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Corrosion-Free Carbon Fiber Reinforced Polymer for Prestressed Piles

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16. Abstract:

This study investigated the feasibility of replacing traditional steel strands and spiral reinforcement in bridge piles with carbon fiber reinforced polymer (CFRP) strands and spiral reinforcement. CFRP is a corrosion-free material, whereas the conventional steel reinforcement used in a traditional pile is prone to corrosion when exposed to chlorides. The Virginia Department of Transportation (VDOT) placed CFRP in 18 piles in two bents of the Nimmo Parkway Bridge over West Neck Creek in Virginia Beach.

Initially, two CFRP-reinforced concrete test piles were cast for the project. To fabricate these piles, a buffer material was used to protect the ends of the strands prior to placing them in the couplers used for prestressing. The couplers had CFRP strands in chucks on one end and the steel strands in chucks on the other end. Prestressing force was applied through the steel strands. Concretes used in the piles had conventional slump. To minimize damage during consolidation, rubber tipped vibrators were used. Concretes were steam cured under insulating blankets; however, the couplers used for prestressing the CFRP strands were protected from high heat by keeping the area exposed to the environment. Heat above 122 °F was thought to cause slipping of the strands in the couplers. After the concrete had cured sufficiently, the piles were detensioned and removed from the forms. When the contractor was ready for driving the piles, the CFRP piles were shipped to the jobsite, instrumented, and successfully driven at one end of each of the two bents. Since the fabrication and driving operation with the test piles were successful, the remaining 16 CFRP-reinforced piles were cast and driven in two of the bents.

This project provided VDOT with the ability to implement the use of corrosion-free reinforcement in prestressed piles where corrosion is a concern, such as those exposed to brackish or saltwater. To guide VDOT in selecting projects where premium reinforcement such as CFRP would be economically justified, a life-cycle cost analysis was performed using the actual costs of the Nimmo Parkway contract and maintenance plans contained in consultant reports created for another VDOT structure: the Hampton Roads Bridge-Tunnel. These reports provided pile maintenance plans designed to extend the service life of a heavily trafficked VDOT structure in an aggressively corrosive environment. Although user costs of maintenance activities are potentially significant factors in VDOT decisions when VDOT's costs between alternatives are similar, the life-cycle cost analysis in this study focused on VDOT costs alone because in exchange for high construction costs for piles with corrosion-free reinforcement, user costs for corrosion mitigation in those piles is nil. Thus in an aggressively corrosive environment, if agency costs for 100 years of service from premium-reinforced piles can be shown to be competitive with discounted construction and corrosion mitigation costs of conventional piles, user costs add no substance to the decision criteria.

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ABSTRACT

This study investigated the feasibility of replacing traditional steel strands and spiral reinforcement in bridge piles with carbon fiber reinforced polymer (CFRP) strands and spiral reinforcement. CFRP is a corrosion-free material, whereas the conventional steel reinforcement used in a traditional pile is prone to corrosion when exposed to chlorides. The Virginia Department of Transportation (VDOT) placed CFRP in 18 piles in two bents of the Nimmo Parkway Bridge over West Neck Creek in Virginia Beach.

Initially, two CFRP-reinforced concrete test piles were cast for the project. To fabricate these piles, a buffer material was used to protect the ends of the strands prior to placing them in the couplers used for prestressing. The couplers had CFRP strands in chucks on one end and the steel strands in chucks on the other end. Prestressing force was applied through the steel strands. Concretes used in the piles had conventional slump. To minimize damage during consolidation, rubber tipped vibrators were used. Concretes were steam cured under insulating blankets; however, the couplers used for prestressing the CFRP strands were protected from high heat by keeping the area exposed to the environment. Heat above 122 °F was thought to cause slipping of the strands in the couplers. After the concrete had cured sufficiently, the piles were detensioned and removed from the forms. When the contractor was ready for driving the piles, the CFRP piles were shipped to the jobsite, instrumented, and successfully driven at one end of each of the two bents. Since the fabrication and driving operation with the test piles were successful, the remaining 16 CFRP-reinforced piles were cast and driven in two of the bents.

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FINAL REPORT

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INTRODUCTION

In 2010, the Virginia Department of Transportation (VDOT) completed the 3-year phased transition from the use of epoxy-coated reinforcing bars in bridge deck construction to corrosion-resistant reinforcement. This change was a response to escalating maintenance and traffic delay costs associated with concrete repairs because of corrosion of the steel reinforcement in aging bridge decks. VDOT's shift demonstrated that the selection process for concrete-reinforcing materials should henceforward consider more than initial costs.[1] Instead, the important factors were recognized to be construction costs plus comprehensive future costs of deck maintenance operations (often calculated using life-cycle cost [LCC] analysis), especially when minor changes in construction material costs could significantly reduce future maintenance costs and inconvenience the traveling public.[1]

The use of corrosion-resistant prestressed strands in bridge elements was not included in the scope of VDOT's initial examination of conventional reinforcement in bridge structures. Yet although strands are used in relatively small quantities in bridge structures, they are subjected to greater stress than in traditional deck reinforcement. In fact, corrosion is even more critical in strands that are under high stress conditions than it is in traditional reinforcing steel bars. Wires in prestressed strands can fracture with little section loss because of the higher stress in each wire and the stress intensity in the area of corrosion, as shown in Figure 1. Then, as corrosion progresses in different wires in an area and more individual wires fracture, the remaining wires in the strand can become overloaded, and an unexpected rapid failure of the structural steel strand can result.

Corrosion-related damage in prestressed elements occurs in both pretensioned and post-tensioned strands, as shown in Figure 1. In Figure 1, above the fiberglass jacket, rust stains are visible on the corner of the pile. Corrosion at this location in a bridge pile that is subjected to saltwater is not surprising since the chloride ions are diffusing into the concrete from two surfaces. The larger concern in this case, however, is that if corrosion is occurring above the fiberglass jacket, undetected corrosion could be occurring inside the jacket.

Figure 1. Corrosive Attack in Section of an External Steel Tendon After 17 Years (*left*); Corroding Piles, With Oldest Piles Being Driven in Late 1950s Requiring Repair by Early 1980s (*right*)[3]

As reported by Hartt et al., the use of fiberglass jackets as a stand-alone repair was found to hide corrosion damage under the flexible fiberglass jacket.[2] Hartt et al. also demonstrated that once corrosion begins to degrade a bridge element, future repairs in the vicinity of the original damage will most likely follow. For piles, this is of great concern since repairs are costly and difficult because these elements generally are load-carrying members under the deck. In many cases, traffic must be interrupted with lane closures and work zones that limit traffic flow and increase traffic hazards. In heavily traveled structures, the cost of traffic controls and repairs can easily approach a significant percentage of the cost of building a new structure in addition to being very inconvenient to the traveling public. Bridge structures are expected to last at least 75 years and preferably 100 years. Therefore, it is critical that the reinforced concrete piles be designed with materials that resist corrosion or are corrosion free so that the piles will reach the intended design life with minimum, if any, disruptions of traffic flow because of corrosion mitigation.

Fortunately, there are corrosion-free strand and spiral material options for prestressed concrete elements. CFRP is a composite material that derives its behavior by optimizing the properties of two or more materials that are combined in a specified way, which in this case creates advantageous longitudinal properties. Although different types of CFRP reinforcement exist, this study focused on CFRP strands that were developed and sometimes referred to as carbon fiber composite cable. This type of CFRP is a corrosion-free strand material that has the appearance of a conventional seven-wire strand and the flexibility to be spooled.

Carbon fiber composite cable was first used in the beams of the Shinmiya Bridge built in 1988 off the coast of Japan.[4] This bridge, which was a replacement structure for a bridge built 20 years earlier that failed because of corrosion, continues to show no signs of corrosion. CFRP does not corrode; it is corrosion free. In the United States, the same CFRP strand material was placed in a Michigan bridge structure that has undergone continuous monitoring since construction was completed in 2001, showing favorable results.[5] Currently several other bridges in Michigan have been constructed using CFRP, and more bridges are expected in the future. In addition, the stay cables of a cable-stayed bridge in Maine were constructed with CFRP. Other research has also shown favorable results when this material was used as a structural component.[6, 7]

Elements with CFRP are expected to last a long time. ElSafty et al., in a recent report from the Florida Department of Transportation, indicated excellent performance of CFRP when subjected to alkaline solutions at 60 °C for more than 7,000 hours. During testing, the CFRP sample maintained the guaranteed tensile strength and elastic modulus, indicating it was suitable for prestressing applications.[8] Currently higher initial costs and/or concerns regarding required changes in fabrication processes involving couplers and preparation of CFRP strand ends seem to be impeding market penetration of CFRP. However, as discussed previously, it is no longer assumed that initial costs necessarily indicate the best long-term cost choice, and adaptation to new fabrication processes can be achieved through training and practice, as with all new technology.

In a marine environment, corrosion-related damage to conventionally reinforced prestressed piles is common. Pile repairs are costly and difficult since piles are generally load-carrying members under the deck, and access to some or all of the piles may be severely constrained. In many cases, work zones must be established, which cause both travel delays and safety concerns. Moreover, access and construction in a marine environment can result in additional challenges and concomitant costs when compared to inland repairs. CFRP strand is a corrosion-free reinforcement, and its use therefore precludes corrosion-related repairs, even when piles are exposed to severe environments such as brackish water and seawater.

PURPOSE AND SCOPE

The purpose of this study was to demonstrate that CFRP in prestressed piles could be effectively employed for bridge structures at locations with a high risk for corrosion. The study focused on fabricating piles with CFRP by precasters and the associated documentation to ensure VDOT's successful implementation of CFRP strand as a replacement material for traditional steel strand. The study consisted of documenting the fabrication and driving of 18 bridge piles for the Nimmo Parkway bridges over West Neck Creek in Virginia Beach. This information was then used to facilitate the generation of the necessary documents for implementation of corrosion-free CFRP reinforced pile. In addition, an LCC analysis was performed to determine if the relatively high-cost product would be cost-effective over the desired service life in comparison with conventional reinforcement in concrete piles.

METHODS

This study documented the construction materials, casting, and placement of the first set of CFRP-reinforced piles supporting a highway bridge in the United States. Details on the CFRP reinforcement, the fresh and hardened concrete properties, and the pile geometry are also included.

Overview

The project on the Nimmo Parkway over West Neck Creek in Virginia Beach has two bridges with 272 piles supporting the longer of the two bridges. In the longer bridge, 250 piles had conventional uncoated steel reinforcement, 18 had CFRP reinforcement, and 4 were reinforced with stainless steel strands and a spiral. The cross section of the 24-in-square CFRP pile with a circular spiral is shown in Figure 2. Design information for the conventional steel strand piles and the CFRP piles is summarized in Table 1.

The 18 CFRP production piles were all cast at two plants owned by the same fabricator. Initially, two CFRP test piles were cast in November 2012 at the producer's Plant 1. These test piles were driven in October 2013. During driving, the test piles were instrumented and the dynamic response was compared to that of piles with conventional steel strands in the same structure. One year later, in November 2013, 16 production piles were cast by the same producer but at a different facility (Plant 2). These piles were then driven in December 2013. VDOT placed both the test and production CFRP piles in two bents of the longer bridge. This was the first time in the world that concrete piles were completely fabricated with CFRP reinforcement and noncorrosive ties and lifting devices and placed in a bridge. At a cost of $58 million, this construction project was completed in September 2014.

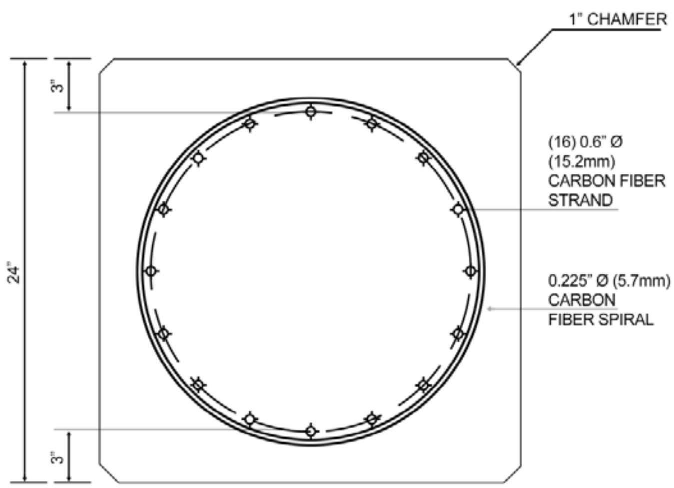

Figure 2. Cross Section of Pile

Table 1. Design Information for Conventional and CFRP Piles in Nimmo Parkway Bridges

Property	Conventional Steel Strand Piles	CFRP Piles
Pile size (number and location)	24-in square (250 in all bents except 12 and 13)	24-in square (18 in bents 12 and 13)
No. of strands in each pile	16	16
Strand diameter	0.5 in	0.6 in
Strand pattern	Square	Circle
Spiral	Galvanized W3.5 (0.211-in diameter)	CFRP (0.225-in diameter)
Initial tension per strand	31 kips	34 kips
Minimum ultimate strength	270 ksi (low relaxation)	338 ksi (low relaxation)
Area of strand	0.196 in^2	0.179 in^2
Initial prestress per strand	31/0.196 = 158 ksi	34/0.179 = 190 ksi
Initial prestress/Fu	58.5%	44.5%

CFRP = carbon fiber reinforced polymer; Fu = ultimate strength.

CFRP Properties

The manufacturer indicated that the CFRP would meet the properties that they have listed on their website.[9] It is important to note that their listed total elongation is 1.7 percent, which does not meet the requirements of ASTM A416, i.e., a minimum value of 3.5 percent. CFRP has been shown to have a bond strength that is equal to or greater than that of conventional steel prestressing strand.[4]

Piles

Concrete Properties

The mixture proportions for the CFRP test piles cast at Plant 1 and the CFRP production piles cast at Plant 2 are given in Table 2. A commercially available air-entraining admixture, a retarding admixture, and a high-range water-reducing admixture were also added to the concrete. Conventional VDOT piles exposed to marine and brackish water conditions contain 2 gal/yd^3 of calcium nitrite corrosion inhibitor. Although the use of calcium nitrite for corrosion inhibition is not needed with CFRP, calcium nitrite also acts as an accelerating admixture and helps achieve high early strengths in concrete. The specified 28-day compressive strength was 5,000 psi, and the release strength was 3,500 psi. The specified air content was 3 to 7 percent. Because of the addition of a high-range water-reducing admixture, a maximum slump of 9 in was permitted provided there was no visible segregation.

Concrete was tested at the fresh state for slump (ASTM C143), air content (ASTM C173), density (ASTM C138), and initial concrete temperature (ASTM C1064) and at the hardened state for compressive strength (ASTM C39), elastic modulus (ASTM C469), and permeability (ASTM C1202).

Table 2. Mixture Proportions of Concretes for CFRP Piles (lb/yd^3)

Ingredient	Plant 1 (Test Piles)	Plant 2 (Production Piles)
Type III portland cement	511	494
Type F fly ash	171	211
Coarse aggregate (No. 67)	1,683	1,683
Fine aggregate (natural sand)	1,355	1,292
Water	238	235
Maximum water–cementitious material ratio	0.35	0.33
Calcium nitrite (gal/yd^3)	2	2

CFRP = carbon fiber reinforced polymer.

Casting and Driving of Piles

Researchers at the Virginia Transportation Research Council (VTRC) documented the fabrication of the CFRP piles including the end preparation of strands, prestressing, concrete placement, steam curing, and detensioning. The driving of a pile is a physical process, as the repetitive blows to the pile head drive the pile into the ground. Therefore, the CFRP piles were visually inspected for cracked or damaged concrete prior to and after driving. The test piles were instrumented to determine the dynamic response for comparison to that of the piles with conventional steel strands.

RESULTS AND DISCUSSION

The test and production piles were monitored for the placement of reinforcement and concrete and the prestressing and detensioning of the strands, and the concrete properties of the piles were determined. The driving response of the test piles was also obtained and compared to that of the piles with conventional reinforcement.

Test Piles

Two test piles with CFRP were cast at Plant 1 in the same prestressing bed; one of the piles (P1) was 76 ft long, and the other pile (P2) was 82 ft long.

Reinforcement Placement and Prestressing

The CFRP used in this project, carbon fiber composite cable, is a carbon fiber, derived from polyacrylonitrile, with an amine-cured epoxy matrix. It has low ductility and is anisotropic, resulting in high strength in the axial direction, but the strength decreases as the applied force rotates toward the transverse direction. CFRP can also burn, so CFRP can be cut using an angle grinder with an abrasive cutting blade rather than an oxy-fuel torch. Further, careful handling is required to avoid abrading or nicking the CFRP strand. These characteristics of CFRP still allowed all of the CFRP piles to be cast at a precaster's facility using the same prestressing equipment and concrete that is used to fabricate conventional steel reinforced piles (Figure 3).

Figure 3. Pile With Carbon Fiber Reinforced Polymer at Casting Yard

However, special handling requirements are necessary for the preparation of CFRP ends for stressing. Jacks do not directly grip and pull the end of the CFRP. Instead, steel strands are attached to CFRP strand by a coupler (Figure 4), and jacks then grip and pull the steel strands. To couple the steel and CFRP strand, the steel strand was placed in one-half of the coupler with a traditional chuck to secure it and the CFRP was prepared with special buffer materials and placed in the other end of the coupler. The CFRP end was prepared for the coupler by wrapping it with a mesh sheet made of layers of metal and plastic, followed by insertion of the wrapped end into a braided stainless steel grip, as shown in Figure 5. The prepared end was held by four-part wedges evenly inserted in a chuck barrel. Because of the time required for end preparation, daily cycles for the production of CFRP piles were not achieved, although conventional piles were prepared and detensioned in a 24-hour cycle.

Figure 4. Carbon Fiber Composite Cable and Steel Couplers Joined (*left*); Couplers Staggered and Tensioned (*right*)

Figure 5. CFRP End Preparation for Tensioning Using Coupler. This requires (a) layered mesh sheets (b) to be wrapped around CFRP and taped (gray helical wrapping with red tape along the edge of the mesh sheet) and then (c) a braided grip to be slid over the mesh sheets and also taped. CFRP = carbon fiber reinforced polymer.

After all couplers were assembled, they were staggered and a preload of 5 kips was applied with the prestressing jack. Although continuous loading is currently used, during this early fabrication, the jack was loaded in increments of 10 kips until the maximum tension of 34 kips was achieved. For conventional steel reinforcement, continuous and rapid loading is done by completing prestressing within 30 seconds. At each preload and then at maximum load, the extension of the CFRP was measured. There was no noticeable slippage of the strand, and the actual elongation matched the calculated figure. The reduced elongation of CFRP compared to the ASTM requirement of a minimum 3.5 percent did not compromise the prestressing operation.

For safety reasons regarding the use of a new strand material at this facility, the CFRP was maintained prestressed overnight. On the following day, CFRP spirals that were already in the prestressing bed (placed before the strands) were tied to the CFRP strands with plastic ties. The CFRP spiral for each pile was light and could be carried easily by one person (Figure 6). There was no sagging in the CFRP strands after placement of the CFRP spiral; sagging would be normal with conventional steel reinforcement because of the weight of the steel. For each pile, two lifting devices were placed. The lifting device incorporated threaded rods that were placed in cardboard tubes to avoid contact of the steel with the CFRP and the spiral. Later, after the lifting devices were used to remove the pile from the bed, the lifting devices and the cardboard tubes were removed from the piles and the holes grouted (Figure 6). With no steel remaining in the finished pile, these piles are a corrosion-free option when long-term durability is important.

Corrugated plastic pipe was used at the head of the pile where dowels are placed for connection to the pile bent. The plastic prevented contact between the conventional steel reinforcement in the pile caps and the CFRP, which could have created a galvanic cell between the reinforcing steel and the CFRP. This precaution was taken although the CFRP wires are coated with a thin layer of polyester tape that maintains the round shape of each wire. Although the polyester tape should prevent galvanic interaction, the use of the plastic pipe eliminated the possibility of contact between the steel and CFRP strand, and it also ensures that the CFRP strand is protected from abrasion damage during subsequent construction activities.

Figure 6. Spiral for Pile Carried by One Person (*left*); Lifting Device (*right*)

Concrete Placement

Overview

Concrete was placed in the bed and consolidated using internal vibrators with rubber heads to prevent damage to the CFRP (Figure 7). Upon completion of concrete placement, the bed was covered and the test specimens were placed on a rack at one end of the bed. At this location, temperatures were lower than at the remainder of the bed to ensure that slippage of CFRP strand within the couplers did not occur.

A thermocouple inserted at a depth of 2 in inside the concrete surface monitored the test pile temperature during steam curing. Another thermocouple was placed in the enclosure at each end of the bed. Although the concrete temperature reached 135 °F (lower than the allowable 180 °F), near the couplers the temperature remained well below 122 °F, which deterred slipping of the CFRP strands in the coupler. The specified minimum release strength of 3,500 psi was achieved overnight. The CFRP piles were then ready for detensioning and removal from the bed.

Figure 7. Concrete Consolidation Using Rubber Tipped Vibrators

Concrete Properties

Concrete was batched in a central plant and delivered in trucks with augers carrying 5 yd^3 each. The first (B1) and fourth (B2) of the five loads needed for each pile were sampled for fresh and hardened concrete tests. These specimens were steam cured overnight in the prestressing bed with the test piles and then brought to the VTRC laboratory, where they were kept in a moist room until testing.

Workable concretes with proper air contents were achieved. The hardened concrete properties are summarized in Table 3. The 7-day strength and permeability values are the average of two specimens, and the 28-day values are the average of three specimens. The compressive strengths at 7 days exceeded the specified minimum 28-day strength of 5,000 psi. The elastic modulus at 7 days was determined for B1 only, and it was more than 4 million psi; at 28 days, it exceeded 4.8 million for both batches.

The permeability values for the test pile steam-cured specimens at 28 days were 3226 C for B1 and 4382 C for B2. However, these specimens were kept moist at room temperature after the initial steam curing. Therefore, the high values are attributed to the relatively low curing temperatures and the presence of calcium nitrite. Although it is true that the temperature of the beams reached 135 °F (accelerated curing), the concrete test specimens were located near the couplers during the initial steam curing instead of near the beams. In the region near the couplers, the insulating blankets were rolled back at the ends to ensure that the couplers were exposed to lower temperatures (varying between 79 °F and 91°F), which also reduced the curing temperature of the concrete samples.

Achieving VDOT's specified maximum permeability value for prestressed elements requires accelerated curing. Accelerated curing, 1 week at room temperature and 3 weeks at 100 °F, enables the reduction in permeability expected in the long term (several months) to occur at an early age of 28 days. The VDOT-specified maximum permeability value for prestressed elements is 1500 °C. The values for specimens from each batch that were tested after accelerated curing were 570 °C for B1 and 767 °C for B2. These values are much lower and meet the VDOT specification, which indicates that these concretes will have a high resistance to the penetration of chloride ions.

Table 3. Hardened Concrete Properties

Test	Age (days)	Test Piles		Production Piles	
		B1	**B2**	**B3**	**B4**
Compressive strength (psi)	7	5,830	5,410	5,670	5,910
	28	7,740	7,530	6,800	7,000
Elastic modulus (10^6 psi)	7	4.42	---	3.90	3.94
	28	4.82	4.86	4.02	4.23
Splitting tensile strength (psi)	7	520	505	470	525
	28	635	635	575	600
Permeability, steam cure (C)	28	3226	4382	4224	4343
Permeability, accelerated cure (C)[a]	28	570	767	---	---

--- = no data.
[a] Accelerated cure: 1 week at room temperature and 3 weeks at 100 °F.

Detensioning

Overview

The steel strands at both ends of the bed were cut using a torch. This was done in a manner similar to that used with conventional detensioning operations using a predetermined cutting sequence. Since two piles were cast in the same bed with a space between them, the CFRP between the two piles was cut using a grinder with an abrasive blade to prevent the burning of the CFRP. The piles were then lifted and stored next to the forms. The visible imperfections on the piles are commonly found on concrete precast products with conventional slump and were considered acceptable.

Driving Operation

Two CFRP-reinforced piles were driven as test piles along with other traditional steel reinforced test piles during the construction of the Nimmo Parkway Bridge (Figure 8). During driving, the ram weight was 10,141 lb and the hammer stroke was 5.7 to 9.2 ft. The dynamic analysis indicated that there were no differences in the driving responses of piles with CFRP and conventional piles with steel strands. (Later, the 16 CFRP production piles were also driven with no problems.) The reduced elongation of CFRP compared to the ASTM requirement of a minimum of 3.5 percent elongation did not compromise the driving operation. The test piles demonstrated that although CFRP requires special end preparation (Figure 5) and some handling accommodations (Figures 6 and 7), a CFRP-reinforced pile can be driven in the same way as a pile with conventional steel strands.

Figure 8. Preparing for Pile Driving (*left*); Pile in Place after Driving Showing No Signs of Damage to Upper Portion of Pile (*right*)

Production Piles

Overview

One year after casting the test piles, the contractor ordered the production piles. They were cast at Plant 2 with the mixture proportions shown in Table 2 (for Plant 2). A commercially available air-entraining admixture, a water-reducing and retarding admixture, and a high-range water-reducing admixture were also added. Four piles were cast concurrently in a bed. As in the test piles, the preparation of the piles included spiral placement, strand placement, end preparation, placement into the couplers, prestressing, casting of concrete, curing, and detensioning. Detensioning required more than a 24-hour cycle, as in the earlier test piles. Each set of four piles in a bed was completed within 2 days from the beginning of reinforcement placement to removal from forms.

Production piles were also steam cured. The temperature in the beam reached 145 °F. The production specimens were kept at the end of the bed with the couplers, again for the reason that temperatures were lower at the end of the bed and would deter slippage of the strand within the couplers. The plant used temperature-matched curing to determine the compressive strength for detensioning.

Concrete Properties

Two batches of concrete denoted B3 and B4 were tested; workable concretes and specified air contents were obtained. The hardened concrete properties are given in Table 3. The 7-day compressive strengths exceeded the specified minimum 28-day strength of 5,000 psi. Although the permeability values for the steam-cured production piles were high, as shown in Table 3, the values were similar to those for the test batches without the accelerated cure. If accelerated curing had been used, very low values would have been expected, consistent with the test piles.

Life-Cycle Cost Analysis

In the Nimmo Parkway contract, the average bid cost of 1 linear foot of a pile prestressed with CFRP was about 4 times the average bid cost for the conventional pile (about $361 and $87, respectively). Although CFRP has already demonstrated superior performance against conventional reinforcement products in a variety of environments,[4-7] a cost multiple of this size might preclude VDOT's use of the product based on construction cost alone in the absence of economic analysis that could demonstrate its long-term cost advantages over conventional materials.

Although CFRP is a costly material in the construction phase compared to conventional reinforcement, according to Grace et al. it can be the least costly option over a service life of 20 to 40 years if traffic volume is high and bridge geometry is problematic.[10] meaning that potential user costs of maintenance activities are high. Yet the corrosiveness of the bridge environment, in combination with high ADT, is as important as bridge geometry in calling for durable construction materials. For this reason, an economic analysis of hypothetical piles in the Hampton Roads Bridge-Tunnel (HRBT) was performed using pile fabrication and installation costs from the Nimmo Parkway contract and actual consultant maintenance plans for existing (conventional) HRBT piles that were devised to extend their service life to approximately 100 years before replacement.[11, 12] If a CFRP-reinforced pile is demonstrably less costly than a conventionally reinforced pile over a 100-year service life in terms of agency costs only, the addition of user costs reflecting the HRBT's actual high traffic volumes and problematic geometry regarding pile access would only underscore the cost advantage of CFRP-reinforced piles.

The HRBT consists of four bridges, two eastbound and two westbound, supported by 1,858 piles set in the ocean bed, and two tunnels; the bridges in each direction are connected by tunnels in the midsections. The bridge structures in the HRBT system each carry an average daily traffic of about 42,800 vehicles (well over the 95th percentile for VDOT structures) across the water where several tributaries combine and flow into the Chesapeake Bay. VDOT recently examined strategies for maintenance of the HRBT, generating several detailed consultant reports that provided the costs of maintenance activities that rely on the jacketing of existing piles to extend their life.[11, 12]

The Nimmo Parkway contract provides the cost for fabrication and installation of the hypothetical conventionally reinforced pile used in this analysis. The consultant reports provide unit costs for initial and subsequent jacketings which are applied over time to the pile to culminate in a 100-year pile service life that is consistent with SHRP 2 guidance for a structure such as the HRBT.[13] The jacketing schedule of the hypothetical pile mirrors the factual history of the existing HRBT piles and consultant recommendations for their future maintenance or replacement.

To contrast with the hypothetical conventional pile, a new CFRP-reinforced pile is hypothetically fabricated and installed at the Nimmo Parkway cost. Their respective costs are compared in terms of the present values of their lifetime costs discounted at a 3 percent rate.[14] (No price adjustment for inflation is included because the Nimmo Parkway contract and the consultant reports were within a few years of each other.) Two key premises of the analysis are that (1) the CFRP pile does not require jacketing, carbon being an inherently corrosion-free reinforcement material, and (2) the conventionally reinforced pile can reach 100 years of service life by means of jacketing alone.

Table 4 shows the initial construction costs of the hypothetical 60-ft CFRP-reinforced pile and the hypothetical 60-ft conventionally reinforced pile. Pile costs per linear foot for both reinforcement types directly reflect the Nimmo Parkway contract. For both pile types, the winning bid unit cost fell between the average bid and the minimum bid, and thus the cost spread is relevant.

Table 5 shows maintenance activities and costs for the hypothetical conventional pile, as provided in the consultant recommendations, for 42 years in service. Two jacket lengths were evaluated. The 12-ft jacket is based on back-calculations from square feet of piling recommended for jacketing on the HRBT in the consultant reports. The 18-ft jacket accommodates moderately deeper ocean floor depths and reflects consultant recommendations in the reports that jacketing occasionally reach to the mudline. The time sequence of jacketing assumed for the hypothetical conventional pile conforms to that of actual maintenance of the piles in the HRBT eastbound lanes that were constructed in 1974 as documented in the consultant reports: at pile age 22 years, initial fiberglass jacketing was applied, which was removed at pile age 42 years.

Table 4. Construction Costs for Hypothetical Conventional and CFRP Piles

Source of Cost	Reinforcement Material			
	Conventional Steel		CFRP	
	Nimmo Parkway Average Bid	Nimmo Parkway Minimum Bid	Nimmo Parkway Average Bid	Nimmo Parkway Minimum Bid
Construction cost, $/linear foot	$87	$67	$361	$320
Construction cost, $/60-ft pile	$5,220	$4,020	$21,643	$19,200

Table 5. Maintenance Costs for Hypothetical Conventional Concrete Piles for 42 Years in Service

Maintenance Activity	Epoxy-Filled Fiberglass Jacket at 22 years, $650/LF (24-in square pile)	Existing Jacket Removal at 42 years, $250/LF	Concrete Substructure Surface Repair for Epoxy FRP jacket at 42 years, $800/SY (24-in square pile)	Maintenance Cost to 42 Years
Current cost 12-ft jacket	$7,800	$3,000	$8,533	$19,333
Present value cost 12-ft jacket	$4,071	$867	$2,466	$7,403
Current cost 18-ft jacket	$11,700	$4,500	$12,800	$29,000
Present value cost 18-ft jacket	$6,106	$1,300	$3,699	$11,105

LF = linear foot; FRP = fiber reinforced polymer; SY = square yard.

At 42 years of service, a choice in future maintenance strategies for the pile arises in the consultant reports for the remainder of the targeted 100-year service life, as shown in Tables 6 and 7. Option 1 consists of continuous galvanic jacketing, and Option 2 consists of a single impressed current cathodic protection (ICCP) jacket. In fact, ICCP jacketing is the preferred alternative for a 50-year extension of pile service life according to one report, an extension that the report states is achievable with proper jacket maintenance. The additional costs of meticulous ICCP jacket maintenance are excluded from the present analysis, however, resulting in a conservative estimate of the total cost of a 50-year extension of pile service life from ICCP jacketing alone.

Table 6. Maintenance Costs of Conventional Pile, Age 42 years to End of Service Life: Option 1

Maintenance Activity	FRP Galvanic Jacket at 42 years, $1,200/LF (24-in square pile)	Same at 62 Years	Same at 82 Years	Maintenance Cost to End of Service Life
Current cost 12-ft jacket	$14,400	$14,400	$14,400	$43,200
Present value cost 12-ft jacket	$4,161	$2,304	$1,276	$7,740
Current cost 18-ft jacket	$21,600	$21,600	$21,600	$64,800
Present value cost 18-ft jacket	$6,242	$3,456	$1,913	$11,611

FRP = fiber reinforced polymer; LF = linear foot.

Table 7. Maintenance Costs of Conventional Pile, Age 42 years to End of Service Life: Option 2

Maintenance Activity	ICCP Jacket at 42 years, $322/SF (24-in square pile)
Current cost 12-ft jacket	$30,912
Present value cost 12-ft jacket	$8,932
Current cost 18-ft jacket	$46,368
Present value cost 18-ft jacket	$13,398

ICCP = impressed current cathodic protection; SF = square foot.

Figure 9 sums the present values of lifetime costs (construction and maintenance costs, if any) for each type of pile, showing the two mutually exclusive options available for the conventional pile and evaluating future costs at a discount rate of 3 percent. These figures assume that the service life of 100 years provided by galvanic jacketing is equivalent for practical purposes to the 92-year service life provided by ICCP jacketing. Further, it is again noted here that VDOT researchers have determined that the requirements for problem-free performance of ICCP jackets are demanding compared to those of galvanic jackets with sacrificial anodes, causing agency costs for Option 2 to be conservative.[15]

Figure 10 summarizes the results by showing the whole life cost ratios for CFRP-reinforced piles relative to those for conventionally reinforced piles under the assumptions given earlier for this analysis. The results indicate that the cost-effectiveness of the CFRP pile increases with length of jacket required by a conventional pile, regardless of maintenance option.

	Conventional Pile		CFRP Pile	
Maintenance Paths	Average Construction Bid	Minimum Construction Bid	Average Construction Bid	Minimum Construction Bid
Option 1, 12-ft jacket	**$ 20,363**	**$ 19,163**	**$ 21,643**	**$ 19,200**
Option 1, 18-ft jacket	**$ 27,936**	**$ 26,736**		
Option 2, 12-ft jacket	**$ 21,555**	**$ 20,355**		
Option 2, 18-ft jacket	**$ 29,723**	**$ 28,523**		

Figure 9. Present Value of Whole Life Costs of Piles. CFRP = carbon fiber reinforced polymer.

Maintenance Paths	Average Construction Bid	Minimum Construction Bid
Option 1, 12-ft jacket	**106%**	**100%**
Option 1, 18-ft jacket	**77%**	**72%**
Option 2, 12-ft jacket	**100%**	**94%**
Option 2, 18-ft jacket	**73%**	**67%**

Figure 10. Whole Life Cost Ratios of CFRP Pile to Conventional Pile. CFRP = carbon fiber reinforced polymer.

The results in Figure 10 suggest that CFRP piles may be especially cost-competitive with conventionally reinforced bridge piles when longer pile jackets are required, assuming that maintenance consists primarily of jacketing to achieve a long service life.

Currently, 4 years after the Nimmo Parkway project was completed, a second LCC analysis is possible between the alternative concrete pile reinforcing materials of CFRP, stainless steel strand, and conventional reinforcing steel. This analysis of construction costs compares "ex ante" cost data (before contract terms were known) to "ex post" cost data (after contract terms were known) that resulted partly because of unexpectedly aggressive material price adjustments that followed VDOT's advertisement of a large bridge replacement project to be undertaken in the near future**.**

Figure 12 shows reinforcing material costs per foot of pile calculated for 24-in concrete piles that are 65 ft in length based on three current standard concrete pile designs corresponding to the three reinforcement materials shown in Figure 11. It will be noted that both Figure 11 and the quantities in Figure 12 show that pile designs are substantially alike for the three materials.

Spiral length is calculated in accordance with Equation 1.

$$Spiral\ length = N\ x\ \sqrt{P^2 + C^2} \qquad \text{[Eq. 1]}$$

where

N = number of turns
P = pitch (inches)
C = circumference of spiral.

Figure 13 shows the same calculations based on costs that resulted from active price point positioning following disclosure during project advertisement that the prime contractor would be authorized to choose the pile reinforcement material.

Although it is not defensible to expect the lowest prices in Figure 13 to be the market norm in the future, the power of competition between materials manufacturers pursuing coveted projects is self-evident in these results. Therefore, as projects and fabrication experience with premium materials accumulate, it is a reasonable expectation that price differentials could narrow between corrosion-free and high-grade corrosion-resistant reinforcements and conventional reinforcement, creating more competitive initial (i.e., construction) costs for premium materials and, as a consequence, even more beneficial life-cycle costs relative to those of conventional materials.

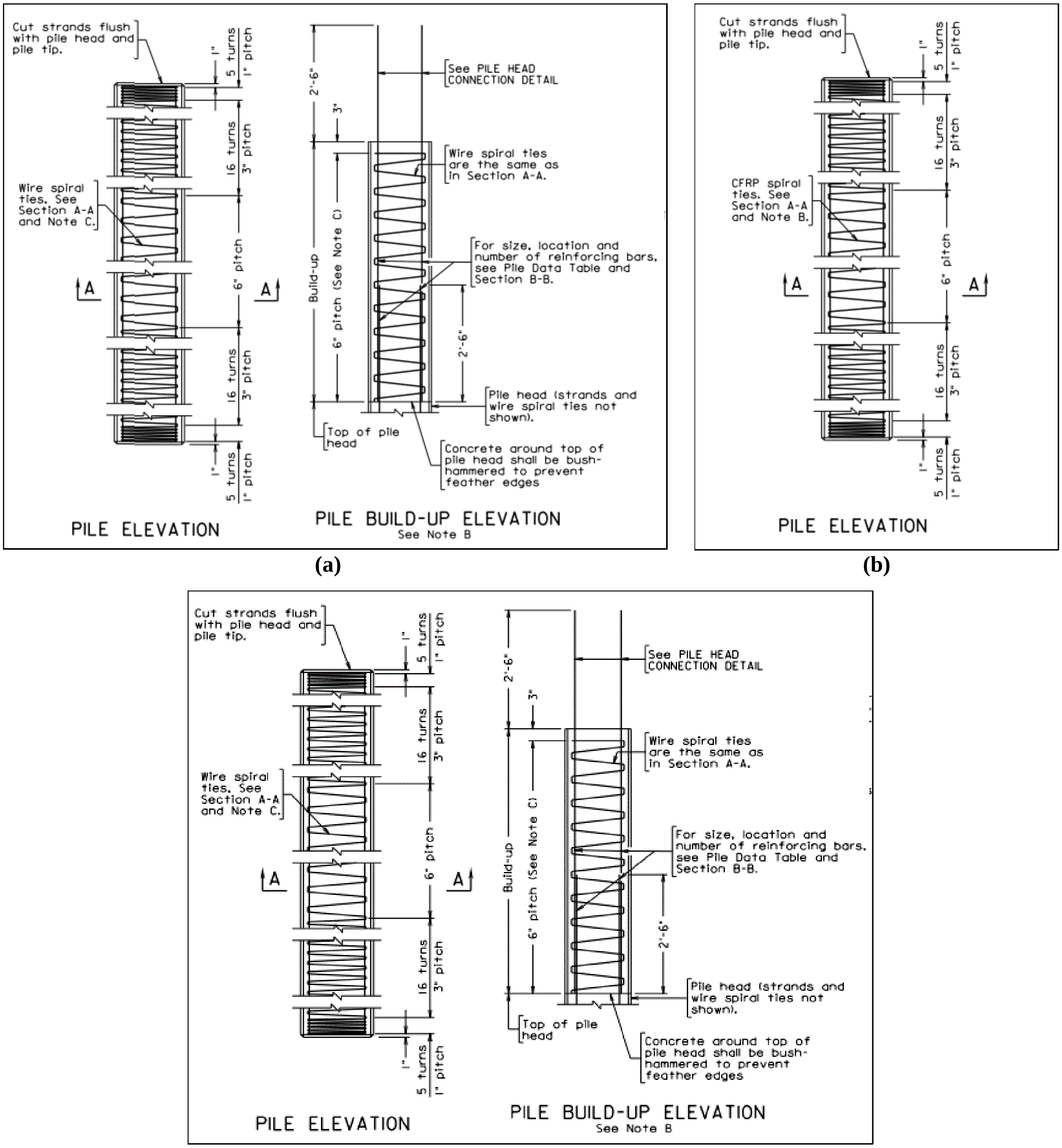

Figure 11. Design Schemas: (a) stainless steel strand; (b) CFRP; and (c) conventional steel strand reinforcement for concrete piles. CFRP = carbon fiber reinforced polymer.

	Stainless Steel	Unit cost		CFRP	Unit cost		Conventional Steel	Unit cost	
# Strands/pile	24			16			16		
Strand (LF)	1560	$	3.70	1040	$	3.80	1040	$	0.57
Strand waste (LF)	768	$	3.70	512	$	3.80	512	$	0.57
Spiral (LF)	750	$	1.73	750	$	4.80	750	$	0.52
Rebar (LF)	120	$	3.70	120	$	3.70	120	$	0.57
Anchoring devices	NA		NA	32	$	150.30	NA		NA
Buffer material	NA		NA	32	$	67.00	NA		NA
Material cost per LF of pile	**$160**			**$260**			**$21**		

Figure 12. Pile Reinforcement Unit Costs Because of Materials, Before Project Advertisement. CFRP = carbon fiber reinforced polymer; LF = linear feet; NA = not available.

	Stainless Steel	Unit cost		CFRP	Unit cost		Conventional Steel	Unit cost	
# Strands/pile	24			16			16		
Strand (LF)	1560	$	2.50	1040	$	2.28	1040	$	0.27
Strand waste (LF)	768	$	2.50	512	$	2.28	512	$	0.27
Spiral (LF)	750	$	1.17	750	$	1.20	750	$	0.25
Rebar (LF)	120	$	2.50	120	$	2.50	120	$	0.27
Anchoring devices	NA		NA	32		(1)	NA		NA
Buffer material	NA		NA	32		(1)	NA		NA
Material cost per LF of pile	**$108**			**$73**			**$10**		

Figure 13. Pile Reinforcement Unit Costs Because of Materials, After Project Advertisement. CFRP = carbon fiber reinforced polymer; LF = linear feet; NA = not available; (1) = Absorbed by material manufacturer.

SUMMARY OF FINDINGS

- *To achieve an accurate measurement of the long-term permeability of the concrete, accelerated curing was needed since the samples were kept with the couplers and were not exposed to high temperatures during steam curing at the plant.*

- *CFRP-reinforced piles were successfully driven without any damage to the piles using conventional methods. During driving, CFRP-reinforced piles responded in a manner similar to that of conventional steel-reinforced piles.*

- *The reduced elongation of CFRP compared to the ASTM requirement of a minimum 3.5 percent did not compromise the prestressing or the driving operations.*

CONCLUSIONS

- *Functional piles requiring no steel reinforcement but instead completely reinforced with CFRP strands and a circular spiral can be fabricated and driven.*

- *CFRP-reinforced 24-in square piles can be successfully produced at prestressing plants using locally available concrete materials and prestressing equipment with additional end preparation.*

- *The additional requirements that CFRP be handled with care to prevent damage to the strand and be cut using a grinder can easily be incorporated into the standard practices of a precaster.*

- *Consolidation of concrete with conventional slump and containing CFRP can be achieved using rubber tipped vibrators.*

- *Additional fabrication time is required because of the extra time needed to prepare the CFRP ends, place them into the chuck, and then place them into the coupler. Improvements in the end preparations are expected to provide daily cycles of less than 24 hours.*

- *To prevent slipping, couplers can be protected from high temperature by removal of the steam blankets where couplers are located.*

- *Analysis of life-cycle costs to VDOT supported the use of CFRP reinforcement in concrete piles located hypothetically in a water crossing with high chloride exposure and challenging bridge geometry when a pile service life of 90 to 100 years is desired. The whole life cost advantage of CFRP-reinforced piles rises as conventional pile jacket length increases. Additional experience in handling CFRP, improvements in end preparations enabling 24-hour cycles, and price adjustments responding to incentivizing contract terms could further improve the life-cycle cost comparison of CFRP and conventional materials.*

- *Recent competition between manufacturers of reinforcement materials seeking to be chosen by the prime contractor produced perhaps unique but significant unit cost reductions and demonstrated the potential power of contract terms to influence the initial cost of structures.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division and Materials Division should use corrosion-free reinforcement in concrete piles located in the severe marine environment in the eastern part of the state. This recommendation is based on LCC analysis, current maintenance options and costs to offset corrosion, and market costs observed at the time of the study.*

2. *VTRC should initiate a study for improving the end preparation of CFRP strands to enable a daily production cycle, as is the common practice with conventional steel strands.*

IMPLEMENTATION AND BENEFITS

Implementation

Recommendation 1 has been implemented. VDOT's Structure and Bridge Division now requires the use of corrosion-free or corrosion-resistant piles in the eastern part of the state where severe exposure conditions exist. More pile applications with CFRP are expected.

Recommendation 2 has been implemented. VTRC has initiated a study investigating improvements to the anchoring system to reduce end preparation time. The study is expected to be completed within 3 years of the publication of this report.

Benefits

The implementation of Recommendation 1 is expected to eliminate the corrosion problem commonly encountered in piles and will extend the service life of piles, relieving VDOT of costly repairs and preventing costly inconvenience to the traveling public. Relief from work zone safety hazards benefits both VDOT and the public. Temporary repairs such as the use of mortar, grouts, anodes, and/or jackets do not reliably provide the long service life desired; neither do they provide long life in a cost-effective way relative to the use of corrosion-free pile construction materials. The combination of high-quality concretes VDOT is using and corrosion-free reinforcement is expected to provide at least 100 years of service life with minimal maintenance, if any. This will result in VDOT savings during the service life, eliminate inconvenience to travelers caused by corrosion-related pile repairs, and improve traffic safety.

The implementation of Recommendation 2 will initiate research into reducing CFRP end preparation time during prestressing operations that will enable the precaster to return to daily production cycles, thus increasing production rates for precast products using CFRP. This will benefit VDOT by reducing the current cost for piles in addition to the inherent cost reduction in extending the service life with minimal maintenance.

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