Abstract

Recent efforts in the United States have led to the standardization of test methods for FRP composites for reinforcing and repairing concrete. These efforts are transitioning standards, originally published by the American Concrete Institute (Committee 440K), as ASTM standards under ASTM Committee D30, Composite Materials. One of the methods recently published involves the transverse shearing of FRP rods. FRP rods come under shear loading as represented by this test, when crossing an inadvertent or intentional transverse cracks, such as when they are used as dowels in concrete pavements or as shear reinforcements in cracked wood timbers. This paper will briefly review the six test methods that have been published under ASTM D30. The paper reviews the recently published ASTM test method on transverse shear, which has been developed using a modular fixture to allow for shearing of smooth and deformed bars with a diameter of 10 mm (#3) to 32 mm (#10). The paper provides test results on commercial rebar produced in North America.

Keywords: FRP concrete reinforcements, test methods, transverse shear
1. Introduction

The use of FRP composite materials in civil engineering infrastructure applications has grown significantly over the last 20 years [1]. These applications have included the use of stand-alone composites for use in bridges and buildings, and the use of composites as components in conjunction with traditional structural materials: wood, steel and Portland cement concrete. This paper focuses on the development of composite materials for use with concrete, and specifically on the development of test methods for the assessment of these specialized materials. To provide an example of test method development and validation, the paper focuses on the development of a method for determining the transverse shear of FRP rods used for internal concrete reinforcement.

Figure 1 illustrates the maturation of the infrastructure composites industry. In civil engineering practice, the emergence of new structural material systems necessitates the development of three classes of information: design guidelines, material specifications, and test methods. In North America, much of this development has taken place within three organizations: the American Society for Civil Engineers (ASCE), the American Concrete Institute (ACI) and ASTM International.

![Figure 1. Stages in the Development of a “Composites for Infrastructure” Market](image)

Design guidelines, which outline procedures for calculations of permissible element forces and material stresses, are adopted by the national building codes and act as the mandatory procedures for designing building structures in the given material system. Existing design guidelines for FRP concrete reinforcements the ACI Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars [2]. Material specifications identify the type of materials that may be used for a given application, and the tests that must be performed to characterize and qualify the materials. A comprehensive blueprint for material specifications for infrastructure composites has been published by Bank et al. [3]. An application-specific specification for composite reinforcements for concrete has been published by the American Concrete Institute [4]. In the United States, the development of test methods takes place mostly within ASTM – and the development of these methods is the primary focus of this paper.

2. ASTM Test Methods for FRP Composite Reinforcements

ASTM test methods for polymeric composite materials have primarily been promulgated through technical Committees D20 (Plastics) and D30 (Composite Materials). Since 2006,
ASTM Subcommittee D30.05 (Structural Test Methods) has been refining standards developed by ACI Committee 440K, first published in 2004 [5], into ASTM test methods. The test method development has transitioned from ACI to ASTM, per an agreement between the two organizations. This activity has resulted in the publication of six ASTM standards (Table 1). These methods cover materials used for internal concrete reinforcements, as well as externally-bonded FRP materials typically used for structural repairs. The original ACI guide methods have been revised and improved through the ASTM balloting and revision process, with additional laboratory testing and test fixture development taking place for many of the standards.

Table 1. ASTM D30 test methods.

<table>
<thead>
<tr>
<th>ASTM No.</th>
<th>Title</th>
<th>Publication Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>D7617</td>
<td>Standard Test Method for Transverse Shear Strength of Fiber Reinforced Polymer Matrix Composite Bars</td>
<td>2011</td>
</tr>
<tr>
<td>D7522</td>
<td>Standard Test Method for Pull-Off Strength for FRP Bonded to Concrete Substrate</td>
<td>2009</td>
</tr>
<tr>
<td>D7616</td>
<td>Method For Determining Apparent Overlap Splice Shear Strength Properties Of Wet Lay-Up Fiber-Reinforced Polymer Matrix Composites Used For Strengthening Civil Structures</td>
<td>2011</td>
</tr>
</tbody>
</table>

A brief description of five of the test methods appears below. A more detailed explanation of the transverse shear test method (ASTM D7617) follows.

2.1 Test Methods for Internal Concrete Reinforcements

2.1.1 ASTM D7205: Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars

ASTM D7205 describes the method for sampling, conditioning, gripping and testing a composite rebar in tension [6]. Because these bars have textured coatings or undulating surfaces (from irregular molds and/or spiral wraps), it is not typically possible to grip them in a collet and still achieve a valid test result. The method therefore provides for an internally-threaded sleeve to be placed over the ends of the bar, and bonded to the bar with either a cementitious or polymeric grout. Once the grout is cured, this anchor is used to fix the specimen into the testing machine. Although this is the recommended anchor, but other gripping techniques are permitted as long as consistent stock break failures are achieved.

The method also provides guidance for calculating the cross-sectional area of bars with irregular cross-sections. This so-called nominal cross-sectional area is determined by
immersing bars of a known length in a fluid to determine the volume of fluid displaced (Archimedes method). In the United States, steel reinforcing bars are sold in standard sizes, with standard cross-sectional areas. Many manufacturers supply composite reinforcing bars according to this standard, so the method also allows for tensile strength and modulus to be calculated according to these standard areas, as given in ASTM A615 [7].

2.1.2 ASTM D7337: Standard Test Method for Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars

ASTM D7337 assesses the ability of composite bars to withstand sustained loading by establishing the tensile creep-rupture capacity of the bars [8]. The method relies on the tension testing method (D7205) for test fixtures and anchors, and requires that tension testing be used to establish the baseline tensile strength of the bar. A series of four creep-rupture tests with 5 specimens each are performed. The series with the highest load level (shortest time to creep rupture failure) must contain at least 4 specimens whose failure time is greater than one hour. The series with the lowest load level (longest time to creep rupture failure) must contain at least one specimen whose failure time is greater than 8000 hours. In this way, the creep-rupture times will span at least three decades. Based on test results, the method provides calculations for the million-hour creep rupture capacity of the bar.

2.2 Test Methods for External Concrete Reinforcements


The ASTM D7565 test standard, first published in 2009, describes requirements for sample preparation, tensile testing, and results calculation for wet-layup or pre-impregnated composite laminates intended to be fabricated and installed in the field [9]. The composite may be a 0-degree unidirectional laminate or a cross-ply (0/90-type) laminate with elastic symmetry about the mid-plane. Continuous and discontinuous fibers are permitted. The principal test variables could be, for example, the material constituents and fabrication method, the size of the specimen, or the type of laminate. The test results can be used for material specifications, quality control and assurance, structural design and analysis, and research and development. Laminates may be fabricated at field sites (e.g., witness panels) or in shop environments.

2.2.2 ASTM D7522: Standard Test Method for Pull-Off Strength for FRP Bonded to Concrete Substrate

The quality, integrity and overall performance of bonded FRP retrofit systems are largely dependent on adhesion of the FRP system to the concrete substrate. ASTM D7522 provides a simple method for acceptance testing of bonded FRP systems [10].

The D7522 test method was developed to assess the adhesion of FRP plates or wet lay-up fabrics used for concrete repair. The ‘pull-off strength’ derived from this test method can be used in the control of the quality of adhesives and in the theoretical equations for designing FRP systems for external reinforcement. The D7522 test method involves adhering a rigid disk to the surface of the FRP to be tested. The test sample is isolated from the surrounding FRP by a circular hole produced using a core drill. Using a pull-off test apparatus the disk is subject to gradually increasing direct tension perpendicular to the plane of the FRP until a plug of material is detached exposing the plane of limiting strength within the system. The nature of the failure is qualified in accordance with the percent of adhesive and cohesive failures, and the actual interfaces and layers through which the failure occurs. The pull-off strength is computed based on the maximum indicated force and the size of the plug.
2.2.3 ASTM D7616: Method For Determining Apparent Overlap Splice Shear Strength Properties Of Wet Lay-Up Fiber-Reinforced Polymer Matrix Composites Used For Strengthening Civil Structures

ASTM D7616 provides a standardized procedure for preparing and testing overlap shear splice samples using wet lay-up composite materials [11]. Overlap shear splices of wet lay-up composite sheets are commonly used in external strengthening applications for reinforced concrete structures. Typical scenarios include cases where the entire surface of the concrete being strengthened is inaccessible or where the overall length of a single saturated laminate would be difficult to manage. Because the composites cure in situ and shear stress can be transferred from one laminate to another without the addition of a supplementary adhesive material, overlap shear splices provide a convenient means for extending the coverage of wet lay-up composites over large areas.

This standard includes guidance for sizing overlap shear splice panels, which are subsequently cut into 1 in wide specimens for tensile testing. Some latitude is given to the user in specifying the length of the overlap splice, and panel dimensions are specified for 1 in, 2 in, 3 in, 4 in, 6 in, and 8 in overlaps. The standard refers to other established test methods for the creation of the test specimen (ASTM 7565) and the tension testing of the cured coupons (ASTM D3039).

3. ASTM D7617: Standard Test Method for Transverse Shear Strength of Fiber Reinforced Polymer Matrix Composite Bars

The remainder of the paper discusses ASTM D7617 in more detail. ASTM D7617 describes the method for sampling, conditioning, fixturing and testing composite reinforcing bars and smooth round rods in transverse shear [12]. FRP bars are loaded in transverse shear as a consequence of dowel action in reinforced concrete beams. They may also be inserted as dowels at joints in concrete pavements, or be used to reinforced concrete or other materials in direct shear. Researchers that have focused on applications for FRP bars loaded in transverse shear include: Amy and Svecova (shear strengthening of timber) [13], Dulude et al. (punching shear strength of GFRP-reinforced concrete) [14], Eddie et al (dowels in concrete pavements) [15] and Gentry (shear strengthening of glued-laminated timber) [16]. A recent paper by Gentry describes the transverse shear test method in greater detail, and outlines the use of the method for durability testing of GFRP bars [17].

3.1 Summary of the Transverse Shear Test

The transverse shear test fixture cradles a 225 mm length of bar, supported along its length except for a 25 mm gap centered on the length of the bar. The bar is pressed down onto the supporting seat with set screws to hold it in place. A steel blade, 25 mm thick and machined to fit snugly around the bar, is pressed on the bar with a universal testing machine, causing the middle 25 mm section to be sheared from the bar. Two lower blades, with the same diameter slots as the upper blade, support the bar adjacent to the shearing planes. Two shear planes are formed during the test so that the bar fails in double shear. The transverse shear test fixture is shown in Fig. 2(A), along with a section of 9.5 mm diameter smooth rod that has been sheared in the fixture. The upper blade is shown sitting loose at the upper left of the fixture. In Fig. 2(B), the lower assembly is shown disassembled. The fixture comes apart to allow for swapping of the lower blades, which are specific to the diameter of the bar being sheared.

The standard calls for the test to be completed by inserting the assembled fixture into a universal compression machine, and compressing the upper blade with the machine in displacement control. According to the draft standard, the displacement rate should be selected so that the test article fails at a time between 1 and 10 minutes.
3.2 Transverse Shear Test Results

The primary test result is the transverse shear stress, calculated as the one-half of the peak failure load (to account for double shear) divided by the cross-sectional area of the specimen. Two typical stress-displacement diagrams, taken from 9.5 mm round rods, are show in Fig. 3. In Fig. 3(A), the diagram exhibits the results typically observed when two shearing faces form simultaneously (this is the most common result). In Fig. 3(B), the observed results are indicated when one face forms and begins to shear, and the second face forms somewhat later during the test. Note that the slope of the diagram is not consistent, and that no useful stiffness or “modulus” value is provided by the test.

3.3 Typical Test Results on Commercial GFRP Bars

Two suppliers of GFRP reinforcing bars in North America provided bars for testing in the prototype fixture. Bar “A” has a helical wrap with a moderate amount of abrasive surface material to promote bond. Bar “B” is highly textured, with a significant amount of larger-size abrasive material. The transverse shear strength of the six most commonly-specified bar sizes are given in Table 2 below. The bars were tested at displacement rates leading to shear failures at approximately three minutes into the loading regime (earlier work by the author has shown that test results are sensitive to displacement rates [17]). The cutting blades were the same for the both the “A” and “B” bars, and were machined to fit as tightly as possible on the bars, without necessitating the removal of any of the surface texture on the bars. The transverse shear strength is calculated using the so-called “standard” cross-sectional area for U.S. reinforcing bars per ACI 440.6-08 [4] – and as given in ASTM A615 [7].

The tests show that the average transverse shear strength in GFRP bars is around 200 MPa. This is almost 4 times the likely interlaminar shear strength that would be observed in a short-beam or other test aimed at assessing the unconfined shear strength of the bar [18]. The data shows little variability, with coefficients of variation well below that expect in tension tests of GFRP rebar [19]. There exists a modest downward trend of transverse shear strength as function of bar size. This trend is more noticeable in the type”B” GFRP bars.
Figure 3. Example stress-displacement diagram from transverse shear tests. In test (A) both failure surfaces form simultaneously, in test (B) the second failure surface forms after the first failure surface.

Table 2. Transverse shear strength of commercially-produced GFRP bars.

<table>
<thead>
<tr>
<th>U.S. Bar Size</th>
<th>Nominal Diameter (mm)</th>
<th>Standard Cross-Sectional Area (mm²)</th>
<th>Bar Type “A” Transverse Shear Strength (MPa)</th>
<th>COV</th>
<th>Bar Type “B” Transverse Shear Strength (MPa)</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>#3</td>
<td>10</td>
<td>71</td>
<td>212.5</td>
<td>2.62%</td>
<td>235.3</td>
<td>4.74%</td>
</tr>
<tr>
<td>#4</td>
<td>13</td>
<td>129</td>
<td>209.7</td>
<td>1.36%</td>
<td>192.5</td>
<td>1.99%</td>
</tr>
<tr>
<td>#5</td>
<td>16</td>
<td>200</td>
<td>199.2</td>
<td>2.07%</td>
<td>188.3</td>
<td>4.44%</td>
</tr>
<tr>
<td>#6</td>
<td>19</td>
<td>284</td>
<td>203.0</td>
<td>3.10%</td>
<td>181.3</td>
<td>6.37%</td>
</tr>
<tr>
<td>#7</td>
<td>22</td>
<td>387</td>
<td>204.1</td>
<td>1.42%</td>
<td>173.7</td>
<td>2.54%</td>
</tr>
<tr>
<td>#8</td>
<td>25</td>
<td>509</td>
<td>200.5</td>
<td>1.67%</td>
<td>162.3</td>
<td>2.63%</td>
</tr>
</tbody>
</table>

4. Conclusions

The publication of test methods for infrastructure composites indicates that the market for FRP concrete reinforcing materials is maturing. These test methods, along with design guidelines and material specifications, are providing engineers with the technical basis to design and rehabilitate concrete structures with composite materials.

The transverse shear test method is useful for characterizing the strength of a bar crossing a tight crack or joint, but the method does not provide a general shear strength for design in other situations.

5. Acknowledgements

Figures 2 and 3 as published in the text are adapted, with permission, from ASTM D7617/D7617M-11, all copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.
6. References


