Evaluation of UHPC as a Repair Material for Corroded Steel Bridge Girders

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Abstract: Corrosion damage of steel girder ends is a prevalent problem throughout the United States. This damage is often caused by leaking expansion joints, which deposit water and chlorides on the girders. Section loss at these critical locations can be detrimental to the bearing capacity of the girder. Current repair methods are costly, time consuming, and disruptive to traffic. A new repair method has been proposed by the University of Connecticut and the Connecticut Department of Transportation using ultra-high performance concrete (UHPC) to repair these corroded steel girder ends. The repair consists of welding headed shear studs to the undamaged portions of the web and encasing the girder in UHPC. The shear studs provide an alternate load path from the girder to the UHPC panels to bypass the corroded region. A series of full-scale 54-in. (1.37-m) deep plate girder specimens were tested to evaluate the load-carrying performance of the UHPC repair with different panel heights, stud layouts, and UHPC materials. The experimental program included a baseline corroded girder with no repair and three corroded girders repaired with UHPC. Conventional forming and casting techniques were used for each of the repairs in order to establish standard procedures that could be adopted for field implementation. One of the girders was exposed to simulated service-level vibrations during curing to demonstrate the ability to implement the repair without interrupting traffic. The results show that the UHPC repair presents a viable option for restoring the load bearing capacity of damaged girders with reduced plate thicknesses due to corrosion.

Keywords: UHPC, Rehabilitation, Corrosion, Girder Ends, Bridge Maintenance

1. Introduction

Ultra-high performance concrete (UHPC) has been cited for its advantages as a repair material in several projects. UHPC has been used to retrofit deteriorated and seismically deficient concrete piers and abutments by encasing them in a thin layer of UHPC (Doiron 2016). This technique was also used to repair corroded steel bent legs for bridge approach spans. It was noted that encasing the corrosion in UHPC would mitigate future corrosion because of the enhanced durability of UHPC. UHPC requires smaller thicknesses and development lengths of dowel bars to achieve the target capacity of the design (Graybeal 2019). An alternative to current expansion joint replacement has been proposed and implemented using a field-cast UHPC link slab to provide a durable seal for expansion joints without attracting significant structural loads (Graybeal 2017). UHPC has been used as an overlay to rehabilitate deteriorated reinforced concrete bridge decks.

Another research project is currently investigating the feasibility of rehabilitating deteriorated reinforced concrete beams with a thin strip of UHPC to restore flexural capacity (Murthy et al. 2018). These are just a few applications demonstrating the advantages of UHPC and the potential to use the material to solve several critical problems with the crumbling bridge infrastructure.
One prevalent issue with steel bridges is corrosion damage of girder ends. Leaking expansion joints expose the steel to water and chlorides from the road above causing a serve amount of section loss. The current repair method replaces the corroded steel with new steel. This is done by either removing the deteriorated region and installing a new section or attaching a new steel section over the damaged region. This conventional repair method requires the bridge to be closed for the duration of the project and is extremely labor intensive, leading to traffic delays and increased project costs.

A proof-of-concept project was completed to develop a new repair method for corroded steel girder ends (Esmaili Zaghi et al. 2015; Zmetra et al. 2017). The proposed repair method was to weld headed steel shear studs to the non-corroded portion of the web and encase the corrosion damage and shear studs with UHPC. The repair was designed to restore the bearing and shear capacity of the girder that was reduced due to simulated corrosion damage. The project determined that the UHPC repair created an alternative load path, which allowed the bearing and shear forces carried by the end of the girder to bypass the damaged region. The repair method not only proved to be structurally effective, but also showed potential to reduce construction durations and improve work-zone safety.

Recently, a series of push-out experiments were conducted to evaluate the strength of headed shear studs welded to a thin web embedded in UHPC for various stud configurations (Kruszewski et al. 2018a; 2018b). The controlling failure mechanism for the push-out tests was shear failure of the headed studs. Minimal damage was observed in the UHPC panels. Prior to failure, the studs experienced significant yielding. When a concentric loading was applied, the layout and spacing of the headed shear studs had minimal effect on the capacity; however, the moment induced on the studs from eccentrically applied loads reduced the shear capacity.

2. Objective and Scope

The University of Connecticut has been working to develop a more economical repair method that for corroded steel girder ends using UHPC. The aim of the proposed repair is to minimize traffic disruptions, lane closures, and surface preparation as well as eliminate the need for jacking of the superstructure. Experimental tests were conducted on four plate girders to assess the full-scale performance of the repair. The objective of the experiments was to demonstrate the practicality of implementing the repair in place of conventional methods. The four plate girders tested included a damaged girder with simulated section loss as a baseline and three damaged girders repaired with UHPC. The repair designs for the three damaged girders varied the UHPC panel geometry and stud configurations. The goal of this study was to provide recommendations for the design and construction of the proposed UHPC repair.

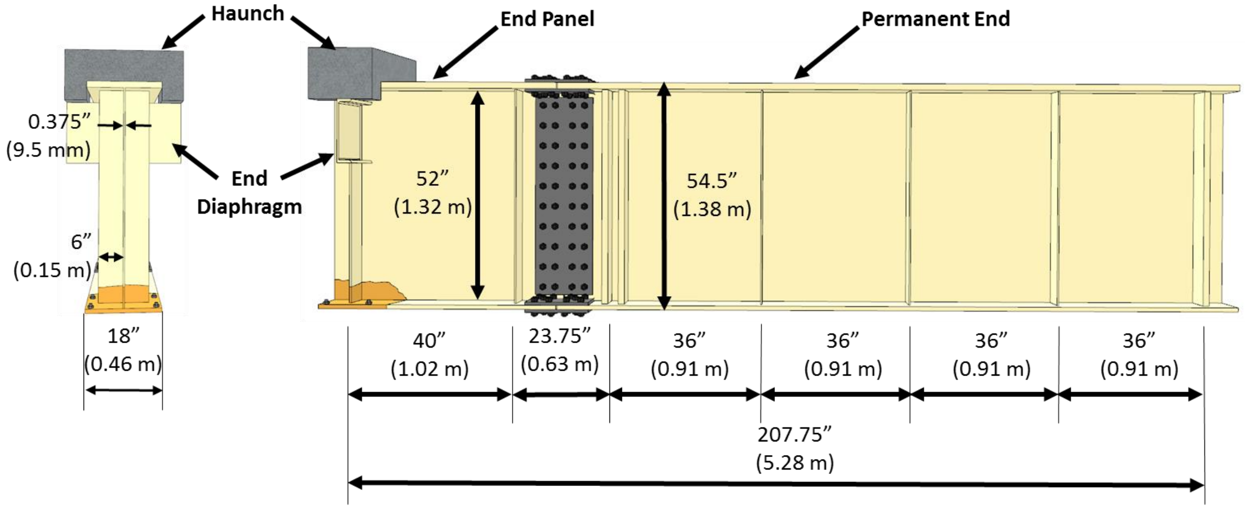
3. Experimental Program

3.1 Research Methodology

A total of four full-scale plate girders were tested in a modified three-point bend test setup. The plate girder design was representative of typical bridges in Connecticut that have exceeded their 50-year design life. The final design of the plate girder is shown in Figure 1. The plate girders were designed with a depth-to-thickness ratio of 144 and a stiffener spacing-to-depth ratio of 0.74, which is common for highway overpass bridges.

Simulated section loss was applied to the web and bearing stiffeners at the girder end of all four plate girders as shown in Figure 2. The target minimum section loss was 66% reduction of the 0.375-in. (9.5-mm) web and 50% reduction of the 0.5-in. (13-mm) bearing stiffeners. The level and pattern of corrosion damage implemented was based on observations from inspection reports of structurally deficient steel bridges in Connecticut.

The three repaired girders were designed to support the as-built bearing and shear capacity of the end panel of the plate girder. The design of each repair varied based on the stud layout and spacing and the UHPC material, strength, and panel geometry. This experimental study will not only test the structural performance of the repair, but will identify best construction practices and evaluate the ability to implement the repair while the bridge is under service loads.



(a) **(b)**

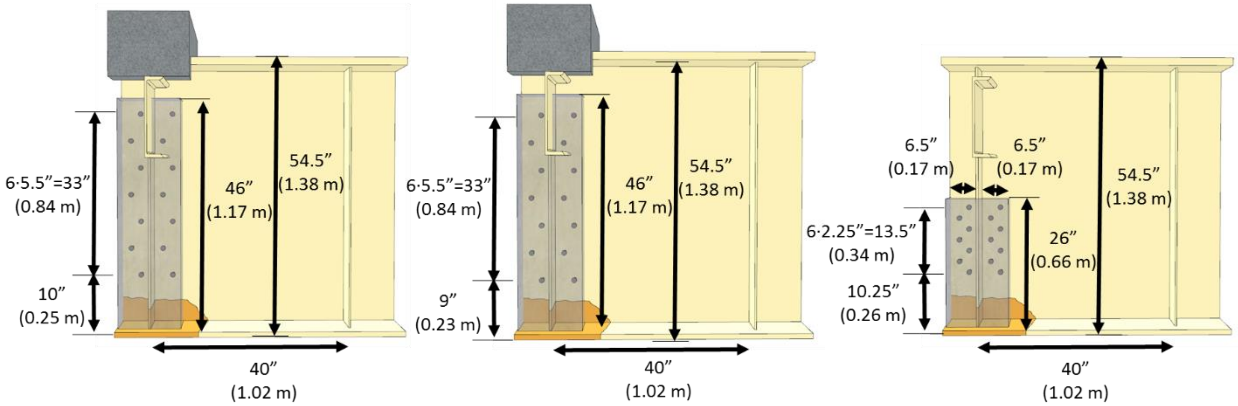
Figure 1: Final plate girder design: a) Cross-section; b) Elevation

Figure 2: Simulated corrosion damage

3.2 Design of the UHPC Repair

A capacity design approach was used to determine the number of headed shear studs for the UHPC repair needed to restore the full bearing and shear capacity of the end panel. The final layout of the shear studs for all three repaired girders is shown in Figure 3. Each repair design included a total of twenty-eight 0.5-in. (13-mm) diameter headed shear studs. Four columns of seven studs were included on either side of the web and bearing stiffeners. The studs were staggered on opposite sides of the web to avoid stress concentrations. Two of the repairs contained a full-height UHPC repair panel. The difference between the stud configurations of the two full-height repairs was that the studs on the Full Height 1 repair were placed 1 in. (25.4 mm) higher than the Full Height 2 repair. The third repair was a half-height repair (Half Height).

The properties of the UHPC material used for each of the three repairs are identified in Table 1. The two commercially available UHPC mixes were used. The primary differences between these UHPC mixes include: 1) the strength gain and 2) the rheological properties. The first mix, UHPC 1, is a slower setting mix, but ultimately reaches a higher compressive strength than the UHPC 2 mix. However, the UHPC 1 mix is more viscous, which may lead to problems with application of the repair for tight girder end geometries. UHPC 2 is a fast setting highly flowable UHPC mix. The two UHPC mixes both included 2% by volume of steel fibers.



(a) (b) (c)

Figure 3: UHPC repair design: a) Full Height 1; b) Full Height 2; c) Half Height

Table 1: UHPC Unconfined Compressive Strength

Experiment	Material	f'_c [ksi (MPa)]
Full Height 1	UHPC 1	29.3 (202)
Full Height 2	UHPC 2	25.3 (174)
Half Height	UHPC 2	23.3 (161)

3.3 Construction of the UHPC Repair

The UHPC repair was implemented under conditions representative of those that would be experienced in the field. The final shear stud configuration of the Full Height 2 and Half Height repairs are shown in Figure 4. The studs were welded to the web of the girder according to standard field welding practices by a certified iron worker.

The formwork used for casting of the UHPC panels is shown in Figure 5. Standard plywood formwork was used for construction of the panels. The formwork could be customized to account for obstructions at the girder end such as end diaphragms or deck haunches. The formwork was attached to the plate girder with epoxy and secured with threaded rods. The threaded rods were passed through holes drilled in the web of the girder to clamp the formwork on either side of the web. The formwork was designed to be water tight because of the rheological properties of the UHPC material. Gaps in the formwork were filled with construction caulk.

The total volume of a single repair panel was limited to less than 5 ft^3 (0.142 m^3) to allow for the use of a portable high-shear mixer. The top of the formwork was left open to allow for the UHPC to be cast from above. The rheological properties of the UHPC allowed for the material to easily flow into the formwork and encase the end geometry even with complexities such as the end diaphragm and deck haunch.

During casting of the Full Height 2 repaired girder, service-level vibrations were applied to the girder to evaluate implementing the repair while the bridge is under traffic. No adverse effects were observed during casting or after concrete curing due to the vibrations applied to the girder.

Figure 4: Final shear stud configuration: a) Full Height 2; b) Half Height

Figure 5: Formwork for UHPC panel: a) Full Height 2; b) Half Height

3.4 Experimental Test Setup

The overall experimental test setup is shown in Figure 6. The plate girders were tested over a 208-in. (5.28-mm) span. A point load was applied at approximately 3/10 of the span closest to the damaged end panel. The girder was mounted on two polyurethane disc sliding bearings to allow for rotational and translational movement of the girder during testing. Chains were attached to the top flange of the girder to provide lateral stability due to the absence of a composite concrete deck. A force controlled, increasing cyclical loading was applied to the girder while the specimens remain elastic. After plastic behavior was observed, displacement-based loading cycles were applied to analyze the post-failure performance of the girders. Instrumentation was used to monitor forces, strains, and deformations during testing.

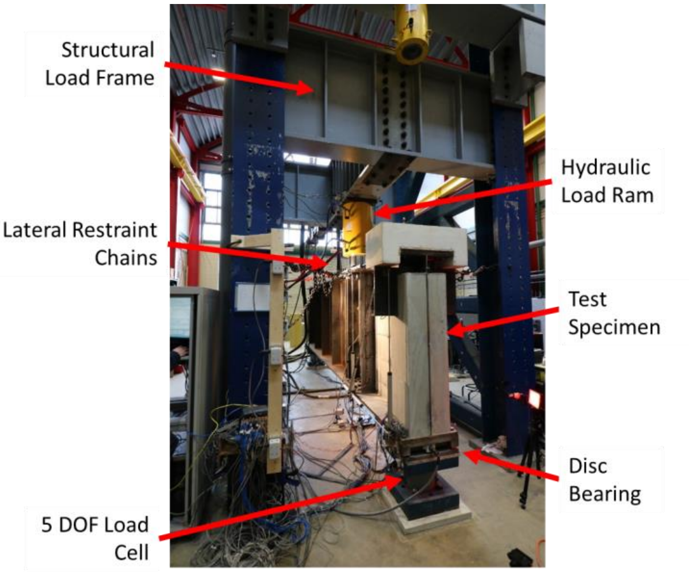


Figure 6: Experimental test setup

4. Experimental Results

The results of the destructive experimental tests were analyzed to evaluate the global performance of the UHPC repair as well as the performance of critical repair elements such as the UHPC and shear studs. The following results sections are divided into two parts. The first section details the overall performance of the plate girders including the stiffness of the system and failure mode. The second section discusses the local effects of the repair on the global performance of the plate girder.

4.1 Overall Performance

The bearing force versus mid-span displacement response for the four experimental plate girder tests is shown in Figure 7. The baseline damaged girder failed due to localized buckling of the damaged region of the web and stiffener. The simulated section loss introduced to the girder significantly reduced the bearing capacity of the specimen. No damage was found outside of the corroded region of the girder end. This localized buckling failure is consistent with observations in the field when girders experience severe corrosion damage.

Typically, the design failure mode for stiffened web plate girders is shear buckling of the end panel. The web of the end panel fails with a half sine wave buckled shape. The failure modes of the Full Height 2 and Half Height repaired girders are shown in Figure 8. All three repaired girders failed due to shear buckling of the end panel. The Half Height repaired girder failed with a half sine wave buckled shape similar to the design failure mode. However, the two full-height girders had a full sine wave buckled shape. This was caused by the additional bracing provided by the full-height UHPC panel on the web of the girder. The UHPC panel stiffened the end panel, which increased the buckling capacity and forced the failure mode to shift to second mode buckling. The capacities of the Full Height 1 and Full Height 2 repaired girders were approximately 12% and 5% larger than the Half Height repaired girder, respectively.

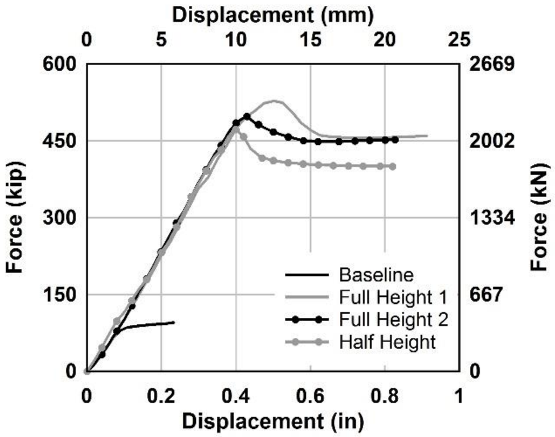
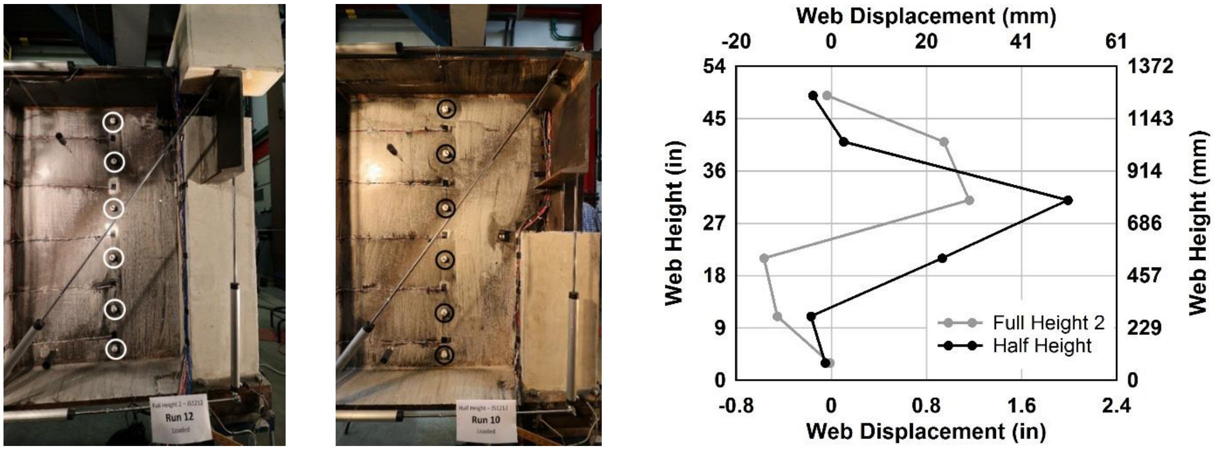


Figure 7: Bearing force vs. mid-span displacement



(a) (b) (c)

Figure 8: Plate girder failure modes: a) Full Height 2; b) Half Height; c) Web height vs. web displacement

4.2 Local Behavior

The ability of the repair to prevent failure from occurring in the damaged region indicates that the repair may provide an alternative load path for bearing and shear forces to bypass the reduced section. The bracing provided by the UHPC panel also prevented the damaged region from experiencing localized buckling in the reduced section.

Axial strain gauges were imbedded in seven shear studs within one of the columns of studs to analyze the force transfer from the web of the girder through the studs. The bearing force vs. axial stud strain relationships for the top and bottom studs for all three repaired girders are shown in Figure 9. The results showed that the studs at the bottom of the repair were activated first. As the demand on the repair increased, the forces in the studs redistributed and the studs at the top of the repair were activated. For both the Full Height 1 and Full Height 2 repairs, the studs at the top of the repair experienced significant yielding. However, the studs in the Half Height repair experienced minimal yielding with negligible permanent deformation.

The relationship between the force per stud and the slip between the web and UHPC panel was analyzed to investigate the demand on the shear studs for each of the repairs. Kruszewski et al. (2018a) determined that shear failure of the studs occurred at panel slips between 0.157-0.197 in. (4-5 mm). The force versus slip relationship for all three repaired girders is shown in Figure 10. The Full Height 1 and Full Height 2 repaired girders experienced maximum panel slips of 0.116 in. (2.94 mm) and 0.127 in. (3.22 mm), respectively, which corresponded to approximately 70-80% of the maximum slip capacity of the studs. Conversely, the Half Height repaired girder experienced a maximum panel slip of 0.021 in. (0.53 mm), which corresponded to 13% of the maximum slip capacity of the studs. This indicates that significantly less demand was placed on the half-height repaired girder compared to the full-height repairs.

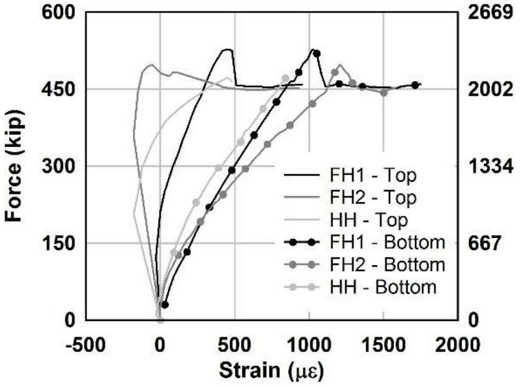


Figure 9: Bearing force vs. axial stud strain

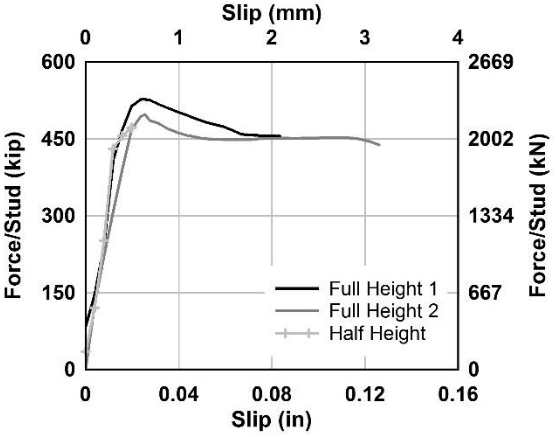


Figure 10: Bearing force vs. UHPC panel slip

5. Summary and Conclusions

The study presented evaluated the full-scale performance of a new repair method for corroded steel girder ends using UHPC. A series of four full-scale experimental three-point bend tests were conducted on plate girders with severe section loss. Three different repair designs were tested on damaged girders. The goal of the study was to demonstrate the constructability and structural performance of the repair for field implementation.

The results of this study highlight the advantages of the proposed UHPC repair method over traditional repair methods. The repair provides engineers with flexibility when designing the height of the UHPC panel and the layout of the headed shear studs. Because of the unique properties of UHPC, the design of the repair may be customized for girder ends with complex geometries and tight spacings. These advantages are critical to be able to adopt different designs for a wide variety of bridge configurations.

Through implementation of the repair, it was observed that simple, conventional construction practices may be used when constructing the repair in the field. The headed shear studs may be easily welded to the non-corroded portions of the web of the girder. The UHPC panels may be formed using conventional wood formwork, which may be adjusted for complex designs. The results of the simulated service-level vibrations during testing indicated that the repair may be implemented in-situ, preventing extended closures and traffic disruptions.

The experimental results showed that all three repair designs effectively restored the bearing and shear capacity of the plate girder lost due to corrosion damage. The full-height UHPC repairs provided additional bracing to the damaged end panel increasing the overall capacity of the plate girder. The half-height UHPC repair provided less bracing and experienced a smaller overall capacity compared to the full-height repairs. However, the half-height repair had smaller UHPC panel slips compared to the full-height repairs indicating that there was less demand on the shear studs. Therefore, a half-height repair may be a more efficient design in-terms of both ease of construction and structural performance. In summary, the proposed UHPC repair method may be considered as a cost-effective alternative repair of corrosion damaged steel girder ends.

6. References

Doiron, G. (2016). "Pier Repair/Retrofit Using UHPC: Examples of Completed Projects in North America." *First International Interactive Symposium on UHPC*, July 18-20, 2016, Des Moines, Iowa.

Esmaili Zaghi, A., Wille, K., Zmetra, K., and McMullen, K. (2015). "Repair of Steel Beam/Girder Ends with Ultra High Strength Concrete." Connecticut Department of Transportation. University of Connecticut. SPR-2282. Phase I(Report #CT-2282-F-15-2).

Graybeal, B. (2019). "Design and Construction of Field-Cast UHPC Connections." FHWA-HRT-19-011.

Graybeal, B. A. (2017). "Emerging UHPC-based bridge construction and preservation solutions." *International Symposium on Ultra-High Performance Fibre-Reinforced Concrete.*, October 2-4, 2017, Montpellier, France.

Kruszewski, D., Wille, K., and Zaghi, A. E. (2018a). "Push-out behavior of headed shear studs welded on thin plates and embedded in UHPC." *Engineering Structures*, 173, 429-441.

Kruszewski, D., Wille, K., and Zaghi, A. E. (2018b). "Design considerations for headed shear studs embedded in ultra-high performance concrete as part of a novel bridge repair method." *Journal of Constructional Steel Research*, 149, 180-194.

Murthy, A. R., Karihaloo, B., and Priya, D. S. (2018). "Flexural behavior of RC beams retrofitted with ultra-high strength concrete." *Construction and Building Materials*, 175, 815-824.

Zmetra, K. M., McMullen, K. F., Zaghi, A. E., and Wille, K. (2017). "Experimental Study of UHPC Repair for Corrosion-Damaged Steel Girder Ends." *Journal of Bridge Engineering*, 22(8), 04017037.

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