

Evaluation of Bond of Reinforcing Steel in UHPC: Design Parameters and Material Property Characterization

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Abstract: As a material on the leading edge of concrete innovation, ultra-high performance concrete (UHPC) allows the design of innovative structural components and offers the opportunities to develop new techniques for construction, repair, and retrofit. Compared to the traditional normal strength concrete which is brittle under tension, UHPC-class materials exhibit very high compressive strength and enhanced cracking and post-cracking behavior in tension. The advanced mechanical properties of the UHPC-class material create many opportunities for innovation in design, but also challenge the use of most current design specifications which are based on traditional normal strength concrete. This paper presents the evaluation of the bond between the reinforcing steel and UHPC-class materials. The material properties including the compressive strength and the tensile characteristics of UHPC are presented. The effect of design parameters, including the embedment length, concrete cover, and bar spacing on bond strength is assessed. A total of five different, commercially-available UHPC-class materials with various fiber contents are included in the evaluation. Results indicate that the embedment length of reinforcing bar in UHPC can be significantly reduced. Guidance on the embedment of reinforcing steel in UHPC is provided.

Keywords: UHPC, Reinforcing Bar Bond, Tensile Response, Compressive Strength, Structural Design

1. Introduction

As a material on the leading edge of concrete innovation, ultra-high performance concrete (UHPC) allows the design of innovative structural components and offers the opportunities to develop new techniques for construction, repair, and retrofit. Among many other advanced properties of this class material, UHPC-class materials have a very high compressive strength, low water-to-cementitious materials ratios, and exhibit pseudo strain hardening behavior in tension due to the high volumetric percentage of fiber reinforcement. The advanced mechanical properties of the UHPC-class material create many opportunities for innovation in design, but also challenge the use of most current design specifications which are based on traditional normal strength concrete. The research presented in this paper is one of the many efforts conducted at the Turner-Fairbank Highway Research Center of Federal Highway Administration to characterize this class of material and to facilitate use in structural applications.

The bond between concrete and reinforcing steel is an important topic in structural concrete as the performance of the structural concrete relies on the composite behavior between reinforcing steel and concrete. In general, factors that affect the bond strength include the tensile and compressive strength of the concrete materials, the volume of concrete confining the reinforcement, which are related to the dimensional parameters like bar embedment length, bar spacing, and concrete cover, presence of confinement, and reinforcement surface condition. UHPC materials have a higher tensile strength and greater tensile ductility than conventional concrete, and the enhanced mechanical behavior of UHPC materials can lead to the reduction, or even elimination, of the use of steel reinforcement in structural members. This paper presents the evaluation of the bond between the reinforcing steel and UHPC-class materials. Direct tension pullout tests were conducted and all above mentioned parameters were investigated. Five UHPC mixtures were considered in the study. Compressive strength and direct tension tests were conducted to characterize the UHPC mechanical properties.

2. UHPC Mixtures

Five UHPC mixtures were included in the study. The mix design for each mixture and corresponding fibers used in each mixture are presented in Table 1 and Table 2, respectively. It should be noted that the mix designs shown in the table correspond to the mix designs and fiber contents recommended by the manufacturers. The fiber contents can be adjusted based on the application, and in this study a fiber content of 2% (by volume) was tested for each UHPC mixture for comparison purpose. A higher fiber content, either recommended by the manufacturer such as the 3.1% and 4.6% for UHPC mixes A and C, respectively, or selected by the researchers such as 3.25%, 4%, and 3.25% for UHPC mixes B, D, and E, respectively, were also tested.

3. Testing Methods

3.1. Direct Tension Pullout Test

Direct tension pullout tests, with a novel test specimen design and associated loading apparatus, were conducted in this study. The test setup was developed to mimic the tension-tension lap splice configuration that may be encountered in a field-deployed connection system. As shown in Figure 1, the pullout test specimens were UHPC strips cast on top of precast concrete slabs. The No.8 (25 mm diameter) bars extended 8 inches (20.3 cm) from the precast concrete slab. UHPC strips were cast on top of the precast slab with the No. 8 bars in the center of the strips. Each

testing bar was situated so as to be embedded into the UHPC strip and located between two of the No. 8 bars.

Table 1. UHPC Mix Designs

Designation	A		B		C		D		E	
Mix Design	lb/yd ³	kg/m ³								
Pre-blended dry powders	3503 [†]	2078 [†]	3516	2086	3600	2136	3700	2195	3236	1920
Water	278	165	354	210	268	159	219	130	379	225
Chemical admixtures	23	13.7	48	28.7	preblended*		89 ^{††}	53 ^{††}	73	44
Steel fiber content	416	247	88+179	52+106	613	364	263	156	263	156
Steel fiber type (refer to Table 2)	Type I		Type II and III		Type IV		Type V		Type V	
Steel fiber content by volume[‡]	3.1%		2.0%		4.6%		2.0%		2.0%	

[†]: Not pre-blended but come in as separate ingredient, which include fine silica sand, finely ground quartz flour, Portland cement, and amorphous micro-silica.

*: The chemical admixtures were dry powders and pre-blended with the premix.

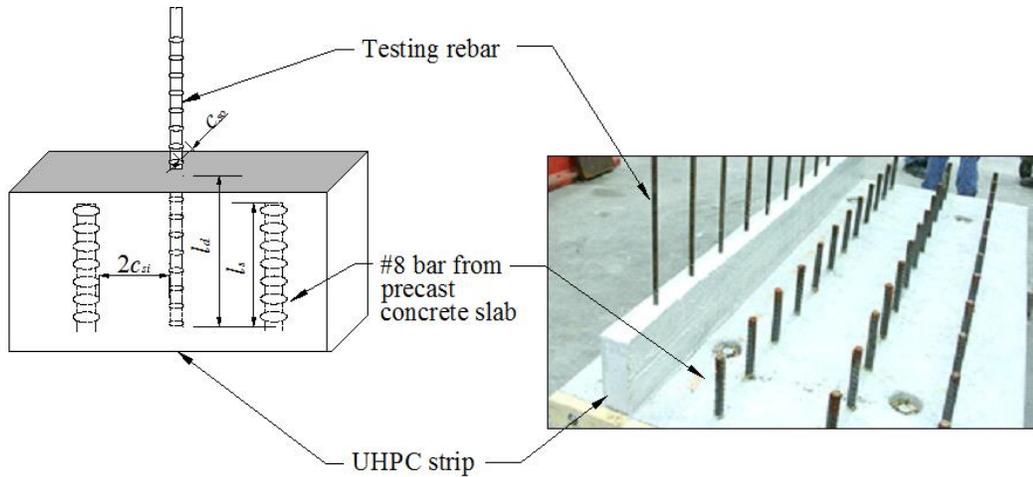
^{††}: It includes three chemicals, a modified phosphonate plasticizer, a modified polycarboxylate high-range water-reducing admixture, and a non-chloride accelerator

[‡]: Fiber content recommended by the manufacturer, which can be adjusted depending on the application

Table 2. Steel Fiber Properties

Fiber Type	Fiber Material	Tensile Strength	Length	Cross Section	Geometry
Type I	Steel	160 ksi (1100 MPa)	1.18 in. (30 mm)	Round cross section, 0.022 in. (0.55 mm) diameter	hooked ends [†]
Type II	Brass coated steel	≥ 305 ksi (≥ 2100 MPa)	0.5 in. (13 mm)	Round cross section, 0.012 in. (0.3 mm) diameter	straight
Type III	Brass coated steel	≥ 305 ksi (≥ 2100 MPa)	0.79 in. (20 mm)	Round cross section, 0.012 in. (0.3 mm) diameter	straight
Type IV	Brass coated steel	348 ksi (2400 MPa)	0.5 in. (13 mm)	Round cross section, 0.012 in. (0.3 mm) diameter	straight
Type V	Brass coated steel	399 ksi (3750 MPa)	0.5 in. (13 mm)	Round cross section, 0.008 in. (0.2 mm) diameter	straight

[†]: fibers were adhered together in bundles with a water-soluble adhesive



Note: c_{so} , side cover; $2c_{si}$, bar clear spacing to the adjacent No.8 bar; l_d , embedment length; l_s , lap splice length.

Figure 1. Configuration of Pull-Out Test Specimens.

The pullout test was conducted using the fixture showing in figure 2. A hydraulic jack was placed on a steel chair, and the steel chair stands on the precast slab. When a pullout force is applied, the fixture reacts against the precast slab. With such a setup, the reinforcing bars being tested as well as the extended No. 8 bars are both placed in tension. The UHPC surrounding these bars transfers the loads between them. This test setup simulates structural configurations wherein lap spliced reinforcement is loaded in tension.

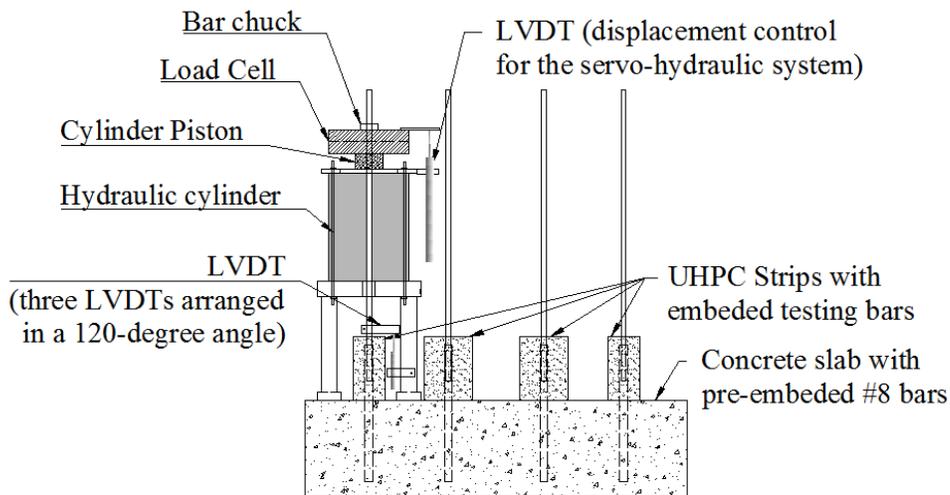


Figure 2. Pull-Out Test Loading setup.

3.2. Compressive Tests

The compressive tests cylinders were standard 3×6 in. (76.2×152.4 mm) cylinders. The compressive mechanical testing was completed through modified version of the ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. The

employed test method has been used multiple times in the past (Graybeal 2007, Graybeal and Stone 2012). From the standpoint of the ASTM C39 test method, the load rate was increased from 35 psi/second (0.24 MPa/second) to 150 psi/second (1.0 MPa/second) due to the high compressive strength of UHPC and the duration of test that would result from the slower load rate.

3.3. Direct Tension Tests

Understanding the tensile response of UHPC is critical to use this type of material. A simple and reliable direct tension test was developed at the FHWA's Turner-Fairbank Highway Research Center (Graybeal and Baby 2013) and was used in this study. The test method was loosely based on the existing standardized tensile test method for metals described in ASTM E8/E8M (8), commonly referred to as the "dog bone test". An illustration of the specimen shape and gripping setup is shown in Figure 3. Prismatic specimens with dimension of 2×2×17 in. (51×51×432 mm) are used and tapered aluminum plates are glued on two opposite faces at each end of the specimen using a high strength, high-stiffness epoxy. The specimen is axial loaded with a hydraulic-actuated, computer-controlled load frame. The load and deformation within the gage length are recorded. Further details can be obtained from Graybeal and Baby (2013).

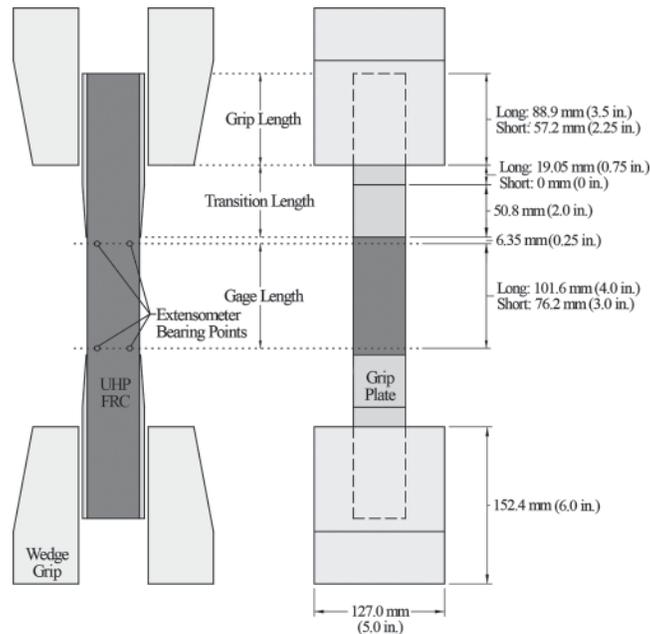


Figure 3. Direct tension test method setup. (from Graybeal and Baby 2013)

The test method allows for capturing the tensile response of the UHPC materials, especially for the pseudo strain hardening behavior. Graybeal and Baby (2013) summarized four idealized phases of the tensile response of UHPC materials based on direct tension test, shown in Figure 4. The phases include an elastic phase until the occurrence of the first cracking, the multi-cracking phase where the matrix cracks repeatedly and the fibers bridging the cracks are engaged, the crack straining phase characterized by the crack saturation and the increase of the crack openings in the existing cracks, and the final localization phase where all the deformation is dominated by the widening of an individual crack and the behavior is defined by debonding and pullout fiber mechanisms.

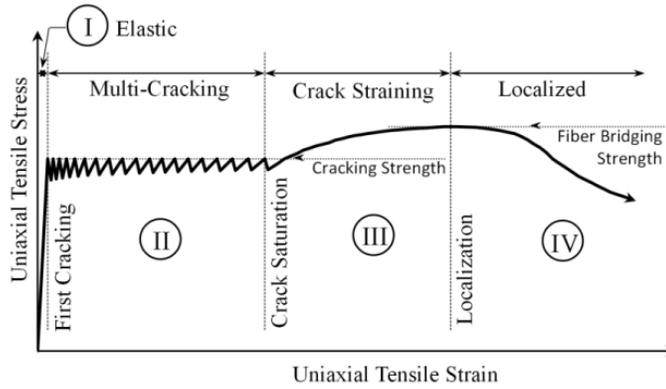


Figure 4. Idealized uniaxial tensile mechanical response of UHPC. (from Graybeal and Baby 2013).

4. Results

4.1. Bond Strength

A typical bar stress versus slip curve for a steel bar embedded in UHPC is presented in Figure 5. The bar stress f_s is calculated as the applied load divided by the cross section area of the bar. The displacement is measured along a loaded portion of the bar at about two inches (51 mm) above the top surface of UHPC strip. For comparison, the bar stress versus slip curve for a traditional concrete [compressive strength of 4700 psi (32.5MPa)] with the same setup as UHPC is also included in Figure 5. It should be noted that after the bar stress reaches the maximum at bond failure, the bar stress dropped quickly for the bar embedded in concrete while it gradually decreased for the bars in UHPC.

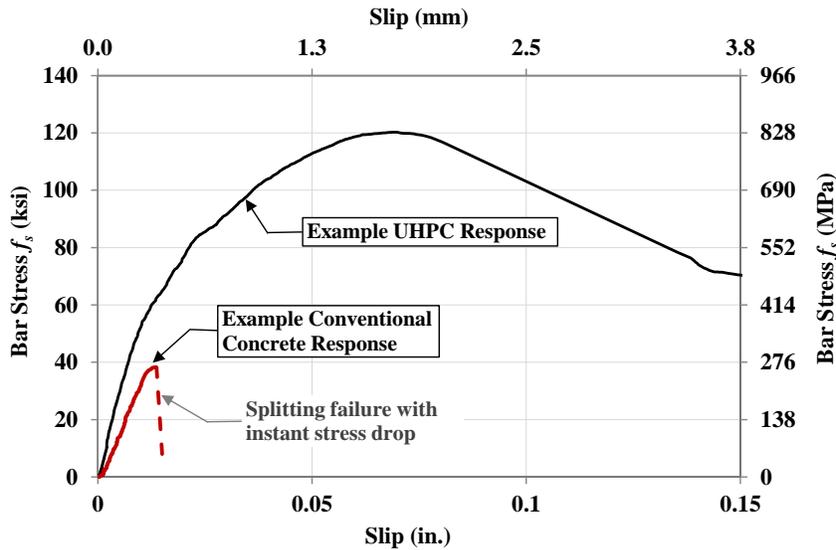


Figure 5. Bar Stress versus Slip at Loaded Bar End.

Over 500 reinforcing bar bond tests were conducted. The factors that affect reinforcement bond strength, including the embedment length, bar spacing, concrete cover, bar size, bar type,

and concrete compressive strength were extensively evaluated. The main findings can be summarized below. Further details can be found in research by Yuan and Graybeal (2014) and Yuan and Graybeal (2015).

- Increasing the embedment length of the reinforcing bar increases bond strength.
- The relationship between the bond strength and the bonded length for bar embedded in UHPC is nearly linear, indicating that UHPC exhibits enhanced performance as compared with traditional high-strength concrete.
- Bond strength increases as the clear cover increases.
- Non-contact lap splice specimens exhibit higher bond strength than contact lap splice specimens, due to the fact that the tight spacing in contact lap splice limits the ability of the fiber reinforcement to locally enhance the mechanical resistance of the UHPC.
- When the bar clear spacing is so large that the induced diagonal cracks from the pullout force will not intersect with the adjacent bars, the adjacent bar will not help stop the propagation of the diagonal cracks and the bond strength becomes a function of the tensile mechanical properties of the UHPC.
- Models that used bar spacing and side cover to predict reinforcing bar bond strength in conventional concrete may need to be reevaluated in consideration of the added crack propagation resistance provided by the fiber reinforcement in UHPC.
- An increase in the compressive strength of the UHPC results in an increased bond strength.
- For bars with larger diameter, the bond strength decreases.
- Bars that yield before bond failure have less ultimate bond strength than similarly configured high-strength bars that do not yield before bond failure.
- The epoxy-coated bars have lower bond strength than similarly configured uncoated bars.

As part of the large test matrix evaluated in the study, the bond tests with different UHPC mixtures are presented in this paper and the results are summarized in Table 3. All of these specimens were tested with No. 5 bars and were detailed to have an embedment length of $8d_b$, a side cover of $3d_b$, and a bar center to center spacing of 4 in. (102 mm) (clear spacing between $2d_b$ and l_s), where d_b is the diameter of the steel bar. As shown, all the UHPC mixtures with a 2% (by volume) fiber content and compressive strength between 13.3 and 16.3 ksi (92 and 112 MPa) reached a bar stress at bond failure well above 75 ksi (517 MPa). When higher fiber contents were used, UHPC mixtures A, B, and D had similar bond strength as the corresponding mixtures with 2% (by volume) fiber, while UHPC mixtures C and E exhibited improved bond strength.

Table 3. Bar stress at bond failure for different UHPC formulas

	UHPC A		UHPC B		UHPC C		UHPC D		UHPC E		
Fiber content, by volume, %	2.0	3.1 [†]	2.0 [†]	3.25%	2.0%	4.6 [†]	2.0 [†]	4.0	2.0 [†]	3.25	
Compressive Strength, ksi	16.0	15.2	16.3	14.7	13.6	10.8	13.5	14.5	13.3	14.6	
$f_{s, max}$ at bond failure, ksi	avg.	123	124	137	124	126	147	132	130	109	136
	min.	118	121	127	115	118	131	117	124	100	122
	max	126	128	145	142	135	157	143	142	116	145
No. of Tests	3	3	4	5	4	6	10	5	5	5	

[†]: Fiber content recommended by the manufacturer, which can be adjusted depending on the application.

1 ksi = 6.895 MPa

Design recommendations for steel reinforcing bars embedded in UHPC were developed for deformed bars reaching the lesser of the bar yield strength or 75 ksi (517 MPa) at bond failure. These recommendations are presented in *Design and Construction of Field-Cast UHPC Connections* (Graybeal 2014) and are reiterated here:

- Bar size from No. 4 to No. 11,
- Uncoated or epoxy coated bar,
- Minimum embedment length of $8d_b$,
- Minimum clear cover of $3d_b$,
- Bar clear spacing between $2d_b$ and l_s ,
- Minimum UHPC compressive strength of 13.5 ksi (93 MPa), and
- A maximum flow of 10 in. (254 mm) after 20 drops following the ASTM C1437 tests to minimize fiber segregation.

4.2. Compressive Strength

The compressive strength for the five UHPC mixtures at ages between one day and 125 days are reported in Figure 6. Each of the UHPC mixtures were tested with two different fiber contents. All the cylinders were air cured in a laboratory condition with an ambient temperature of 72 °F (22 °C). The observations based on the compression strength test are as follows.

- The tested UHPC materials gained strength quickly (laboratory condition with air curing). UHPC D, which used an accelerator, had the most rapid strength gain reaching a compressive strength around 13.5 ksi (93 MPa) at one day after casting. Other UHPC materials gained strength slightly slower than UHPC D and could reach a compressive strength higher than 13.5 ksi (93 MPa) within 4 or 5 days.
- Similar to conventional concrete, most strength development happened well within the first 28 days and the strength gain after that is minimal.
- Increasing the fiber content does not seem to have much effect on the compressive strength. The mixtures with higher fiber content had slightly higher, if not the same, compressive strength than the corresponding mixes with 2% (by volume) fiber.

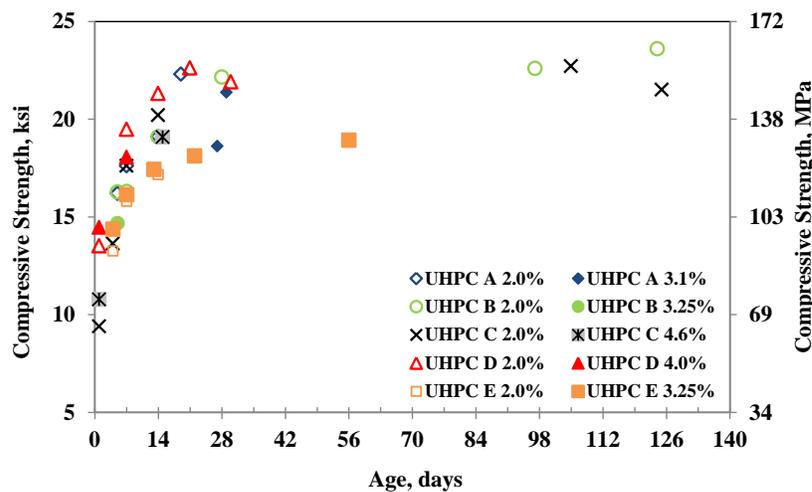


Figure 6. Compressive Strength.

4.3. Direct Tension Test

The tensile performance of the UHPC mixtures is presented in Figure 7. All the direct tension specimens were tested at the same age when the pull-out bond test was conducted. The compressive strength of the UHPC mixtures can be found in Table 3. As shown in Figure 7(a), all UHPC mixtures (except for UHPC C) with 2% (by volume) fiber exhibited similar ductile tensile behavior, where the specimens first reached the first cracking strength (end of the elastic phase, refer to Figure 4), then the stress sustained or increased with more defamation, followed by stress decrease due to crack localization. For UHPC C, the axial tensile stress started to slowly decrease shortly after reaching the first cracking strength. All UHPC mixtures in Figure 7(a) had the first cracking strength higher than or equal to 0.8 ksi (5.5 MPa). When higher fiber content was used, the UHPC mixtures exhibited different tensile behaviors. Two obvious changes comparing the mixtures in Figure 7(b) with the mixtures the Figure 7(a) are higher first cracking strength and more obvious cracking straining phase (refer to Figure 4). More analysis is being performed and will be reported in the future publications.

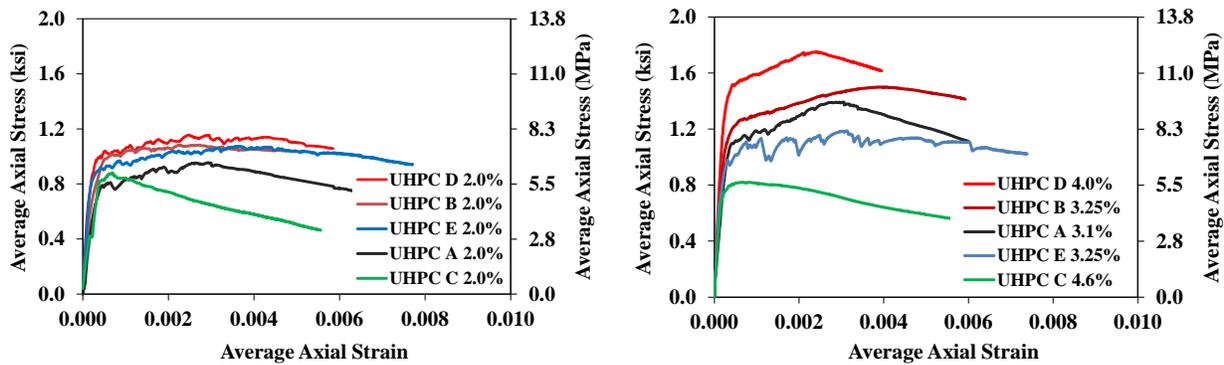


Figure 7. Tensile stress-strain response for (a) UHPC mixtures with 2% (by volume) fiber, and (b) UHPC mixtures with more than 2% (by volume) fiber.

5. Conclusions

The research discussed herein focused on assessing the bond strength of deformed reinforcing bar in UHPC and UHPC material properties in terms of compressive and tensile responses. A total of five commercial-available UHPC mixtures were evaluated. It was found that the bond behavior of deformed reinforcing steel in UHPC is different from that in traditional concrete in many aspects and the reinforcing steel development length in UHPC can be significantly reduced. Guidance on the embedment of deformed reinforcing bars into UHPC is provided. Regarding mechanical properties, all the tested UHPC materials reached a compressive strength higher than 13.5 ksi (93 MPa) within 5 days (laboratory condition with air curing). While the fiber content does not significantly effect on compressive strength, it does significantly affect the tensile response, with sustained tensile capacities ranging from 0.8 ksi (5.5 MPa) to more than 1.2 ksi (8.3 MPa).

6. Acknowledgments

The research was funded by the U.S. Federal Highway Administration. This support is gratefully acknowledged. This research project could not have been completed were it not for the dedicated support of the federal and contract staff associated with the FHWA Structural Concrete Research Program. PSI, Inc. provided laboratory support to FHWA under contract DTFH61-10-D-00017 through the duration of this research project. The publication of this report does not necessarily indicate approval or endorsement of the findings, opinions, conclusions, or recommendations either inferred or specifically expressed herein by the Federal Highway Administration or the United States Government.

7. References

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Submission ID: 102

Title: EVALUATION OF BOND OF REINFORCING STEEL IN UHPC: DESIGN PARAMETERS AND MATERIAL PROPERTY CHARACTERIZATION

Status: Accept

Reviewer 1:

Author Comments: General Comments:

The abstract leads the reader to believe that the correlation between bond strength and material properties such as UHPC compressive and tensile strength will be discussed, but this is not presented in the paper. The content of the abstract or the content of the paper should be revised.

Response: Updated. Thanks.

The frequently use the phrase "2 volumetric % fiber". This wording is cumbersome, appears odd to the reader, and should be revised. "2% fiber by volume" is more straight forward.

Response: Updated.

Specific Comments:

1.Abstract - "commercial-available" should be "commercially-available".

Response: Updated. Thanks.

2.Introduction, second paragraph, first sentence – This sentence is cumbersome and should be re-written for clarity.

Response: Updated. Thanks.

3.Introduction, second paragraph, second sentence – The word "confining" should be changed to "surrounding" or something similar. The use of this word is misleading.

Response: The "confining" indicates that the surrounding concrete restricts the free movement of steel. The authors believe it is an appropriate description here.

4.Section 3.1, first paragraph, forth line – The "f" in figure need to be capitalized.

Response: Updated. Thanks.

5.Section 3.2, fourth line – The word "engaged" should be changed to "used"

Response: Updated. Thanks.

6.Section 4.1. eighth bullet point – "large diameter" bars should be more well defined here. Is "large" No. 10 and greater? Define.

Response: The largest bar tested in the study is No.11. It is stated in later discussion where design guidance is provided. Here, as a general discussion for the effect of the bar size, it is true in general (which is also true in conventional concrete). The authors do not think it is necessary to add the actual bar size here.

7.Section 4.1, General – There is no mention of reinforcing bar type / grade when the authors discuss results from the different UHPC types.

Response: Other UHPC mixtures were evaluated with a certain bar type and size (Grade 120 No. 5 bar) and the results were compared among different UHPCs. The effect of bar type/grade was only evaluated with Type D UHPC and it is believed that they will have the same effect when other UHPCs were tested.

8. Section 4.1, design recommendation – At no point in the paper do the authors define the terms “db” or “ls”. For completeness these should be properly defined.

Response: added on page 7 where the term d_b was first introduced.

9. Section 4.2, second bullet – “convention” should be “conventional”

Response: changed. Thanks.

10. Section, 4.3 forth sentence – “ductal” should be “ductile”

Response: changed. Thanks.

Reviewer 2:

Author Comments: As the length of contribution is limited, I miss some more details of test results, for instance bond test results. But I understand that 500 test result would fill up one contribution. Nice and comprehensive text full of information. Leave it as is.

Response: Thanks.