Design of Corrosion-Free Concrete Structural Elements Using Fiber-Reinforced Polymer and Stainless Steel Reinforcements

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Corrosion of carbon steel reinforcement or prestressing strands results in the deterioration of concrete structures and is one of the major challenges faced by bridge structures. Carbon steel reinforcement in concrete bridges and other structural elements can corrode due to environmental factors, especially in marine environments and cold regions where deicing salts are used. Reinforcement corrosion can lead to failures, which endanger public safety and have significant economic impacts—owners may spend billions of dollars for inspections, maintenance, repair, or even decommissioning and reconstruction. Viable corrosion-resistant alternatives on the market include, but are not limited to, various types of fiber-reinforced polymers (FRPs), epoxy-coated steel, galvanized steel, high-chromium steel, and different types of stainless steel. This article focuses on FRP and stainless steel types of reinforcement and their applications in bridge design.

To illustrate the implications and challenges of using these sorts of materials, **Fig. 1** compares the stress-strain relationships of various types of FRPs and stainless steel as well as conventional carbon steel used for reinforcement in concrete.

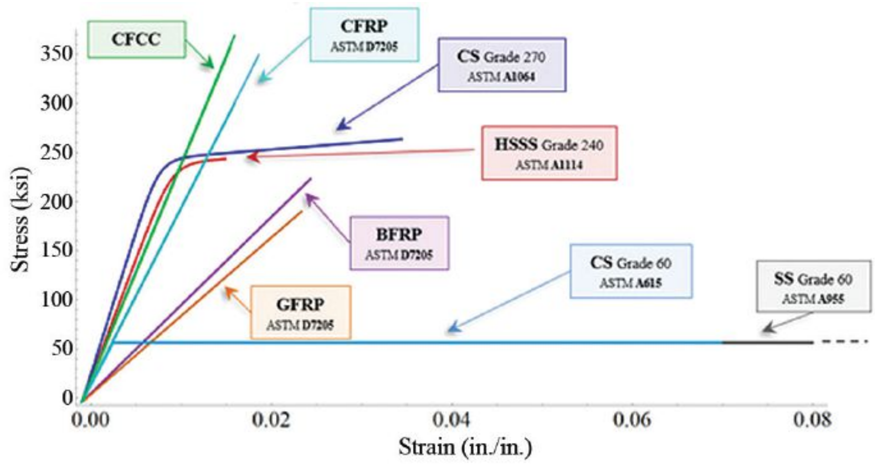
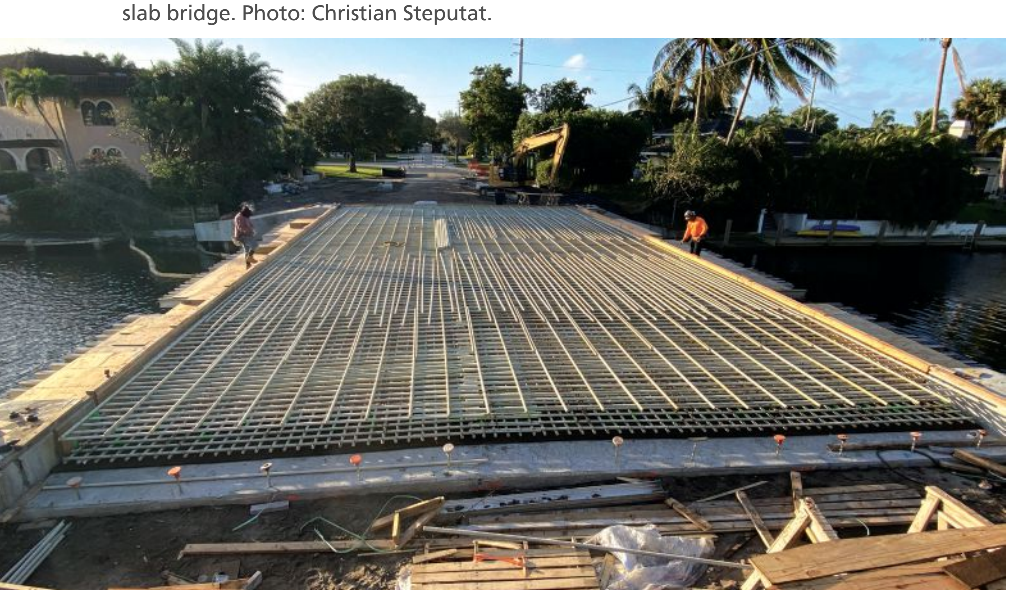


Figure 1. Comparison of the stress-strain relationships of several types of reinforcing bars and prestressing strands. Note: BFRP = basalt-fiber-reinforced polymer; CFCC = carbon-fiber composite cable; CFRP = carbon-fiber-reinforced polymer; CS = carbon steel; GFRP = glass-fiber-reinforced polymer; HSSS = high-strength stainless steel; SS = stainless steel. Figure: University of Houston.

FRP Materials

Almost four decades ago, researchers and designers introduced FRP as a viable alternative to steel reinforcement. However, the use of any new material in bridge construction depends on the availability of guide specifications. For instance, the American Association of State Highway and Transportation Officials' *AASHTO LRFD Design Guide Specifications for GFRP-Reinforced Concrete*[1] provides design provisions for the use of glass-fiber-reinforced polymer (GFRP) reinforcing bars, which facilitates the use of GFRP products in concrete bridge structures (**Fig. 2**). (See the Creative Concrete Construction article in the Summer 2020 issue of *ASPIRE*® for an example of the use of GFRP reinforcement in bridges.) GFRP reinforcing bars are currently manufactured in sizes no. 2 to 11. One of the most remarkable differences between GFRP and steel reinforcing bars is that the external deformations of the GFRP bars are not standardized. Instead, to ensure appropriate bond to concrete, the manufacturer provides bar surface deformations such as molding deformations with the bar or winding fibers around the bar. Surface profiles for GFRP bars are also not standardized as they are for steel bars.

Figure 2. Glass-fiber-reinforced polymer reinforcement for a cast-in-place, continuous flat-slab bridge. Photo: Christian Steputat.



Carbon-fiber-reinforced polymer (CFRP) strands have been used in the design and construction of prestressed concrete girders, piles, and other members. CFRP has a guaranteed ultimate tensile strength that typically

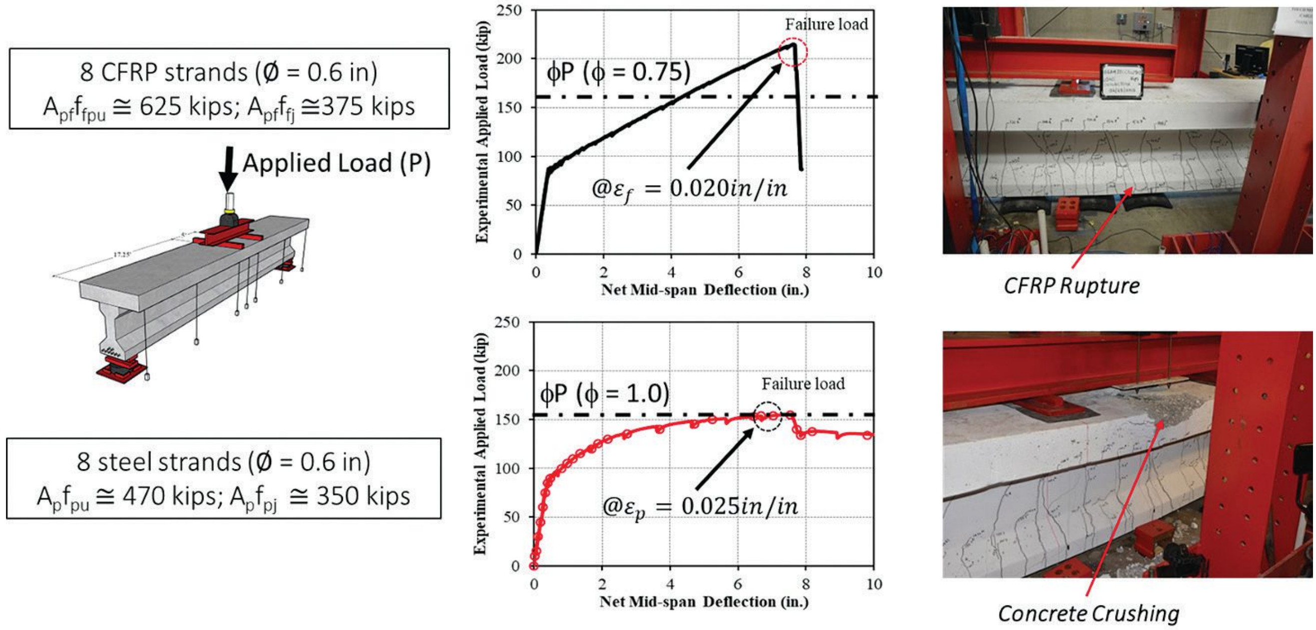


Figure 3. Comparison of load-deformation relationships and failure types of girders prestressed with carbon-fiber-reinforced polymer strands and conventional carbon steel strands. Note: CFRP = carbon-fiber-reinforced polymer. A_p = area of prestressing steel; A_{pf} = area of prestressing CFRP; f_{fj} = initial tensioning stress of CFRP; f_{fpu} = ultimate tensile strength of CFRP; f_{pj} = initial tensioning stress of prestressing steel; f_{pu} = ultimate tensile strength of prestressing steel; Ø = diameter; ϕ = resistance factor; ε_f = strain in prestressing CFRP; ε_p = strain in prestressing steel. Figure: University of Houston. (see also Reference 3)

exceeds 350 ksi, which is greater than the 270 ksi ultimate tensile strength of conventional prestressing steel strands. However, CFRP reinforcement—unlike conventional reinforcement—remains elastic until failure, which means it is a brittle material. CFRP reinforcement is also relatively expensive and has some challenges regarding anchorage when used for prestressing (pretensioned and post-tensioned) concrete. In 2018, AASHTO published its first design specifications for prestressing concrete elements using this material.[2]

Research has shown that despite CFRP's brittleness, prestressed concrete girders using CFRP can exhibit relatively large deformations at ultimate strength.[3] **Figure 3** compares test results of two prestressed concrete beams: one with CFRP strands and the other with conventional steel strands. AASHTO Type I beams with an 8-in.-thick by 3-ft-wide deck were loaded at two points spaced 5 ft apart at the center of the span, which was 38.5 ft. The beams were pretensioned with eight 0.6-in.-diameter strands. Both beams had the same concrete compressive strength and were designed as tension controlled. The beam with the CFRP strands exhibited strand rupture failure, whereas the beam with the conventional steel strands failed due to concrete crushing after steel yielding. The jacking stress of CFRP was limited to 70% of the guaranteed ultimate tensile strength f_{pu} (which was 370 ksi for the strands used), and the resistance factor ϕ for flexure was 0.75 to address the brittle strand behavior. When the area of prestressing strands is equal in both test beams, the cracking moment M_{cr}, the factored nominal moment ϕM_n, and the ultimate deflection are comparable (Fig. 3). The experimental test results were within 5% of predicted values.

FRPs have been used not only for flexural reinforcement but also as stirrups (**Fig. 4**). Perhaps one of the greatest challenges to the full deployment of FRP reinforcement is that bent shapes must be created during manufacture, before polymerization of the thermoset resin. Polymerization of the resin is irreversible; therefore, bends must be made while the resin is still viscous—it is impossible to bend or straighten a bar on site. This characteristic of FRP reinforcement makes procurement difficult and can result in significant time delays if errors are made in bending the bars, or if bars are damaged during shipping or at the construction site. Additionally, the bar strength at a bend is significantly lower than that of the straight portion.

Stainless Steel Materials

The corrosion resistance of stainless steel reinforcement is much superior to that of conventional carbon steel reinforcement. By using stainless steel reinforcing bars, structures can achieve a service life of 100 years or more. Even though the availability of stainless steel reinforcement may be more limited than that of conventional or epoxy-coated reinforcement, there are many stainless steel reinforcement manufacturers and suppliers worldwide.

Figure 4. Assembly of the glass-fiber-reinforced polymer reinforcement cage for a cast-in-place concrete bent cap. Photo: Christian Steputat.

There are many types of stainless steel (for example, alloys 2205, 2304, 316, and 316L). Because the different types of stainless steel have different mechanical and corrosion-resistant characteristics, attention must be paid to the intended use. For stainless steel prestressing strand, it is recommended to use only high-strength duplex alloy 2205. These low-relaxation strands are produced in Grade 240 with a modulus of elasticity of about 24,000 ksi and typically have a total elongation at rupture of about 1.6%. Consequently, prestressed concrete members with high-strength stainless steel alloy 2205 strands can have reduced ductility and require a lower ϕ factor than prestressed concrete members with conventional steel strands.

Relevant NCHRP Projects

To advance the use of novel materials, the National Cooperative Highway Research Program (NCHRP) has initiated three multiyear projects with the goal of developing recommendations for AASHTO LRFD bridge design, materials, and construction specifications. The first project, NCHRP 12-97, covered the use of CFRP strands for prestressing. This project was completed in 2018, and design and materials specifications were developed and published in NCHRP Report 907, *Design of Concrete Bridge Beams Prestressed with CFRP Systems*.[3] The second project, NCHRP 12-120: Stainless Steel Strands for Prestressed Concrete Bridge Elements, has similar goals but focuses on high-strength stainless steel alloy 2205 strands. This project is currently scheduled to be completed in April 2023. The third project, NCHRP 12-121: Guidelines for the Design of Prestressed Concrete Bridge Girders Using FRP Auxiliary Reinforcement, investigates the use of GFRP, CFRP, and basalt-fiber-reinforced polymers as auxiliary reinforcement in prestressed concrete girders. It is currently scheduled to be completed in April 2024.

NCHRP 12-97

The objective of this project was to develop design and material guide specifications in the AASHTO LRFD format for concrete beams prestressed with CFRP strands or bars, using either pretensioning or post-tensioning (bonded or unbonded). The design of concrete bridge members prestressed with CFRP systems depends on several factors such as CFRP material properties, load transfer mechanisms, anchorage properties, sustained loads, and environmental conditions. In the report, design requirements for serviceability and strength are addressed using stress limits for CFRP strands and bars. Design considerations covered in the report include harped strand configurations, prestress losses, durability, fatigue, bond, transfer and development lengths, and unbonded prestressing. The design of CFRP prestressed concrete requires special attention to address the unique requirements associated with the use of a high-strength, elastic, brittle, orthotropic, composite material. These complexities of material behavior require tailored design guidelines and specifications.

NCHRP 12-120

The overall objective of this research is to develop design guidelines and construction specifications in AASHTO LRFD format for the use of stainless steel strands in prestressed concrete members. Superior corrosion-resistant characteristics of stainless steel strands come with some drawbacks compared with conventional carbon steel strands: lower ultimate tensile strength, lower modulus of elasticity, lower ultimate strain (ductility), and increased notch sensitivity. Given these differences, the project is addressing factors such as tensioning stress limits, harped strands, bond characteristics, transfer and development lengths, prestress losses, and creep-rupture of prestressing strands. The design of bridge elements other than beams, including piles and slabs, is also covered. (See the Concrete Bridge Technology articles in the Spring 2018 issue of *ASPIRE*, which address aspects of stainless steel strand in structural design and considerations for fabrication of prestressed concrete piles using stainless steel strand.)

NCHRP 12-121

The main objectives of this research project are to propose modifications to the two referenced AASHTO FRP guide specifications[1,2] and to develop guidelines for the design of prestressed concrete girders using FRP auxiliary reinforcement. The intended outcome of this study is to offer guidance so that engineers can confidently use FRP auxiliary reinforcement with the corrosion-resistant prestressing strands evaluated in NCHRP 12-97 and NCHRP 12-120 to provide safe, economical, and durable prestressed concrete structures in aggressive environments. Topics considered include:

- Properties of FRP reinforcement with glass, basalt, and carbon fibers
- Shear behavior of prestressed concrete bridge girders with FRP shear reinforcement
- Use of FRP reinforcement for interface shear, anchorage zone, confinement, and web-splitting reinforcement
- Detailing of FRP auxiliary reinforcement

Conclusion

The use of these corrosion-resistant materials for concrete bridge elements requires reconsideration of the conventional design approaches as the material properties of both FRP and stainless steel reinforcement are significantly different from those of conventional reinforcement. These differences affect the design approach, but the deformability of concrete structures using these materials can be comparable to traditional materials by adjusting design factors and methods. The NCHRP projects are intended to provide guidance that will allow use of these novel materials to improve the service life of concrete bridge structures.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2018. *AASHTO LRFD Design Guide Specifications for GFRP-Reinforced Concrete*, 2nd ed. Washington, DC: AASHTO.
2. AASHTO. 2018. *Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems*. Washington, DC: AASHTO.
3. Belarbi, A., M. Dawood, P. Poudel, M. Reda, H. Tahsiri, B. Gencturk, S. H. Rizkalla, and H. G. Russell. 2019. *Design of Concrete Bridge Beams Prestressed with CFRP Systems*. National Cooperative Highway Research Program Report 907. Washington, DC: Transportation Research Board. https://doi.org/10.17226/25582.