PROJECT

Harkers Island Bridge Replacement: NCDOT's First FRP-Reinforced Concrete Bridge

by Trey Carroll, Ashvin Patel, and Ahmad Ighwair, North Carolina Department of Transportation

For the North Carolina Department of Transportation's Harkers Island bridge replacement project, a new fiber-reinforced-polymer reinforced concrete structure replaces two 50-year-old bridges. Harkers Island can be seen in the background. Photo: Balfour Beatty.

The Harkers Island bridge replacement project is the North Carolina Department of Transportation's (NCDOT's) first bridge entirely reinforced with fiber-reinforced-polymer (FRP) reinforcing bars and prestressing strands. Harkers Island is located in Carteret County, N.C., near the southern end of the Outer Banks and adjacent to the Cape Lookout Lighthouse and Cape Lookout National Seashore. The bridge crosses a tidal area known as The Straits and is less than 4 miles from two ocean inlets. The $60 million design-bid-build project is 3200 ft long with 28 spans and features a navigational span with 125 ft of horizontal clearance and 45 ft of vertical clearance.

The bridge replaces two sequential 50-year-old bridges: the Earl C. Davis Memorial Bridge, which is a swing-span movable bridge, and Carteret County Bridge No. 96. Together, these structures have provided the only vehicular access and hurricane evacuation route for Harkers Island. The swing-span bridge is in poor condition due to severe corrosion deterioration, and mechanical issues can frequently prevent it from opening to commercial and recreational vessel

profile

HARKERS ISLAND BRIDGE / CARTERET COUNTY, NORTH CAROLINA

BRIDGE DESIGN ENGINEER: North Carolina Department of Transportation Structures Management Unit, Raleigh

CONSULTANTS: Roadway design: RS&H, Charlotte, N.C.; geotechnical engineering: S&ME Inc., Charlotte, N.C.

PRIME CONTRACTOR: Balfour Beatty Infrastructure Inc., Wilmington, N.C.

CONCRETE SUPPLIER: S&W Ready Mix, Clinton, N.C.

PRECASTER: Coastal Precast Systems LLC, Chesapeake, Va.—a PCI-certified producer

OTHER MATERIAL SUPPLIERS: Glass-fiber-reinforced-polymer reinforcement: Owens Corning, Concord, N.C., and New South Construction Supply, Greenville, S.C.; carbon-fiber-reinforced-polymer prestressing strand and spiral: Tokyo Rope USA, Canton, Mich.

traffic. Bridge No. 96 is functionally obsolete and required an emergency full-superstructure replacement in 2013 because the steel prestressing strands in the original cored-slab superstructure were extremely corroded.

NCDOT classifies this area of the state as highly corrosive due to the coastal marine environment. The standard corrosion-protection policy of the NCDOT Structures Management Unit for highly corrosive areas is to use concrete superstructures and substructures with increased concrete cover, epoxy-coated reinforcing steel, and concrete admixtures including calcium nitrite corrosion inhibitor, silica fume, and fly ash. During project development and planning, NCDOT recognized the need to provide a more durable concrete replacement structure that could withstand the harsh saltwater environment and provide greater resiliency than its predecessors.

Coinciding with the start of preliminary bridge design in 2017, NCDOT completed a state-sponsored research project with North Carolina State University to investigate the feasibility of using carbon-fiber-reinforced-polymer (CFRP) strands and glass-fiber-reinforced-polymer (GFRP) stirrups in prestressed concrete components. The research project greatly improved NCDOT's knowledge, experience, and acceptance of FRP reinforcing materials. NCDOT began looking for opportunities to use FRP materials as a corrosion protection measure. (See the Professor's Perspective article on page 54 of this issue of *ASPIRE*®.)

After internal meetings and discussions with various NCDOT technical units, including Construction, Materials & Tests, and Geotechnical Units, NCDOT leadership identified the Harkers Island bridge replacement as the project to implement the use of FRP reinforcing materials. They supported the effort to design the entire structure with FRP materials and, to the fullest extent possible, eliminate steel reinforcement. The size and scope of the structure were considered to be a benefit because the economies of scale would make the costs of the FRP reinforcing materials more competitive with those of traditional reinforcing materials. Additionally, NCDOT was awarded a $1 million Accelerated Innovation Deployment Demonstration grant from

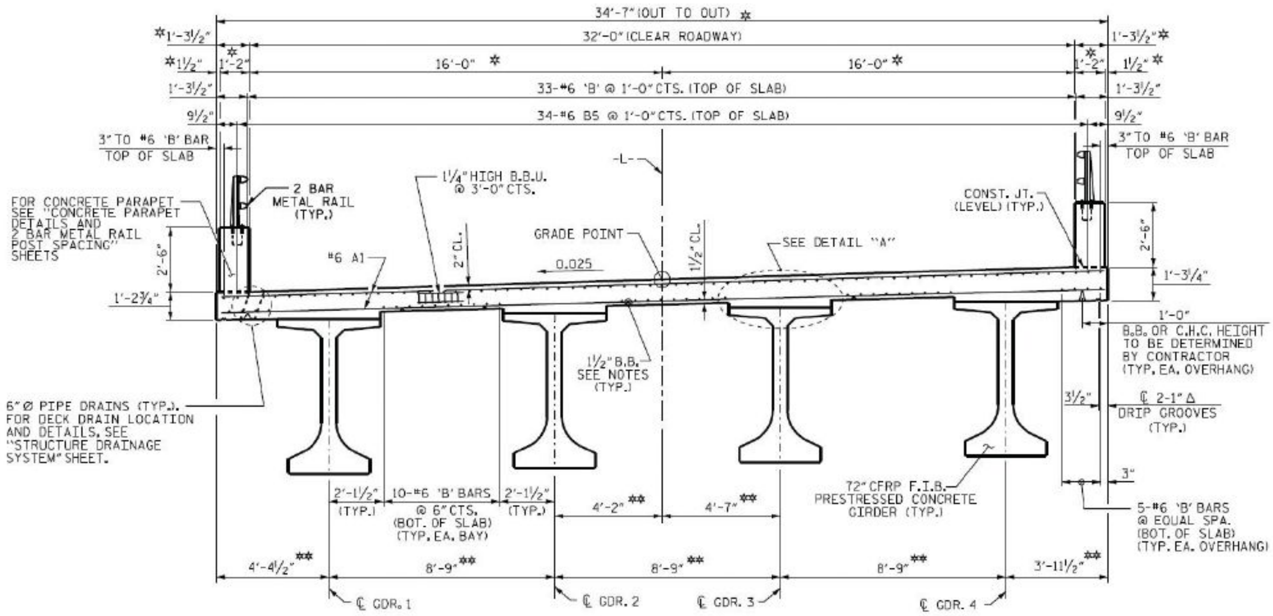
The 164-ft navigational span features five 78-in.-deep Florida I-beams with glass-fiber-reinforced-polymer stirrups and prestressed with carbon-fiber-reinforced-polymer strands. The span provides 125 ft of horizontal clearance and 45 ft of vertical clearance for vessel traffic. Photo: North Carolina Department of Transportation.

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: 3200-ft-long bridge consisting of 28 spans of precast, prestressed concrete Florida I-beam (FIB) girders (span length up to 164 ft); the structure has a 45-ft vertical navigational clearance and an out-to-out width of 34 ft 7 in., with two 12-ft-wide lanes and 4-ft-wide shoulders

STRUCTURAL COMPONENTS: Fifty-six 54-in.-deep FIB girders (5580 linear ft total), forty-four 72-in.-deep FIB girders (5707 linear ft total), and fifteen 78-in.-deep FIB girders (1815 linear ft total), all with an 8¼-in.-thick cast-in-place sand lightweight concrete deck. Nineteen pile bents with cast-in-place bent caps and precast, prestressed concrete 24-in.-square piles, 10 three-column bents with cast-in-place concrete caps, and footings supported on precast, prestressed concrete 24-in.-square piles. All precast, prestressed concrete components are reinforced with carbon-fiber-reinforced-polymer (CFRP) strands and glass-fiber-reinforced-polymer (GFRP) bars; all cast-in-place concrete components are reinforced with GFRP reinforcement. End bents and roadway approaches are scour-protected by prestressed concrete sheet piles with steel prestressing strands.

BRIDGE CONSTRUCTION COST: $60 million ($540/ft^2)



The superstructure of the bridge has an out-to-out width of 34 ft 7 in., with two 12-ft-wide lanes and 4-ft-wide shoulders. The 8¼-in. cast-in-place sand lightweight concrete deck is reinforced with glass-fiber-reinforced-polymer bars and supported by prestressed concrete Florida I-beam girders. All Figures: North Carolina Department of Transportation.

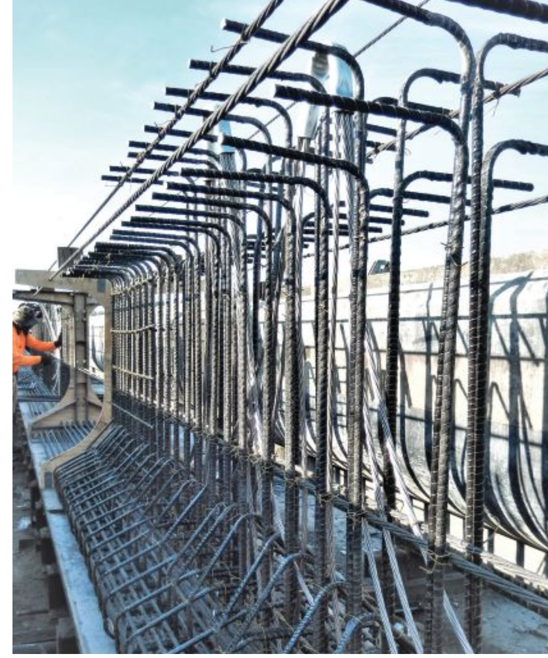
the Federal Highway Administration to assist with offsetting FRP material costs. The size and scope of the project would also allow NCDOT and industry partners to better understand the opportunities and challenges associated with use of FRP materials that are often not realized when nontraditional materials and methods are used at a smaller scale. NCDOT anticipated a learning curve for all parties during design, fabrication, and construction, with the expectation that after the first precast concrete components were fabricated and substructure units placed, production processes would become more efficient.

Superstructure

The bridge superstructure has an out-to-out width of 34 ft 7 in., with two 12-ft-wide lanes and 4-ft-wide shoulders. The cast-in-place (CIP) sand lightweight concrete deck is 8¼ in. thick and reinforced with no. 6 GFRP bars. The deck is supported by precast concrete Florida I-beam (FIB) girders prestressed with CFRP strand. The GFRP-reinforced deck was designed in accordance with the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*.[1] Sand lightweight concrete was used to reduce the dead load on the prestressed concrete girders and substructure, providing a more economical design by reducing both GFRP and CFRP material quantities, as well as substructure size. NCDOT's standard practice is to detail partial-depth prestressed concrete deck panels for corrosive sites. However, removable forms were specified for this project due to the use of sand lightweight concrete in the deck and the desire to avoid metal stay-in-place forms. For bridge expansion joints, foam joint seals with elastomeric concrete headers were located between the two- or three-span continuous units. Link slabs were used to minimize joints. The use of link slabs is advantageous for GFRP bars because it allows the use of straight bars exclusively. Detailing continuous-for-live-load diaphragms with bars having multiple bends would have been challenging to produce in GFRP reinforcement. The only steel reinforcement specified in the bridge superstructure or substructure is epoxy-coated reinforcing steel in the concrete parapet of the NCDOT standard two-bar metal rail. The two-bar metal rail is a common bridge rail used throughout North Carolina and is recognized for its aesthetics. NCDOT successfully crash tested the steel-reinforced bridge rail to the criteria specified in AASHTO's *Manual for Assessing Safety Hardware*[2] and decided against modifying the rail for GFRP reinforcing bars.

In multiple locations, the prestressed concrete Florida I-beam girders are supported by a cast-in-place bent cap on 24-in.-square prestressed concrete piles using carbon-fiber-reinforced-polymer strand and spiral. The average pile length for the project is 100 ft. Photo: North Carolina Department of Transportation.

The 8¼-in. sand lightweight concrete deck is reinforced with no. 6 glass-fiber-reinforced-polymer bars. Removable forms are used for deck construction. Photo: North Carolina Department of Transportation.



Production photo of a 100-ft-long, 54-in.-deep Florida I-beam precast concrete girder prestressed with forty-four 0.6-in.-diameter carbon-fiber-reinforced-polymer strands and reinforced with glass-fiber-reinforced-polymer stirrups. Photo: North Carolina Department of Transportation.

The CFRP prestressed concrete FIB girders were designed as simply supported for dead and live loads. Twenty-five of the 28 spans consist of a four-girder cross section using 54- or 72-in.-deep FIB girders with maximum span lengths of 100 or 130 ft, respectively. However, because the navigational span is 164 ft, an additional girder line and deeper girders were necessary to achieve a reasonable design using CFRP strands. As a result, the three spans around the navigational channel have a five-girder cross section with 78-in.-deep FIB girders.

Each 54-, 72-, and 78-in. FIB girder has forty-four, fifty-six, and sixty-four 0.6-in.-diameter CFRP prestressing strands, respectively. The 54-in.-deep girders had a 28-day design concrete compressive strength of 8 ksi and the 72- and 78-in.-deep girders were designed with 8.5-ksi concrete compressive strength. At the time of design, the manufacturer's guaranteed ultimate tensile strength for the CFRP prestressing strands was 339 ksi. The FIB girders use a typical NCDOT strand pattern with two strands in the 7-in.-wide web.

Contract plans provided design alternatives, giving the contractor the option to select either 0.63-in.-diameter CFRP or no. 5 GFRP stirrups for shear reinforcement. Contract provisions required the contractor to use the same stirrup material in all prestressed concrete girders. The higher strength and higher modulus of elasticity of the CFRP would enable the use of fewer stirrups in each girder, but the material cost per linear foot is less for GFRP than for CFRP. The alternatives were provided to encourage competitive material pricing and address potential supply chain challenges. The contractor elected to use GFRP stirrups for the project. A benefit of using the FIB girder shape is that many of the bar types and dimensions are interchangeable among the different girder sizes.

The CFRP prestressed concrete FIB girders were designed in accordance with the *AASHTO LRFD Bridge Design Specifications*,[3] the *AASHTO Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems*,[4] the American Concrete Institute's *Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures* (ACI PRC-440),[5] and other technical reports. Engineers from state transportation agencies, including those from Florida, Michigan, and Virginia, provided valuable insights and collaboration throughout the design process.

The design of concrete girders prestressed with steel strand is generally controlled by service limit states (stresses), but for CFRP prestressed concrete girders the design was controlled in multiple instances by the strength limit state due to the 0.75 resistance factor that is applied for both compression and tension-controlled components. A design strand jacking force of $0.70f_{pu}$ (where f_{pu} is the design ultimate strength of the prestressing strand) was used for the CFRP prestressing strands.

The prestressed concrete girders are supported on steel-laminated elastomeric bearing pads with stainless steel sole plates and anchor bolts.

Substructure, Foundations, and Walls

The substructure of the bridge consists of pile bents and post-and-beam bents on pile-supported footings. The end bents and 17 of the interior bents are GFRP-reinforced CIP concrete bent caps on five or six 24-in.-square CFRP prestressed concrete piles. Ten interior bents are GFRP-reinforced CIP concrete bent caps on three columns with a footing supported by ten or fifteen 24-in.-square CFRP prestressed concrete piles. Substructure units were designed for vessel collision, which required battered piles. Owing to limitations with manufacturing larger-diameter bends in GFRP reinforcing bars, the main flexural reinforcement for the caps, columns, and footings are no. 8 bars. The members were designed using 90-ksi ultimate strength with a 0.7 environmental strength-reduction factor for the no. 8 GFRP bars. Stirrups, column spiral, and

Cast-in-place concrete footing is reinforced with glass-fiber-reinforced-polymer reinforcing bars. Not visible are the ten 24-in.-square precast concrete piles prestressed with carbon-fiber-reinforced-polymer strand. Photo: North Carolina Department of Transportation.

other miscellaneous reinforcing bars are predominately no. 5 GFRP bars. The CIP concrete substructure components were designed in accordance with the *AASHTO LRFD Bridge Design Specifications* and the *AASHTO Bridge Design Guide Specifications for GFRP-Reinforced Concrete*. The strength limit state required resistance factors of 0.55 for compression and tension-controlled components and 0.75 for shear.

One challenge of using GFRP material is providing adequate reinforcement to satisfy crack-control requirements. To avoid increasing the size of the substructure components and to provide a component that was easier to construct, NCDOT made exceptions to some of the crack-control requirements. Pile lengths for the 212 piles vary from 60 to 120 ft, with most of the piles being approximately 100 ft in length. The 24-in.-square CFRP prestressed concrete piles have sixteen 0.6-in.-diameter CFRP prestressing strands, 0.28-in.-diameter CFRP spiral, and 10-ksi design concrete strength.

Each end bent and approach roadway is protected from scour by a prestressed concrete sheet-pile wall. Prestressed concrete sheet-pile walls have a long history in North Carolina of providing durable, low-maintenance scour protection. The individual 2-ft 6-in.-wide by 1-ft-thick sheet piles range in length from 37 to 56 ft. Each sheet pile is prestressed with 22 conventional 0.6-in.-diameter, 270-ksi low-relaxation steel prestressing strands. Because the walls are not in constant contact with saltwater, the decision was made to use conventional steel strand and reinforcement in the sheet piles. Calcium nitrite corrosion inhibitor, silica fume, and fly ash were added to the concrete mixture to enhance durability and longevity of the sheet piles.

Project Construction

The project was let to construction in July 2021 and four bids were received. The winning contractor immediately started work because of a moratorium that prohibits any in-water work from April 1 through September 30 each year. By October 1, the contractor had commenced installing a temporary work bridge, and by November, crews were driving the first CFRP prestressed concrete test piles. The prestressed concrete piles and 54-in.-deep FIB girders were delivered to the jobsite by truck, and the 72- and 78-in.-deep FIB girders were delivered by barge.

There were initial construction challenges that involved revising

Installing formwork for cast-in-place concrete substructure columns reinforced with glass-fiber-reinforced-polymer reinforcing bars. Photo: Balfour Beatty.

Precast, prestressed concrete sheet-pile walls protect end bents and approach roadways from scour. Photo: North Carolina Department of Transportation.

GFRP bar details to accommodate manufacturing limitations. Extra splices were added to bent bars due to fabrication tolerances associated with bending GFRP. When the first CFRP prestressed concrete piles were field cut to the correct elevation, minor cracking occurred at the location of the CFRP strand. The cause of the cracking was attributed to the Hoyer effect of the CFRP strand, and the cracking in most instances was contained within the bent cap or footing. Later, it was noticed that the more time that elapsed between the pile casting and field cutting, the less likely it was that cracks would occur; eventually, no cracking was observed.

Collaboration among the contractor, precaster, FRP suppliers, and NCDOT contributed greatly to the success of the project. As of this writing, the project is nearing completion, with only a few spans of deck remaining to be placed, followed by barrier rail installation. The contractor is scheduled to have the bridge ready for traffic by the end of 2023, which will be 10 months ahead of the contract schedule.

The Harkers Island bridge replacement project is a monumental project for NCDOT. The lessons learned throughout the design and construction of this project are already being applied to other active NCDOT projects using CFRP and GFRP reinforcement. The project has accelerated the adoption of FRP materials by NCDOT and promotes new business practices that will provide longer-lasting structures with improved durability and greater resiliency in North Carolina's corrosive coastal environments.

References

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5. American Concrete Institute (ACI). 2007. *Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures*. ACI PRC-440-07. Farmington Hills, MI: ACI.

Trey Carroll is an assistant state structures engineer and Ashvin Patel and Ahmad Ighwair are bridge engineers in the Structures Management Unit of the North Carolina Department of Transportation in Raleigh.

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