Implementation of UHPC for the Repair of a Steel Bridge with Corrosion Damage in Connecticut, USA

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Abstract:

Corrosion problems at girder ends have become one of the most pressing challenges in the maintenance of aging steel bridges. In the past five years, the Connecticut Department of Transportation has been working with the University of Connecticut to develop and validate a novel method for the repair of corroded girder ends using ultra-high performance concrete (UHPC). This repair involves welding shear studs onto the intact portions of web plates and encasing the girder end with UHPC to develop an alternate load path for bearing forces. The extensive data from small- and full-scale experiments, complemented by comprehensive finite element simulations, has sufficiently demonstrated the structural viability of the repair and its applicability for use with various girder end geometries. The Connecticut Department of Transportation is moving forward with the first large-scale implementation of the repair on a heavily-trafficked four-span bridge on Interstate 91. The bridge, located east of New Haven, spans three railroad tracks. In this project, several unique parameters have considerably limited the viable repair options. These parameters include 1) the complex geometry of the bridge due to the varying skew angles between spans, 2) the severity of corrosion damage at numerous locations (with a total of 42 beam ends requiring retrofitting), 3) significant construction constraints due to heavy daily traffic, and 4) limited access due to operation of the railroad tracks. Use of the proposed UHPC repair is expected to address these constraints by accommodating various girder end geometries, expediting construction, and minimizing traffic interruptions. This will be accomplished with no significant added cost. This paper presents the lessons learned during the design and construction of the bridge repair. It is expected that this information will facilitate future applications of this promising repair method and enable different states to more efficiently enhance the safety of aging bridges.

Keywords: Corroded Steel Girder Ends, Repair Method, Repair Design, Field Evaluation

1. Introduction

Many highway bridges in the US have a steel girder superstructure system (FHWA 2017). A majority of these bridges were constructed between 1950-1980 and designed for a 50-year lifespan (NACE International 2016). The average age of steel girder bridges in the US is approximately 63 years, meaning that many of these bridges have reached or surpassed their service life (FHWA 2017). The need to repair and replace aged bridges, compounded with the increase in traffic demands, has put a significant burden on federal, state, and local agencies. Therefore, innovative and cost-effective solutions are necessary to address these challenges (Davis et al. 2013).

Corrosion damage is the cause of approximately 15% of the structurally deficient bridges in the United States. It is estimated that the United States spends $8.3 billion annually on the repair and replacement of highway bridges that suffer from corrosion damage (Koch et al. 2002). Deck leakage at expansion joints is a major cause of corrosion damage in steel girder bridges as shown below (Figure 1a). Corrosion of the web and bearing stiffeners decreases bearing capacity (Kayser and Nowak 1989; Albhaisi and Nassif 2015). The current repair technique for corroded steel girder ends involves removing and replacing the damaged sections with new steel (Figure 1b). The conventional repair procedure detailed by FHWA requires the bridge to be jacked up before the damaged section is removed to reduce in-situ stresses in the member (Rossow 2003). This procedure is costly and requires extensive amount of construction time (Close, Jenssen, and Miller, P.C. 2011). With severe budgetary constraints, and the alarming rate of the progression of corrosion damage in bridges across the nation, the necessity of developing novel methods to address this issue has become increasingly evident.

Figure 1. A representative example of a) corroded girder end and b) conventional repair method

To respond to this crisis, the Connecticut Department of Transportation (CTDOT) has pioneered the development of an alternative repair strategy by supporting a promising research project at the University of Connecticut (UCONN). A repair concept using ultra-high performance concrete (UHPC) was investigated through a two-phase research project. In Phase I, the applicability of the repair method as a structurally effective and practical alternative repair strategy to restore the capacity of corroded beam/girders was investigated (Zmetra et al. 2015; Esmaili Zaghi et al. 2015; Zmetra et al. 2017; Zmetra 2015). The proposed repair involves casting UHPC around the corroded steel section. The UHPC is connected to the intact portion of the web via shear studs. A schematic of the repair is shown in Figure 2. Details of welding the shear studs using a stud gun are shown in Figure 3.

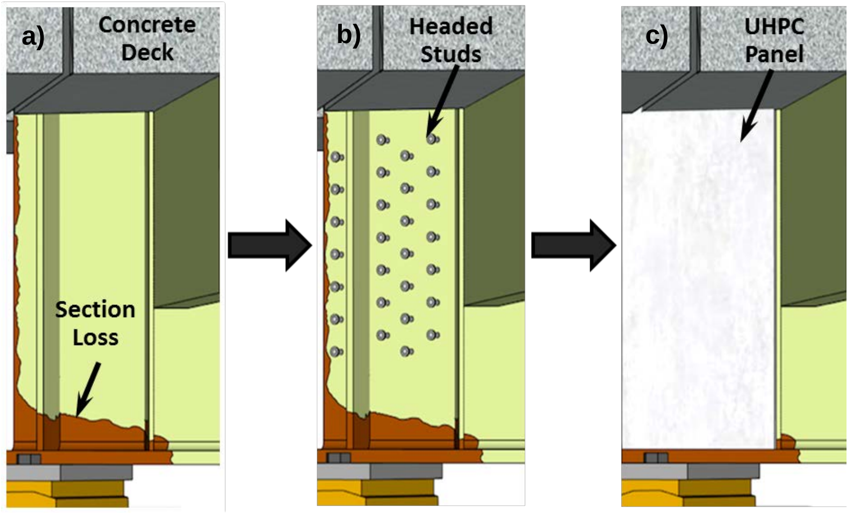

Figure 2. Schematic of UHPC Repair showing a) corrosion at girder end, b) studs welded to intact web plate, and c) UHPC panel cast.

Figure 3. Welding of headed shear studs including a) ferrule, b) welding on a vertical plate, and c) finished product.

Phase II investigated the application and performance of the repair for full-scale girders. Full-scale experimental tests were conducted on plate girders with reduced web and bearing stiffener sections to simulate corrosion damage. Three plate girder specimens were repaired using various repair geometries. One of the test specimens was vibrated during the curing of the UHPC to simulate traffic vibration. This test was conducted to determine the effects of vehicular live load on the set and strength of the UHPC. Vibration data from a local bridge in CT was used as the signal input for the vibration. The simulated live load was found to have no effect on the curing of the UHPC. Phase II also investigated the performance of shear studs welded to the web of a girder and embedded in UHPC through a large number of push-off tests (Kruszewski et al. 2018a; Kruszewski et al. 2018b). The behavior of shear studs with various parameters including diameters, spacing, and layouts was experimentally investigated to develop a formulation for stud capacities and identify design limitations. These tests also explored the effects of surface preparation of the web plate and exposure to corrosion on the performance of the repair. Surface preparation was investigated as minimizing the removal of existing paint from the girder may result in significant savings in time and cost. The results showed that the repair gained full strength when only locally removing paint at the locations where studs were to be welded. The impact of corrosion of the performance of the repair was evaluated by testing push-out specimens that were exposed to accelerated electrochemical corrosion. The specimens exposed to accelerated deterioration reached the same capacity as the baseline specimens, confirming the corrosion resistance and impermeability of the UHPC.

The results from Phases I and II show that the UHPC repair can increase the capacity of a damaged girder beyond that of an intact, un-corroded, steel girder. When adequately designed, the repair can eliminate local bearing failure at the ends of girders with corrosion damage. These two phases have successfully established the considerable promise of the novel approach to address the pressing challenge of catching up with the rate of corrosion on bridges. Following the successful completion of the experimental studies, CTDOT selected a bridge for the first large-scale implementation of the repair. The four-span bridge, located east of New Haven, spans three railroad tracks and carries the heavily trafficked Interstate 91. This paper presents the background, design, and proposed construction methods for this field implementation of the UHPC repair. The unique constraints of the project which resulted in limited viable repair options are noted. The rationale for the design is presented and casting methods to address the geometric and access constraints are proposed.

2. Overview of the Bridge

The bridge scheduled to be repaired is a rolled steel beam and concrete deck structure consisting of four simple spans with a total length of 273 ft (83.2 m). The beams have partial length cover plates welded to the bottom flange. The beams have variable sizes with heights ranging from 33-36 in (838-914 mm) and different end conditions (with and without bearing stiffeners). The reinforced concrete deck is composite with the steel beams. The bridge carries Interstate 91 in New Haven and spans three Amtrak tracks. The structure was originally constructed in 1965. The plan view of the bridge is shown in Figure 4 and an image of the structure is shown in Figure 5.

In this project, several unique constraints have considerably limited the viable repair options including the: 1) complex geometry of the bridge due to the varying skew angles between spans (25.9° and 35.9°), 2) diversity of beam end details due to the connection plates, end diaphragms and stiffener plates, 3) severity of corrosion damage at numerous locations (with a total of 42 beam ends requiring retrofitting), 4) significant construction constraints due to heavy daily traffic (average daily traffic (ADT) of 67,000 vehicles/day in one direction), and 5) limited access due to operation of the railroad tracks. The UHPC repair was selected for the project based on a review of feasible rehabilitation and replacement options. The UHPC repair does not require the full roadway to be closed as it can be implemented with minimal lane closures. This attribute was particularly attractive due to the high ADT carried by the bridge. In addition to its high strength, UHPC has additional properties which make it attractive for the repair. The steel fiber reinforcement in the mix provides tensile ductility without the need for rebar reinforcement. The low permeability and corrosion resistance of the UHPC is expected to eliminate the need for further repairs of the beam ends. It is anticipated that the UHPC repairs will be permanent until the superstructure is replaced.

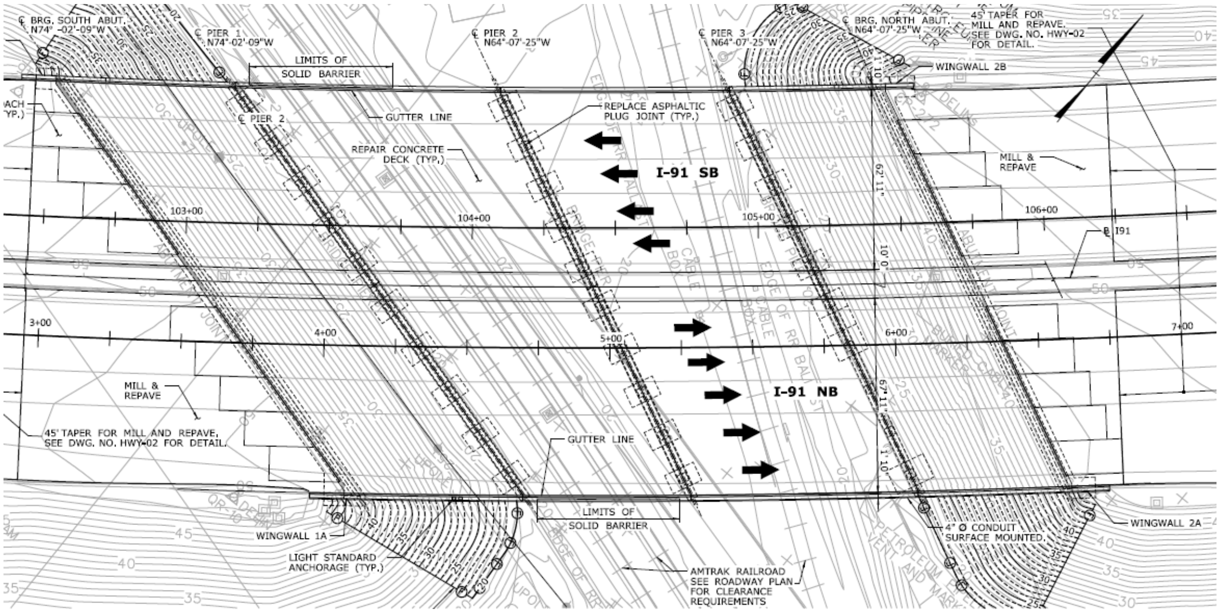

Figure 4. General plan view of bridge in New Haven, CT scheduled to undergo UHPC repair at beam ends.

Figure 5. Image of bridge in New Haven, CT scheduled to undergo UHPC repair at beam ends.

2.1. Condition of the Bridge

The bridge was rated as structurally deficient during the inspection and evaluation performed in 2016. All beam ends have rust, peeling paint, and areas with laminar rust (Figure 6). Web ends and bearing stiffeners have substantial section loss, resulting in reductions in the bearing and shear capacities. The maximum reductions in bearing and shear capacity according to the 2018 inspection report were 72% and 15.5%, respectively. Over 50% of the paint on the structure is deteriorated. The end diaphragms and corresponding connection plates have areas with laminar rust, section loss, and perforations.

Figure 6. Representative beam end corrosion on the bridge

3. Design Methods

The first step in the design is to identify the force demands to determine the required number of studs. UCONN proposed three scenarios to determine the force demand on the repair: Live Load, Strength I, and Capacity Design. The calculations for each limit state are based on the AASHTO Bridge Design specifications (AASHTO, 2012). The Live Load scenario is defined as the shear demand generated from HL-93 loading. This includes the dynamic allowance factor of 1.75 based on Table 3.4.1-1 of AASHTO (AASHTO, 2012). This design scenario assumes that the current condition of the girder is sufficient to carry the permanent loads of the structure and live load is carried by the new load path through the headed studs to the UHPC panels. The Strength I scenario requires the UHPC repair to carry the loads from the shear or bearing demand, including distribution factors. The Capacity Design is the most conservative proposed design for the repair. This approach requires the repair to restore the original shear or bearing capacity of the girder. The shear and bearing strength of the beam can be determined using AASHTO 6.10.10.4.3 and AASHTO 6.10.11.2.3, respectively.

After the force demands are calculated, the number of studs required to achieve the desired capacity must be determined. Push-out specimens of headed shear studs embedded in UHPC conducted at UCONN and by researchers at other institutions have shown that shearing of the stud controls the failure of the repair. This failure mode is consistent for UHPC, but may vary for lower strength concrete. The capacities of the headed studs from the experimental studies were validated through a formulation for the shear capacity of headed studs embedded in high-strength concrete (Equation 1) developed by Hegger et al. (Hegger et al.).

$$P_u = A_{sc}F_u + \eta f'_c d_{wc} l_{wc} \qquad \text{(Eq. 1)}$$

where A_{sc} is the area of the stud shank, F_u is the ultimate tensile capacity of the stud, f'_c is the compressive strength of the concrete, d_{wc} is the diameter of the weld collar, l_{wc} is the height of the weld collar, and η is an empirical factor (typically 2.5 for UHPC). This equation shows that the stud capacity is the sum of the material strength of the stud shank, $A_{sc}F_u$, and the bearing contribution of the weld collar on the concrete, $\eta f'_c d_{wc} l_{wc}$.

For the repair of the bridge in New Haven, the Capacity Design method was used. As the research at UCONN focused on repairs that had shear studs applied using a stud gun, the capacities found are only applicable to studs welded using the same method. The reason for this restriction is that the weld collar created from shooting the studs significantly contributes to the load carrying capacity of the studs. Therefore, it is essential for the design that the studs are welded using a stud gun in the field. A stud diameter of 0.625 in (15.8 mm) was chosen for the repair due to the force demands and limited spacing for studs due to the variable skews. The number of studs needed per beam end varied based on the original capacity of each beam. For the repair of the bridge in New Haven, the number of studs required ranged from 20 to 40. The capacity of the repair is also influenced by the strength of the concrete. Therefore, the specification requires a minimum strength of 18 ksi (124 MPa) at 28 days.

4. Proposed Construction Method

This project had various geometric and access constraints, which added complexity to how the repairs would be implemented. A half-height repair was not feasible since a sufficient number of studs with adequate spacing could not be welded to the intact portions of the web due to the height of the corrosion. Each beam end required a different number of studs and stud layout due to various field conditions such as presence or lack of bearing stiffeners, skew, and beam size. Samples of two stud layouts are shown in Figure 7a and b for beams with and without bearing stiffeners, respectively.

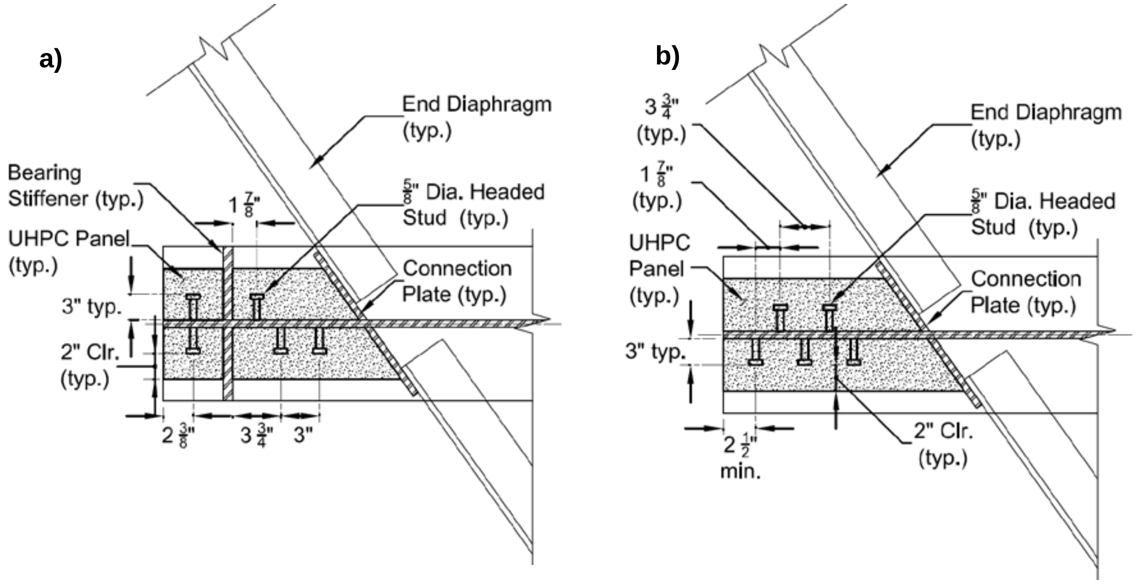

Figure 7. Sample stud layouts for beam ends a) with bearing stiffeners and b) without bearing stiffeners.

The need for a full height repair combined with the access limitations due to the connection plates and end diaphragms, made casting the repair panels from the underside of the deck challenging. An additional concern was transporting concrete from the work zone on the roadway to the underside of the deck. As a result of these challenges, the UHPC will be cast from the top of the deck. During casting, traffic will be restricted on the lanes directly above the beams undergoing UHPC repair. Drilled holes, outside of the limits of the top flange, will be used to funnel the UHPC. A PVC distribution system was proposed by UCONN to fill multiple panels through the same deck hole (Figure 8). The system consists of a network of 3 in (76 mm) pipes including one feeder pipe, a distribution line, and a runner pipe to each form. The system was tested in a lab setting by filling the feeder pipe and measuring if the UHPC rose to equal levels in each of the runner pipes. The test was successful with the height of the concrete in each runner pipe equalizing in four minutes. Thus, this casting method was proposed in the design drawings as a recommended method. In order to use the proposed casting method, a positive pressure head must be maintained between the pipes connecting to different cells of the formwork. The pipes used to transport UHPC to the formwork must be a minimum of 3 in (76 mm) in diameter for running lengths up to 3 ft (0.91 m) in order to match the test that was conducted. For longer running lengths, a larger diameter pipe would be required. In addition, a 2% fibers by volume was tested in the lab evaluation. Significantly higher percentages of fibers should be tested prior to using the proposed method. Drawings for the proposed casting methods are shown in Figure 9. Following form removal, all interfaces between the steel beams and the UHPC panels will be sealed with a silicone sealant.

Figure 8. Test of PVC distribution system for casting of UHPC showing a) distribution system and b) filling of feeder pipe.

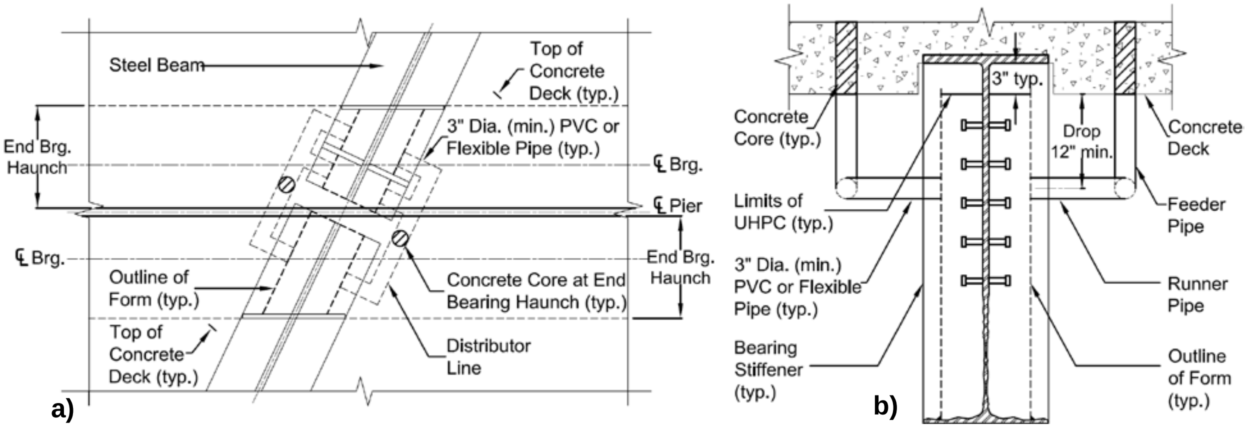

Figure 9. UHPC pouring detail including a) plan view and b) section view

Preventing leakage or failure of the formwork for the UHPC casting was of significant importance for this field implementation. The forms must be water tight to prevent leakage and be able to withstand the pressure head created by the UHPC due to its rheological properties. The railroad tracks underneath may be impacted if the forms fail. Thus, the contractor will need to demonstrate the forms are watertight prior to casting. Additionally, an auxiliary containment system for the UHPC will be provided at each beam end repair location. For future implementations, it is highly recommended that designers provide drawings to show potential formwork and casting methods to contractors. Depending on the prevalence of use of UHPC in the state, and the familiarity of the contractors in working with the material, it is also suggested to provide additional information on the mixing, casting, and workability of UHPC at a pre-bid meeting.

5. Discussion & Conclusions

This paper presents the background, design, and construction methods for the field implementation of a UHPC repair on corroded steel beam ends on a bridge in Connecticut, USA. The repair has undergone extensive experimental and analytical studies at the University of Connecticut. This research showed the efficiency of headed studs as a reliable shear-transfer mechanism and characterized the failure mode and capacity of various stud diameters and layouts. This project showcased how the repair has transitioned from a lab setting to a field implementation there the design was done by a consultant and the repair will be constructed by a contractor. The transition in the design phase was smooth, showing that the designers were comfortable with the performance of the repair. The implementation of the UHPC repair will allow CTDOT to extend the service life of a bridge on a key interstate while minimizing traffic delays for the traveling public.

Bids for the contract closed in October 2018 and beam end repairs using UHPC are anticipated to begin as early as April 2019. Using the UHPC beam end repair did not significantly add to the total rehabilitation cost for the bridge. It is the hope of the authors that providing information on the design and casting methods for the repair will encourage future implementations of the repair in other states. Extensive documentation will be collected during the employment of the repair to share best practices and lessons learned with designers, contractors, and owners.

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