Development length of reinforcing bars in UHPC: An experimental and analytical investigation

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Abstract: Over the last decade, Ultra High Performance Concrete (UHPC) is being used extensively in the accelerated bridge construction projects as a joint fill material between precast deck panels, box beams and decked bulb-tee girders. The current available design guidelines and connection details were arrived for such specific applications and using limited experimental research on rebar development in UHPC. These details cannot be reliably extended for different applications without more experimental testing. Also, there is no reliable design equation for estimating the development length of different sizes of rebar in UHPC. An experimental study is currently ongoing to understand the effect of rebar size, and rebar cover on the development length of rebar in UHPC. A total of 72 pull out tests and 6 beam tests with different embedment length and side cover were conducted using #4, #5, #6 and #7 bars. 3D finite element models for the test specimens using ABAQUS were developed to capture the observed behavior. The experimental results and the lessons learned from this study are presented in this paper.

Keywords: UHPC, reinforcing bar, bond strength, anchorage, development length

1. Introduction

Ultra-High Performance Concrete (UHPC) exhibits very high compression strength, an improved tensile behavior and a sustained post cracking strength. These exceptional properties offer designers more efficient ways to design structural components and build using smaller and more efficient cross sections. However, its use has so far been within very niche areas like joint fill materials between precast deck panels and largely within the purview of accelerated bridge construction techniques. One of the primary requirements to remedy this and to make its use more widespread; is to develop design guidelines for development length of rebar in UHPC. The research discussed in this paper adds to the ongoing investigations being carried out by Fehling et al. (2012) and Yuan and Graybeal (2014).

For the purposes of studying the development length of reinforcing bars in UHPC, experimental investigation was carried out in two phases. The first phase of investigation involved pull out testing of #4(M13), #5(M16) A615 grade 60 bars and #6(M19), #7(M22) A615 grade 80 bars. The test setup for these pull out tests was developed in a manner that eliminates the formation of compressive stress field in the UHPC surrounding the rebar. The embedment length and side cover were varied from 6db to $8d_b$ (d_b= diameter of the rebar) and $1d_b$ to $3.5d_b$, respectively. In the second phase, six small UHPC beams with lap splices were tested under four-point bending. These beam splice test specimens mimic a more realistic simulation of full size members used in actual construction. The beams were subjected to four-point loading and were embedded with #6 (M19) and #7(M22) rebar. The clear cover for these tests was 1 in. (25.4 mm) and 1.5 in. (50.8 mm). The rebar were spliced at the beam mid-span for a length of $6d_b$ in the constant moment region.

Strain gauges mounted on rebar and a non-contact displacement measurement system (NDI Optotrak system) were used to capture critical strains and the rebar slip with respect to concrete. A 3D finite element model of the test setups using ABAQUS (2012) was also developed to gain an understanding and check the adequacy of existing material models in simulating UHPC and bond behavior. The results from an experimental investigation aimed at understanding the dependency of embedment length, side cover, and lap splice length on bond strength development in UHPC are presented in this paper. The results add to the existing data set of UHPC bond tests.

2. Previous Research

Experimental investigations were performed by Fehling et al. (2012) to establish the steel stress versus slip values. As part of this investigation, rectangular UHPC blocks were embedded with 12 mm (0.47 in) dia BST 500 S rebar which has a yield strength of 500 MPa (72.5 ksi).The concrete cover and embedment length for these investigations was varied from $1d_b$ to $2.5d_b$ and from $2d_b$ to $12d_b$ respectively. The results from these tests indicated three major failure modes, concrete cone, V-type splitting and splitting. Although, in most cases mixed failure modes were observed, it was evident that concrete cone type failure primarily occurred in samples with low embedment length ($2d_b$ to $4d_b$) and high concrete cover ($2d_b$ to $2.5d_b$) and splitting type failure occurs in high embedment ($8d_b$ to $12d_b$) specimens. For specimens with $1d_b$ concrete cover, the yield stress of 500 MPa (72.5 ksi) in the rebar was reached when the anchorage length was more than $8d_b$ and the corresponding slip values at peak stress were in the range of 0.5 mm (0.02 in). Similarly for specimens with 1.5 d_b, $2d_b$, and $2.5d_b$ concrete cover, the yield stress was reached in samples with anchorage length more than $6d_b$, $5d_b$, and $4d_b$ respectively.

In an extensive research carried for the U.S. Federal Highway Administration by Yuan and Graybeal (2014), over 200 pull out tests were performed to study the effects of embedment length, concrete cover, bar spacing, concrete strength, bar size, bar type, and yield strength. The research yielded a set of design recommendations for applications involving UHPC. They were able to conclude that for #4(M13) to #8(M25) (uncoated or epoxy coated) bars, the yield strength of 75 ksi (517 MPa) can be attained with a minimum embedment length of $8d_b$, a minimum side cover of $3d_b$, and a minimum clear spacing between bars of $2d_b$. Graybeal (2012) also performed Pull out tests on #4(M13), #5(M16) and #6(M19) ASTM A615 Grade 60 bars embedded for a length of 2.9 in (75 mm), 3.9 in (100 mm), 4.9 in (125 mm) respectively in 15.7 in (400 mm) dia UPHC cylinders as part of the work for FHWA work investigating field cast UHPC bridge deck connections. In all of these tests the bars fractured before bond failure.

3. Experimental Work

The experimental investigation was carried out in two phases involving pull out testing of A615 grade 60, #4(M13), #5(M16) bars and A615 grade 80 #6(M19), #7(M22) in Phase-I and beam splice testing using grade 80 #6(M19), #7(M22) bars in Phase-II testing.

3.1 Test Specimen Details

In the Phase-I investigation, a test setup (see Fig.1b) was developed at the Large Scale Structures Lab (LSSL) in University of Alabama (UA) to eliminate the formation of compressive stress field within the UHPC block, as compared to traditional pullout test setup (see Fig. 1c). The specimens (see Fig.1a) consisted of two rectangular UHPC blocks connected with two intermediate rebar labelled Bar_2. In this Fig.1a; H, T, W indicate the height, width and thickness of the rectangular UHPC blocks; Cs1 and Cs2 indicate the concrete clear cover to the sides of Bar_1 and Cs3 and Cs4 indicate the concrete clear cover of Bar_2; Ld1 and Ld2 indicate the embedded length of Bar_1 and Bar_2 respectively. This specimen would be mounted on an MTS testing machine and loading was applied to the bars labeled Bar_1 at the top and bottom as shown in Fig.1b. Further, this setup allowed us to test for two different rebar sizes at one time. Each of the test specimens was designed so that the total area of both Bar_2's would be similar to Bar_1. This ensured that all four bars would be in similar stress states while the test is being conducted.

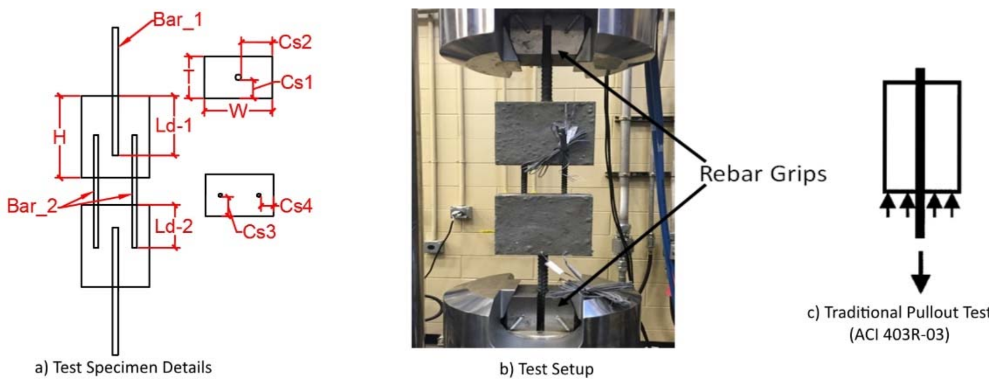


Figure 1 Pullout test specimen and test setup details.

ACI 408R-03 (2003) recommends that pullout tests should not be used as a sole basis for determining the development length, citing the formation of compressive struts between support points and reinforcing bar as a factor that impacts the bond development. So, in Phase-II testing, beam with splices were tested to realistically simulate the stress states in the vicinity of the rebar. A total of six specimens have so far been tested with #6 (M19) and #7 (M22) bars, with a concrete cover of 1 in. (25.4 mm) and 1.5 in. (38.1 mm). The splice beam specimens included beams with a single bar and two bars spliced at mid-span. Fig. 2a shows the typical details of the beam splice specimen, where 'c_1' represents the concrete bottom cover, 'c_2' and 'c_3' indicate the side cover and spacing between the bars respectively in the specimens with two bars. Table 3 provides the complete details of each of the test specimens.

3.2 Material Properties

The UHPC mix design (refer Table 1) used for this investigation included Premix (Ductal® JS1000) provided by Lafarge®, super plasticizer and 2% (by volume) steel fibers. The specimens once casted were covered with a plastic sheet and were transferred after 24 hours to an environmental chamber maintained at 110^o F and 65% humidity for another 48 hrs. The measured UHPC compressive strength was 21 ksi at time of testing. The measured yield strength of #4(M13), #5(M16) bars and #6(M19), #7(M22) was 70 ksi (483 MPa) and 90 ksi (621 MPa) respectively.

Table 1 UHPC Mix Design

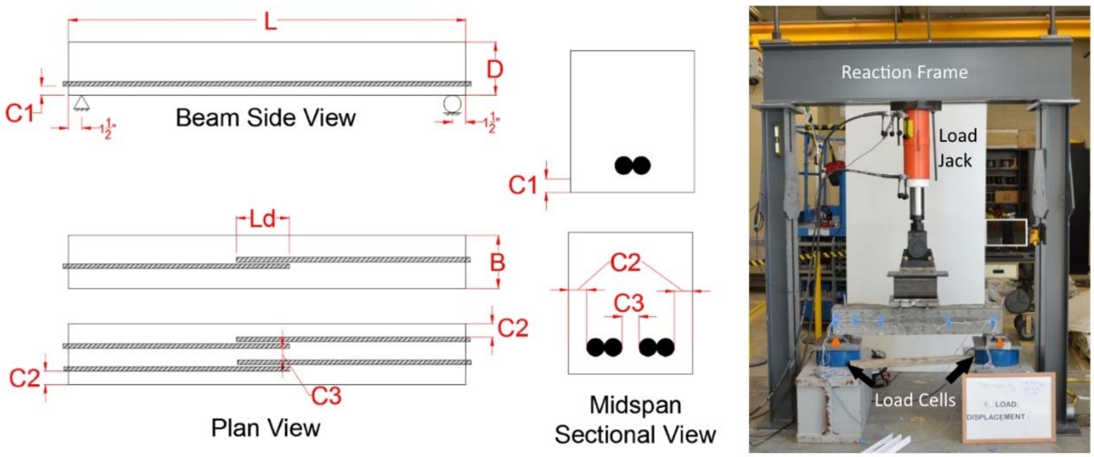
Material	lb/yd^3 (kg/m^3)
Premix	3699 (2268)
Water	219 (134)
Superplasticizer	51 (31)
Steel Fiber-2%	263 (161)

Table 2 Pull out test specimen details (Phase-I testing). (1 in. =25.4 mm)

Specimen No	Bar_1	Bar_2	Ld1	Ld2	Cs1	Cs2	Cs3	Cs4	H	W	T	Min. cover	
	bar size (US)		(in d_b)						(in.)			Bar_1	Bar_2
P1	# 7	# 4	8	8	1.9	4.1	3.5	4.25	8	8	4	1.9	3.5
P2	# 7	# 5	8	8	1.7	4.0	2.8	3.2	8	8	4	1.7	2.8
P3	# 7	# 4	8	8	1.7	4.0	3.5	4	8	8	4	1.7	3.5
P4	# 7	# 5	8	8	1.9	4.0	2.8	1.6	8	8	4	1.9	1.6
P5	# 7	# 4	6	6	1.7	4.0	3.5	2	8	6.25	4	1.7	2.0
P6	# 7	# 4	6	6	1.9	4.1	3.5	4	8	6.25	4	1.9	3.5
P7	# 7	# 5	6	6	1.9	4.0	2.8	3.2	8	6.25	4	1.9	2.8
P8	# 7	# 4	6	6	1.7	4.0	3.5	2	8	6.25	4	1.7	2.0
P9	# 7	# 5	10	10	3	5.2	4.4	3	12	10	6.1	3	3
P10	# 7	# 5	8	8	3	5.2	4.4	3	9	10	6.1	3	3
P11	# 7	# 5	6	6	3	5.2	4.4	3	6	10	6.1	3	3
P12	# 7	# 5	10	10	1.8	3	2.2	2	12	7	4	1.8	2
P13	# 6	# 4	8	8	3	4.8	4.8	3	7	8	5.3	3	3
P14	# 6	# 4	8	6	3	4.8	4.8	3	6	8	5.3	3	3
P15	# 6	# 4	10	10	2.2	3.7	3	2	9.5	7	4	2.2	2
P16	# 6	# 4	10	10	1.5	3.7	2.5	2	9.5	7	3	1.5	2

Table 3 Beam splice test specimen details.

Specimen number	Bar Size (US)	No. of Bars	L_d	c_1	c_2	c_3	L	B	D
			(in d_b)	(in.)					
B1	6	1	6	1.5	-	-	40	5	6
B2	6	2	6	1.5	1	1	40	6	6
B3	7	1	6	1.5	-	-	45	5	6
B4	7	2	6	1.5	0.8	0.8	45	6	6
B5	6	1	6	1	-	-	40	5	6
B6	6	2	6	1	1	1	40	6	6



a) Specimen Details

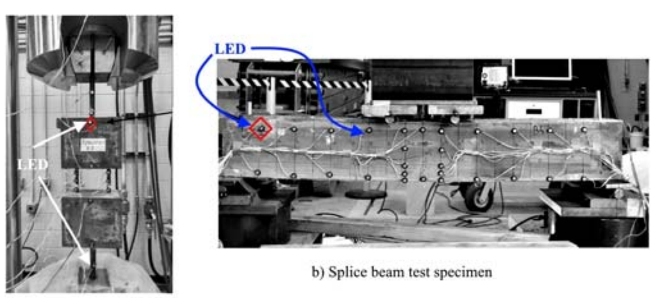
b) Test Setup

Figure 2 Beam splice test details (Phase-II testing).

3.3 Instrumentation and Test Setup

The test setup for pull out tests (see Fig. 2a) consisted of the specimen held in standard MTS uniaxial testing machine. The top rebar was held with wedge grips and were loaded under displacement control at a rate of 0.01 in/min in the elastic zone, at 0.05 in/min the plastic region and at 0.1 in/min until failure. Data was gathered continuously during the tests from the steel strain gauges, the MTS machine and NDI Optotrak system. The LED placement for collecting displacements is as shown in Fig.3.

The splice beam specimens (see Fig.2b) were tested using a standard 4-point bending setup. Two load cells placed under each of the supports and the load was applied using a 200 kip (900 kN) hydraulic load jack. The beam specimen were loaded gradually at an approximate rate of 1 kip/min. The LEDs placed on the beam as shown in Fig.3 enabled the collection of displacement field data. The data from the load cells, a pressure gauge attached to the load jack and from the strain gauges placed on the rebar was simultaneously collected.



a) Pull out test specimen

b) Splice beam test specimen

Figure 3 LED layout used on test specimens during Phase-I and Phase-II testing

4. Test Results and Analytical Modelling

Bond behavior in concrete is significantly affected by the volume of concrete around the bars, and the tensile and bearing strength of concrete and an improved resistance to splitting cracks reduces the required development lengths. It was thus expected in UHPC that there would be a considerable reduction in development length of rebar compared to regular concrete.

For a majority of specimens splitting type of cracks (see Fig.4a) was the primary failure mechanism. Specimen P6 which had a relatively high concrete cover (3.5 d_b) and low embedment length (6 d_b) when compared to other test specimens showed a cone type failure (see Fig.4b).

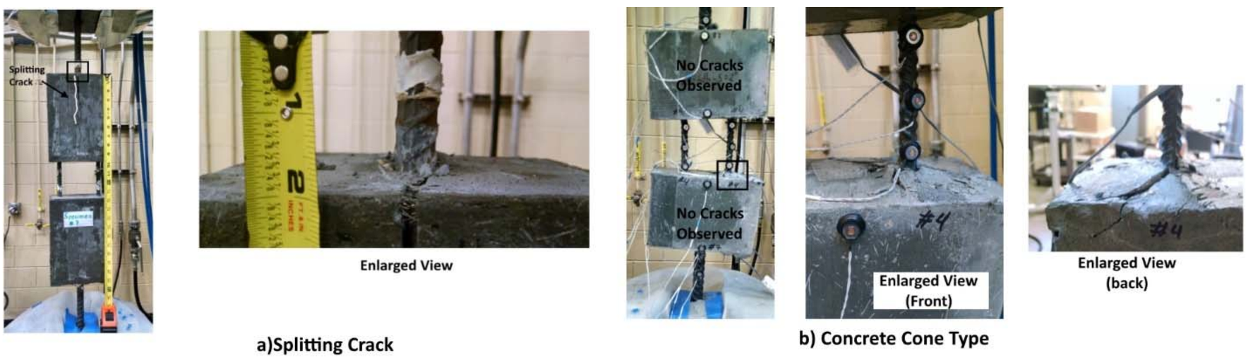


Figure 4 Failure mechanisms observed in pull out test specimens.

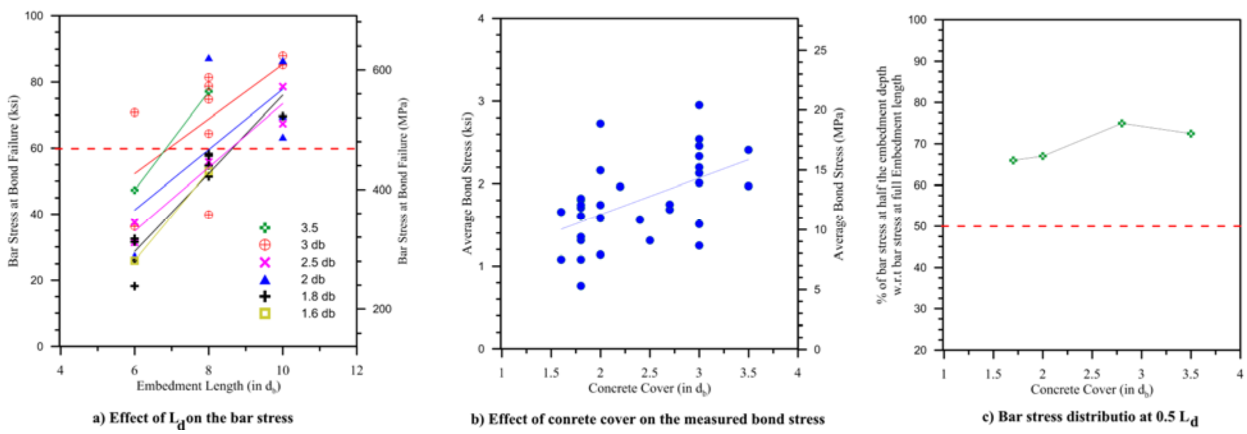


Figure 5 summary of experimental results from the pull out testing.

Fig.5a shows the measured bar stress at failure for different embedment length and cover values. The bar stress at bond failure increased with the increase in the embedment length (see Fig.5a) and a higher bond stress was achieved before experiencing failure with increase in cover thickness (see Fig. 5b). A minimum embedment length of 8d_b and a concrete cover of 3d_b was sufficient for the rebar to develop a stress of 60 ksi (415 MPa). Further, it was also observed that increasing the embedment length to10d_b resulted in bars consistently achieving a minimum stress of 60 ksi at specimen failure for concrete covers as low as 1.8d_b. Based on the readings from strain gauges at the half the embedded length, it can be observed that the bar stress at half the embedment length decreases to around 65% of the peak stress value for concrete cover less than 2d_b and 75% for higher concrete cover (see Fig. 5c).

Table 4 provides a summary of the test results from the Phase-II testing. In the table, Bar -#E and Bar- #W represent one set of bars spliced together and measured moment is back calculated using load cell data. It should be noted that the specimens have been spliced for a length of $8d_b$ but the strain gauges have been placed at a distance of 6 d_b from free end of the bars. It can be observed from Table 4 that none of the bars reached 60 ksi at beam failure. The failure mechanism in all of the specimens was through the formation of shear cracks indicating an inadequate section size to reach the full yield capacity of the rebar (see Fig. 6a). Fig. 6b shows the load on the beam against the stress in rebar for specimen B1. It can be seen that the stress increased linearly with applied load indicating that a bond failure has not occurred.

Table 4 Summary of test results from the splice beam tests

Test Specimen	Measured Moment (Kip-ft)	Bar stress at $6d_b$ @ failure (ksi)			
		Bar-1E	Bar-1W	Bar-2E	Bar-2W
B1	19.7	59.1	38.5	N/A	N/A
B2	33.8	51.9	37.4	49.1	39.3
B3	25.2	NA	37.7	N/A	N/A
B4	35.7	31.9	41.8	43	31.9
B6	29.5	45.8	44.2	34.64	39.46

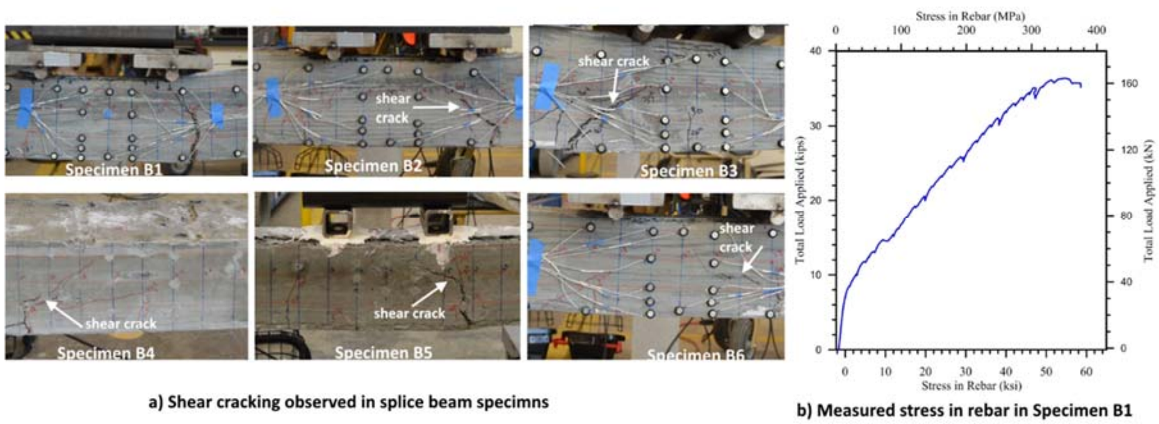
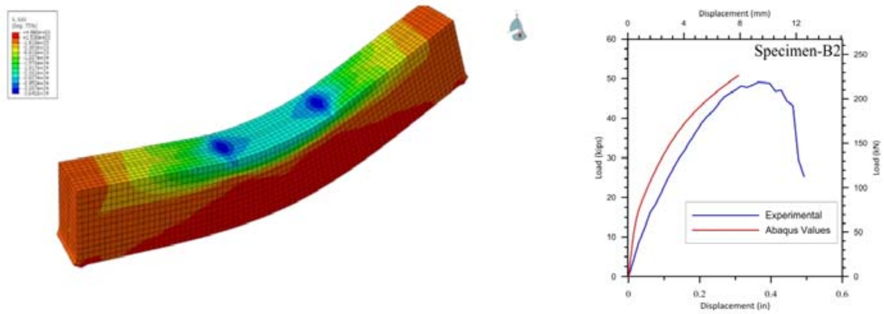


Figure 6 Shear cracking and measured rebar stress in beam splice specimen.

The beam specimens were also modelled in ABAQUS (see Fig.7a) to get a better estimate of the expected bar stress in the beams than the traditionally used methods like moment curvature analysis. A comparison of the results obtained from the analysis to the measured values are presented in Table 6. The rebar is assumed to be perfectly bonded to the surface of the UHPC. This is modelled using an embedded constraint. Three material models are available in ABAQUS for modelling of concrete/UHPC. The brittle cracking model, which assumes that the compressive behavior is purely linear elastic. The smeared cracking model, which assumes that there is no permanent strain associated with cracking thus allowing cracks to close completely if the stress across them becomes compressive. UHPC does not warrant such simplifying assumptions and may lead to inaccurate simulation hence these models were not adopted. So, UHPC was modelled using the concrete damaged plasticity model, which is characterized by two failure mechanisms tensile cracking and compressive crushing and accounts for the stiffness degradation mechanisms associated with these failure modes. The parameters used to define this material model in

ABAQUS are provided in Table 5. This material model has been typically been made for normal concrete, in which the post cracking stiffness loss is considerably higher than in UHPC. The deviations seen in Table 6 and Fig. 7b can be attributed to this reason.



a) ABAQUS model showing stresses at peak loading

b) Comparsion of meaured and predicted load - displacement response

Figure 7 ABAQUS modelling and comparison of load-displacement response

Table 5 Concrete Damaged Plasticity Variables

Dilation Angle	Eccentricity	fb0/fc0	K	Viscosity Parameter
31	0.1	1.16	0.67	0.001

Yield Stress	Cracking Strain
1400	0
1720	0.000943
1750	0.003323
400	0.013823
10	0.019823

Yield Stress	Inelastic Strain
23900	0
24000	0.001
100	0.007

Table 6 Comparison of experimental and predicted values from ABAQUS model.

Specimen	Results from ABAQUS		Values from experiment	
	Stress in bar (ksi)	Displacement (in)	Stress in bar (ksi)	Displacement (in)
B1	61	0.52	59.1/38.5	0.26
B2	42.8	0.31	51.9/37.4/49.1/39.3	0.37
B3	69.7	1.1	37.7	0.26
B4	51.637	0.66	31.9/41.8/43/31.9	0.35
B5	49.58	0.36	NA	0.27
B6	46.3	0.23	45.8/44.2/34.6/39.5	0.24

5. Summary and Conclusion

The following conclusions are arrived based on the analyses and test results presented in this paper,

1) To develop a stress of 60 ksi in bars embedded in UHPC, a minimum embedment length of $8d_b$ along with a minimum concrete cover of $3d_b$ is required.
2) The bond stress distribution along the rebar embedded in UHPC may not be uniform as the bar stress did not reduce to 50% of the peak value at half the embedment length.
3) The concrete damaged plasticity model in ABAQUS does not fully capture the stiffness degradation in the sustained cracking phase of UHPC.

6. References

1. ACI Committee 408. Bond and Development of Straight Reinforcing Bars in Tension (ACI 408R-03). Technical Report. Farmington Hills, MI: American Concrete Institute, 2003.
2. ACI-318. Building Code Requirements for Structural Concrete. American Concrete Institute, 2011.
3. Dassault Systemes. "ABAQUS 6.12." Providence, RI: ABAQUS Inc., 2012.
4. Fehling, E, P Lorenz and T Leutbecher. "Experimental Investigations on Anchorage of Rebars in UHPC." Proceedings of Hipermat 2012 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials. Ed. Schmidt M, et al. Kassel, Germany, 2012. 533-540.
5. Graybeal, B. Behavior of Field-Cast Ultra-High Performance Concrete Bridge Deck Connections under Cyclic and Static Structural Loading. Springfield, VA: National Technical Information Service, 2012.
6. Yuan, J and Graybeal, B. "Bond of Reinforcement in Ultra-High-Performance Concrete." ACI Structural Journal 112.6 (2015): 851-860.
7. Yuan, Jiqiu and Benjamin A Graybeal. Bond Behavior of Reinforcing steel in Ultra High Performance Concrete. Technical Report. Mc Lean, VA: FHWA, 2014.

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