Bond between Ultra-High Performance Concrete and Steel Bars

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1. ABSTRACT

As continued research on Ultra High Performance Concrete (UHPC) becomes more readily available, researchers are becoming increasingly interested in developing new structural applications for the material. UHPC performance under tension and compression are well understood, however studies on the interaction between UHPC and Steel Bar reinforcement remains limited and data for non-proprietary UHPCs are sparse. The current work attempts to clarify this. A series of bar pull out tests were conducted using plain and epoxy-coated grade 60 bars with nominal diameters of 13 mm, 16 mm, and 19 mm. Other experimental parameters include three development lengths (50 mm, 75 mm and 100 mm). Testing shows that bond stress achieved increases at low embedded lengths and that 1% fiber volume content in UHPC vs. 2% fiber volume content leads to a reduction of approximately 24% in bond strength.

Keywords: UHPC, ultra-high performance concrete, lap splice, bar bond

2. INTRODUCTION AND MOTIVATION:

All reinforced concrete structures rely on the bond relationship between the concrete and steel reinforcement bars. Studies on the bond between regular concretes, high strength concretes, other cementitious materials and steel bars have been available for some time now [e.g. Slater, 1920, Gilkey, 1956, ACI 2003]. However, those investigating this behavior in UHPC remain limited and will continue to be an obstacle to the materials' widespread adoption until more research becomes available. The experimental program reported on in this paper addresses this gap and aimed to quantify the bond strength between ultra-high performance concrete and steel bar reinforcement for a range of influential design parameters, including bar coating, nominal bar size, embedment length and fiber content.

3. BACKGROUND AND PREVIOUS RESEARCH

3.1. Bond Development of Steel Bars Embedded in UHPC

There is limited published data on the bonding behavior between UHPCs and steel reinforcement bars and most of the work has been completed on proprietary UHPCs. Graybeal performed pull out tests for #4, #5, and #6 bars embedded 75, 100 and 125 mm respectively into UHPC cylinders, with all of the steel bars fracturing before bond failure [Graybeal, 2010, 2014]. Graybeal recently has shown that under static conditions, UHPC specimens are capable of developing bond stresses of approximately 20 – 35 MPa in bar pull out specimens and are largely dependent on bar spacing, concrete cover, and development length and bar size. In a different study, Swenty and Graybeal performed pull out tests on #4 bars embedded into 150 mm concrete cubes. Two different UHPC mixes were used, one achieving bar fracture and the other achieving bar yield [2004]. Performing pull out tests on 12 mm diameter bars, varying concrete cover and embedment lengths, Fehling et al. determined that increasing cover widths and embedment lengths increased the bond stress, reaching those sufficient for bar yield [2012]. Holschemacher et al. reported achieving bond stresses up to 60 MPa using 12 mm bars in UHPC cylinders [2004]. Saleem et al. investigated the development length requirements for high strength steel bars in UHPC, concluding that #10 and #22 (#3 and #7 imperial sizes) bars require 12 d_b and 18 d_b to develop adequately [2013]. Jungwirth et. al. performed tests on 20 mm and 12 mm diameter bars, reaching bond stresses of 38 MPa and 66 MPa [2004]. Of the literature currently available on bond, data only exists on testing performed using Ductal® or Ceracem®, both proprietary concretes No published data currently exists for non-proprietary UHPCs. Additionally, there is some discrepancy in existing data regarding the peak bond stress UHPC is capable of achieving during the pull out tests, with some studies reporting values as high as 66 MPa, or as a low as 9.8 MPa.

4. EXPERIMENTAL PARAMETERS AND PROCEDURE

4.1. Bar Pull Out Testing Program and Test Set Up

The simple bar pull out test is the most widely used measure of bond capacity in concrete due to its simplicity and ease of implementation. In order to minimize the effects of the compressive region developed during testing, a modified method of supporting the concrete was implemented [Chao, 2009]. Unlike the traditional bar pull out case where the entire surface of the concrete is used as a support, the method used utilizes the high bearing strength of the UHPC to minimize the surface area needed. More details regarding this experimental configuration can be found in.

The experimental program investigated the effects of several parameters on the bonding between the UHPC and embedded steel bars. Three bar diameters were tested at, 13 mm, 16 mm and 19 mm, for both plain and epoxy coated bars. Each of the bars was subjected to embedment lengths of 50, 75 and 100 mm, corresponding to different multiples of the bar diameters, d_b. Additionally, two different bar sizes (16 mm and 19 mm) were used to investigate the differences caused by fiber alignment during casting. Specimens were cast with fibers preferentially aligned parallel with the bar and transversely to the bar. Two different bar sizes (16 mm and 19 mm) were used to evaluate the effect of fiber content at 1% and 2% by volume.

The naming convention for the tests performed is as follows: the first entry represents the bar size and coating (black bars, i.e. not coated, or epoxy coated), followed by the embedded length in d_b (bar diameter), the fiber volume percentage, the casting orientation. For example, 13B-8.0-2represents a 13 mm diameter plain black bar, 8 D_b (100 mm), with 2% fibers by volume.

5. RESULTS AND DISCUSSION

5.1. Bar Pull-Out Results

The UHPC specimens were constructed using a previously designed low cost, generic form of UHPC. Extensive details regarding the materials strengths in tension and compression as well as other material properties can be found in [Alkaysi, 2015, 2016]. Detailed results of the testing are shown in table 1.

Table 1: Test Results for Simple Bar Pull Out

Name	Mode of Failure			τ_{bond} MPa (ksi)			f'c average
	1	2	3	1	2	3	MPa (ksi)
Effect of Embedded Length & Coating							
13B-8.0-2%	Fracture	Fracture	-	19.2 (2.8)	19.3 (2.8)	-	189.4 (27.5)
13E-8.0-2%	Fracture	Fracture	-	19.2 (2.8)	19.3 (2.8)	-	189.4 (27.5)
13B-6.0-2%	Fracture	Yield, Slip	-	22.9 (3.3)	21.7 (3.2)	-	188.9 (27.4)
13E-6.0-2%	Fracture	Yield, Slip	-	23.5 (3.4)	22.8 (3.3)	-	188.9 (27.4)
13B-4.0-2%	Slip	Yield, Slip	-	32.7 (4.7)	33.5 (4.9)	-	191.0 (27.5)
13E-4.0-2%	Slip	Yield, Slip	-	26.2 (3.8)	30.2 (4.4)	-	191.0 (27.5)
16B-6.4-2%	Slip	Slip	Slip	16.0 (2.6)	15.3 (2.2)	18.6 (2.7)	189.4 (27.5)
16E-6.4-2%	Slip	Slip	Slip	16.2 (2.4)	18.3 (2.7)	19.2 (2.8)	189.4 (27.5)
16B-4.8-2%	Slip	Slip	-	18.8 (2.7)	16.7 (2.4)	-	188.9 (27.4)
16E-4.8-2%	Slip	Slip	-	18.2 (2.6)	19.9 (2.9)	-	188.9 (27.4)

Name	Mode of Failure			τ_{bond} MPa (ksi)			f'c average
	1	2	3	1	2	3	MPa (ksi)
16B-3.2-2%	Slip	Slip	-	30.9 (4.5)	31.0 (4.5)	-	191.0 (27.5)
16E-3.2-2%	Slip	Slip	-	30.9 (4.5)	31.5 (4.6)	-	191.0 (27.5)
19B-5.3-2%	Slip	Slip	-	14.5 (2.1)	14.3 (2.1)	-	189.4 (27.5)
19E-5.3-2%	Slip	Slip	-	14.7 (2.1)	15.2 (2.2)	-	189.4 (27.5)
19B-4.0-2%	Slip	Slip	-	18.6 (2.7)	16.5 (2.4)	-	188.9 (27.4)
19E-4.0-2%	Slip	Slip	-	21.2 (2.8)	16.9 (2.4)	-	188.9 (27.4)
19B-2.6-2%	Cone	Cone	-	20.1 (2.9)	25.8 (3.7)	-	191.0 (27.5)
19E-2.6-2%	Cone	Cone	-	26.3 (3.8)	20.1 (2.9)	-	191.0 (27.5)
Effect of Fiber Volume Content							
16E-6.4-1%	Slip	Slip	Slip	14.0 (2.0)	14.8 (2.1)	15.5 (2.2)	180.1 (26.1)
16E-6.4-2%*	Slip	Slip	Slip	15.4 (2.2)	18.5 (2.7)	18.9 (2.7)	188.9 (27.4)
19B-4.0-1%	Slip	Slip	-	10.5 (1.5)	11.6 (1.7)	-	180.1 (26.1)

*These specimens are similar to 16E-6.4-2%-P-28D listed earlier in the table. They represent an additional set that was cast at the same time and from the same UHPC batch as 16E-6.4-1%-P-28D to provide more confidence in the experimental data.

Testing showed three failure modes for UHPC bonding (Figure 1); bar fracture, slip of the bar from the UHPC, and a conical shaped failure in which the UHPC attached to the bar separates from the UHPC cube. Data on peak measured forces and associated bond stresses are listed in table 1. The peak average bond stress is computed as the achieved pull out force divided by the initial surface area of the embedded portion of the bar, as follows:

$$\tau_{bond} = \frac{F_{bar,max}}{\pi d_B l_d}$$

Where $F_{bar,max}$ is the peak force in the bar, taken as failure in the specimen, d_b is the bar diameter (in mm) and l_d is the embedded length (mm).

(a) (b)

Figure 1: (a) Bar Slip, and (b) Conical Concrete Failure

5.2. Effect of Embedment Length

Figure 2 plots the bond stresses measured vs. embedment in mm and normalized to bar diameter (d_b). In general for all bar diameters tested, when embedment increases, the bond stresses decreases, almost linearly. This suggests that an uneven distribution of bond stresses occurs along the length of the bar. Figure 2a shows the relationship for 13 mm bars. Each of the bars at 4 db failed via bar slip, whereas the specimens at 6 db experienced yielding of the steel bar, prior to bar slippage. Figure 2b shows the results of embedment for 16 mm dia. bars. Unlike the 13 mm dia. bar, no 16 mm dia. bars reached yield or bar fracture. All of the specimens failed via bar slip. At 6.4 d_b, black bars were able to reach a slightly higher bond stress vs. their epoxy counter parts. This also occurred at 3.2 d_b, though at 4.8 d_b. Again, for both bar types, τ_{bond} averaged for all of the tests decreased with increasing embedment, which is again attributed to the uneven force distribution along the length of the bar. Figure 2c shows the data for 19.0 mm dia. bars. At 5.3 d_b and 4.0 d_b embedment, all of the bars experienced slip. At 2.6 d_b, all specimens failed due to a conical separation in the concrete. As such, data points at this embedment do not represent bond strength, but merely the peak pullout force achieved prior to concrete cone failure, and are therefore removed from the analysis of the overall test data. In these cases, the UHPC bonded to the bar separated from the UHPC in the cube, leading to a drop in sudden strength. As seen with the previous bar diameters, as embedment increases, τ_{bond} decreases. Additionally, no noticeable trends were observed regarding peak bond strength in plain bars vs. epoxy coated bars.

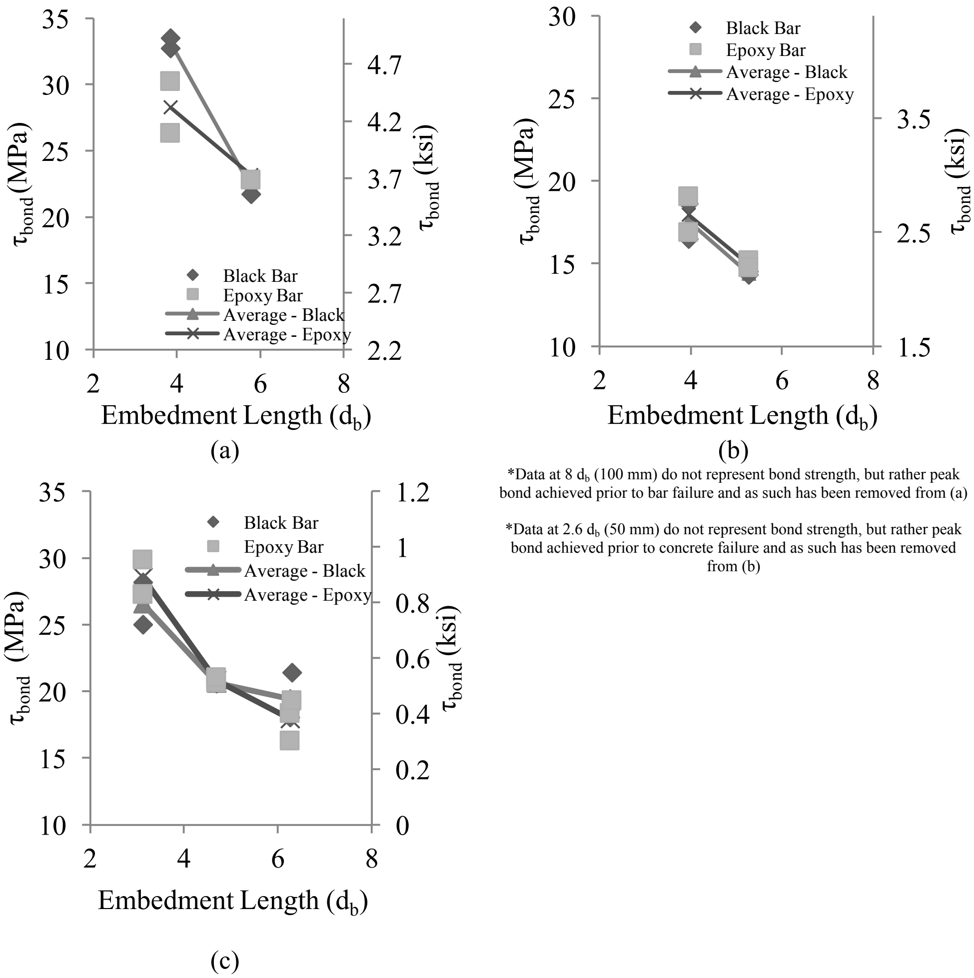


Figure 2: (a) Peak Bond Stress vs. Embedment Length in d_b for 13 mm bars, (b) 16 mm bars and (c) 19 mm bars

Figure 3 plots the peak bar stress versus embedment length (as a function of d_b) for all specimens with parallel-oriented fibers, at 2% fibers by volume and 28 days cured. As expected the increase in embedment results in an increase in the peak bar stresses.

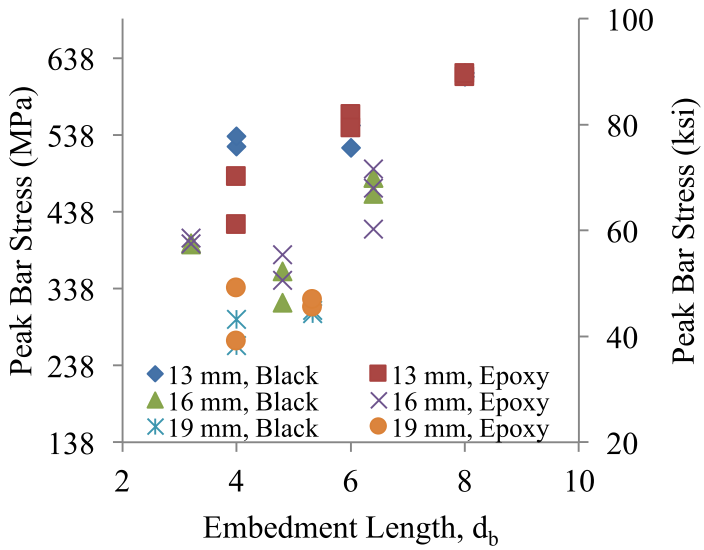
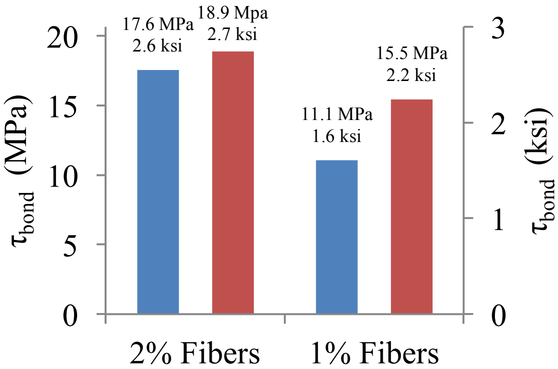


Figure 3: (a) Peak Bond Stress Achieved vs. Embedded Length and (b) Peak Bar Stress vs. Embedded Length, 2% fiber vol., Parallel Fiber Orientation, 28 days cured

5.3. Effects of Fiber Volume Content

Two series of bar pull out tests were tested containing 1% fibers by volume and compared to those tested containing 2% fibers by volume. Figure 4a shows τ_{bond} compared for the 19 mm and 16 mm bar specimens at 1% and 2% fibers by volume. For the 16 mm bars, τ_{bond} decreased by 18% as the fiber volume dropped from 2% to 1%. For the 19 mm bars, specimens containing only 1% fibers developed 36% less bond strength than those with 2% fibers. The larger drop in strength for the 19 mm bar is likely influenced by differences in the number of ribs embedded from specimen to specimen, since at the lower embedded length the effect of ribs is more pronounced. Figure 4b shows τ_{bond} compared for the two fiber contents normalized to the square root of the compressive strength ($\sqrt{f'c}$). The normalized τ_{bond} showed similar differences; 36% less bond between 2% and 1% fibers for the 19 mm specimens and 15% less bond between 2% and 1% fibers in the 16 mm specimens. This seems to confirm that τ_{bond} is dependent on the quantity of fibers available to bridge any cracks forming under loading, rather than the differences in compressive strength associated with fiber volume quantity.



(a)

Figure 4: (a) Peak Bond Stress Achieved at 1% and 2% Fibers by volume: 19 mm bars, Embedded 4.0 d_b (Blue) and 16 mm bars (Red), Embedded 6.0 d_b

6. CONCLUSION

- At the lower limits of embedment lengths, increasing embedment leads to a reduction in the peak bond stress. This is attributed to an uneven distribution of force along the length of the bar, a fact that is established for high strength concretes.
- Changes in steel fiber content by volume resulted in differences between 21% and 36% in bond strength achieved in the simple pull out test. Similar differences in bond were seen when normalized to √f'c, suggesting that the bond strength is dependent on the quantity of fibers available to bridge any cracks forming under loading, rather than the differences in compressive strength associated with fiber volume quantity.

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