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Factors affecting bond development between Ultra High Performance Concrete (UHPC) and steel bar reinforcement

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ABSTRACT

The advent of Ultra High Performance Concrete (UHPC) has led to strong interest in developing new structural applications for the material. While UHPC's tensile and compression behaviors are relatively well understood, an in-depth analysis of UHPC's behavior at the component level, specifically the bond strength between UHPC and steel bar reinforcement is lacking and the published data shows large scatter. In the presented study, a series of bar pull out tests was performed in order to characterize the bond strength of a non-proprietary UHPC blend. The 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, 75 and 100 mm), two casting orientations (longitudinal and transverse to the steel bar reinforcement), two steel fiber volume contents (1% and 2%) and early age bond strength at 1, 3 and 7 days curing. Results from pull out testing show that bond strength decreases with increased embedment length suggesting a non-uniform distribution of bond strengths. Differences in steel fiber content yielded significant differences in bond strength of up to 36% when using 1% vs. 2% fiber volumes. Early age testing showed that 75% of compressive and bond strength in UHPC is developed within 7 days of casting.

1. Background and motivation

Ultra-High Performance Concrete (UHPC) is commonly defined as a cementitious material with compressive strength in excess of 150 MPa. The exceptional performance of UHPC is attributed to its high packing density, which is achieved by carefully controlling the size and distribution of the constituent particles, and incorporating high strength, non-continuous steel fibers. Fiber reinforcement promotes ductility, high tensile strength and energy absorption capacity [20,29,25,26,27,28].

Early versions of UHPC required difficult and expensive curing techniques [14], but recent advances in UHPC technology have simplified the manufacturing process (e.g. [26,27,28]. Researchers have been able to achieve UHPCs with compressive strengths as high as 280 MPa, without the use of special curing processes [26,27,28]. With strengths in compression approaching that of mild steels, finding new uses for UHPCs is intriguing many practitioners, who want to use the material in their projects. However, broad usage is hindered by the current high cost of the material and lack of test results, and understanding in general, of UHPCs behavior at the structural level.

1.1. Compressive and tensile behavior of UHPC

The high compressive strength of UHPC is well known and established [12,13]. Larrard and Sedran [6] produced a concrete mortar with a compressive strength of 236 MPa. Wille et al. [26–28] was able to prepare UHPCs with 28-day compressive strengths in excess of 200 MPa without requiring the use of expensive curing techniques. Graybeal [14] has shown that UHPC reaches a peak strength of around 150 MPa at 0.003 strain (0.3%). Wille et al. [26–28] showed that when reinforced with steel fibers, UHPC mixes were able to achieve 0.6% strain capacity in tension prior to strain softening. More information regarding the tensile and compressive behavior of UHPCs can be found in the works by Wille et al. [26–28] and Wille and Gustavo Parra-Montesinos [30] and Graybeal [14,16].

1.2. Bond development of steel bar reinforcement embedded in UHPC

There is limited published data on the bonding behavior between UHPCs and steel bar reinforcement. 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 [11,12]. Graybeal [12] recently has shown that under static conditions, UHPC specimens are capable

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of developing bond strengths 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 [24] 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. Performing pull out tests on 12 mm diameter bars, varying concrete cover and embedment lengths, Fehling et al. [8] determined that increasing cover widths and embedment lengths increased the bond strength, reaching those sufficient for bar yield. Holschemacher et al. [17] reported achieving bond strengths up to 60 MPa using 12 mm bars in UHPC cylinder. Saleem et al. [22] 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. Jungwirth and Muttoni [18] performed tests on 20 mm and 12 mm diameter bars, reaching bond strengths of 38 MPa and 66 MPa. Marchand et al. [19] investigated Bond in UHPFRC (ultra-high performance fiber reinforced concrete) for 10–22 mm diameter bars, report bond values from 4.6 MPa to as high as 76.3 MPa. Of the literature currently available on bond, data only exists on testing performed using Ductal® [21] 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 strength 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 [11].

1.3. Motivation for present study

All reinforced concrete structures rely on the bond relationship between the concrete and steel bar reinforcement. 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. A total of 57 bar pull out tests were performed, with parameters including bar coating, nominal bar size, embedment length, and UHPC casting orientation. Previous studies have shown that casting orientation can impact the final strength of UHPC because of preferential alignment of fibers along the casting direction [30].

Additionally, the early-age strength of the UHPC-steel bond was studied. Construction downtimes are costly and influence their surrounding area socially and economically. Using UHPC's enhanced material properties (compared to traditional concretes) makes it an efficient alternative with rapid strength gain. Bond information at the early stages of UHPC curing is essential for this application, and thus the early age bond strength of UHPC was evaluated through bar pull out tests performed at 1, 3 and 7 day curing intervals.

2. Experimental parameters and procedure

2.1. 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. It is also considered the least accurate testing method as it tends to overestimate the bond capacity as stated in ACI Committee 408 [1]. In the traditional pull out test, load on the steel bar placed into tension results in compressive forces in the surrounding concrete as it reacts against the rigid support surface holding the specimen. In most reinforced concrete structures under flexure loading, and in contrast to the traditional pull out test method, both the steel bar reinforcement and concrete are under tension during loading.

In order to minimize the effects of the compressive region during testing, a modified method of supporting the concrete was implemented as shown in Fig. 1a. This method was proposed by [5]. Unlike the traditional bar pull out case where the entire surface of the concrete is used as a support, the employed method makes use of the high bearing strength of the UHPC to minimize the surface area needed. The configuration uses four small steel plates to support the specimen, distancing the concrete directly adjacent to

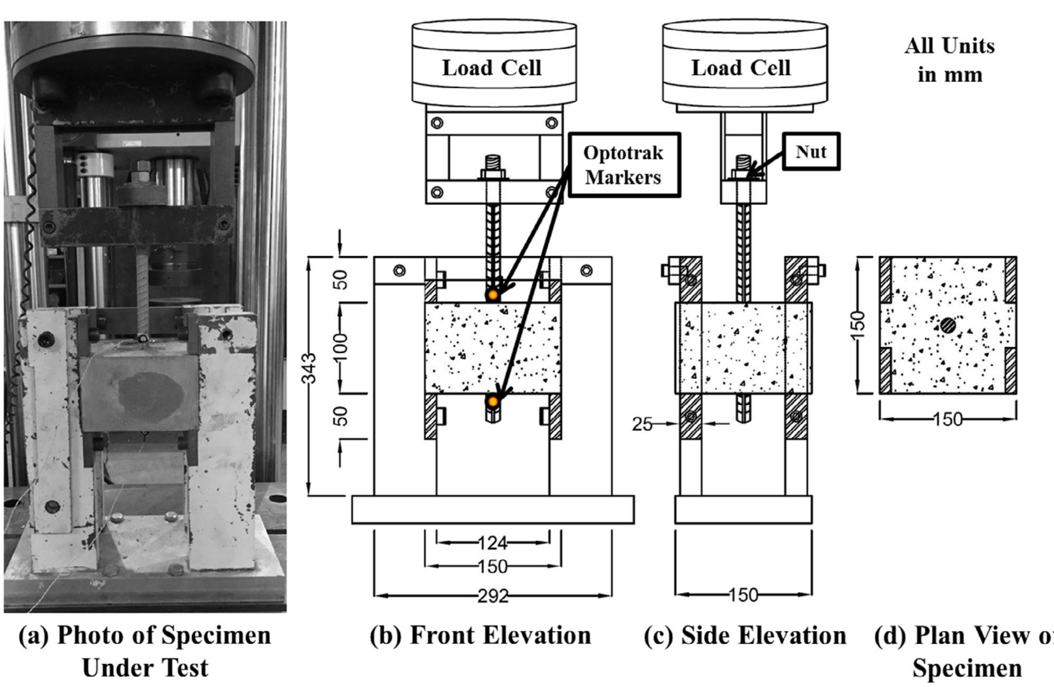

Fig. 1. Test Set Up Details and Views.