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Bond strength of tension lap splice specimens in UHPFRC

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HIGHLIGHTS

- Study of bond splitting strength of splice joint with UHPFRC under direct tension.
- Effect of fibre contents in UHPFRC, splice length, bar diameter were investigated.
- With UHPFRC, splice length can be reduced by almost 3 times the design code required.
- Significant increase in bond strength was noted by increasing the fibre content.
- No significant effect of bar diameter between 25 mm and 35 mm on bond strength was noted.

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ABSTRACT

Outstanding tensile properties of ultra-high performance fibre reinforced concrete (UHPFRC) initiate innovative applications that take advantage of the bond improvement with reinforcement (precast element connections, seismic strengthening of deficient lap splices, etc.). Tests on lap splice specimens under direct tension were performed to investigate the influence of UHPFRC fibre content on bond strength. Three fibre contents (V_f) were examined with large reinforcing bar diameter (d_b) and multiple splice lengths. According to strain hardening response of UHPFRC under direct tension, results show a considerable improvement of bond performance and splitting crack control. For UHPFRC mix with V_f = 4% per volume, a splice length of 12 d_b was found sufficient to achieve yielding of 400 MPa reinforcement; with 10 d_b length a bond stress around 10 MPa is reached. The contribution of the fibres was clearly highlighted through this experimental study, a strong relationship between the bond performance and both the maximum tensile strength and strain ductility of UHPFRC was noted.

1. Introduction

The proper behaviour of any reinforced concrete elements is guaranteed by the bond performance between concrete and reinforcing bars. In many reinforced concrete elements, anchorages and lap splices of deformed bars are located in zones with little concrete confinement and concrete cover typically inferior to twice bar diameter (<2 d_b). Splitting of concrete may occur when the confinement is small, leading to lap splice failure. As stated by Plizzari [1], concrete splitting makes bond behaviour very sensitive to confinement. Indeed, the role played by splitting cracks in bond failure emphasises the importance of both the tensile properties of concrete cover and the use of confining reinforcement [2]. In a lack of transverse reinforcement, the radial pressure induced by bar ribs is only balanced by the concrete cover strength. The resisting mechanism is provided initially by the tensile properties of the uncracked part of the surrounding concrete and then by the available post-cracking energy associated with the cracking process.

Adding steel fibres in the splice region of a concrete member can greatly increase the bond performance. It has been shown that the increase in bond strength in presence of fibres were even more effective in high-strength concrete [3,4]. Furthermore, the presence of steel fibres not only improves the bond strength, but also delays the formation and propagation of splitting cracks, which makes splitting bond failure more ductile.

The availability of self-compacting ultra-high performance reinforced concrete (UHPFRC) offers new and innovative opportunities for the construction and repair of concrete structures. Although they are recognised and classified according to their compressive strength, UHPFRC are mainly characterised by their outstanding ductile tensile properties [5] and extremely low permeability [6]. UHPFRC exceptional tensile characteristics make them ideal materials to improve the resisting mechanism of the concrete

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surrounding lapped reinforcement by efficiently counteracting the bursting pressure generated by bar ribs and consequently significantly enhancing the bond behaviour and performance.

The first study on the performance assessment of bond in UHPFRC was carried out with the first UHPFRC known as Compact Reinforced Concrete [7]. Direct pull-out bond tests were used, in which one of the two lapped bars had a shorter embedded length. Test results showed that a steel stress of 463 MPa can be developed in the reinforcement for an embedded length of 10.6 d_b, with a large volume fraction of short steel fibres ($V_f = 6\%$), small bar diameter (8 mm) and small concrete cover ($c/d_b = 0.625$). This configuration has provided an equivalent average bond stress of 10.9 MPa. Several studies were then undertaken on the same type of anchorage test with specimens of similar geometry in order to investigate the effect of bar diameter, concrete cover to bar diameter ratio, and amount of transverse reinforcement [8]. A maximum bar diameter of 16 mm was studied. Results globally showed that a full anchorage for high-yield stress deformed bars ($f_y \approx 600$ MPa) can be achieved with an anchorage length between 5 and 10 d_b with the concrete cover and transverse reinforcing bars considered.

An extensive experimental program using pull-out tests was conducted by Kurita [9] with the aim of identifying the basic properties of UHPFRC improving the bond performance with consideration to concrete compressive strength (from 70 to 180 MPa), bar diameter (from 19 to 51 mm), fibre volume fraction (from 0% to 6%) and concrete cover c/d_b (from 2 to 6.1). They observed that the bond strength increased proportionally with concrete compressive strength leading to average bond strength up to 40 MPa for bar diameter of 22 mm. Surprisingly, no outstanding increase of bond strength was noted with a significant increase of fibre content. As for normal concrete, the state of stresses of the concrete in pull out tests fails to capture the effect of UHPFRC tensile properties on bond, confirming that these tests are clearly not suitable to reveal the main contribution of UHPFRC on the bond performance. Recent studies have also observed a maximum bond stress evaluated from pull out test between 40 and 69 MPa [10,11]. Nevertheless, the improvement of bond stress obtained with the increase of fibre dosage from 0% to 1% or 1.5% varied significantly between studies. A study on modified direct pull out test were carried out by Chao [12], with a relatively large concrete confinement equal to $c/d_b = 2.5$. Two volumes fraction of fibres with five types of fibres were selected. Test set-up was designed to obtain splitting failure through UHPFRC concrete cover before bar pull out. All specimens showed significant bond strength enhancement and crack control. The maximum bond strength was 11.3 MPa, much lower than previous values obtained in the aforementioned studies. Moreover it was found that the confining action provided by UHPFRC with 2% of square twisted steel fibres is more pronounced in comparison to stirrups for an equivalent amount of reinforcement.

Some studies investigated at the structural level different innovative applications that take advantage of UHPFRC improvement on bond performance. It has been shown that the use of UHPFRC in the lap splice region allowed to: (1) strengthen seismically existing bridge piers with poor detailing at their bottom [13–19], (2) significantly reduce the joint lengths between precast-slab lengths for building [8,20] and bridges construction [21,22], (3) create an alternative proposal for moment-resisting frames (beam-column) in precast building with innovative joint connection [23].

With such a wide functionality and opportunity offered by UHPFRC joints, extensive studies on the bond behaviour between UHPFRC and steel reinforcement are still limited. A large range of commercialised UHPFRC is now available. However, no study on lap splice specimen under tension with the UHPFRC has been undertaken to examine the influence of its tensile properties on the bond performance of the joint. In addition, the studies on an alternative connection between precast elements [8,21,22] were limited to small bar diameters ($d_b \leqslant 20$ mm). This paper presents the results of an investigation on the behaviour of tensile lap splice specimens with different UHPFRC mixes, on long embedded length and low confinement. The project aimed to provide average bond strength values for design.

The role played by splitting cracks in bond failure emphasises the importance of tensile properties of concrete and their high fracture energy. Many recent studies have shown a considerable improvement in bond with UHPFRC. However, most of them did not focused on the influence of the fibre volume fraction on bond performance. The need to represent splitting failure over a long anchorage length is needed to clearly understand the contribution of UHPFRC on lap splice. The aim of this study is to properly examine the influence of UHPFRC fibre volume fraction on bond strength through experimental conditions close to actual structural applications, considering large bar diameters and a splice test system under direct tension. In order to isolate the contribution of UHPFRC tensile characteristics on bond performance, no transverse reinforcement was provided.

2. Experimental investigation

2.1. Test specimens and test parameters

Test specimens selected in this project consisted of two pairs of spliced bars cast into an UHPFRC prism without transverse reinforcement. Direct tensile forces were applied on spliced bars inducing tensile stresses in the concrete prism (Fig. 1). Several studies [24–29] have shown the potential of this configuration, allowing both to study the bond strength of full scale lap splice without performing large beam splice specimen, and providing detailed information on the local bond behaviour with the surrounding concrete in tension. Experimental investigations on normal and high strength concretes reported that the maximum bond strength

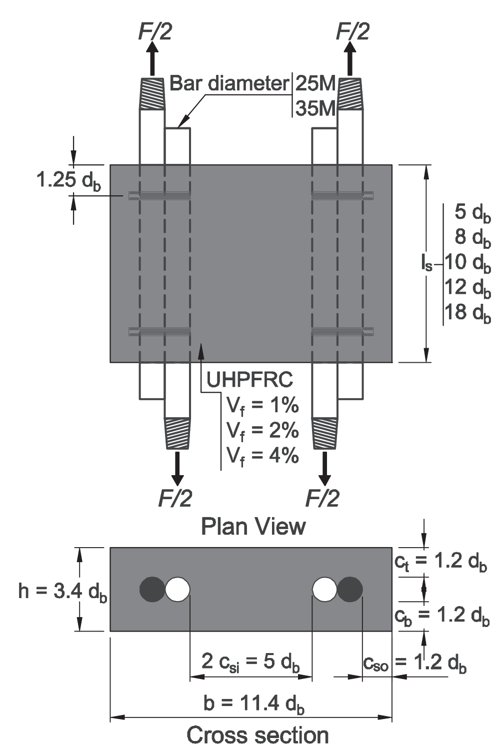

Fig. 1. Details of test specimen, elevation view, section detail.