Corrosion-Resistant Fiber-Reinforced Polymer Reinforcement for Concrete Structures

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An article in the July–August 1993 issue of *PCI Journal* opens with the observation, "By the 1980s, the technology that spawned the original AASHTO I-beams was 30 years old. The beams had more than met their intended goals, but times were changing: sophisticated structural analysis, improved materials and fabricating techniques, and advanced construction methods were being introduced at a rapid pace."[1] Readers today may note that this opening statement does not mention durability, resilience, or sustainability. Perhaps the author felt confident that the durability challenges for reinforced and prestressed concrete had been resolved, especially considering a 50-year nominal design life. It is not surprising that "resilience" and "sustainability" were not mentioned; these terms as currently used were absent from our lexicon in the early 1990s.

Increased Target Service Life

In 1994, the first edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2] increased the nominal design life from 50 to 75 years. This change was partially based on the performance of existing bridge stock, but it also reflected the reality of a growing bridge inventory, which exceeded 570,000 structures in 1990 and could not affordably be replaced every 50 years.[3] By this time, a longer design life was feasible because the industry had improved its understanding of the mechanisms involved in the corrosion of steel reinforcement and how they are exacerbated by long-term chloride diffusion and carbonation.[4]

Three decades later, the U.S. highway bridge inventory exceeds 623,000 bridges.[5] Another notable development is that bridge deck areas are often much greater than in the past, due to capacity and safety improvements such as additional travel lanes, wider roadway and bicycle shoulders, and additions of sidewalks on many non-limited-access bridges. Furthermore, increasing urbanization, managed lanes, and a generally more constrained roadway network have resulted in significant increase in the associated earth-retaining and water-conveyance structures, which are also predominantly reinforced concrete, including precast concrete. Additionally, there have been significant advancements in reinforced concrete structural materials technologies, such as fiber-reinforced polymers (FRP), high-strength stainless-steel strands and reinforcing bars, and ultra-high-performance, steel-fiber-reinforced concrete. Simultaneously, societal expectations for safety, maintainability, and reliability are increasing, while the intensity of both natural and human made shocks and stressors from the surrounding environment are also on the rise .[6,7]

With sufficient concrete cover, good detailing, and appropriate workmanship practices, uncracked high-performance concrete and carbon-steel reinforcement typically provide adequate durability to achieve a 75-year target service life. However, asset managers and bridge owners still face susbstantial durability challenges, including mitigating in-service concrete cracking (especially for bridge decks in colder regions), achieving corrosion resistance in low-level trestle bridges in coastal areas, and meeting target service-life expectations of 100 to 150 years.

One solution to such challenges is the use of extremely corrosion-resistant reinforcement. Of the available material classes that could meet an enhanced (100-year) target service life in an extremely corrosive environment, FRP reinforcing bar and prestressing strands are one practical solution and are the focus of this article.[8] A follow-up article presenting state-of-the-art stainless-steel reinforcing bar and strand reinforcement as another viable option is planned as part 2 of this series.

Developments in FRP Reinforcement

Many developments have occurred since our article, "Glass Fiber-Reinforced Polymer (GFRP) Reinforcement for Bridge Structures," in the Summer 2020 issue of *ASPIRE*®. The following are worth highlighting:

- The publication of the American Concrete Institute's *Building Code Requirements for Structural Concrete with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary* (ACI CODE-440.11-22)[9]

The 17th Street Bridge replacement over Indian River in Vero Beach, Fla., includes 168 prestressed concrete Florida slab beams with fiber-reinforced-polymer reinforcement. The 45-ft long beams use carbon-fiber-reinforced-polymer strands and glass-fiber-reinforced-polymer auxiliary reinforcement. All Photos: Florida Department of Transportation.

The Florida slab beams, piles, and bent caps of a low-level observation deck at the U.S. Route 1 bridge replacement in Jupiter, Fla., have carbon-fiber-reinforced-polymer prestressing strands and glass-fiber-reinforced-polymer reinforcement.

- The publication of ASTM D8505-23[10] for higher-modulus and higher-strength FRP reinforcing bars
- Forthcoming updates to the second edition of the *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*[11] and to Section 16, Fibre-Reinforced Structures, of the *Canadian Highway Bridge Design Code* (CSA S6:2019)[12]
- Other new, revised, and forthcoming design, construction, and material specifications and guidelines. For example, the National Cooperative Highway Research Program (NCHRP) project 12-121 is preparing recommendations for auxiliary (non-prestressed) FRP reinforcement for prestressed concrete to complement AASHTO's *Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems*.[13]

Moreover, there has been significant research published in the last decade that can further advance design provisions related to axial columns and other components, seismic and fire design, durability of basalt and glass FRP reinforcing bars, and feasibility of using seawater or sea sand in concrete mixtures for marine applications.

It is hoped that construction operations can be streamlined by commercial applications of several innovations, including product development of post-production formable resin systems that will allow shop bending of FRP reinforcing bar at either regional distribution centers or remote facilities; mechanical connection systems for direct splicing and coupling of FRP reinforcement; and grid and mesh FRP systems for accelerated construction. ASTM Subcommittee D30.10 is currently standardizing grid and mesh FRP systems, and CFRP reinforcing and strand material specifications are also being completed.

In addition, nondestructive testing inspection technologies continue to advance; these changes were recently highlighted in the Federal Highway Administration–sponsored *A Framework for Field Inspection of In-service FRP Reinforced or Strengthened Concrete Bridge Elements*,[14] and a supporting TechBrief is anticipated soon. The AASHTO Committee on Bridges and Structures' Safety and Evaluation technical committee (formerly T-18) will ballot the associated bridge element updates for *The Manual for Bridge Evaluation*[15] at the committee's next annual meeting.

Finally, oversight and certification organizations for both product testing and evaluation have matured. Examples include the AASHTO Product Evaluation and Audit Solutions program for composite concrete reinforcing; NEx: An ACI Center of Excellence for Nonmetallic Building Materials; and the FRP Institute for Civil Construction auditing program.

Project Applications

Several state departments of transportation have made significant investments into the development and construction of FRP-reinforced precast concrete and reinforced concrete bridge components. More than two decades ago, the Michigan Department of Transportation (MDOT) began using CFRP prestressing strands for various concrete components. MDOT started this work in 2001 with the Bridge Street bridge in Southfield, Mich., and the agency continues to design and construct bridges with CFRP post-tensioned and prestressed components as part of the state's traditional bridge replacement and rehabilitation program. MDOT was also instrumental in securing a CFRP strand manufacturing facility in the United States.

The Virginia Department of Transportation was another early adopter of CFRP prestressing strand. Its largest project to date, the $3.9 billion Hampton Roads Bridge-Tunnel Expansion, began construction in 2020. (See the Project article in the Fall 2024 issue of *ASPIRE* for more information about the Hampton Roads marine trestles.) This significant project includes considerable quantities of FRP-reinforced precast, prestressed concrete cylinder piles and I-girders in the 5 miles of marine trestle spans.

The North Carolina Department of Transportation (NCDOT) recently completed the 3200-ft Harkers Island Bridge with prestressed concrete Florida I-beams and piles. The bridge deck, pile footings, and caps all contain GFRP reinforcement. NCDOT is also expected to begin construction on the 3.3-mile U.S. Route 64 over Alligator River bridge replacement in early 2025 and will use similar FRP-reinforced cast-in-place and precast concrete components.

The Florida Department of Transportation has completed or advanced design on more than 67 bridges with FRP-reinforced cast-in-place and precast concrete components. The 2017 Halls River Bridge demonstration project in Homosassa and the current 17th Street Bridge east end replacement in Vero Beach provide salient examples.

Design Refinements Based on Research

Currently, the most actively researched topic related to GFRP-reinforced concrete construction is seismic performance. ACI CODE-440.11-22 has very restrictive requirements related to GFRP-reinforced concrete under Section 1.4.13, including restrictions on its use in Seismic Design Categories (SDCs) D through F as well as restrictions in SDCs B and C for members that are part of the lateral-load-resisting system.

Recent refinement of several design parameters for various limit states should improve the efficiency of FRP-reinforced concrete for future designs, improving both sustainability and resilience. As clarifying examples, ACI CODE-440.11-22 increased the environment reduction factor C_E (accounting for degradation of GFRP under high-alkalinity) from 0.70 to 0.85 for outdoor exposure conditions. This can provide a 21% increase in the strength limit state capacities. Similarly, the standardization of high elastic modulus E_f and high tensile strength f_u basalt and glass FRP reinforcement under ASTM D8505-23, provides up to 33% increased component flexural resistance under both strength limit state and service limit state for crack control, sustained load, and transient load-induced fatigue. The higher modulus contributes a 33% increase to the reinforcing component strength for transverse shear capacity V_f, while ACI CODE-440.11-22 increased the associated maximum tensile strain of shear stirrups e_{ft} from 0.004 to 0.005, harmonizing with *Design and Construction of Building Structures with Fibre-Reinforced Polymers* (CSA S806)[16] for buildings and the forthcoming edition of the *Canadian Highway Bridge Design Code* (CSA S6:25)[17] for bridges. The increased strain limit provides a 25% increase to the shear reinforcement contribution V_f.

Both ACI and AASHTO technical committees are continuing work to refine interface shear and precast concrete beam shear provisions, with supporting research being done by NCHRP Project 12-121, NEx, and several Canadian research groups. The refinements are expected to yield further design economy and reduce the cost differential between traditional carbon-steel-reinforced and FRP-reinforced concrete/precast concrete. Opportunities exist for further refinement of resistance factors for axial, flexural, and shear design under the strength limit state, and there is a need for calibration and harmonization of ductility concepts and redundancy (both component and system). For example, regarding the flexural resistance factors, AASHTO now treats all CFRP precast concrete components essentially as compression-controlled designs, with a conservative resistance factor of 0.75 for both compression-controlled and tension-controlled designs.

Lastly, when envisioning the concrete and cement road maps for decarbonization by 2050, resilience (durability, robustness, and self-healing), and sustainability (global warming potential, adaptability, and reuse) will be important factors for design guidance and eventual codification will be critical. Here, the use of FRP reinforcement along with concrete that includes recycled aggregate and even seawater may result in a pivotal advancement.

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