Construction and Building Materials 186 (2018) 351–366

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental and numerical study of the performance of ultra high performance fiber reinforced concrete for the flexural strengthening of full scale reinforced concrete members

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HIGHLIGHTS

- The UHPFRC layers produce a large increase in the stiffness of the RC beams.
- Steel bars to the UHPFRC layer increase dramatically the load carrying capacity.
- Effective bonding between UHPFRC and concrete was identified.
- The amount of reinforcement affects significaly the performance of the layers.

ARTICLE INFO

Article history:
Received 30 July 2017
Received in revised form 16 July 2018
Accepted 17 July 2018

Keywords:
UHPFRC
Full Scale
Strengthening
UHPFRC to concrete interfaces
Push-off tests
Finite element analysis

ABSTRACT

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a cementitious material with enhanced mechanical characteristics. The superior mechanical properties of UHPFRC compared to conventional concrete, as well as the ease of preparation and application, make the use of this material attractive for strengthening applications. In the present study, an extensive experimental investigation on full scale Reinforced Concrete (RC) beams strengthened with UHPFRC layers has been conducted. Additional UHPFRC layers with and without steel bars have been added to the RC beams and the effectiveness of the examined technique has been examined through flexural tests. An additional investigation has been conducted on the interface characteristics between UHPFRC and concrete through push-off tests. Finally, finite element analysis has been conducted and crucial parameters of the examined technique have been investigated. The results of the present study indicated that the strengthening with UHPFRC layers is a well promising technique, as in all the examined cases the performance of the strengthened elements was improved. Also, a good interface connection between UHPFRC and concrete was identified, with low measurements of slips at the interface.

1. Introduction

Most of the new Reinforced Concrete (RC) structures which are built nowadays meet the criteria for safe building design. Nevertheless, we cannot claim the same for structures built in the past. These old structures make up the majority of the total number of existing structures today. The majority of these structures have been designed either without any regulations, or based on old code provisions which have been proved to be structurally deficient. Consequently, the loading carrying capacity system of these structures need to be upgraded. The present research is focused on the strengthening of RC elements using UHPFRC layers.

To date, there are several published studies on the mechanical properties of UHPFRC. Kang et al. [1] and Yoo et al. [2] examined the effect of fiber content on the flexural strength of UHPFRC, and it was found that both the flexural strength and the structural ductility increased at increasingly fiber content. The effect fiber content on the tensile characteristics of UHPFRC was investigated by Paschalis and Lampropoulos [3] and for the different fiber contents, different stress-strain models were proposed. Also, in this study, the effect of curing regime on the tensile characteristics of UHPFRC was investigated and the optimum curing period was proposed. Neocleous et al. [4], used an inverse finite element analysis

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https://doi.org/10.1016/j.conbuildmat.2018.07.123
0950-0618/

method to derive the tensile characteristics of Steel Fiber Reinforced Concrete (SFRC), while Nicolaides et al. [5] developed an optimum mixture for Ultra High Performance Cementitious Composites using components available in Cyprus. The fiber distribution is an important parameter affecting the performance of UHPFRC and this was highlighted by Ferrara et al. [6]. The study of the performance of UHPFRC in earthquake prone areas is of high importance. Paschalis and Lampropoulos [7] investigated the response of UHPFRC under cyclic loading for different fiber contents, and a constitutive model which can predict the hysteretic characteristics of UHPFRC under cyclic loading was proposed. The unique properties of UHPFRC have also been extensively investigated in numerous previous studies [8–14].

The use of UHPFRC for repair and strengthening applications has been investigated in a limited number of experimental, analytical and numerical studies. Habel et al. [15] conducted an extensive analytical investigation on the performance of composite UHPFRC-concrete elements under the assumption of perfect bond between the old and the new element where the effectiveness of this technique was highlighted. Numerical study has been presented by Lampropoulos et al. [16] where the structural performance of beams strengthened with UHPFRC layers has been studied through Finite Element Analysis and comparisons with conventional methods have also been presented. Bruhwiler and Denarie [17] presented a realistic application of the UHPFRC for the rehabilitation of RC structures, such as a road bridge, a bridge pier and an industrial floor, and the benefits of the application of UHPFRC for the rehabilitation of concrete structures were highlighted. Safdar et al. [18], investigated the application of UHPFRC as a repair material and the flexural response of composite UHPFRC-RC elements was examined. The experimental results indicated that the use of UHPFRC layers increased the stiffness and the resistance of the elements. Talayeh and Bruhwiler [19] investigated the performance of reinforced UHPFRC beams subjected to bending and shear in a cantilever beam setup and they found that most of the specimens failed due to a flexural failure at a force of 2–2.8 higher than the resistance of the control specimens.

The flexural strengthening of RC members using RC layers is a popular and reliable technique. The use of the UHPFRC for the same purposes is a well promising technique which can increase the performance of the technique. However, further research on this topic is consider necessary in order to investigate all these crucial parameters concern the examined technique. According to Tsioulou et al. [20], in case of RC elements strengthened with additional concrete layers, one of the most crucial parameters is the behaviour of the interface between the old and the new concrete since inadequate bonding may lead to premature failure of the strengthened elements. The behavior of the interface between the existing RC elements and the new UHPFRC layers is a crucial topic which has not been studied to date and needs investigation. The present study aims to investigate in depth the performance of UHPFRC for the strengthening of existing RC members and to provide useful information to both the scientific community and practitioners through an extensive experimental and numerical investigation. Crucial parameters which have never been investigated before, such as the interface characteristics between UHPFRC and concrete, the effect of layer depth and steel ratio on the performance of the examined technique, are investigated in the present study. Also, in the present study, suggestions for the application of the examined technique in real practice are presented.

The experimental part of the present study is focused on the flexural strengthening of RC beams using different strengthening configurations. More specifically, the performance of full scale RC beams strengthened with additional UHPFRC layers was investigated. UHPFRC layers with and without steel bars were cast to the tensile side of beams and the specimens were tested under 4 point flexural loading. During the testing, measurements of the slip at the interface between the UHPFRC layer and the existing RC beams were recorded and the results were compared with available data in the literature for concrete to concrete interfaces. Additionally, push-off tests were conducted in order to evaluate the characteristics of conventional concrete to UHPFRC interfaces. Finally, finite element analysis was conducted and crucial parameters of the examined technique were investigated numerically.

2. Experimental program

2.1. Experimental program for the strengthening of existing RC beams and the push-off tests

In the present study, six identical RC beams were constructed and used for the evaluation of the performance of RC beams strengthened with UHPFRC layers. Two RC beams were used as control beams for the evaluation of the performance of existing beams prior to strengthening, while four beams were strengthened with layers at the tensile side. In case of the strengthened beams, the additional UHPFRC layers were applied two months after the casting of the initial beams and the strengthened beams were tested over four months. For this investigation, two beams were strengthened with UHPFRC layers and two beams were strengthened with UHPFRC layers and steel bars (Table 1).

The geometry and the reinforcement of the initial beams are presented in Fig. 1. As shown in this figure, the existing RC beams were reinforced at the tensile side with two longitudinal ribbed steel bars with a diameter of 12 and a length of 2150 mm. On the contrary, the reinforcement at the compressive side of beams was used to support the stirrups. In order to avoid shear failure of the beams, shear reinforcement, according to Eurocode 2 [21] was placed along the whole length of the beams. More specifically, stirrups with a diameter of 10 mm and a spacing of 150 mm were placed as shear reinforcement. Plastic spacers were used in order to ensure the required concrete cover of 25 mm of the reinforcement. The constructed UHPFRC layers had a depth of 50 mm, a breadth of 150 mm and were cast along the whole length of the tensile side of the beams (Fig. 2). Two ribbed steel bars with a diameter of 10 mm, a length of 2150 mm and a concrete cover of 25 mm were used as a reinforcement of the UHPFRC layers. All the steel bars of the present investigation were grade B 500C.

Finally, for the push-off tests two concrete cubes with a side length of 100 mm were prepared first and placed in the moulds, and later on, the UHPFRC cube was cast. The geometry of the specimens is presented in Fig. 3. The specimens were tested two months after casting.

2.2. Preparation of the materials

For the preparation of the examined beams, the reinforcement was assembled first, and then it was placed in the moulds. Once the reinforcement was ready, the concrete was poured in the

Table 1
Examined Specimens.

Beam	Strengthening Technique
P1	Control beam
P2	Control beam
U1	UHPFRC layer
U2	UHPFRC layer
UB1	UHPFRC layer and bars
UB2	UHPFRC layer and bars