FRP Bars—From Certification to Field Use

A summary of key documents needed for implementation of FRP reinforcing bars

by Antonio Nanni

Interest in fiber-reinforced polymer (FRP) bars for concrete reinforcement is undoubtedly growing. However, as would be the case for any new technology introduced in the construction industry, this interest is not matched by the availability of consensus-based, well-established, and well-recognized standards and specifications. Owners, engineers, and contractors do not necessarily know which tools are at their disposal for safely mandating, specifying, designing, procuring, constructing, and inspecting FRP-reinforced concrete structures. Similarly, manufacturers of FRP bars may not know what needs to be done to have their products qualified (certified) and ultimately accepted for use in construction projects.

The purpose of this article is to present specifications related to FRP as well as the process from certification to field implementation of FRP reinforcement in reinforced concrete (RC) structures in the United States. The article focuses on documents currently available and adopted by various departments of transportation (DOTs) and building officials.

ASTM Specification Compliance

ASTM D7957/D7957M[1] is a material standard specification for solid round glass-vinyl ester FRP bars. It provides physical and mechanical limits and prescribes both qualifying characterization tests and quality control tests to be performed; it does not address design. This specification is currently referenced in the AASHTO GFRP-RC Guide Spec. 2018[2] and ICC-ES AC454.[3] Although the ACI 440.1R design guide[4] doesn't reference this specification, the new building code for GFRP-reinforced concrete, currently under development by ACI Committee 440, Fiber-Reinforced Polymer Reinforcement, certainly will.

There are also other ASTM test methods pertaining to the use of FRP bars that are referenced in the ASTM D7957/D7957M material specification. As these test methods have evolved over time, it has been found that there is a need to define some basic material properties in documents such as the ASTM D7205/D7205M[5] tensile test method. Further, some inconsistencies have been discovered in terminology and definitions (including, for example, bar diameter tolerances). While many of these conflicts have been resolved, some continue to result in confusion.

The following section discusses implications of ASTM D7957/D7857M for certification, design, procurement, and quality assurance; and it demonstrates these conflicts through a discussion of two hypothetical bar manufacturers. Only SI system units are used in the discussion of the products made by these manufacturers.

Implications

To understand the implications of ASTM D7957/D7957M, only geometrical and tensile properties are discussed herein for simplicity and because they directly affect design and procurement.

Consider that two manufacturers, identified as Pultruder A and Pultruder B, are making M16 (No. 5) GFRP bars meeting the material requirements listed in Table 2 and 3 of ASTM D7957/D7957M (Fig. 1). While Table 2 (Fig. 1(a)) shows the minimum thresholds in terms of properties with the respective test methods, Table 3 (Fig. 1(b)) provides the cross-sectional area ranges and the minimum guaranteed tensile force.

With reference to Fig. 1(b) and Fig. 2, an important observation is made with respect to area limits. To accommodate various forms of bond-enhancing surface treatments for FRP bars, ASTM D7957/D7957M introduces the concept of using the Archimedes method (by specific gravity with tolerances) to determine the "measured cross-sectional area" of a bar. Although this value must be reported, geometric and mechanical properties are determined using the nominal dimensions listed in ASTM D7957/D7957M Table 3 (Fig. 1(b)). The under-allowance for bar areas based on the nominal areas varies between 6 and 9%, while the over-allowance varies between 72 and 9% with increasing bar size (Fig. 2). Clearly, surface deformations needed for bond, such as sand coating, cannot be scaled and have a major impact on smaller-size bars. Further, the values of the guaranteed force

TABLE 2 Property Limits and Test Methods for Quality Control and Certification[A,B]

Property	Limit	Test Method
Fiber Mass Content	≥70 %	ASTM D2584 or ASTM D3171
Glass Transition Temperature	Midpoint temperature ≥100 °C [212 °F]	ASTM E1356
Degree of Cure	≥95 %	ASTM E2160
Measured Cross-Sectional Area	Table 3	ASTM D7205/D7205M, subsection 11.2.5.1
Ultimate Tensile Force	Table 3	ASTM D7205/D7205M
Tensile Modulus of Elasticity	≥44 800 MPa [6 500 000 psi]	ASTM D7205/D7205M
Ultimate Tensile Strain	≥1.1 %	ASTM D7205/D7205M
Moisture Absorption in 24 h	≤0.25 % in 24 h at 50 °C [122 °F]	ASTM D570, subsection 7.4

[A]For the determination of each of the property limits, five random samples shall be obtained from each production lot. Each individual sample shall satisfy the property limits.
[B]For bent bars, the tests are performed on the straight portion of the bars.

(a)

TABLE 3 Geometric and Mechanical Property Requirements

Bar Designation No.	Nominal Dimensions		Measured Cross-Sectional Area Limits mm² [in.²]		Minimum Guaranteed Ultimate Tensile Force kN [kip]
	Diameter mm [in.]	Cross-Sectional Area mm² [in.²]	Minimum	Maximum	
M6 [2]	6.3 [0.250]	32 [0.049]	30 [0.046]	55 [0.085]	27 [6.1]
M10 [3]	9.5 [0.375]	71 [0.11]	67 [0.104]	104 [0.161]	59 [13.2]
M13 [4]	12.7 [0.500]	129 [0.20]	119 [0.185]	169 [0.263]	96 [21.6]
M16 [5]	15.9 [0.625]	199 [0.31]	186 [0.288]	251 [0.388]	130 [29.1]
M19 [6]	19.1 [0.750]	284 [0.44]	268 [0.415]	347 [0.539]	182 [40.9]
M22 [7]	22.2 [0.875]	387 [0.60]	365 [0.565]	460 [0.713]	241 [54.1]
M25 [8]	25.4 [1.000]	510 [0.79]	476 [0.738]	589 [0.913]	297 [66.8]
M29 [9]	28.7 [1.128]	645 [1.00]	603 [0.934]	733 [1.137]	365 [82.0]
M32 [10]	32.3 [1.270]	819 [1.27]	744 [1.154]	894 [1.385]	437 [98.2]

(b)

Fig. 1: ASTM D7957/D7957M[1] requirements for GFRP bars: (a) property limits and corresponding test methods for quality control and certification; and (b) geometric and mechanical properties (copied from Reference 1)

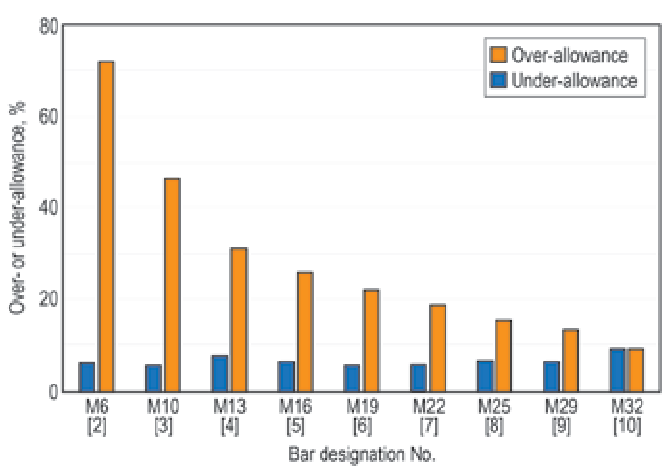

Fig. 2: ASTM D7957/D7957M under- and over-allowances for bar areas for different bar sizes

reported in Table 3 are the sample average minus three standard deviations, while the measured areas and the elastic modulus (with minimum listed in Table 2) are computed as the sample average. The guaranteed force is a function of the bar cross-sectional area and, if the guaranteed strength is computed based on the nominal or measured area, its value decreases with the increase of the bar size due to a well-known composites' phenomenon called shear-lag.[6] Conversely, the tensile elastic modulus is known to remain constant irrespective of the bar size.

Both the ultimate force and the elastic modulus of FRP bars are determined using the ASTM D7205/D7205M test method, where the modulus is calculated based on the nominal area as stipulated in the standard. ASTM D7205/D7205M currently states that the measured area should be used when the difference between measured and nominal areas exceeds 20%. Because ASTM D7205/D7205M was issued before ASTM D7957/D7957M, this requirement is no longer applicable, and the nominal area is always used. Work on future iterations of D7205/D7205M can be expected to harmonize the terminology and definitions with those used in D7957/D7957M.

Certification: Pultruder A and Pultruder B each make M16 bars with the properties shown in Table 1. Both bars pass based on the values listed in columns 4, 5, and 6. Thus, the M16 bars from both manufacturers will be certified if the limits on all other properties as stipulated in the specification are also met. If certification would require a modulus based on measured area, however, bars from Pultruder B would not pass.

Design: The design of an FRP-RC structure using bars compliant with ASTM D7957/D7957M follows AASHTO GFRP-RC Guide Spec. 2018 or the ACI 440.1R design guide, depending on the intended use (that is, transportation structure or building structure). Irrespective of the use, the engineer of record (EOR) designs the structural element(s) using the nominal M16 tensile parameters: $E = 44{,}800$ MPa and $f_{fu} = 130{,}000/199 = 653$ MPa.

At the time of the design, the EOR does not know whether bars will be supplied by Pultruder A or Pultruder B because the selection and purchase of a specific bar is a prerogative of the contractor, provided that the bar is certified. Designs can only be based on nominal properties as listed in the material specifications, although in the case of transportation

Table 1:
Geometrical and tensile properties of M16 bars as produced by Pultruder A and B

Pultruder	Nominal diameter, mm	Nominal area, mm^2	Measured area, mm^2	Guaranteed force, kN	Elastic modulus,* MPa	Elastic modulus,† MPa	Pass, Y/N
A	15.9	199	195	131	44,850	45,770	Y
B	15.9	199	235	150	49,000	41,494	Y

*Based on nominal area.

†In the United States, the modulus calculated on measured area is used for neither certification nor for design.

Table 2:
Geometrical and tensile properties of No. 5 bars produced by Pultruder A and B

Pultruder	Nominal diameter, in.	Nominal area, $in.^2$	Measured area, $in.^2$	Guaranteed force, kip	Elastic modulus,* ksi	Elastic modulus,† ksi	Pass, Y/N
A	0.625	0.31	0.29	29.2	6550	7002	Y
B	0.625	0.31	0.37	32.1	7150	5991	Y

*The modulus is calculated based on the nominal area.

†For FDOT, the modulus calculated on measured area is used for neither certification nor design.

structures, some state DOTs have developed their own specifications.

Procurement: The contractor awarded the project, as designed by the EOR, needs to purchase certified bars. The contractor would likely select the supplier (Pultruder A or Pultruder B) with the least costly bars.

Quality assurance (field acceptance): ASTM D7957/D7957, Section 10.2, Quality Control and Certification, currently states: "For the determination of each of the property limits, five random samples shall be obtained from each production lot. Each individual sample shall satisfy the property limits as given in Table 2." Further, Paragraph 10.4 states: "Samples from each production lot to be used for preparing test specimens shall be selected by the manufacturer on a random basis."

These requirements are considered onerous and unreasonably penalizing, as eight independent properties need to be determined using five repetitions. In addition, it is not clear if the standard requires the manufacturer to compute guaranteed values from the five repetitions. New language is expected to be proposed for the specification's revision (currently in progress).

FDOT Compliance

Section 932-3 of the Florida DOT (FDOT) Standard Specifications[7] contains material requirements for FRP reinforcing bars used in highway projects and related construction contracts as referenced in the contract documents for transportation projects in Florida. This specification does not address design, which is referenced in FDOT "Fiber Reinforced Polymer Guidelines (FRPG)."[8] The FRPG states that the design of all concrete members containing GFRP reinforcing bars shall be in accordance with the AASHTO GFRP-RC Guide Spec. 2018. Further, the FRPG allows the use of basalt FRP (BFRP) bars, and it prescribes the same design criteria for BFRP as for GFRP.

The following section discusses implications of FDOT and AASHTO requirements for certification, design, procurement, and quality assurance. Further, it demonstrates potential conflicts through a discussion of two hypothetical bar manufacturers. Note that only U.S. customary system units are used in the discussion of the products.

Implications

Consider that Pultruder A and B are making No. 5 GFRP (or BFRP) bars meeting the material requirements of Section 932-3 of FDOT Standard Specifications, listed in Table 932-6 and 932-7 (Fig. 3). (Note: FDOT updates specifications on a semiannual basis as needed, so these tables may change accordingly. For the latest version, refer to **www.fdot.gov/programmanagement/implemented/specbooks/default.shtm**.)

Because both manufacturers meet requirements of Section 105, Contractor Quality Control General Requirements, of FDOT Standard Specifications, it is also assumed that they are currently listed in the FDOT's Production Facility Listing available at **www.fdot.gov/materials/quality/programs/qualitycontrol/materialslistings/postjuly2002.shtm**.

Certification: Pultruder A and B each make No. 5 bars with the properties shown in Table 2. Bars from both manufacturers pass based on the values listed in columns 4, 5, and 6. Thus, these No. 5 bars are certified (if the limits on all other properties as stipulated in the specification are also met) and these manufacturers can be listed in FDOT Production Facility Listing.

If certification would require a modulus based on measured area, bars from Pultruder B would not pass.

Design: The design of an FRP-RC structure per Section 932-3 of FDOT Standard Specifications follows AASHTO GFRP-RC Guide Spec. 2018. The EOR designs the structural element using the nominal No. 5 bar tensile parameters: $E = 6500$ ksi and $f_{fu} = 29.1/0.31 = 93.9$ ksi.

As in the previous example, the EOR does not know which manufacturer (Pultruder A or Pultruder B) will supply bars for the project.

Procurement: The contractor awarded the project needs to purchase certified bars from a manufacturer in the FDOT Production Facility Listing. Because in this case both manufacturers are listed, the selection might be based on best price.

Quality assurance (field acceptance): The EOR will sample some of the bars supplied to the site and have them tested for quality assurance. The current language in the FDOT Standard Specifications, Section 932-3.4.1 Sampling, reads as follows:

"The Engineer will select a minimum of six straight bars with minimum lengths of 7 feet each and a minimum of five bent bars from each shipment, representing a random production LOT, per bar size of FRP reinforcing for testing in accordance with Table 932-9. Testing shall be conducted, at the Contractor's expense, by a Department approved independent laboratory. Each test shall be replicated a minimum of three times per sample. Submit the test results to the Engineer for review and approval prior to installation. Testing will not be required for bars to be used solely as reinforcement for sheet pile bulkheads, but LOT samples will still be selected and retained by the Engineer until final acceptance of the work."

Based on requirements listed in Table 932-9 (Fig. 4), laboratory tests of sampled specimens must demonstrate that each specimen has $E \geq 6500$ ksi (based on nominal area) and $F_t \geq 93.9$ ksi.

Ohio DOT Specification Compliance

Section 705.28 of Ohio DOT (ODOT) "Construction and Material Specifications"[9] (C&MS) is a material specification standard that refers to ASTM D7957/D7957M with three notable exceptions:

- The mean tensile modulus of elasticity limit shall meet or exceed 8,700,000 psi or 60,000 MPa (the limit is 6,500,000 psi or 44,800 MPa per Table 1 and 2 in ASTM D7957/D7957M);

Table 932-6
Sizes and Tensile Loads of FRP Reinforcing Bars

Bar Size Designation	Nominal Bar Diameter (in)	Nominal Cross Sectional Area (in²)	Measured Cross-Sectional Area (in²)		Minimum Guaranteed Tensile Load (kips)	
			Minimum	Maximum	BFRP and GFRP Bars	CFRP Bars
2	0.250	0.049	0.046	0.085	6.1	10.3
3	0.375	0.11	0.104	0.161	13.2	20.9
4	0.500	0.20	0.185	0.263	21.6	33.3
5	0.625	0.31	0.288	0.388	29.1	49.1
6	0.750	0.44	0.415	0.539	40.9	70.7
7	0.875	0.60	0.565	0.713	54.1	-
8	1.000	0.79	0.738	0.913	66.8	-
9	1.128	1.00	0.934	1.137	82.0	-
10	1.270	1.27	1.154	1.385	98.2	-

(a)

Table 932-7
Physical and Mechanical Property Requirements for Straight FRP Reinforcing Bars

Property	Test Method	Requirement	Specimens per LOT
Fiber Mass Fraction	ASTM D2584 or ASTM D3171	≥70%	5[n]
Short-Term Moisture Absorption	ASTM D570, Procedure 7.1; 24 hours immersion at 122°F	≤0.25%	5[m]
Long-Term Moisture Absorption	ASTM D570, Procedure 7.4; immersion to full saturation at 122°F	≤1.0%	5[m]
Glass Transition Temperature (Tg)	ASTM D7028 (DMA) or ASTM E1356 (DSC; T_m)/ASTM D3418 (DSC; T_{mg})	≥230°F ≥212°F	3[m]
Total Enthalpy of Polymerization (Resin)	ASTM E2160	Identify the resin system used for each bar size and report the average value of three replicates for each system	--
Degree of Cure	ASTM E2160	≥95% of Total polymerization enthalpy	3[n]
Measured Cross-Sectional Area	ASTM D7205	Within the range listed in Table 932-6	10[n]
Guaranteed Tensile Load[a]		≥ Value listed in Table 932-6	
Tensile Modulus		≥6,500 ksi for BFRP and GFRP ≥18,000 ksi for CRFP	
Alkali Resistance with Load	ASTM D7705; Procedure B, set sustained load to 30% of value in Table 932-6; 3 months test duration, followed by tensile strength per ASTM D7205	≥ 70% Tensile strength retention	5[m]
Transverse Shear Strength	ASTM D7617	>22 ksi	5[n]
Horizontal Shear Strength[p]	ASTM D4475	>5.5 ksi	5[n]
Bond Strength to Concrete, Block Pull-Out	ACI 440.3R, Method B.3 or ASTM D7913	>1.1 ksi	5[m]

a – Guaranteed tensile load shall be equal to the average test result from all three lots minus three standard deviations.
n – Tests shall be conducted for all bar sizes produced.
m – Tests shall be conducted for the smallest, median, and largest bar size produced.
p – Only required for BFRP bars.

(b)

Fig. 3: FDOT Standard Specifications, Section 932-3,[7] material requirements: (a) sizes and tensile loads of FRP reinforcing bars; and (b) physical and mechanical property requirements for straight FRP reinforcing bars (copied from Reference 7)

Table 932-9
Testing Requirements for Project Material Acceptance of FRP Reinforcing Bars

Property	Test Method	Requirement	Test Required for Straight Bar	Test Required for Bent Bar
Fiber Mass Fraction	ASTM D2584 or ASTM D3171	≥70%	Yes	Yes – bent portion[b]
Short-Term Moisture Absorption	ASTM D570, Procedure 7.1; 24 hours immersion at 122°F	≤0.25%	Yes	Yes – bent portion[b]
Glass Transition Temperature	ASTM D7028 (DMA) or ASTM E1356 (DSC; T_m)/ ASTM D3418 (DSC; T_{mg})	≥230°F ≥212°F	Yes	Yes – bent portion[b]
Degree of Cure	ASTM E2160	≥95% of Total polymerization enthalpy	Yes	Yes – bent portion[b]
Measured Cross-sectional Area	ASTM D7205	Within the range listed in Table 932-6	Yes	Yes – straight portion
Guaranteed Tensile Load[a]		≥ Value listed in Table 932-6	Yes	No
Tensile Modulus		≥6,500 ksi for BFRP and GFRP ≥18,000 ksi for CFRP	Yes	No

a – Guaranteed tensile load shall be equal to the average test result from all three lots minus three standard deviations.
b – Bent portion specimens shall be extracted from a central location within a 90° bend.

Fig. 4: FDOT testing requirements for project material acceptance of FRP reinforcing bars (copied from Reference 7)

Table 3:
Minimum ultimate tensile force according to ODOT and ASTM D7957/D7957M

Bar size	Minimum guaranteed ultimate tensile force, kip (kN)	ASTM D7957/D7957M minimum guaranteed ultimate tensile force, kip (kN)
2 (M6)	6.1 (27)	6.1 (27)
3 (M10)	13.2 (59)	13.2 (59)
4 (M13)	27.6 (123)	21.6 (96)
5 (M16)	36.6 (163)	29.1 (130)
6 (M19)	51.9 (231)	40.9 (182)
7 (M22)	68.5 (305)	54.1 (241)
8 (M25)	89.9 (400)	66.8 (297)
9 (M29)	124 (550)	82.0 (365)
10 (M32)	138 (615)	98.2 (437)

- The mean ultimate tensile strain limit shall meet or exceed 1.4% (the limit is 1.1% per Table 1 and 2 in ASTM D7957/D7957M); and
- The minimum guaranteed ultimate tensile force shall be as listed in Table 3 (and compared to current ASTM D7957/D7957M requirements).

The exceptions in terms of modulus and guaranteed tensile adopted by ODOT are very significant and refer to what is known as "generation 2" bars.

The following section discusses implications of ODOT and AASHTO requirements for certification, design, procurement, and quality assurance.

Implications

Certification: Bar manufacturer certification according to ODOT is described in Supplement 1138.[10] Producers/suppliers conforming to this supplement become responsible for ensuring that all certified GFRP materials meet specification requirements. Producers/suppliers must submit a written quality control plan (QCP) to the Office of Materials Management (OMM) for approval. The QCP includes the procedures and processes for ordering, testing, accepting, verifying, controlling, storing, shipping, documenting, and recording GFRP materials compliance with ODOT specifications. There is no standard quality control plan. Each producer/supplier will develop their own plan.

Design: ODOT's "Bridge Design Manual"[11] follows AASHTO LRFD Bridge Design Spec. 2020[12] and, therefore, does not directly address design of GFRP-reinforced concrete members. GFRP is only mentioned in Section 309.4 of the ODOT design manual related to railings. It may be implied that the design of all concrete members containing GFRP reinforcing bars shall be in accordance with the AASHTO GFRP-RC Guide Spec. 2018.

Regarding design, the ODOT's standard material for concrete reinforcement will remain epoxy-coated reinforcing steel at present. The choice to use GFRP reinforcement is a preference selected on a case-by-case basis. If contractors elect to switch from epoxy-coated reinforcement to GFRP, as shown in the contract documents, a value engineering change proposal must be submitted in accordance with ODOT C&MS, Section 105.19, and it must be accepted by ODOT. If accepted, the contractor assumes all design responsibility associated with the material change.

Procurement: The contractor awarded the project must purchase certified bars. According to Supplement 1138, producers/suppliers will be furnished sample ID numbers for each GFRP construction material item they are certified to supply. They must include a bill of lading with any certified GFRP materials shipments.

Quality assurance (field acceptance): According to Supplement 1138, random inspections will be performed. ODOT quality assurance inspectors (QAIs) will check testing procedures, QCP compliance, actual dimensions, and documentation at the certified producer/supplier. OMM may obtain random samples from the producer's/supplier's stock or at the project. Random samples will be tested. For any nonspecification materials, OMM will determine the cause.

TxDOT Specifications Compliance

The Texas Department of Transportation (TxDOT) updates its "Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges" (Spec Book) every 10 years. The current Spec Book[13] was issued in 2014 and covers FRP bars in Section 2.13 and references the first edition of AASHTO GFRP Spec. 2009[14] in Section 4, Material Specifications, when GFRP bars are required in the plans.

However, in 2017 the TxDOT introduced (and revised in 2019) standard details for GFRP slab top mat reinforcement and prestressed concrete I-girder spans (IGFRP). The associated material notes specify that GFRP bars conform to ASTM D7957/D7957M, except for requiring a minimum modulus of elasticity of 7500 ksi.

The following section discusses implications of TxDOT and AASHTO requirements for certification, design, procurement, and quality assurance.

Implications

Certification: TxDOT requires sample certification demonstrating that the GFRP bar supplier has produced bars meeting material specifications outlined in AASHTO GFRP Spec. 2009. Except when using the IGFRP standard details, the governing material specification is ASTM D7957/D7957M with a minimum modulus of elasticity of 7500 ksi, provided 2 months before fabrication. Upon shipment of the GFRP bars, producers/suppliers must furnish certification in compliance with the material specifications. There is no standard quality control plan. Each producer/supplier develops their own plan.

Design: TxDOT Bridge Design Manual[15] references the design of GFRP reinforced concrete deck/slab to the AASHTO GFRP Spec. 2009. The manual does not reference any other application for GFRP reinforcement except for bridge decks/slabs. It is expected that the next edition of the Bridge Design Manual slated for publication in 2021 will update its reference to the next edition of the AASHTO GFRP-RC Guide Spec. 2018.

Procurement: A contractor procuring GFRP reinforcement in Texas for a cast-in-place slab and conforming to the IGFRP standard details would have to meet the requirements of AASHTO GFRP-RC Guide Spec. 2018, ASTM D7957/D7957M, and the minimum modulus of elasticity of 7500 ksi.

Quality assurance (field acceptance): Contrary to other standards, field acceptance is not considered under TxDOT's Spec Book, because the material certification must be furnished upon shipment of the GFRP bars. The material specification does, however, specify the sampling frequency and number of specimens to be selected for quality control and quality assurance (QC/QA) testing at a certified laboratory.

MaineDOT Specifications Compliance

The Maine Department of Transportation (MaineDOT) does not have a standard specification explicitly for GFRP reinforcement. However, MaineDOT does have a special provision that can be used on a project-specific basis in the omitted "Section 530" in the MaineDOT Standard Specifications.[16] This provision contains language on materials, documentation, schedule of material, fabrication, projection of material, and splicing. Product acceptance criteria and information can be downloaded as a pdf at **www.maine.gov/mdot/research/products/**, following the link to: "Glass Fiber Reinforced Polymer Bars (PDF)." The MaineDOT Bridge Design Guide[17] and standard specifications are not updated on a yearly basis. The following section discusses implications of MaineDOT and AASHTO requirements for certification, design, and quality assurance; and it provides observations regarding the existing standards.

Certification: MaineDOT intends to make GFRP reinforcement compliant with ASTM D7957/D7957M and requires vendors to be preapproved through the MaineDOT product evaluation coordinator. The approval process requires a copy of the technical data sheet, safety data sheet, and third-party independent test results.

Design: MaineDOT does not reference a design guide for GFRP reinforced concrete, but it is implied that the governing standard is AASHTO GFRP-RC Guide Spec. 2018 and the MaineDOT Bridge Design Guide should be used for design on federally funded transportation projects.

Quality assurance (field acceptance): The MaineDOT may require a field evaluation before final acceptance and inclusion into their Qualified Product List (QPL) at their discretion, with all products recertified by the manufacturer every 5 years. A list of qualified FRP and GFRP suppliers (handled separately) is available at **www.maine.gov/mdot/research/products/**.

Observations: Because MaineDOT standards are not updated on a frequent basis, their specifications and design guide are not as current as standards produced by other state DOTs. Further, adoption of a standard specification for GFRP reinforcement may have been hindered by limited access to qualified testing facilities or a limited quantity of projects mandating GFRP reinforcement.

ICC-ES AC454 Compliance for Buildings

For FRP reinforcement to become mainstream in concrete building structures, two things need to occur. First, ACI Committee 440 must publish a building code (currently under development), and second, the new ACI 440 building code has to be referenced by the model code for adoption in every state. In the interim, it is possible to obtain a building permit if the specified materials show compliance with the intent of the model code by meeting the criteria listed in 2021 IBC, Section 104.11,[18] and 2021 IRC, Section R104.11.[19]

The purpose of the ICC-ES AC454 acceptance criteria document is to establish requirements for GFRP and BFRP bars to be recognized in an ICC-ES building code compliance evaluation report (ESR) issued on behalf of a bar manufacturer. AC454 provides guidelines for the evaluation of alternative reinforcement, where the building codes do not provide design provisions or requirements for testing and determination of physical and mechanical properties.

Further, AC454 provides the required test methods and evaluation provisions for quantifying the performance characteristics of FRP bars that satisfy the objectives of the building codes when used as flexural reinforcement in structural concrete members such as beams, shallow foundations, and one-way or two-way slabs; as shear reinforcement for flexural members; or as longitudinal reinforcement for columns and walls. The following section discusses implications of this acceptance criteria document for certification, design, procurement, and quality assurance; and it demonstrates these conflicts through a discussion of two hypothetical bar manufacturers.

Implications

Consider that Pultruder A and B are making No. 5 GFRP or BFRP bars and received an ESR from ICC-ES. This example is again limited to tensile properties for simplicity.

Certification: If Pultruder A and B have each obtained an ESR for their bars, it means that they satisfied the requirements of ASTM D7957/D7957M for measured area, guaranteed tensile force, and tensile modulus of elasticity. As an example, this is the text of AC454 for tensile force:

"…The ultimate tensile force for product certification shall be measured according to ASTM D7205/D7205M with the number of test specimens indicated in Section 4.7 of this criteria…

…The minimum guaranteed tensile force shall meet the property requirement values listed in Table 3 of ASTM D7957 for bar designations 2 through 10…"

Design: The design of an FRP-RC structure using AC454 will follow ACI 440.1R. The EOR designs the structural element(s) using the nominal No. 5 bar tensile parameters of E = 6500 ksi and f_{fu} = 29.1/0.31 = 93.9 ksi. The design is usually based on nominal properties unless the owner allows the EOR to preselect the reinforcement supplier and the EOR uses the properties certified in the ESR.

To obtain a building official approval, the EOR adds language in the bid documents requesting that the FRP reinforcement to be used in the project is certified with a building code compliance report (ESR). For example, the project specification could include the following language:

Reference Documents

ICC-ES Acceptance Criteria (AC454)

ACI 440.1R-15

Submittal Requirements

Submit design calculations for FRP-RC that include the following:

1. *Detailed calculations for the proposed FRP-RC structure certified by a professional engineer registered in the state of XXX, for approval by the engineer of record.*
2. *Develop design calculations to meet the requirements set forth in ACI 440.1R-15.*
3. *FRP materials must meet the requirements set forth in the ICC-ES Acceptance Criteria (AC454), based on tension forces and modulus limits.*
4. *Independent test data from ISO 17025 accredited labs confirming material properties used in the design calculations as per ASTM D7957/D7957.*

Materials

FRP reinforcement considered for use under this specification must be provided with a valid ESR issued by ICC-ES.

Procurement: The contractor awarded the project needs to purchase bars from a manufacturer possessing a valid ESR, which is the case for Pultruder A and B. Obviously, the contractor selects the cheaper bar to be used in the field.

Quality assurance (field acceptance): The bid document will specify the requirements of the project, which include special inspection requirements of Chapter 17 of the 2021 IBC. Language to this effect in the bid documents may be added:

Field Quality Control

Laboratory Testing:

1. *Record lot numbers of FRP reinforcement used, along with location of installation.*
2. *Test samples using ASTM D7957/D7957M. Follow ASTM procedures and manufacturer's published testing methods during testing. Use only pre-qualified accredited testing laboratories.*
3. *Make testing results available within 3 weeks of sample submission. Provide values based on nominal dimensions of the ultimate tensile strength, tensile modulus, and percent elongation.*

Quality Acceptance

Provide certification from the manufacturer (valid ESR) showing that the FRP reinforcement conforms to AC454 requirements.

In Summary

Significant progress has been made in the last few years to provide the technical, legal, and contractual framework necessary for the deployment of FRP reinforcement for concrete structures in the United States. However, much more needs to be done for the full implementation of this technology.

In the case of transportation structures, regulations at the federal level would help in resolving the current fragmentation among DOTs (refer to Fig. 5). In addition to specifications and guides, AASHTO could consider adding a module on design and load rating of concrete bridges with FRP reinforcement in the collection of software tools available in the AASHTOWare platform, similar to AASHTOWare Bridge Design and Bridge Rating (**www.aashtoware.org/products/bridge/bridge-overview/**). In addition, in the next revision of "Guide Specification for Service Life Design of Highway Bridges,"[20] consideration could be given to inclusion of FRP in Section 4.2.4.2.2-1 as a type of reinforcement belonging to "Class D – highly corrosion resistant materials," to help designate value for longer service life up to 100 or 150 years.

For building structures, there is the compelling need for a design code in mandatory language that would eventually be adopted by reference in IBC.

Technology transfer efforts need to accompany the development of standards and specifications not only to provide awareness, but, as importantly, to install confidence and remove perception of risk from all stakeholders.

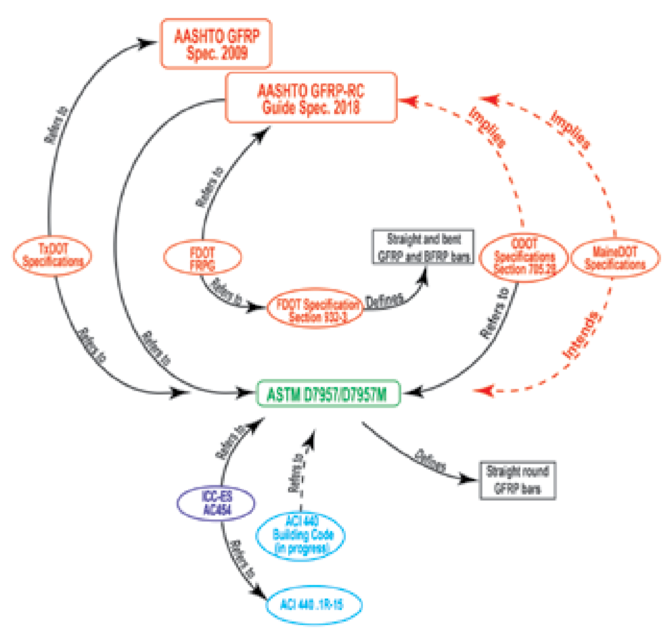

Fig. 5: Currently, specifications and design guides for use of FRP bars are linked only by direct or indirect reference to ASTM D7957/D7957M

Acknowledgments

The author gratefully acknowledges the partial financial support of the NSF Center for the Integration of Composites into Infrastructure (CICI) under grant No. 1916342.

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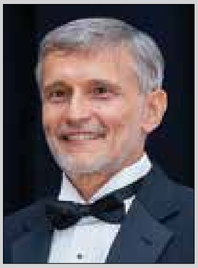

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