# Effect of Steel Reinforcement Type and Diameter on the Strength of Non-Contact Lap Splice Connections using UHPC

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**Abstract:** Accelerated bridge construction (ABC) reduces construction time and lane closures. As such, these projects are effective for construction and rehabilitation of bridges in areas of high traffic or limited access. Ultra-high performance concrete (UHPC) has increased the ability of designers and contractors to effectively and efficiently complete ABC projects. UHPC provides many advantages for ABC connections due to its high compressive and tensile strength, durability characteristics, and rheological properties. In recent years, the Federal Highway Administration has been conducting research on non-contact lap splice connections for prefabricated bridge elements using UHPC. The research presented in this paper focuses on one aspect of that research: bond between steel rebar and UHPC. The overarching goal of this research was to develop design guidance for UHPC-rebar lap splices. Experimental testing was conducted to quantify the influence of concrete cover, bar type, bar yield strength, and bar diameter on the UHPC-rebar bond strength. Sixty-seven direct tension pull-out tests were conducted to supplement data from previous research. Newly conducted pull-out tests focused on larger bar diameters, and included #8 (No. 25) and #11 (No. 36) bars. The results showed that larger diameter bars and epoxy coated bars have lower capacities than uncoated bars, smaller diameter bars.

**Keywords:** UHPC, Accelerated Bridge Construction, Connections, Design Criteria, Bond Strength

## 1. Introduction

Accelerated bridge construction practices are becoming more popular for improving construction efficiency in terms of traffic interruptions, overall project costs, and construction safety. The use of prefabricated bridge elements (PBE) is one practice which is widely used. PBEs provide advantages for engineers and contractors because they can be constructed off-site and quickly assembled in the field. The assembly of PBEs requires structural connections between elements to ensure adequate force transfer throughout the structural system. These connections are the critical links which govern the overall structural performance. Typically, PBEs are grouted together with a network of deformed steel reinforcing bars or mechanical connectors. However, lap splices with deformed reinforcing bars and normal strength concrete require relatively wide connections with congested reinforcement details to meet the force demands on the connection.

Ultra-high performance concrete (UHPC) has been proven to be an effective alternative to conventional cementitious closure pour materials for PBE connections. UHPC-class materials are characteristically self-consolidating and extremely durable with a high early strength and tensile ductility. UHPC has been shown to have strong bond between both precast concrete and deformed steel reinforcing bars (Haber and Graybeal 2018; 2018; Yaun and Graybeal 2014). These advantages can greatly reduce the size and complexity of field-cast UHPC connection details compared with conventional detailing, which can greatly simplify the structural design and fabrication of these critical connections.

## 2. Objective and Scope

The Structural Concrete Research Group at the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) have conducted numerous studies on non-contact lap splice connections for PBEs using UHPC. The experimental testing presented in this paper was conducted to supplement the existing TFHRC data. Sixty-seven direct tension pull-out tests were conducted. The focus of the research was the performance of larger diameter bars, including #8 (No. 25) and #11 (No. 36) bars, embedded in UHPC. Other variables studied included concrete clear cover, bar type (epoxy coated vs. uncoated), and bar yield strength. The behavior of pull-out specimens was analyzed and compared based on maximum bar stress and bond slip at failure.

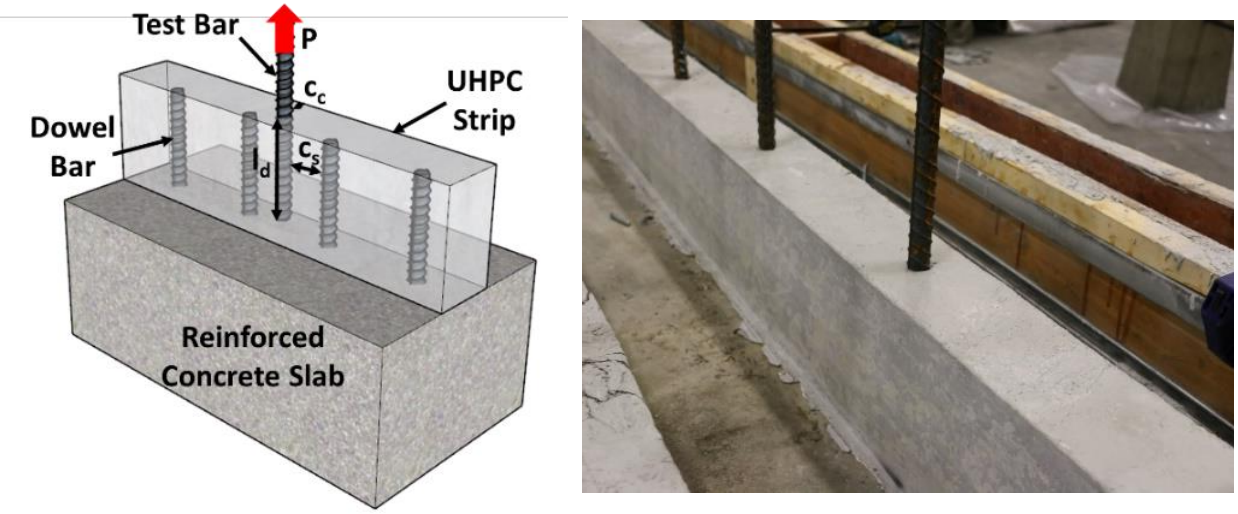
## 3. Previous Research

Approximately five hundred direct tension pull-out tests have been performed by FHWA-TFHRC to determine the effect of embedment length, concrete cover, bar spacing, concrete strength, bar type, and bar yield strength on bond strength (Haber et al. 2018; Yuan and Graybeal 2015). This research was used to develop design recommendations for embedment and lap splice length in field-cast UHPC connections; this guidance was originally published in 2014, and has been recently updated (Graybeal 2014; 2019). Recommendations are provided for side cover, bar spacing, and minimum compressive strength for lap splice connections using #4 (No. 13) to #8 (No. 25) bars in UHPC; however, much of the research used to develop the guidance was conducted on #4 (No. 13), #5 (No. 16) and #7 (No. 22) bars. Additional research on bond of reinforcing steel to UHPC has been conducted by Saleem et al.(2012), Lagier et al.(2015), Alkaysi and El-Tawil (2016), Ronanki et al. (2016), and Zhou and Qiao (2018). These studies have combined to study various embedment lengths, bar sizes, side covers, effect of epoxy coating, and structural performance of connections.

## 4. Experimental Program

### *4.1 Research Methodology*

A total of sixty-seven direct tension pull-out tests were conducted on steel reinforcing bars embedded in UHPC. Tests were conducted on ASTM A615 Gr. 60 and/or ASTM A1035 Gr. 120 #5 (No. 16), #8 (No. 25), and #11 (No. 36) bars; the Gr. 60 bars were tested with and without epoxy coatings (ASTM 2016a; 2016b). Tests were conducted with same pull-out test configuration used by Yuan and Graybeal (2015); this test is shown in Figure 1. For the study presented herein, the embedment length ($l_e$), clear cover ($c_c$), and clear spacing ($c_s$) between reinforcement were varied. The embedment length, $\mathrm{l_d}$, ranged from a minimum of $4d_b$ to a maximum of $8d_b$, where $d_b$ is the diameter of the test bar. The clear cover, $c_c$, ranged from approximately $1d_b$ (minimal cover) to $2d_b$. Many of the tests conducted by Yuan and Graybeal (2015) and Haber and Graybeal (2018) used $2d_b$ clear cover. Furthermore, the original FHWA design guidance used $2d_b$ as the minimum cover allowed (Graybeal 2014). The clear spacing, $c_s$, of the reinforcement varied from $3d_b$ to approximately $8d_b$. One UHPC formulation was used for all of the tests conducted, which is discussed in the following section.



a) Schematic of Test Parameters b) Photo of UHPC Test Strip

**Figure 1. Direct Tension Pull-out Test used by Yuan and Graybeal (2015)**

### *4.2 Materials*

The UHPC used in this research was a proprietary formulation commercially available on the U.S. market. The UHPC had a pre-bagged powder mixture that contained all solids except for steel micro-fiber reinforcement. The mix design included three liquid chemical admixtures: a superplasticizer, a high-range water reducer, and an accelerator. The steel micro-fiber reinforcement had a nominal length of 0.5 inches (13 mm), a nominal diameter of 0.008 inches (0.2 mm), and a nominal tensile strength of 399 ksi (3,750 MPa). The steel fiber content was 2% by volume. The mix proportions for this UHPC are listed in Table 1.

UHPC was mixed according to manufacture recommendations. After placement, UHPC cured under laboratory conditions for approximately 24 ± 1 hours prior to pull-out testing. The UHPC was required to have a minimum compressive strength of 12.5 ksi (86.2 MPa) prior to testing. The compressive strength of the UHPC was determined according to ASTM C1856 (ASTM 2017).

The tensile properties of the steel reinforcement were tested according to ASTM A370 (ASTM 2017). Tests were conducted on a 220-kip (980-kN) servo-controlled universal testing machine. Table 2 lists relevant tensile properties of the reinforcement.

**Table 1. UHPC Mix Proportions**

| UHPC Mix | Amount, lb/yd$^3$ (kg/m$^3$) |
|---|---|
| Premix | 3700 (2195) |
| Water | 219 (130) |
| Plasticizer | 30 (18) |
| Water reducer | 20 (12) |
| Accelerator | 39 (23) |
| Steel fibers | 263 (156) |

**Table 2. Steel Properties**

| Bar Size | Bar Type | Grade | Yield Strength, ksi (MPa) | Tensile Strength, ksi (MPa) |
|---|---|---|---|---|
| #5 (No. 16) | Epoxy-coated | 60 | 67.9 (468) | 104.3 (719) |
| #8 (No. 25) | Epoxy-coated | 60 | 63.4 (437) | 95.6 (659) |
| #8 (No. 25) | Uncoated | 60 | 67.4 (464) | 101.7 (702) |
| #8 (No. 25) | Uncoated | 120 | 115.5 (797) | 163.2 (1125) |
| #11 (No. 36) | Uncoated | 120 | 133.5 (921) | Not measured* |

* Tensile strength of Gr. 120 #11 (No. 36) bars exceeded the capacity of the testing machine

### *4.3 Direct Tension Pull-out Tests*

As previously noted, the experimental test set-up used herein was the same as the configuration used by Yuan and Graybeal (2015). The test setup was designed to be representative of a tension-tension non-contact lap splice configuration; similar to those found in field-cast connections between precast elements. Photos of the test set-up are shown in Figure 2.

Precast concrete slabs were fabricated with an arrangement of #8 (No. 25) dowel bars for tests conducted on #8 (No. 25) bars and smaller. For the tests conducted on #11 (No. 36) bars, #11 (No. 36) dowels were used. UHPC strips were cast directly atop the precast concrete slab with the dowel bars in the center of the strip. Test bars were placed at the desired location within the strip by varying the embedment length, clear cover, and clear spacing between the test bar and dowel bar; shown in Figure 1. The embedment length was measured from the top of the UHPC strip to the bottom of the test bar. The clear cover was measured from the edge of the UHPC strip to the nearest edge of the test bar. The clear spacing was measured from the edge of the nearest dowel bar to the edge of the test bar.

The tests were conducted by pulling the test bars out of the UHPC strip using a servo-controlled hydraulic jack. The force applied to the test bar was measured by an on-board load cell. Load was applied in displacement control at a rate of 0.2 in./min, which was measured by an on-board linear variable displacement transformer (LVDT). The bond slip of the test bar was measured at the interface between the test bar and the UHPC strip. This measurement was captured using a commercially available digital image correlation (DIC) displacement system.

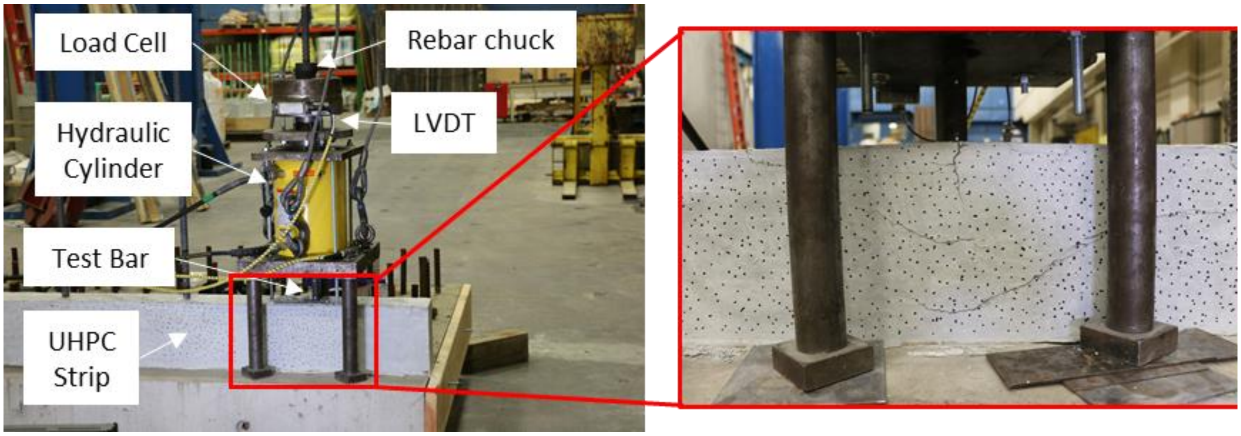


**Figure 2. Experimental Test Setup**

## 5. Experimental Results

### *5.1 Bar Type*

Figure 3 presents data from previous research conducted at TFHRC on #5 (No. 16) bars with a $2d_b$ clear cover and $5d_b$ clear spacing; the error bars shown here and throughout denote the maximum and minimum values for the average bar stress. A total of five epoxy coated #5 (No. 16) bars were tested; 2, 1, and 2 at $4d_b$, $6d_b$, and $8d_b$ embedment, respectfully. Nine #5 black bars were tested; 2, 5, and 2 for $4d_b$, $6d_b$, and $8d_b$ embedment, respectfully. Fifteen Gr. 120 #5 (No. 16) bars; 2, 4, and 9 with $4d_b$, $6d_b$, and $8d_b$ embedment, respectfully .The results showed that epoxy-coated #5 (No. 16) bars develop less stress before failure compared with black and high-strength bars. Epoxy-coated bars developed 79%, 75%, and 84% of the maximum stress of the uncoated, Gr. 60 bars for embedment lengths of $4d_b$, $6d_b$, and $8d_b$, respectively. The difference in yield strength between Gr. 60 and Gr. 120 uncoated bars seemed to have minimal effect on peak stress achieved for embedment lengths of $4d_b$ and $6d_b$. However, the uncoated Gr. 120 #5 (No. 16) bars tested with $8d_b$ embedment length had 10% larger stresses than the uncoated Gr. 60 #5 (No. 16) bars.

Figure 4 shows results from tests conducted as a part of the current study on uncoated Gr. 60, uncoated Gr. 120, and epoxy-coated Gr. 60 #8 (No. 25) bars. Three tests were conducted for each parameter set for the #8 bars (No. 25). These tests were meant to evaluate the effect of bar type on larger diameter bars. Pull-out tests were conducted with $4d_b$, $6d_b$, and $8d_b$ embedment lengths with a target clear cover of $2d_b$ and $3d_b$ clear spacing). The effect of the epoxy coating was not as prevalent for the #8 (No. 25) bars as it was for #5 (No. 16) bars; however, there was still an observed reduction in peak stress. For the bars tested with $4d_b$, $6d_b$, and $8d_b$ embedment length, the epoxy coated bars developed approximately 94%, 84%, and 90% of the maximum stress of the uncoated Gr. 60 bars, respectively. The effect of the yield stress on peak stress was also observed. The Gr. 120 bars developed stresses that were larger than the Gr. 60 bars; the Gr. 60 bars did not reach their full tensile capacity. In an extreme case, the Gr. 120 bars with an $8d_b$ embedment length achieved an average peak stress that was 32% higher than the maximum stress in the uncoated Gr. 60 bars.

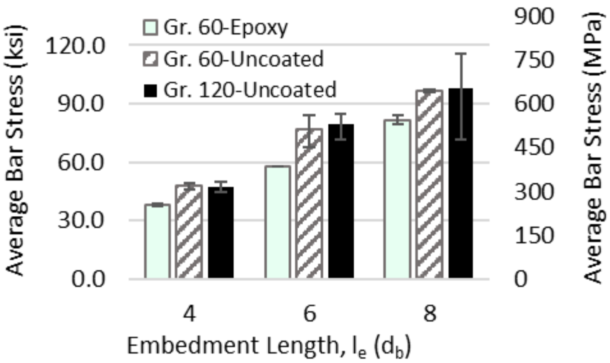


**Figure 3. Effect of Bar Type for #5 (No. 16) Bars – Bar Stress vs. Embedment Length**

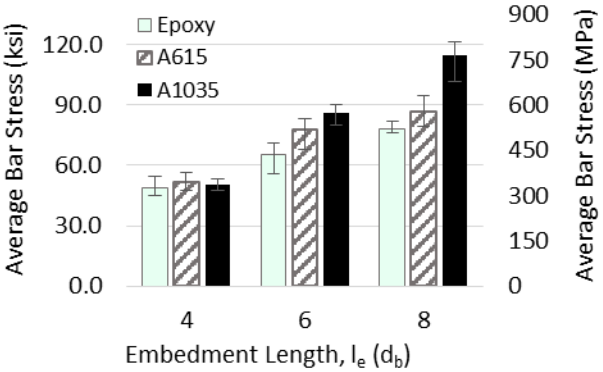


**Figure 4. Effect of Bar Type for #8 (No. 25) Bars – Bar Stress vs. Embedment Length**

## *5.2 Side Cover*

Side cover has been shown to significantly impact the capacity of UHPC lap splice connections (Yuan and Graybeal 2015). When embedment and splice lengths held constant, the amount of concrete cover and spacing between reinforcement governs the failure mode of UHPC lap splice connections. If the clear cover is small, UHPC fails by transverse splitting or by a cone-like failure. If there is sufficient cover, then the failure mode tends to be longitudinal splitting along the UHPC strip. The effect of side cover is shown in Figure 5 and 6. The data shown includes previous TFHRC data, and newly collected data from this study.

Previous tests were conducted on seven Gr. 120 #5 (No. 16) bars with an $8d_b$ embedment length and a target clear cover of 1in. (25.4 mm), which is $1.6d_b$, and on three Gr. 60 epoxy-coated #8 (No. 25) bars with an $8d_b$ embedment length and a target clear cover of $1d_b$. From the current study, additional tests were conducted on uncoated Gr. 120 #8 (No. 25) and #11 (No. 36) bars and epoxy-coated, Gr. 60 #5 (No. 16) bars. All these additional tests were conducted with either an $8d_b$ embedment length, and target covers of $1d_b$, $1.6d_b$, and $2d_b$. Three tests were conducted for each of the parameters sets for #8 bars, while two tests were conducted for each test set for #11 bars.

For smaller diameter bars, the effect of clear cover was not found to have a major impact on the peak bar stress, however it did dictate the failure mode of the connection. For both the uncoated Gr. 120 and epoxy-coated Gr. 60 #5 (No. 16) bars, the difference $1.6d_b$ and $2d_b$ clear cover had less than a 5% effect on the peak bar stress. Reducing the clear cover from $2d_b$ to $1d_b$ had a greater effect on the #8 (No. 25) and #11 (No. 36) bars. The peak stress in the Gr. 120 #8 (No. 25) and #11 (No. 36) bars with $1d_b$ were 17% and 28% smaller than with $2d_b$ clear cover, respectively. Similarly, the peak stress in the epoxy-coated #8 (No. 25) bars was reduced by 16% between $2d_b$ and $1d_b$ clear cover.

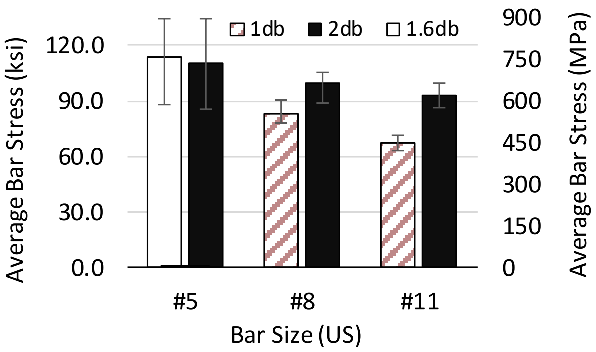


Figure 5. Effect of Cover for Uncoated Gr. 120 Bars – Bars Stress vs. Bar Size

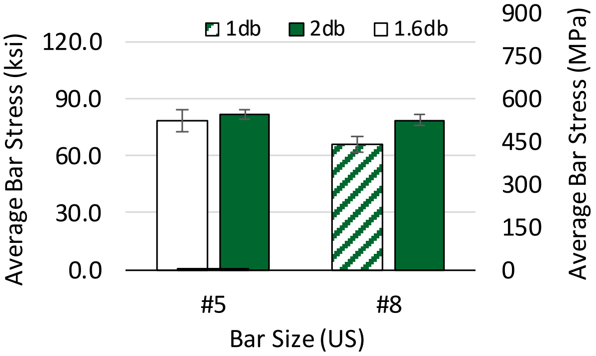


Figure 6. Effect of Cover for Epoxy Coated Gr. 60 Bars – Bars Stress vs. Bar Size

### *5.3 Bar Size*

Figure 7 shows the results for the effect of bar size considering uncoated Gr. 120 bars. The data shown for #5 (No. 16) bars was collected by Yuan and Graybeal (2015). A large percentage of the tests conducted by the FHWA were on uncoated, Gr. 120 #5 (No. 16) bars. The data shown for uncoated Gr. 120 #8 (No. 25) and #11 (No. 36) bars was collected during this study to investigate bar size effect. The clear spacing of the bars varied for the different bar sizes, but were within the range of the FHWA design guidance (Graybeal 2019). Fourteen tests were conducted on #5 (No. 16) bars with a $5d_b$ clear spacing and $2d_b$ clear cover; 2, 4, and 8 tests for $4d_b$, $6d_b$, and $8d_b$ embedment, respectfully. Nine tests were conducted on #8 (No. 25) bars with a $5d_b$ clear spacing and $2d_b$ clear cover; 3 for each embedment length. Eight tests were conducted on #11 (No. 36) bars with a $3.25d_b$ clear spacing and $2d_b$ clear cover; 2, 4, and 2 tests for $4d_b$, $6d_b$, and $8d_b$ embedment, respectfully.

The results showed that bar size had minimal apparent effect on the peak stress in the bar for $4d_b$ and $6d_b$ embedment lengths. However, as the embedment length increased to $8d_b$, there was a noticeable difference in the stresses developed in the larger diameter bars compared to the smaller diameter bars. The average peak stress in #8 (No. 25) and #11 (No. 36) bars was 90% and 84% of that recorded for #5 (No. 16) bars for an $8d_b$ embedment length. The #8 (No. 25) and #11 (No. 36) bars have a larger bond area compared to the #5 (No. 16) bars, which increases the pull-out strength demand on the UHPC.

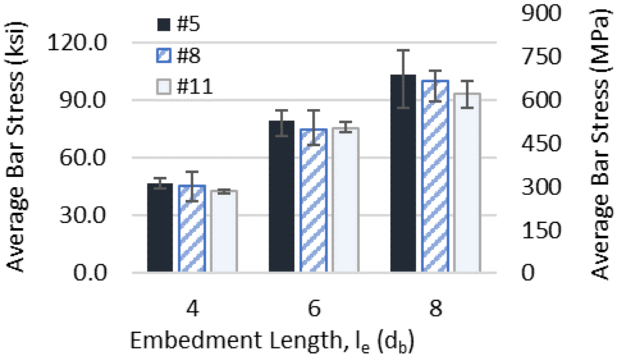


Figure 7. Effect of Bar Size for Uncoated, Gr. 120 Bars – Bar Stress vs. Embedment Length

## 6. Summary and Conclusions

The bond behavior of reinforcing steel bars embedded in UHPC has been widely studied for bars smaller than #8 (No. 25), however minimal research has been conducted on larger diameter bars. The research presented in this paper focused on the performance of larger diameter reinforcing bars embedded in UHPC. The paper also investigated the effect of clear cover, bar type, and bar coating. Sixty-seven direct tension pull-out tests were conducted. The following conclusions can be made based on the experimental data collected:

- Epoxy-coatings have a greater effect on the development of stresses in smaller diameter bars than for larger diameter bars. The presence of an epoxy-coating reduces the peak stress of bars with full embedment and a smaller bond area.
- Bars with a higher yield stress can achieve higher peak stresses than similar bars with lower yield stresses. This is likely due to the yield plateau, which is exhibited in lower yield strength bars. The effect of yield stress was more apparent in larger diameter bars with longer embedment length.
- Decreasing the clear cover reduced the tensile capacity of the connections with larger diameter bars.
- Overall, larger diameter bars developed lower peak stresses than the smaller diameter bars, therefore refinements may be required for existing embedment and lap splice guidelines for field cast UHPC connections with bars larger than #8 (No. 25).
- The results of this research were used to aid in the development of new design guidelines for field cast UHPC connections for larger diameter reinforcing bars (Graybeal 2019).

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## 8. Acknowledgements

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