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Modified Fiber Reinforced Concrete Repairs for Corroded Steel Beam Ends

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Abstract:

One common form of costly bridge maintenance is repairing corroded steel beam ends under leaking joints. Recently, the University of Connecticut and the Connecticut Department of Transportation have developed a practical repair strategy in which shear studs are welded to undamaged sections of the corroded steel beam and then ultra-high-performance concrete (UHPC) is cast around the corroded steel beam end. The purpose of this project was to evaluate how UHPC repairs on steel beam ends can be modified to make the beam ends easier to construct in the field, either by Virginia Department of Transportation (VDOT) work crews or by contractors. The two modifications that this project focused on included using other types of fiber reinforced concretes (FRCs) in place of UHPC and using threaded rods instead of shear studs to transfer load from the steel beam to the FRC panels.

A literature review showed that very high-performance concrete and engineered cementitious composite have the necessary strengths for FRC beam end repairs and offer convenience, availability, and cost savings advantages compared with UHPC. Threaded rods were also found to have sufficient strength, ductility, and fatigue resistance to be used in FRC beam end repairs. They offer ease of installation, worker and environmental safety, and cost savings advantages compared with welded shear studs.

Small-scale durability testing showed that applying a caulking or epoxy coating to the edge interface between the steel and hardened FRC can prevent saltwater moisture penetration into this edge interface, increasing the durability of this repair type. Existing chlorides should still be removed from the steel surface before casting FRC.

Two VDOT districts conducted a mockup and initial implementation of these repairs. These field trials displayed the importance of viscosity, fiber dispersion, and aggregate gradation on the pumpability and workability of the FRC mixture, ensuring durability and structural integrity of the repair. Partial-depth FRC repairs can eliminate the need for coring through the bridge deck and using polyvinyl chloride, or PVC, distribution systems to deliver FRC to the formwork. Pumps can be necessary if hand delivering FRC to the partial-depth repairs is not feasible. Therefore, the decision to use partial- versus full-depth repairs is application specific.

A cost analysis showed that if FRC beam end repairs are widely implemented, they can save VDOT approximately $39 million per year on steel beam end repairs. These cost savings could be reallocated to other bridge repair or maintenance actions.

The study concluded that other FRCs, such as very high-performance concrete and engineered cementitious composite, and threaded rods can be used in FRC beam end repairs as a modification to the UHPC repair method the University of Connecticut and Connecticut DOT developed. Based on this conclusion, the Virginia Transportation Research Council recommends that the VDOT Structure and Bridge Division implement guidance for using FRC beam end repairs into the VDOT *Manual of the Structure and Bridge Division*. The benefits to using FRC repairs include cost savings, easier installation for VDOT work crews and contractors, and better durability than traditional repairs.

Supplemental materials can be found at https://library.vdot.virginia.gov/vtrc/supplements.

FINAL REPORT

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Virginia Transportation Research Council
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ABSTRACT

One common form of costly bridge maintenance is repairing corroded steel beam ends. Recently, the University of Connecticut and the Connecticut Department of Transportation developed a practical repair strategy in which shear studs are welded to undamaged sections of the corroded steel beam and then ultra-high-performance concrete (UHPC) is cast around the corroded steel beam end. The purpose of this project was to evaluate how these repairs can be modified to make it easier to construct in the field, either by Virginia Department of Transportation (VDOT) work crews or contractors. Two modifications that this project focused on included using other types of fiber reinforced concretes (FRCs) in place of UHPC and using threaded rods instead of shear studs to transfer load from the steel beam to the FRC panels.

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INTRODUCTION

As of fiscal year 2020, the Virginia Department of Transportation (VDOT) allocates approximately $215 million per year on bridge maintenance and an additional $225 million per year on replacement or major rehabilitation of structurally deficient bridges. One key contributor to this costly maintenance is the replacement or repair of corroded steel beam ends under leaking joints. These joints leak water and de-icing salt from the roadway above and down onto the steel beam end below. The water and de-icing salt accumulate and cause corrosion damage and section loss in the beam end, as Figure 1 shows.

Typically, these corroded steel beam ends are repaired by either welded or bolted repairs. A welded repair is commonly considered a permanent repair and consists of cutting out the corroded section of the beam end and welding a new beam section in its place. A welded repair typically requires lane closures and jacking up the beam to support its weight while cutting out and welding a new beam end back in place. Bolted repairs are constructed by installing new repair plates on either side of the beam web and bottom flange and bolting them to the existing beam. A bolted repair may require jacking the beam, similar to the welded repair. If the beam is not jacked before repair installation, the new repair plates will carry live load only. The decision to select either a welded or bolted repair depends on the cost of the repair, extent of the corrosion damage at the beam ends, and the expected remaining service life of the bridge, among other factors.

Figure 1. Photos Showing Corrosion Damage Associated with Leaking Joint Along Interstate 95 in Richmond, Virginia, in 2011 Before Deck Replacement: (a) Little Corrosion Damage Away from the Joint; (b) Secondary Member Adjacent to the Joint with Extensive Corrosion Damage and Perforation (yellow dashed ellipse); (c) Heavy Corrosion Damage at Beam Ends Directly Under the Joint

From the mid-2010s to the early 2020s, the University of Connecticut conducted numerous research studies with the Connecticut Department of Transportation (DOT) on a practical repair strategy in which shear studs were welded to undamaged sections of the corroded steel beam and then ultra-high-performance concrete (UHPC) was cast around the corroded steel beam end (Figure 2). In this way, UPHC provides an alternate load path to bypass the corroded portion of the steel beam. This research included laboratory testing on small-scale specimens (Kruszewski et al., 2018; Zaghi et al., 2016), medium-scale beam specimens (Zmetra et al., 2017), and large-scale beam specimens, as well as finite element analysis (McMullen, 2019). This repair method addresses only corrosion damage in the beam web. It does not address corrosion damage to the beam bottom flange.

Figure 2. Photos Showing Installation of Ultra-High-Performance Concrete Beam End Repair (Haber et al., 2022)

Since the completion of the research by the University of Connecticut, the Connecticut DOT has implemented numerous bridge repairs using this technique with successful results (Hain et al., 2019; Hain and Zaghi, 2021). In most of these repairs, the Connecticut DOT has used full-depth repairs, in which the depth of the UHPC panel was equal to the depth of the beam web. These full-depth repairs required formwork construction and then placing concrete from above the concrete bridge deck. This required holes to be drilled in the concrete deck and traffic restrictions during UHPC casting. Polyvinyl chloride, or PVC, piping systems were then used to distribute UHPC from above the concrete deck into the formwork of each repair. Field instrumentation showed that the repairs were performing successfully and that the UHPC panels provided an alternate load path to the deteriorated beam ends.

More recently, the University of Connecticut and Connecticut DOT have investigated partial-depth repairs, in which the UHPC panel extends only for a partial depth of the web (Lassy et al., 2023). Partial-depth repairs allow for a much easier placement of UHPC into the formwork without traffic closures during repair installation, drilling holes in the concrete deck, and a PVC piping system to distribute UHPC into the formwork. These partial-depth repairs have shown promising testing results from the University of Connecticut and have been successfully implemented on in-service bridges by the Connecticut DOT.

Since the research and implementation success of these UHPC repairs in Connecticut, other state DOTs and transportation agencies have used them as well, including New York DOT (American Association of State Highway and Transportation Officials [AASHTO], n.d.), Texas DOT (Fan et al., 2022), and the St. Clair County Road Commission in Michigan (Haber et al., 2022). AASHTO highlighted the overall success of using both full- and partial-depth UHPC beam end repairs by naming the method as an innovation initiative (AASHTO, n.d.). The AASHTO Innovation Initiative website contains useful information on these types of repairs, including typical detail schematics by Connecticut DOT and New York DOT, a UHPC material specification by New York DOT, and design guidelines by Connecticut DOT.

In addition, the Federal Highway Administration (FHWA) published design guidelines for using these types of repairs (Haber et al., 2022). FHWA's guidance also details the benefits of this repair method as follows:

- Enhanced durability—UHPC provides high freeze-thaw resistance and low permeability to reduce further corrosion.
- Constructability—UHPC can be placed into easily constructed formwork during short time windows and may reduce the need to jack the beam being repaired.
- Minimal user impact—This repair method reduces lane closures, onsite mobilization, and repair time and can be constructed during off-peak hours.
- Repair versatility—This repair method can be adapted to different field conditions, such as complex geometry and limited access, such as highly skewed bridges.
- Low maintenance requirements—This repair method should require minimal maintenance if properly detailed and installed.

Because of the extent of research and implementation of this repair strategy, the potential is great for it to be used within VDOT. Although these UHPC beam end repairs have been very successful, potential modifications could simplify the repairs for either VDOT work crews or contractors to construct in the field. First, other fiber reinforced concretes (FRCs), such as very high-performance concrete (VHPC) or engineered cementitious composite (ECC), could be used instead of UHPC. ECC, VHPC, and UHPC provide deflection hardening that enables tight cracks (less than 0.1 mm in crack width) to resist water and solution penetration. VDOT has had good experience with ECC and VHPC in field applications. These concretes often have better workability and are less expensive than UHPC. Second, it is possible that threaded rods could be used to transfer load between the steel beam and the FRC panel instead of shear studs. Shear studs require surface preparation of the existing steel in the field before welding. This requirement can be problematic if the existing coating is lead-based. Furthermore, welding shear studs requires a qualified welder to conduct the work. Using threaded rods for load transfer could be much easier for VDOT work crews for both challenges.

PURPOSE AND SCOPE

The purpose of this project was to evaluate how conventional UHPC repairs on the webs of steel beam ends can be modified to make it easier to construct them in the field, either by VDOT work crews or contractors. The two modifications that this project focused on were the use of other types of FRCs in place of UHPC and the use of threaded rods, instead of shear studs, to transfer load from the steel beam to the FRC panel. Note that this repair method addresses only corrosion damage on the beam web and not on the beam flanges.

The scope of this project included a literature review, durability testing in the laboratory, field testing, and analysis. The field testing included a simulated mockup and field implementation of this repair type. The analyses included structural analysis in developing design guidance and cost analysis of these repairs.

METHODS

Overview

This research project consists of five tasks to achieve the primary research objective. The listed research tasks are described in detail in the following sub-sections:

1. Literature review.
2. Durability testing of small-scale samples.
3. Field evaluations.
4. Development of VDOT design guidance.
5. Cost analysis.

Literature Review

The literature review focused on the following two topics as they relate to FRC beam end repairs, which are discussed in further detail in the following sections:

- Potential FRCs for use.
- Potential to use threaded rods instead of shear studs.

Fiber Reinforced Concretes

Because of Virginia Transportation Research Council's (VTRC) extensive research and VDOT's implementation of many different types of FRCs, much of the literature reviewed focused on previous VTRC and VDOT projects related to UHPC, VHPC, and ECC. This literature review was focused on the applicability of FRCs for beam end repairs.

Threaded Rods

Researchers also reviewed literature on threaded rods to determine their potential use instead of shear studs on FRC beam end repairs. This review included the University of Connecticut's UHPC beam end repair research and other reports and research specific to threaded rods and their use in structural applications.

Durability Testing of Small-Scale Samples

Durability tests were conducted to evaluate if saltwater moisture could penetrate the edge interface between a steel surface and surrounding FRC to cause further corrosion of the steel. This step is important to the durability of FRC beam end repairs because saltwater moisture penetration into this edge interface could lead to further corrosion of the steel beam and, more importantly, further corrosion of the shear studs or threaded rods. Corrosion of the shear studs or threaded rods is undesirable because their primary function is to transfer load from the damaged steel beam into the FRC panel. If the shear studs or threaded rods were to corrode so they could not transfer load, they would render the repair ineffective.

Durability tests were focused on small-scale samples, simulating FRC beam end repairs. These small-scale samples consisted of a 1/2-inch thick by 2-inch wide by 9-inch long ASTM A36 steel plate embedded into an FRC cylinder. The steel plates used in these samples were clean and had no existing corrosion. Clean steel plates were used for convenience in these samples. This scenario differs from steel on beam ends to be repaired, which would contain corrosion and chlorides on their surface. In this case, the existing corrosion and chlorides on a beam end must be removed from the steel before placing the FRC panel. Otherwise, corrosion of the steel could continue, even without additional saltwater penetrating the steel-FRC edge interface. Existing corrosion and chlorides can be removed from existing steel beams using methods similar to what is specified in Section 411.05 of the VDOT *Road and Bridge Specifications* for applying coatings to existing structures (VDOT, 2020). Alternatively, induction coating removal and laser ablation coating removal could be used to clean the steel surfaces that are to be encased in FRC. Induction and laser ablation coating removal produced clear surfaces free of chlorides (Sharp et al., 2025). This option could be good when using welded shear studs in the FRC repair because the steel must be cleared before welding the shear studs.

The FRC cylinder on the samples was 4-inches in diameter by 8-inches in height, made of ECC. Figure 3 shows a photo of one of these durability samples. ECC was selected as the FRC to be used for these durability samples because it has lower strengths than UHPC or VHPC and, therefore, would provide a lower limit of bond strength. These samples were constructed by casting ECC into a cylinder mold and placing the steel plate into the ECC before it hardened. ECC used in these samples was a prepackaged material from VDOT's Materials Approved List and already included the fibers within the bag (VDOT, 2021).

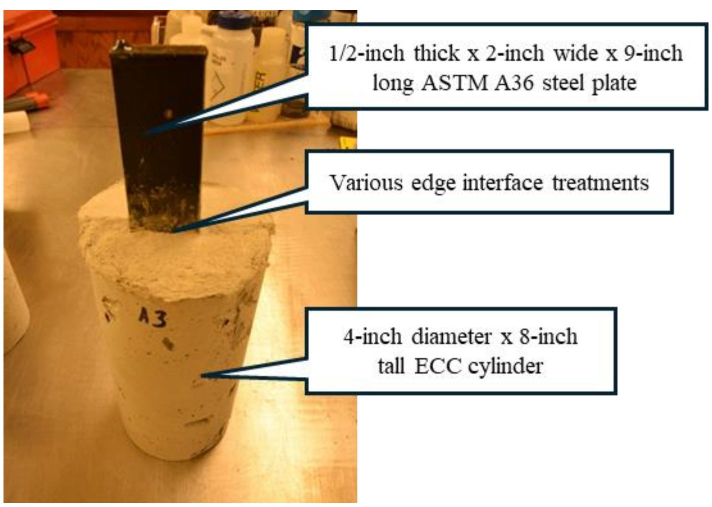

Figure 3. Photo of Small-Scale Durability Test Specimen. ECC = engineered cementitious composite.

Various treatments were evaluated at the steel-FRC edge interface to determine their relative effectiveness in preventing saltwater moisture penetration. One treatment compared uncoated with coated steel to evaluate if the FRC bonded to uncoated or coated steel enough to prevent saltwater moisture penetration. An epoxy-type coating was applied to the coated steel samples before inserting the coated steel plates into wet ECC. A second treatment examined placing (1) nothing, (2) caulking, or (3) a coating onto the steel-FRC edge interface approximately 7 days after the ECC had hardened. The purpose of this examination was to evaluate if some form of adhesive barrier, such as caulking or coating, could be used to prevent saltwater moisture from penetrating the steel-FRC edge interface. An industrial-type caulking and epoxy-type coating were used for these samples and were compared with control samples that had nothing applied to the edge interface. Three replicate samples were made for each steel surface type and adhesive barrier combination, making 18 specimens. These treatments were allowed to cure for 7 days before initiating the durability testing. Table 1 shows the experimental test matrix for this testing.

Table 1. Test Matrix for Small-Scale Durability Tests

Edge Interface Treatment	# Tested	Details
Steel surface	2	Uncoated or epoxy-coated
Adhesive barrier	3	Nothing, industrial caulking, or epoxy-coated
Replicates	3	For repeatability

A durability testing procedure was developed to evaluate these samples. The testing procedure considered (1) saltwater wetting and drying cycles and (2) freezing and thawing cycles. Saltwater wetting and drying cycles were included because FRC beam end repairs were expected to be subjected to saltwater either from a joint above, if the joint was not eliminated during the repair process, or from a saltwater source below, if present at the bridge site. The saltwater wetting and drying cycles were developed using ASTM D5894 for guidance but were altered to fit the VTRC's corrosion chamber and complete the testing in a reasonable amount of time (ASTM International, 2021). The standard ASTM D5894 testing procedure includes ultraviolet exposure. However, this project did not include ultraviolet exposure because the bridge deck above is expected to predominantly shade these FRC beam end repairs from ultraviolet rays.

The durability testing procedure includes freezing and thawing cycles because the FRC beam end repairs are also expected to be subject to these cycles during winters in Virginia. These freezing and thawing cycles are important because if saltwater moisture were to penetrate the steel-FRC edge interface, freezing cycles could cause it to expand and potentially crack the surrounding FRC. The freezing and thawing cycles were developed using ASTM C666 for guidance but were altered to fit VTRC's environmental chamber and complete the testing in a reasonable amount of time (ASTM International, 2015).

Figure 4 shows the overall durability testing procedure. The procedure consisted of placing the specimens into VTRC's corrosion chamber and applying 84 cycles of saltwater wetting and drying for 1 week. Each cycle was 2 hours long. The first part of the cycle consisted of spraying a 5% sodium chloride solution for 10 seconds, followed by a holding time of 59 minutes and 50 seconds to maintain the moist air condition. Researchers applied a 1-hour drying process by purging clean air and increasing the temperature to 95 °F. After this process was completed, the samples were placed into VTRC's environmental chamber, and 28 cycles of freezing and thawing were applied during 1 week. Each cycle was 6 hours long and consisted of temperature ramps from 70 °F to -10 °F, with holding times at the upper and lower temperatures. The -10 °F temperature represents an extremely low temperature in Virginia during the winter, and 70 °F represents a reasonable increase from the low temperature. This combination of 84 saltwater wetting and drying cycles and 28 freezing and thawing cycles was completed three times during 6 weeks.

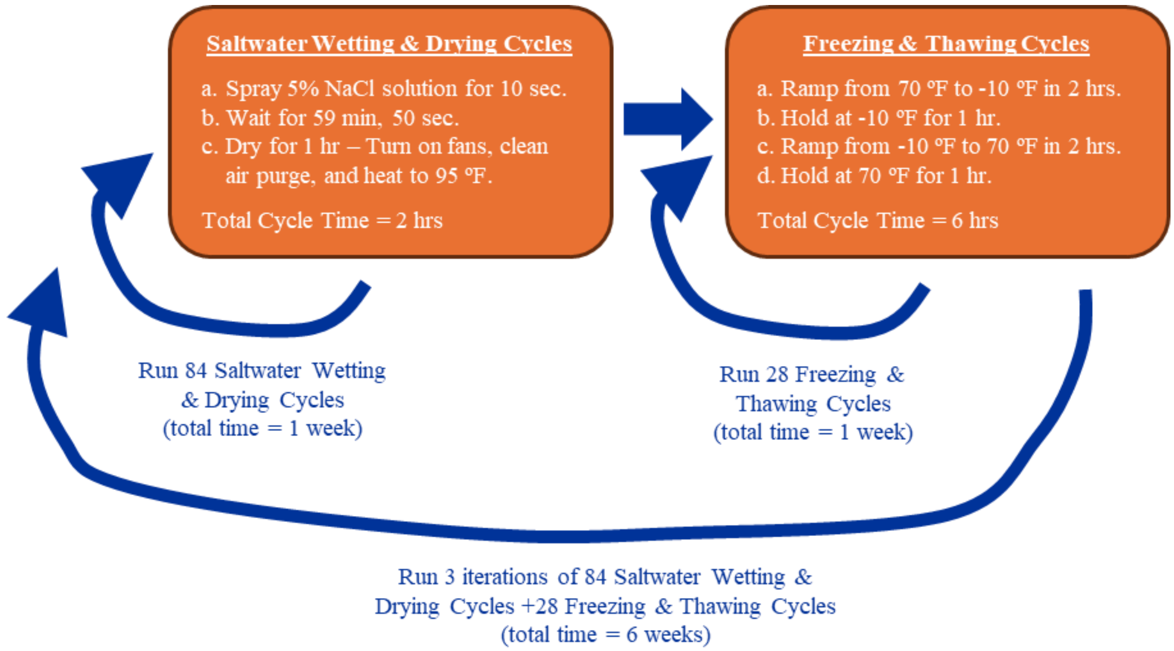

Figure 4. Small-Scale Durability Testing Procedure. NaCl = sodium chloride.

After the durability testing was completed, the exterior of the samples was visually analyzed, focusing on the steel-FRC edge interface. After this step was complete, approximately one-half of the ECC was cut away from the steel plate using a water jet. The cut was made as close as possible to the steel plate and the remaining ECC was removed using a hammer. Care was taken not to damage the steel surface. Once one side of the steel plate was exposed, it was visually analyzed to evaluate the corrosion that had occurred during the durability testing.

Field Evaluations

The field evaluations in this project focused on the following two applications, which are discussed in further detail in the sections that follow:

- Mockup testing in the VDOT Culpepper District.
- Initial VDOT implementation in the VDOT Northern Virginia District.

Mockup Testing

Researchers conducted a mockup test of multiple FRC beam end repairs at the Louisa Residency in the VDOT Culpepper District in January 2023 to evaluate the potential for the two modifications of the UHPC beam end repairs, including using a different FRC instead of UHPC and threaded rods instead of welded shear studs.

To perform this mockup, the district provided two corroded steel beams with diaphragms from a recently retired bridge. The beams were closely spaced because they were from a bridge with a timber deck. The two beams were placed on wooden sawhorses to simulate beam ends on an actual bridge. The district work crew also provided threaded rods with washers and nuts, lumber for constructing formwork, and bags of prepackaged VHPC for simulating the repair. Both partial- and full-depth repairs were performed in the mockup. Figure 5 shows photos of the steel beams used in the mockup test setup.

Figure 5. Photos of the Mockup Test Setup: (a) Overall View of Two Retired Bridge Beams; (b) Closeup View Between Beams; (c) Side View of One Beam; (d) Closeup of Corrosion Damage to One Beam

Initial VDOT Implementation

Researchers performed an initial implementation project for using FRC beam end repairs in the VDOT Northern Virginia District in September 2024. This initial VDOT implementation was performed on the Bristow Road Bridge (Federal ID 14306), which carries Bristow Road/Route 619 over Cedar Run near Brentsville, Virginia. All five bridge beam lines had experienced corrosion damage at both abutments with leaky joints. Therefore, plans were made to construct repairs at all 10 beam ends. Figure 6 shows an example of the extensive corrosion at one of the beam ends on the Bristow Road Bridge before FRC repairs.

Figure 6. Example of Beam End Corrosion Damage on Bristow Road Bridge Before FRC Repairs

The VDOT Northern Virginia District performed design calculations and developed drawings for the FRC beam end repairs. The FHWA guidance on UHPC beam end repairs was used during this process (Haber et al., 2022). The district work crew installed the repair with VTRC on site to observe and provide input. After the repairs were completed, VTRC discussed the design and installation process with the district for their feedback.

VTRC visited the Bristow Road Bridge in February 2025, approximately 5 months after the repairs were completed, to perform a visual inspection and evaluate the repair performance since installation.

Development of VDOT Design Guidance

The Connecticut DOT and FHWA provide guidelines for designing and detailing UHPC beam end repairs (Connecticut DOT, 2022; Haber et al., 2022). Researchers reviewed these two documents to determine if either could be used directly as VDOT guidance for FRC beam end repairs or if other modifications were necessary.

Cost Analysis

The VDOT Northern Virginia District provided VTRC with cost data for the Bristow Road Bridge repair project. These data included costs for traffic control, required materials and equipment, and labor. The data provided the baseline cost estimate for VDOT's initial implementation of FRC beam end repairs constructed by VDOT work crews.

The VDOT Salem District also provided VTRC with estimated costs for the Bristow Road Bridge repairs if VDOT work crews constructed those repairs using a traditional bolted repair in which steel channels were bolted to either side of the beam webs and a steel plate was bolted to the bottom of the beam flanges. A traditional bolted repair was used as a comparison because this is typical of how a bridge in its condition would be repaired. This method provided a means of cost comparison between the new FRC beam end repairs and a traditional bolted beam end repair.

The VDOT Richmond District also provided VTRC with cost estimates for bolted beam end repairs constructed by a contractor. These cost estimates were based on typical repair lengths of 5 and 7 feet. The cost also included steel, bolted assemblies, and welding of bearing stiffeners. The Richmond District provided two cost estimates, one based on its previous on-call contract and one based on its current on-call contract.

RESULTS

Literature Review

This section contains the literature review results on potential FRCs and the prospect of using threaded rods in FRC beam end repairs.

Fiber Reinforced Concretes

The optimal FRC mixtures for beam end repair applications should provide satisfactory fresh and hardened concrete properties, including workability, sufficient compressive strengths, enhanced tensile and flexural strengths, and improved crack control and durability. VTRC researchers have been investigating three commercially available types of FRC suitable for beam end repair applications known as UHPC, VHPC, and ECC (Ozyildirim et al., 2020; Ozyildirim and Sharifi, 2022). They are typically used as prepackaged materials for convenience and the availability of ingredients. In most ECC and VHPC field applications, fibers were not in the bag and were added during mixing.

All three FRCs have high compressive and high tensile strengths, which are based on the type and amount of fibers within them. Regarding compressive strength, UHPC can be expected to reach at least 17,500 psi, VHPC can be greater than 11,500 psi, and ECC can range from 6,000 to 8,000 psi. In terms of fiber type, UHPC uses steel wire, VHPC uses hooked-end steel, and ECC uses polyvinyl alcohol fibers. The fiber content in all three FRCs is typically 2% by volume of concrete. These FRCs have high workability, low permeability, and high ductility and exhibit deflection hardening that enables tight (< 0.1 mm) crack widths, which resist penetration of water and solutions. The FRCs can be classified as high-performance fiber reinforced concretes because of these characteristics.

In more specific detail, UHPC typically includes steel wire fibers with a length of 13 mm, a diameter of 0.2 mm, and an aspect ratio of 65. UHPC and VHPC have a maximum water-cementitious materials ratio (w/cm) of 0.25. The hooked-end steel fibers used in VHPC are typically 1.4 in long with an aspect ratio of 45. These mixtures have high tensile and flexural strengths, with UHPC being higher than VHPC. FHWA promotes using UHPC in applications when high strengths and improved durability are needed. VDOT uses VHPC mainly in Virginia adjacent member connections (Kedar et al., 2017; Ozyildirim and Sharifi, 2022). At VTRC, researchers have tested several in-house and prepackaged UHPC and prepackaged VHPC. Test results showed that UHPC had an average compressive strength of 19,000 psi and an average splitting tensile strength of 2,500 psi at 28 days (Ozyildirim and Sharifi, 2022). VHPC had an average compressive strength of 13,000 psi and an average splitting tensile strength of 1,700 psi at 28 days (Ozyildirim and Sharifi, 2025).

ECC was developed at the University of Michigan and contains high dosages of 8 mm long polyvinyl alcohol fibers. It uses mortar sand but no coarse aggregate. At VTRC, researchers have evaluated several prepackaged ECC mixtures, with compressive strengths of approximately 7,000 psi and splitting tensile strengths of around 900 psi after 28 days (Ozyildirim and Sharifi, 2025). ECCs can have varying setting times. In laboratory testing, FRCs exhibited initial set times ranging from 30 minutes to 4 hours, indicating that varying working times is possible, especially in field applications. Based on VTRC experience, ECC, VHPC, and UHPC are recommended to be mixed in efficient mixers to ensure good distribution of fibers. If only a small amount of material is required at a jobsite, it can be mixed with dual paddle mixer.

VDOT has used all three FRCs in different connection applications, such as Virginia adjacent member connections, link slabs, and shear keys. Additional applications, such as overlays, are also being investigated. FRCs for these applications can be produced with varying levels of compressive, tensile, and flexural strengths using in-house or prepackaged materials. However, prepackaged materials are preferred during construction because of the availability of ingredients, convenience, and uniformity.

Although all three FRCs being evaluated are typically self-consolidating, the workability of the FRC mixtures is critical for ensuring proper placement and consolidation within the confined spaces of steel beam end repairs. The steel fibers in UHPC and VHPC can tend to settle in mixes with high slump flow. At lower slump flow values, the consolidation of concrete and the clumping or balling of fibers can be of concern. Given the space limitations and the need for complete formwork filling in the beam end repairs, achieving an optimal slump flow is essential. A well-designed FRC mixture should exhibit sufficient fluidity to flow around the shear studs or threaded rods in the repair area and fully encapsulate the steel beam ends without segregation or excessive bleeding. A proper balance between viscosity, fiber dispersion, and aggregate gradation enhances the pumpability and workability of the FRC mix, ensuring durability and structural integrity of the repair.

Threaded Rods

In their research on the UHPC beam end repairs using welded shear studs, the University of Connecticut also conducted tests on similar connections made with threaded rods (Kruszewski, 2018; Kruszewski and Zaghi, 2019, 2021). These small-scale tests were similar to other research studies investigating shear studs and consisted of a steel wide flange beam with UHPC panels cast against each flange. Threaded rods were inserted through holes in each flange and tightened with nuts to provide load transfer between the steel beam and UHPC panels. The specimens were loaded to induce a shear failure through the threaded rods and were tested to failure. Based on these tests, the researchers noted that "similar results are obtained for 0.5-in threaded bars" when comparing the results with specimens constructed with shear studs (Kruszewski and Zaghi, 2019). The researchers also noted that "experimental studies are needed to fully understand the fatigue behavior of threaded bars … before their field implementation" (Kruszewski and Zaghi, 2019). To summarize, the University of Connecticut research showed that threaded rods have similar strength and ductility performance as welded shear studs but lack experimental fatigue data to justify their use.

However, when examining other literature sources, researchers found that many fatigue tests were conducted on threaded rods used as shear connectors (Azad et al., 2019; Kayir, 2006; Kreitman et al., 2016; Kwon et al., 2011, 2012). Many of these tests used threaded rods as post-installed shear connectors to provide composite action between a previously non-composite concrete bridge deck and a steel girder. Threaded rods for these tests were connected to the composite system via three main connection types: (1) nuts tightened on top and bottom of the steel girder top flange with the threaded rod extending upward into the concrete deck, (2) nuts tightened in a blockout near the top of the concrete deck and on the bottom of the steel girder top flange, and (3) nuts tightened on the bottom of the steel girder top flange and adhesive used to connect the threaded rod to the concrete deck. Regardless of the connection type, the basic principle of the connection is the same as the use case for threaded rods in FRC beam end repairs. That is, the threaded rod provides shear force transfer between a concrete element and a steel beam. Based on both small- and large-scale testing, the threaded rod connections produced better fatigue performance than welded shear stud connectors as AASHTO *LRFD Bridge Design Specifications* describes (AASHTO, 2024). Therefore, threaded rods appear suitable to use in FRC beam end repairs when considering the fatigue limit state.

The AASHTO *LRFD Bridge Design Specifications* also provides fatigue guidance for holes in the base metal of bolted connections (AASHTO, 2024). Holes with non-pretensioned bolts have a much lower fatigue resistance than holes with pretensioned bolts because the bolt pretensioning process induces compressive stress in the base metal around the hole. These compressive stresses help slow fatigue crack growth, thereby improving overall fatigue resistance. Therefore, threaded rods used in FRC beam end repairs should be pretensioned to provide the best fatigue resistance of the overall connection.

Threaded rods also provide the benefit of easier surface preparation compared with shear studs before installation. Before shear studs can be welded onto steel bridges, all coating on the steel must be removed, and the steel must be cleaned to a bright metal. Typically, when removed in small areas as required for welding shear studs, bridge coatings are removed using a grinding wheel. This process is relatively simple, but it can become much more challenging if the coating is lead based. According to the VDOT requirements for working with lead-based coatings, grinding qualifies as a "hot work" process, which necessitates stringent engineering controls to keep workers and the surrounding public safe. However, drilling through lead-based coatings, as required if using threaded rods, qualifies as a "cold work" process and does not require engineering controls (VDOT, 2018, 2022). Therefore, threaded rods provide a much more worker-friendly and environmentally friendly option than welded shear studs.

Finally, shear studs used in steel bridge applications require a certified welder, according to AASHTO and American Welding Society (AWS) D1.5 Bridge Welding Code (AASHTO and AWS, 2020). This requirement can be costly and require scheduling coordination. However, threaded rods provide a benefit because no special certifications are required for their installation.

Overall, the use of threaded rods instead of shear studs appears to provide the necessary strength, ductility, and fatigue resistance required for FRC beam end repair applications. Using threaded rods also provides benefits in terms of worker and environmental safety, as well as the ease and cost of installation.

Durability Testing of Small-Scale Samples

The small-scale durability samples were constructed in VTRC's concrete laboratory. The ECC used in the samples had a short set time of 30 minutes and a range of water content according to the product technical datasheet. Therefore, the maximum water content was used to provide better workability. The ECC was mixed using a dual paddle drill mixer, as Figure 7 shows. Casting the small-scale specimens was successful without any issues.

Figure 7. Mixing Engineered Cementitious Composite with Dual Paddle Mixer for Small-Scale Durability Samples

After the different treatment options (shown in the test matrix in Table 1) were applied and allowed to cure, the durability testing commenced and lasted for 6 weeks. As described previously, the samples were cut open using a water jet. Then, the portion of the steel plates previously embedded in ECC was examined to determine the extent of saltwater moisture penetration between the steel and ECC edge interface. Figure 8 shows representative photos of the steel plates after removal from the ECC for each sample type after the durability testing was complete.

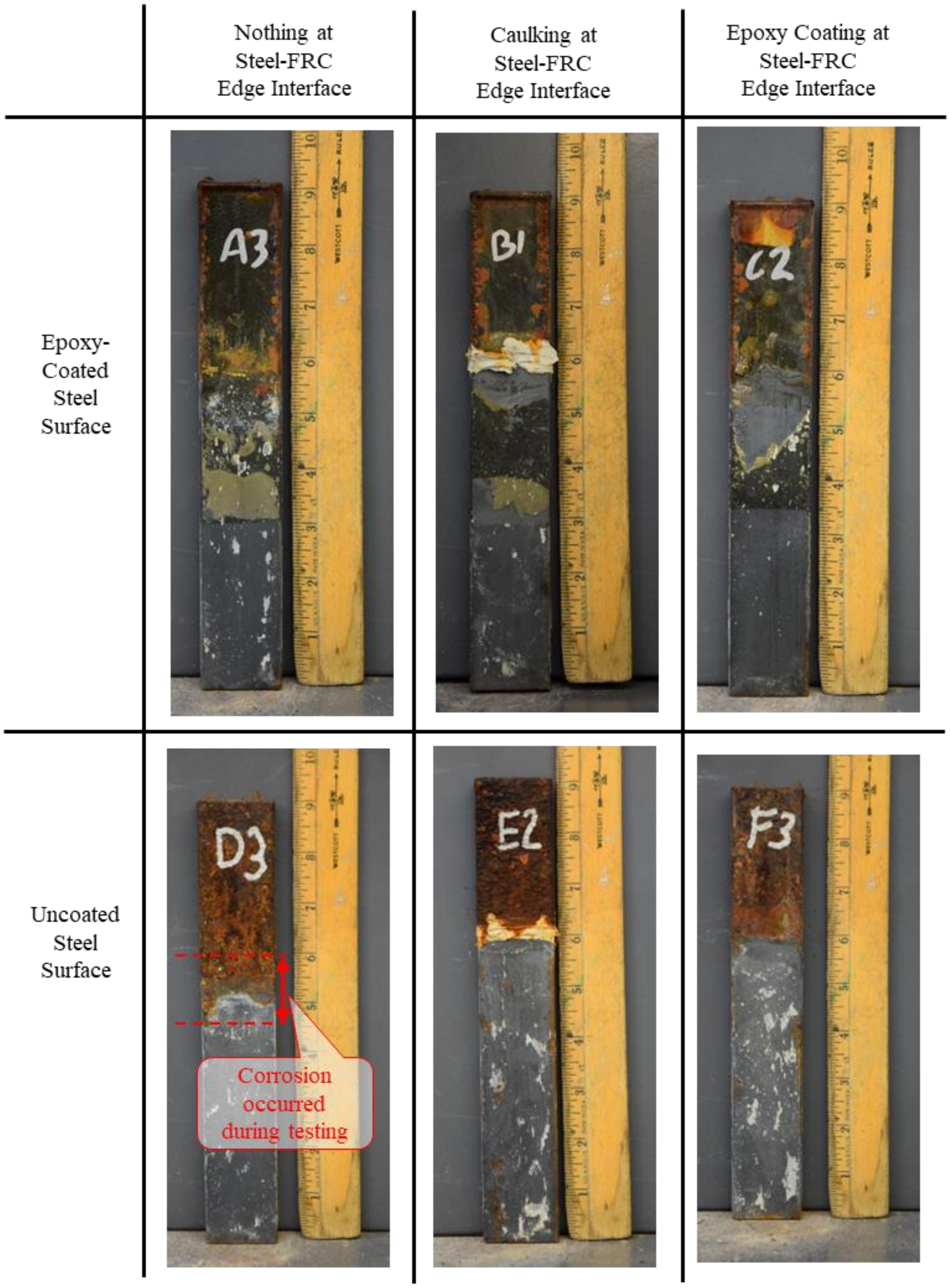

Figure 8. Photos of the Steel Plates After Removal from Engineered Cementitious Composite for Each Sample Type After Durability Testing

All the photos in Figure 8 include a ruler for scale and to aid in indicating corrosion to the portion of the steel plate embedded in ECC. Because the bottom 6 inches of each steel plate were embedded in ECC, the 6-inch marking on the ruler can be used as a reference point. Any material above that mark on the steel plate was expected to have corroded because it was exposed during the durability testing. Any material below that mark on the steel plate was embedded in the concrete. Thus, corrosion on that portion of the steel plates indicates that saltwater penetrated between the steel-ECC edge interface to cause the corrosion.

As the photos in Figure 8 show, only one sample type displayed any noticeable corrosion below the 6-inch mark on the ruler. This sample consisted of an uncoated steel surface, and nothing was applied to the steel-FRC edge interface. Based on the three samples of this type tested, the corrosion extended approximately 1 to 1.5 inches below the 6-inch mark on the ruler. It is not surprising that this sample type displayed corrosion because it was the least corrosion resistant of all the sample types. Because nothing had been applied to the steel-FRC surface, the saltwater applied during the durability testing likely infiltrated this edge interface and easily caused the uncoated steel to corrode.

The other five sample types experienced little or no corrosion below the 6-inch mark on the ruler, indicating that the treatment applied to the sample type effectively prevented corrosion on the embedded portion of the steel. This result means that applying caulking or epoxy coating effectively prevents saltwater infiltration at the steel-FRC edge interface. Both options can be easily applied to an actual FRC beam end repair in the field, making them simple, effective options for extending the service life of FRC beam end repairs. The epoxy-coated steel with nothing applied to the steel-FRC edge interface also performed well, with no additional corrosion on the steel plate. This option could be applied in the field, but the entire steel beam end to be encased in FRC must be coated. This option would likely be more time-consuming and costly than applying caulking or coating to the steel-FRC edge interface.

Field Evaluation

This section contains the results of the field evaluations on both the mockup testing and the initial implementation of FRC beam end repairs in VDOT.

Mockup Testing

The mockup test began with the district work crew using a magnetic drill to drill holes into both beam webs. VTRC and the district work crew had agreed on the locations of the holes. After all the holes were drilled, threaded rods were inserted into the holes, and nuts and washers were placed on either side of the beam web. The nuts were tightened using a socket wrench, which required the full effort of a district work crew member. An additional nut was placed on each end of the threaded rods to simulate the head of a shear stud to prevent the FRC panel from pulling out from the threaded rods. Figure 9 shows photos of the magnetic drill and the threaded rods after being installed into a beam web.

Figure 9. Installation of Threaded Rods During Mockup: (a) District Work Crew Member Using Magnetic Drill to Drill Holes; (b) Threaded Rods After Being Installed into a Beam Web

Once the threaded rods had been successfully installed, formwork for the FRC repairs was constructed. Workers constructed formwork for a full-depth repair on one beam and formwork for a partial-depth repair on the other beam. In general, the formwork was installed with no major challenges. Small openings between the steel beams and formwork were filled with spray foam or foam backer rods. The perimeter of the formwork was also caulked to prevent leakage. Figure 10 shows photos of both the full- and partial-depth repairs.

Figure 10. Formwork During Mockup: (a) Full-Depth Repairs; (b) Partial-Depth Repairs

As Figure 10 shows, the full-depth repair included PVC piping to simulate placing FRC through a bridge deck on top of the beams. The PVC piping system added some complexity to the mockup, but the district work crew successfully constructed it. They noted that the full-depth formwork with PVC piping systems would be difficult to construct on bridges with close beam spacings, such as those on steel beam bridges with timber decks.

Water and steel fibers were added to the prepackaged VHPC material for the mix. Mixing was accomplished using a handheld dual paddle mixer. Workers added 20% more water than specified on the bag (approximately 0.6 gallon per bag) to ensure easy flow through the PVC piping. However, the high sump values raised concerns about potential fiber segregation and settlement. During mixing, only one large bucket was used. The district work crew noted that it would be helpful to have multiple buckets so that one could be used for mixing VHPC and the other for placing VHPC into the repair formwork. Figure 11 shows examples of mixing and placing VHPC into the formwork.

Figure 11. Mixing and Placing Fiber Reinforced Concrete During Mockup: (a) Mixing VHPC with Paddle Mixer; (b) Placing VHPC into Polyvinyl Chloride Piping to Fill Full-Depth Repair; (c) Partial-Depth Repair After Filling with VHPC. VHPC = very high-performance concrete.

Placing VHPC into the repairs went well, and the VHPC had sufficient flow to travel through the PVC piping. The district work crew noted that a non-zero amount of VHPC was “lost” because of priming the PVC piping system and that it would need to be accounted for when determining quantities for future repairs performed in the field if using full-depth repairs. A few areas in the formwork leaked, but extra backer rods were placed in these small voids to contain the VHPC.

Overall, the mixing process went well, with no major challenges. The district work crew noted that they preferred the partial-depth repairs because they were easier to construct, did not require PVC piping systems to be constructed, required less VHPC, and made for easier VHPC placement.

During the mixing process, samples were also made to be tested in VTRC’s concrete lab. These samples included 7- and 28-day compressive strengths and 28-day splitting tensile strength. Table 2 shows the results for these tests. As Table 2 shows, all tests proved that VHPC had satisfactory strengths, even with the extra amount of water added to the mix to allow it to flow better through the PVC piping.

Table 2. Test Results for Very High-Performance Concrete Used in Mockup Test

Test	Result (psi)
7-Day Compressive Strength	10,760
28-Day Compressive Strength	13,730
28-Day Splitting Tensile Strength	1,425

After approximately 1 week, the mockup repairs were demolded, and fiber settlement was noticed. Consequently, concrete with similar proportions was later prepared in the VTRC concrete laboratory to study the slump flow values needed for a homogeneous mixture without fiber settlement. Tubes measuring 3-feet high and 3-inches in diameter were filled with VHPC, allowed to cure, and then cut vertically to observe the distribution of fibers visually.

Segregation of fibers and aggregates was observed when excessive water, about 20% more than recommended (0.6 gallon per bag), was used. This amount of water is the same used in the mockup testing. Figure 12 shows one of the VHPC tubes after being cut open. The high slump values of 30 inches, which were obtained with extra water, were shown to cause settlement of fibers. This observation suggests that high flow values should be avoided. On the other hand, VHPC mixtures with low flow values had difficulty passing through the 3-inch diameter tube, suggesting that low flow values should also be avoided. Therefore, an optimal amount of water should be added to the mix to balance segregation and flowability. This optimal amount may be slightly higher than the maximum amount of water recommended by the manufacturer and can be determined by trial batching.

Figure 12. Mixture with Extra Water and High Slump Flow of 30 Inches Exhibited Segregation

With a recommended maximum water amount of 0.5 gallons per bag, a slump flow value of 24 inches was achieved, resulting in well-distributed fibers and aggregate dispersion (Figure 13). Strength tests were also performed on samples made using this mixture (Table 3). As Table 3 shows, all tests produced satisfactory strength values.

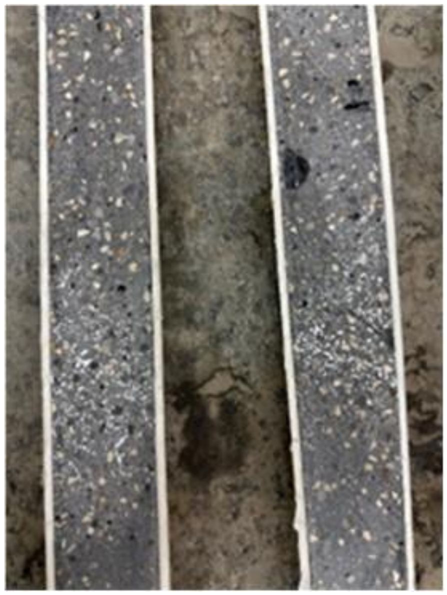

Figure 13. Mixture with the Recommended Amount of Water and a Slump Flow of 21 Inches Had Good Distribution of Steel Fibers

Table 3. Test Results for Very High-Performance Concrete Used in 3-Feet High, 3-Inch Diameter Tubes for Testing Fiber Distribution

Test	Result (psi)
7-Day Compressive Strength	14,400
28-Day Compressive Strength	17,730
28-Day Splitting Tensile Strength	1,775

Initial VDOT Implementation

As noted, the VDOT Northern Virginia District used the FHWA guidance on UHPC beam end repairs to develop designs and details for the FRC beam end repairs for the Bristow Road Bridge project. The FHWA guidance recommends that the designer determine the strength limit states from three possible loading scenarios: live load only, entire design load, or restoration of original capacity. The VDOT Northern Virginia District elected to use the entire design load to be conservative. Using the FHWA design guidance and experience with using FRCs in the past, the district specified a compressive strength of 12,000 psi, leading to the selection of VHPC. The district also specified using 1/2-inch diameter welded shear studs to transfer load between the existing steel beam and the VHPC panels. Overall, the district noted that the design process was relatively easy. Figure 14 shows drawings of the details for the VHPC beam end repairs on the Bristow Road Bridge.

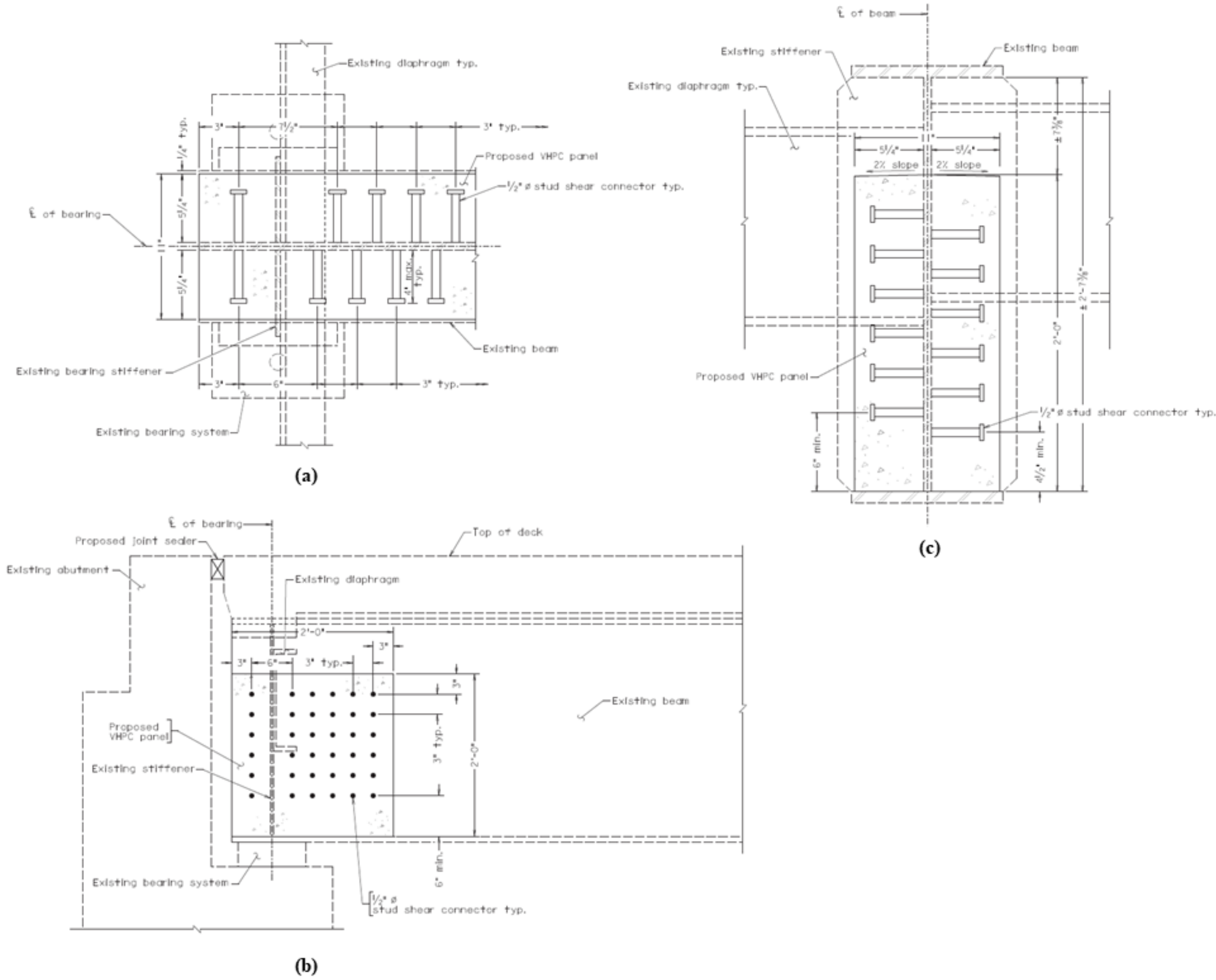

Figure 14. Drawings for Initial Implementation of Fiber Reinforced Concrete Beam End Repair Project in VDOT's Northern Virginia District: (a) Plan View; (b) Elevation View; (c) Section View

The drawings also included the following notes:

- Prepare the existing surface before performing work. Preparation includes but is not limited to removing debris, loose rust, and paint.
- No paint shall be applied under the VHPC panel.
- All bevels for concrete shall be 3/4 inch.
- Headed studs shall be welded to clean sections of the web. Studs may be welded in sections of the web with minor (up to 1/16-inch) section loss. Studs must be installed following standard stud welding practices using conventional stud guns.
- The stud spacing shall be a minimum of 3 inches and a maximum of 6 inches. The spacing may vary within this range to accommodate the number of studs required. In addition, studs shall be a minimum of 2 inches clear from other steel elements such as but not limited to stiffeners and diaphragms.
- At locations where the use of a stud gun is not possible because of limited clearance, a maximum of three studs may be welded using an all-around 5/16-inch fillet weld. If more than three studs in any given beam end need to be welded using a fillet weld, the engineer

shall be notified. If the minimum number of studs cannot be placed because of certain field conditions, the engineer shall be notified before proceeding.

- Studs shall conform to ASTM A108, type B, and shall be in accordance with 226.02(d) of the VDOT *Road and Bridge Specifications* (ASTM International, 2024; VDOT, 2020). Stud welding details, procedures, and testing methods shall conform to the AASHTO/AWS D1.5 Bridge Welding Code (AASHTO and AWS, 2020).
- All exposed interfaces between the VHPC panel and steel beam shall be sealed with joint sealant.

Furthermore, the drawings included the following instructions:

- The minimum number of studs required per beam end is 36.
- Elevation detail shows the available locations for stud placement.
- The field team determines stud locations and notifies the engineer for confirmation before placement.
- Studs shall not be aligned with those placed on the other side of the web, except as shown.

Because it was their first implementation of an FRC beam end repair, the VDOT Northern Virginia District elected to conduct a mockup specimen before installing the VHPC beam end repairs on the Bristow Road Bridge. This mockup consisted of a beam end cut out from a retired bridge. Formwork was constructed on both sides of the beam web, then VHPC was placed on one side of the web, and typical concrete was placed on the other. The district noted that this mockup was an additional expense to the project but believed that the learning opportunities encountered during the mockup were worth the additional expense. Figure 15 shows a photo of the mockup specimen.

Figure 15. Photo of the Mockup Specimen Constructed Before the Bristow Road Bridge Repairs

Once it was time for the repairs to be installed on the Bristow Road Bridge, the stud locations were all cleaned using wire brushes. This process was relatively simple because the existing beams were made from uncoated weathering steel, so no coating removal was required. The district noted that some shear studs had to be moved slightly from the locations specified in the drawing in Figure 14 to avoid areas with extensive corrosion. The district noted that it was difficult to have a standard plan for the stud locations because the corrosion on all 10 beam ends was slightly different. After the studs were welded, all the formwork was constructed for the partial-depth repairs. Figure 16 shows examples of one of the beams after the studs had been welded and the formwork constructed.

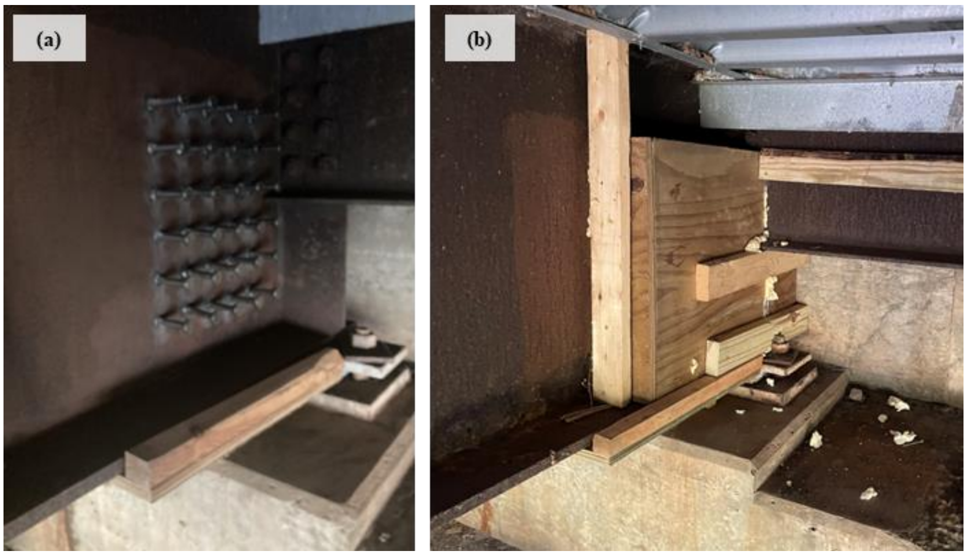

Figure 16. Photos of Bristow Road Bridge Repairs Before Fiber Reinforced Concrete Installation: (a) Shear Studs After Welding; (b) Formwork

Prepackaged VHPC was mixed with water and steel fibers using a high-shear 15.6-cubic-foot mixer (Figure 17a). A trailer pump was also rented to facilitate transporting the mixed VHPC from the mixer to the beam ends (Figure 17b). Approximately 1 cubic yard (130 bags) of VHPC was mixed in multiple batches. The capacity of the mixer was about 54 bags per batch. To ensure proper mixing and prevent segregation, each batch was limited to a maximum of 32 bags. To ensure thorough mixing, increments of 10 bags were added to the required water amount. At the final mixing stage, 2% steel fibers (2.8 pounds per bag) were incorporated, requiring two 44-pound bags of steel fibers. Although the recommended maximum water content was 0.5 gallons per bag, the desired flowable mix for pumping and placement was not achieved. The water content was then increased to 0.56 gallons per bag, which resulted in a highly flowable and pumpable mixture. Delivering the VHPC materials into each of the beam end formwork was accomplished with a 2-inch diameter hose (Figure 18).

Figure 17. Photos of Bristow Road Bridge Repair Fiber Reinforced Concrete Installation: (a) High-Shear Mixer; (b) Trailer Pump

Figure 18. Photo of Bristow Road Bridge Repair Installation Showing Pumping Very High-Performance Concrete Mixture into Formwork

Workers tapped the forms with a hammer to aid in proper consolidation, even though the VHPC was a self-consolidating mixture. However, when forms were demolded after approximately 1 week, surface imperfections indicated a lack of fiber consolidation, clumping, or balling. Figure 19 shows photos of proper and imperfect surface finishes. Even though good finished surfaces were obtained in some cases, clogging of the flow through fiber conglomeration or lack of sufficient consolidation occurred in other cases. This occurrence raised awareness of the need for mechanical vibration in future projects rather than simply tapping the formwork with a hammer. The district indicated that they used ECC to patch the imperfect surfaces. The district also placed ECC at the steel-VHPC edge interface to seal out moisture and salts and prevent future corrosion.

Figure 19. Photos of Bristow Road Bridge Repairs After Formwork Removal: (a) Proper Surface Finish; (b) Imperfect Surface Finish Requiring a Patch

Test cylinders were taken to the VTRC concrete laboratory and tested for the compressive and splitting tensile strengths. The average 28-day compressive strength was 13,770 psi, exceeding the required minimum strength of 12,000 psi, and the average 28-day splitting tensile strength was 1,990 psi, exceeding the minimum of 1,400 psi specified in Virginia adjacent member connections. One of the tested cylinders was cut vertically to determine the distribution of the steel fibers (Figure 20). The distribution of fibers was uniform in the cylinder, indicating that the addition of 12% more water than recommended by the manufacturer did not cause fiber settling or strength reduction.

Figure 20. Well-Distributed Steel Fibers in Very High-Performance Concrete Used in Bristow Road Bridge Repairs

Overall, the VDOT Northern Virginia District had a very positive experience with VDOT's initial implementation of FRC beam end repairs. The district indicated that they were interested in using threaded rods for load transfer between the steel beam and VHPC panel rather than shear studs. By using shear studs, the district required both a qualified welder and generator rental to power the shear stud welding gun. The qualified welder and the generator rental led to additional expenses, and the qualified stud welder required additional scheduling. Using threaded rods would allow the district work crew to easily install the repairs using their existing equipment.

The district also noted that full-depth repairs would be beneficial in some applications. The full-depth repairs could be filled by coring a hole in the concrete deck above the repairs. Although this procedure would require lane closures, it would also eliminate the need for the pump trailer and the challenges related to pumping.

Development of VDOT Design Guidance

The Connecticut DOT and FHWA guidelines provide similar information for designing UHPC beam end repairs. Overall, this information includes the following:

- Strength limit states include three possible scenarios:
  - Design for live load only: This scenario assumes the corroded structure can resist dead load, and the repair is needed only to resist live load. The design load for this case would be only the live load portion of the AASHTO Load and Resistance Factor Design Strength I load combination.
  - Entire design load: This scenario assumes the repair resists the entire factored AASHTO Load and Resistance Factor Design Strength I load combination.
  - Restoration of original capacity: This scenario assumes the repair resists the entire capacity of the original beam end, which could be the shear capacity of the end panel or the capacity of the bearing stiffener. This approach is the most conservative because these values could far exceed the factored design loading.
- Number of shear studs required for both strength and fatigue.
- Location and layout of shear studs, including minimum cover and spacing requirements.
- Required strength of FRC used in repair.
- Dimensions of FRC panel in repair, including whether FRC is full-depth (in contact with the bottom of the top flange) or partial-depth (FRC extends part way up the beam web).
- Stud welding requirements according to AASHTO/AWS D1.5 Bridge Welding Code (AASHTO and AWS, 2020).
- Corrosion mitigation and inspection should include the following:
  - Detail formwork such that the UHPC panel completely covers the bottom flange width to prevent ponding.
  - Placing UHPC panels on both sides of the beam web to prevent continued corrosion on an exposed web.
  - Sloping the top of partial-depth panels away from the beam web and caulking the UPHC-steel edge interface to keep water away from the steel beam.

This same guidance can be used for VDOT's FRC beam end repairs with minor modifications. VDOT prefers to design for actual conditions to the extent that they can be modeled, meaning designing for combined live and dead loads. In addition, VDOT requires that the version of AASHTO's *Standard Specification for Highway Bridges* in effect at the time of original bridge construction be used to rehabilitate existing structures (AASHTO, 1996). If the relevant version is not accessible, the engineer may use the 16th edition of that specification. This flexibility means that both allowable stress and load factor designs may be used. Therefore, both should be incorporated into the design methodology.

The design methodology does not need modification if FRC is used instead of UHPC. FRCs such as VHPC and ECC will likely provide slightly less strength values than UHPC but should still be sufficient for beam end repairs. Strength values for FRCs can be input into the design equations to determine if they are sufficient.

When using threaded rods instead of welded shear studs, some modifications to the design methodology are required. When designing the number and size of threaded rods, the net tensile area must be used to determine the resistance or allowable stress of each threaded rod. This action is necessary because the threads will be in the shear plane between the steel beam and the FRC panel. Table 4 shows the comparison of unthreaded areas and net tensile areas of threaded rods with diameters of 3/8 inch, 1/2 inch, and 5/8 inch, which will likely be the diameters used on FRC beam end repairs.

Table 4. Net Tensile Area and Pretension Forces for Grade 55 Threaded Rods to Be Used in Fiber Reinforced Concrete Beam End Repairs

Threaded Rod Diameter (inch)	Unthreaded Area (inch^2)	Net Tensile Area (inch^2)	Pretension Force for Grade 55 Threaded Rods (kips)
3/8	0.110	0.077	4
1/2	0.196	0.141	7
5/8	0.307	0.226	12

Based on the literature review, threaded rods were found to have better fatigue resistance than welded shear studs when used to provide composite action between a concrete deck and steel girder. Therefore, using the welded shear stud fatigue design equations provided in the FHWA guidance is conservative. However, like the strength limit state, the net tensile area of the threaded rod must be used in the fatigue design equations.

Another modification includes adding a requirement for pretensioning the threaded rods to the existing steel beam. As previously stated, pretensioning the threaded rods will improve the fatigue performance of the holes in the steel beam. The AASHTO *Bridge Construction Specifications* require pretension forces in high-strength bolts to be 70% of the material's ultimate strength. The same requirement could be used for threaded rods in FRC beam end repairs. The VDOT *Road and Bridge Specifications* require high-strength anchor bolts to meet the requirements of AASHTO M314 Grade 55 (VDOT, 2020). These anchor bolts have a nominal ultimate strength requirement of 75 ksi. It seems likely that the same material specification could be used for threaded rods in FRC beam end repair applications. Therefore, the pretension forces for threaded rods with diameters of 3/8 inch, 1/2 inch, and 5/8 inch meeting the requirements of AASHTO M314 Grade 55 were calculated and are shown in Table 4. These low levels of pretension can be achieved by hand tightening to the full effort of a laborer and do not require specific guidance for turn-of-nut or direct tension indicating washers.

In addition, if threaded rods were used in FRC beam end repairs, a requirement for an AASHTO/AWS D1.5 certified shear stud welder could be waived (AASHTO and AWS, 2020).

VTRC developed a design guide and a spreadsheet to aid in the design process of FRC beam end repairs with the modifications discussed in this report. The design guide, titled *Design Guidelines for FRC Repairs on Corroded Steel Beam Ends*, and the spreadsheet, titled FRC Beam End Repair Design Spreadsheet, can be found in the Supplemental Material accompanying this report.

Cost Analysis

Table 5 provides the cost information for multiple types of beam end repairs, including the following:

- VHPC beam end repairs constructed by VDOT work crews.
- Bolted beam end repairs constructed by VDOT work crews.
- Bolted beam end repairs constructed by a contractor based on a previous on-call contract.
- Bolted beam end repairs constructed by a contractor based on the current on-call contract.

Table 5. Cost Comparisons Between Fiber Reinforced Concrete and Bolted Beam End Repairs Constructed by VDOT Work Crews and Contractors

Cost Item	Cost			
	VHPC Repair Constructed by VDOT Work Crews[a]	**Bolted Repair Constructed by VDOT Work Crews[b]**	**Bolted Repair Constructed by Contractor under Previous On-Call Contract[c]**	**Bolted Repair Constructed by Contractor under Current On-Call Contract[c]**
Subtotal for traffic control, materials, and equipment	$ 54,700	$ 96,700[d]	Not provided	Not provided
Subtotal for labor	$ 43,400	$ 17,500	Not provided	Not provided
Total project cost	$ 98,000	$114,200	Not provided	Not provided
Total cost/beam end repair	**$ 9,800**	**$ 11,400**	**$10,100–13,500**	**$41,500–56,600**

VHPC = very high-performance concrete. [a] Provided by VDOT Northern Virginia District. [b] Provided by VDOT Salem District. [c] Provided by VDOT Richmond District. [d] Includes $12,500 for traffic control and $84,200 for materials and equipment.

Some of these cost estimates were itemized in terms of a lump sum for traffic control, materials, and equipment and a lump sum for labor. Other cost estimates were provided in terms of a total cost per beam end repair. All cost estimates were rounded to the nearest $100 for easier comparison.

When comparing the repairs constructed by VDOT work crews, approximately 55% of the total cost is from traffic control, materials, and equipment for the VHPC repairs, whereas approximately 45% of the cost comes from labor. These figures differ from the bolted repairs constructed by VDOT crews, in which 85% of the cost comes from traffic control, materials, and equipment, whereas only 15% of the cost comes from labor. Of this 85%, approximately 75% of the total cost comes from materials, which is likely because concrete typically costs less than steel but requires more labor to install. When comparing the actual cost per beam end repair constructed by VDOT work crews, the FRC repairs cost approximately $1,600 less than the traditional bolted repairs.

The cost of the bolted beam end repairs constructed by contractors under the previous on-call contract is similar to the bolted repair cost constructed by VDOT work crews. However, the cost of bolted beam end repairs by contractors under the current on-call contract has greatly increased—up from an average of $11,800 to an average of $49,100. It is unknown why the cost of bolted beam end repairs by contractors increased so much between the two on-call contracts. No matter the reason, this cost increase of approximately four times is significant. Overall, the FRC beam end repairs constructed by VDOT work crews cost an average of approximately $2,000 less than bolted repairs constructed by contractors under the previous on-call. This cost savings increases to roughly $39,300 under the current on-call contract.

To evaluate potential annual cost savings for VDOT if FRC beam end repairs were widely implemented, researchers estimated the number of steel beam end repairs conducted within VDOT annually. VDOT's bridge inspection data during the past 10 years were used for the estimate. First, all culverts and all bridges with a superstructure made of material other than steel were removed from the dataset. Steel girder bridges with timber and metal decks were included in the dataset because the FRC beam end repairs could easily be implemented for bridges with these deck types. Repairs with these deck types could be simple to construct because timber and metal decking could be easily removed to facilitate easier FRC placement. Steel trusses and movable bridges were also included in the dataset because the FRC beam end repairs could be compatible with both, depending on the bridge geometry. Much of the remaining dataset consisted of steel girder bridges with concrete decks.

Next, the inspection data were analyzed to determine how many beam ends in the remaining dataset displayed an improvement in condition between a previous inspection and a subsequent inspection. For example, a previous inspection may have occurred in 2018, followed by a subsequent inspection in 2020. Beam and girder ends are noted within VDOT's inspection data as Virginia element number 811, which refers to the last 5 feet of a beam or girder end. Each beam end on a bridge is rated as one of four different condition states: CS1, CS2, CS3, and CS4. These condition states represent the condition of the beam end in increasing levels of damage. For steel beam ends, CS1 represents no corrosion or cracking, with all connections in place and functioning as intended. By contrast, CS4 represents evidence of section loss or pack rust, cracking, missing fasteners, broken welds, and distortion. In addition, the condition either warrants a structural review, or a review has determined that the defects affect the strength or serviceability of the element.

A beam end repair was assumed to have occurred if the number of beam ends rated as CS1 increased between a previous and subsequent inspection. Only CS1 was considered because it was impossible to determine whether the beam ends in other condition states had improved or deteriorated between inspections. For example, a beam end rated as CS2 during the previous inspection could have either improved to CS1 or deteriorated to CS3 during the subsequent inspection. An increase in CS1 beam ends was taken as a likely indication that repairs had been made to improve their condition. Table 6**Error! Reference source not found.** shows the results of this analysis, with the estimated number of steel beam end repairs broken up by VDOT district and year. The year indicates the year of the subsequent inspection, although the repair could have occurred anytime between the previous and subsequent inspections.

Table 6. Number of Steel Beam End Repairs Conducted by VDOT Districts Since 2016, Estimated Using VDOT Element Number 811 Inspection Data

VDOT District Number and Name	Estimated Number of Steel Beam End Repairs per Year										Total
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025[a]	
1 - Bristol	16	38	154	114	21	46	40	53	200	158	**840**
2 - Salem	0	26	26	460	40	14	1	89	49	35	**740**
3 - Lynchburg	26	54	77	20	49	53	78	12	144	0	**513**
4 - Richmond	0	54	215	313	159	452	266	228	199	48	**1934**
5 - Hampton Roads	118	31	131	327	246	228	281	370	284	3	**2019**
6 - Fredericksburg	0	77	198	69	36	12	72	380	62	13	**919**
7 - Culpepper	0	0	0	0	60	142	142	33	84	23	**484**
8 - Staunton	0	14	9	33	175	93	70	171	147	9	**721**
9 - Northern Virginia	0	3	51	123	57	63	70	200	409	19	**995**
Total	**160**	**297**	**861**	**1,459**	**843**	**1,103**	**1,020**	**1,536**	**1,578**	**308**	**9,165**

[a] Through April 2025.

Table 6 shows that VDOT has conducted an estimated 9,165 steel beam end repairs since the beginning of 2016. The data in the table were collected through April 2025, representing a period of 9.33 years. Therefore, VDOT has conducted an average of 982 steel beam end repairs per year during this period. These data do not differentiate between repairs constructed by VDOT work crews or contractors.

A potential annual cost savings for VDOT was then calculated using the cost savings associated with FRC beam end repairs and the estimated number of steel beam end repairs conducted each year (Table 7). This cost savings assumes widespread implementation of FRC beam end repairs, as if FRC beam end repairs were used on 100% of the steel beam end repairs conducted within VDOT. Because the cost savings associated with the construction method differed greatly (repairs constructed by either VDOT work crews versus contractor), the annual cost savings were calculated for three different construction method scenarios: 100% of repairs constructed by VDOT work crews, 50% by VDOT work crews and 50% by contractors, and 100% by contractors. Costs for repairs constructed by a contractor used the pricing for the current on-call contract because this amount is the cost VDOT currently pays for bolted repairs.

Table 7. Potential Annual VDOT Cost Savings Associated with Widespread Implementation of Fiber Reinforced Concrete Beam End Repairs

	Fiber Reinforced Concrete Beam End Repairs by Construction Method		
	100% by VDOT Work Crews	**50% by VDOT Work Crews, 50% by Contractors**	**100% by Contractors**
Annual VDOT Cost Savings	$1.6 million	$20.1 million	$38.6 million

As Table 7 shows, if VDOT work crews constructed 100% of the repairs, the annual VDOT savings would be approximately $1.6 million. On the other hand, if contractors constructed 100% of the repairs, the annual VDOT savings would be roughly $38.6 million. If VDOT work crews constructed 50% of the repairs and contractors constructed 50% of the repairs, the annual cost savings would be approximately $20.1 million. No matter what the construction method, these values represent significant annual cost savings for VDOT that could potentially be used to perform a greater number of repair or maintenance actions within a given year.

It is also likely that these cost savings will increase over time as VDOT work crews and contractors gain more experience using FRC beam end repairs. Recall that the FRC beam end repair cost was based on the initial experience of VDOT work crews using VHPC and welded shear studs. Reducing the cost of FRC beam end repairs could be achieved by using threaded rods instead of shear studs, thus eliminating the need for a qualified stud welder and generator rental and needing fewer traffic control requirements. The cost of FRC beam end repairs could also be reduced by using ECC instead of VHPC. Furthermore, the increased use of partial-depth repairs, instead of full-depth, could reduce costs by limiting or eliminating the need for traffic control during repair installation. For illustrative purposes, if the cost of FRC beam end repairs were reduced by 20% based on additional experience and revised practices, the annual VDOT cost savings would be $3.5 million if VDOT work crews constructed 100% of the repairs, $40.5 million if 100% by contractors, and $22.0 million if 50% by VDOT work crews and 50% by contractors.

In addition to direct cost savings, FRC beam end repairs offer the following other areas in which costs will be saved but are difficult to quantify:

- Faster for construction—FRC beam end repairs can be installed quickly. Bolted repairs cannot be installed until a fabrication contract is in place and the steel repair plates have been fabricated, including potential bending and drilling of holes. On the other hand, FRC repairs can be installed almost immediately if FRC mixes and threaded rods are in stock.
- Alternative to steel repairs—FRC beam end repairs offer an alternative to the traditional steel bolted beam end repairs. Having multiple repair options creates competition, which can help keep down the costs of the available options. This scenario is especially important because of the significant increase in bolted repairs from the previous VDOT on-call contract to the current on-call contract.
- Better for worker safety—When constructing steel bolted repairs, workers may be required to lift and install the heavy steel repair plates. However, with FRC beam end repairs, the FRC can either be pumped or proportioned to minimize heavy lifting loads.
- Long-term durability—FRC beam end repairs are likely to be more durable than steel bolted repairs when detailed properly. This durability is because FRC beam end repairs can be detailed to shed water and chlorides. In contrast, bolted steel repairs typically have crevices that commonly trap water and chlorides to cause future corrosion.

CONCLUSIONS

- *The UHPC beam end repairs developed by the University of Connecticut and the Connecticut DOT can be modified to use other FRCs, including VHPC and ECC.* These other FRCs can provide the strengths required for beam end repairs, better availability, and are less expensive than UHPC. Furthermore, VDOT work crews have had good experience using these other FRCs in field applications.

- *The UHPC beam end repairs developed by the University of Connecticut and the Connecticut DOT can be modified to use threaded rods instead of shear studs to provide load transfer between the steel beam end and the FRC panel.* Threaded rods have sufficient strength, ductility, and fatigue performance for these applications and can provide easier installation because VDOT work crews can install them. The threaded rods can also provide cost savings because a qualified stud welder and generator rental are not required.

RECOMMENDATIONS

1. *The VDOT Structure and Bridge Division should implement guidance into the VDOT "Manual of the Structure and Bridge Division," Part 2, Chapter 32, for using FRC beam end repairs for deteriorated steel beams—including the use of FRCs, such as VHPC and ECC—and threaded rods to provide load transfer between the FRC panels and steel beam.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, the Structure and Bridge Division will implement guidance on FRC beam end repairs into the VDOT "Manual of the Structure and Bridge Division," Part 2, Chapter 32, within 3 years of the publication of this report. VTRC has developed initial design and installation guidance and a design spreadsheet for using FRC beam end repairs. The design guide and spreadsheet are in the Supplemental Material accompanying this report and are titled *Design Guidelines for FRC Repairs on Corroded Steel Beam Ends* and FRC Beam End Repair Design Spreadsheet. This initial guidance was based on the FHWA UHPC beam end repair guidance but contains revisions based on the results of this research. The VDOT Structure and Bridge Division can use this initial guidance as a starting point and revise it as they see fit. The Structure and Bridge Division can discuss this guidance with the VDOT Materials Division as necessary.

Benefits

The benefits of implementing the Recommendation include potential cost savings, less reliance on contractors, and increased service life of repairs. If widely implemented, FRC repairs can save VDOT approximately $39 million per year on steel beam end repairs. These cost savings could be reallocated to other bridge repair or maintenance actions. In addition, with the modifications of using other FRCs instead of UHPC and using threaded rods instead of welded shear studs, VDOT work crews can construct FRC beam end repairs. The mockup and initial implementation of this type of repair showed that VDOT work crews have the necessary equipment or can easily procure it (such as the pump rental) and the expertise required for these repairs. This result means that VDOT can rely less on contractors to install these repairs, leading to potential cost savings and fewer scheduling bottlenecks. Finally, FRC beam end repairs are likely more durable than traditional bolted repairs. Bolted beam end repairs contain connected parts that are susceptible to crevice corrosion. When the chlorides are removed and the steel-FRC edge interfaces are properly sealed, FRC beam end repairs can be expected to have long service lives without needing another repair.

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