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Strengthening of reinforced concrete beams using ultra high performance fibre reinforced concrete (UHPFRC)

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ABSTRACT

In this study the efficiency of the use of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) for the strengthening of existing Reinforced Concrete (RC) beams has been investigated. Experimental work has been conducted to determine UHPFRC material properties. Dog-bone shaped specimens have been tested under direct tensile loading, and standard cubes have been tested in compression. These results have been used for the development of a numerical model using Finite Element Method. The reliability of the numerical model has been validated using further experimental results of UHPFRC layers tested under flexural loading. Further numerical study has been conducted on full-scale beams strengthened with UHPFRC layers and jackets, and these results were compared to respective results of beams strengthened with conventional RC layers and with combination of UHPFRC and steel reinforcing bars. Superior performance was observed for strengthened beams with UHPFRC three side jackets, and the efficiency of this technique was highlighted by comparisons with other strengthening techniques.

1. Introduction

A novel technique used to improve the performance of existing structural elements is the application of additional Ultra High Performance Fibre Reinforced Concrete (UHPFRC) layers or jackets in connection to the existing elements. The efficiency of this technique has not been adequately studied, and there are not any published studies on the evaluation of this method with comparisons to other traditional strengthening methods such as the use of Reinforced Concrete (RC) layers and jackets.

The technique of strengthening using additional RC layers and jackets is one of the most commonly used techniques in seismic areas. There are several published experimental and theoretical studies on beams and columns strengthened with conventional concrete [1–15]. A crucial parameter in this technique, which can considerably affect the durability and the performance of the strengthened structures, is the concrete shrinkage strain of the additional layers/jackets. Additional stresses are induced in strengthened elements, and cracking of the new layer and/or debonding may occur [8–15]. The use of UHPFRC could potentially improve both durability and resistance due to its superior mechanical properties.

This study is focused on the addition of UHPFRC layers or jackets to existing RC beams. UHPFRC is a novel material with superior strength and energy absorption. There are several published studies on UHPFRC and the mechanical properties of this material have been studied extensively [16–21]. The percentage of the steel fibres is one of the most crucial parameters affecting the flexural strength and the ductility of UHPFRC elements. According to published experimental studies [16,17], increment of the steel fibres amount, results to an increment of the flexural strength, while the ductility is reduced. The effect of fibres' orientation and distribution in the mix was investigated by Kang and Kim [18]. According to this study [18], fibres' orientation and distribution has negligible effect in the pre-cracking behaviour while in the post-cracking phase, this considerably affects the material properties. Experimental test methods appropriate for the evaluation of the mechanical properties of UHPFRC were proposed by Hassan et al. [19]. A detailed investigation on the assessment of the performance of UHPFRC was presented by Toledo et al. [20], and the development of the mechanical properties of UHPFRC with the time was extensively studied by Habel et al. [21]. The direct tensile behaviour of UHPFRC was examined by Kang et al. [16], and tri-linear tensile fracture model with softening phase was proposed via an inverse analysis. An inverse finite element analysis method was also proposed by Neocleous et al. [22] for deriving the tensile characteristics of Steel Fibre Reinforced Concrete (SFRC). The effect

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of fibre distribution on UHPFRC was highlighted in Ferrara et al. [23]. In this study the effect of different fibre orientations was examined. For this reason, slabs with the same size but different flowing direction were cast. From these slabs, beam specimens were cut with their axis parallel and perpendicular to the flow direction. From the results it was evident that the orientation of the fibres considerably affects the mechanical performance of fibre reinforced cementitious composites [23].

The findings presented in the previous studies are mostly focused on the mechanical properties of UHPFRC, and there are other published studies on strengthening applications [24–31]. Farhat et al. [24] examined beams strengthened with UHPFRC strips. Epoxy adhesive was used for the bonding between UHPFRC and the initial beam. In this study [24], UHPFRC prevented shear failure of the beams and the failure load was increased up to 86%. Brühwiler and Denarie [25] and Brühwiler [26] studied the application of UHPFRC for the rehabilitation of crash barrier wall of highway bridge, bridge pier, and industrial floors, and the efficiency of this method for cast in-situ and prefabrication, using standard equipment for concrete manufacturing, was highlighted. The application of UHPFRC for the repair and strengthening of beam-column joints was investigated by Beschi et al. [29] and remarkable bearing capacity increment was observed [29]. Combination of UHPFRC with reinforcing steel bars for the rehabilitation of existing concrete elements was examined by Habel et al. [27] and this technique was found to be quite promising, since the existing structures were efficiently strengthened and their resistance and their ultimate moment were considerably increased [27]. An analytical model for elements strengthened with combined UHPFRC and steel bars was proposed by Noshiravani and Brühwiler [28] together with a simplified formulation for the shear resistance of the composite members [28]. Magri et al. [30] investigated the combination of UHPFRC with Textile Reinforced Mortar (TRM) and increment of maximum load capacity and ductility of the examined specimens was observed [30].

However, until now, there are not any published studies on three sides jacketing with UHPFRC, and there are not any direct comparisons of the use of UHPFRC layers or jackets with traditional strengthening techniques. The main aim of this paper is to investigate the effectiveness of the addition of UHPFRC layers or jackets to RC beams and to conduct a critical comparison of the effectiveness of this novel technique with traditional strengthening methods using RC layers. In this paper, a numerical investigation is presented first (Section 2) on initial, prior to strengthening, RC beams. Experimental work was conducted to determine the actual material characteristics in tension and compression and, using these data, a numerical model was developed for the simulation of UHPFRC. The accuracy of the model was further validated with flexural tests on UHPFRC layers (Section 3). An extensive numerical investigation was conducted on beams strengthened with layers and jackets (Section 4). The performance of these specimens was compared to respective results of elements strengthened with additional RC layers, and the superior performance of beams with three side UHPFRC jacket was highlighted (Section 5).

2. Reinforced concrete beams prior to strengthening: Numerical modelling and experimental validation

The Initial, prior to strengthening, Beam (IB) examined in this study is based on a previous experimental program [7]. Initial beam's cross sectional dimensions were 150 mm by 250 mm and the length was equal to 2200 mm. The reinforcement consisted of two bars with a diameter of 12 mm (2H12) made of steel with a characteristic yielding stress value of 500 MPa in the tensile side with a cover of 25 mm (Fig. 1a). The characteristic cylinder concrete compressive strength of the initial beam at 28 days was found equal to 39.5 MPa. The effective span was equal to 2000 mm and the beam was tested under a four-point bending loading with an imposed deflection rate of 0.008 mm/s. The distance between the two loading points in the middle of the span was equal to 500 mm (Fig. 1b).

For the finite element analysis, ATENA software [32] was used. Concrete was simulated with an eight-node element, with nonlinear behaviour and softening branches in both tension and compression using SBETA constitutive model [32]. The ascending compressive branch of this model is based on the formula

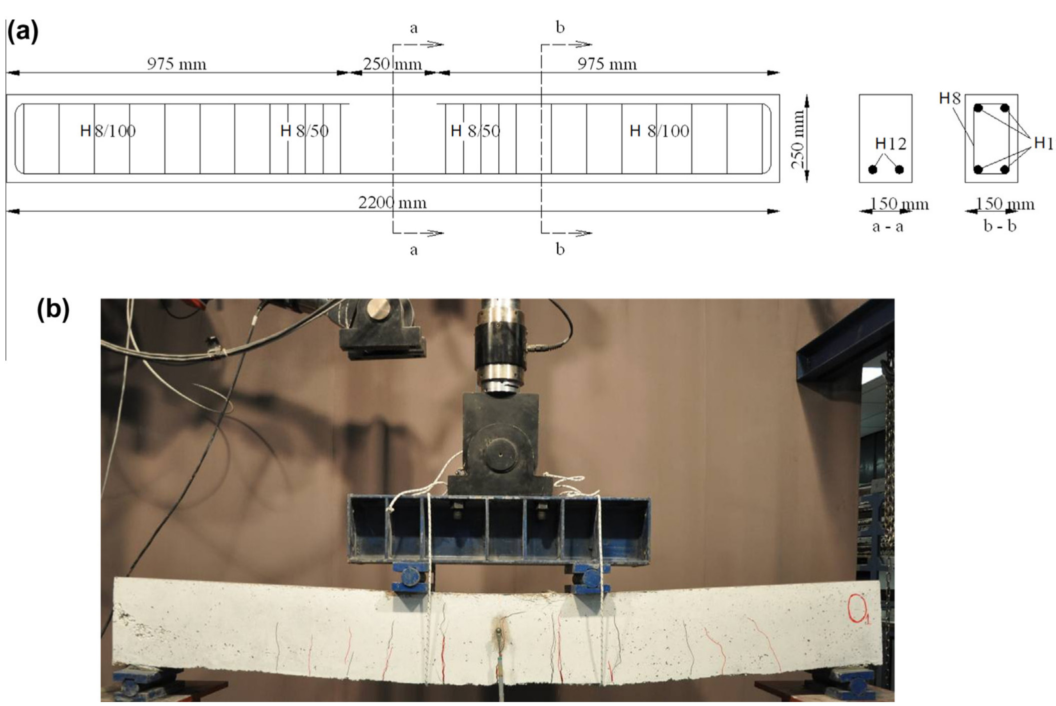

Fig. 1. (a) Geometry and (b) testing setup of IB [7].