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FINAL REPORT ~ FHWA-OK-23-04

# BOND BEHAVIOR OF EPOXY-COATED REINFORCING BARS IN NON-PROPRIETARY UHPC

David Darwin, Ph.D., P.E.
Matthew O'Reilly, Ph.D., P.E.
Rémy D. Lequesne, Ph.D., P.E.
Sanjeeb Thapa

Department of Civil, Environmental & Architectural Engineering
The University of Kansas
Lawrence, Kansas

October 2023

OKLAHOMA
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# BOND BEHAVIOR OF EPOXY-COATED REINFORCING BARS IN NON-PROPRIETARY UHPC

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**Submitted by:**
David Darwin, Ph.D., P.E.
Matthew O'Reilly, Ph.D., P.E.
Rémy D. Lequesne, Ph.D., P.E.
Sanjeeb Thapa
Department of Civil, Environmental & Architectural Engineering
The University of Kansas

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16. ABSTRACT

Non-proprietary ultra-high-performance concrete (UHPC) mixtures were developed for use in closure strips between precast members on reinforced concrete bridges. The mixtures contained ODOT approved Type I portland cement, slag cement, silica fume, graded fine aggregate, two high-range water-reducers (HRWRs), one of which incorporated a viscosity modifying admixture, and 2% by volume of 0.5-in. steel fibers. Several HRWRs of each type were included in the evaluations. Mixtures were evaluated based on flow, fiber distribution, flexural properties, compressive strength, and effect on bond strength using a modified pullout test and the ASTM A944 beam-end test for No. 5 uncoated, ASTM A755 epoxy-coated, and ASTM A1124 textured-epoxy-coated reinforcing bars. The UHPC mixture with the best properties was used to cast a closure strip between two precast sections to determine the splice strength of No. 4, No. 5, and No. 8 uncoated, epoxy-coated, and textured-epoxy-coated reinforcing bars with minimum clear covers ranging from 1.00 to 2.63 in. The results of the splice test were used to develop design recommendations. The study showed that UHPC can be made using ODOT approved materials. The splice strength of reinforcing bars in UHPC is two times the value in conventional concrete. The negative effects of epoxy coating on bond strength are lower in UHPC than in conventional concrete. ASTM A1124 textured epoxy-coated bars have the same bond strength as uncoated bars. The design procedures described in this report are based on UHPC with a minimum compressive strength at the time of load application of not less than 12 ksi, with a flow between 8 and 10 in. and good fiber distribution.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| SYMBOL | WHEN YOU KNOW | MULTIPLY BY | TO FIND | SYMBOL |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| in$^2$ | square inches | 645.2 | square millimeters | mm$^2$ |
| ft$^2$ | square feet | 0.093 | square meters | m$^2$ |
| yd$^2$ | square yard | 0.836 | square meters | m$^2$ |
| ac | acres | 0.405 | hectares | ha |
| mi$^2$ | square miles | 2.59 | square kilometers | km$^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| ft$^3$ | cubic feet | 0.028 | cubic meters | m$^3$ |
| yd$^3$ | cubic yards | 0.765 | cubic meters | m$^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in m$^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9<br>or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/m$^2$ | cd/m$^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/in$^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| SYMBOL | WHEN YOU KNOW | MULTIPLY BY | TO FIND | SYMBOL |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| mm$^2$ | square millimeters | 0.0016 | square inches | in$^2$ |
| m$^2$ | square meters | 10.764 | square feet | ft$^2$ |
| m$^2$ | square meters | 1.195 | square yards | yd$^2$ |
| ha | hectares | 2.47 | acres | ac |
| km$^2$ | square kilometers | 0.386 | square miles | mi$^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| m$^3$ | cubic meters | 35.314 | cubic feet | ft$^3$ |
| m$^3$ | cubic meters | 1.307 | cubic yards | yd$^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/m$^2$ | candela/m$^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/in$^2$ |

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# CHAPTER 1: INTRODUCTION

Ultra-high-performance concrete (UHPC) is a class of fiber-reinforced cementitious materials that exhibit much higher compressive and tensile strengths than conventional concrete. ACI 239R-18 defines UHPC as concrete with a minimum specified compressive strength of 22,000 psi (150 MPa), although design values closer to 14,000 psi (97 MPa) are sometimes appropriate for accelerated bridge construction (ABC) applications because of the short curing time available before the bridge is opened to traffic (Yuan and Graybeal 2014). The high compressive strengths are the result of (1) low water-to-cementitious materials (*w/cm*) ratios, near 0.2, (2) enhanced homogeneity obtained by eliminating coarse aggregates in the concrete matrix, and (3) material selection and optimized gradation that maximize the packing density of the matrix.

The high tensile strength of most UHPC materials, which frequently exceeds 1000 psi (7 MPa), is attributable to the high content of steel fibers. Most UHPC mixtures use a volume fraction of 1 to 3% (Lawler, Wagner, and Tadros 2020) of straight steel fibers. These fibers typically have tensile strengths of 285 to 410 ksi (1900 to 2830 MPa), lengths of 0.5 or 0.75 in. (13 or 19 mm), and length-to-diameter aspect ratios of 65 to 95.

One of the key advantages of UHPC is its ability to develop reinforcing steel with very short embedment lengths, resulting in a principal use of UHPC in bridge-deck closure strips, which can be very narrow. Bond strength generally increases with increasing compressive strength and fiber content, but existing research (Haber et al. 2018) indicates there may be a point of diminishing returns. In addition, key questions remain as to the effects of bar spacing, bar deformation pattern (not addressed in earlier studies), and the influence of bar coatings.

The development of UHPC dates to the early 1970s (Yudenfreund 1972a, 1972b, 1972c). The earliest commercial applications involved the use of the proprietary product Ductal® in Europe in the 1990s. Ductal® has been in use and the subject of research in the U.S. since 2006 (Graybeal 2006, Russell and Graybeal 2013). In addition to this and other proprietary products, non-proprietary UHPC is now in use (Russell and Graybeal 2013). Recent research (Floyd et al. 2021) has shown that non-proprietary UHPC has lower compressive strengths than proprietary UHPC but has similar tensile and bond strengths to proprietary UHPC, but additional research is needed in this area, particularly with regards to development of epoxy-coated reinforcement (ECR) typically used in bridge decks. Of special interest is the application of UHPC with newly available textured-epoxy-coated bars (ASTM A1124), which offer the potential of further reducing splice length and the width of closure strips.

## 1.1 Objectives

The objectives of this study are as follows:

1. Develop non-proprietary UHPC mixtures using ODOT materials.
2. Evaluate UHPC mixtures in modified pullout and beam-end specimens.
3. Perform beam splice tests to establish data that can be used to design lap splice lengths for use in bridge deck closure strips as a function of concrete compressive strength, and bar size, cover, splice length, spacing, and bar surface properties.
4. Develop design recommendations for splice length in non-proprietary UHPC.

## 1.2 Previous Work

### 1.2.1 Non-proprietary UHPC

Wille and Boisvert-Cotulio (2015) conducted a study to assess the mechanical properties and cost-effectiveness of ultra-high-performance concrete by exploring various constituent materials in its design. Their research was conducted in three stages to satisfy both time efficiency and material performance in UHPC design. The first stage involved investigating the cementitious paste, followed by an investigation of the cementitious/aggregate matrix (cementitious paste + aggregate) in the second stage. The final stage focused on the investigation of the composite (cementitious/aggregate matrix + fibers). The researchers optimized UHPC mix designs without fibers based on locally available materials from specific regions of the United States of America. Their resulting mix design recommendation for cost-effective ultra-high-performance concrete without fibers for the upper-midwestern United States is listed in Table 1.1.

**Table 1.1:** Mix Design Proposed by Willie and Boisvert-Cotulio (2015)

| Materials | Mix Design (lb/yd$^3$) |
|---|---|
| Cement | 1269 |
| Silica fume | 317 |
| Fly ash | 308 |
| Fine aggregate | 1903 |
| High-range water reducer | 46 |
| *w/cm* | 0.24 |

Aljawad et al. (2022) also recommended baseline mix proportions using primarily Kansas-based materials listed in Table 1.2 to produce concrete with 1, 7, and 28-day compressive strengths of 13.1, 16.8, and 19.6 ksi, respectively.

**Table 1.2:** Mix Design Proposed by Aljawad et al. (2022)

| Materials | Mix Design (lb/yd$^3$) |
|---|---|
| Cement | 1362 |
| Silica fume | 274 |
| Water | 312 |
| Fine aggregate | 1909 |
| High-range water reducer | 26.0 |
| Fibers | 265 |
| *w/cm* | 0.20 |

### 1.2.2 Bond Strength

The bond strength of deformed reinforcing bars in conventional concrete is governed by two failure modes – pullout and splitting – splitting being the more common. Pullout involves the crushing or shearing of the concrete between the deformations and only occurs in cases where the bar is highly confined by concrete cover, confining reinforcement, or both. Splitting occurs as the bar slides with respect to the concrete; the deformations on the bars act as wedges, placing the concrete in tension perpendicular to the bar. The force in the bar required to split the concrete increases as the length of the bar in contact with the concrete and as the confinement provided to the bar by increased cover or confining reinforcement increases. The effect of length is not proportional to the bonded length; thus, doubling the embedded length will not double the force in a bar at bond failure. The contribution of the concrete in bond is roughly proportional to the compressive strength to the ¼ power (not the square root as appears in design codes and specifications) (Darwin et al. 1996, ACI Committee 408 2003). The effectiveness of the confining reinforcement increases with increases in (1) the area of steel confining a given length of bar, (2) the size of the bar (bigger diameter bars are helped more by confining reinforcement), and (3) the compressive strength of the concrete (in this case, it is a function of the square root of the compressive strength) (Darwin et al. 1996, ACI Committee 408 2003).

It is well known that in both conventional concrete and UHPC, bond strength is affected by the nature of the bar surface. Conventional epoxy coatings, commonly used where corrosion is a concern, reduce the friction force between the bar and concrete and require greater embedment lengths to develop a given force than uncoated bars under the same conditions. As such, ACI 318 (2019) and the AASHTO LRFD Bridge Specifications (2020) require that the development length for epoxy-coated bars be increased by 20% to 50% relative to uncoated bars. Sherwin-Williams has developed a textured-epoxy coating that tests show provides a bond strength equivalent to that of uncoated bars while simultaneously providing corrosion protection at least as good that exhibited by conventional epoxy-coated steel (Aryal et al. 2023). For that reason, this study incorporates this new coated steel (specified under the new ASTM standard A1124) within the test matrix.

### 1.2.3 UHPC Bond Strength Studies

Yuan and Graybeal (2014) examined the bond strength of coated and uncoated reinforcing bars cast in proprietary UHPC using modified “direct tension pullout” specimens (Figure 1.1). A single UHPC mixture was evaluated, with a steel fiber content of 2% by volume and an average one-day compressive strength of 13.5 ksi. Variables included bar type (uncoated A615, epoxy-coated A615, and uncoated A1035), side cover ($2d_b$ to $3.5d_b$), embedment length ($4d_b$ to $10d_b$), spacing between bars (0.1 in., representing a contact lap splice, to 5.7 in.), UHPC compressive strength (13.2 to 19.9 ksi, controlled by varying the time between casting and testing), and bar size (No. 4, No. 5, and No. 7, with the majority of tests being performed on No. 5 bars). The test specimen measures the strength of a splice, loaded (importantly) so as to prevent a compressive strut forming through the concrete between the points of load application and the deformations on the bar. Yuan and Graybeal found that, as expected, bond force at failure increased as side cover, embedment length, and compressive strength increased. They noted that existing ACI methods for calculating bond strength, including the assumption that the bond force at failure was proportional to $\sqrt{f'_c}$ and splice length, did not accurately reflect the behavior of bars in UHPC. They also observed that contact lap splices exhibited lower bond strengths than closely spaced noncontact splices, but that bond strength decreased as bar spacing increased. The lower strength of the contact splices was presumed to be due to the fact that that the steel fibers in the UHPC around bars in contact splices could not be oriented as effectively as they could around bars in the noncontact splices. Except in a limited number of cases, the noncontact splices did not meet the ACI (ACI Committee 318 2019) and AASHTO (2020) limitation that the clear spacing between spliced bars must be less than or equal to one-fifth the lap length. In the tests, epoxy-coated bars exhibited lower bond strengths than uncoated bars with the same test parameters, and bars that yielded prior to bond failure had lower bond strengths than those that did not.

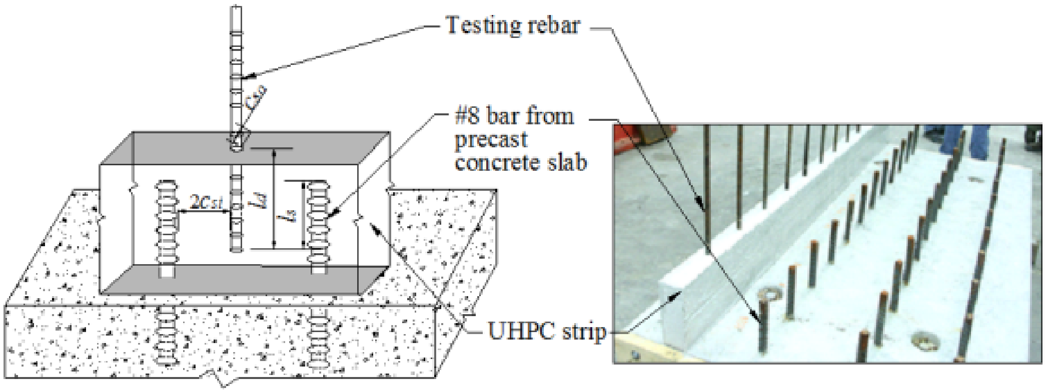
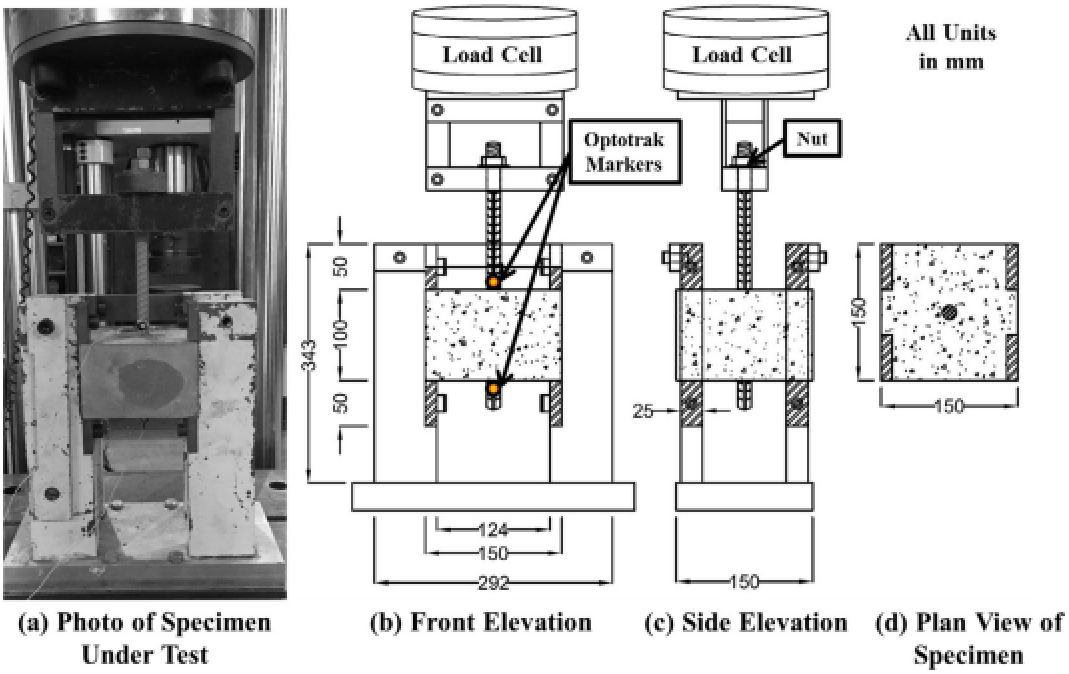


**Figure 1.1:** Modified Pullout Test Specimen (Yuan and Graybeal 2014)

El-Tawil et al. (2016) and Alkaysi and El-Tawil (2017) evaluated the bond of epoxy-coated and uncoated reinforcing bars in UHPC as part of a larger study aimed at developing a non-proprietary UHPC mix for the Michigan Department of Transportation. Most of the specimens evaluated (Figure 1.2) were pullout test specimens modified so as to limit the effect of compressive struts within the concrete intercepting the surface of the reinforcing bar; four splice specimens with three spliced bars each were also tested. For the latter, the spacing between each pair of bars in a splice was not given, although the spacing between the bars on either side of the splice region was. Two UHPC mixtures, with steel fiber contents of 1% and 2% by volume, were evaluated. The other components in the mixtures were otherwise identical. The UHPC had an average one-day compressive strength of 7.7 ksi and an average 28-day compressive strength of 27.4 ksi. Primary variables for the pullout tests included bar size (No. 4, No. 5, and No. 6), the presence or absence of an epoxy coating (pullout tests only), and embedment length (2.6$d_b$ to 8$d_b$); a limited number of specimens were also cast to investigate the effect of fiber content (1% and 2% by volume), curing age/strength (1, 3, 7, and 28 days, corresponding to compressive strengths of 7.7, 12.8, 18.1, and 27.4 ksi), and casting direction (concrete placed parallel or perpendicular to the bars). The authors found that an assumed bond stress on the surface of the bars of $1.1\sqrt{f'_c}$ could conservatively predict bond strength, though in many cases this was excessively conservative, as stresses as high as five times this value were achieved. Alkaysi and El-Tawil reported that 75% of the 28-day bond strength was achieved at 7 days; it should be noted, however, that the UHPC in their study had a lower early strength and a higher long-term strength gain than most UHPC mixtures. The splice specimens evaluated by El-Tawil et al. (2016) consisted of precast panels with a UHPC closure strip in which epoxy-coated bars were spliced. The epoxy-coated bars had a cover of 1.4 in. for No. 5 coated bars with a splice length of 3.6 in. El-Tawil et al. found that pullout specimens with similar cover and embedment lengths exhibited bond strengths on average about 12% greater than those exhibited by the splice specimens. The specimens with the 2% fiber content had bond strengths about 9 and 16% higher than those with the 1% fiber content in the splice and pullout tests, respectively. Epoxy-coated bars exhibited lower bond strengths than companion uncoated bars in the pullout tests.



(a) Photo of Specimen Under Test (b) Front Elevation (c) Side Elevation (d) Plan View of Specimen

**Figure 1.2:** Pullout Test Setup Details and Views (Alkaysi and El-Tawil 2017)

Lee and Lee (2015) tested simulated closure strips containing UHPC between precast deck panels. The closure strips contained five spliced No. 5 bars with the splices consisting of straight, hooked, or U-looped bars. The closure strips ranged in width from 3.9 to 9.8 in. and the lap splice lengths ranged from 2.4 to 6.3 in. The concrete cover was 1.3 in., and the bars on the opposite side of the splice were spaced 3 in. center-to-center in the UHPC strip. Concrete compressive strengths ranged from 19.2 to 21.0 ksi with fiber (straight 0.5 in.) contents of 1.0, 1.3, and 1.6%. Bond strength increased with fiber content, and a splice length of 6.3 in. ($10d_b$) was sufficient to develop the straight bars for the mixture with a fiber content of 1.6%, but not for the mixtures with the lower fiber contents.

Peruchini et al. (2017) evaluated coated bars in UHPC in pullout and simulated deck panel tests. The UHPC mixture had a 1.8% fiber content and 14-day strengths (the age at testing) ranging from 12.5 to 14.1 ksi. Two types of pullout specimen (Figures 1.3 and 1.4), described as pullout bond curb and splice-connection bond curb, had clear covers between 1.0 and 2.5 in., with 3 in. and 6 in. spacing between bars and embedment lengths ranging from 1.5 to 10.5 in., were tested in a fashion that, in some cases, only partially limited the formation of compressive struts through the UHPC between the load points and the bar. The deck panels had covers of 1.0 and 1.75 in., with the bars on the opposite side of the splice spaced 3 in. center-to-center in the UHPC strip; the spliced bars had lateral rebar offsets of 0 to 2 in. to investigate the effect of construction tolerances on reinforcement and girder placement, and the splice lengths ranged from 1 to 5 in. No. 5 epoxy-coated bars were used in all tests. Peruchini et al. found that increasing cover increased bond strength in the pullout bond curb specimens and that embedment lengths greater than 7.5, 6.0, and 4.5 in. were sufficient to fracture the reinforcement for bars with covers of 1.0, 1.75, and 2.5 in., respectively. Somewhat shorter lengths were needed to develop the desired strength in the splice-connection bond curb tests. In the deck panel tests, splice strengths increased with splice length and cover. Splice strengths were about the same for bars with offsets of 0 and 1 in. but decreased by about 14% for bars offset by 2 in. The deck panels gave splice strengths about 14% below those of the splice-connection bond curb specimens.

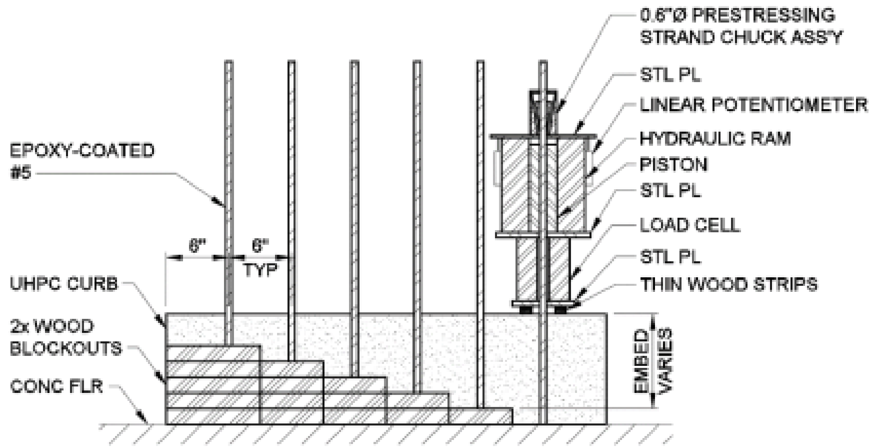


**Figure 1.3:** Pullout Curb with Testing Apparatus (Peruchini et al. 2016)

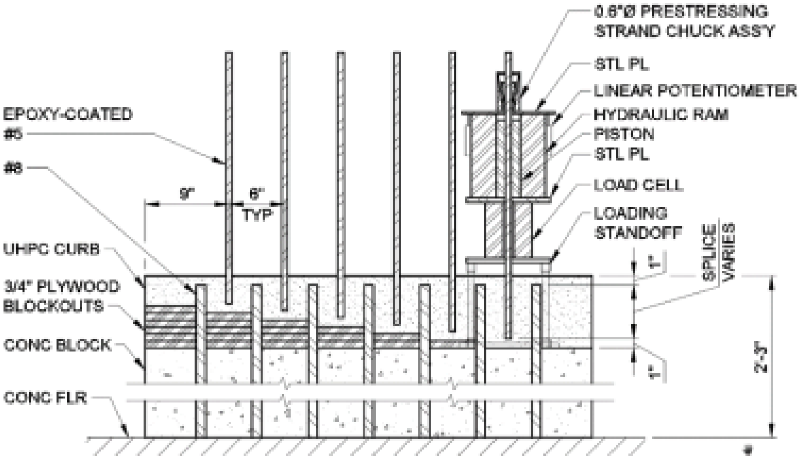


**Figure 1.4:** Splice-Connection Bond Curb with Testing Apparatus (Peruchini et al. 2016)

Zhou and Qiao (2018) evaluated the bond strength of coated reinforcement using a modified pullout test similar to that used by Yuan and Graybeal (2014). No. 5 epoxy-coated reinforcement was evaluated in UHPC with a compressive strength between 10.7 and 10.9 ksi at 7 days (the age at testing) and a steel fiber content of 2%. Bars had a cover of 1 or 2 in., a center-to-center spacing between the anchoring bars of 6.89 in., and embedment lengths between $8d_b$ and $14d_b$. Zhou and Qiao noted that the load-slip behavior for coated bars in UHPC was similar to that of coated bars in normal concrete and that with 2-in. cover and an embedment length of $12d_b$ were sufficient to reach the nominal yield strength of the bars.

A 2018 study by Haber et al. expanded on the bond strength work by Yuan and Graybeal (2014) as part of a larger study examining the plastic and hardened properties of UHPC. The first part of the study concerning bond strength used the modified direct tension pullout test developed by Yuan and Graybeal. Haber et al. examined five proprietary UHPC mixes with compressive strengths between 9 and 23 ksi, fiber volumes between 1.0 and 4.5%, clear covers of 2.0 or 3.0$d_b$, and embedment lengths of 8$d_b$ or 10$d_b$. Uncoated No. 5 A1035 bars were used for all tests. Haber et al. found that bond strength was mixture dependent and not necessarily tied to the fiber content. For the shorter development length (8$d_b$), bond strength increased as fiber content increased from 2 to 4.5%. For a 10$d_b$ (6.25 in.) development length, fiber content no longer played a role in bond strength. Other research has demonstrated a similar insensitivity to fiber contents at and above 2% by volume (Yoo et al. 2014) .

The second part of the Haber et al. study evaluated the bond strength in UHPC using simulated closure strips of UHPC between two precast concrete deck panels. The closure strip was 6 in. wide, 6 in. deep, and 28 in. long, with two mats of uncoated No. 5 reinforcement with four bars in each mat projecting 5.5 in. from the precast panels, giving 5-in. (8$d_b$) splices. The bars were spaced 6 in. on center, with a clear cover of 1 in. Panel specimens were loaded in four-point bending with the closure strip in a constant moment region. Panels were loaded under approximately 2 million cycles of cyclic loading, followed by monotonic loading to failure. Five panel specimens were tested, one for each of the five proprietary UHPC mixtures in the study. Haber et al. found that all five panels exhibited good performance, with consistent, ductile loading responses. Failure in all cases was due to crushing of the concrete in the precast members, not bond failure.

Floyd et al. (2021) tested pullout and splice specimens with non-proprietary UHPC as part of a study for the Accelerated Bridge Construction University Transportation Center (ABC-UTC). The tests evaluated the bond strengths of uncoated No. 3, No. 5, and No. 8 bars cast in UHPC with fiber contents of 1.0, 2.0, 4.0, and 6.0% by volume. The pullout specimens had embedments of 2$d_b$, 4$d_b$, 6$d_b$, 8$d_b$, and 10$d_b$ with a debonded region before the bonded length equal to the bonded length. The design of this pullout specimen is preferable to that of traditional pullout specimens but still results in some compression from the load points through the concrete to the surface of the bar within the embedded length. Bond strength increased with increasing fiber content for the No. 5 bars but was largely insensitive to fiber content above 2% for the No. 8 bars and not sensitive to fiber content for the No. 3 bars. In addition, fiber contents of 1% and 2% were evaluated in small cross-section (7 × 7 in.) splice beams. Two No. 5 bars were spliced at midspan – the splice length was just 2$d_b$. Specimens with proprietary UHPC were compared to specimens with non-proprietary UHPC with the former producing the higher splice strength. The mixtures with the 2% fiber contents resulted in higher splice strengths than those with 1% fiber. Because of the non-proportional relationship between splice length and splice force, it is not clear how the splice test results provided with these specimens can be used to guide design.

The existing body of research leaves many unanswered questions as to the bond strength of UHPC in the field. Most of the existing research of bond of coated reinforcement has used modified pullout specimens. ACI Committee 408 (2003) does not recommend pullout specimens for the evaluation of bond due to the test setup confining the concrete around the test bar, resulting in increased bond strengths, but the direct tension pullout test developed by Yuan and Graybeal (2014) has overcome most of the drawbacks of typical pullout tests. In spite of this, only a realistic state of stress, such as provided by a splice test, can provide data that can be used to develop design criteria.

## 1.3 Scope

This study aims to achieve the objectives outlined in Section 1.1 by developing UHPC mixtures and evaluating the bond behavior of reinforcing bars in UHPC mixtures, as described in Chapter 2. One-hundred-forty-four batches of UHPC were prepared for this study. Those UHPC mixtures with a minimum 8-in. spread and a 7-day compressive strength of at least 14 ksi were considered promising mixtures. A subset of these promising mixtures underwent evaluation through flexure tests, pullout tests, and beam-end tests. The most favorable mixture was employed in the construction of beam-splice specimens. Twenty-eight splice specimens were cast and tested to collect data for the development of design provisions for splice length for uncoated, epoxy-coated, and textured-epoxy-coated bars in UHPC.

# CHAPTER 2: EXPERIMENTAL WORK

The experimental portion of this research focused on three tasks to assess the bond behavior of reinforcing bars in non-proprietary ultra-high-performance concrete (UHPC). The first task focused on the development of non-proprietary UHPC mixtures with a minimum flow of 8 in. and a minimum compressive strength of 14 ksi at seven days using ODOT approved materials. The second task focused on the evaluation of bond strengths obtainable with UHPC mixtures in modified pullout and beam-end specimens as affected by the UHPC mixtures, and the third task focused on determining the splice strengths obtainable with the most favorable UHPC mixture using beam-splice specimens.

Details of the materials, mixture proportions, mixing procedures, specimen fabrication, and tests for UHPC mixtures are presented first in Sections 2.1 to 2.4, followed by the details of specimen preparation and test setup for the pullout, beam-end, and beam-splice tests, which are presented in Sections 2.5 to 2.8.

## 2.1 Materials

Table 2.1 describes the materials used to develop UHPC mixtures, their source and specific gravity.

**Table 2.1:** Material Properties

| Material | Source | Product Name | Specific Gravity |
|---|---|---|---|
| Type I/II Portland Cement | Monarch Cement Company | Type I Portland Cement | 3.19 |
| Silica fume | Norchem | Silica fume | 2.30 |
| Fly ash* | Latan | Class C fly ash | 2.64 |
| Slag cement | Skyway Cement Company | Slag | 3.01 |
| Sand | Van Eaton Ready Mix | Oklahoma Sand | 2.62 |
| Sand | Twin Cities Ready Mix | Oklahoma Sand | 2.63 |
| Sand | Midwest Concrete Materials | Kansas River Sand | 2.63 |
| Steel Fibers | Hiper Fiber | 0.0079 in. × 0.5 in. Fibers | 7.85 |
| HRWR** | Euclid Chemicals | Plastol 6400 EXT | 1.09 |
| HRWR** | GCP Applied Technologies | Advacast 600 | 1.07 |
| HRWR** | GCP Applied Technologies | Advacast 555 | 1.07 |
| HRWR** | GCP Applied Technologies | Advacast 593 | 1.10 |
| HRWR** | Master Builders Solutions | MasterGlenium 7500 | 1.05 |
| HRWR** | Master Builders Solutions | MasterGlenium 7710 | 1.05 |
| HRWR** | Master Builders Solutions | MasterGlenium 7920 | 1.07 |
| HRWR** | Chryso | Chryso Fluid Premia 150 | 1.06 |
| HRWR** | Chryso | Chryso Fluid Optima 100 | 1.06 |
| Set-accelerating admixture | GCP Applied Technologies | Daraset 400 | 1.38 |

*Used only on preliminary mixtures; ** High Range Water Reducer

The steel fibers satisfied ASTM A820. The properties of the reinforcing steel used in this study are reported in Table 2.2. Three types of bars, uncoated, epoxy-coated and textured-epoxy-coated (as shown Figures 2.1 to 2.3), were used in this study. The coatings were supplied by Sherwin Williams. Pullout and beam-end tests were performed on uncoated, epoxy-coated, and textured-epoxy-coated ASTM A1035 CS Grade 100 No. 5 bars. Splice tests were performed on uncoated, epoxy-coated, and textured-epoxy-coated ASTM A1035 CS Grade 100 No. 4, No. 5, and No. 8 bars. Stress-strain curves were obtained for two bars of each nominal size in accordance with ASTM A370. The yield stress was calculated using the 0.2% offset method. Bar deformations were measured following ASTM A1035 and ACI 408R-03. The relative rib area was calculated in accordance with ACI 408R-03. Stress versus stress curves for each bar size are presented in Figures B.1 to B.3 of Appendix B.

**Figure 2.1:** Uncoated bars

**Figure 2.2:** Epoxy-coated bars

**Figure 2.3:** Textured-epoxy-coated bars

**Table 2.2:** Properties of Reinforcing Steel

| Bar Size | Nominal Diameter (in.) | Yield Strength† (ksi) | Tensile Strength† (ksi) | Average Rib Spacing (in.) | Average Rib Height* (in.) | Average Rib Height Side 1** (in.) | Average Rib Height Side 2** (in). | Gap Width Side 1 (in.) | Gap Width Side 2 (in.) | Relative Rib Area, $R_r$** |
|---|---|---|---|---|---|---|---|---|---|---|
| No. 4 | 0.500 | 128.2 | 171.0 | 0.334 | 0.021 | 0.022 | 0.021 | 0.119 | 0.117 | 0.054 |
| No. 5 | 0.625 | 131.1 | 168.8 | 0.423 | 0.031 | 0.032 | 0.029 | 0.124 | 0.122 | 0.063 |
| No. 8 | 1.000 | 136.6 | 177.9 | 0.666 | 0.050 | 0.048 | 0.047 | 0.178 | 0.190 | 0.063 |

† Per ASTM A370
*Per ASTM A1035
**Per ACI 408R-03

## 2.2 Mixture proportions

Ninety trial batches were made with different mixture proportions, constituents, and water-to-cementitious materials (*w/cm*) ratio. The *w/cm* ratio of the mixtures ranged from 0.171 to 0.22. Trial batches were prepared in small and large volumes with nominal yields ranging from 0.027 $ft^3$ to 1.32 $ft^3$. Small batches were prepared to obtain plastic concrete properties and track early-age strength. Large batches were prepared to track the compressive strength for up to 28 days. UHPC that had a minimum flow of 8 in. and nominal compressive strength of 14 ksi at seven days were considered successful. The mixture proportions and properties of the few successful trial batches are reported in Tables A.1 to A.3 of Appendix A.

Two mixture designs, Mixture A and Mixture B, reported in Table 2.3, were selected based on their 7-day compressive strength, workability, and fiber distribution to cast most of the pullout specimens, as well as all beam-end and beam-splice specimens. In total, 54 batches were prepared for these specimens.

**Table 2.3:** UHPC Mixture Proportions (Cubic Yard Basis) for Mixtures A and B

| Material Type | Mixture A | Mixture B |
|---|---|---|
| **Cement (lb)** | 1210 | 1191 |
| **Slag (lb)** | 587 | 576 |
| **Silica Fume (lb)** | 161 | 161 |
| **Fine Aggregate (lb)** | 1607 | 1656 |
| **Water (lb)** | 302 | 280 |
| **HRWR (lb)** | 55 (P150) | 46 (A555) |
| **HRWR (lb)** | 24 (O100) | 23 (A593) |
| **Set Accelerating Admixture** | - | 35 (DS400) |
| **Fibers (lb) (2% by volume)** | 265 | 265 |
| ***w/cm* ratio** | 0.183 | 0.183 |

**Notation:** HRWR: High Range Water Reducer, P150: ChrysoPremia 150, O100: Chryso Optima 100, A555: Advacast 555, A593: Advacast 593, DS400: Daraset 400, *w/cm* ratio: water to cementitious materials ratio

## 2.3 Mixing procedures

The materials were weighed approximately one hour before mixing, except for batches prepared to cast beam-splice specimens. For beam-splice specimen batches, the materials except fibers and water, were weighed approximately 24 hours prior to mixing and placed in a freezer maintained a XX°F to lower the temperature of the UHPC mixture to provide more working time for casting specimens. For pullout and beam-end specimen batches, ice equivalent to 40 % of the mixing water was used to lower the temperature of the mixtures. Small batches with nominal yields ranging from 0.027 to 0.0756 $ft^3$ were prepared using a 10 Quart Hobart Mixer (Figure 2.4). Large batches with nominal yield ranging from 0.486 to 1.32 $ft^3$ were prepared using a Mortarman 120 Plus mixer (Figure 2.5) and counter-current pan mixer (Figure 2.6).

**Figure 2.4:** 10-Quart Hobart Mixer

**Figure 2.5:** Mortarman 120 Plus Mixer

**Figure 2.6:** Counter-Current Pan Mixer

For the small batches, the following mixing procedure recommended by Wille and Boisvert-Cotulio (2015) was used (Note: Set accelerating admixtures were rarely used in the small batches):

1. Mix sand and silica fume for 5 minutes.
2. Add cement and any other cementitious materials and mix for an additional 5 minutes.
3. Add one-third of the HRWR to the water. Add water-HRWR mixture and mix for 5 minutes.
4. Add the remaining HRWR and set accelerating admixture, if any, and mix for 5 minutes.
5. Add fibers gradually and mix for 5 minutes.

For the large batches, the following mixing procedure was used.

1. Mix sand with 50 % water and start the mixer.
2. Add cement and cementitious materials and mix for 4 minutes.
3. Add remaining water, all HRWRs, and set accelerating admixture, if any, and mix for 8 minutes.
4. Add fibers and mix for 8 minutes.

## 2.4 UHPC tests

### 2.4.1 Plastic concrete properties

Plastic concrete properties were measured for all batches within 5 minutes after mixing. Tests of the plastic properties included measuring the flow (ASTM C1856), temperature (ASTM C1064), and unit weight (ASTM C138).

### 2.4.2 Hardened concrete properties

The compressive strength of the UHPC mixtures was measured in accordance with ASTM C1856. For small batches, two or three 3 × 6 in. cylinders were cast in steel molds to track early strength. For large batches, 12 3 × 6 in. cylinders were cast in steel molds to track compressive strength for up to 28 days. Cylinders were demolded 24 ± 1 hr after casting. The cylinders were end ground prior to testing.

The flexural strength of UHPC Mixtures A and B was measured in accordance with ASTM C 1609 using beams with the dimensions given in Table 3 of ASTM C1856. For both mixtures, six 3 × 3 × 12 in. (width × depth × length) beams were cast in steel molds. The beams were demolded 24 ± 1 hr after casting. Figure 2.7 shows the flexure specimens. Three beams from each mixture were tested at an age of 3 days and the other three beams were tested at an age of 7 days. These tests were performed using the equipment shown in Figure 2.8. It is noteworthy that ASTM C1856 does not specify loading rates for beams with a 3 x 3 in. nominal cross-section. Therefore, the loading rates shown in Table 2.4 were applied during the tests to effectively collect the data when the specimens were cracking while also ensuring that the test did not exceed 30 to 45 minutes in duration.

**Figure 2.7:** Flexure specimens

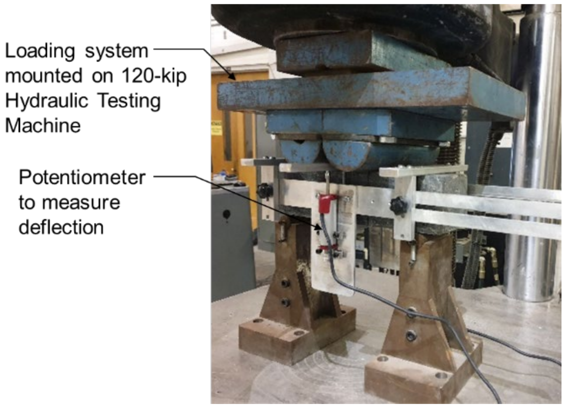


**Figure 2.8:** Flexure test setup

**Table 2.4:** Loading rates for flexure test

| Loading Zone (lb) | Loading Rate (in./min) |
|---|---|
| 0 to 250 | 0.1 |
| Up to net deflection of L/900 | 0.004 |
| Beyond net deflection of L/900 | 0.012 |

## 2.5 Pullout test specimens, test setup and procedures

Direct tension pullout tests developed by Yuan and Graybeal (2014), shown in Figure 1.1, were conducted in this study. The test setup developed by Yuan and Graybeal (2014) mimics a tension-tension lap splice and moves the compression reaction away from the UHPC.

UHPC strips cast on precast concrete base slabs, as shown in Figures 2.9 to 2.11, were used in the pullout tests. Four base slabs were cast. Each slab had nominal dimensions of 72 ×

36 ×16 in. (length × width × depth). No. 8 bars extended 12 in. from Base Slab 1 and 7 in. from Base Slabs 2-4. The base slabs and UHPC strips were prepared using plywood forms. UHPC strips were demolded 24 ± 1 hr after casting.

**Figure 2.9:** Pullout Specimens cast on Base Slab 1

**Figure 2.10:** Pullout Specimens cast on Base Slabs 2 and 3

**Figure 2.11:** Pullout Specimens cast on Base Slab 4

Twenty-two batches of UHPC, based on the previously successful mixture designs, and each with 2% steel fibers by volume, were prepared to cast the pullout specimens. These batches were prepared before the Mixtures, A and B, were finalized. The mixture proportions for these twenty-two UHPC batches are presented in Tables 2.5 and 2.6. Batches 3 and 6 to 12 were based on Mixture A, while batches 15 to 22 were similar to Mixture B, both shown in Table 2.3. The pullout specimens cast on Base Slab 1 consisted of UHPC strips with nominal dimensions of 36 × 3.125 × 13 in. (length × width × depth). The pullout specimens cast on Base Slabs 2, 3 and 4 consisted of UHPC strips with nominal dimensions of 72 × 3.125 × 8 in. (length × width × depth).

**Table 2.5:** Mixture Proportions (Cubic Yard Basis) for Pullout Specimens Batches 1-12

| **Material Type** | **Batch 1,2** | **Batch 3, 6-12** | **Batch 4** | **Batch 5** |
|---|---|---|---|---|
| **Cement (lb)** | 1185 | 1210 | 1213 | 1213 |
| **Slag (lb)** | 575 | 587 | 588 | 588 |
| **Silica Fume (lb)** | 158 | 161 | 161 | 161 |
| **Fine Aggregate (lb)** | 1574 | 1607 | 1610 | 1610 |
| **Water (lb)** | 329 | 302 | 312 | 312 |
| **HRWR (lb)** | 54 (P150) | 55 (P150) | 46 (P150) | 66 (P150) |
| **HRWR (lb)** | 23.5 (O100) | 24 (O100) | 20 (O100) | - |
| **Fibers (lb) (2% by volume)** | 265 | 265 | 265 | 265 |
| ***w/cm* ratio** | 0.20 | 0.183 | 0.183 | 0.183 |

**Notation:** HRWR: High Range Water Reducer, P150: ChrysoPremia 150, O100: Chryso Optima 100, *w/cm* ratio: water to cementitious materials ratio

**Table 2.6:** Mixture Proportions (Cubic Yard Basis) for Pullout Specimens Batches 13-22

| | **Batch** | **Batch** |
|---|---|---|
| **Material Type** | **13-14** | **15-22** |
| **Cement (lb)** | 1229 | 1191 |
| **Slag (lb)** | 597 | 576 |
| **Silica Fume (lb)** | 164 | 161 |
| **Fine Aggregate (lb)** | - | 1656 |
| **No. 10 Sieve Sand (Size < 2 mm) (lb)** | 1663 | - |
| **Water (lb)** | 291 | 280 |
| **HRWR (lb)** | 48 (P150) | 46 (A555) |
| **HRWR (lb)** | 21 (O100) | 23 (A593) |
| **Set Accelerating Admixture** | - | 35 (DS400) |
| **Fibers (lb) (2% by volume)** | 265 | 265 |
| ***w/cm* ratio** | 0.171 | 0.183 |

**Notation:** HRWR: High Range Water Reducer, P150: ChrysoPremia 150, O100: Chryso Optima 100, A555: Advacast 555, A593: Advacast 593, DS400: Daraset 400, *w/cm* ratio: water to cementitious materials ratio

The pullout tests were performed using the fixture shown in Figure 2.12. The load was applied using a hydraulic jack while the fixture rested on the precast slab. The load cell, placed between the hydraulic jack and reinforcing bar chuck, was used to measure the applied load.

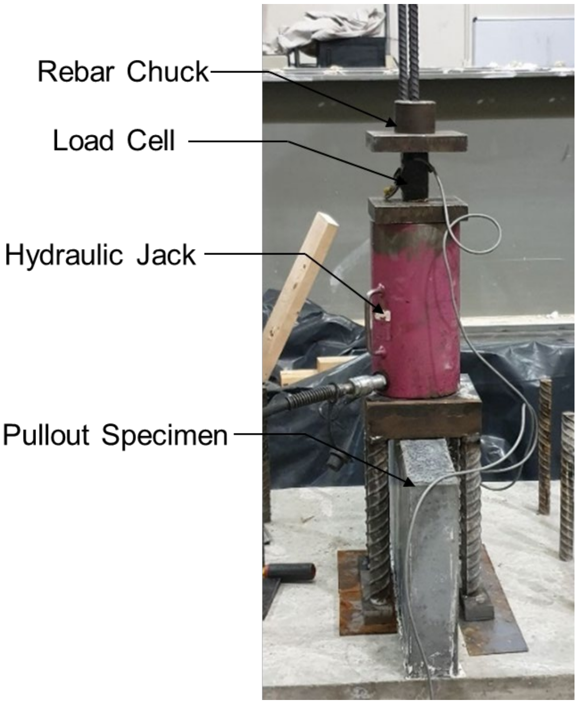


**Figure 2.12:** Pullout Test Apparatus

## 2.6 Beam-end specimens, test setup and procedures

Modified ASTM A944 beam-end specimens were used in this study as an alternate means of evaluating bond strength in UHPC. These specimens have nominal dimensions of 24 × 9 × 20 in. (length × width × depth) and consist of two components: base blocks and UHPC bond blocks, as illustrated in Figures 2.13 and 2.14. The base blocks, shown in Figure 2.14, were cast using normal-strength concrete with a 7-day strength of 5 ksi. These blocks were prepared using plywood forms and Styrofoam, as shown in Figure 2.15. A set retarder was applied to the top and sides of the Styrofoam a few hours before casting. Formwork and Styrofoam were removed 24 ± 1 hours after casting, and the bonding region was sprayed with water to achieve an exposed aggregate appearance, as demonstrated in Figure 2.16. UHPC bond blocks, with nominal dimensions of 6 × 9 × 5 in. (length × width × depth), were cast on top of the base blocks using plywood forms, as shown in Figure 2.17.

**Figure 2.13:** Beam-End Specimens

**Figure 2.14:** Base Blocks for Beam-End Specimens

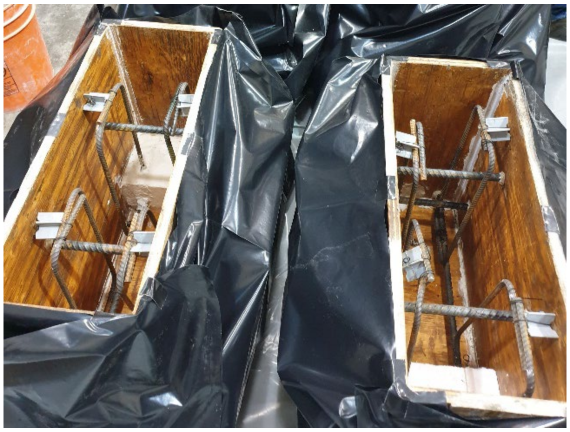


**Figure 2.15:** Base Blocks Formwork

**Figure 2.16:** Exposed Aggregate Look of Base Blocks

**Figure 2.17:** UHPC Bond Block Formwork

Four batches of UHPC were prepared to cast the bond blocks for the beam-end specimens, with two batches (1 and 2) using Mixture A and two batches (3 and 4) using Mixture B. The mixture proportions for these four UHPC batches are detailed in Table 2.7.

**Table 2.7:** Mixture Proportions (Cubic Yard Basis) for Beam-end Specimens Batches 1-4

|  | **Batch** | **Batch** |
|---|---|---|
| **Material Type** | **1-2** | **3-4** |
| **Cement (lb)** | 1210 | 1191 |
| **Slag (lb)** | 587 | 576 |
| **Silica Fume (lb)** | 161 | 161 |
| **Fine Aggregate (lb)** | 1607 | 1656 |
| **Water (lb)** | 302 | 280 |
| **HRWR (lb)** | 55 (P150) | 46 (A555) |
| **HRWR (lb)** | 24 (O100) | 23 (A593) |
| **Set Accelerating Admixture** | - | 35 (DS400) |
| **Fibers (lb) (2% by volume)** | 265 | 265 |
| ***w/cm* ratio** | 0.183 | 0.183 |

**Notation:** HRWR: High Range Water Reducer, P150: ChrysoPremia 150, O100: Chryso Optima 100, A555: Advacast 555, A593: Advacast 593, DS400: Daraset 400, *w/cm* ratio: water to cementitious materials ratio

The beam-end tests were performed in accordance with ASTM A944 using the test apparatus shown in Figure 2.18.

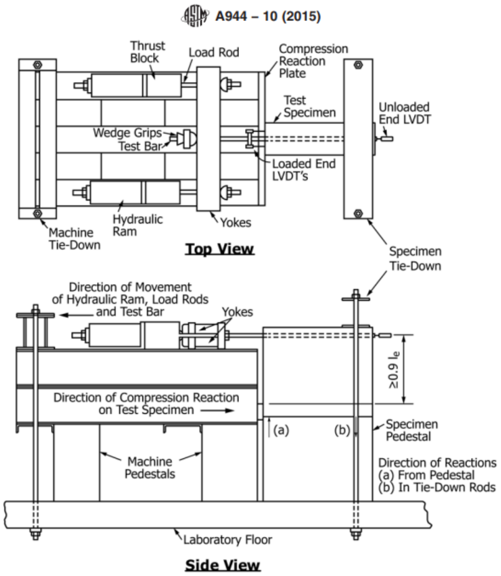


**Figure 2.18:** Beam-End Test (Darwin and Graham 1993, ASTM A944)

## 2.7 Beam-splice specimens, test setup and procedures

The beam-splice tests were conducted to assess bond strength and to develop design provisions for splice lengths of reinforcing bars in UHPC. The beam-splice specimens, with nominal dimensions of 12 ft × 20 in. × 8 or 10 in. (effective length × width × depth), consist of two side panels cast with high-strength concrete with a nominal compressive strength of 14 ksi, which are spliced across a close strip containing UHPC. The use of high-strength concrete in the side panels served the purpose of reducing the time needed before casting the UHPC strips.

The side panels were cast using plywood forms, as depicted in Figure 2.19. A set retarder was applied to the formwork side corresponding to the bonding region a few hours before casting. The side forms were removed 24 ± 1 hours after casting, and the bonding regions were sprayed with water to achieve an exposed aggregate appearance, as shown in Figure 2.20. UHPC strips were cast using plywood forms, as shown in Figure 2.21.

**Figure 2.19:** Beam-Splice Specimen Side Panels

**Figure 2.20:** Exposed Aggregate Look of Side Panel

**Figure 2.21:** Formwork for Casting UHPC Strip for Beam-Splice Specimen

Figure 2.22 shows the plan view of the test specimen. Each specimen had three test bars spliced in tension region. The specimens with a 2.5 in. nominal concrete cover, labeled as C2.5 in Table 3.9, had top-cast test splices, while specimens with a 1 in. nominal concrete cover, labeled as C1, in Table 3.9 had bottom-cast test splices. Specimens with bottom-cast test splices were inverted prior to testing. Additionally, all specimens had two bars spliced in compression region, as shown in Figure 2.23. The bar size, bar type, nominal lap splice length and bar spacing for test splices varied for different specimens, as shown in Table 2.11. The bar size, bar type, and nominal lap splice length for bars spliced in compression region were the same as those of tension region. Moreover, all spliced bars in the compression region had a center-to-center bar spacing of three bar diameters. Figure 2.24 shows the side view of a beam-splice specimens during testing.

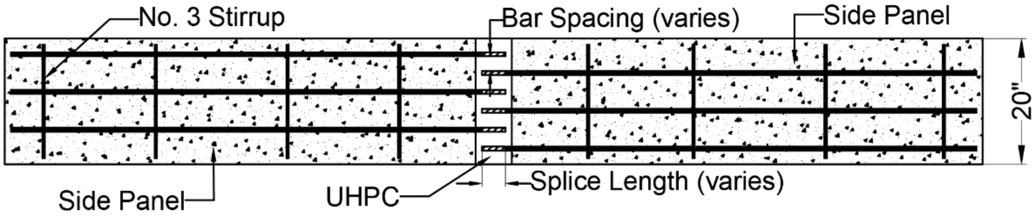


**Figure 2.22:** Test Splices Plan View

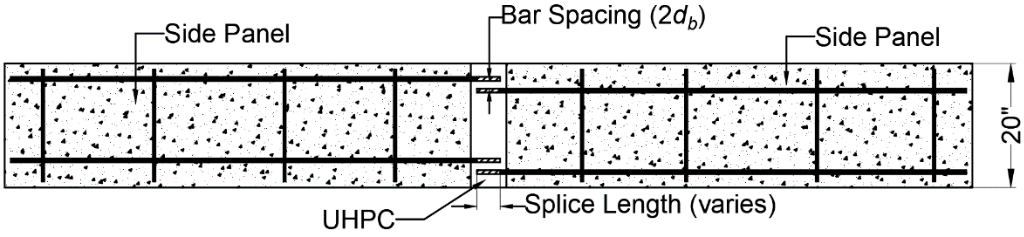


**Figure 2.23:** Bars Spliced in Compression Region Plan View

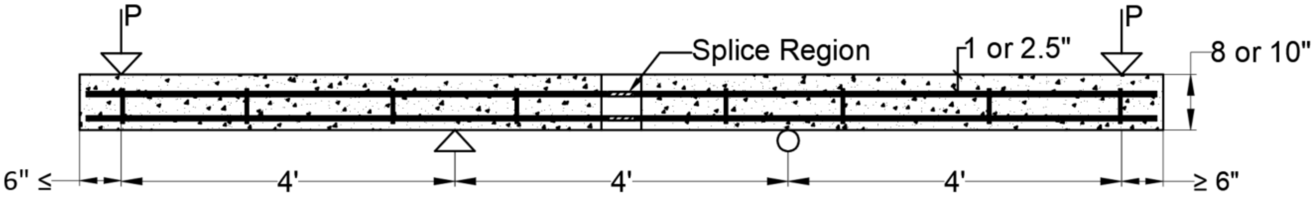


**Figure 2.24:** Beam-Splice Specimens Side View during Testing

The usual spacing between the spliced bars was 6 in. center-to-center within the side panels; however, there were exceptions. For five splice specimens, identified by the specimen IDs U5-L3.75-C2.5-Sp1$^7/_8$, E5-L3.75-C2.5-Sp1$^7/_8$, T5-L3.75-C2.5-Sp1$^7/_8$, U4-L3-C2.5- Sp1$^1/_2$, and E4-L3-C2.5- Sp1$^1/_2$, as detailed in Table 3.9, the center-to-center spacing between the spliced bars within the side panels was either 3$^3/_4$ in. (specimens with No. 5 bars) or 3 in.

(specimens with No. 4 bars). No. 3 stirrups and $^{3}/_{8}$-in. diameter zinc threaded rods, as shown in Figure 2.25, were used in side panels to secure the test bars in place.

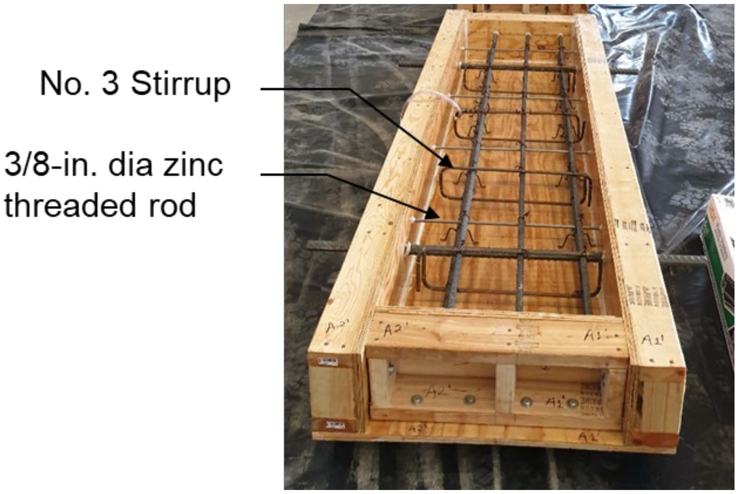


**Figure 2.25:** Reinforcing Steel Configuration in Side Panels

Twenty-eight batches of UHPC were prepared using Mixture B to cast the closure strips for beam-splice specimens.

The splice tests were performed using the four-point bending test setup shown in Figure 2.26. Beams were tested with the bars in tension on the upper side of the member to allow for easy observation of the splice region during loading. The load was applied using four hydraulic jacks resting on two steel spreader beams placed on top of the test specimen. Threaded rods with nuts above the test setup and below the strong floor (Figure 2.26) transmitted the applied loads from the hydraulic jacks to the strong floor. Load cells, placed above the hydraulic jacks were used to measure the applied load. Three potentiometers, one at mid-span and one beneath each of the loading points, were used to measure the vertical displacements of the test specimens. The deflection of the test specimens was calculated as the difference between the upward displacement at the mid-span and the average of the downward displacements measured beneath the loading points.

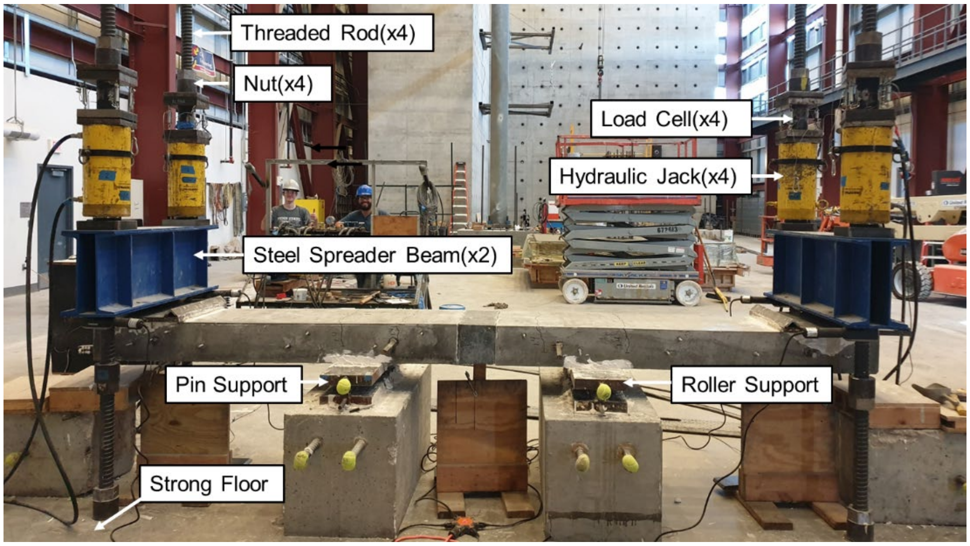


**Figure 2.26:** Beam-Splice Test Setup

## 2.8 Bond test program

The main parameters investigated in pullout tests were the splice length of the No. 5 bars to the No. 8 bars extending from the base slab, the bar spacing, and the type of reinforcing bar (uncoated, epoxy-coated, and textured-epoxy-coated). Nominal properties of pullout specimens are detailed in Table 2.8. The primary parameters investigated in beam-end tests were the type of reinforcing bar (uncoated, epoxy-coated, and textured-epoxy-coated) and the UHPC Mixture, A or B. Nominal properties of beam-end specimens are shown in Table 2.9. The main parameters investigated in splice tests were splice length of reinforcing bars, bar size, concrete cover, bar spacing, and type of reinforcing bars. Nominal properties of beam-splice specimens are shown in Table 2.10.

**Table 2.8:** Pullout Specimens Nominal Properties

| Specimen ID | $f_c'$ ksi | $\ell_{dn}$ in. | $\ell_{sn}$ in. | $c_{son}$ in. | $c_{sin}$ in. | No. of bars tested |
|---|---|---|---|---|---|---|
| U5-L2.75-Sp4 | 14 | 3.75 | 2.75 | 1.25 | 1.69 | 5 |
| E5-L2.75-Sp4 | 14 | 3.75 | 2.75 | 1.25 | 1.69 | 5 |
| U5-L4-Sp4 | 14 | 5.00 | 4.00 | 1.25 | 1.69 | 5 |
| E5-L4-Sp4 | 14 | 5.00 | 4.00 | 1.25 | 1.69 | 5 |
| T5-L4-Sp4 | 14 | 5.00 | 4.00 | 1.25 | 1.69 | 5 |
| U5-L5.25-Sp4 | 14 | 6.25 | 5.25 | 1.25 | 1.69 | 5 |
| E5-L5.25-Sp4 | 14 | 6.25 | 5.25 | 1.25 | 1.69 | 5 |
| T5-L5.25-Sp4 | 14 | 6.25 | 5.25 | 1.25 | 1.69 | 5 |
| U5-L6-Sp4 | 14 | 7.00 | 6.00 | 1.25 | 1.69 | 5 |
| E5-L6-Sp4 | 14 | 7.00 | 6.00 | 1.25 | 1.69 | 5 |

| Specimen ID | $f_c'$ ksi | $\ell_{dn}$ in. | $\ell_{sn}$ in. | $c_{son}$ in. | $c_{sin}$ in. | No. of bars tested |
|---|---|---|---|---|---|---|
| T5-L6-Sp4 | 14 | 7.00 | 6.00 | 1.25 | 1.69 | 3 |
| U5-L2.75-Sp1$^3/_{16}$ | 14 | 3.75 | 2.75 | 1.25 | 0.28 | 5 |
| E5-L2.75-Sp1$^3/_{16}$ | 14 | 3.75 | 2.75 | 1.25 | 0.28 | 5 |
| U5-L6-Sp1$^3/_{16}$ | 14 | 7.00 | 6.00 | 1.25 | 0.28 | 5 |
| E5-L6-Sp1$^3/_{16}$ | 14 | 7.00 | 6.00 | 1.25 | 0.28 | 5 |
| T5-L6-Sp1$^3/_{16}$ | 14 | 7.00 | 6.00 | 1.25 | 0.28 | 5 |

**Notation:**

• Specimen ID notation example: U5-L2.75-Sp4, the first term U5 represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5 Bars); L2.75 represents a nominal splice length of 2.75 in.; Sp4 represents a nominal center-to-center spacing of 4 in. between the test bar and nearest No. 8 splice bar extended from the base slab.

- $f_c'$: target compressive strength of UHPC at testing
- $\ell_{dn}$: Nominal embedment length
- $\ell_{sn}$: Nominal splice length
- $c_{son}$: Nominal side cover
- $c_{sin}$: Nominal half the clear spacing of test bars to the nearest No. 8 extended bars

**Table 2.9:** Beam-End Specimens Nominal Properties

| Specimen ID | $f_c'$ ksi | $\ell_{sn}$ in. | Nominal Top Cover in. | Nominal Side Cover 1 in. | Nominal Side Cover 2 in. | Nominal Average Side Cover in. | UHPC Mixture | No. of bars tested |
|---|---|---|---|---|---|---|---|---|
| U5-L5 | 14 | 5 | 2.19 | 4.19 | 4.19 | 4.19 | A | 4 |
| E5-L5 | 14 | 5 | 2.19 | 4.19 | 4.19 | 4.19 | A | 4 |
| T5-L5 | 14 | 5 | 2.19 | 4.19 | 4.19 | 4.19 | A | 4 |
| U5-L5 | 14 | 5 | 2.19 | 4.19 | 4.19 | 4.19 | B | 4 |
| E5-L5 | 14 | 5 | 2.19 | 4.19 | 4.19 | 4.19 | B | 4 |
| T5-L5 | 14 | 5 | 2.19 | 4.19 | 4.19 | 4.19 | B | 4 |

**Notation:**

• Specimen ID notation example: U5-L5, the first term U5 represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5 Bars); L5 represents a nominal splice length of 5 in.

- $f_c'$: target compressive strength of UHPC at testing
- $\ell_{sn}$: Nominal splice length

**Table 2.10:** Beam-Splice Specimens Nominal Properties

| Specimen ID | $b$ in. | $h$ in. | $b_u$ in. | $f_c'$ ksi | $\ell_{dn}$ in. | $\ell_{sn}$ in. | $c_{cn}$, in. | $c_{cn}$, in. |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Top** | **Side** |
| U5-L3.75-C2.5-Sp3 | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 2.5 | 2.19 |
| E5-L3.75-C2.5-Sp3 | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 2.5 | 2.19 |
| T5-L3.75-C2.5-Sp3 | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 2.5 | 2.19 |
| U5-L5-C2.5-Sp3 | 20 | 8 | 7.00 | 14 | 6.00 | 5.00 | 2.5 | 2.19 |
| E5-L5-C2.5-Sp3 | 20 | 8 | 7.00 | 14 | 6.00 | 5.00 | 2.5 | 2.19 |
| U5-L6.25-C2.5-Sp3 | 20 | 8 | 8.25 | 14 | 7.25 | 6.25 | 2.5 | 2.19 |
| E5-L6.25-C2.5-Sp3 | 20 | 8 | 8.25 | 14 | 7.25 | 6.25 | 2.5 | 2.19 |
| U5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 2.5 | 5.00 |
| E5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 2.5 | 5.00 |
| T5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 2.5 | 5.00 |
| U5-L3.75-C1-Sp3 | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 1.0 | 2.19 |
| E5-L3.75-C1-Sp3 | 20 | 8 | 5.75 | 14 | 4.75 | 3.75 | 1.0 | 2.19 |
| U5-L5.5-C1-Sp3 | 20 | 8 | 7.50 | 14 | 6.50 | 5.50 | 1.0 | 2.19 |
| E5-L5.5-C1-Sp3 | 20 | 8 | 7.50 | 14 | 6.50 | 5.50 | 1.0 | 2.19 |
| T5-L5.5-C1-Sp3 | 20 | 8 | 7.50 | 14 | 6.50 | 5.50 | 1.0 | 2.19 |
| U5-L5.5-C1-Sp1$^{7}/_{8}$ | 20 | 8 | 7.50 | 14 | 6.50 | 5.50 | 1.0 | 5.00 |
| E5-L5.5-C1-Sp1$^{7}/_{8}$ | 20 | 8 | 7.50 | 14 | 6.50 | 5.50 | 1.0 | 5.00 |
| T5-L5.5-C1-Sp1$^{7}/_{8}$ | 20 | 8 | 7.50 | 14 | 6.50 | 5.50 | 1.0 | 5.00 |
| U4-L3-C2.5-Sp3 | 20 | 8 | 5.00 | 14 | 4.00 | 3.00 | 2.5 | 2.25 |
| E4-L3-C2.5-Sp3 | 20 | 8 | 5.00 | 14 | 4.00 | 3.00 | 2.5 | 2.25 |
| U4-L4-C2.5-Sp3 | 20 | 8 | 6.00 | 14 | 5.00 | 4.00 | 2.5 | 2.25 |
| E4-L4-C2.5-Sp3 | 20 | 8 | 6.00 | 14 | 5.00 | 4.00 | 2.5 | 2.25 |
| U4-L3-C2.5-Sp1$^{1}/_{2}$ | 20 | 8 | 5.00 | 14 | 4.00 | 3.00 | 2.5 | 6.00 |
| E4-L3-C2.5-Sp1$^{1}/_{2}$ | 20 | 8 | 5.00 | 14 | 4.00 | 3.00 | 2.5 | 6.00 |
| U8-L6-C2.5-Sp3 | 20 | 10 | 8.00 | 14 | 7.00 | 6.00 | 2.5 | 2.00 |
| E8-L6-C2.5-Sp3 | 20 | 10 | 8.00 | 14 | 7.00 | 6.00 | 2.5 | 2.00 |
| U8-L8-C2.5-Sp3 | 20 | 10 | 10.00 | 14 | 9.00 | 8.00 | 2.5 | 2.00 |
| E8-L8-C2.5-Sp3 | 20 | 10 | 10.00 | 14 | 9.00 | 8.00 | 2.5 | 2.00 |

**Notation:**

- Specimen ID notation example: U5-L3.75-C2.5-Sp3, the first term U5 represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5 Bars); L3.75 represents a nominal splice length of 3.75 in.; C2.5 represents a nominal concrete top cover of 2.5 in.; Sp3 represents a nominal center-to-center spacing of 3 in. between the spliced bars
- $b$: nominal beam width
- $h$: nominal beam depth
- $b_u$: nominal width of UHPC strip between precast slabs

- $f_c'$: target compressive strength of UHPC at testing
- $\ell_{dn}$: Nominal embedment length
- $\ell_{sn}$: Nominal splice length
- $c_{cn}$: Nominal concrete cover

# CHAPTER 3: TEST RESULTS

## 3.1 UHPC test results

### 3.1.1 Plastic concrete properties

Table 3.1 summarizes the plastic properties of Mixtures A and B shown in Table 2.1 of Chapter 2. Mixture A exhibited higher flow (10.13 in.) and a greater unit weight (155.7 lb/ft³) compared to Mixture B, which had a flow of 9.75 in. and a unit weight of 153.6 lb/ft³. Additionally, when observed visually after mixing, Mixture B demonstrated superior fiber distribution compared to Mixture A.

**Table 3.1:** Plastic Properties of UHPC Mixtures A and B

| Properties | Mixture A | Mixture B |
|---|---|---|
| **Flow (in.)** | 10.13 | 9.75 |
| **Unit Weight (lb/ft$^3$)** | 155.7 | 153.6 |
| **Temperature (°F)** | 76 | 74 |

### 3.1.2 Hardened concrete properties

Table 3.2 shows the compressive strength of the two mixtures. Mixture A exhibited slightly higher early strengths, with values of 9.56 ksi and 14.95 ksi at 1 and 7 days, than Mixture B, which achieved 8.57 and 14.40 ksi at 1 day and 7 days, respectively. In the long term, however, Mixture B surpassed Mixture A, with a strength of 18.44 ksi at 28 days, compared to Mixture A, which reached a strength of 16.54 ksi at the same age.

**Table 3.2:** Compressive Strength of UHPC Mixtures A and B

| Batch / Strength | Mixture A | Mixture B |
|---|---|---|
| **1 day (ksi)** | 9.56 | 8.57 |
| **3-day (ksi)** | 12.13 | 11.89 |
| **7-day (ksi)** | 14.95 | 14.40 |
| **14-day (ksi)** | 15.45 | 15.10 |
| **28-day (ksi)** | 16.54 | 18.44 |

Tables 3.3 and 3.4 show the flexure test results for Mixtures A and B, respectively. In two of the beams of Mixture B tested at the age of 3 days, the fracture occurred outside the middle third of the span. The results for these beams were discarded and are not included in the test results. Mixture B exhibited better flexural performance than Mixture A, with an extreme fiber stress at peak strength of 2885 psi, compared to the average for three specimens for Mixture A of 1900 psi at an age of 3 days.

**Table 3.3:** Flexure Test Results for Mixture A

| **Specimen ID** | **A-1** | **A-2** | **A-3** | **A-4** | **A-5** | **A-6** |
|---|---|---|---|---|---|---|
| **L, in.** | 9 | 9 | 9 | 9 | 9 | 9 |
| **$P_1$, lbf** | 4607 | 3829 | 4268 | 5809 | 6580 | 5794 |
| **$f_1$, psi** | 1535 | 1275 | 1425 | 1935 | 2195 | 1930 |
| **$\delta_1$, in.** | 0.002 | 0.0015 | 0.0015 | 0.003 | 0.0025 | 0.0025 |
| **$P_p$, lbf** | 6909 | 5436 | 4738 | 8239 | 9288 | 7520 |
| **$f_p$, psi** | 2305 | 1810 | 1580 | 2745 | 3095 | 2505 |
| **$\delta_p$, in.** | 0.0375 | 0.0140 | 0.0160 | 0.0220 | 0.0200 | 0.0165 |
| **$P_{600}^D$, lbf** | 6474 | 4201 | 4702 | 7958 | 9214 | 7451 |
| **$f_{600}^D$, psi** | 2160 | 1400 | 1565 | 2655 | 3070 | 2485 |
| **$P_{150}^D$,** | 6120 | 5649 | 3636 | 6635 | 6503 | 5782 |
| **$f_{150}^D$, psi** | 2040 | 1885 | 1210 | 2210 | 2170 | 1925 |
| **$T_{150}^D$, in. - lbf** | 380 | 280 | 260 | 450 | 470 | 400 |
| **$f_{e,150}^D$, psi** | 2110 | 1555 | 1445 | 2500 | 2610 | 2220 |
| **$R_{T,150}^D$, %** | 137.5 | 122 | 101.5 | 129 | 119 | 115 |
| **Age at testing, days** | 3 | 3 | 3 | 7 | 7 | 7 |

**Notation:** Specimen ID notation example: A-1 represents beam specimen 1 of Mixture A.
L: span length
$P_1$: First-Peak Load
$P_p$: Peak Load
$\delta_1$: Net deflection at First-Peak Load
$\delta_p$: Net deflection at Peak Load
$f_1$: First-Peak Strength
$f_p$: Peak Strength
$P_{600}^D$: Residual Load at net deflection of L/600
$f_{600}^D$: Residual Strength at net deflection of L/600
$P_{150}^D$: Residual Load at net deflection of L/150
$f_{150}^D$: Residual Strength at net deflection of L/150
$T_{150}^D$: Area under the load vs. net deflection curve 0 to L/150
$f_{e,150}^D$: Equivalent flexural strength
$R_{T,150}^D$: Equivalent flexural strength ratio

**Table 3.4:** Flexure Test Results for Mixture B

| **Specimen ID** | **B-1** | **B-2** | **B-3** | **B-4** |
|---|---|---|---|---|
| **L, in.** | 9 | 9 | 9 | 9 |
| **$P_1$, lbf** | 6434 | 7194 | 7590 | 8337 |
| **$f_1$, psi** | 2145 | 2400 | 2530 | 2780 |
| **$\delta_1$, in.** | 0.005 | 0.005 | 0.005 | 0.005 |
| **$P_p$, lbf** | 8652 | 9636 | 10505 | 12235 |
| **$f_p$, psi** | 2885 | 3210 | 3500 | 4080 |
| **$\delta_p$, in.** | 0.0220 | 0.0270 | 0.0265 | 0.0275 |
| **$\mathbf{P_{600}^{D}}$, lbf** | 8148 | 8765 | 9812 | 10707 |
| **$\mathbf{f_{600}^{D}}$, psi** | 2715 | 2920 | 3270 | 3570 |
| **$\mathbf{P_{150}^{D}}$,** | 6781 | 7321 | 8025 | 10039 |
| **$\mathbf{f_{150}^{D}}$, psi** | 2260 | 2440 | 2675 | 3345 |
| **$\mathbf{T_{150}^{D}}$, in. - lbf** | 450 | 500 | 540 | 640 |
| **$\mathbf{f_{e,\,150}^{D}}$, psi** | 2500 | 2780 | 3000 | 3555 |
| **$\mathbf{R_{T,\,150}^{D}}$, %** | 116.5 | 116 | 118.5 | 128 |
| **Age at testing, days** | 3 | 7 | 7 | 7 |

Note: For an explanation of specimen IDs and each parameter, refer to the notation provided with Table 3.3

Table 3.5 presents the average flexure test results of Mixture A and Mixture B (for three specimens each) at an age of 7 days. Mixture B demonstrated superior properties in all cases, including a higher average peak strength of 3595 psi and a peak deflection of 0.0270 in., compared with Mixture A, which had an average peak strength 2780 psi and a peak deflection of 0.0195 in.

**Table 3.5:** Comparative Average Flexural Test Results for Mixtures A and B at 7 Days

| **Specimen ID** | **Mixture A** | **Mixture B** |
|---|---|---|
| **$f_1$, psi** | 2020 | 2570 |
| **$f_p$, psi** | 2780 | 3595 |
| **$\delta_p$, in.** | 0.0195 | 0.0270 |
| **$\mathbf{f_{600}^{D}}$, psi** | 2735 | 3255 |
| **$\mathbf{f_{150}^{D}}$, psi** | 2100 | 2820 |
| **$\mathbf{f_{e,\,150}^{D}}$, psi** | 2445 | 3110 |

Note: For an explanation of specimen IDs and each parameter, refer to the notation provided with Table 3.3

## 3.2 Pullout tests

The pullout test bars are identified to represent the variables associated with the bar being tested. For example, for the bar identified as U5-L2.75-Sp4-B9S3, the first term, U5, represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated, and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5); L2.75 represents a nominal splice length of 2.75 in.; Sp4 represents a nominal center-to-center spacing of 4 in. between the test bar and the nearest No. 8 splice bar extended from the base slab; B9S3 represents the Batch 9 (as reported in Tables 2.6 and 2.7) of UHPC casting on precast Slab 3.

Twenty-two pullout specimens containing multiple test bars-six per specimen on Base Slab 1, eight per specimen on Base Slab 2, six per specimen on Base Slab 3, and two per specimen on Base Slab 4 were cast and tested for a total of 92 reinforcing bars covering uncoated, epoxy-coated, and textured-epoxy-coated ASTM A1035 Grade 100 No. 5 bars. The specimens had a nominal splice length of 2.75, 4, 5.25, or 6 in., a nominal side cover of two bar diameters, $2d_b$, a nominal center-to-center spacing between the test bar and the nearest No. 8 splice bar of either $1^3/_{16}$ or 4 in., and a UHPC compressive strength ranging from 13.04 to 14.79 ksi. The nominal embedment length was one inch greater than the nominal splice length for all reinforcing bars. The main parameters investigated in this test included the splice length of reinforcing bars, the bar type, and the bar spacing. The actual measurements of embedment length, splice length, side cover, center-to-center spacing between the test bar and the nearest No. 8 splice bar, and test results are shown in Table 3.6. All pullout tests reported in Table 3.6 were performed seven days after casting the UHPC.

During the initial phase of the investigation, six pullout specimens were cast and tested on Base Slab 1, involving a total of 14 reinforcing bars. This phase served as a trial for the test fixture. The test results of two reinforcing bars were significantly affected by cracks that extended from the testing of adjacent bars. Similar to observations made by Yuan and Graybeal (2014), the reinforcing bars at the very ends of the UHPC strips consistently exhibited lower strength, possibly due to variations in fiber distribution within the UHPC, as noted by Yuan and Graybeal (2014). The test results for all these reinforcing bars are not included in Table 3.6; they are instead reported in the Table D.1 in Appendix D.

**Table 3.6:** Pullout Test Results

| Specimen ID | $f_{cm}$ ksi | $\ell_d$ in. | $\ell_s$ in. | $c_{so}$ in. | $c_{si}$ in. | $f_{s,\max}$ ksi |
|---|---|---|---|---|---|---|
| U5-L2.75-Sp4-B9S3 | 13.69 | 3.81 | 2.81 | 1.25 | 1.81 | 43 |
| U5-L2.75-Sp4-B10S3 | 14.42 | 3.88 | 2.88 | 1.25 | 1.75 | 49 |
| U5-L2.75-Sp4-B10S3 | 14.42 | 3.69 | 2.69 | 1.25 | 1.66 | 57 |
| E5-L2.75-Sp4-B9S3 | 13.69 | 3.81 | 2.81 | 1.25 | 1.78 | 48 |
| E5-L2.75-Sp4-B9S3 | 13.69 | 3.75 | 2.75 | 1.25 | 1.75 | 37 |
| E5-L2.75-Sp4-B10S3 | 14.42 | 3.75 | 2.75 | 1.25 | 1.78 | 58 |
| U5-L4-Sp4-B7S2 | 14.79 | 5.19 | 4.19 | 1.06 | 1.56 | 76 |
| U5-L4-Sp4-B8S2 | 14.49 | 5.19 | 4.19 | 1.06 | 1.59 | 73 |

| Specimen ID | $f_{cm}$ ksi | $\ell_d$ in. | $\ell_s$ in. | $c_{so}$ in. | $c_{si}$ in. | $f_{s,\text{max}}$ ksi |
|---|---|---|---|---|---|---|
| U5-L4-Sp4-B8S2 | 14.49 | 5.13 | 4.13 | 1.06 | 1.63 | 69 |
| E5-L4-Sp4-B7S2 | 14.79 | 5.06 | 4.06 | 1.00 | 1.50 | 60 |
| E5-L4-Sp4-B7S2 | 14.79 | 5.19 | 4.19 | 1.19 | 1.47 | 63 |
| E5-L4-Sp4-B8S2 | 14.49 | 5.19 | 4.19 | 1.06 | 1.53 | 69 |
| T5-L4-Sp4-B16S4 | 13.29 | 5.19 | 4.19 | 1.19 | 1.63 | 60 |
| U5-L5.25-Sp4-B11S2 | 14.60 | 6.31 | 5.31 | 1.25 | 1.56 | 131 |
| U5-L5.25-Sp4-B12S3 | 13.19 | 6.44 | 5.44 | 1.25 | 1.63 | 116 |
| U5-L5.25-Sp4-B12S3 | 13.19 | 6.19 | 5.19 | 1.19 | 1.56 | 114 |
| E5-L5.25-Sp4-B11S2 | 14.60 | 6.31 | 5.31 | 1.25 | 1.44 | 79 |
| E5-L5.25-Sp4-B11S2 | 14.60 | 6.38 | 5.38 | 1.19 | 1.47 | 93 |
| E5-L5.25-Sp4-B12S3 | 13.19 | 6.31 | 5.31 | 1.25 | 1.63 | 107 |
| T5-L5.25-Sp4-B22S2 | 13.21 | 6.50 | 5.50 | 1.19 | 1.53 | 110 |
| T5-L5.25-Sp4-B22S2 | 13.21 | 6.31 | 5.31 | 1.06 | 1.56 | 103 |
| T5-L5.25-Sp4-B22S2 | 13.21 | 6.31 | 5.31 | 1.13 | 1.53 | 119 |
| U5-L6-Sp4-B19S2 | 14.46 | 7.06 | 6.06 | 1.25 | 1.66 | 114 |
| U5-L6-Sp4-B19S2 | 14.46 | 7.00 | 6.00 | 1.13 | 1.69 | 114 |
| U5-L6-Sp4-B19S2 | 14.46 | 7.06 | 6.06 | 1.25 | 1.53 | 118 |
| E5-L6-Sp4-B20S2 | 13.47 | 7.00 | 6.00 | 1.25 | 1.56 | 121 |
| E5-L6-Sp4-B20S2 | 13.47 | 6.88 | 5.88 | 1.25 | 1.50 | 130 |
| E5-L6-Sp4-B20S2 | 13.47 | 7.06 | 6.06 | 1.13 | 1.69 | 120 |
| T5-L6-Sp4-B21S3 | 13.87 | 7.00 | 6.00 | 1.19 | 1.59 | 118 |
| T5-L6-Sp4-B21S3 | 13.87 | 6.88 | 5.88 | 1.25 | 1.50 | 126 |
| U5-L2.75-Sp1$^{3}/_{16}$-B17S3 | 13.04 | 3.69 | 2.69 | 1.19 | 0.13 | 59 |
| U5-L2.75-Sp1$^{3}/_{16}$-B17S3 | 13.04 | 3.69 | 2.69 | 1.13 | 0.19 | 57 |
| U5-L2.75-Sp1$^{3}/_{16}$-B17S3 | 13.04 | 3.56 | 2.56 | 1.25 | 0.19 | 59 |
| E5-L2.75-Sp1$^{3}/_{16}$-B18S3 | 13.04 | 3.69 | 2.69 | 1.13 | 0.19 | 49 |
| E5-L2.75-Sp1$^{3}/_{16}$-B18S3 | 13.04 | 3.75 | 2.75 | 1.06 | 0.19 | 60 |
| E5-L2.75-Sp1$^{3}/_{16}$-B18S3 | 13.04 | 3.69 | 2.69 | 1.00 | 0.25 | 48 |
| U5-L6-Sp1$^{3}/_{16}$-B13S2 | 13.74 | 7.19 | 6.19 | 1.25 | 0.22 | 129 |
| U5-L6-Sp1$^{3}/_{16}$-B13S2 | 13.74 | 7.25 | 6.25 | 1.25 | 0.25 | 127 |
| U5-L6-Sp1$^{3}/_{16}$-B13S2 | 13.74 | 7.31 | 6.31 | 1.13 | 0.22 | 129 |
| E5-L6-Sp1$^{3}/_{16}$-B14S2 | 14.18 | 7.25 | 6.25 | 1.25 | 0.13 | 82 |
| E5-L6-Sp1$^{3}/_{16}$-B14S2 | 14.18 | 7.44 | 6.44 | 1.13 | 0.16 | 92 |

| Specimen ID | $f_{cm}$ ksi | $\ell_d$ in. | $\ell_s$ in. | $c_{so}$ in. | $c_{si}$ in. | $f_{s,\,\max}$ ksi |
|---|---|---|---|---|---|---|
| E5-L6-Sp$1^{3}/_{16}$-B14S2 | 14.18 | 7.13 | 6.13 | 1.19 | 0.13 | 107 |
| T5-L6-Sp$1^{3}/_{16}$-B15S4 | 13.29 | 7.06 | 6.06 | 1.19 | 0.16 | 102 |
| T5-L6-Sp$1^{3}/_{16}$-B15S4 | 13.29 | 7.00 | 6.00 | 1.19 | 0.16 | 110 |
| T5-L6-Sp$1^{3}/_{16}$-B15S4 | 13.29 | 7.00 | 6.00 | 1.19 | 0.16 | 118 |

**Notation:**

- Specimen ID notation example: U5-L2.75-Sp4-B9S3, the first term U5 represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5 Bars); L2.75 represents a nominal splice length of 2.75 in.; Sp4 represents a nominal center-to-center spacing of 4 in. between the test bar and nearest No. 8 splice bar extended from the base slab; B9S3 represents the Batch 9 (as reported in Tables 2.6 and 2.7) of UHPC casting on precast slab 3.

- $f_{cm}$: Compressive strength of UHPC at testing
- $\ell_d$: Actual measurement of embedment length
- $\ell_s$: Actual measurement of splice length
- $c_{so}$: Actual measurement of the side cover
- $c_{si}$: Actual measurement of half the clear spacing of test bars to the nearest No. 8 extended bars
- $f_{s,\max}$: Bar stress at bond failure

The notation, $\ell_d$, $\ell_s$, $c_{so}$, and $c_{si}$, is adopted from ACI 408R-03 “Bond and Development of Straight Reinforcing Bars in Tension” (ACI Committee 408 2003).

Figure 3.1 illustrates the average bar stress at failure for the different types of reinforcing bars with different nominal splice lengths and bar spacing. Uncoated and epoxy-coated bars with splice lengths and bar spacings, respectively, of 2.75 in. and $1^{3}/_{16}$ in., and 6 in. and 4 in. represent the bond strength in Mixture B. All textured-epoxy-coated bars were tested for the bond strength in Mixture B, while the other bars were tested in Mixture A or batches similar to Mixture A with slight variations in mixture proportions, as reported in Table 2.5 of Chapter 2. The test results reveal that, in general, the maximum bar stress increased with an increase in splice length. However, an exception was observed for uncoated bars with a bar spacing of 4 in. and a splice length of 6 in. In this case, bar stress increased from 50 ksi to 120 ksi as the splice length increased from 2.75 inches to 5.25 inches with a bar spacing of 4 in. A slight reduction in average bar stress, from 120 ksi to 115 ksi, was observed as the splice length increased from 5.25 inches to 6 inches. These variations may be the result of differences in fiber distribution within the UHPC. Epoxy-coated bars exhibited an increase in average bar stress from 48 ksi to 124 ksi as the splice length increased from 2.75 in. to 6 in. Similarly, textured-epoxy-coated bars exhibited an increase in average bar stress from 60 ksi to 122 ksi as the splice length increased from 4 in. to 6 in.

Uncoated bars generally exhibited higher average bar stress than epoxy-coated and textured-epoxy-coated bars in most cases. For one test with a splice length of 6 in. and a bar spacing of 4 in., epoxy-coated bars exhibited higher average bar stress than the other two bar types. With a splice length of 5.25 in. and a bar spacing of 4 in., textured-epoxy-coated bars had a higher average bar stress (111 ksi) than epoxy-coated bars (93 ksi), while epoxy-coated bars had a higher average bar stress (64 ksi) than textured-epoxy-coated bars (60 ksi) with a splice length and bar spacing of 4 in.

For similar test parameters, uncoated bars exhibited higher average bar stress at failure with a bar spacing of $1^{3}/_{16}$ than for a bar spacing of 4 inches. In contrast, epoxy-coated bars had higher average bar stress with a bar spacing of $1^{3}/_{16}$ in. for shorter splice length (2.75 in.), but a higher average bar stress with a bar spacing of 4 in. for longer splice length of 6 in.

The pullout test results did not exhibit a specific trend. This lack of a clear trend might be attributed to variations in fiber distribution within the UHPC, which could mask the effects of splice length and bar coatings.

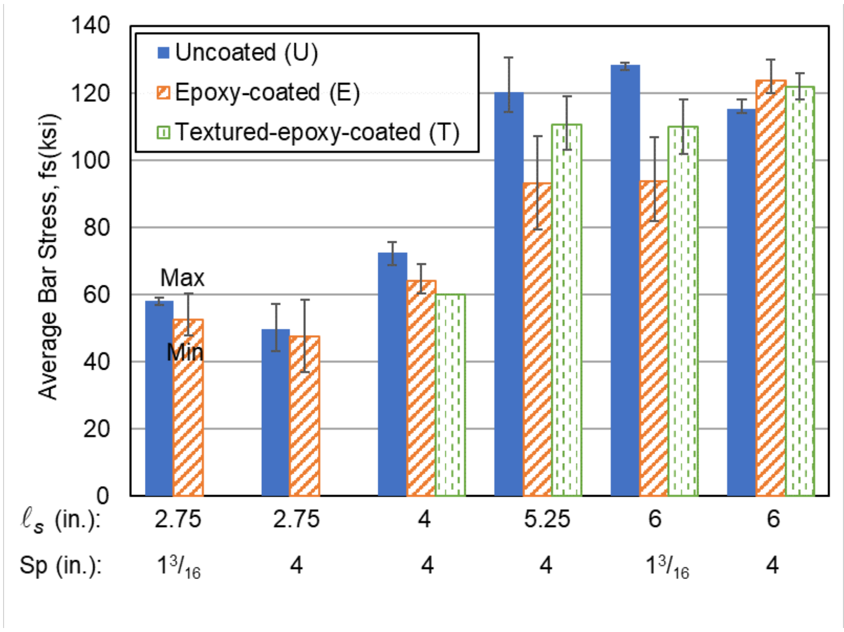


**Figure 3.1:** Average Bar Stress at Failure for Different Reinforcing Bar Types

During the tests, the specimens exhibited splitting and open diagonal cracks in the UHPC, the latter similar to breakout cracks in anchorage tests, as shown in Figures 3.2 and 3.3.

**Figure 3.2:** Splitting Cracks on Pullout Specimen

**Figure 3.3:** Open Diagonal Cracks on Pullout Specimen

## 3.3 Beam-end specimen tests

Twenty-four beam-end specimens were cast and tested. The main parameters investigated in the beam-end tests were the bar type and the UHPC Mixture, A or B. Four uncoated, four epoxy-coated, and four textured-epoxy-coated No. 5 bars with a splice length of 5 in. were tested for each UHPC mixture. The specimens cast with Mixture A were tested in two groups, B1 and B2, respectively, six and seven days after casting. Similarly, the specimens cast with Mixture B were tested in groups B3 and B4, respectively, six and seven days after casting. Figure 3.4 shows the splitting observed in the test specimens at failure.

**Figure 3.4:** Splitting Cracks on Beam-End Specimen

The test results are summarized in Tables 3.7 and 3.8.

**Table 3.7:** Beam-End Test Results (Mixture A)

| Specimen ID | $f_{cm}$ ksi | $\ell_s$ in. | Top Cover in. | Side Cover 1 in. | Side Cover 2 in. | Average Side Cover in. | $f_{s,\ max}$ ksi |
|---|---|---|---|---|---|---|---|
| U5-L5-6D-B1 | 13.42 | 5.06 | 2.13 | 4.13 | 4.00 | 4.06 | 62 |
| U5-L5-6D-B1 | 13.42 | 5.06 | 2.25 | 4.25 | 4.06 | 4.16 | 71 |
| U5-L5-7D-B2 | 14.24 | 5.06 | 2.50 | 4.13 | 4.13 | 4.13 | 68 |
| U5-L5-7D-B2 | 14.24 | 5.06 | 2.44 | 4.06 | 4.25 | 4.16 | 73 |
| E5-L5-6D-B1 | 13.42 | 5.00 | 2.06 | 4.19 | 4.06 | 4.13 | 58 |
| E5-L5-6D-B1 | 13.42 | 5.00 | 2.38 | 3.94 | 4.25 | 4.09 | 72 |
| E5-L5-7D-B2 | 14.24 | 5.13 | 2.06 | 4.31 | 4.19 | 4.25 | 64 |
| E5-L5-7D-B2 | 14.24 | 5.06 | 2.44 | 4.25 | 4.25 | 4.25 | 73 |
| T5-L5-6D-B1 | 13.42 | 5.06 | 2.31 | 4.19 | 4.19 | 4.19 | 62 |
| T5-L5-6D-B1 | 13.42 | 5.13 | 2.25 | 4.19 | 2.25 | 3.22 | 95 |
| T5-L5-7D-B2 | 14.24 | 5.00 | 2.19 | 4.25 | 4.06 | 4.16 | 68 |
| T5-L5-7D-B2 | 14.24 | 5.00 | 2.38 | 4.06 | 4.25 | 4.16 | 85 |

**Notation:**

- Specimen ID notation example: U5-L5-6D-B1, the first term U5 represents the type and size of the bar, and the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size( 5 for No. 5 Bars); L5 represents a nominal splice length of 5 in.; 6D represents the age of UHPC at testing, which is 6 days in the example; B1 represents the Batch 1(as reported in Table 2.8) of UHPC casting for beam-end specimens.
- $f_{cm}$: Compressive strength of UHPC at testing

- $\ell_s$: Actual measurement of splice length
- $f_{s,\max}$: Bar stress at bond failure

**Table 3.8:** Beam-End Test Results (Mixture B)

| Specimen ID | $f_{cm}$ ksi | $\ell_s$ in. | Top Cover in. | Side Cover 1 in. | Side Cover 2 in. | Average Side Cover in. | $f_{s,\max}$ ksi |
|---|---|---|---|---|---|---|---|
| U5-L5-7D-B3 | 13.57 | 5.06 | 2.25 | 4.25 | 4.125 | 4.19 | 90 |
| U5-L5-7D-B3 | 13.57 | 4.94 | 2.25 | 4.13 | 4.250 | 4.19 | 111 |
| U5-L5-8D-B4 | 14.49 | 4.88 | 2.13 | 4.13 | 4.188 | 4.16 | 102 |
| U5-L5-8D-B4 | 14.49 | 5.00 | 2.38 | 4.13 | 4.375 | 4.25 | 115 |
| E5-L5-7D-B3 | 13.57 | 4.88 | 2.38 | 4.13 | 4.250 | 4.19 | 81 |
| E5-L5-7D-B3 | 13.57 | 4.88 | 2.25 | 4.13 | 4.250 | 4.19 | 91 |
| E5-L5-8D-B4 | 14.49 | 5.13 | 2.38 | 4.38 | 4.125 | 4.25 | 86 |
| E5-L5-8D-B4 | 14.49 | 5.00 | 2.38 | 4.25 | 4.125 | 4.19 | 94 |
| T5-L5-7D-B3 | 13.57 | 4.94 | 2.13 | 4.25 | 4.125 | 4.19 | 105 |
| T5-L5-7D-B3 | 13.57 | 4.81 | 2.50 | 4.38 | 4.250 | 4.31 | 102 |
| T5-L5-8D-B4 | 14.49 | 4.81 | 2.25 | 4.13 | 4.313 | 4.22 | 90 |
| T5-L5-8D-B4 | 14.49 | 5.00 | 2.13 | 4.13 | 4.250 | 4.19 | 99 |

Note: For an explanation of specimen IDs and each parameter, refer to the notation provided with Table 3.7

Ignoring the 1.0 ksi difference in compressive strength between groups B1 and B2, the uncoated bars developed bar stresses between 62 and 73 ksi, with an average of 68 ksi, the epoxy-coated bars developed bar stresses between 58 and 73 ksi, with an average of 67 ksi, and the textured-epoxy-coated bars developed bar stresses between 62 and 95 ksi, with an average of 78 ksi, for Mixture A. Similarly, for Mixture B, and again ignoring the 1.0 ksi difference in compressive strength between groups B3 and B4, the uncoated bars developed bar stresses between 90 and 115 ksi, with an average of 104 ksi, the epoxy-coated bars developed bar stresses between 81 and 94 ksi, with an average of 88 ksi, and the textured-epoxy-coated bars developed bar stresses between 90 and 105 ksi, with an average of 99 ksi.

Figure 3.5 compares the average bar stresses for different bar types cast in Mixtures A and B. For Mixture A, the textured-epoxy-coated bars had the highest average bar stress, 78 ksi, while the epoxy-coated bars had the lowest average bar stress, 67 ksi. For Mixture B, the uncoated bars had the highest average bar stress, 104 ksi, and epoxy-coated bars had the lowest average bar stress, 88 ksi. All three types of reinforcing bars exhibited higher average bar stress in Mixture B than in Mixture A. The higher bond strength for the bars cast in Mixture B is likely attributable to the better fiber distribution and higher flexural strength of Mixture B compared to Mixture A.

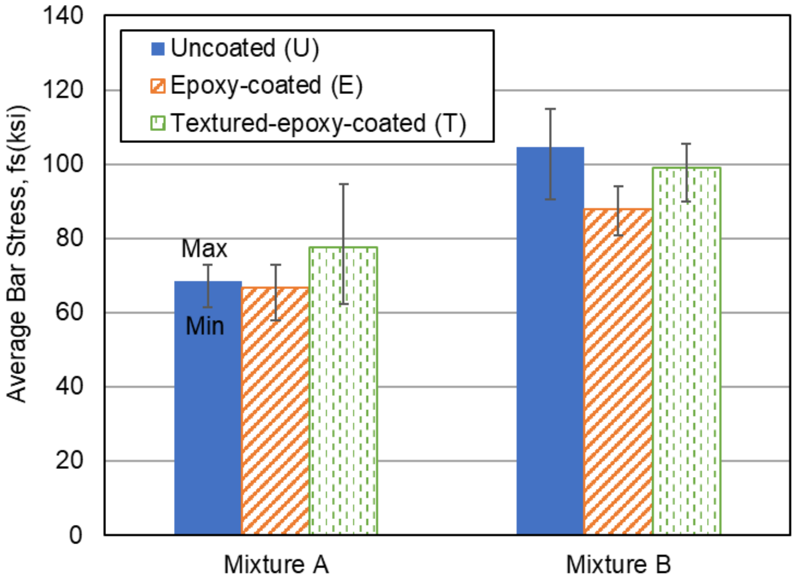


**Figure 3.5:** Comparison of Average Bar Stress for Different Bar Types in Mixtures A and B

## 3.4 Beam-splice specimen tests

Beam-splice specimens are identified to represent the variables associated with the test. For example, for the specimen identified as U5-L3.75-C2.5-Sp3, the first term, U5, represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated, and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5); L3.75 represents a nominal splice length of 3.75 in.; C2.5 represents a nominal concrete top cover of 2.5 in.; Sp3 represents a nominal center-to-center spacing of 3 in. between the spliced bars. Each specimen had three spliced bars at top and two spliced bars at bottom during testing. Splice specimens with No. 8 test bars had a 10 in. depth while the specimens with No. 4 and No. 5 test bars had 8 in. depth. All specimens were cast using UHPC batches based on Mixture B because of its superior flexural performance and bond performance in beam-end tests compared to Mixture A. The first splice specimen, ID U5-L3.75-C2.5-Sp3, was tested eight days after casting the UHPC strip while the remaining all specimens were tested seven days after casting the UHPC strip.

Twenty-eight beam-splice specimens were cast and tested covering uncoated, epoxy-coated, and textured-epoxy-coated ASTM A1035 Grade 100 No. 4, No. 5, and No. 8 reinforcing bars. The specimens with No. 4 test bars had a nominal splice length of either 3 or 4 in., a concrete top cover of 2.5 in., and a center-to-center spacing between the spliced bars of either $1^1/_2$ or 3 in. The specimens with No. 5 test bars had a nominal splice length of either 3.75, 5, 5.5 or 6.25 in., a concrete top cover of 2.5 in. of a bottom cover of 1 in., and a center-to-center spacing between the spliced bars of either $1^7/_8$ or 3 in. The specimens with 1 in. bottom cover were inverted prior to testing. The specimens with No. 8 test bars had a nominal splice length of either 6 or 8 in., a concrete top cover of 2.5 in., and a center-to-center spacing between the spliced bars of 3 in. The nominal embedment length was 1 in. greater than the nominal splice length for all specimens.

The main parameters investigated included the splice length of reinforcing bars, bar size, bar type, bar spacing, and concrete cover. At failure, the specimens exhibited splitting cracks on the top and sides of UHPC closure strip, as shown in Figures 3.6 and 3.7. Specimens with a top cover less than the side cover exhibited splitting cracks on the top, while specimens with top cover greater than side cover exhibited the splitting cracks on the sides of the UHPC strip, strongly suggesting that minimum of the top or side concrete cover governs the failure of the specimen.

**Figure 3.6:** Splitting Cracks on the Top of UHPC Strip in Beam-Splice Specimen

**Figure 3.7:** Splitting Crack on the Side of UHPC Strip in Beam-Splice Specimen

The test results are reported in Table 3.9. Maximum bar stresses at bond failure were calculated using elastic cracked section analysis (Darwin and Dolan 2021). Equations 3.1 to 3.5 (Darwin and Dolan 2021) were employed for calculating the maximum bar stress.

$$f_{s,\max} = \frac{M}{A_s jd} \tag{3.1}$$

$$j = 1 - \frac{k}{3} \tag{3.2}$$

$$k = \sqrt{(\rho n)^2 + 2\,\rho n} - \rho n \tag{3.3}$$

$$\rho = \frac{A_s}{bd} \tag{3.4}$$

$$n = \frac{E_s}{E_c} \tag{3.5}$$

where: $f_{s,max}$ = maximum bar stress at bond failure

$M$ = maximum bending moment at the joint of UHPC strip and side panels

$\rho$ = reinforcement ratio

$A_s$ = area of longitudinal tension reinforcement

$b$ = width of beam-splice specimen

$d$ = effective depth of beam-splice specimen

$E_s$ = modulus of elasticity of steel = 29,000 ksi

$E_c$ = modulus of elasticity of concrete = $57000\sqrt{f'_{cm}}$

$f'_{cm}$ = compressive strength of side panels in psi

**Table 3.9:** Beam-Splice Test Results

| **Specimen ID** | **$f_{cm}$, ksi Side Panels** | **$f_{cm}$, ksi UHPC** | **$\ell_d$ in.** | **$\ell_s$ in.** | **$c_c$, in. Top** | **$c_c$, in. Side** | **$f_{s,\,max}$ ksi** |
|---|---|---|---|---|---|---|---|
| U5-L3.75-C2.5-Sp3 | 11.48 | 15.37 | 4.75 | 3.75 | 2.59 | 2.22 | 91 |
| E5-L3.75-C2.5-Sp3 | 11.4 | 14.33 | 4.75 | 3.75 | 2.44 | 2.25 | 82 |
| T5-L3.75-C2.5-Sp3 | 9.56 | 14.62 | 4.75 | 3.75 | 2.63 | 2.28 | 103 |
| U5-L5-C2.5-Sp3 | 13.45 | 14.74 | 6.00 | 5.00 | 2.56 | 2.22 | 115 |
| E5-L5-C2.5-Sp3 | 10.83 | 14.5 | 6.00 | 5.00 | 2.69 | 2.25 | 102 |
| U5-L6.25-C2.5-Sp3 | 11.40 | 14.26 | 7.25 | 6.25 | 2.66 | 2.25 | 125 |
| E5-L6.25-C2.5-Sp3 | 10.67 | 13.41 | 7.25 | 6.25 | 2.56 | 2.16 | 128 |
| U5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 12.03 | 14.08 | 4.75 | 3.75 | 2.44 | 4.97 | 95 |
| E5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 10.67 | 13.58 | 4.75 | 3.75 | 2.5 | 5.00 | 93 |
| T5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 14.33 | 13.95 | 4.75 | 3.75 | 2.63 | 5.06 | 84 |
| U5-L3.75-C1-Sp3 | 12.03 | 13.9 | 4.75 | 3.75 | 1.22 | 2.19 | 71 |
| E5-L3.75-C1-Sp3 | 10.67 | 13.97 | 4.75 | 3.75 | 1.22 | 2.19 | 70 |
| U5-L5.5-C1-Sp3 | 11.74 | 13.19 | 6.50 | 5.50 | 1.22 | 2.19 | 116 |
| E5-L5.5-C1-Sp3 | 11.79 | 12.92 | 6.50 | 5.50 | 1.00 | 2.09 | 92 |
| T5-L5.5-C1-Sp3 | 12.15 | 13.49 | 6.50 | 5.50 | 1.03 | 2.25 | 110 |

| Specimen ID | $f_{cm,}$ ksi Side Panels | $f_{cm,}$ ksi UHPC | $\ell_d$ in. | $\ell_s$ in. | $c_c$, in. Top | $c_c$, in. Side | $f_{s,\ max}$ ksi |
|---|---|---|---|---|---|---|---|
| U5-L5.5-C1-Sp1$^{7}/_{8}$ | 12.81 | 12.85 | 6.50 | 5.50 | 1.09 | 2.69 | 121 |
| E5-L5.5-C1-Sp1$^{7}/_{8}$ | 13.81 | 14.16 | 6.50 | 5.50 | 1.06 | 2.78 | 104 |
| T5-L5.5-C1-Sp1$^{7}/_{8}$ | 13.81 | 13.70 | 6.50 | 5.50 | 1.03 | 2.75 | 121 |
| U4-L3-C2.5-Sp3 | 10.67 | 13.00 | 4.00 | 3.00 | 2.69 | 2.25 | 122 |
| E4-L3-C2.5-Sp3 | 10.67 | 13.88 | 4.00 | 3.00 | 2.59 | 2.31 | 109 |
| U4-L4-C2.5-Sp3 | 11.34 | 12.95 | 5.00 | 4.00 | 2.75 | 2.25 | 160 |
| E4-L4-C2.5-Sp3 | 13.13 | 13.93 | 5.00 | 4.00 | 2.72 | 2.28 | 143 |
| U4-L3-C2.5-Sp1$^{1}/_{2}$ | 10.7 | 14.14 | 4.00 | 3.00 | 2.47 | 6.06 | 117 |
| E4-L3-C2.5-Sp1$^{1}/_{2}$ | 14.33 | 14.37 | 4.00 | 3.00 | 2.59 | 6.03 | 89 |
| U8-L6-C2.5-Sp3 | 14.88 | 12.29 | 7.00 | 6.00 | 2.50 | 2.00 | 64 |
| E8-L6-C2.5-Sp3 | 14.88 | 12.53 | 7.00 | 6.00 | 2.53 | 1.94 | 48 |
| U8-L8-C2.5-Sp3 | 13.13 | 13.42 | 9.00 | 8.00 | 2.50 | 1.97 | 81 |
| E8-L8-C2.5-Sp3 | 13.13 | 11.15 | 9.00 | 8.00 | 2.63 | 1.94 | 57 |

**Notation:**

- Specimen ID notation example: U5-L3.75-C2.5-Sp3, the first term U5 represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5 Bars); L3.75 represents a nominal splice length of 3.75 in. between the spliced bars; C2.5 represents a nominal concrete top cover of 2.5 in.; Sp3 represents a nominal center-to-center spacing of 3 in. between the spliced bars
- $f_{cm}$: Compressive strength of concrete at testing
- $\ell_d$: Actual measurement of embedment length
- $\ell_s$: Actual measurement of splice length
- $c_c$: Actual measurement of concrete cover
- $f_{s,max}$: Maximum bar stress at bond failure

As described in more detail in Chapter 4, the test results show that the bond strength of reinforcing bars increases with an increase in the splice length. Specifically, for uncoated No. 5 bars, the bar stress at splice failure increased from 91 ksi to 125 ksi as the splice length increased from 3.75 in. to 6.25 in. with bar spacing of 3 in. and a concrete top cover of 2.5 in. Similarly, for uncoated No. 4 bars, the bar stress increased from 122 ksi to 160 ksi as the splice length increased from 3 in. to 4 in. For the uncoated No. 8 bars, the bar stress increased from 64 ksi to 81 ksi as the splice length increased from 6 in. to 8 in. Epoxy-coated and textured-epoxy coated bars exhibited similar trends of increasing in bar stress at splice failure with an increase in splice length.

The uncoated bars exhibited higher bar stresses at splice failure than the epoxy-coated bars in all cases, except for the No. 5 bars with a nominal splice length of 6.25 in. In this instance, the epoxy-coated bars exhibited slightly higher bar stress,128 ksi, than the uncoated bars, 125 ksi. The textured-epoxy-coated bars exhibited varying levels of bar stress with respect to the uncoated bars. For the specimen with No. 5 test bars and a nominal splice length of 3.75 in., a nominal concrete top cover of 2.5 in., and a nominal center-to-center bar spacing of 3 in., the textured-epoxy-coated bars exhibited a higher bar stress, 103 ksi, than the uncoated bars, 91 ksi. When the same test parameters were applied, except the bar spacing was $1^{7}/_{8}$ in., the textured-epoxy-coated bars exhibited lower bar stress, 84 ksi, than the uncoated bars, 95 ksi. For the specimen with No. 5 test bars and a nominal splice length of 5.5 in., a nominal concrete top cover of 1 in., and a nominal bar spacing of $1^{7}/_{8}$ in., both uncoated and textured-epoxy-coated bars exhibited the same bar stress of 121 ksi.

The No. 5 bar specimens showed an increase in the bar stress at splice failure as the center-to-center spacing between the spliced bars decreased from 3 in. to $1^{7}/_{8}$ in., except for the textured-epoxy-coated bars with a nominal splice length of 3.75 in. and a nominal concrete top cover of 2.5 in. For that specimen, the bar stress decreased from 103 ksi to 84 ksi as the spacing decreased from 3 in. to $1^{7}/_{8}$ in. In contrast, specimens with No. 4 bars exhibited a decrease in bar stress as the bar spacing decreased from 3 in. to $1^{1}/_{2}$ in.

A single splice test was performed to investigate each combination of parameters. A detailed analysis of the overall test results is described in Chapter 4.

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# CHAPTER 4: ANALYSIS OF TEST RESULTS AND DEVELOPMENT OF DESIGN PROVISIONS

This chapter describes the analysis of the test results, with emphasis on the splice tests and the development of proposed design provisions for the splice length of uncoated and coated reinforcement in ultra-high-performance concrete (UHPC).

## 4.1 Analysis

The splice strength of the uncoated, epoxy-coated, and textured-epoxy-coated bars in UHPC can be compared to that of uncoated bars cast in conventional concrete by comparing the bar forces at splice failure, $T_{\max}$ presented in Chapter 3, with bar forces calculated using the descriptive (best-fit) expression developed by ACI Committee 408 (2003) for uncoated bars in contact splices without confining reinforcement, $T_{408}$, shown in Eq. (4.1) with notation modified to apply to this study.

$$T_{408} = A_b f_s = \left(59.9\ell_s c_b' + 2400A_b\right)\left(0.1\frac{c_{\max}}{c_{\min}} + 0.9\right) f_c'^{1/4} \tag{4.1}$$

where $T_{408}$ = bar force at splice failure, lb

$A_b$ = bar area, in.$^2$

$f_s$ = bar stress at splice failure. psi

$\ell_s$ = splice length. In.

$c'_b$ = distance (cover) from center of a bar being developed to the nearest concrete surface (in the ACI 408 evaluation, $c'_b$ is taken as the smaller of the minimum cover to the center of the bar and half the center-to-center spacing of the bars + 0.25 in. Spacing between bars is not considered in this comparison because splices in UHPC should be non-contact splices where cover, not the spacing between the bars appears to govern), in.

$c_{\max}$ = larger of the minimum cover to the center of the bar and half the center-to-center spacing of the bars+ 0.25 in., in.

$c_{\min}$ = smaller of the minimum cover to the center of the bar and half the center-to-center spacing of the bars+ 0.25 in., in.

$\left(0.1\frac{c_{\max}}{c_{\min}} + 0.9\right) \le 1.25$; taken as 1.0 for non-contact splices in UHPC

$f_c'$ = compressive strength of concrete, psi

Comparisons between the bar forces at splice failure for the uncoated, epoxy-coated, and textured-epoxy-coated bar specimens are shown in Tables 4.1, 4.2, and 4.3, respectively. For uncoated bars, $T_{\max}/T_{408}$ ranged from 1.72 to 2.92, with a mean of 2.23 and a coefficient of variation of 0.177. For epoxy-coated bars, $T_{\max}/T_{408}$ ranged from 1.29 to 2.47, with a mean of 1.94 and a coefficient of variation of 0.193, and for textured-epoxy-coated bars, $T_{\max}/T_{408}$ ranged from 1.71 to 2.92, with a mean of 2.37 and a coefficient of variation of 0.227.

**Table 4.1:** Comparisons Between Splice Strength of Uncoated Bars, $T_{\max}$, and Values for Contact Splices Based on ACI Committee 408 (2003) Descriptive Equation, $T_{408}$, Eq. (4.1)

| Specimen ID | $f_{cm}$, ksi | $\ell_s$ In. | $c_b'$ in. | $f_s$ ksi | $d_b$ in. | $A_b$ in.$^2$ | $T_{\max}$ kips | $T_{408}$ kips | $T_{\max}/T_{408}$ |
|---|---|---|---|---|---|---|---|---|---|
| U4-L3-C2.5-Sp1$^{1}/_{2}$ | 14.14 | 3 | 2.47 | 117 | 0.5 | 0.2 | 23.400 | 10.564 | 2.22 |
| U4-L3-C2.5-Sp3 | 13 | 3 | 2.25 | 122 | 0.5 | 0.2 | 24.400 | 9.922 | 2.46 |
| U4-L4-C2.5-Sp3 | 12.95 | 4 | 2.25 | 160 | 0.5 | 0.2 | 32.000 | 11.510 | 2.78 |
| U5-L3.75-C1-Sp3 | 13.9 | 3.75 | 1.22 | 71 | 0.625 | 0.31 | 22.010 | 11.816 | 1.86 |
| U5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 14.08 | 3.75 | 2.44 | 95 | 0.625 | 0.31 | 29.450 | 14.839 | 1.98 |
| U5-L3.75-C2.5-Sp3 | 15.37 | 3.75 | 2.22 | 91 | 0.625 | 0.31 | 28210 | 14618 | 1.93 |
| U5-L5.5-C1-Sp1$^{7}/_{8}$ | 12.85 | 5.5 | 1.09 | 121 | 0.625 | 0.31 | 37.510 | 12.841 | 2.92 |
| U5-L5.5-C1-Sp3 | 13.19 | 5.5 | 1.22 | 116 | 0.625 | 0.31 | 35.960 | 13.384 | 2.69 |
| U5-L5-C2.5-Sp3 | 14.74 | 5 | 2.22 | 115 | 0.625 | 0.31 | 35.650 | 16.555 | 2.15 |
| U5-L6.25-C2.5-Sp3 | 14.26 | 6.25 | 2.25 | 125 | 0.625 | 0.31 | 38.750 | 18.614 | 2.08 |
| U8-L6-C2.5-Sp3 | 12.29 | 6 | 2.00 | 64 | 1 | 0.79 | 50.560 | 29.423 | 1.72 |
| U8-L8-C2.5-Sp3 | 13.42 | 8 | 1.97 | 81 | 1 | 0.79 | 63.990 | 33.146 | 1.93 |
| | | | | | | | | **Max** | 2.92 |
| | | | | | | | | **Min** | 1.72 |
| | | | | | | | | **Mean** | 2.23 |
| | | | | | | | | **STDEV** | 0.394 |
| | | | | | | | | **COV** | 0.177 |

**Table 4.2:** Comparisons Between Splice Strength of Epoxy-Coated Bars, $T_{\max}$, and Values for Contact Splices Based on ACI Committee 408 (2003) Descriptive Equation, $T_{408}$, Eq. (4.1)

| Specimen ID | $f_{cm}$, ksi | $\ell_s$ In. | $c_b'$ in. | $f_s$ ksi | $d_b$ in. | $A_b$ in.$^2$ | $T_{\max}$ kips | $T_{408}$ kips | $T_{\max}/T_{408}$ |
|---|---|---|---|---|---|---|---|---|---|
| E4-L3-C2.5-Sp1$^{1}/_{2}$ | 14.37 | 3 | 2.59 | 89 | 0.5 | 0.2 | 17.800 | 10.843 | 1.64 |
| E4-L3-C2.5-Sp3 | 13.88 | 3 | 2.31 | 109 | 0.5 | 0.2 | 21.800 | 10.203 | 2.14 |
| E4-L4-C2.5-Sp3 | 13.93 | 4 | 2.28 | 143 | 0.5 | 0.2 | 28.600 | 11.800 | 2.42 |
| E5-L3.75-C1-Sp3 | 13.97 | 3.75 | 1.22 | 70 | 0.625 | 0.31 | 21.700 | 11.831 | 1.83 |
| E5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 13.58 | 3.75 | 2.5 | 93 | 0.625 | 0.31 | 28.830 | 14.851 | 1.94 |
| E5-L3.75-C2.5-Sp3 | 14.33 | 3.75 | 2.25 | 82 | 0.625 | 0.31 | 25.420 | 14.438 | 1.76 |
| E5-L5.5-C1-Sp1$^{7}/_{8}$ | 14.16 | 5.5 | 1.06 | 104 | 0.625 | 0.31 | 32.240 | 13.048 | 2.47 |
| E5-L5.5-C1-Sp3 | 12.92 | 5.5 | 1.00 | 92 | 0.625 | 0.31 | 28.520 | 12.542 | 2.27 |
| E5-L5-C2.5-Sp3 | 14.5 | 5 | 2.25 | 102 | 0.625 | 0.31 | 31.620 | 16.586 | 1.91 |
| E5-L6.25-C2.5-Sp3 | 13.41 | 6.25 | 2.16 | 128 | 0.625 | 0.31 | 39.680 | 17.967 | 2.21 |
| E8-L6-C2.5-Sp3 | 12.53 | 6 | 1.94 | 48 | 1 | 0.79 | 37.920 | 29.338 | 1.29 |
| E8-L8-C2.5-Sp3 | 11.15 | 8 | 1.94 | 57 | 1 | 0.79 | 45.030 | 31.498 | 1.43 |
| | | | | | | | | **Max** | 2.47 |
| | | | | | | | | **Min** | 1.29 |
| | | | | | | | | **Mean** | 1.94 |
| | | | | | | | | **STDEV** | 0.376 |
| | | | | | | | | **COV** | 0.193 |

**Table 4.3:** Comparisons Between Splice Strength of Textured-Epoxy-Coated Bars, $T_{\max}$, and Values for Contact Splices Based on ACI Committee 408 (2003) Descriptive Equation, $T_{408}$, Eq. (4.1)

| **Specimen ID** | **$f_{cm}$, ksi** | **$\ell_s$ In.** | **$c_b'$ in.** | **$f_s$ ksi** | **$d_b$ in.** | **$A_b$ in.$^2$** | **$T_{\max}$ kips** | **$T_{408}$ kips** | **$T_{\max}/T_{408}$** |
|---|---|---|---|---|---|---|---|---|---|
| T5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 13.95 | 3.75 | 2.63 | 84 | 0.625 | 0.31 | 26.040 | 15.269 | 1.71 |
| T5-L3.75-C2.5-Sp3 | 14.62 | 3.75 | 2.28 | 103 | 0.625 | 0.31 | 31.930 | 14.585 | 2.19 |
| T5-L5.5-C1-Sp1$^{7}/_{8}$ | 13.7 | 5.5 | 1.03 | 121 | 0.625 | 0.31 | 37.510 | 12.834 | 2.92 |
| T5-L5.5-C1-Sp3 | 13.49 | 5.5 | 1.03 | 110 | 0.625 | 0.31 | 34.100 | 12.785 | 2.67 |
| | | | | | | | | Max | 2.92 |
| | | | | | | | | Min | 1.71 |
| | | | | | | | | Mean | 2.37 |
| | | | | | | | | STDEV | 0.538 |
| | | | | | | | | COV | 0.227 |

As described above, the ratios of bar forces in the current tests to those based on the ACI Committee 408 (2003) descriptive equation have mean values of 2.23, 1.94, and 2.37 for the uncoated, epoxy-coated, and textured-epoxy-coated bar specimens, respectively. Thus, the splice strengths of uncoated and textured-epoxy-coated bars in UHPC exceed two times the values observed in conventional concrete for bars without confining reinforcement. At 1.94, the value is almost as high for epoxy-coated bars. The results show, as they did for the pullout and beam-end specimens described in Chapter 3, that textured-epoxy-coated bars give the same nominal splice strength as uncoated bars, matching observations in conventional concrete (Aryal et al. 2023). Although only four splice tests were performed with textured-epoxy-coated bars, the combination of the results with those for the beam-end specimens provides clear evidence that textured epoxy-coated bars provide bond strength equivalent to that of uncoated bars. The ratio of the forces attained by the epoxy-coated bars to that obtained by uncoated bars in UHPC is 0.87, higher than values of less than 0.7 for splices in conventional concrete (Treece and Jirsa 1989), showing a much lower negative effect of epoxy-coating in UHPC.

Figure 4.1 compares the bar force for developed and spliced bars at failure, $A_b f_s$, normalized with respect to $f_c'^{1/4}$, with the product of the development or splice length, $\ell_d$, to the smaller of the minimum concrete cover to the center of the bar or half of the center to center bar space for bars in conventional concrete ($c_{\min} + 0.5d_b$). The figure shows that, based on a dummy-variables analysis,[1] the bar forces at failure increase in a linear, but non-proportional fashion, with respect to $\ell_d\,(c_{\min} + 0.5d_b)$ and that larger bars exhibit higher bond forces than smaller bars for the same value of $\ell_d\,(c_{\min} + 0.5d_b)$.

To determine if similar relationships exist for bars in UHPC, the bar forces at splice failure, $T_{\max}$, are plotted with respect to the product of the splice length, $\ell_s$, and the distance (cover) from center of a bar being developed to the nearest concrete surface, $c_b'$, in Figures 4.2 and 4.3 for uncoated and epoxy-coated bars, respectively. A similar analysis is not performed

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[1] A dummy-variables analysis is based on the assumption that, for multiple populations, in this case, bars of different sizes, a change in one variable, in this case $\ell_d\,(c_{\min} + 0.5d_b)$, will have the same incremental effect on a second variable, in this case $A_b f_s \,/\, f_c'^{1/4}$, for all populations but that the absolute value of the second variable can be different for each population.

for textured-epoxy-coated bar splice bars because only four specimens were tested with those bars.

As shown in Figures 4.2 and 4.3, the relationships between the bond forces at splice failure and the product $\ell_s \times c_b'$ are similar to those shown in Figure 4.1 for bars in conventional concrete. Bar forces increase in a linear but non-proportional fashion with respect to $\ell_s \times c_b'$ and the larger bars exhibit higher bond forces at the same value $\ell_s \times c_b'$. The best fit lines in Figures 4.2 and 4.3 have the form:

$$T_{\max} = A_b f_s = m\left(\ell_s \times c_b'\right) + b \tag{4.2}$$

The values of the slope *m* and intercept *b* are given in Table 4.4. The location of the data points, above or below the best-fit lines shown in Figures 4.2 and 4.3, exhibit no relationship to the concrete compressive strength, leading to the conclusion that variations in compressive strength within the range exhibited by UHPC mixtures with the same proportions do not play a role in the splice strength of bars in UHPC. Interestingly, the slope *m*, 1.41, is, within three significant figures, equal for uncoated and epoxy-coated bars. The No. 8 bars exhibit a noticeably higher bond strength with respect to the No. 4 and No. 5 bars for uncoated reinforcement than for epoxy coated reinforcement.

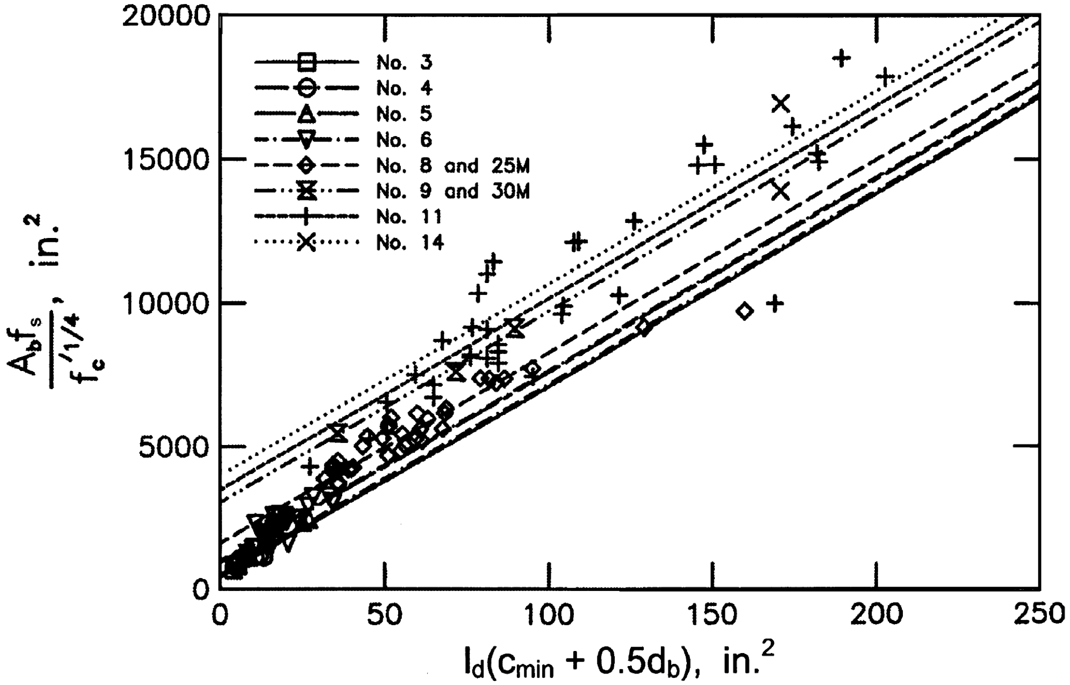

**Figure 4.1:** Bar force at failure, $T_{\max} = A_b f_s$, normalized with respect to $f_c'^{1/4}$ versus product of development or splice length $\ell_d$ and the smaller of the minimum concrete cover to center of bar or half of center-to-center bar spacing ($c_{\min} + 0.5d_b$) for reinforcing bars in conventional concrete (Darwin et al. 1996).

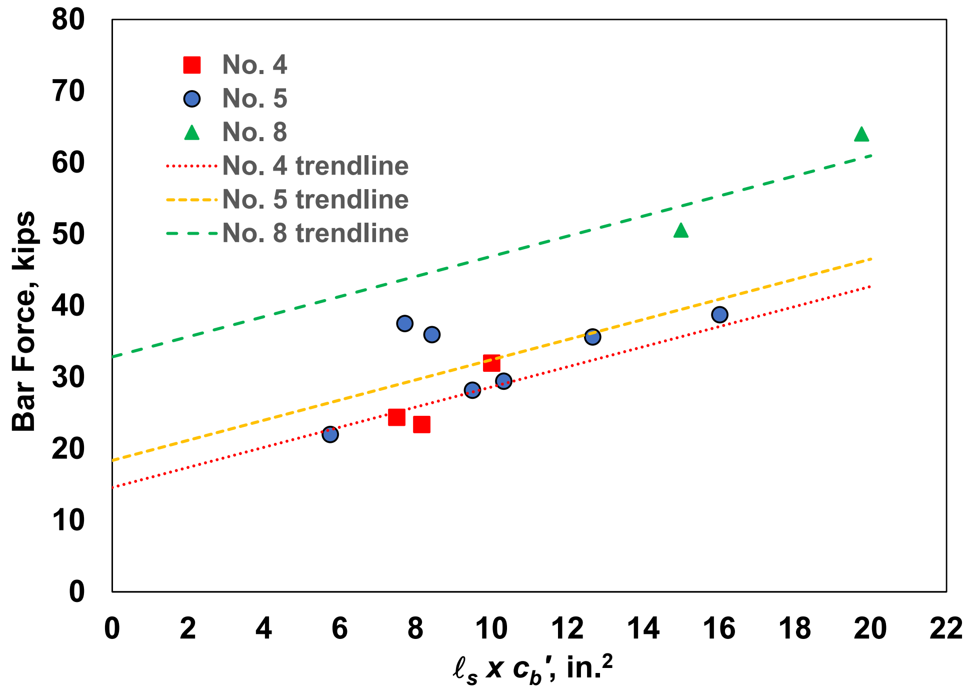

**Figure 4.2:** Bar force at failure $T_{\max} = A_b f_s$ versus product of splice length, $\ell_s$, and distance (cover) from center of a bar being developed to nearest concrete surface, $c_b'$, for uncoated bars in UHPC

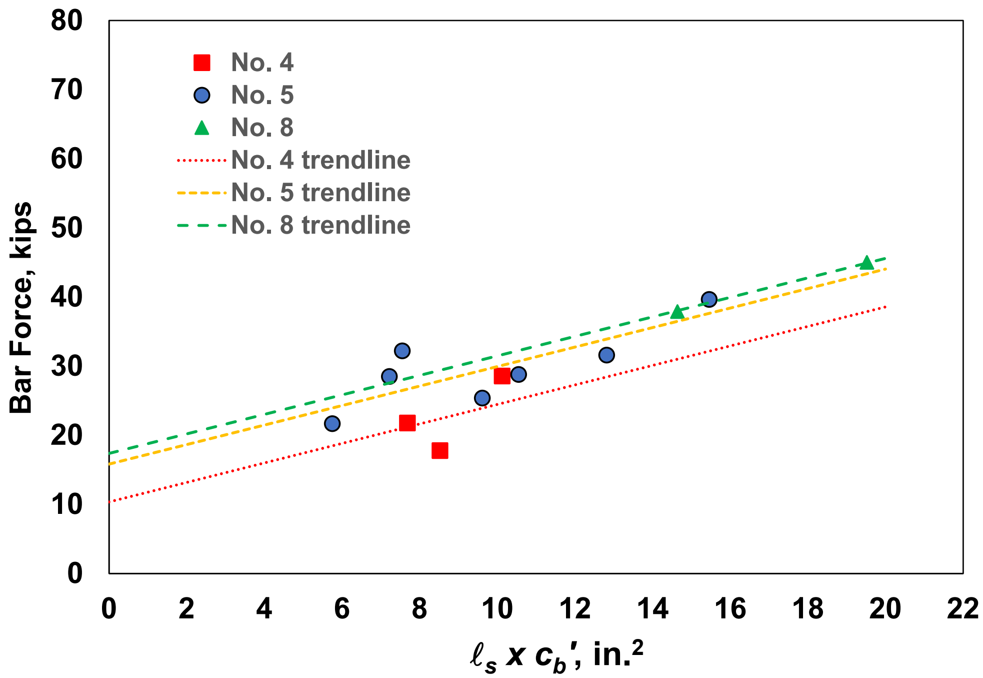

**Figure 4.3:** Bar force at failure $T_{\max} = A_b f_s$ versus product of splice length, $\ell_s$, and distance (cover) from center of bar being developed to nearest concrete surface, $c_b'$, for epoxy-coated bars in UHPC

**Table 4.4:** Slopes and Intercepts for Relationships Between Bar Force at Failure $T_{\max} = A_b f_s$ and Product of Splice Length and Distance (Cover) from Center of Bar Being Developed to Nearest Concrete Surface, $\ell_s \times c_b'$, shown in Figures 4.2 and 4.3 for Uncoated and Epoxy-Coated Bars in UHPC

| | **U** | **U** | **U** | **E** | **E** | **E** |
|---|---|---|---|---|---|---|
| **Bar size** | **Slope, *m*** | **Intercept, *b*** | ***b*/*d*$_b$** | **Slope, *m*** | **Intercept, *b*** | ***b*/*d*$_b$** |
| No. 4 | 1.41 | 14.57 | 29.15 | 1.41 | 10.35 | 20.70 |
| No. 5 | 1.41 | 18.37 | 29.39 | 1.41 | 15.81 | 25.30 |
| No. 8 | 1.41 | 32.83 | 32.83 | 1.41 | 17.35 | 17.37 |
| | | Mean | 30.46 | | Mean | 21.12 |

**Notation:** U = Uncoated bars, E = Epoxy-coated bars

Using the mean values of the ratio between the intercept $b$ and the bar diameter $d_b$ and rounding the values of $b/d_b$ slightly results in the following expressions for the relationship between the bar force at failure, now termed $T_{\text{calc}}$, and the product $\ell_s \times c_b'$ and $d_b$. For uncoated and epoxy-coated bars, respectively.

Uncoated bars:
$$T_{\text{calc}} = A_b f_s = 1.41\left(\ell_s \times c_b'\right) + 30 d_b \tag{4.3}$$

Epoxy-coated bars:
$$T_{\text{calc}} = A_b f_s = 1.41\left(\ell_s \times c_b'\right) + 21 d_b \tag{4.4}$$

Equations (4.3) and (4.4) can be represented by a single expression as

$$T_{\text{calc}} = A_b f_s = 1.41\left(\ell_s \times c_b'\right) + 30\lambda_{cfu} d_b \tag{4.5}$$

where $\lambda_{cfu}$ = coated bar factor for spliced bars in UHPC
= 1.0 for uncoated and textured-epoxy-coated bars
= 0.7 for epoxy-coated bars

Comparisons between $T_{\max}$ and $T_{\text{calc}}$ are shown for the uncoated, epoxy-coated, and textured-epoxy-coated splice specimens in Tables 4.5, 4.6, and 4.7, respectively. For uncoated bars, $T_{\max}/T_{\text{calc}}$ ranged from 0.82 to 1.27, with a mean of 1.00 and a coefficient of variation of 0.136. For epoxy-coated bars, $T_{\max}/T_{\text{calc}}$ ranged from 0.79 to 1.36, with a mean of 1.05 and a coefficient of variation of 0.146, and for textured-epoxy-coated bars, $T_{\max}/T_{\text{calc}}$ ranged from 0.76 to 1.29, with a mean of 1.5 and a coefficient of variation of 0.219.

**Table 4.5:** Comparisons Between Splice Strength of Uncoated Bars, $T_{max}$, and Values Based on Eq. (4.5), $T_{calc}$

| Specimen ID | $f_{cm}$, ksi | $\ell_s$ In. | $c_b'$ in. | $f_s$ ksi | $d_b$ in. | $A_b$ in.$^2$ | $T_{max}$ kips | $T_{calc}$ kips | $T_{max}/T_{calc}$ |
|---|---|---|---|---|---|---|---|---|---|
| U4-L3-C2.5-Sp$^{1}/_{2}$ | 14.14 | 3 | 2.47 | 117 | 0.5 | 0.2 | 23.400 | 26.506 | 0.88 |
| U4-L3-C2.5-Sp3 | 13 | 3 | 2.25 | 122 | 0.5 | 0.2 | 24.400 | 25.575 | 0.95 |
| U4-L4-C2.5-Sp3 | 12.95 | 4 | 2.25 | 160 | 0.5 | 0.2 | 32.000 | 29.100 | 1.10 |
| U5-L3.75-C1-Sp3 | 13.9 | 3.75 | 1.22 | 71 | 0.625 | 0.31 | 22.010 | 26.853 | 0.82 |
| U5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 14.08 | 3.75 | 2.44 | 95 | 0.625 | 0.31 | 29.450 | 33.304 | 0.88 |
| U5-L3.75-C2.5-Sp3 | 15.37 | 3.75 | 2.22 | 91 | 0.625 | 0.31 | 28.210 | 32.141 | 0.88 |
| U5-L5.5-C1-Sp1$^{7}/_{8}$ | 12.85 | 5.5 | 1.09 | 121 | 0.625 | 0.31 | 37.510 | 29.626 | 1.27 |
| U5-L5.5-C1-Sp3 | 13.19 | 5.5 | 1.22 | 116 | 0.625 | 0.31 | 35.960 | 30.635 | 1.17 |
| U5-L5-C2.5-Sp3 | 14.74 | 5 | 2.22 | 115 | 0.625 | 0.31 | 35.650 | 36.604 | 0.97 |
| U5-L6.25-C2.5-Sp3 | 14.26 | 6.25 | 2.25 | 125 | 0.625 | 0.31 | 38.750 | 41.332 | 0.94 |
| U8-L6-C2.5-Sp3 | 12.29 | 6 | 2.00 | 64 | 1 | 0.79 | 50.560 | 51.150 | 0.99 |
| U8-L8-C2.5-Sp3 | 13.42 | 8 | 1.97 | 81 | 1 | 0.79 | 63.990 | 57.862 | 1.11 |
| | | | | | | | | **Max** | 1.27 |
| | | | | | | | | **Min** | 0.82 |
| | | | | | | | | **Mean** | 1.00 |
| | | | | | | | | **STDEV** | 0.136 |
| | | | | | | | | **COV** | 0.136 |

**Table 4.6:** Comparisons Between Splice Strength of Epoxy-Coated Bars, $T_{max}$, and Values Based on Eq. (4.5), $T_{calc}$

| Specimen ID | $f_{cm}$, ksi | $\ell_s$ In. | $c_b'$ in. | $f_s$ ksi | $d_b$ in. | $A_b$ in.$^2$ | $T_{max}$ kips | $T_{calc}$ kips | $T_{max}/T_{calc}$ |
|---|---|---|---|---|---|---|---|---|---|
| E4-L3-C2.5-Sp$^{1}/_{2}$ | 14.37 | 3 | 2.59 | 89 | 0.5 | 0.2 | 17.800 | 22.513 | 0.79 |
| E4-L3-C2.5-Sp3 | 13.88 | 3 | 2.31 | 109 | 0.5 | 0.2 | 21.800 | 21.329 | 1.02 |
| E4-L4-C2.5-Sp3 | 13.93 | 4 | 2.28 | 143 | 0.5 | 0.2 | 28.600 | 24.769 | 1.15 |
| E5-L3.75-C1-Sp3 | 13.97 | 3.75 | 1.22 | 70 | 0.625 | 0.31 | 21.700 | 21.228 | 1.02 |
| E5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 13.58 | 3.75 | 2.5 | 93 | 0.625 | 0.31 | 28.830 | 27.996 | 1.03 |
| E5-L3.75-C2.5-Sp3 | 14.33 | 3.75 | 2.25 | 82 | 0.625 | 0.31 | 25.420 | 26.674 | 0.95 |
| E5-L5.5-C1-Sp1$^{7}/_{8}$ | 14.16 | 5.5 | 1.06 | 104 | 0.625 | 0.31 | 32.240 | 23.769 | 1.36 |
| E5-L5.5-C1-Sp3 | 12.92 | 5.5 | 1.00 | 92 | 0.625 | 0.31 | 28.520 | 23.303 | 1.22 |
| E5-L5-C2.5-Sp3 | 14.5 | 5 | 2.25 | 102 | 0.625 | 0.31 | 31.620 | 31.191 | 1.01 |
| E5-L6.25-C2.5-Sp3 | 13.41 | 6.25 | 2.16 | 128 | 0.625 | 0.31 | 39.680 | 34.914 | 1.14 |
| E8-L6-C2.5-Sp3 | 12.53 | 6 | 1.94 | 48 | 1 | 0.79 | 37.920 | 41.642 | 0.91 |
| E8-L8-C2.5-Sp3 | 11.15 | 8 | 1.94 | 57 | 1 | 0.79 | 45.030 | 48.523 | 0.93 |
| | | | | | | | | **Max** | 1.36 |
| | | | | | | | | **Min** | 0.79 |
| | | | | | | | | **Mean** | 1.05 |
| | | | | | | | | **STDEV** | 0.153 |
| | | | | | | | | **COV** | 0.146 |

**Table 4.7:** Comparisons Between Splice Strength of Textured-Epoxy-Coated Bars, $T_{\max}$, and Values Based on Eq. (4.5), $T_{\text{calc}}$

| Specimen ID | $f_{cm}$, ksi | $\ell_s$ In. | $c_b'$ in. | $f_s$ ksi | $d_b$ in. | $A_b$ in.$^2$ | $T_{\max}$ kips | $T_{\text{calc}}$ kips | $T_{\max}/T_{\text{calc}}$ |
|---|---|---|---|---|---|---|---|---|---|
| T5-L3.75-C2.5-Sp1$^{7}/_{8}$ | 13.95 | 3.75 | 2.63 | 84 | 0.625 | 0.31 | 26.040 | 34.308 | 0.76 |
| T5-L3.75-C2.5-Sp3 | 14.62 | 3.75 | 2.28 | 103 | 0.625 | 0.31 | 31.930 | 32.458 | 0.98 |
| T5-L5.5-C1-Sp1$^{7}/_{8}$ | 13.7 | 5.5 | 1.03 | 121 | 0.625 | 0.31 | 37.510 | 29.161 | 1.29 |
| T5-L5.5-C1-Sp3 | 13.49 | 5.5 | 1.03 | 110 | 0.625 | 0.31 | 34.100 | 29.161 | 1.17 |
| | | | | | | | | **Max** | 1.29 |
| | | | | | | | | **Min** | 0.76 |
| | | | | | | | | **Mean** | 1.05 |
| | | | | | | | | **STDEV** | 0.230 |
| | | | | | | | | **COV** | 0.219 |

## 4.2 Design provisions

Converting Eq. (4.5) for use in design involves two steps: First, to solve for the splice length $\ell_s$ and then to replace $f_s$ with the desired bar stress for use in design and embed a strength reduction factor in the expression to establish an appropriate level of reliability. Solving Eq. (4.5) for $\ell_s$ gives

$$\ell_s = \frac{A_b f_s - 30\lambda_{cfu} d_b}{1.41 c_b'} \tag{4.6}$$

Based on long practice in calculating development and splice lengths for reinforcing steel, the specified yield strength, $f_y$, will be used as the bar stress, $f_s$, for design together with a resistance factor $\phi = 0.8$ incorporated into the design to select the reinforcement prior to designing the splice (Darwin et al. 1998, ACI Committee 408 2003). Setting $f_s = f_y$ and using $\phi = 0.8$ with some rounding gives

$$\ell_s = \frac{A_b f_y/\phi - 30\lambda_{cfu} d_b}{1.41 c_b'} = \frac{A_b f_y/0.8 - 30\lambda_{cfu} d_b}{1.41 c_b'} = \frac{1.25 A_b f_y - 30\lambda_{cfu} d_b}{1.41 c_b'} \tag{4.7}$$

Simplifying Eq. (4.7) with minor rounding gives

$$\ell_s = \frac{A_b f_y - 24\lambda_{cfu} d_b}{1.1 c_b'} \tag{4.8}$$

where $\lambda_{cfu}$ = coated bar factor for spliced bars in UHPC

= 1.0 for uncoated and textured-epoxy-coated bars

= 0.7 for epoxy-coated bars

Application of Eq. (4.8) is limited to bars ranging in size from No. 4 to No. 8, the range in bar sizes used in this study, and the splice length to the minimum multiple of bar diameter used in this study, $6d_b$. The UHPC used must contain a minimum of 2% by volume of ½-in. straight steel fibers satisfying ASTM A820. The concrete producer must achieve a minimum compressive strength of 14 ksi at seven days prior to the initiation of construction and achieve not less than 12 ksi in the field at the time of load application. The mixture must exhibit a flow between 8 and 10 in., when tested in accordance with ASTM C1856, and good fiber distribution, as evaluated by the engineer. The center-to-center spacing of the spliced bars shall not exceed 3 in., the maximum used in this study. Contact splices are not desirable, but are not prohibited.

The splice lengths corresponding to the design criteria for No. 4 through No. 8 bars with clear covers between 1 and 3 in. are shown in Table 4.8 for Grade 60 and 80 uncoated and textured-epoxy-coated bars and in Table 4.9 for Grade 60 and 80 epoxy-coated bars.

**Table 4.8:** Splice lengths (in.) for uncoated and textured-epoxy-coated bars in UHPC

| **Grade** | **60** | **60** | **60** | **60** | **60** | **80** | **80** | **80** | **80** | **80** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Clear Cover, in.** | **1.0** | **1.5** | **2.0** | **2.5** | **3.0** | **1.0** | **1.5** | **2.0** | **2.5** | **3.0** |
| **Bar size** | | | | | | | | | | |
| **No. 4** | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.6 | 3.0 | 3.0 | 3.0 | 3.0 |
| **No. 5** | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 8.9 | 5.9 | 4.5 | 3.8 | 3.8 |
| **No. 6** | 7.6 | 5.1 | 4.5 | 4.5 | 4.5 | 15.6 | 10.4 | 7.8 | 6.3 | 5.2 |
| **No. 7** | 13.6 | 9.1 | 6.8 | 5.5 | 5.3 | 24.5 | 16.4 | 12.3 | 9.8 | 8.2 |
| **No. 8** | 21.3 | 14.2 | 10.6 | 8.5 | 7.1 | 35.6 | 23.8 | 17.8 | 14.3 | 11.9 |

**Table 4.9:** Splice lengths (in.) for epoxy-coated bars in UHPC

| **Grade** | **60** | **60** | **60** | **60** | **60** | **80** | **80** | **80** | **80** | **80** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Clear Cover, in.** | **1.0** | **1.5** | **2.0** | **2.5** | **3.0** | **1.0** | **1.5** | **2.0** | **2.5** | **3.0** |
| **Bar size** | | | | | | | | | | |
| **No. 4** | 3.3 | 3.0 | 3.0 | 3.0 | 3.0 | 6.9 | 4.6 | 3.5 | 3.0 | 3.0 |
| **No. 5** | 7.4 | 4.9 | 3.8 | 3.8 | 3.8 | 13.0 | 8.7 | 6.5 | 5.2 | 4.3 |
| **No. 6** | 12.5 | 8.4 | 6.3 | 5.0 | 4.5 | 20.5 | 13.7 | 10.3 | 8.2 | 6.8 |
| **No. 7** | 19.4 | 12.9 | 9.7 | 7.7 | 6.5 | 30.3 | 20.2 | 15.1 | 12.1 | 10.1 |
| **No. 8** | 27.8 | 18.5 | 13.9 | 11.1 | 9.3 | 42.2 | 28.1 | 21.1 | 16.9 | 14.1 |

If Eq. (4.8) is solved for $f_y$, and treated as $f_{s,\mathrm{design}}$, which is then compared with $f_s$ in the tests, for uncoated bars, $f_s/f_{s,\mathrm{design}}$ ranges from 1.03 to 1.60, with a mean of 1.26 and a coefficient of variation of 0.136. For epoxy-coated bars, $f_s/f_{s,\mathrm{design}}$ ranges from 1.00 to 1.71, with a mean of 1.32 and a coefficient of variation of 0.146, and for textured-epoxy-coated bars, $f_s/f_{s,\mathrm{design}}$ ranges from 0.96 to 1.62, with a mean of 1.32 and a coefficient of variation of 0.218. In this comparison, only one specimen, textured-epoxy-coated specimen T5-L3.75-C2.5-Sp1$^7/_8$, has a value of $f_s/f_{s,\mathrm{design}}$ below 1.0. The comparison indicates that the proposed design procedure is satisfactory for design.

# CHAPTER 5: SUMMARY AND CONCLUSIONS

## 5.1 Summary

Non-proprietary ultra-high-performance concrete (UHPC) mixtures were developed for use, primarily, in closure strips between precast members on reinforced concrete bridges. Ninety mixtures containing ODOT approved Type I portland cement, slag cement, silica fume, graded fine aggregate, two high-range water-reducers (HRWRs), one of which incorporated a viscosity modifying admixture, and 2% by volume of 0.5-in. steel fibers meeting the requirements of ASTM A820 were evaluated. Several HRWRs of each type were included in the evaluations. The mixtures were evaluated based on flow (a measure of workability), fiber distribution, flexure properties, compressive strength, and effect on bond strength using a modified pullout test and the ASTM A944 beam-end test for No. 5 uncoated, ASTM A775 epoxy-coated, and ASTM A1124 textured-epoxy-coated reinforcing bars. The UHPC mixture with the best properties was used to cast the closure strip between two precast sections to determine the splice strength of No. 4, No. 5, and No. 8 uncoated, epoxy-coated, and textured-epoxy-coated reinforcing bars with minimum clear covers ranging from 1.00 to 2.63 in. The results of the splice tests were used to develop design recommendations. The design procedures described in this report are based on UHPC that achieves a minimum compressive strength of 14 ksi prior to the initiation of construction and not less than 12 ksi in the field with a flow between 8 and 10 in. when tested in accordance with ASTM C1856 and good fiber distribution.

## 5.2 Conclusions

The following conclusions are based on the experimental results and analyses presented in this report.

1. UHPC can be made using ODOT approved materials.

2. The admixtures used in UHPC play a significant role in its flow properties and distribution of fibers. As a result, they can affect the bond strength that can be developed in the material.

3. The splice strength of reinforcing bars in UHPC is two times the value of contact splices without confining reinforcement in conventional concrete at same compressive strength.

4. Splice strength in UHPC is independent of small variations in compressive strength that occur from batch to batch for a given mixture.

5. The negative effects of epoxy coating on bond strength are lower in UHPC than in conventional concrete.

6. ASTM A1124 textured epoxy-coated bars have the same splice strength in UHPC as uncoated bars for non-contact splices as investigated in the study.

## 5.3 Recommendations

1. The splice length design procedures presented in this report should be limited to No. 8 and smaller bars, a center-to-center spacing of the spliced bars of not more than 3 in., and

UHPC mixtures with 0.5-in. straight steel fibers meeting the requirements of ASTM A820 and fiber contents equal to 2% of the concrete volume.

2. The concrete producer should achieve a minimum compressive strength of 14 ksi prior to the initiation of construction and achieve not less than 12 ksi in the field at the time of load application.

3. The mixture should exhibit a flow between 8 and 10 in., when tested in accordance with ASTM C1856, and good fiber distribution, as evaluated by the engineer.

4. Contact splices are not desirable, but should not be prohibited.

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# APPENDIX A: UHPC TRIAL BATCHES

**Table A.1:** Mixture Proportions (Cubic Yard Basis)

| Material Type | Batch 1 | Batch 2 | Batch 3 | Batch 4 |
|---|---|---|---|---|
| **Type I/II Portland Cement (lb)** | 1163 | 1213 | 1224 | 1229 |
| **Slag Cement (lb)** | 564 | 588 | 594 | 597 |
| **Silica Fume (lb)** | 155 | 161 | 163 | 164 |
| **Fine Aggregate (lb)** | 1544 | 1610 | 1626 | - |
| **No. 10 Sieve Sand (Size < 2 mm) (lb)** | - | - | - | 1663 |
| **Water (lb)** | 323 | 312 | 290 | 291 |
| **HRWR (lb): Chryso Premia 150** | 53 | 46 | 53 | 48 |
| **HRWR (lb): Chryso Optima 150** | 23 | 20 | 23 | 21 |
| **Fibers (lb) (2% by volume)** | 265 | 265 | 265 | 265 |
| ***w/cm* ratio** | 0.200 | 0.183 | 0.174 | 0.171 |

**Table A.2:** Plastic Properties of UHPC Mixtures

| Properties | Batch 1 | Batch 2 | Batch 3 | Batch 4 |
|---|---|---|---|---|
| **Spread (in.)** | 8.75 | 8.50 | 10.25 | 9.50 |
| **Unit Weight (lb/ft$^3$)** | 151.9 | 154.4 | 155.5 | 156.3 |
| **Temperature (°F)** | 82 | 73 | 71 | 76 |

**Table A.3:** Compressive Strength of UHPC Mixtures

| Batch / Strength | Batch 1 | Batch 2 | Batch 3 | Batch 4 |
|---|---|---|---|---|
| **1 day (ksi)** | 9.92 | 9.56 | 7.42 | 8.28 |
| **3-day (ksi)** | 12.17 | - | - | - |
| **7-day (ksi)** | 13.60 | 14.84 | 13.65 | 15.04 |
| **14-day (ksi)** | 14.31 | 15.77 | 14.23 | 16.39 |
| **28-day (ksi)** | 15.06 | 17.88 | 15.82 | 17.63 |

# APPENDIX B: STRESS VERSUS STRAIN FOR REINFORCEMENT

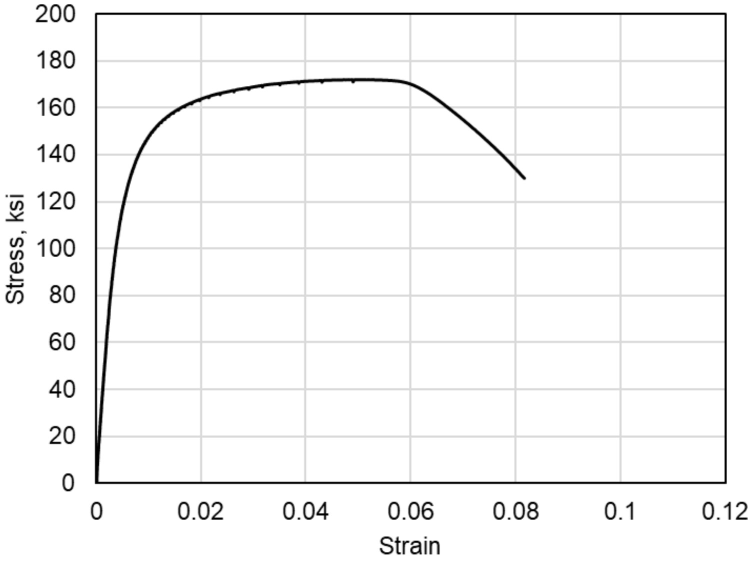

**Figure B.1:** Stress versus strain for A1035 Grade 100 No. 4 reinforcing bar

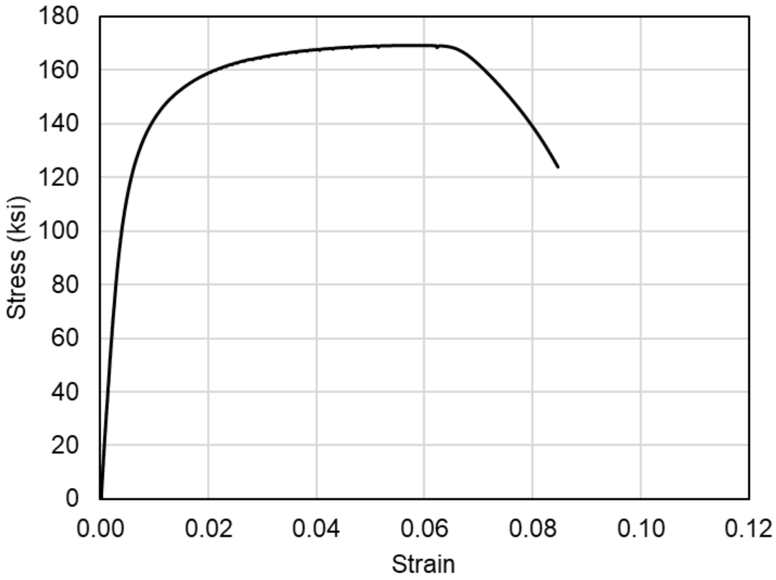

**Figure B.2:** Stress versus strain for a1035 Grade 100 No. 5 reinforcing bar

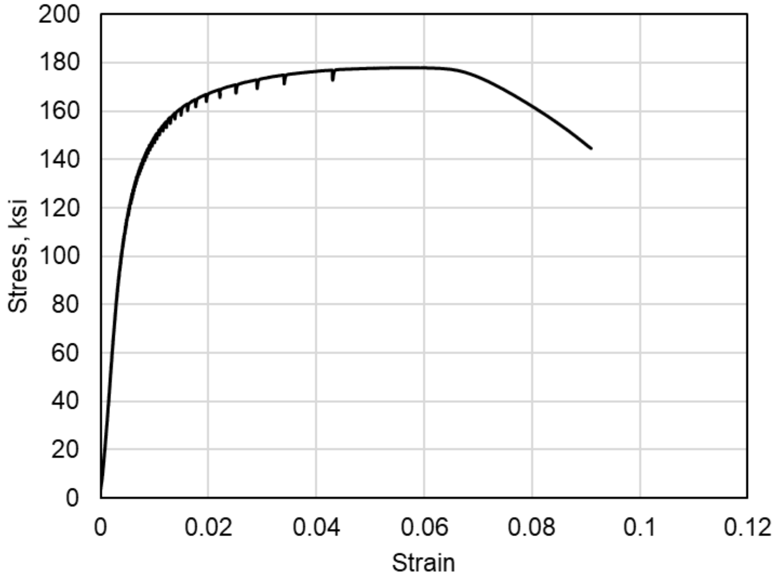

**Figure B.3:** Stress versus strain for A1035 Grade 100 No. 8 reinforcing bar

# APPENDIX C: LOAD VERSUS DEFLECTION FOR FLEXURE SPECIMENS

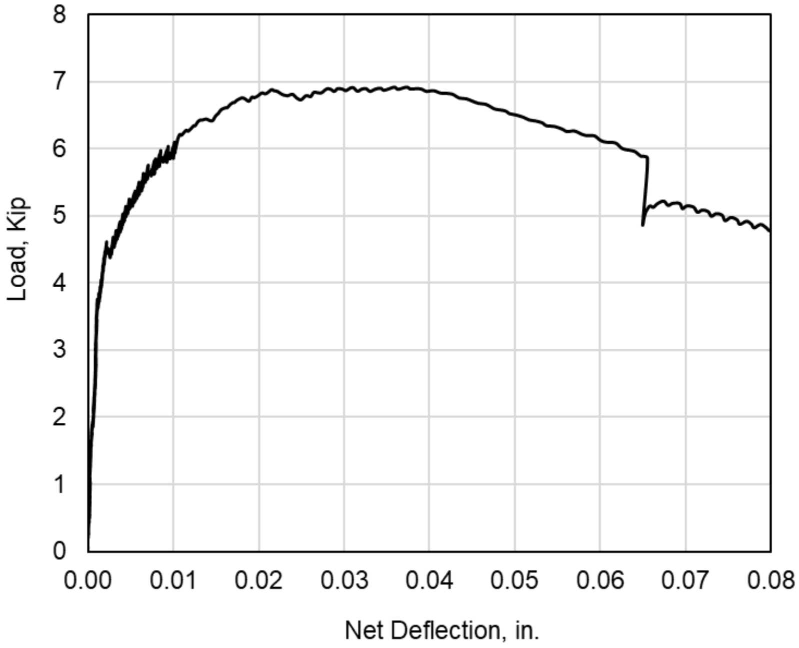

**Figure C.1:** Load versus Deflection for A-1

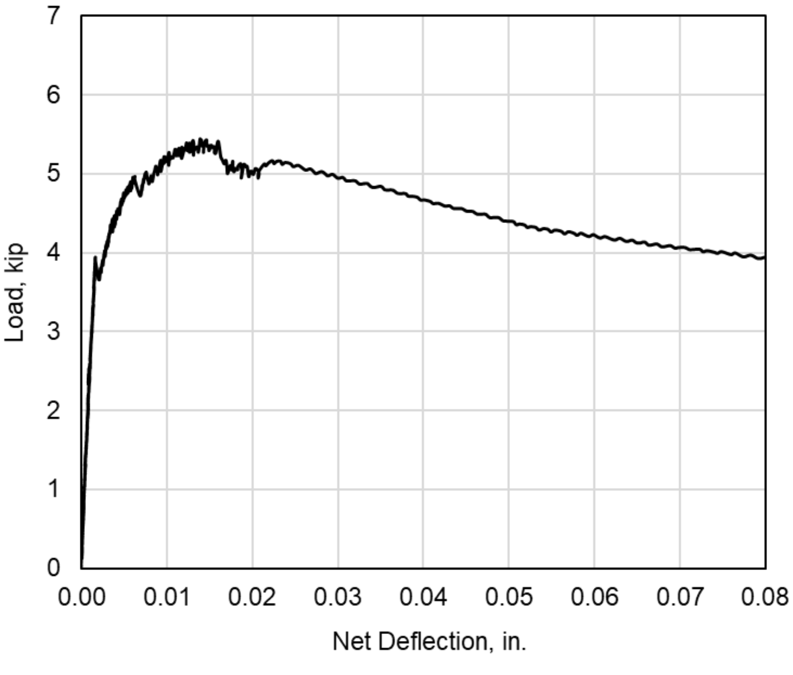

**Figure C.2:** Load versus Deflection for A-2

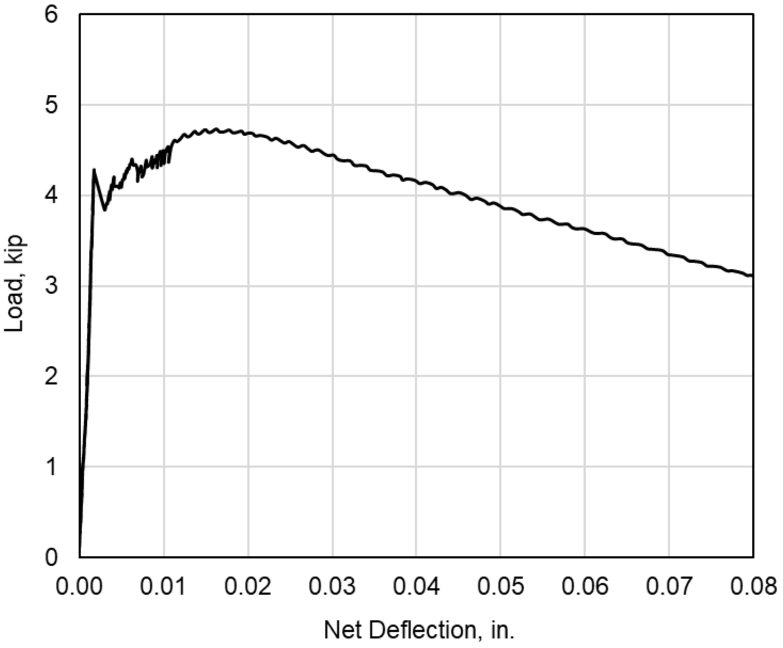

**Figure C.3:** Load versus Deflection for A-3

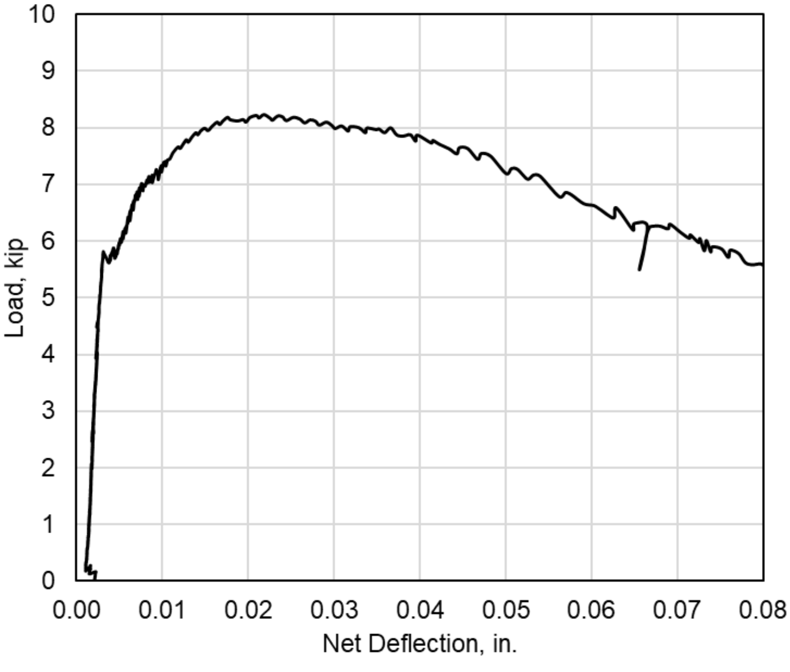

**Figure C.4:** Load versus Deflection for A-4

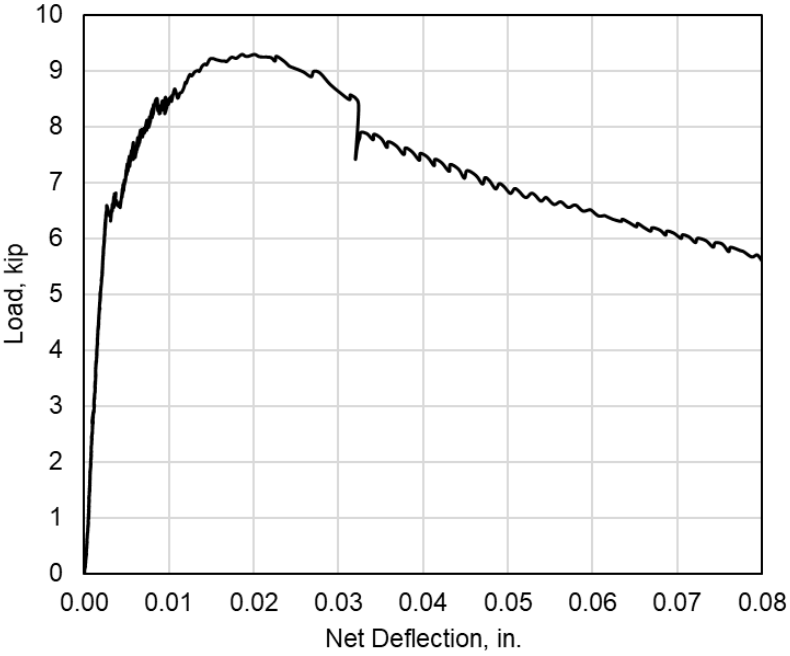

**Figure C.5:** Load versus Deflection for A-5

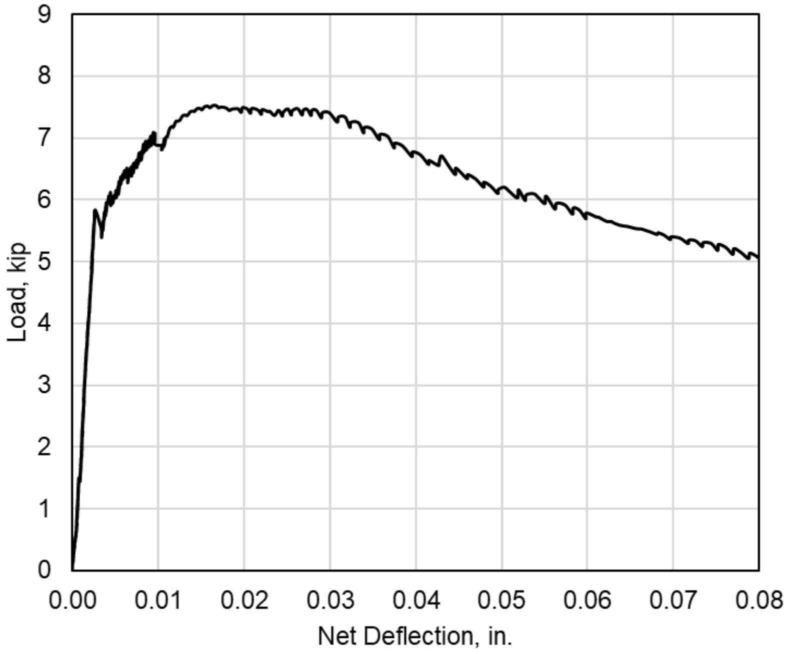

**Figure C.6:** Load versus Deflection for A-6

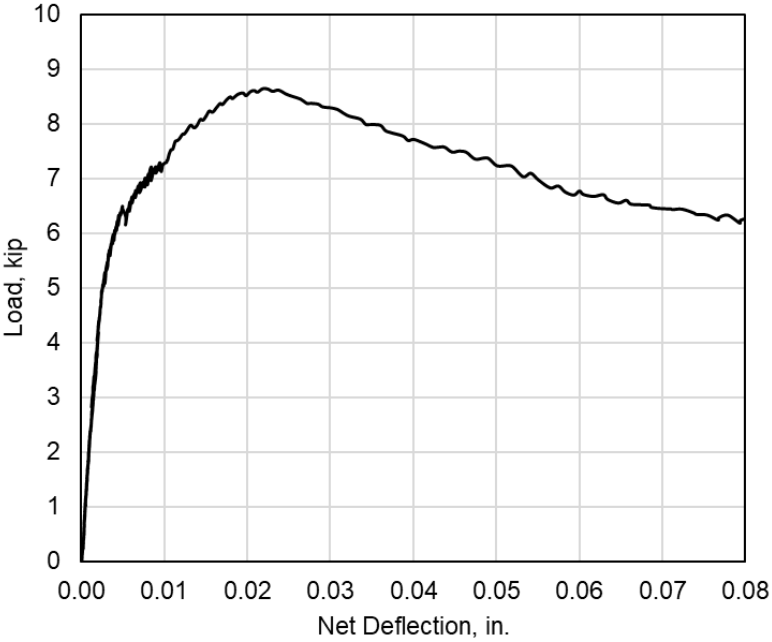

**Figure C.7:** Load versus Deflection for B-1

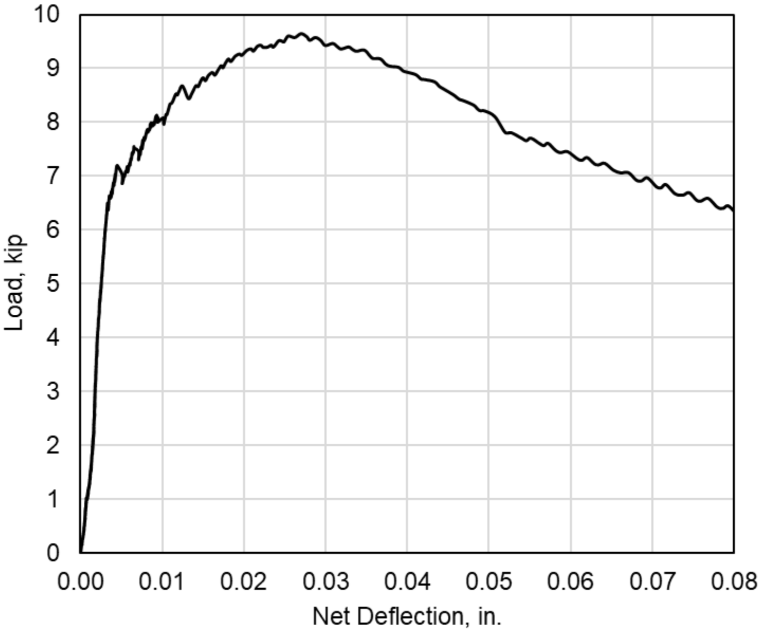

**Figure C.8:** Load versus Deflection for B-2

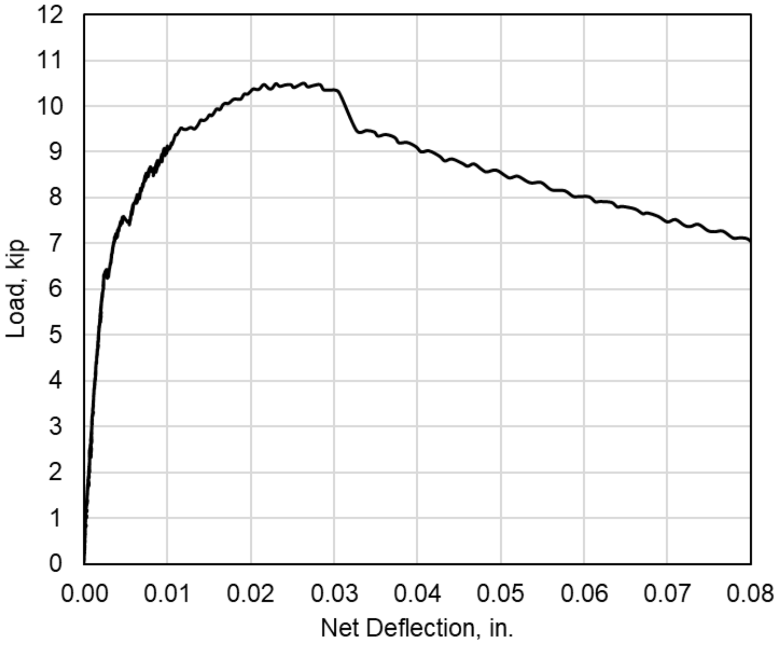

**Figure C.9:** Load versus Deflection for B-3

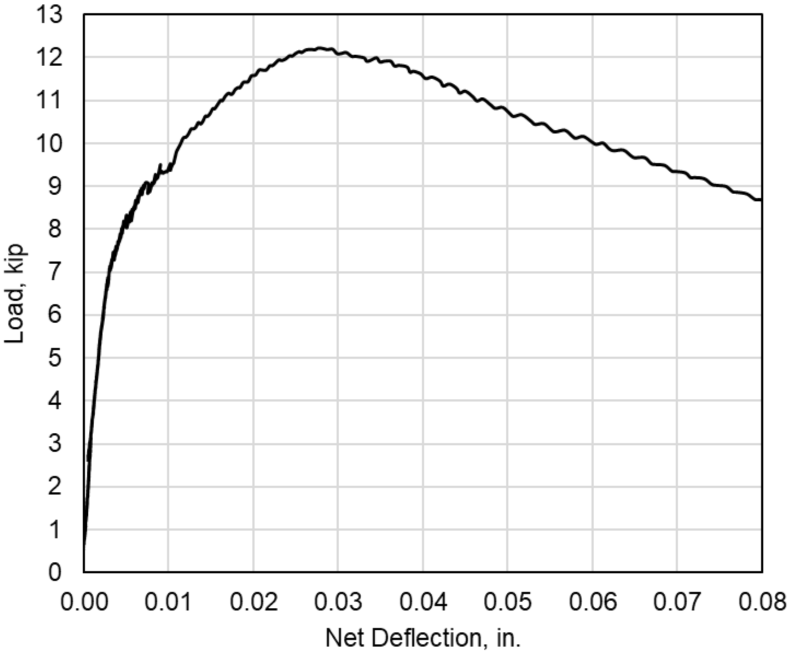

**Figure C.10:** Load versus Deflection for B-4

# APPENDIX D: PULLOUT TEST RESULTS

**Table D.1:** Pullout Test Results

| Specimen ID | $f_{cm}$ ksi | $\ell_d$ in. | $\ell_s$ in. | $c_{so}$ in. | $c_{si}$ in. | $f_{s,\text{ max}}$ ksi |
|---|---|---|---|---|---|---|
| U5-L2.75-Sp5-B1S1-6D | 13.56 | 4 | 3 | 1.13 | 2.03 | 65 |
| U5-L4-Sp5-B1S1-6D | 13.56 | 5.2 | 4.2 | 1.19 | 2 | 83 |
| U5-L5-Sp4-B2S1-2D | 11.33 | 5.9 | 4.9 | 1.06 | 1.63 | 33 |
| U5-L5-Sp5-B2S1-2D | 11.33 | 5.8 | 4.8 | 1.25 | 2 | 36 |
| T5-L5-Sp5-B2S1-2D | 11.33 | 6 | 5 | 1.13 | 2.19 | 52 |
| T5-L5-Sp4-B2S1-2D | 11.33 | 6.1 | 5.1 | 1.13 | 1.69 | 16 |
| E5-L5-Sp5-B3S1-4D | 12.45 | 4.9 | 3.9 | 1.38 | 2.31 | 57 |
| E5-L5-Sp5-B3S1-4D | 12.45 | 6.1 | 5.1 | 1.13 | 2.25 | 83 |
| T5-L6.25-Sp5-B4S1-2D | 11.95 | 7.6 | 6.6 | 1.25 | 2.13 | 93 |
| E5-L6.25-Sp5-B4S1-2D | 11.95 | 7.5 | 6.5 | 1.25 | 2.25 | 96 |
| U5-L4-Sp5-B5S1-3D | 12.79 | 5.2 | 4.2 | 1.19 | 2.13 | 66 |
| U5-L5.25-Sp5-B5S1-3D | 12.79 | 6.4 | 5.4 | 1.25 | 2.22 | 88 |
| T5-L4-Sp5-B6S1-2D | 12.57 | 5.1 | 4.1 | 1.25 | 2.03 | 68 |
| T5-L4-Sp5-B6S1-2D | 12.57 | 5.4 | 4.4 | 1.25 | 2.00 | 78 |
| U5-L4-Sp4-B7S2-7D* | 14.79 | 5.1 | 4.1 | 1.25 | 1.53 | 52 |
| U5-L4-Sp-B7S2-7D* | 14.79 | 5.2 | 4.2 | 1.19 | 1.56 | 64 |
| E5-L4-Sp4-B8S2-7D* | 14.49 | 5.2 | 4.2 | 1.19 | 1.69 | 44 |
| E5-L4-Sp4-B8S2-7D* | 14.49 | 5.2 | 4.2 | 1.13 | 1.53 | 43 |
| U5-L2.75-Sp4-B9S3-7D* | 13.69 | 3.9 | 2.9 | 1.25 | 1.78 | 43 |
| U5-L2.75-Sp4-B9S3-7D* | 13.69 | 3.7 | 2.7 | 1.19 | 1.78 | 43 |
| E5-L2.75-Sp4-B10S3-7D* | 14.42 | 4.0 | 3.0 | 1.25 | 1.84 | 31 |
| E5-L2.75-Sp4-B10S3-7D* | 14.42 | 3.7 | 2.7 | 1.13 | 1.72 | 39 |
| U5-L5.25-Sp4-B11S2-7D* | 14.6 | 6.3 | 5.3 | 1.25 | 1.59 | 95 |
| U5-L5.25-Sp4-B11S2-7D* | 14.6 | 6.3 | 5.3 | 1.19 | 1.53 | 90 |
| E5-L5.25-Sp4-B12S3-7D* | 13.19 | 6.3 | 5.3 | 1.19 | 1.53 | 69 |
| E5-L5.25-Sp4-B12S3-7D* | 13.19 | 6.1 | 5.1 | 1.19 | 1.50 | 64 |
| U5-L6-Sp1$^{3}/_{16}$-B13S2-7D* | 13.74 | 7.2 | 6.2 | 1.25 | 0.19 | 108 |
| U5-s6-Sp1$^{3}/_{16}$-B13S2-7D* | 13.74 | 7.3 | 6.3 | 1.25 | 0.19 | 112 |
| E5-L6-Sp1$^{3}/_{16}$-B14S2-7D* | 14.18 | 7.3 | 6.3 | 1.25 | 0.16 | 78 |
| E5-L6-Sp1$^{3}/_{16}$-B14S2-7D* | 14.18 | 7.3 | 6.3 | 1.19 | 0.16 | 91 |

| Specimen ID | $f_{cm}$ ksi | $\ell_d$ in. | $\ell_s$ in. | $c_{so}$ in. | $c_{si}$ in. | $f_{s,\max}$ ksi |
|---|---|---|---|---|---|---|
| T5-L6-Sp1$^{3}/_{16}$-B15S4-7D* | 13.29 | 7.0 | 6.0 | 1.19 | 0.09 | 102 |
| T5-L6-Sp1$^{3}/_{16}$-B15S4-7D* | 13.29 | 7.0 | 6.0 | 1.13 | 0.19 | 93 |
| T5-L4-Sp4-B16S4-7D* | 13.29 | 5.1 | 4.1 | 1.13 | 1.69 | 61 |
| T5-L4-Sp4-B16S4-7D** | 13.29 | 5.2 | 4.2 | 1.13 | 1.53 | 55 |
| T5-L4-Sp4-7D-B16S4-7D** | 13.29 | 5.0 | 4.0 | 1.19 | 1.63 | 46 |
| T5-L4-Sp4-B16S4-7D* | 13.29 | 5.0 | 4.0 | 1.06 | 1.63 | 54 |
| U5-L2.75-Sp1$^{3}/_{16}$-B17S3-7D* | 13.04 | 3.8 | 2.8 | 1.13 | 0.16 | 55 |
| U5-L2.75-Sp1$^{3}/_{16}$-B17S3-7D* | 13.04 | 3.6 | 2.6 | 1.13 | 0.16 | 43 |
| E5-L2.75-Sp1$^{3}/_{16}$-B18S3-7D* | 13.04 | 3.75 | 2.75 | 1.25 | 0.19 | 49 |
| E5-L2.75-Sp1$^{3}/_{16}$-B18S3-7D* | 13.04 | 3.63 | 2.63 | 1.06 | 0.19 | 53 |
| U5-L6-Sp4-B19S2-7D* | 14.46 | 7.1 | 6.1 | 1.25 | 1.59 | 96 |
| U5-L6-Sp4-B19S2-7D* | 14.46 | 7.1 | 6.1 | 1.13 | 1.59 | 87 |
| E5-L6-Sp4-B20S2-7D* | 13.47 | 7.1 | 6.1 | 1.25 | 1.50 | 97 |
| E5-L6-Sp4-B20S2-7D* | 13.47 | 6.9 | 5.9 | 1.25 | 1.53 | 101 |
| T5-L6-Sp4-B21S3-7D* | 13.87 | 7.1 | 6.1 | 1.19 | 1.56 | 105 |
| T5-L5.25-Sp4-B22S2-7D* | 13.21 | 6.3 | 5.3 | 1.19 | 1.56 | 84 |
| T5-L5.25-Sp4-B22S2-7D* | 13.21 | 6.4 | 5.4 | 1.19 | 1.63 | 57 |

* Reinforcing Bars at the end of Pullout Specimens

** Test Affected by cracks extending from the testing of the adjacent bars

**Notation:**

• Specimen ID notation example: U5-L2.75-Sp5-B1S1-6D, the first term U5 represents the type and size of the bar, the letter represents the type of bar (U for uncoated, E for epoxy-coated and T for textured-epoxy-coated) and the number represents bar size (5 for No. 5 Bars); L2.75 represents a nominal splice length of 2.75 in.; Sp5 represents a nominal center-to-center spacing of 5 in. between the test bar and nearest No. 8 splice bar extended from the base slab; B1S1 represents the Batch 1 (as reported in Tables 2.6 and 2.7) of UHPC casting on precast slab 1.; 6D represents the age of UHPC at testing, equal to 6 days in the example.

- $f_{cm}$: Compressive strength of UHPC at testing
- $\ell_d$: Actual measurement of embedment length
- $\ell_s$: Actual measurement of splice length
- $c_{so}$: Actual measurement of the side cover
- $c_{si}$: Actual measurement of half the clear spacing of test bars to the nearest No. 8 extended bars
- $f_{s,\max}$: Bar stress at bond failure

The notation, $\ell_d$, $\ell_s$, $c_{so}$, and $c_{si}$, is adopted from ACI 408R-03 “Bond and Development of Straight Reinforcing Bars in Tension” (ACI Committee 408 2003).

# APPENDIX E: LOAD VERSUS DEFLECTION FOR BEAM-SPLICE SPECIMENS

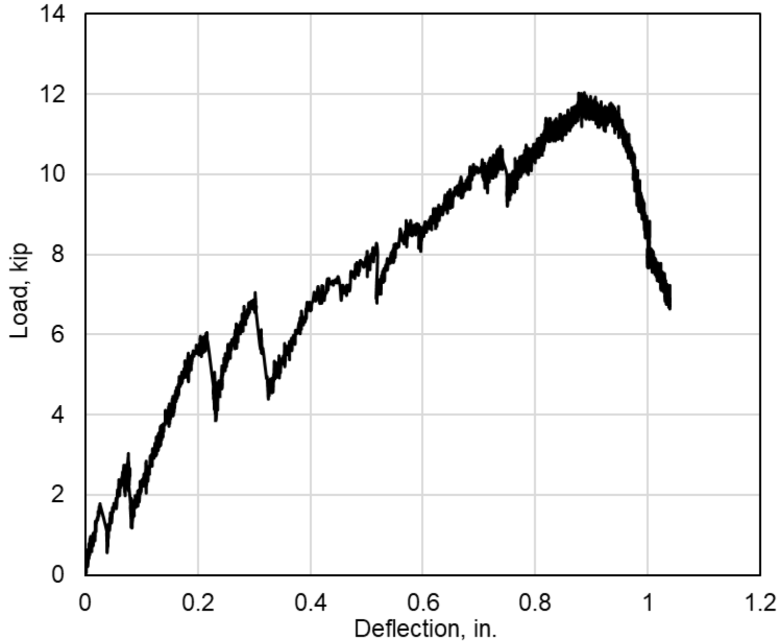

**Figure E.1:** Load vs Deflection Plot for Specimen U5-L3.75-C2.5-Sp3

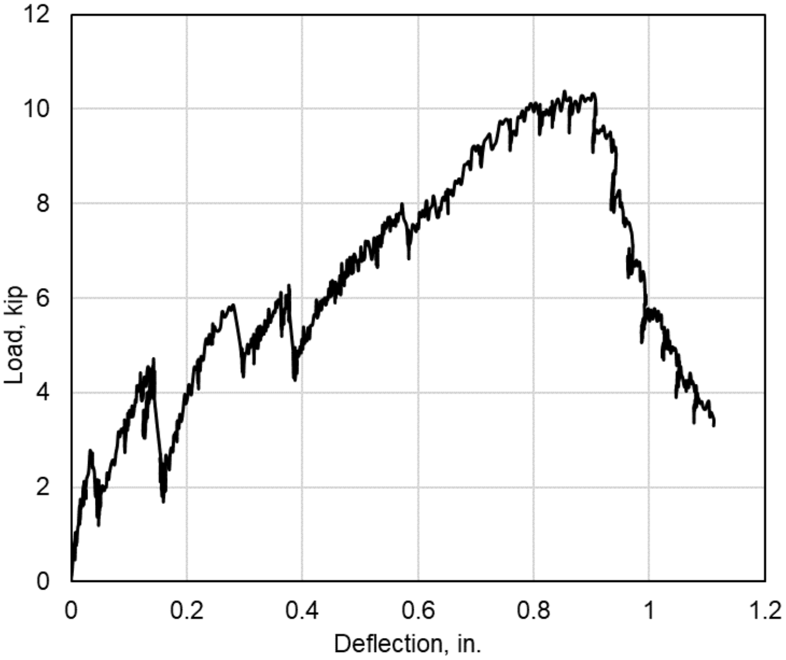

**Figure E.2:** Load vs Deflection Plot for Specimen E5-L3.75-C2.5-Sp3

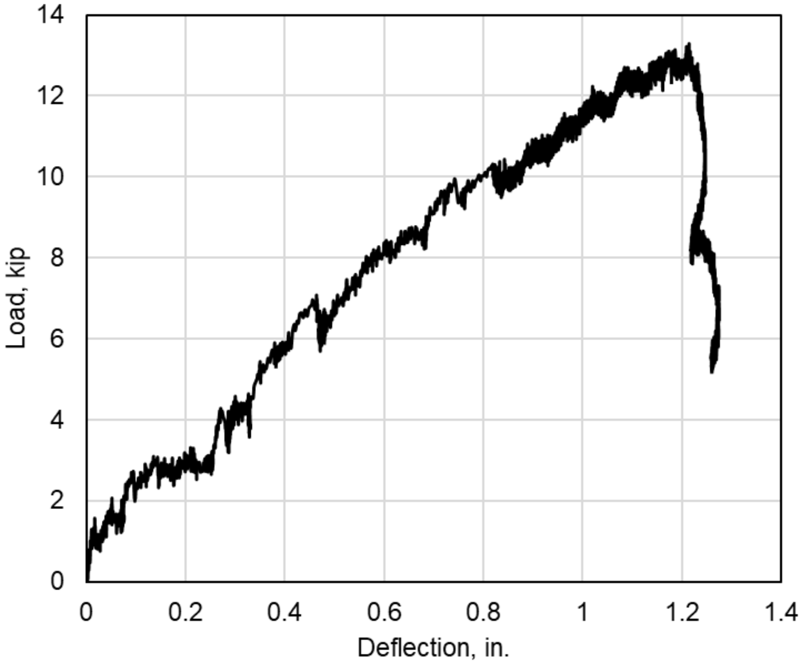

**Figure E.3:** Load vs Deflection Plot for Specimen T5-L3.75-C2.5-Sp3

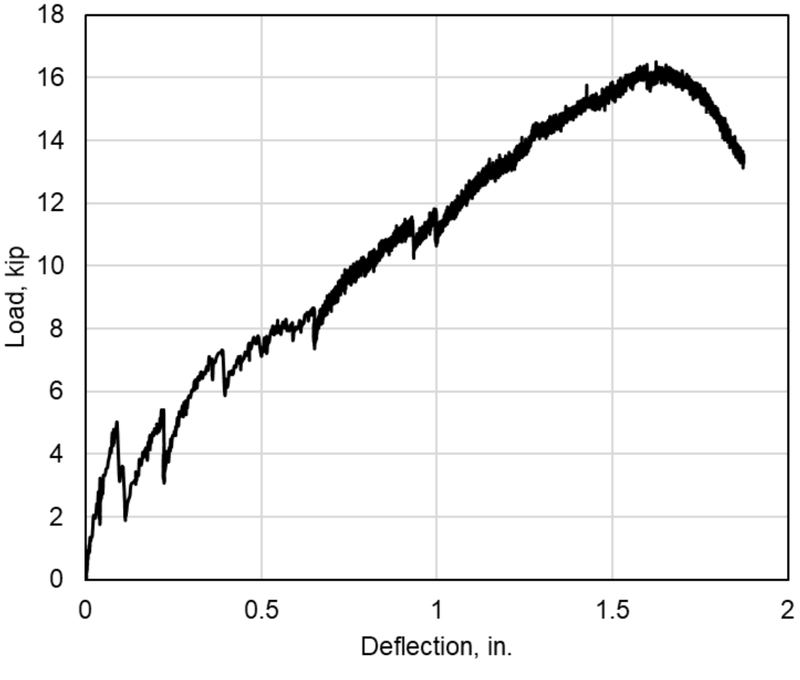

**Figure E.4:** Load vs Deflection Plot for Specimen U5-L5-C2.5-Sp3

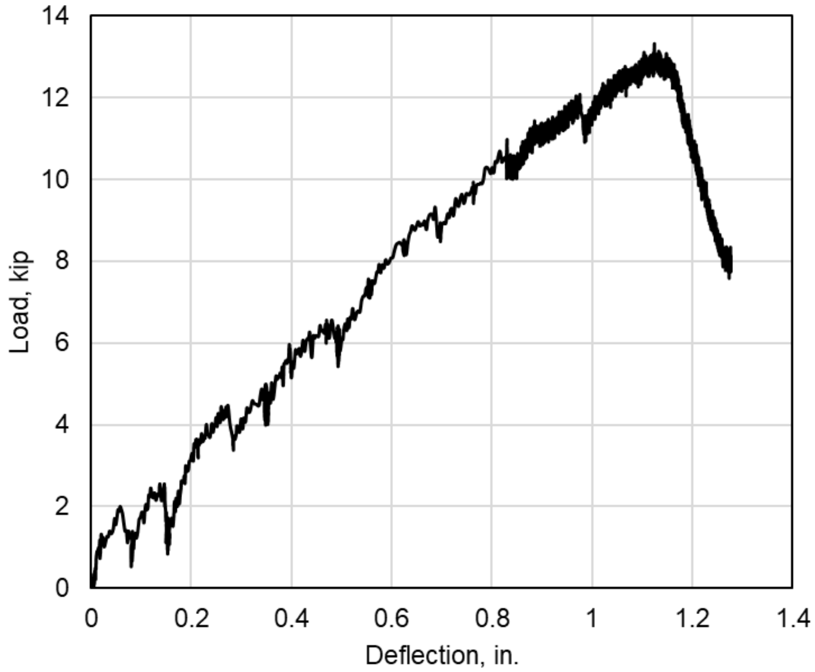

**Figure E.5:** Load vs Deflection Plot for Specimen E5-L5-C2.5-Sp3

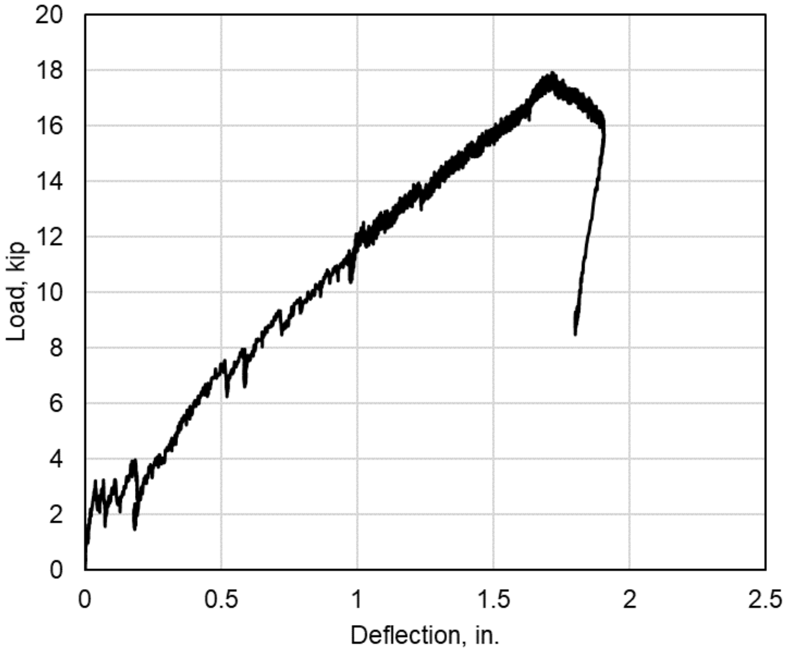

**Figure E.6:** Load vs Deflection Plot for Specimen U5-L6.25-C2.5-Sp3

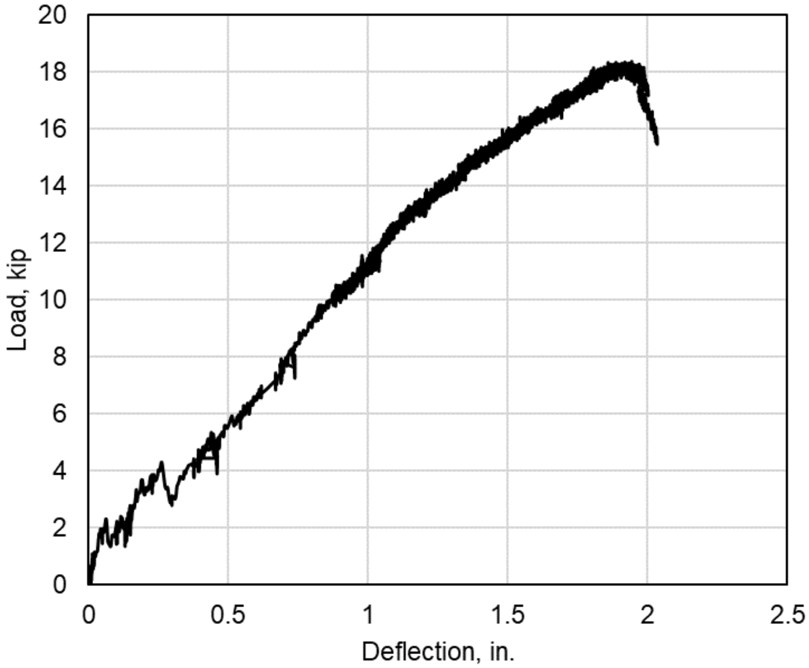

**Figure E.7:** Load vs Deflection Plot for Specimen E5-L6.25-C2.5-Sp3

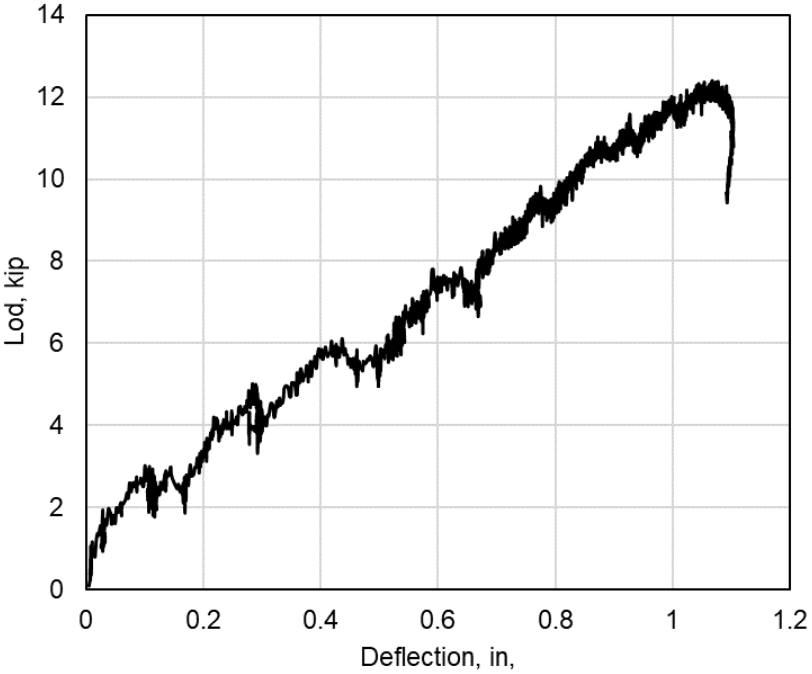

**Figure E.8:** Load vs Deflection Plot for Specimen U5-L3.75-C2.5-Sp1$^{7}/_{8}$

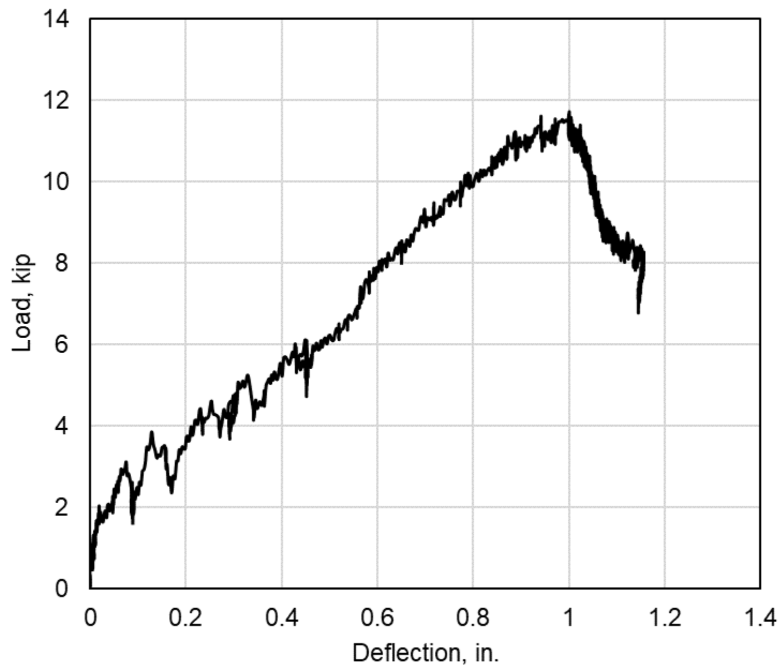

**Figure E.9:** Load vs Deflection Plot for Specimen E5-L3.75-C2.5-Sp1$^7/_8$

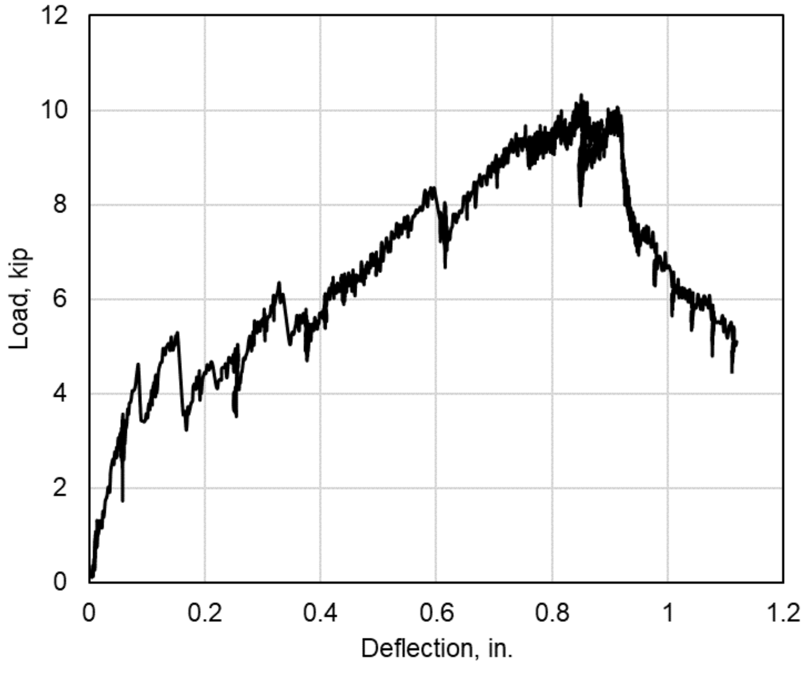

**Figure E.10:** Load vs Deflection Plot for Specimen T5-L3.75-C2.5-Sp1$^7/_8$

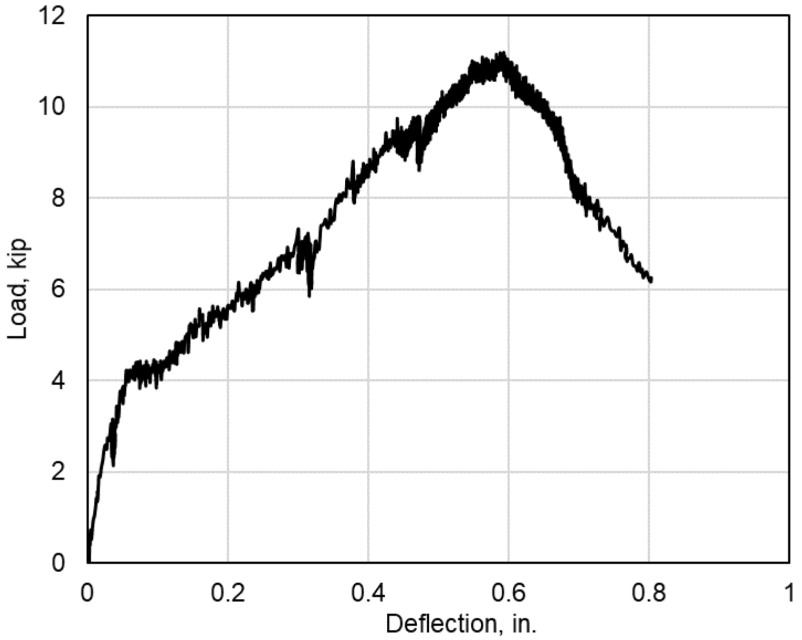

**Figure E.11:** Load vs Deflection Plot for Specimen U5-L3.75-C1-Sp3

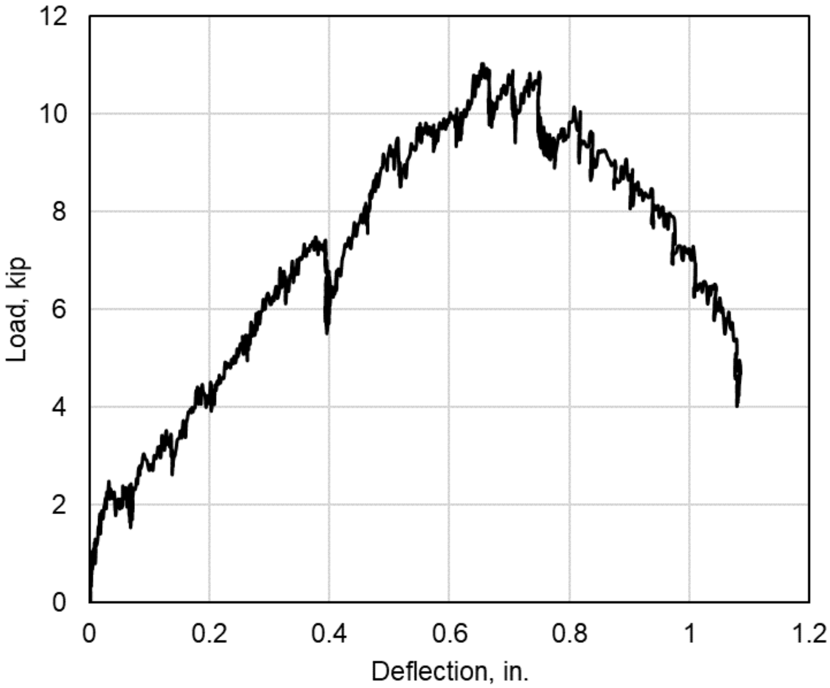

**Figure E.12:** Load vs Deflection Plot for Specimen E5-L3.75-C1-Sp3

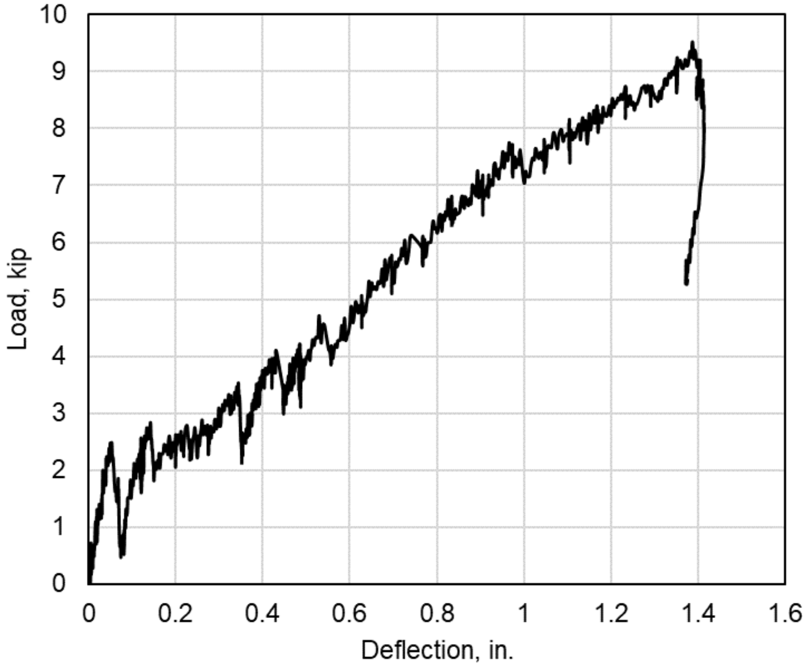

**Figure E.13:** Load vs Deflection Plot for Specimen U4-L3-C2.5-Sp3

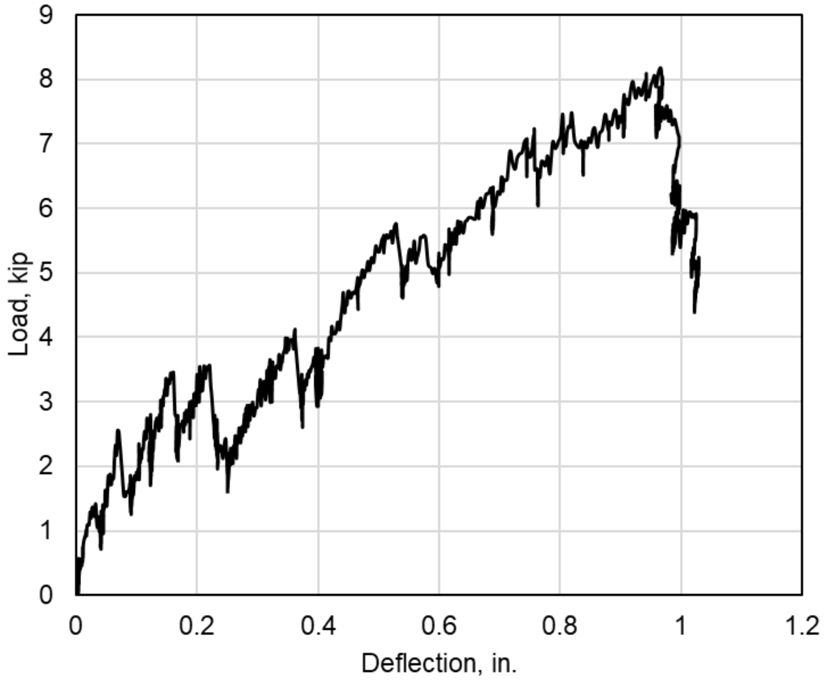

**Figure E.14:** Load vs Deflection Plot for Specimen E4-L3-C2.5-Sp3

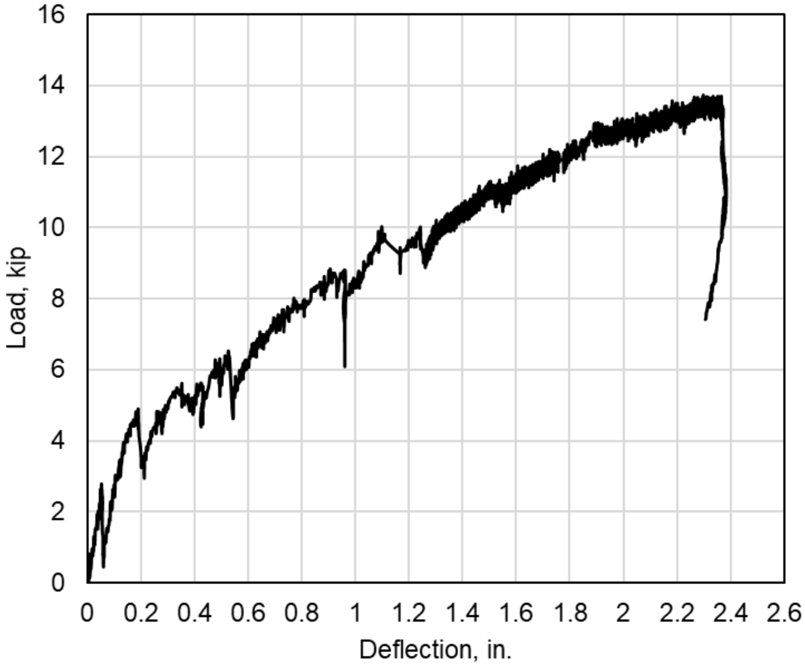

**Figure E.15:** Load vs Deflection Plot for Specimen U4-L4-C2.5-Sp3

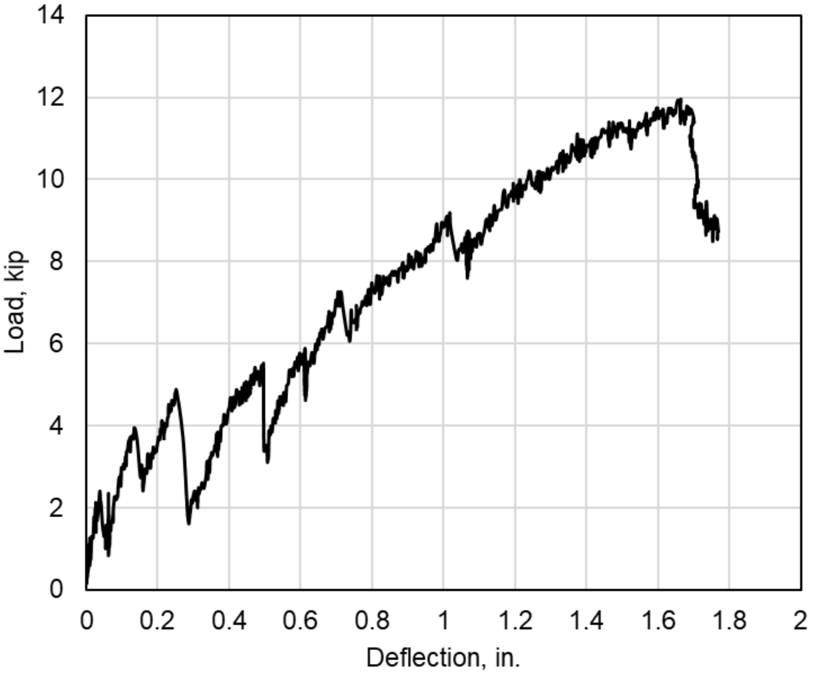

**Figure E.16:** Load vs Deflection Plot for Specimen E4-L4-C2.5-Sp3

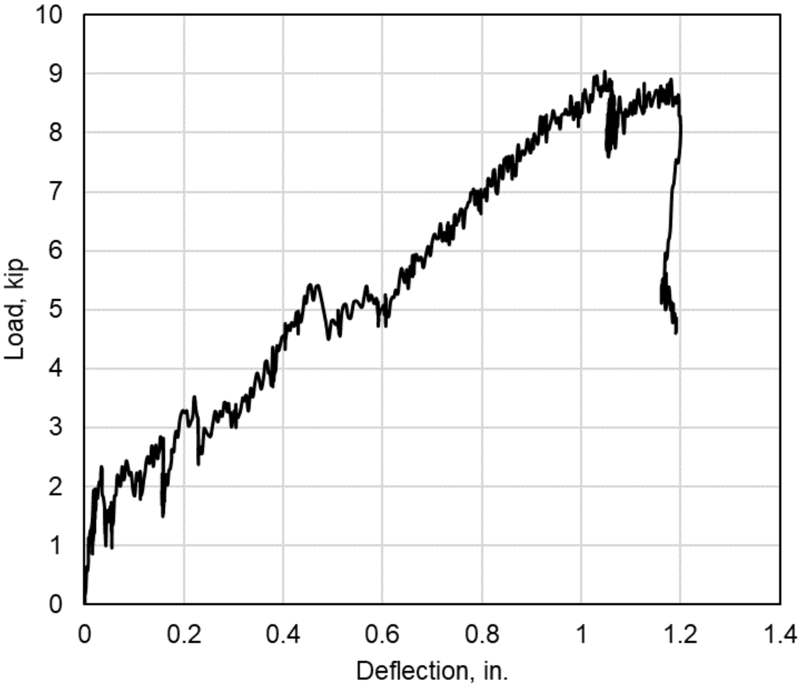

**Figure E.17:** Load vs Deflection Plot for Specimen U4-L3-C2.5-Sp1$^1/_2$

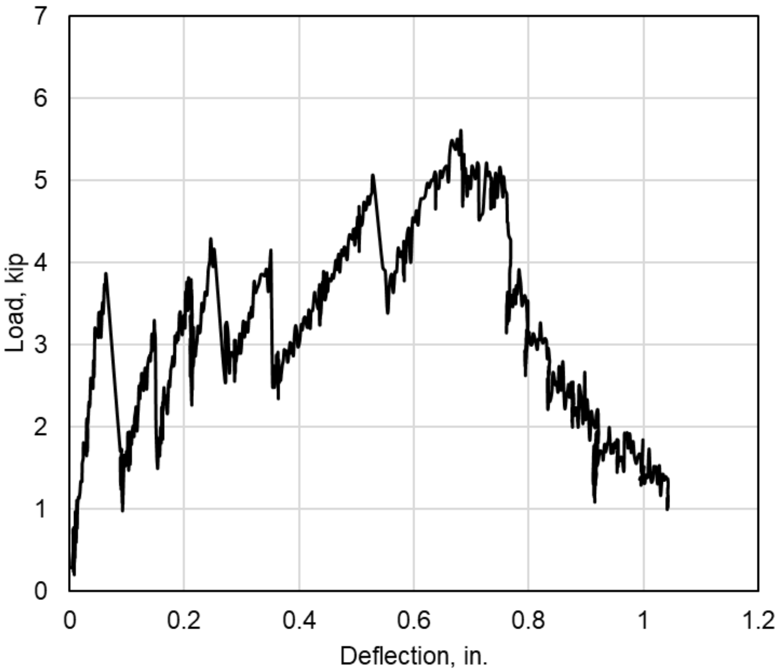

**Figure E.18:** Load vs Deflection Plot for Specimen E4-L3-C2.5-Sp1$^1/_2$

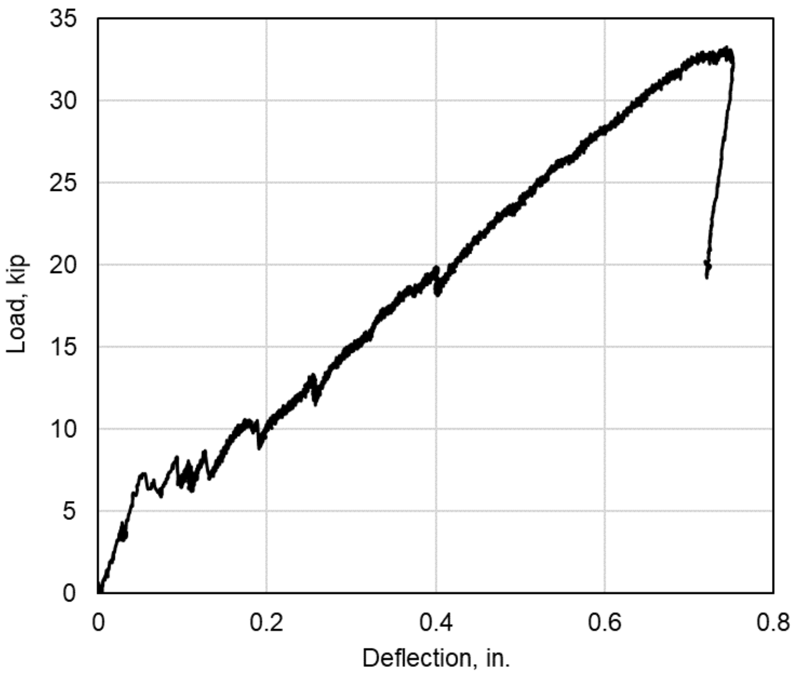

**Figure E.19:** Load vs Deflection Plot for Specimen U8-L6-C2.5-Sp3

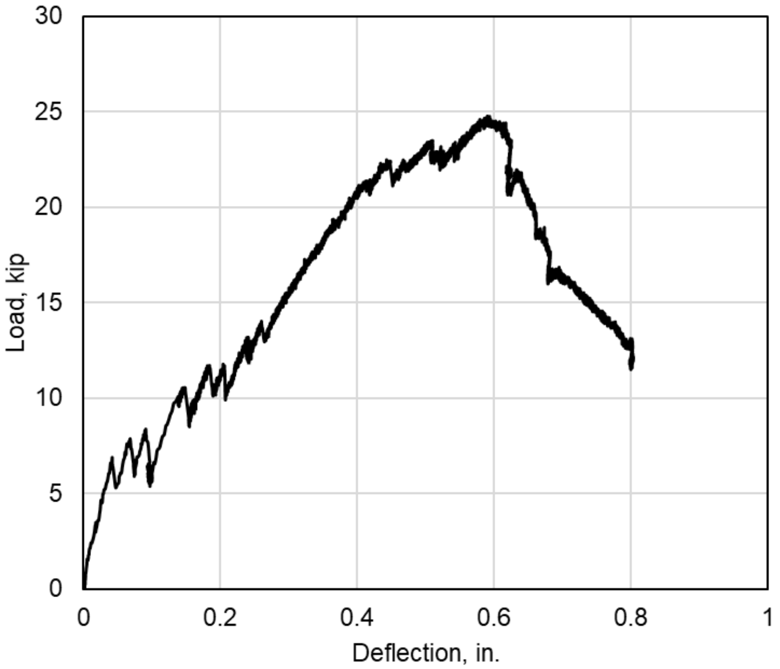

**Figure E.20:** Load vs Deflection Plot for Specimen E8-L6-C2.5-Sp3

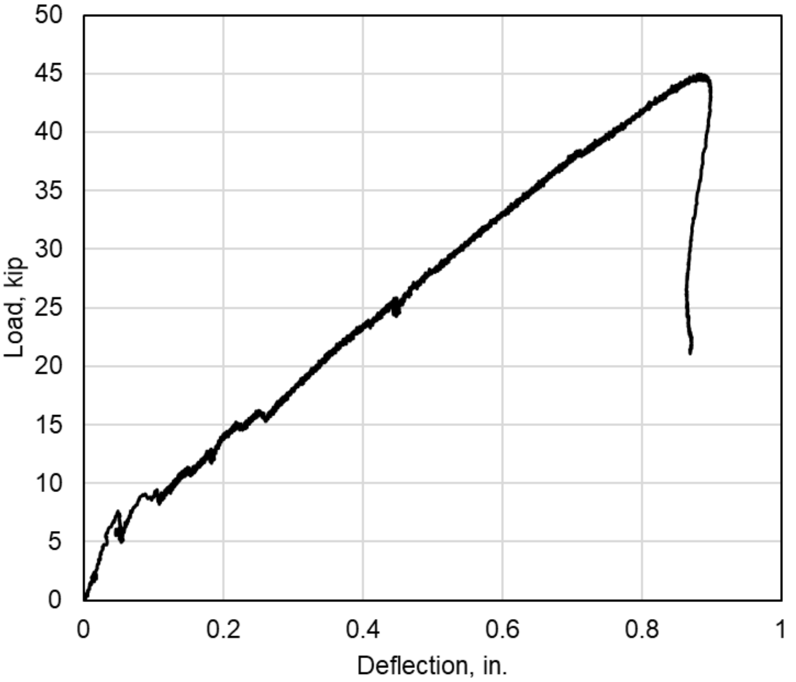

**Figure E.21:** Load vs Deflection Plot for Specimen U8-L8-C2.5-Sp3

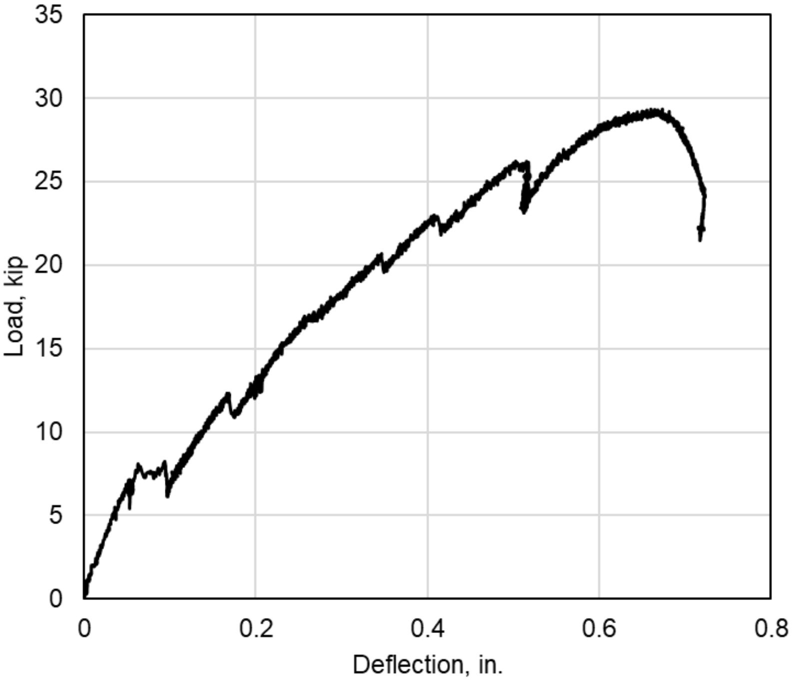

**Figure E.22:** Load vs Deflection Plot for Specimen E8-L8-C2.5-Sp3

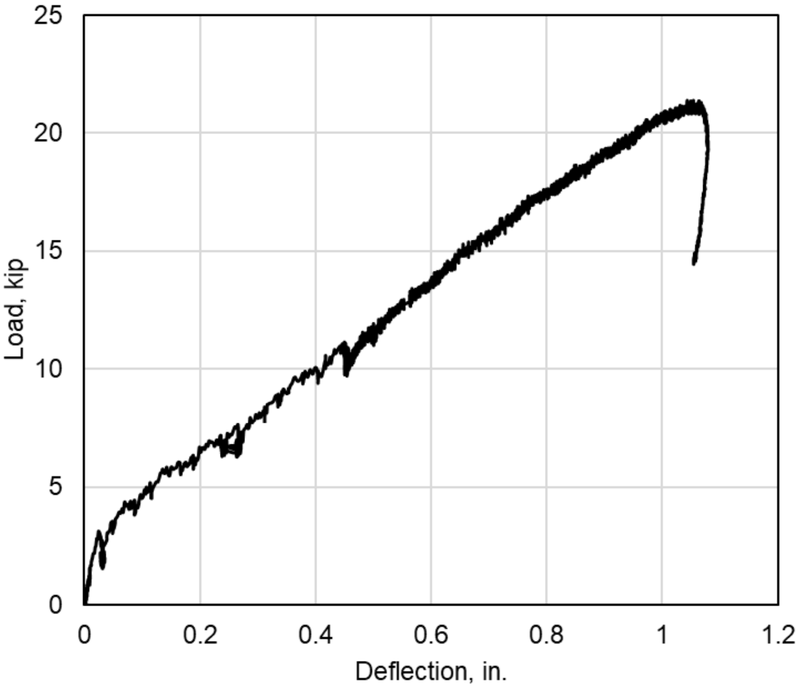

**Figure E.23:** Load vs Deflection Plot for Specimen U5-L5.5-C1-Sp3

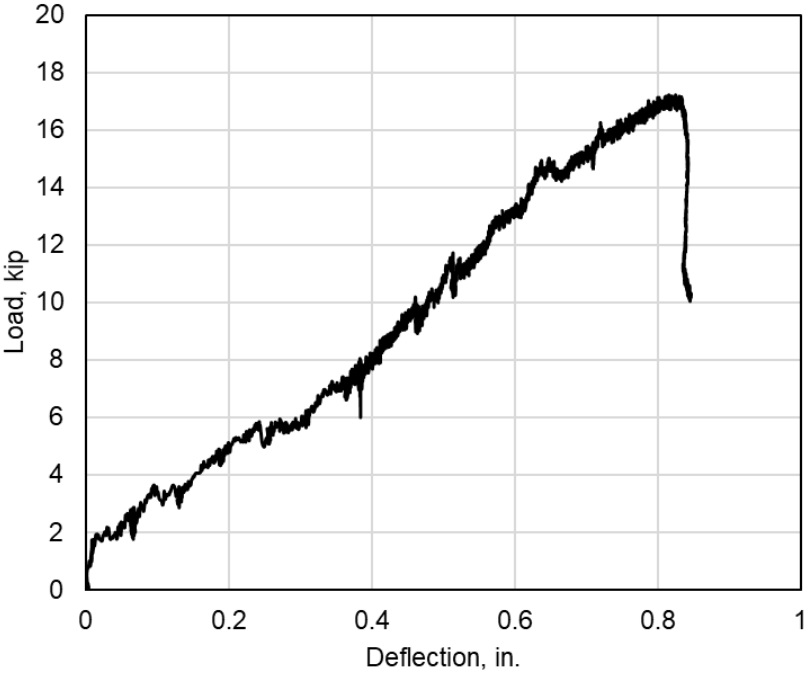

**Figure E. 24:** Load vs Deflection Plot for Specimen E5-L5.75-C1-Sp3

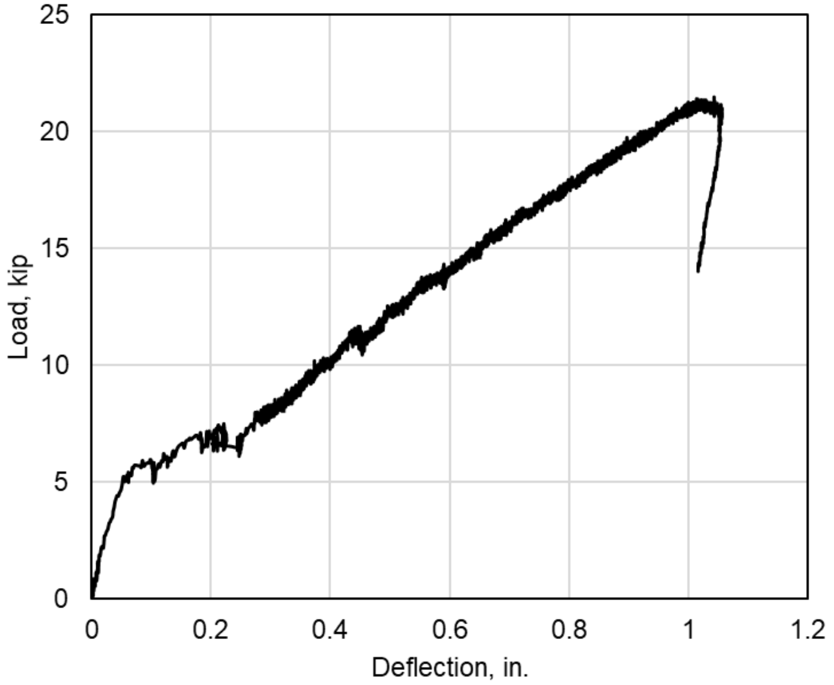

**Figure E.25:** Load vs Deflection Plot for Specimen T5-L5.5-C1-Sp3

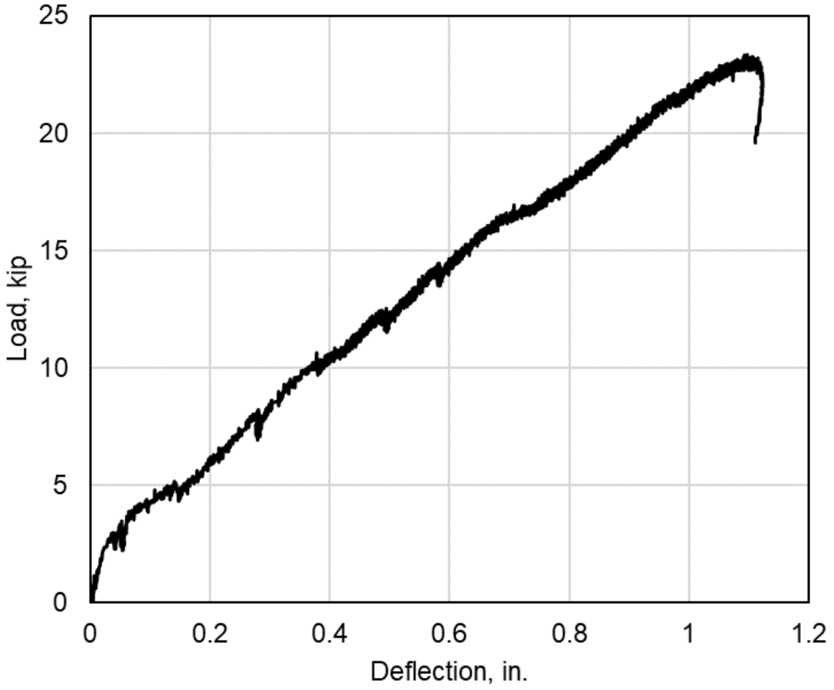

**Figure E.26:** Load vs Deflection Plot for Specimen U5-L5.5-C1-Sp1$^{7}/_{8}$

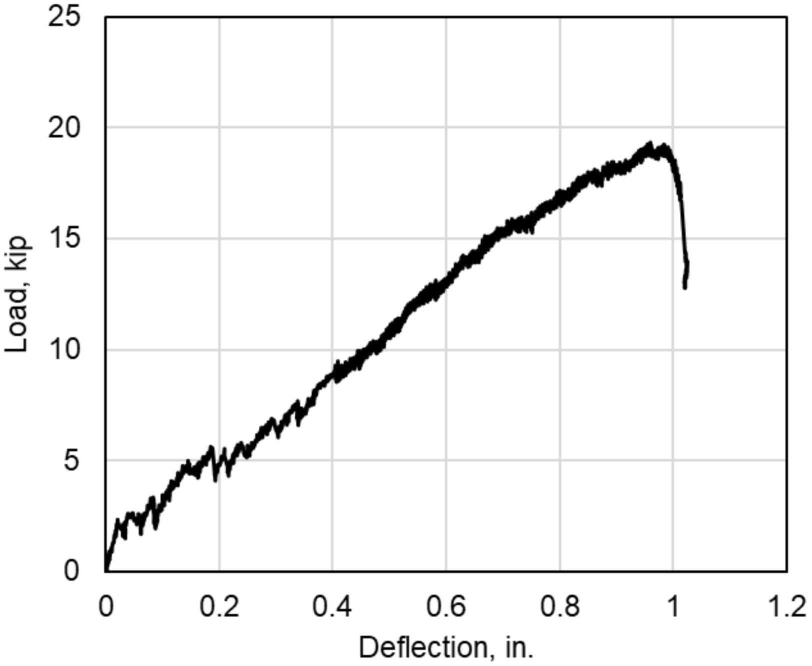

**Figure E.27:** Load vs Deflection Plot for Specimen E5-L5.5-C1-Sp1$^{7}/_{8}$

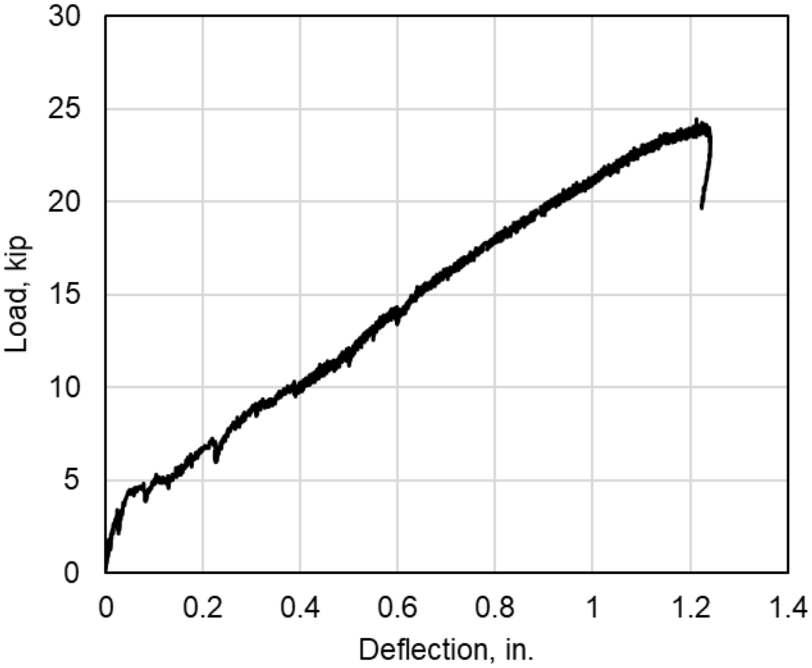

**Figure E.28:** Load vs Deflection Plot for Specimen T5-L5.5-C1-Sp1$^{7}/_{8}$