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AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete

2ND EDITION



AMERICAN ASSOCIATION
OF STATE HIGHWAY AND
TRANSPORTATION OFFICIALS

AASHTO

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SECTION 1

INTRODUCTION

1.1—SCOPE

These specifications offer a description of the properties of glass fiber-reinforced polymer (GFRP) reinforcing bars as well as provisions for the design and construction of structural concrete bridge members reinforced with GFRP bars.

GFRP reinforcement shall be in the form of deformed or sand-coated bars, or both, to provide bond with concrete.

These specifications are not intended to supplant proper training or the exercise of judgment by the Design Professional, and state only the minimum requirements necessary to provide for public safety. The Owner or the Design Professional may require the sophistication of the design or the quality of materials and construction to be higher than the minimum requirements.

The Design Professional shall be familiar with the provisions of the *AASHTO LRFD Bridge Design Specifications* and latest interim specifications, as well as with the design of conventional reinforced concrete structures.

The commentary directs attention to other documents that provide suggestions for carrying out the requirements and intent of these specifications. However, those

C1.1

GFRP materials have emerged as an alternative noncorrosive material for reinforcing bars for concrete structures (Iyer and Sen, 1991; Neale and Labossiere, 1992; White, 1992; Nanni, 1993; Nanni and Dolan, 1993; Dolan et al., 1996; El-Badry, 1996; Humar and Razaqpur, 2000; Burgoyne, 2001; Cosenza et al., 2001; Figueiras et al., 2001; Teng, 2001; Triantafillou, 2007; Bank, 2007; El-Sayed and Benmokrane, 2008; Nanni et al., 2014). GFRP reinforcing bars offer advantages over steel reinforcement due to their noncorrosive nature, which makes them attractive for bridge structures such as beams (Nanni 1993; 2003; Thériault and Benmokrane, 1998; Ashour, 2006; Bentz et al., 2010; Matta et al., 2013), columns (De Luca et al., 2010; Mohamed et al., 2014; Hadhood et al., 2017), decks (Bradberry, 2001; Nanni and Faza, 2002; Benmokrane et al., 2004; 2006; 2007a; 2007b), and traffic railings (Buth et al., 2003; El-Salakawy et al., 2003; Matta and Nanni, 2009; Ahmed et al., 2013; Sennah and Mostafa, 2018). Due to other differences in the physical and mechanical behavior of GFRP materials as opposed to steel, unique guidance on the design and construction of concrete bridges reinforced with GFRP bars is needed.

The term “shall” denotes a requirement for compliance with these specifications. The term “should” indicates a strong preference for a given criterion. The term “may” indicates a criterion that is usable, but other local and suitably documented, verified, and approved criteria may also be used in a manner consistent with the LRFD approach to bridge design.

Together with straight and hooked GFRP bars used as longitudinal reinforcement, GFRP stirrups in the form of C-shaped bars, spirals, etc., may be implemented to ensure that shear resistance meets safety requirements.

documents and this commentary are not intended to be a part of these specifications.

Material specifications and construction specifications consistent with these design specifications are provided in ASTM D7957/D7957M and Section 6, respectively.

1.2—DEFINITIONS

Design Professional—The architect, engineer, architectural firm, or engineering firm responsible for the design of the bridge and issuing Contract Documents or administering the Work under Contract Documents, or both.

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 product of fusion that has cooled without crystallizing.

Grating—A two-dimensional (planar) or three-dimensional (spatial) rigid array of interconnected GFRP pultruded shapes other than deformed bars.

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

Lightweight concrete—Concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kcf, as determined in conformance with ASTM C567/C567M.

Reinforced concrete—Structural concrete containing no less than the minimum amounts of GFRP reinforcement specified herein.

Structural concrete—All concrete used for structural purposes.

1.3—LIMITATIONS

Prestressed applications; GFRP reinforcement in combination with steel reinforcing bars to resist the same force effect; use of fiber types other than glass, such as carbon, basalt, and aramid fibers; and the use of grid and gratings as well as smooth and hollow-type GFRP reinforcing bars are not covered in these specifications. Assembly of GFRP mats using GFRP bars addressed in these specifications is allowed.

Plain GFRP reinforcing bars used as dowels (that is, devices that transfer shear load across concrete joints), where the intended function requires slip of the dowel, are not covered in these specifications.

The use of lightweight concrete reinforced with GFRP bars is not covered in these specifications and may be specified by the Owner.

The assumed failure mechanism of GFRP-reinforced flexural members shall not be based on the formation of plastic hinges as GFRP materials demonstrate a linear elastic behavior up to failure. Moment redistribution in continuous members shall not be considered for GFRP-reinforced concrete bridge members.

C1.3

GFRP reinforcing bars with a smooth external surface are not covered by these specifications, as their use as concrete reinforcement is restricted due to lack of bond development with concrete. Hollow-type GFRP bars are not considered due to unknown performance as reinforcement for concrete.

The design and construction of lightweight concrete members internally reinforced with GFRP bars is not covered because of the lack of research on this subject. The Owner may specify the use of lightweight concrete based on evidence from physical tests approved by the Owner.

The use of GFRP reinforcing bars in members to be designed for seismic loads is not covered in these specifications.

GFRP reinforcing bars have a significantly lower compressive strength than tensile strength. The strength of any GFRP reinforcing bar in compression shall be ignored in design calculations.

The use of GFRP bars as compression reinforcement of flexural members is not recommended. Placing GFRP reinforcing bars in the compression zone of flexural members is permitted provided that they are not taken into account for the determination of the member flexural resistance.

1.4—DESIGN PHILOSOPHY

These specifications are based on limit state design principles where structural components shall be proportioned to satisfy the requirements at all appropriate service, fatigue and creep rupture, strength, and extreme event limit states. In many instances, serviceability or fatigue and creep rupture limits may control the design.

Provisions related to limit states analysis, general design and location features, loads and load factors, and structural analysis and evaluation shall comply with the *AASHTO LRFD Bridge Design Specifications*.

C1.4

The limit states specified herein are intended to provide for a buildable, serviceable bridge, capable of safely carrying design loads for a specified lifetime.

1.5—REFERENCES

AASHTO. *AASHTO LRFD Bridge Design Specifications*, 8th Edition, LRFD-8. American Association of State Highway and Transportation Officials, Washington, DC, 2017.

AASHTO. AASHTO M 195, Standard Specification for Lightweight Aggregates for Structural Concrete. AASHTO, Washington, DC, 2011.

Ahmed, E.A., Matta, F., and Benmokrane, B. “Steel Post-and-Beam Barrier with GFRP-Reinforced Concrete Curb and Bridge Deck Connection.” *Journal of Bridge Engineering*, 18(11), 2013, pp. 1189–1197.

Ashour, A.F. “Flexural and Shear Capacities of Concrete Beams Reinforced with GFRP Bars.” *Construction and Building Materials*, 20(10), 2006, pp. 1005–1015.

ASTM. ASTM C567/C567M-14, Standard Test Method for Determining Density of Structural Lightweight Concrete. ASTM International, West Conshohocken, PA, 2014.

ASTM. ASTM D7957/D7957M-17, Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement. ASTM International, West Conshohocken, PA, 2017.

Bank, L.C. *Composites for Construction: Structural Design with FRP Materials*. Wiley, Hoboken, NJ, 2007, 560 p.

Benmokrane, B., El-Salakawy, E., Desgagné, G., and Lackey, T. “FRP bars for bridges.” *Concrete International*, 26(8), 2004, pp. 84–90.

Benmokrane, B., El-Salakawy, E., El-Ragaby, A., and Lackey, T. “Designing and Testing of Concrete Bridge Decks Reinforced with Glass FRP Bars.” *Journal of Bridge Engineering*, 11(2), 2006, pp. 217–229.

Benmokrane, B., El-Salakawy, E., El-Gamal, S., and Goulet, S. “Construction and Testing of Canada’s First Concrete Bridge Deck Totally Reinforced with Glass FRP Bars: Val-Alain Bridge on Highway 20 East.” *Journal of Bridge Engineering*, 12(5), 2007a, pp. 632–645.

Benmokrane, B., El-Salakawy, E., El-Ragaby, A., and El-Gamal, S. “Performance Evaluation of Innovative Concrete Bridge Deck Slabs Reinforced with Fibre-Reinforced Polymer Bars.” *Canadian Journal of Civil Engineering*, 34(3), 2007b, pp. 298–310.

Bentz, E.C., Massam, L., and Collins, M.P. “Shear Strength of Large Concrete Members with FRP Reinforcement.” *Journal of Composites for Construction*, 14(6), 2010, pp. 637–646.

Bradberry, T.E. “Concrete Bridge Decks Reinforced with Fiber-Reinforced Polymer Bars,” *Transportation Research Record 1770*. Transportation Research Board, Washington, DC, 2001, pp. 94–104.

Burgoyne, C., Editor. *Non-Metallic Reinforcement for Concrete Structures—(FRPRCS-5)*. Proc., Int. Conf., Cambridge, UK, 2001.

Buth, C.E., Williams, W.F., Bligh, R.P., Menges, W.L., and Haug, R.R. *Performance of the TxDOT T202 (MOD) Bridge Rail Reinforced with Fiber Reinforced Polymer Bars*. Report FHWA/TX-03/0-4138-3, Texas Transportation Institute, College Station, TX, 2003, 100 pp.

Cosenza, E., G. Manfredi, and A. Nanni, Editors. *Composites in Construction: A Reality*. Proc., Int. Workshop, Capri, Italy, ASCE, Reston, VA, 2001.

De Luca, A., Matta, F., and Nanni, A. “Behavior of Full-Scale GFRP Reinforced Concrete Columns under Axial Load.” *ACI Structural Journal*, 107(5), 2010, pp. 589–596.

Dolan, C.W., S. Rizkalla, and A. Nanni, Editors. *Fiber Reinforced-Polymer Reinforcement for Concrete Structures—Fourth International Symposium (FRPRCS-4)*. ACI Special Publication No. 188, American Concrete Institute, Farmington Hills, MI, 1999.

El-Badry, M., Editor. “Advanced Composite Materials in Bridges and Structures.” Proc., ACMBS-II, Montreal, Canada, 1996.

El-Salakawy, E., Benmokrane, B., Masmoudi, R., Brière, F., and Breumier, E. “Concrete Bridge Barriers Reinforced with Glass Fiber-Reinforced Polymer Composite Bars.” *ACI Structural Journal*, 100(6), 2003, pp. 815–824.

El-Sayed, A.K., and Benmokrane, B. “Evaluation of the New Canadian Highway Bridge Design Code Shear Provisions for Concrete Beams with Fiber-Reinforced Polymer Reinforcement.” *Canadian Journal of Civil Engineering*, 35(6), 2008, pp. 609–623.

Figueiras, J., L. Juvandes, and R. Furia, Editors. “Composites in Construction.” Proc., CCC 2001, Porto, Portugal, 2001.

Hadhood, A., Mohamed, H.M., and Benmokrane, B. “Axial Load–Moment Interaction Diagram of Circular Concrete Columns Reinforced with CFRP Bars and Spirals: Experimental and Theoretical Investigations.” *Journal of Composites for Construction*, 21(1), 2017, 04016092.

Humar, J., and A.G. Razaqpur, Editors. “Advanced Composite Materials in Bridges and Structures.” Proc., 3rd Inter. Conf., Ottawa, Canada, 2000.

Iyer, S.L., and R. Sen, Editors. “Advanced Composite Materials in Civil Engineering Structures.” Proc., American Society of Civil Engineers, New York, NY, 1991.

Matta, F., El-Sayed, A.K., Nanni, A., and Benmokrane, B. “Size Effect on Concrete Shear Strength in Beams Reinforced with Fiber-Reinforced Polymer Bars.” *ACI Structural Journal*, 110(4), 2013, pp. 617–628.

Matta, F. and Nanni, A. “Connection of Concrete Railing Post and Bridge Deck with Internal FRP Reinforcement.” *Journal of Bridge Engineering*, 14(1), 2009, pp. 66–76.

Mohamed, H.M., Afifi, M.Z., and Benmokrane, B. “Performance Evaluation of Concrete Columns Reinforced Longitudinally with FRP Bars and Confined with FRP Hoops and Spirals under Axial Load.” *Journal of Bridge Engineering*, 19(7), 2014, 04014020.

Nanni, A., Editor. *Fiber-Reinforced-Plastic (FRP) Reinforcement for Concrete Structures: Properties and Applications. Developments in Civil Engineering*, Vol. 42, Elsevier, Amsterdam, The Netherlands, 1993.

- Nanni, A. "Flexural Behavior and Design of RC Members Using FRP Reinforcement." *Journal of Structural Engineering*, 119(11), 1993, pp. 3344–3359.
- Nanni, A. "North American Design Guidelines for Concrete Reinforcement and Strengthening Using FRP: Principles, Applications, and Unresolved Issues." *Construction and Building Materials*, 17(6-7), 2003, pp. 439–446.
- Nanni, A., and C.W. Dolan, Editors. "FRP Reinforcement for Concrete Structures." Proc., ACI SP-138, American Concrete Institute, Detroit, MI, 1993.
- Nanni, A., and Faza, S. "Designing and Constructing with FRP Bars: an Emerging Technology." *Concrete International*, 24(11), 2002, pp. 53–58.
- Nanni, A., De Luca, A., and Jawaheri Zadeh, H. *Reinforced Concrete with FRP Bars—Mechanics and Design*. Taylor & Francis, New York, NY, 2014, 397 p.
- Neale, K.W., and P. Labossiere, Editors. "Advanced Composite Materials in Bridges and Structures." Proc. Canadian Society for Civil Engineering, Montreal, Canada, 1992.
- Sennah, K., and Mostafa, A. "Performance of a Developed TL-5 Concrete Bridge Barrier Reinforced with GFRP Hooked Bars: Vehicle Crash Testing." *Journal of Bridge Engineering*, 23(2), 2018, 04017139.
- Teng, J.G., Editor. "FRP Composites in Civil Engineering." Proc. CICE 2001, Hong Kong, China, 2001, Volumes 1 and 2.
- Thériault, M., and Benmokrane, B. "Effects of FRP Reinforcement Ratio and Concrete Strength on Flexural Behavior of Concrete Beams." *Journal of Composites for Construction*, 2(1), 1998, pp. 7–16.
- Triantafillou, T., Editor. "Fiber-Reinforced Polymer Reinforcement for Concrete Structures." Proc. of the 8th Int. Conf. (FRPRCS-8), Patras, Greece, 2007.
- White, T.D., Editor. "Composite Materials and Structural Plastics in Civil Engineering Construction." Proc. of The Materials Engineering Congress, American Society of Civil Engineers, New York, NY, 1992, pp. 532–718.