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Experimental investigation of bond behavior of mild steel reinforcement in UHPC

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is a relatively new class of advanced cementitious composite material, which exhibits high compressive and tensile strengths. The discrete steel fiber reinforcement included in UHPC allows the material to maintain a tensile capacity beyond cracking of the cementitious matrix. The bond behavior of deformed reinforcing bar in UHPC is investigated in this study by conducting pull out tests and beam tests with lap splices. The rebar used for these tests are #4 (M13), #5 (M16) A615 grade 60 bars and # 6(M19), #7 (M22) A615 grade 80 bars. The embedment length and side cover for the pull out tests were varied from $6d_b$ to $8d_b$ (d_b = diameter of the rebar) and $1d_b$ to $3.5d_b$, respectively. The beam tests were conducted under four-point loading and the clear cover for these tests was varied from $1d_b$ to $3d_b$. The rebar for all beam specimens were spliced at mid-span for a length of $8d_b$. The beam specimens were instrumented to capture the strains at different points along the splice length. 16 pull out and 12 beam tests were completed and the effect of embedment length, concrete cover, bar size and bar type on the bond strength were investigated. This paper presents the details of this experimental investigation and adds significant new data on the bond stress distribution along the development length. It was found that the development length of embedded reinforcement in UHPC can be significantly reduced when compared to normal concrete.

1. Introduction and background

Ultra-high performance concrete (UHPC) is a relatively new class of advanced cementitious material, which has been developed over the past few decades to address the need for a material with superior mechanical and durability properties [1]. UHPC is composed of an optimized gradation of granular constituents, a very low water-to-cementitious materials ratio (less than 0.25), and a high percentage of discontinuous internal fiber reinforcement. The optimized material gradation leads to a dense packing structure in UHPC, resulting in compressive strengths in the range of 22 ksi (150 MPa). The presence of steel fibers makes this material to have a ductile tensile behavior and exhibit a sustained post-cracking tensile strength [2]. The current design standards such as ACI 318-14 [3] for normal and high strength concrete structures are not appropriate for economical design of structures with UHPC as the enhanced compressive and tensile behavior of UHPC is not well accounted for in current design codes. The enhanced mechanical properties of UHPC also lead to an increase in the bond between UHPC and deformed steel bar [4], allowing for a reduction in the length required to develop yield capacity of a reinforcing bar. Composite action between concrete and reinforcing steel cannot occur without bond. Therefore, the bond performance of rebar plays a major role in the behavior of reinforced concrete structures when subjected to static and dynamic loads, especially for crack width control. A high bond value will lead to small cracks, close to each other, while a lower bond value will lead to larger cracks. Insufficient bond can generate sudden failure with very low ductility. The bond behavior is governed by different factors such as the geometry of the bar (relative rib area), the mechanical properties of the concrete, the thickness of the concrete surrounding the rebar and the confinement conditions due to stresses perpendicular to the axis of the bar and due to the presence of transverse reinforcement (rebars or fibers). The bond behavior in regular concrete is well studied and some of the commonly adopted test setups for development length related studies in normal strength concrete (NSC) and high strength concrete (HSC) are shown in Fig. 1 [5].

Experimental studies to characterize the development length of rebar in UHPC have been carried out in recent times. The majority of these experimental studies used standard [6–8] or modified [9,4] pull out test setups for understanding the bond behavior, as it is easy to fabricate and test the specimens. However, the standard pull-out test setup as shown in Fig. 1a leads to the formation of compressive stresses in the concrete block, which helps to enhance the bond development

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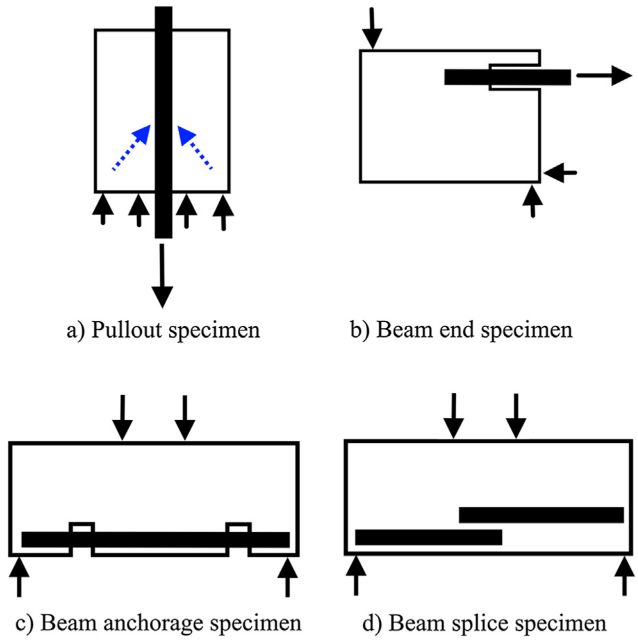

Fig. 1. Commonly adopted test setups for rebar development length studies [5].

and thus lead to shorter development lengths. Accordingly, ACI 408 R-03 [5] recommends that pullout tests should not be the sole basis for determining the development lengths. Fehling et al. [9], Yuan and Graybeal [4] modified their pull out test setup to minimize the formation of compressive struts. Additional research is also available in the form modified beam end tests performed by Saleem et al. [10] and lap splice tests under direct tension conducted by Lagier et al. [11]. A summary of these studies is presented below.

Saiidi and Mostafa [6] performed pullout tests on steel bars embedded in UHPC filled corrugated ducts as part of a study which developed an accelerated bridge construction detail for a column-to-foundation connection. The corrugated ducts were embedded in a 24 in. diameter normal concrete column and received mild-steel reinforcement and filled with UHPC. They tested #8 (M25) (d_b = 1 in. (25 mm), where d_b is the nominal diameter of the bar), and #11 (M36) (d_b = 1.41 in. (36 mm)) bars with embedment lengths of $3d_b$, $4d_b$, $5d_b$, $8d_b$, and $12d_b$. Through these tests it was seen that, measured average bond stresses developed along the embedment length of a rebar in UHPC was eight times higher than that of rebar in normal concrete. Marchand et al. [7] investigated the bond development length in Ultra High Performance Fiber Reinforced Concrete (UHPFRC) by testing 51 pullout test samples. These tests were performed on 0.32 in. (M8), 0.47 in. (M12), and 0.63 in. (M16) diameter bars. The study used variable embedment lengths between $2.5d_b$ and $8d_b$ and clear covers from 0.79 in. (20 mm) to 7.64 in. (194 mm). It was concluded from these tests that, for the bar sizes tested, a minimum of $8d_b$ embedment length with 0.79 in. (20 mm) cover is required for the full development of the bar. Alkaysi and El-Tawil [8] performed pullout tests to study the effects of embedment length, bar coating, casting orientation, curing age and fiber volume content. The tests were performed on #4 (M13) to #6 (M19) bars for embedment lengths from $2.6d_b$ to $8d_b$. Based on the results from this study the authors conservatively estimate the bond strength in UHPC to be $1.1\sqrt{f'_c}$, where f'_c is the characteristic compression strength of UHPC in MPa. Fehling et al. [9] conducted 20 pull out tests on 0.47 in. (M12) diameter bars embedded in rectangular UHPC blocks. The concrete cover and embedment length in the tests were varied from $1d_b$ to $2.5d_b$ and $2d_b$ to $12d_b$, respectively. In these tests three major failure modes such as cone failure, V-type splitting failure and splitting failure were observed. 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 $2.5d_b$). A splitting type failure was observed in high embedment ($8d_b$ to $12d_b$) specimens. It was concluded from these tests that for specimens with $1.5d_b$, $2d_b$, and $2.5d_b$ concrete cover, the yield stress was reached in samples with embedment length more than $6d_b$, $5d_b$, and $4d_b$ respectively. Yuan and Graybeal [4] conducted over 200 pull out tests to investigate the effect of embedment length, concrete cover, bar spacing, concrete strength, bar size, bar type, and yield strength. Based on the study they concluded that, for #4 (M13) (d_b = 0.5 in.) to #8 (M25) (uncoated or epoxy coated) reinforcing bars, a yield strength of 75 ksi (517 MPa) can be attained with an embedment length of $8d_b$, as long as a minimum side cover of $3d_b$, and a minimum clear spacing between bars of $2d_b$ is provided. Saleem et al. [10] performed 21 pull out tests and 16 beam tests on, #3 (M10) (d_b = 0.375 in.) and #7 (M22) (d_b = 0.875 in.), 100 ksi (690 MPa) mild steel reinforcement to study the effect of embedment length on rebar bond behavior in UHPC. For the beam tests conducted in this study, the reinforcing bars were not spliced; instead they were debonded by using a PVC tube at one end to vary the embedment length. All the specimens had a constant clear cover of 0.5 in. (13 mm) and the embedment length varied from $8d_b$ to $48d_b$. Based on the tests results the authors concluded that, embedment lengths of $12d_b$ and $18d_b$ are required to develop 100 ksi (690 MPa) yield strength, for #3 (M10) and #7 (M22) bars, respectively. Lagier et al. [11] studied the effect of splice length and UHPFRC steel fiber content on development length. For this study they used a single bar diameter of #8 (M25) with $1.2d_b$ concrete cover. The embedment lengths tested were $5d_b$, $8d_b$ and $10d_b$. The fiber contents chosen for testing were 1%, 2% and 4%. The test results indicate that using UHPFRC in splice regions greatly enhances bond performance. An average bond stress of more than 1.45 ksi was developed along embedment length of rebar in all specimens. Further, it was also observed that increasing fiber content limits the propagation of transverse cracks thus improving bond performance. Table 1 shown below provides a summary of these research works and also gives additional details regarding test setup and material properties.

As summarized above, a majority of these studies are mainly based on pullout tests on reinforced UHPC members. Depending on experimental setup used for pullout testing (e.g., Alkaysi and El-Tawil [8]), these tests may not fully represent the strain gradient and stress conditions in surrounding UHPC as expected in flexural members such as beams and columns. Also, strain monitoring along the development length of the rebars was not carried out in most of the tests, which resulted in calculation of only the average bond stress along the entire embedment length instead of a detailed bond distribution. A thorough understanding of bond stress distribution and development length of rebar in UHPC is critical for economical and safe design of the UHPC structures. The research presented in this paper investigates the factors that affect bond of deformed steel bars in UHPC, including embedment length, concrete cover, bar spacing and bar size. This study adds additional experimental data to the existing literature along with quantifying the bond development along the embedment length.

2. Experimental program

In order to investigate the bond behavior of rebar embedded in UHPC, an experimental program consisting of pull-out tests with modified test setup and beam tests with rebar splices were conducted. Only one type of UHPC mix, which is commercially available in North America [12] was used for this study. The UHPC mix design consisted of premix, super plasticizer, high range water reducing agent and 2% steel fibers by volume. The steel fibers were straight, smooth, cylindrical and made of high-tensile-strength steel. They have a diameter of 0.008 in. (0.2 mm) with a length of 0.5 in. (12.7 mm). The typical mix design of UHPC adopted for this study is presented in Table 2. The UHPC used in this study had an average compressive strength of 21 ksi (145 MPa) at