertial effects (time and inertial mass) are irrelevant.

3.2.7 *standard cross-sectional area, n*—the cross-sectional area of a standard numbered steel concrete reinforcing bar as given in Specification A615/A615M, Table 1, and based upon a circular cross section and determined over at least one representative length.

3.2.8 *stirrup, n*—a bar shape comprised of one or more bent bars used to resist shear forces in reinforced concrete.

3.2.9 *tail length, n*—the length provided beyond the bend portion of a bent bar.

3.2.10 *tensile strength, n*—ultimate tensile strength of FRP bars in the direction parallel to the fibers.

3.3 *Symbols:*

3.3.1 A—standard cross-sectional area of a single leg of the FRP bent bar determined according to Test Method D7205/D7205M, mm^2 [in.^{2}]

3.3.2 CV—sample coefficient of variation, in percent

3.3.3 d_b—effective bar diameter taken as the equivalent bar diameter determined according to Test Method D7205/D7205M and is based upon the standard cross-sectional area of the FRP bar, mm [in.]

3.3.4 F_{fu}—ultimate tensile strength parallel to the fibers determined according to Test Method D7205/D7205M, MPa [psi]

3.3.5 F_{fb}—ultimate bend strength of the FRP bent bar, MPa [psi]

3.3.6 L_t—tail length of the FRP bent bar occurring after the bent portion of the bar, mm [in.]

3.3.7 n—number of specimens

3.3.8 P_{fb}—ultimate force capacity of the FRP bent bar, N [lb]

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

3.3.10 r_t—inside radius of the bent portion of an FRP bent bar, mm [in.]

3.3.11 S_{n-1}—sample standard deviation

3.3.12 χ—percentage of the guaranteed tensile strength of the straight portion of the bar that is retained in the bend location

3.3.13 x_I—measured or derived property

3.3.14 $\bar{x}$—sample mean (average)

4. Summary of Test Method

4.1 One or more FRP bent bars, cast into two blocks of concrete, are loaded in tension until failure occurs at the bent portion of the bar. An actuation device is placed in between the two concrete blocks so that the blocks are forced apart, inducing tension on the FRP bent bar.

4.2 Force is recorded throughout the test.

4.3 The principal variables used in the tests are the cross-sectional area, bend radius, and type of FRP bent bar.

5. Significance and Use

5.1 This test method is intended to determine the bend strength developed at a standard twelve bar diameters of embedment and the strength reduction factors of FRP bent bars that are typically used as anchorages in concrete. From this test, a variety of data are acquired that are needed for design purposes. Material-related factors that influence the tensile response of bars and should therefore be reported include the following: constituent materials, void content, volume percent reinforcement, methods of fabrication, and fiber reinforcement architecture. Similarly, factors relevant to the measured tensile response of bars include specimen preparation, specimen conditioning, environment of testing, specimen alignment, and speed of testing. Properties, in the test direction, that may be obtained from this test method include:

5.1.1 Ultimate bend strength of the FRP bent bar and

5.1.2 Percentage of the guaranteed tensile strength of the straight portion of the bar that is retained in the bend location.

5.2 The results may be used for material specifications, research and development, and structural design and analysis.

NOTE 1—Two FRP bends are tested simultaneously in this test method, but in some cases only one bend may rupture. While resulting in a valid failure, notice should be taken that only one bend has been effectively measured and that the final compiled test results using this method could differ from those resulting from single FRP bend testing.

6. Interferences

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

6.2 *Loading Provisions*—The test is completed using a hydraulic jack that exerts equal and opposite forces onto two concrete blocks. The block containing the test section of the FRP bent bar must be free to translate so that force exerted on the bent bars can be accurately measured. Bending of the bent bars during casting of the concrete or testing of the specimen may cause premature failure outside of the bend. Every effort shall be made to minimize bending and uneven loading of the bent bars.

6.3 *Bend Geometry*—In this test standard, the bend in the FRP bar comprises a 90 degree change of direction with a constant radius of curvature through the bend. Bends other than 90 degrees may produce different test results, and are not covered by this standard.

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

6.5 *Variation Tolerance Between Actual and Standard Cross-Sectional Area*—All specimens shall have an actual cross-sectional area that varies no more than +20% and -0% from the bar's standard cross-sectional area

6.6 *Specimen Handling*—During the handling and preparation of specimens, all deformation, heating, outdoor exposure to ultraviolet light, and other conditions possibly causing changes to material properties of the specimen shall be avoided.

7. Apparatus

7.1 *Hydraulic Cylinder*—The hydraulic cylinder shall have force capacity in excess of the capacity of the specimen, and be capable of applying force at the required loading rate. Hand operated testing machines, electro-mechanical cylinders, or motorized pumps having sufficient volume in one or more strokes to complete a test may be used if they satisfy the loading provisions in 11.2.6.

7.2 *Force Indicator*—The testing apparatus force-sensing device (a load cell or similar) shall be capable of indicating the total force being carried by the specimen. This device shall be essentially free from inertia-lag at the specified rate of testing and shall indicate the force with an accuracy over the load range(s) of interest of within ± 1% of the indicated value, as specified by Practices E4.

7.3 *Environmental Test Chamber*—An environmental chamber is required for conditioning and test environments other than ambient laboratory conditions. These chambers shall be capable of maintaining the required relative temperature to within ±3°C [±5°F] and the required relative humidity level to within ±5% RH. In addition, the chambers may have to be capable of maintaining environmental conditions such as fluid exposure or relative humidity during the conditioning and testing.

7.4 The test set-up, shown in Fig. 1, consists of a hydraulic jack to distribute the applied force to the surface of the concrete. A plywood bearing pad 200 mm square and at least 6 mm deep [8 in. square and 0.25 in. deep] in conjunction with steel spreader plates 100 mm square and 6 mm deep [4 in. square and 0.25 in. deep], or similar provisions shall be used at the end of the actuator to spread the force on the concrete blocks and minimize bending forces on the bent bars. Hydraulic cylinder shall be placed in the same plane as the FRP bars, and shall be centrally located between the legs (± 6mm [0.25 in.]). The block containing the test section of the bar shall be placed on top of steel rollers to minimize the friction forces between the block and testing bed. When moving the specimens, special care shall be taken to avoid damaging or displacing the cast FRP bars.

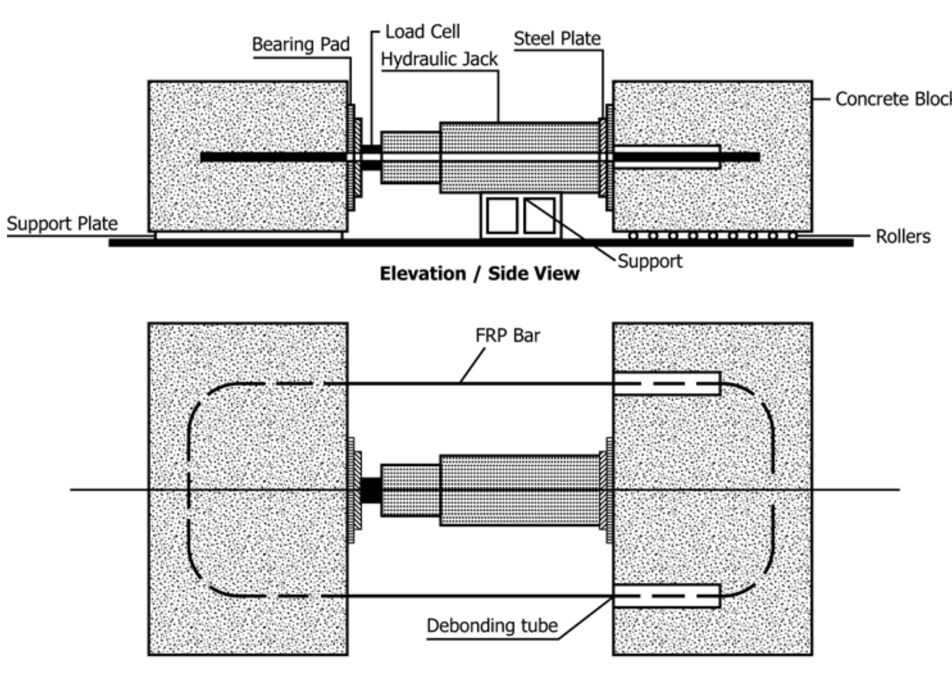

FIG. 1 Test Setup

8. Sampling and Test Specimens

8.1 *Sampling*—At least five specimens shall be tested per test condition. For statistically significant data, the procedures outlined in Practice E122 should be consulted. The method of sampling shall be reported.

8.2 *Geometry:*

8.2.1 FRP bent bars shall be representative of the lot or batch being tested. In general, specimens shall not be subjected to any processing beyond manufacturing.

8.2.2 The cross-sectional area of the FRP bent bar shall be based upon the standard area of the bar. The use of the actual cross-sectional area as described in section 6.4 is allowed if required, but shall be reported and used for all calculations.

8.2.3 Bend angle of FRP bar shall be 90 ± 5 degrees off of straight. Bend angle shall be measured and reported in section 14.1.1.8.

8.2.4 The configuration of a typical specimen is shown in Fig. 1.

8.2.5 The free length of the FRP bars between the two concrete blocks shall not be less than 200 mm [8 in.] with a suggested length of 400 mm [16 in.].

8.2.6 Concrete blocks are dimensioned as shown in Fig. 2. Steel stirrups are optional and may be required to prevent splitting of the concrete blocks prior to a valid FRP rupture in the case of large diameter FRP bars. Use of stirrups shall be reported. The concrete blocks shall be arranged in such a matter that each corresponding face is parallel to the other to ensure proper loading of the samples.

NOTE 2—In some cases, large diameter FRP bars may cause rupture of the concrete block's back face. An increased clear cover or horizontal steel stirrups may be used to prevent this rupture, but shall be reported.

8.2.7 FRP bent bar dimensions are variable, but shall have a tail length (L_t) of 12±1 bar diameters per bend to minimize slippage and to help ensure a valid failure mode. To allow for easier FRP bent bar production, two "C"-shaped bars arranged and used in the same manner as the single FRP bar shown in Fig. 2 may be used in place of a single FRP bar.

8.2.8 A debonding tube is to be used to eliminate straight-bar development of the bent bar. The debonding tube shall fit over the reinforcing bar and cover the straight length of the FRP bar up to the bent portion, and shall be capped or plugged to prevent the tube from filling with concrete during casting.

NOTE 3—The debonding tube may be made of any rigid or flexible encasement that exhibits a surface that will not bond to concrete during curing (such as PVC tubing or other suitable materials).

8.3 *Labeling:*

8.3.1 The specimens shall be labeled so that they will be distinct from each other and traceable back to the raw material, and in a manner that will both be unaffected by the test and not influence the test.

8.4 *Concrete Mix Properties:*

8.4.1 The concrete shall be a standard mixture, with coarse aggregates having a maximum dimension of 10 to 25 mm [3/8 to 1 in.]. It shall be batched and mixed in accordance with the applicable portions of Practice C192/C192M. Deviations to prevent concrete failure or to allow for rapid curing samples shall be reported.

NOTE 4—To ensure that the integrity of the bar is not compromised by the exothermic properties of rapid curing concrete, care is to be taken that the temperature of the bar does not overheat and exceed the T_g of the samples.

8.4.2 The concrete shall have slump of at least 100 + 20 mm [4 + 0.75 in.] in accordance with Test Method C143/C143M. The compressive strength at 28 days shall be at least 30 + 3 MPa [4350 + 400 psi] in accordance with Test Method C39/C39M. A minimum of five standard 150 × 300 mm [6 × 12 in.] or 100 × 200 mm [4 × 8 in.] control cylinders shall be made for determining compressive strength from each batch of concrete.

9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. Conditioning

10.1 Condition per Procedure C of Test Method D5229/D5229M; store at standard laboratory atmosphere (23±3°C

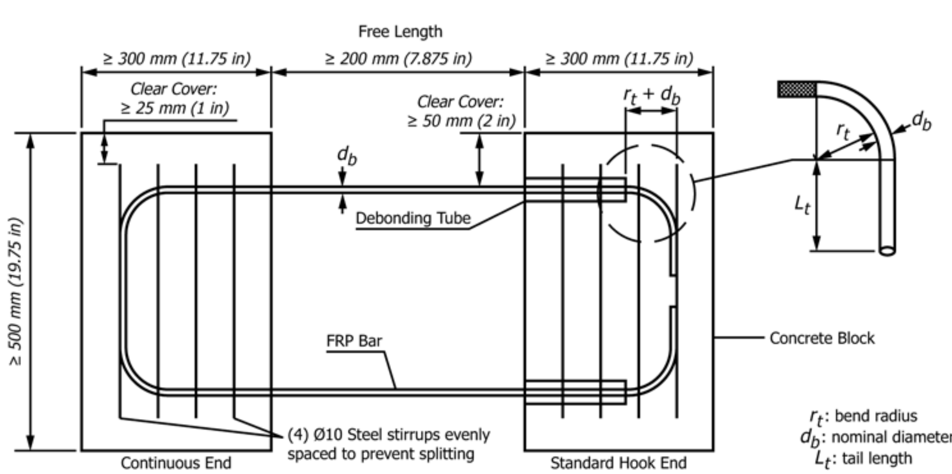

FIG. 2 Specimen Configuration

[73±5°F] and 50±10% RH) unless a different conditioning environment is specified as part of the experiment

11. Test Procedure

11.1 Parameters to be specified prior to test:

11.1.1 The specimen sampling method, specimen type and geometry, conditioning, and the geometry of any traveler samples shall be identical,

11.1.2 The tensile properties and data reporting format desired,

11.1.3 The environmental conditioning test parameters, and

11.1.4 If performed, the sampling method, specimen geometry, and test methods used to determine density, void fraction, and reinforcement volume.

11.2 *General Instructions:*

11.2.1 Determine the standard cross-sectional area of a straight segment of a typical bent bar as described in section 6.4. If necessary, the actual cross-sectional area may be used in place of the standard cross-sectional area. The chosen cross-sectional area shall be used for all calculations and shall be reported in section 14.1.1.7.

11.2.2 Determine the FRP additional bent bar's geometric properties, including the bend radius (measured to the nearest 3 mm [0.125 in.]), the bend angle (measured to the nearest degree), lengths of individual bar legs (measured to the nearest 3 mm [0.125 in.]), and the tail length (measured to the nearest 3 mm [0.125 in.]).

11.2.3 If specific gravity, density, reinforcement volume fraction or void volume fraction are to be reported, use Test Methods D792 (specific gravity, density) and Test Methods D3171 (reinforcement and void volume fractions) for the determination of these properties and select specimens from the same batch of bent bars as those used for the bend strength specimens.

11.2.4 The tensile strength of straight FRP bars with the same standard diameter as the FRP bent bars and straight portions of FRP bent bars shall be evaluated according to Test Method D7205/D7205M. If the straight portion of an FRP bent bar is not sufficiently long enough to conduct Test Method D7205/D7205M testing, a straight bar from the same manufacturing process and composed of the same materials and proportions of materials as the FRP bent bar being tested may be tested. Value shall be calculated using the same cross-sectional area (standard or actual) as was chosen in section 11.2.1.

11.2.5 Unless otherwise specified as part of the experiment, the tests shall be conducted at the standard laboratory atmosphere, 23 ± 3°C [73 ± 5°F] and 50 ± 10% relative humidity.

11.2.6 Taking care not to subject the specimens to any shock, bending, vibration, or torsion, increase the force in the cylinder until the specimen fails. The loading rate shall be selected so that the specimens fail between 1 and 10 minutes from the start of the test. The suggested standard strain rate is 0.01 per minute. If strain control is not available on the testing machine, a nominal piston speed of 0.01 per minute times the specimen free length selected shall be used.

11.2.7 A valid failure is achieved when an FRP rupture or FRP bar slip mode of failure is observed in at least one bent portion of the FRP bent bars.

11.2.8 Specimens failing by way of splitting the concrete block shall be discarded and an additional test shall be performed on a separate specimen of the same lot. If splitting occurs, block dimensions may be increased and steel stirrups may be included in the blocks as necessary.

12. Validation

12.1 Record the applied force at failure and the failure mode for the specimen. If necessary to determine the failure mode, the block shall be split after the test.

13. Calculations

13.1 The bend strength of the FRP bent bar shall be calculated according to Eq 1 and rounded to three significant digits.

$$F_{fb} = \frac{P_{fb}}{2A} \tag{1}$$

where:

F_{fb} = bend strength of the FRP bent bar, MPa [psi]
P_{fb} = ultimate force measured in the bend test, N [lbf], and
A = standard cross-sectional area of single leg of the FRP bent bar as described in section 8.2.2, mm^2 [in.^{2}]. Actual cross-sectional area may be used if required and is calculated as described in section 6.4. The chosen cross-sectional area shall be used for all calculations and shall be reported in section 14.1.1.7.

13.2 The percent of tensile strength retained in the bend is calculated according to Eq 2 and shall be rounded to three significant digits.

$$\chi = \frac{F_{fb}}{F_{fu}} \times 100 \tag{2}$$

where:

χ = percentage of the guaranteed tensile strength of the straight portion of the bar that is retained in the bend location; and
F_{fu} = average ultimate tensile strength parallel to the fibers according to Test Method D7205/D7205M, MPa [psi]. Value shall be calculated using the same cross-sectional area as was used previously in Eq 1.

13.3 *Statistics*—For each series of tests, calculate the average value, standard deviation, and coefficient of variation (in percent) of the resulting bend strength and strength reduction factors as follows:

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

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

$$CV = 100 \times S_{n-1}/\bar{x} \tag{5}$$

where:

$\bar{x}$ = simple mean (average),
S_{n-1} = sample standard deviation,

CV = sample coefficient of variation, in percent,
n = number of specimens, and
x_i = measured or derived property

14. Report

14.1 The test report shall include the following items.

14.1.1 Common items:

14.1.1.1 The trade name, shape, lot number, and, if available, date of manufacture of the FRP bent bars tested.

14.1.1.2 Description of the surface characteristics of the FRP bent bar, including the representative length (Test Method D7205/D7205M) if appropriate.

14.1.1.3 If available from the bar manufacturer, fiber manufacturer, fiber description, fiber lot number, resin system manufacturer, resin system description, and resin system lot number.

14.1.1.4 Upon request, specific gravity, density, and fiber and void volume fractions of the FRP bent bars, and their methods of determination.

14.1.1.5 If available from the bar manufacturer, the process used to fabricate the bent bars.

14.1.1.6 Numbers or identification marks of test bent bars.

14.1.1.7 FRP bent bar designation, diameter, and cross-sectional area. Method of establishing cross-sectional area (actual area or standard area).

14.1.1.8 Bend radius, bend angle, and tail length of FRP bent bar for each sample.

14.1.1.9 Dimensions of concrete block, configuration (diameter and spacing) of steel stirrup confinement (if used), debonded length.

14.1.2 Items related to the properties of concrete:

14.1.2.1 The mixture proportions of cement, fine aggregate, coarse aggregate, admixture (if used), and the water-to-concrete ratio.

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

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

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

14.1.3 Items related to bend strength testing:

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

14.1.3.2 Preconditioning performed on specimens.

14.1.3.3 Date of testing.

14.1.3.4 Calibration dates and methods for all measurement and test equipment.

14.1.3.5 Test temperature and relative humidity during testing.

14.1.3.6 Type and capacity of force indicator.

14.1.3.7 Type and capacity of force actuator.

14.1.3.8 Description of provisions made for: spreading the actuator force on the concrete block, minimizing bending of the specimen during loading, and eliminating drag on the block containing the test section.

14.1.3.9 Results of load system alignment evaluations, if any such evaluations were done.

14.1.3.10 Duration of test, bend strength, and strength reduction factor for each test specimen.

14.1.3.11 Population size, average bend strength, and average strength-reduction factor for the specimens that failed in the bend as intended. Include standard deviation and coefficient of variation.

14.1.3.12 Failure mode and location of failure for each specimen.

15. Precision and Bias

15.1 *Precision*—The single lab repeatability has been determined for commercially available FRP bars of conventional U.S. trade sizes No. 4 and No 5. These results are shown in Table 1. The data in Table 1 was developed using the inch-pound version of this test method. The indices shown in SI units are exact conversions of the values in inch-pound units. Attempts to develop a full precision statement have been unsuccessful. For this reason, full data on precision cannot be given. Anyone wishing to participate in the development of precision data should contact the Chairman, D30.10 ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

15.2 *Bias*—This test method has no bias because the values determined can be defined only in terms of the test method.

16. Keywords

16.1 bent bar; bend strength; concrete reinforcement; fiber reinforced polymer (FRP); stirrup

TABLE 1 Single Lab Repeatability Data for Bent Bar Tests of No. 4 and No. 5 Bars

Bar Size	n	χ	Bend Strength (F_{jb})					
			$\bar{x}$		S_{n-1}		r	
			MPa	psi	MPa	psi	MPa	psi
No. 4	5	76.8 %	530	76 800	55.6	8060	156	22 600
No. 5	6	90.9 %	564	81 800	61.8	8960	173	25 100