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Influence of volume fraction and orientation of fibers on the pullout behavior of reinforcement bar embedded in ultra high performance concrete

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HIGHLIGHTS

- A novel casting device is used to facilitate fiber alignment.
- Pullout behavior is investigated in dependency of fiber orientation and fiber volume fraction.
- High strength reinforcement bars are being pulled out of UHPC.
- UHPC with perpendicularly oriented fibers registers the highest pullout load.
- Load-slip curves show the ductile nature of the failure.

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ABSTRACT

An experimental investigation was carried out to evaluate the effect of fiber volume fraction (V_f) and fiber orientation on the pullout behavior of steel reinforcement bar embedded in Ultra High Performance Concrete (UHPC). The experiments were performed using pullout specimens under tensile stresses and low concrete cover. It was found that the peak pullout load increased with the increase in V_f. When V_f was kept constant at 2%, it was observed that the specimens with perpendicular and parallel fiber orientation with respect to the rebar direction recorded the highest and the lowest pullout load, respectively. Finally, an empirical model equation was developed to predict the bond strength values.

1. Introduction

Ultra High Performance Concrete (UHPC) with high compressive and tensile strength, excellent post-cracking ductility, and improved durability properties as compared to conventional and high performance concrete [1,2] has the potential to replace traditional concrete in reinforced concrete applications, especially in critical beam-column junctions and high shear regions. As the interest in application of rebar-reinforced UHPC grows, the knowledge of the bond stress-slip response of rebar embedded in UHPC becomes essential in order to estimate the development length of rebar and evaluate the overall structural response under applied load.

Rebar allows transfer of tensile stresses across cracks through a combination of chemical adhesion, frictional resistance, and bearing of the ribs on the concrete. Chemical adhesion between the concrete and the steel is the first resistance to be overcome when a small tensile load is applied to the rebar and it ranges from 0.5 to 1.0 MPa in conventional concrete (CC) [3]. Frictional resistance arises due to the micro-irregularities along the surface of the steel, wedging of granular material between the bar and the concrete, and the bearing force component that acts parallel to the rib (Fig. 1a) [3]. Typical frictional resistance values range from 0.4 to 10.0 MPa in CC [4,5].

However, friction and adhesion play a very small role in bond strength compared to the third mechanism, i.e., bearing of the ribs. After breaking free of adhesion, the bar slips slightly and the ribs of the rebar bear against the concrete at an angle creating force components that act both parallel to and perpendicular outward from the length of the rebar (Fig. 1b). The perpendicular component of

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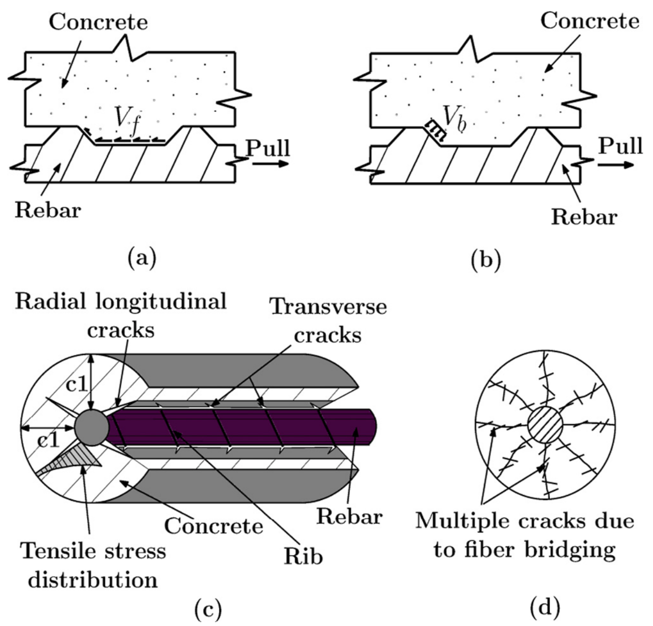

Fig. 1. Bond mechanisms (idealized). a Friction (V_f), after [3], b Bearing of the rib (V_b), after [3], c Radial longitudinal cracks in CC after [6,7], d Crack bridging in Fiber Reinforced Concrete (FRC) after [8]

the bearing force causes a tensile ring of radial stresses to develop along the perimeter of the bar leading to radial cracks, also known as, longitudinal cracks or splitting cracks (Fig. 1c). The aforesaid bond mechanisms are explained in detail elsewhere [3,6,9,10]. In Fiber Reinforced Concrete (FRC), after initial cracking, the tensile ring is redistributed around the whole matrix due to the presence of fibers [8]. Upon further slippage, following the pullout of the fibers, longitudinal cracks develop along the bar axis and this corresponds with the approximate maximum bond strength. At this point, if the fibers can effectively bridge the longitudinal cracks without excessive opening (Fig. 1d) the failure will be a relatively ductile pullout failure. Otherwise the longitudinal cracks will open and the failure will be more of a sudden splitting failure [8].

UHPC has been found to have much higher bond stress than CC as long as necessary cover is available to prevent splitting. Table 1 shows a compilation of available bond stress data vis-à-vis compressive strength (f'_c) of concrete with RILEM [11] recommended (modified) 4.5*db* concrete cover, where *db* is the diameter of the bar. It is evident from Table 1 that the bond stress increases with the increase in f'_c and that the slip at the maximum bond stress in UHPC (without fiber) is generally lower than that of CC due to the higher modulus of elasticity in UHPC. Although many researchers have carried out bond tests with concrete containing fibers, it is obvious from Table 1 that the orientation of fibers did not get much attention in their work. However, at 4.5*db* cover, the concrete cover itself is able to resist the radial tensile stresses preventing longitudinal splitting failure. Therefore, fibers in FRC have little or no effect on the bond behavior as they do not get activated at 4.5*db* cover [12]. In the study of bond between UHPC and steel rebar, fibers have proven to be effective when covers are small enough to induce a splitting type of failure before the full strength of the bar is developed [15,18–21]. Aarup et al. [18] observed that an embedment length of 6.25*db* with 1.8*db* cover achieved the maximum bond stress of 23.6 MPa with a pullout failure (not rebar rupture). In their study, they used Compact Reinforced Composite (CRC) with $f'_c = 165$ MPa and varied the fiber contents between 3% and 6%. Cheung and Leung [19] used no fiber and 2% fibers with 5*db* and 8*db* embedment length and a constant cover of 3.25*db* in high strength fiber reinforced cementitious composites ($f'_c = 150$ MPa). The failure mode in all cases was splitting failure; however, the average pullout strength increased by 144% for 5*db* and 154% for 8*db* embedment lengths when the fiber volume fraction was increased from 0 to 2%. Leutbecher [15] used a constant embedment length of 1.5*db* in UHPC ($f'_c = 150$ MPa) and noticed that at 2.5*db* cover, the maximum pullout strength increased by 70% when the fiber content was increased from 0 to 1%. Saleem et al. [21] tested pull-out specimens of #10 and #22 rebar with 8*db*, 10*db*, 12*db*, and 18*db* (only for #22) embedment lengths and cover of 0.4*db* and 0.2*db*, respectively. They used ultra high strength concrete having $f'_c = 174$ MPa for specimens with #22 rebar and 18*db* embedment length and $f'_c = 166$ MPa for all other specimens. Their results showed that the development lengths of #10 and #22 rebar were 12*db* and 18*db*, respectively. Fehling et al. [20] performed pullout tests on 12 mm diameter ribbed bar embedded in UHPC having V_f = 1.5% and f'_c = 170 MPa. Embedment length and concrete cover (varying from 1*db* to 2.5*db*) were the parameters in their investigation. The major concrete failure modes observed during the tests were cone failure, splitting, and V-type splitting failure. They concluded that a concrete cone failure had little or no residual stress at 7 mm slip. This failure mode was rather brittle and should be avoided. Splitting failure and V splitting failure were more ductile because the fibers were activated and acted as confinement. Yuan and Graybeal [22] conducted direct tension pullout tests of deformed reinforcing bar (lap spliced) embedded in UHPC at 1 day or 7 days after casting (f'_c = 135 MPa at 7 days after casting). The primary parameters in their investigation included the embedment length of reinforcing steel, concrete side cover, bar spacing, compressive strength of UHPC, and type and size of deformed bar. They observed that the bond strength increased with the increase in the embedment length of the bar, the concrete side cover, and the compressive strength of UHPC, respectively, while it decreased with the increase in bar diameter and spacing. They also found out that the bond strength was higher in case of high strength bars that did not yield before bond failure. Lagier et al. [23] investigated the influence of fiber content (V_f) on the bond strength of tension lap splices. They noticed that an increase in fiber content delayed the onset and propagation of first macro-cracks in lap splice leading to an increased bond strength. They further reported that for a given splice length of 10*db*, the ultimate bond stress increased by 29% and 53% due to an increase in V_f from 1% to 2% and 4%, respectively. Holschemacher et al. [13] assessed the bond behavior of conventional as well as 'deep-ribbed' rebar in ultra high strength concrete (UHSC) using pull-out specimens. The parameters used in their experiments included rebar diameter, reinforcement type, surface geometry of the rebar, the concrete cover size, and the loading rate. They reported that UHSC having crushed aggregates with a maximum grain size of 5 mm showed no negative effect with respect to splitting or bond stress. UHSC with 'deep-ribbed' rebar showed better ductility compared to UHSC with conventional rebar. They also observed that the faster the loading rate, the higher the bond stress values and the larger the displacement at maximum bond stress.

Many other researchers have investigated the influence of different parameters such as embedment length of rebar, diameter and type of rebar, concrete strength, and concrete cover on the bond behavior between rebar and UHPC [16,24]. However, research on the effect of fiber orientation and fiber content of UHPC on the bond stress has been very limited [17,25]. Since number of fibers and their orientation influence the crack bridging effort in UHPC [26,27], it is expected that those two parameters would also have an impact on bond behavior between rebar and UHPC, especially at low concrete cover. The goal of this research was to inves-