Experimental Testing for Partial Height UHPC Beam End Encasement on Weathering Steel Bridges in Connecticut

Brian Lassy Jr (Corresponding Author) – PhD Student, University of Connecticut, Department of Civil and Environmental Engineering, Storrs, CT, USA, Email: Brian.Lassy@uconn.edu

Alexandra Hain, PhD, PE – Assistant Professor, University of Connecticut, Department of Civil and Environmental Engineering, Storrs, CT, USA, Email: Alexandra.Hain@uconn.edu

Arash E. Zaghi, PhD, PE, SE – Professor, University of Connecticut, Department of Civil and Environmental Engineering, Storrs, CT, USA, Email: Arash.Esmaili_Zaghi@uconn.edu

Abstract

The use of Ultra-High Performance Concrete (UHPC) beam end encasement has proven to be a viable, cost-effective, and efficient method for rehabilitating corroded steel bridge girders compared to traditional repair techniques. This method, developed jointly by the University of Connecticut and the Connecticut Department of Transportation (CTDOT), has been extensively researched over the past decade. The repair works by welding headed shear studs to intact portions of the web and encasing the beam end in UHPC, creating an alternate load path for bearing and shear forces. Recently, CTDOT has completed two repair implementations using this method, a full-height and partial-height repair, as part of the third phase of research. For the partial height repair application, additional experiments were conducted to evaluate design components that varied from previous research and implementations. This includes the application of the repair on weathering steel, the use of flange studs in addition to web studs, and the reduction of the repair panel from the full depth of the girder to partial height. The results of these experiments confirmed the viability of the design and enabled the successful implementation of the second repair.

Keywords: UHPC, Bridges, Preservation, Rehabilitation, UHPC Encasement, Shear Studs

1. Introduction

Rehabilitation of structurally deficient bridge elements is a cost-effective approach to increasing the service life of bridges compared to full replacement (ASCE). The University of Connecticut (UConn) and the Connecticut Department of Transportation (CTDOT) developed a novel repair method to address the repair of structurally deficient steel girder ends (Zaghi et al.). This repair method increases the shear and bearing capacity of corroded girder ends by welding headed shear studs to intact portions of the beam and encasing them in ultra-high performance concrete (UHPC) to create an alternate load path that bypasses the corroded region (Kruszewski et al. "Design Considerations," Kruszewski et al. "Finite Element Study," Kruszewski et al. "Push-out Behavior," McMullen and Zaghi). To date, this method has been successfully implemented by CTDOT on two bridges in Connecticut, each with unique design aspects (Hain and Zaghi, "Field Implementations," Hain and Zaghi, "Learnings from Field Implementations," Hain et al.). The first implementation, completed in 2019 in New Haven, CT, was a full-height repair with the UHPC

Publication Type: Full Paper
Paper No: 95

encasement spanning the entire depth of the beam end. This successful repair led to the implementation in East Hartford, CT, in 2021 of a partial height repair on a weathering steel bridge (CTDOT, "ITEM #0601060A"). The partial height repair was selected due to the concentration of corrosion at the interface of the web and bottom flange of the girders.

The partial height repair had two main variations from previous implementations that required lab testing and validation: (1) the applicability of the repair on weathering steel, and (2) the design and performance of studs welded to the bottom flange for the transfer of shear loads. Weathering steel is one of the most common bridge steels (Nickerson) and required additional investigation for applicability before implementation due to the unique surface conditions (Morcillo). The requirement for flange studs came from the high concentration of corrosion (~27%) at the interface between the web and bottom flange. Flange studs could effectively be added to bridge the deterioration and restore shear transfer between the web and bottom flange that had been effectively lost due to corrosion. The final implementation (Figure 1) incorporated this design as a partial height repair, minimizing material cost and improving constructability.

Figure 1. Completed beam end repair in East Hartford, CT.

2. Design and Fabrication

Two types of specimens were designed to validate the design: weathering steel push-off tests (Push-Off Specimen) and 45-degree modified push-off tests (Tilted Specimen). The weathering steel push off tests were fabricated to replicate previous research done by UConn to establish the capacity of headed shear studs welded on thin webs encased in UHPC (Kruszewski, “Push-out Behavior”). The goal was to ensure the stud capacity equations proposed by the UConn team (CTDOT, “Guidelines”) used for mild steel beams were applicable for weathering steel and to determine any modifications required for welding. The tilted specimens were a novel experiment designed to validate both a partial height repair as well as flange studs being used to transfer shear forces. The studs used for all experiments were 5/8 in (15.9 mm) in diameter and 3 in (76 mm) in length.

2.1 Weathering Steel Push-Off Specimens

Specimens were cast using the same surface preparation and instrumentation, but two different proprietary UHPC mixtures. Overall, the compressive performance of the two mixtures deviated, with the first set achieving 23.3 ksi (160.6 MPa) and the second set achieving 18.7 ksi (128.9 MPa). The capacity of the weathering steel push-off specimens was calculated based on the ultimate shear capacity of the shear studs. Based on previous research by Kruszewski ("Design Considerations"), the dimensions of the UHPC were considered adequate to develop the full shear capacity of the studs.

Naming for the push-off specimens began with a single letter designation for the UHPC: S and D. In addition to the UHPC mixes, multiple stud spacings were investigated, 3db and 4db, which indicate that the center to center spacing was three diameters and four diameters of the stud, respectively. Finally, the configurations were defined by the layout of the studs on the web, column by row: 4x1, 2x1, 2x2. The different layouts are shown in Figure 2 along with a representative view of the specimens before and after casting.

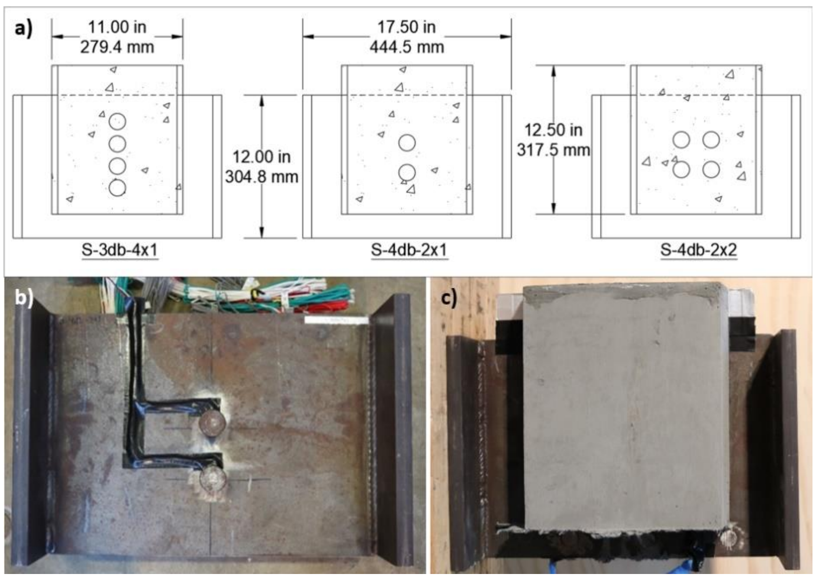

Figure 2. a) CAD model of the three specimen configurations investigated, b) fabricated specimen with strain gauges prior to casting, and c) completed specimen with UHPC panel.

2.2 45-Degree Modified Push-Off Specimen

Several important parameters were incorporated into the design of the tilted specimen: a 0.25 in (6.4 mm) gap between the web and bottom flange, separation between the top of the UHPC block and the top flange to simulate a partial height block, and a 45-degree angle of loading to simulate both bearing and shear loading on the beam. Using a test specimen design that had a complete separation between the web and bottom flange simulated 100% section loss. The 45-degree angle on a specimen was used to simulate both the bearing forces and shear force between the web and bottom flange found on bridge girders. With these considerations, the force demand on each flange stud was calculated by multiplying the force by the cosine of the angle of tilt, or 45-degrees. This design, however, does not consider the effects of friction between the UHPC and the flange.

Three stud configurations were designed for different failure scenarios. First, a control specimen was designed with four studs on each side of the bottom flange, and four studs on each side of the top section's web. Second, a web-stud controlled specimen was designed with three studs on each side of the web, and four studs on each side of the flange. Based on the stud capacity equations used, the flange stud group was intended to have a much higher capacity than the web stud group. Third, a flange-stud controlled specimen was designed with four web studs on each side and two flange studs on each side. This was intended to force failure of the flange studs and show the capacity of the flange studs in a partial height repair.

Fabrication was completed in multiple steps. First, each specimen began as a modified W21x83 beam section, with a portion of the web cut out to reduce the depth of the beam to 16 in (406 mm) with a 0.25 in (6.4 mm) gap between the web sections (Figure 4a). Following modification, the required number of studs were attached with a stud welding gun. Afterwards, the specimens were instrumented with strain gauges. Finally, formwork was built and sealed, and UHPC poured around the specimens. After casting, additional support plates were added for stability during testing. The tilted specimens naming convention references the layout of the web and flange studs. The first component was the layout of the studs on the web, column by row; and the second part was the layout of the studs on the flange, column by row. The resulting specimen names were 4x1_4x1, 3x1_4x1, and 4x1_2x. The different layouts are shown in Figure 3 along with a representative view of the specimens before and after casting.

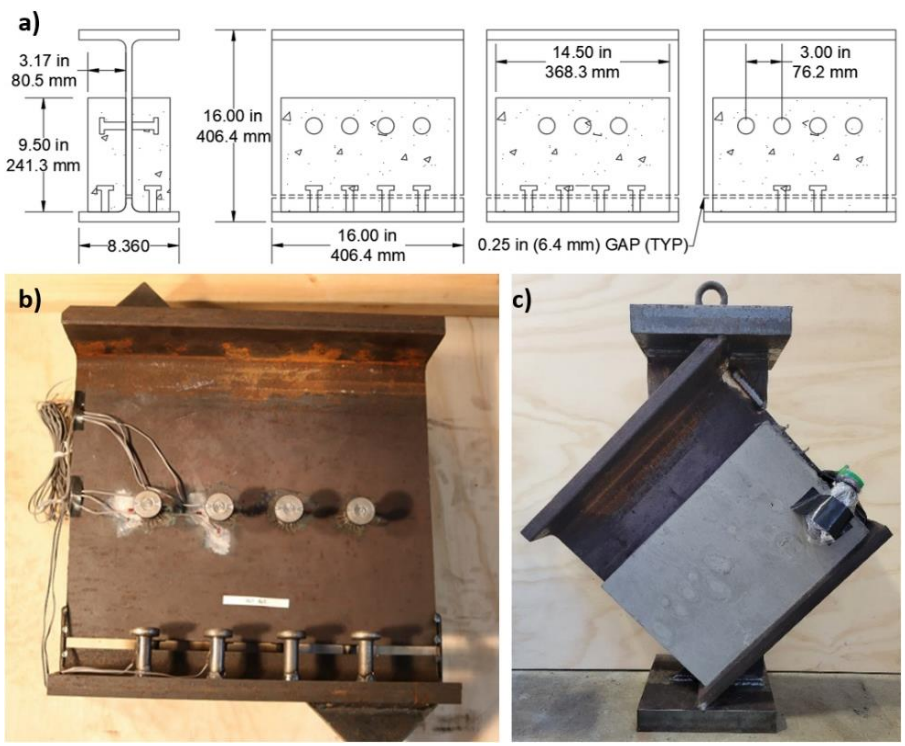

Figure 3. a) CAD model of the three specimen configurations investigated, b) fabricated specimen with strain gauges prior to casting, and c) completed specimen with UHPC panel and support plates.

2.4 Instrumentation and Loading Protocol

Prior to casting the specimens were instrumented with strain gauges on the web and select studs on both the web and flange studs. Prior to testing, each specimen was setup in the load frame with external sensors applied to capture overall displacement as well as panel slip. A laser level was used to ensure that the load was applied to the specimens with no eccentricity. Testing was completed in the load frame of the UConn structures lab. The load frame was fitted with a 500-kip

(2224 kN) hydraulic cylinder. A view of the instrumentation for the different specimens is shown below in Figure 4.

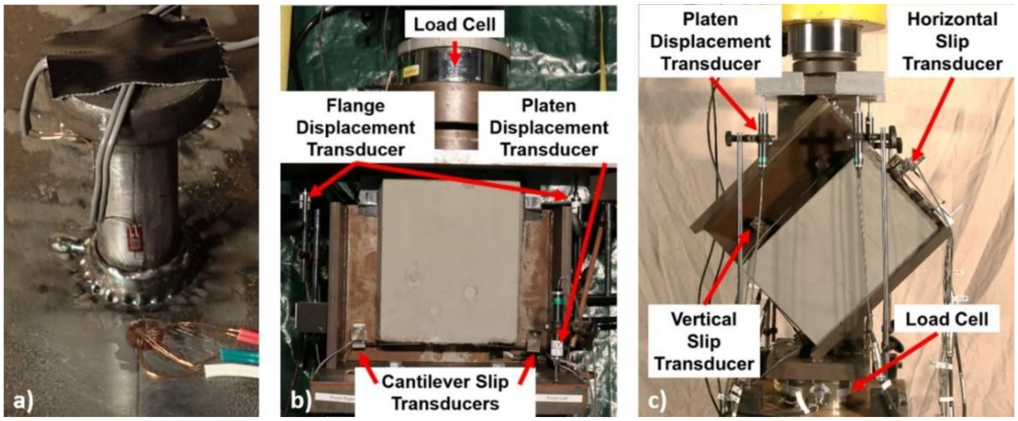

Figure 4. a) Typical strain gauging for one stud, b) external sensors and final setup for a push-off specimen, and c) external sensors and final setup for a tilted specimen.

A cyclic testing protocol was implemented on both sets of specimens. First, three cycles of force-controlled loading were applied up to 60% of the calculated capacity of the web studs for the specimens. Next, a displacement-controlled loading regimen was applied until failure, calibrated to occur at the 10^{th} cycle. Failure was defined as a significant load drop prior to a displacement cycle's target being reached. A significant load drop is defined as the ultimate resistance of one stud in single shear, approximately 25 kips (111 kN). Testing was completed in approximately three hours per specimen for both the push-off and tilted specimen tests.

3. Results

3.1. Weathering Steel Push-Off Specimens

Testing of the weathering steel push-off tests provided results that agreed with Kruszewski ("Design Considerations"). Failure occurred above the force anticipated using the design calculations (CTDOT, "Guidelines"). In most tests, failure occurred as the result of at least one stud failing, which was verified by the magnitude of the force drop. Figure 5a shows an example of a load-slip curve for the S-4db-2x1 specimen. The first four cycles nearly overlapped, as the stress remains in the elastic zone of the studs and UHPC. From this cyclic curve, a backbone curve was generated using the peaks of each cycle as individual data points. Each backbone was then normalized by the number of studs on the specimens for comparison in Figure 5b. For example, the S-4db-2x1 specimen had two studs on each side of the web, so the total force was divided by four. The S-3db-4x1_1 specimen had four studs on each side of the web, so the total force was divided by eight. A summary of the backbone curves for all six weathering steel push-off specimens is shown in Figure 5b. It should be noted that two specimens, S-3db-4x1_2 and D-3db-4x1 both exhibited failing load drops at 0.04 in (1.0 mm) due to UHPC panel splitting at cycles five and six, respectively. Additionally, a summary curve from previous push-off tests using A373-58T steel (Kruszewski, "Push-out Behavior") is shown for reference.

Publication Type: Full Paper
Paper No: 95

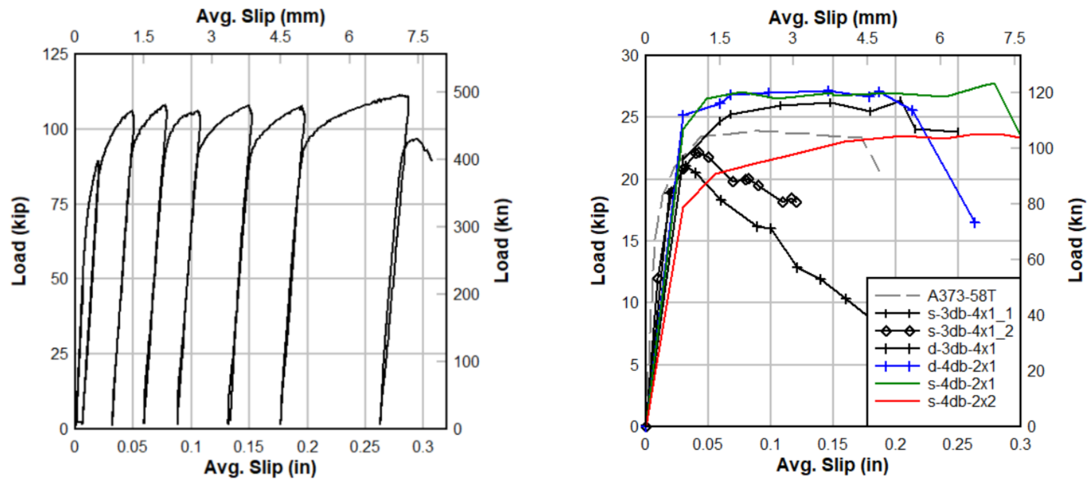

Figure 5. a) Load slip graph from specimen s-4db-2x1, and b) overall backbone curves for all specimens.

3.2. Tilted Specimens

The web studs in the tilted specimens behaved similar to the push-off specimens. The cyclic loading in the force-controlled range overlapped up to the fourth cycle, then began to deform once displacement control began. Cracking in the UHPC block was noted around cycle seven for specimen D-3x1_4x1, cycle five for D-4x1_2x1, and cycle six for specimen D-4x1_4x1. These equated to between 0.08 - 0.12 in (2.0 - 3.0 mm) of displacement. It is noticeable in the example curve for D-4x1_4x1 that cycle six is where the load peaks. As the cracks in the UHPC propagate, a decrease in capacity corresponds with higher displacements. However, as can be seen in Figure 6b that each specimen continued to sustain load until approximately 0.2 in (5.1 mm).

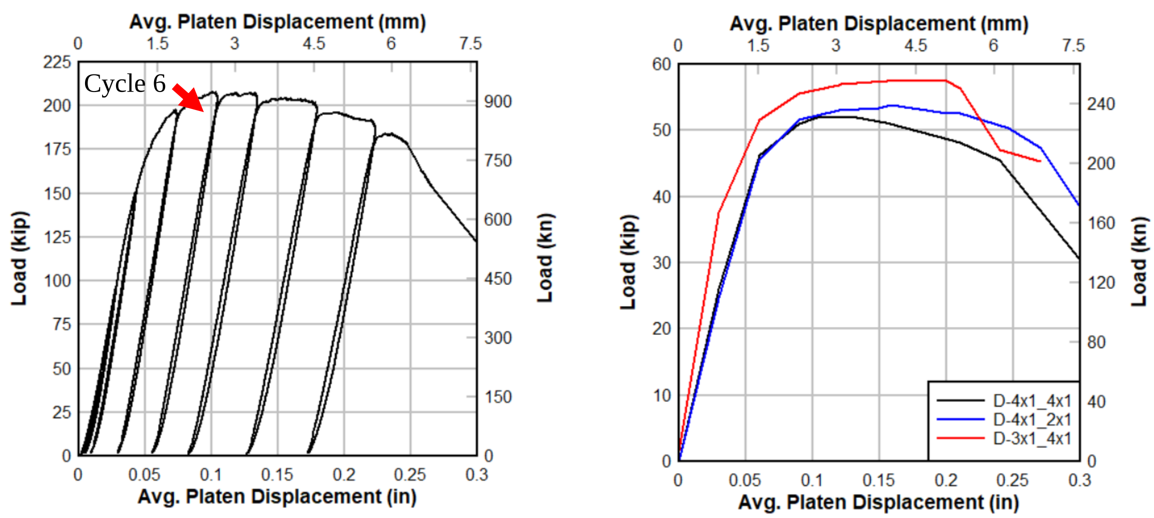

Figure 6. a) Load displacement curve for specimen D-4x1_4x1, and b) backbone curves for all three specimens.

4. Discussion

4.1. Weathering Steel Push Off

The weathering steel push off tests provided insight into the viability of the repair on weathering steel. It was noted that proper surface preparation is integral to the attachment of shear studs to

Publication Type: Full Paper
Paper No: 95

weathering steel. The results did not significantly deviate from prior research into shear studs encased in UHPC and helped to widen the literature on its applicability. The push-off tests provided one significant insight not previously discovered: minimum stud spacing may need to be increased from previously noted acceptable distances. It was noted that each of the 3db spaced specimens had UHPC panel cracking, and most of them had a failure that was controlled by the UHPC panel as opposed to clear stud yielding. Specifically, the D-3db-4x1 and the S-3db-4x1_2 both experiencing significant load drops before reaching a desirable level of displacement. As the studs have a larger plastic deformation zone, there should be significant displacement (up to 0.25 in [6.4 mm]) before total failure. When the UHPC fails before the studs, a lower displacement is observed.

Although further research may be needed to confirm this, one deviation from historical push-off tests by Kruszewski ("Push-out Behavior") could be the material quality. Immediately following the failure of the specimens, it was hypothesized that UHPC failure occurred due to a combination of higher-than-expected stud strength and lower than expected UHPC strength. This was corroborated by conventional material tests on both. The ultimate tensile strength of the studs from testing was 83 ksi (572 MPa), approximately 28% higher than their specified strength. For the in-field implementation, wider spacing and greater UHPC cover was specified to ensure these issues did not occur.

4.2 Tilted Specimens

Although each specimen was designed for a different failure mode, the same outcome was observed for each test. Elastic behavior until yielding began, at which point sustained plastic yielding occurred. At approximately half the total displacement, UHPC cracking occurred. This led to a gradual decrease in bearing load for the specimen until failure, when there was a large drop in resistance.

Overall, the experiment led to strong confidence in the ability of the flange studs to withstand shear forces. Although a failure point was not found, 50% of the entire load was supported by the flange studs, in combination with friction effects. Especially for the specimen with a 2-1 web stud to flange stud ratio, this showed that the flange studs could carry a much higher load than predicted in design. Further investigation will be required to determine the required number of flange studs more efficiently for field rehabilitation, but the current design equations can be considered conservative based on these experiments. Analysis of the tilted specimens is being expanded with finite element analysis to draw further conclusions.

5. Conclusion

Overall, the novel beam end repair method developed by the joint effort of UConn and CTDOT has been successfully implemented in two bridges in Connecticut. The results of the lab testing conducted on the weathering steel push-off and tilted specimens have provided valuable insight into the applicability of the method on weathering steel and the capacity of flange studs in a partial height repair. The design equations for flange studs were shown to be conservative in design, and can be applied in future projects without concern. Additionally, findings from the push-off tests have suggested that a more conservative approach to stud spacing is beneficial, but more detailed research is required to fully correlate spacing requirements to the actual UHPC strength. These results provide confidence in the use of this novel method for the rehabilitation of structurally deficient bridge elements and will likely lead to further applications in the future.

6. References

- ASCE. 2021, *2021 Infrastructure Report Card*, https://infrastructurereportcard.org/wp-content/uploads/2020/12/Bridges-2021.pdf. Accessed 2023.
- CTDOT. "Guidelines for the Utilization of Ultra-High Performance Concrete in the Rehabilitation of Steel Bridge Girder Ends." Connecticut Department of Transportation, 2022.
- CTDOT. "ITEM #0601060A - Beam End Repairs with Ultra High Performance Concrete - Partial Height." Connecticut Department of Transportation, 2022.
- Hain, Alexandra, and Arash E. Zaghi. "Field Implementations of a Novel UHPC Beam End Repair on Steel Girder Bridges in Connecticut, USA." *Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability*, 2022, pp. 2560–2567., https://doi.org/10.1201/9781003322641-320.
- Hain, Alexandra, and Arash E. Zaghi. "Learnings from the Field Implementation of a Novel Ultra-High Performance Concrete Beam End Repair on a Corroded Steel Girder Bridge in Connecticut." *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2675, no. 9, 2021, pp. 703–714., https://doi.org/10.1177/03611981211004128.
- Hain, Alexandra, et al. "Implementation of UHPC for the Repair of a Steel Bridge with Corrosion Damage in CT." Iowa State University Digital Press, *International Interactive Symposium on Ultra-High Performance Concrete*, vol. 2, 2019, Accessed 2022.
- Kruszewski, Dominic, et al. "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*, vol. 149, 2018, pp. 180–194., https://doi.org/10.1016/j.jcsr.2018.07.015.
- Kruszewski, Dominic, et al. "Finite Element Study of Headed Shear Studs Embedded in Ultra-High Performance Concrete." *Engineering Structures*, vol. 188, 2019, pp. 538–552., https://doi.org/10.1016/j.engstruct.2019.03.035.
- Kruszewski, Dominic, et al. "Push-out Behavior of Headed Shear Studs Welded on Thin Plates and Embedded in UHPC." *Engineering Structures*, vol. 173, 2018, pp. 429–441., https://doi.org/10.1016/j.engstruct.2018.07.013.
- McMullen, Kevin F., and Arash E. Zaghi. "Evaluation of UHPC as a Repair Material for Corroded Steel Bridge Girders." Iowa State University Digital Press, *International Interactive Symposium on Ultra-High Performance Concrete*, vol. 2, 2019.
- Morcillo, M., et al. "Weathering Steels: From Empirical Development to Scientific Design. A Review." *Corrosion Science*, vol. 83, 2014, pp. 6–31., https://doi.org/10.1016/j.corsci.2014.03.006.
- Nickerson, Robert. American Iron and Steel Institute, Pittsburgh, PA, 1995, *Performance of Weathering Steel in Highway Bridges*.
- Zaghi, Arash E., et al. Connecticut Department of Transportation, Storrs, CT, 2015, *Repair of Steel Beam/Girder Ends with Ultra High Strength Concrete (Phase I): Final Report*.