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Bond behavior of epoxy-coated rebar in ultra-high performance concrete

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HIGHLIGHTS

- Characterization of bond behavior of epoxy-coated rebar embedded in UHPC.
- Significant influence of embedment length and side cover on bond behavior.
- Good match of the experimental and analytical bond-slip response of epoxy-coated rebar in UHPC.

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ABSTRACT

The bond behavior of epoxy-coated rebar embedded in two different ultra-high performance concrete (UHPC) mixtures is experimentally investigated by a uniaxial pullout test, and the effect of embedment length, side cover, and mixture type on the bond stress-slip relationship is predicted using a double-phase analytical model. The bond mechanism and failure modes of rebar in UHPC are similar to those observed in normal concrete. The embedment length and side cover have significant influence on the bond behavior of epoxy-coated rebar in UHPC, and more drastic bond stress hardening and softening are observed for the case of larger embedment length and side cover. Two UHPC mixtures exhibit comparable bond strength and critical development length because they have close mechanical properties gained at test age. The adopted analytical model matches well with the experimental bond-slip response of epoxy-coated rebar in UHPC, and both the characteristic parameters in the model show an increasing trend when more dramatic hardening and softening of bond stress exhibit.

1. Introduction

Precast decked members for accelerated bridge construction, such as deck bulb tees (DBTs), are presently not used by many state Departments of Transportation (DOTs) on major highways, largely because bridges built with them on minor roads have shown cracks along the longitudinal joints [1,2]. The connections in those bridges used a combination of a grouted joint and welded clips, hoops, hooks, headed rebars, or mechanical couplers. American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications [3] require a minimum development length of $24d_b$ (where d_b is the rebar diameter) for rebar in tension. Some state DOTs and the Federal Highway Administration (FHWA) have recently researched and/or implemented alternative connection approaches which include narrow cast-in-place joints, ultra-high performance concrete (UHPC) for such joints, headed bars to achieve development within the width of the joint, and various combinations thereof [4]. However, headed bars may pose interference problems during erection and possible cover violations if camber is not well controlled. And narrow joints (desirable if expensive cementitious materials are used to fill them) could reduce the available development length below an acceptable level if the precast member has significant sweep. An ideal solution has yet to be found. UHPC has been found to exhibit much higher bond strength than normal concrete, and it could thus improve bond efficiency of reinforcement with narrow connections. The application of UHPC for use in connection details in structures has been gaining popularity, and it requires extensive research into the bond strength and bond-slip behavior between UHPC and rebar.

UHPC is commonly known as an innovative cementitious composite with discontinuous steel fiber reinforcement that possesses superior properties, such as enhanced mechanical strength, energy absorption capacity, and durability compared with conventional concrete [5,6]. The constituents of the UHPC are not totally different from those of the conventional concrete, and they commonly consist of Portland cement, silica fume, quartz flour, fine sand, high-range water-reducing admixture (HRWRA), water, steel fibers, etc. [7]. UHPC significantly benefits from its high packing

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density and dense microstructure by carefully tailoring particle sizes and distributions of all constituents and incorporating discontinuous steel fibers [8–10]. Although initial unit quantity cost of UHPC is much higher than that of conventional concrete, lighter and thinner sections are possible with UHPC for structural members and connections due to its significantly enhanced strength, stiffness, ductility and durability. Thus, UHPC offers tremendous opportunities to construction practitioners and could be of great potential for longer service life and lower maintenance cost than using normal concrete and fiber reinforced concrete [11].

However, there are very limited investigations on the bond behavior of rebar in UHPC [12]. Several experimental configurations have been previously conducted to investigate the bond developed with rebar in concrete as well as UHPC. Modified from ASTM C234 [13], simple steel rebar pullout from an anchored concrete block is widely used to obtain the bond strength of rebar in concrete. This traditional pullout test can investigate influence of type of rebar, development length of rebar, variability of concrete, etc. [12,14–18]. However, it still has some drawbacks, such as it could not reveal the effects of lap-splice and side covers and likely overestimates the bond strength as stated in ACI Committee 408 [19]. Lagier et al. [20,21] developed a specimen configuration to investigate the tensile bond performance of contact lap splice to simulate such a joint design between precast elements. Two pairs of lapped rebars cast into a UHPC specimen were pulled apart. Yuan and Graybeal [22,23] designed a novel test setup to simulate the non-contact lap-splice configuration in a connection system design widely used in the United States. The pullout specimen was a strip of UHPC with embedded rebars, cast on top of a concrete slab with more rebars joining the two concrete sections. The effect of clear side cover as well as the clear spacing between the testing rebar and the joining rebar was accordingly investigated. It has been concluded that the bond strength in UHPC gradually increases with increasing of the embedment length and side cover of rebar, fiber content, compressive strength of UHPC; it is much higher but shows similar trend in comparison to those in normal concrete. The bond strength decreased when the rebar spacing was very small because the contact splice limited the ability of the fiber reinforcement to enhance the strength of the UHPC. When the rebar diameter increased, the bond strength decreased. Also, the epoxy-coated rebars had lower bond strength than the uncoated rebars since the coating reduces the frictional bond. Majority of failure would occur as a splitting crack across the outer cover or between the joining rebars. Regarding the UHPC connection design, it also has been recommended that the rebar size should be from No. 4 to No. 8 and the minimum compressive strength be 93 MPa to obtain the yield stress of rebar at bond failure [22]. In addition, a minimum embedment length of $8d_b$ (where d_b is the rebar diameter) and a minimum side cover of $3d_b$ with a clear rebar spacing between $2d_b$ and l_s (where l_s is the lap splice length) were recommended for design of the connection system.

The main objectives of this research are to determine the critical embedment lengths of rebars in local materials-sourced UHPC and investigate the bond behavior of rebars embedded in such UHPC. Two UHPC mixtures developed using locally sourced materials are produced, thereby avoiding high costs of the proprietary materials. With an intention for connection application in deck bulb tees [24], the direct tension pullout tests are conducted to determine the bond capacity of No. 5 epoxy-coated rebars with a range of embedded lengths and side covers. Direct tension pullout test setup is developed to simulate the non-contact lap-splice configuration in a field-cast connection joint system for deck bulb tees. Furthermore, the experimental bond-slip relationship between epoxy-coated rebar and UHPC is fitted and predicted with an analytical model. Design recommendations are made for epoxy-coated rebars in UHPC based on the experimental and analytical results.

2. Materials and experimental program

2.1. UHPC mixture proportions

The constituent materials of the UHPC mixtures in this study are provided in Table 1, including cement, silica fume, fine sand, steel fibers, HRWRA and water. The Portland cement Type I-II with a specific gravity of 3.15 is used to prepare the UHPC samples, and commercially available silica fume (Rheomac SF 100) provided by BASF Construction Chemicals, LLC is used as a partial replacement of cement to improve the mechanical properties and durability of UHPC. Local natural sand is provided by the Atlas Sand & Rock, Pullman, WA. The sand passed through the ASTM No. 30 (0.6 mm) sieve and over the No. 200 (0.075 mm) sieve is then washed to remove the clay/silt particles and oven-dried at 110 °C (230°F) to achieve zero moisture content. Straight smooth steel fiber (NYCON-SF Type I) with 13 mm in length and 0.2 mm in diameter is used to enhance the ductility and toughness of UHPC. Glenium 3030 NS, a commercially available polycarboxylate-based HRWRA produced by BASF Construction Chemicals, LLC, is used in the UHPC mixes to achieve the desired workability. More importantly, some expensive materials, such as quartz powder and imported fibers, commonly used in commercial products, are not used in this study.

Through a trial test of different UHPC mixes, two types of UHPC mixture proportions (denoted as A4 and C3 in this study) are considered, and their corresponding water to cementitious materials ratios (w/cm) are 0.21 and 0.18, respectively [24]. Since C3 has a lower w/cm than A4, more HRWRA are needed for compensating its flowability. Same amount of Portland cement (890 kg/m^3) is used to produce UPHC; while more silica fume is added for higher w/cm mixture, that is, 20% and 15% of total amounts of total cementitious materials for A4 and C3, respectively. For both the mixtures, 2% per volume of steel fibers are added to achieve ductility, and this volume fraction has been widely used in UHPC mixture design since it provides good compromise between reinforcement, ductility and workability [25].

2.2. Mixing procedures

It is not only good to have these constituent materials in the UHPC mix but also to have them mixed together properly for the expected results associated with a high strength and more durable concrete. Therefore, mixing is to maintain uniformity of these constituents in the UHPC mix. A normal concrete drum mixer with a volume of 100 L is used to mix constituents to produce specimens of UHPC. The entire mixing time is relatively longer than that for conventional concrete due to elimination of coarse aggregate and use of low w/cm ratios in UHPC. Mixing time also depends on the power of the mixer. In this study, the whole mixing time ranges from 40 to 60 min and consists of four stages: (1) mix the dry constituents 10–15 min, (2) add 75% of the water and mix 10–15 min, (3) add the HRWRA and the remaining 25% of water and mix 10–15 min, and (4) add the steel fibers and continue mixing 10–15 min till thoroughly combined. The entire mixing time is

Table 1
UHPC mixture proportions.

Mixture Type	Unit	Mixture A4	Mixture C3
Type I/II Portland Cement	kg/m^3	890	890
Silica Fume	kg/m^3	222	157
Fine Sand	kg/m^3	804	934
Steel Fibers	kg/m^3	142	140
HRWRA	L/m^3	34	57
Water	kg/m^3	234	193
w/cm	–	0.21	0.18