Construction and Building Materials 155 (2017) 45–55

Contents lists available at ScienceDirect

Construction and Building Materials

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

Flexural strengthening of RC beams using UHPFRC laminates: Bonding techniques and rebar addition

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HIGHLIGHTS

- RC specimens strengthened with UHPFRC laminates were tested in the laboratory.
- Two different bonding methods: gluing with epoxy and mechanical anchoring were compared.
- Load carrying capacity of the strengthened RC beams was improved.

ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form 9 August 2017
Accepted 10 August 2017

Keywords:
RC beams
Flexural strengthening
UHPC
Bonding techniques
Anchorage

ABSTRACT

Ultra-high performance fiber-reinforced concrete (UHPFRC) is a cementitious composite with outstanding mechanical and durability properties. Accordingly, this study focuses on the behavior of reinforced concrete (RC) beams that were strengthened with UHPFRC laminates. Firstly, a preliminary study was carried out at material scale to evaluate the effect of fiber volume on the mechanical properties of UHPFRC, and to select suitable fiber reinforcement ratio for laminate production. In the second step, real-sized laminates were tested to define the bare properties of full-scaled laminate and observe the size effect according to material tests before applying them as a strengthening material. Thereafter, in the final step, flexurally deficient RC beams were strengthened with 30 mm thick UHPFRC laminates using two different bonding methods: gluing with epoxy and mechanical anchoring. In addition, longitudinal reinforcing bars were added into the laminates and their effectiveness was evaluated to improve the success of the applied methods. The results showed that UHPFRC laminate usage, especially in the case of anchorage, is an effective technique to improve the load carrying capacity of RC beams. Moreover, it was observed that adding reinforcing bars into the laminates could improve the efficiency of the applied method remarkably.

1. Introduction

In order to keep structures operational, deficient structures or structure parts have to be strengthened. Reinforced concrete jacketing, epoxy bonding steel plates, external post-tensioning, and externally bonding carbon fiber-reinforced polymer (CFRP) are some of the preferred methods for strengthening [1–9]. These methods, however, have several disadvantages such as the difficulty of installation, the heaviness of applied strengthening material, disturbing the household during application, and some durability problems (corrosion risk, lack of fire resistance). Hence, researchers are in search of new techniques and materials, which are easy to apply and sustainable for strengthening.

Recent developments in construction materials technology have yielded new cementitious composites such as ultra-high-performance fiber reinforced concrete (UHPFRC). An intense matrix, and optimized fiber and aggregate phases are essential to reach extraordinary performance much higher than traditional concrete. In this respect, the dosage of steel fiber, which should be optimized for practical application from a cost perspective, can be regarded as a key parameter to increase the mechanical performance of UHPFRC. It was reported that compressive strength and corresponding strain as well as elastic modulus were improved as the fiber volume increased when the fiber volume was studied up to 5% [10]. Although the mechanical performance of UHPFRC is greatly improved by increasing steel fibers, it was revealed that 2.5% was the maximum volume of steel micro-fibers that could be added to the mixture to meet the threshold value of self-compacting criteria [11]. Previous studies have generally pointed

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http://dx.doi.org/10.1016/j.conbuildmat.2017.08.056

out the inclusion of 2% or more steel micro-fiber to achieve a compressive higher than 150 MPa by means of standard curing depending on the design of surrounding cementitious matrix [12,13].

After observing the high performance of UHPFRC, it has come into widespread use for construction of modern structures not only thanks to its strength, but also to its high durability. Besides its usage as structural members [14–19], its use as strengthening or repair material has recently attracted the attention of researchers [20–24].

Prem and Murthy studied strengthening of RC beams by use of UHPFRC overlays [20]. In the study, RC beams with various reinforcement ratios strengthened with UHPFRC overlays of the thickness of 10, 15 and 20 mm. Researchers reported that the retrofitted beams acted monolithically under bending loads and were able to regain their origin flexural capacity in case of 10 mm overlay usage. It was reported that composite beams failed monolithically with no debonding and strength enhancement up to 30%.

Al-Osta et al. studied the strengthening of RC beams by UHPFRC jacketing using precast panels attached by epoxy or fresh cast in a mould [21]. The results showed that three sided jacketing resulted in high capacity enhancement but reduced the ductility. Moreover, it was reported that two-sided and bottom jacketing yielded strength enhancement with high ductility.

Mohammed et al. investigated the possibility of using UHPFRC to strengthen reinforced concrete beams under torsion [22]. The results revealed that UHPFRC could be used as an effective external torsional reinforcement for RC beams. The behavior of strengthened RC beams was better than that of the control beams. Moreover, it was reported that the use of UHPFRC had effect in delaying the growth of crack formation.

Meda et al. investigated the possibility of repairing and strengthening corrosion damaged columns with UHPFRC jacketing [23]. In the experimental study, corrosion damaged RC columns were obtained with an accelerated process through electrolytic cells. A jacket having a thickness of 40 mm was cast with a mixture having a fiber volume of 1.2%, a maximum aggregate size of 1.3 mm and water/binder ratio equal to 0.17 by weight. Researchers reported that it was possible to increase the bearing capacity of the column with corroded rebars, reaching a maximum strength greater than the one of the undamaged element. Abdullah et al. reviewed the properties of UHPFRC to be utilized as repair material for a fire-damaged concrete structure based on previous researches [24]. Researchers emphasize that UHPFRC is suitable to be used as a repair material for fire-damaged structures, and this application indicates strengthening of the repaired structure.

Previous studies have generally dealt with the strengthening of RC beams by gluing UHPFRC laminates or fresh casting of UHPFRC without steel rebar. However, adding reinforcement in the UHPFRC layer is the most efficient way to increase the effect of UHPFRC laminate usage [25]. Moreover, use of mechanical anchorage as an alternative bonding method for UHPFRC laminates, has not been elucidated up to now. In the scope of the study, fiber volume fractions were studied at material scale to select a fiber volume for laminate production. In addition, real sized laminates were tested to clarify their pure behavior under flexural loads. At the final stage, UHPFRC laminates were used as a strengthening material with different bonding methods and with/without internal longitudinal reinforcements. As a result, this study mainly aims to compare the performance of bonding methods (gluing with epoxy or mechanical anchoring) and to evaluate the use of longitudinal reinforcing bars in UHPFRC along with these bonding methods.

2. Experimental program

This paper presents the results of a three-step experimental program. In the first step, material tests were conducted to determine the mix proportions of UHPFRC that can be used for strengthening RC beams when applied as a full scaled laminate. In the second step, real sized laminates were tested to define the bare properties of full-scaled laminates. In the final step, RC beams were strengthened with full scaled UHPFRC laminates and then tested to determine their strength and behavior contribution according to the application.

2.1. Production of UHPFRC

In order to obtain a high-strength matrix phase, which has an adequate workability when high-volume of fibers are used, several preliminary tests were performed. Initially, a suitable matrix was chosen to consider the required fiber volume for producing UHPFRC laminates. After this stage, steel micro-fibers were used to determine the effect of fiber volume on the fresh state and ultimate mechanical performance of UHPFRC. In the scope of the study, a compressive strength of 200 MPa and a flexural strength of 40 MPa were targeted. The fiber volume of UHPFRC was determined to meet these strength values.

2.1.1. Materials and methods

The aggregate skeleton of UHPFRC was composed of 0–0.4 mm and 0.5–1 mm quartz aggregates. Portland cement (CEM I 42.5R) and silica fume (SF) were used as binder materials. A new generation polycarboxylate based superplasticizer (SP) was used in this study. A straight type, brass coated steel micro-fiber with a 13 mm length, 0.20 mm diameter and an aspect ratio of 65 was used as reinforcing material. The direct-tensile strength of the fiber was 2750 MPa.

Mix designs of UHPFRCs, which have extremely low water to binder ratio (0.16), are presented in Table 1. Steel micro-fibers were used at four volume fractions (0%, 1%, 2%, 3%, and 4% by volume). The UHPFRC mixtures were composed of 68% paste in order to ensure enough workability at high fiber volumes. SP dosage was kept constant in order to clarify the effect of fiber volume on workability. A special mixing procedure was followed to obtain a homogenous UHPFRC matrix. First of all, binders, aggregates and steel fibers were mixed. Thereafter, the mix water with half of the SP was added to the dry mix. After premixing, the remaining SP was added to the wet mixture. The final mixing was applied for 10 min at high-speed rotation. The mixtures were poured into prismatic moulds with dimensions of $40 \times 40 \times 160\ mm^3$. The UHPFRC mixtures were poured into the moulds in three layers, and each layer was compacted by 25 strokes of a steel rod during external vibration.

The mortar flow test was carried out in accordance with ASTM C1437 [26]. The mechanical performance of the mixtures was evaluated after steam or 28-day standard curing. As for steam curing, heating period was started after the 6-h delay period. The temperature of the cabin reached 100 °C within six hours and the specimens were kept in this temperature for twelve hours. A gradual cooling period was applied at the end of the curing period in order to avoid thermal cracking. The flexural and compressive strength tests were performed according to ASTM C348 [27] and ASTM C349 [28], respectively. All flexural strengths and load-deflection graphs were obtained by carrying out three-point bending tests by an electromechanic closed-loop testing system (loading rate, 0.5 mm/min). The mid-span deflection was measured using an encoder. After curing (standard or steam), the specimens were loaded from their mid-span, and the clear distance between simple supports was 130 mm. Compressive strength test was applied on the two pieces left from the flexural test. Five specimens ($40 \times 40 \times 160\ mm^3$) for flexural strength and ten specimens for compressive strength were tested for each mixture.

2.1.2. Results and discussion

2.1.2.1. Fresh state performance. Preliminary tests demonstrated that a high paste volume of 68% was needed in order to cope with locking effect of the steel micro-fibers. A flow diameter of about 150 mm was aimed for the neat mixture without fiber, and a constant SP dosage was used for each fiber volume. As a result, steel micro-fiber volume of 1% increased the flow diameter by increasing shear force during mixing, whereas higher volumes of fibers caused a remarkable decrease (Fig. 1). This decrement can be attributed to an additional inner friction due to locking effect of the fibers and high viscosity of the mixtures with an extremely low W/C ratio. Above all, it was possible to easily cast the fresh mixtures into the moulds by means of vibration and hand operations. However, it was not possible to finish the fresh UHPFRC surface properly at a 4% of fiber volume.

2.1.2.2. Mechanical performance. Flexural load versus mid-span deflection curves of the mixtures having different fiber volumes, which are plotted up to 6 mm deflection, are presented in Fig. 2. Fiber volume influenced the behavior of the mixtures markedly. Load carrying capacity and ultimate deflection values of the neat mortar (without fibers) have increased significantly by fibers inclusion. All fiber volumes caused a deflection-hardening behavior that generates a higher load carrying capacity after the first cracking. The high load carrying capacity after the peak load indicates an enhanced toughness [29,30]. Higher peak load and descending tail of the curve caused greater toughness compared to neat UHPFRC without fiber reinforcement. In case of standard curing, the peak loads drastically increased by the fiber volume fractions up to 2%, yet, higher volumes of fiber enhanced the performance slightly. Steam curing enhanced the peak loads of the mixtures having 3% or more fiber volume in comparison with that of standard cured. Moreover, performance differences depending on fiber volume fraction became prominent in the case of