Rebar Development Length of Reinforced UHPC

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Abstract

Recently, Ultra-High Performance Concrete (UHPC) has emerged as a jointing material for accelerated bridge construction (ABC) to connect precast bridge elements. The superior bond between UHPC and rebars allows much shorter development length and simpler connection detail compared to conventional grout. Although the bond and resulting development length has been determined for particular UHPCs in the literature, a general method for estimating the bond strength based on the UHPC's material properties is missing. This research attempts to fill this knowledge gap. As the tensile strength typically governs the bond strength of UHPC, experimental and numerical analyses were performed to investigate the bond behavior of multiple UHPCs with different tensile strengths. A modification to the existing bond strength equation in ACI 318 is proposed based on the bond test results from this study and those from the literature.

Keywords: Ultra-High Performance Concrete, Accelerated bridge construction, UHPC joints, Bond strength, Development length.

1. Introduction

The use of Ultra-High Performance Concrete (UHPC) in bridge-related applications has expanded recently, especially in joints to connect precast bridge elements. The high compressive and tensile strengths and post-cracking ductility of UHPC enable strong bond with steel reinforcement and short rebar development lengths, which greatly simplifies the joint detailing (Graybeal). However, the development lengths reported in the literature are applicable for specific UHPC mixes and experimental parameters, such as test configuration, cover thickness, rebar size, rebar yield strength, etc. A systematic design method is needed to estimate the rebar-UHPC bond strength based on the fundamental material properties.

In general, the bond between the steel reinforcement bars and concrete consists of three components: (a) adhesion, (b) friction, and (c) bearing of the rebar ribs against the surrounding concrete. As the rebar is pulled relative to the concrete, the force is first transferred through adhesion and friction between the rebar and concrete. The adhesion is quickly lost as the rebar starts to slip with respect to the concrete engaging the ribs through bearing on the surrounding concrete. As the slip increases, the friction reduces, and the bearing of the ribs against the surrounding concrete becomes the principal force transfer mechanism.

The bearing of the ribs applies diagonal forces, which can be divided into longitudinal and radial components. The longitudinal component could lead to bond failure due to the crushing of UHPC between the rebar ribs. This is called a pullout failure, and it is governed by the material's

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compressive strength. The radial component leads to expansion in the surrounding UHPC and could cause the bond failure due to the formation of longitudinal splitting cracks. The splitting cracks are resisted by the confinement provided by the UHPC cover and the transverse reinforcement (if provided). The splitting resistance depends on the tensile strength of the UHPC. Thus, the governing bond failure mode (pullout or splitting) depends on the UHPC's mechanical properties (Soliman, Kumar, et al.).

Despite the fibers' bridging effect in UHPC, splitting failure is the most commonly observed failure mode in the bond tests (Alkaysi and El-Tawil; Roy, Hollmann and Wille; Lagier, Massicotte and Charron; J. Yuan and B. Graybeal; Haber and Graybeal). This is especially true for experiments on structural members, such as beam splice tests, where the bond fails mainly due to longitudinal splitting cracks (Dagenais and Massicotte; Ronanki, Aaleti and Valentim). Although a small number of studies have investigated the effects of volume fraction of fibers (Haber and Graybeal; Lagier, Massicotte and Charron; Lee and Lee; Roy, Hollmann and Wille; Alkaysi and El-Tawil) and fiber orientation (Roy, Hollmann and Wille; Shao et al.) on the bond behavior of UHPC, the effects of the UHPC's tensile strength on its bond behavior have not been evaluated.

The Federal Highway Administration (FHWA) in USA proposed development length of steel rebar in UHPC based on UHPC pullout tests of more than 200 specimens with variable parameters including: the embedment length, cover thickness, bar spacing, bar size, and bar type (J. Yuan and B. A. Graybeal; J. Yuan and B. Graybeal). However, they used the same UHPC mixture and the only material variable was the testing age to evaluate the performance of early age UHPC with lower strength. The proposed recommended design criteria suggest a minimum development length, but not the optimum development length, for steel rebar development in UHPC. Other researchers proposed different ways to estimate the rebar-UHPC bond strength. (Roy, Hollmann and Wille) proposed bond estimation equation based only on their test results accounting for the tensile strength and fiber volume fraction in UHPC. (Alkaysi and El-Tawil) and (Yoo et al.) proposed minimum rebar-UHPC bond strength of $1.1\sqrt{f'_c}$ and $5.0\sqrt{f'_c}$, respectively.

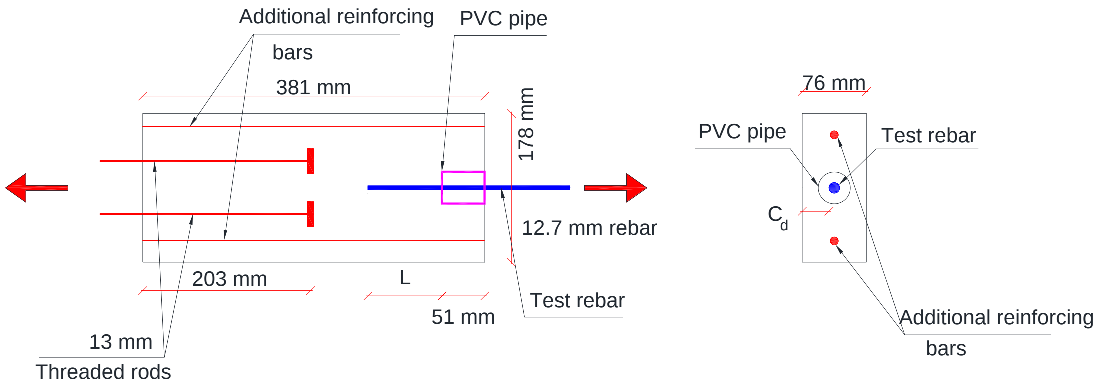
A systematic way to estimate the steel rebar-UHPC bond strength based on the material properties is missing in the literature. This article presents a summary of the experimental data and analytical simulations performed by the authors to understand the effect of the tensile strength of UHPC on the bond strength. The authors' results and simulations and those from the literature are used to propose an update for the bond design equation accounting for UHPC's properties.

2. Effect of UHPC Properties on Bond Strength

The bond behavior between steel reinforcement and UHPC was investigated through experimental and numerical analysis. Three UHPCs were investigated experimentally – two traditional UHPCs with different tensile strengths and strain capacity of about 0.2%, and a third UHPC with tensile strain-hardening behavior, similar to strain-hardening cementitious composites (SHCC), with a strain capacity of about 6.6%. The materials naming was based on the fibers as follows – the first material utilizing only steel fibers is called SF, the second material utilizing steel wool in addition to the steel fibers and is called SFW, and the third material utilizing ultra-high-molecular-weight polyethylene and is called PE.

The specimens were tested in a double tension pullout, as shown in Figure 1 below, to simulate the stress condition in structural applications, where the rebar and the surrounding concrete are in the same state of stress (Roy, Hollmann and Wille; Cheung and Leung; Fehling, Lorenz and

Leutbecher). Specimens with two different thickness of 50.8 mm (2 in) or 76.2 mm (3 in) were prepared to achieve cover thicknesses of 1.5d and 2.5d, respectively (where 'd' is the rebar diameter). The rebar embedment lengths ranged from 3d to 8d for cover thickness of 1.5d, and from 2d to 6d for cover thickness of 2.5d. Further details of the test setup are presented in (Soliman, Heard, et al.).



(a) Double tension pullout setup (b) Cross-section of the specimen

Figure 1: Double tension pullout specimen dimensions

In addition to the above experiments, finite element analysis was used to further evaluate the effect of UHPC tensile strength. For this analysis, three new materials (Mat1, Mat2, and Mat3) were defined with the same compressive strength as the SF-UHPC, but with different tensile strength values. Finite element models of the double tension pullout specimens of these three simulated materials were prepared using the same configurations (cover thickness and embedment length) as those used for the tested specimens.

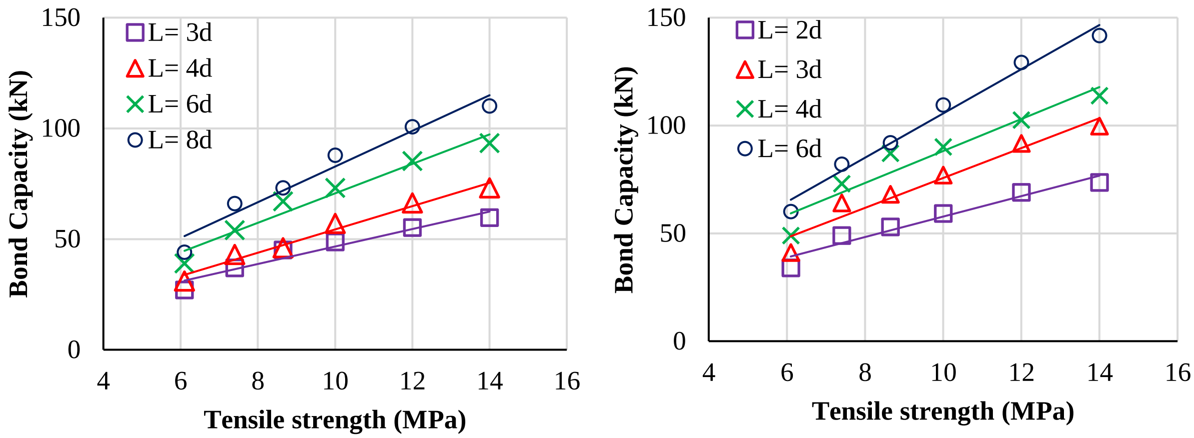
Table 1: UHPC material properties

Material	SF	SFW	PE	Mat1	Mat2	Mat3
Tensile strength (MPa)	6.1	7.4	8.7	10.0	12.0	14.0
Compressive strength (MPa)	150	136	119	150	150	150

The bond capacities of all the tested and the simulated specimen configurations are plotted against the corresponding material tensile strengths in Figure 2 below. A nearly linear relationship is observed between the tensile strength of UHPC and the bond capacity, which is attributed to the splitting failure mode of most of the specimens. This shows that the superior tensile strength of UHPC should be considered for determining the bond strength and the required development length.

3. Bond Tests Database

There are multiple studies in the literature on rebar-UHPC bond. Different types of bond test setups are typically used, which can be broadly classified into two main categories: Beam tests and pullout tests. Beam tests have been conducted in three different configurations. First, as four-point beam splice tests shown in Figure 3(a) (Zuo and Darwin), which consist of placing a rebar splice in the beam region with uniform bending moment to test the bond strength under a uniform tension force. The second configuration is the UHPC joint test like the example shown in Figure 3(b) (Lee and Lee), in which two precast concrete elements are joined using cast-in-place UHPC, relying on the bond between UHPC and the rebar pieces. A joint width is designed to achieve a development length (L) to test its effect on the load transfer. Recently, researchers have also adopted a beam end test to evaluate the beam end behavior similar to the beam development case, but with smaller specimens, as shown in Figure 3(c) (Shao et al.).



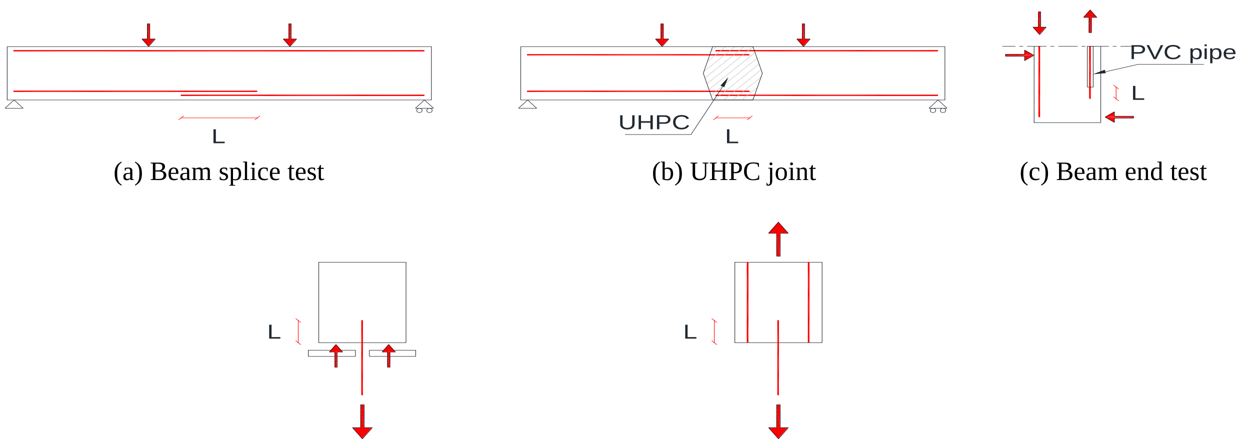
(a) Cover thickness = 1.5d (b) Cover thickness = 2.5d

Figure 2: Relationship between UHPC tensile strength and bond capacity

Compared to the beam tests, the pullout tests are simpler to execute and more practical, especially for comparing the bond behavior of different materials while studying a number of different parameters, such as cover thickness, rebar diameter, confinement, etc. The pullout tests usually consist of a bonded portion of the rebar (with embedment length, L) being pulled out of the concrete. A typical pullout test setup, as shown in Figure 3(d) (ASTM D7913; RILEM), uses a compression support leading to higher confinement of the tested rebar and overestimation of the bond strength. Recently, researchers have modified the classical setup to obtain a double tension pullout test to ensure that both the test rebar and the surrounding concrete are in tension, as shown in Figure 3(e) (Fehling, Lorenz and Leutbecher).

A database of UHPC bond tests is collected from the literature consisting of 61 beam tests from (Lee and Lee; Lee; Dagenais and Massicotte; Alkaysi; Shao et al.; Hung et al.) and 298 double pullout tests from (Fehling, Lorenz and Leutbecher; Haber and Graybeal; Lagier, Massicotte and Charron; Roy, Hollmann and Wille; Cheung and Leung; J. Yuan and B. A. Graybeal; J. Yuan and B. Graybeal). Although (ACI 408R-03) recommends the use of beam splice tests (and not the pullout tests) for characterizing the rebar-concrete bond, only a few studies have used these studies. Similarly, the number of studies implementing the UHPC joint tests and beam end tests is also limited. As a result, the database of UHPC bond tests was expanded by including the studies using double pullout tension as the states of stress in UHPC and rebar are similar to the beam splice experiments.

Among the double pullout tension tests reported in the literature, only those tests were selected in which the rebar's bonded region is confined only by UHPC, i.e., no transverse reinforcement, to focus on the behavior of UHPC. Furthermore, only those experiments in which specimens failed due to bond failure (as opposed to flexural failure or rebar rupture) were selected to estimate the bond strength. The results from this study (utilizing double pullout experiments) are also added to this database. Overall, the database utilizes UHPC with compressive strength ranging from 75 to 191 MPa with most of the specimens containing 2% steel fibers by volume. These bond test results are used to develop an empirical equation to estimate the bond strength of UHPC as discussed below.



(a) Beam splice test (b) UHPC joint (c) Beam end test

(d) Classic pullout test (e) Double tension pullout test

Figure 3: Bond Test Setups

4. Bond Strength Estimation and Development Length

For estimating the bond strength, an approach similar to that in (ACI 318-19) is adopted. Similar to ACI 318-19, the bond strength is estimated based on the cover thickness and embedment length, but the tensile strength of the UHPC is used instead of the compressive strength used for concrete. As discussed in Section 2, the rebar-UHPC bond capacity is directly related to the tensile strength of UHPC. Recent efforts by FHWA (Graybeal and Baby) and (AASHTO) to propose tension testing standards for UHPC will allow the practical use of the tensile properties in structural design. However, the tensile strength is not characterized in the majority of the studies in the database (described in Section 3). For such cases, the tensile strength of UHPC was estimated based on the compressive strength, according to the Equation (1) as proposed by (Russell and Graybeal), where f'_c is the compressive strength of UHPC in psi.

$$f_t = 6.7\sqrt{f'_c} \quad \textbf{(1)}$$

A linear relationship is assumed between the average bond strength (τ) and the cover thickness and the embedment length as follows:

$$\boldsymbol{\tau = \left(A\frac{c_{min}}{d} + B\frac{d}{L}\right)f_t} \quad \textbf{(2)}$$

Here, c_{min} is the minimum of the clear cover thickness and half the spacing between the tested rebar and adjacent rebars, L is the embedment length, d is the rebar diameter, and f_t is the tensile strength of UHPC. A and B are the fitting parameters obtained from a linear regression of the test results using the least squares method. The obtained equation is as shown in Equation (3):

$$\boldsymbol{\tau = \left(1.1\frac{c_{min}}{d} + 5.3\frac{d}{L}\right)f_t} \quad \textbf{(3)}$$

Equation (3) is used to estimate the bond strength of the UHPC bond test results, and the estimation quality to the design equations in the standards (ACI 318-19 and ACI 408-R03) for conventional concrete and to the equations proposed for UHPC in the literature (Roy, Hollmann and Wille; Alkaysi and El-Tawil). The ACI 318-19 specifies the required development length of deformed rebar in normal-strength concrete (f'_c < 70 MPa) based on the bond strength equation proposed by (Orangun, Jirsa and Breen), as shown in Equation (4). In this equation, τ is the average bond stress, c_{min} is the minimum clear cover or half the clear spacing between reinforcement bars (whichever is smaller), d_b is the diameter of rebar, and l_d is the embedment length.

$$\boldsymbol{\frac{\tau}{\sqrt{f'_c}} = 1.2 + 3\frac{c_{min}}{d_b} + 50\frac{d_b}{l_d}} \quad \textbf{(4)}$$

ACI 408R-03 proposed another equation for estimating bond capacity by analyzing a wider range of concrete strengths. It was found that for high-strength concrete, the bond strength increases at a rate less than ($\sqrt{f'_c}$), so Equation (5) utilizes ${f'}_c^{1/4}$, which is valid for concretes with compressive strength of up to 110 MPa. In Equation (5), T_c is the bond capacity, A_b is the cross-sectional area of the rebar, and c_{max} is the maximum of the clear cover and half the spacing between reinforcement bars.

$$\boldsymbol{\frac{T_c}{{f'}_c^{1/4}} = [59.9\, l_d\left(c_{min} + 0.5\, d_b\right) + 2400\, A_b](0.1\frac{c_{max}}{c_{min}} + 0.90)} \quad \textbf{(5)}$$

(Roy, Hollmann and Wille) also proposed a linear equation as a modification to the basic equation by (Orangun, Jirsa and Breen), by adding the effect of the fiber content and replacing the compressive strength by the tensile strength of UHPC, as shown in Equation (6). However, they proposed the equation based on a limited number of test results.

$$\boldsymbol{\tau = \left(0.45\frac{c_{min}}{d} + \frac{38.5}{L} + 0.23\, V_f\right)f_t} \quad \textbf{(6)}$$

(Alkaysi and El-Tawil) proposed an equation to estimate the minimum rebar-UHPC bond strength based on a large number of test results from the literature. However, most of the tests were classic pullout tests, as shown in Figure 3 (d), and they defined the bond strength based on the lower bound of the bond strength to get a simplified equation, as shown in Equation (7):

$$\boldsymbol{\tau = 1.1\sqrt{f'_c}} \quad \textbf{(7)}$$

Table 2 below summarizes the average ratios of experimental/estimated bond strength using these different models to compare their performance. It is observed that the Equation (3) proposed in this study presents a better average estimation ratio, because it is fitted to a wider range of UHPC test results than that used in the previous studies. In addition, Equation (3) provides much lower variation in the estimation compared to the other methods, indicating the suitability of using the tensile strength of UHPC to estimate the bond strength.

Table 2: Comparison of experimental to estimated bond strength ratios for different models

	New equation	Orangun et al 1977 (ACI 318)	ACI 408	Roy et al 2017	Alkaysi and El-Tawil 2015
Mean	1.01	1.57	1.59	1.80	1.88
Standard deviation	0.35	0.51	0.49	0.68	0.86

The development length of the rebar can be determined based on the bond strength, from Equation (3) above. The development length is determined as the embedment length corresponding to the yield strength of the steel rebar (f_y). The left hand side can be represented as the average bond strength as follows:

$$\frac{f_y}{4} \times \frac{d}{L} = \left(1.1\,\frac{C_{min}}{d} + 5.3\,\frac{d}{L}\right) f_t \quad \textbf{(8)}$$

By simplifying the equation, the development length (L) can be determined as shown below:

$$\frac{L}{d} = \frac{\left(\frac{f_y}{4f_t} - 5.3\right)}{1.1\; C_{min}/d} \quad (9)$$

The development length of steel rebar to transfer the yield strength to the UHPC can be determined using Equation (9) utilizing the tensile strength of the UHPC. For example, for a steel rebar with a yield strength of 414 MPa (Grade 60) embedded in a typical UHPC with a tensile strength of 8 MPa, with a clear cover thickness of 2d, the required embedment length is calculated as 3.5d using Equation (9). In comparison, a development length of 32d is needed for the same rebar embedded in normal concrete with a compressive strength of 35 MPa (5 ksi) according to ACI 318-19.

5. Conclusions

Experimental and analytical investigations (using finite element models) were used to evaluate the correlation between UHPC material properties. The results showed that the bond capacity is directly related to the tensile strength of UHPC.

The UHPC bond results from this study and from all the UHPC beam and double tension pullout tests in the literature are used to propose a simplified equation for bond strength estimation of UHPC. The new equation shows a good match with the test results, and a low variation compared to previously proposed equations, indicating good correlation between the tensile strength of UHPC and the bond strength. The new equation results in significantly low development length in UHPC leveraging the high tensile strength and the resulting bond strength.

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