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Strengthening of Reinforced Concrete Beams with Ultra-high Performance Fiber-Reinforced Concrete in Shear

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Abstract. Ultra-high performance fiber-reinforced concrete (UHPFRC) exhibits high compressive and tensile strength together with outstanding durability. Due to these superior properties, UHPFRC is promising for retrofitting existing reinforced concrete (RC) bridges. While research and on-site applications show the significant improvement of RC structures strengthened with UHPFRC in flexure, information regarding the shear behavior of such UHPFRC composite structures is limited. Therefore, the primary objective of the present study is to investigate the efficiency of UHPFRC in enhancing the shear strength of RC beams. The material properties including the compressive and tensile strength, and shrinkage of UHPFRC are experimentally measured. The shear deficient reference beam (RB) is designed, and UHPFRC is applied on the lateral sides of the RB. Two different bonding techniques to apply UHPFRC are employed: (1) casting fresh UHPFRC in-situ; and (2) gluing precast UHPFRC plates with epoxy resin. The interface properties under each technique are examined. Results demonstrate that compared to RB, strengthened beam (ST) with bonded prefabricated UHPFRC using epoxy resin shows an around 110% and 60% enhancement in strength and ductility, respectively. However, with in-situ casting of UHPFRC, due to restrained shrinkage, the delamination between UHPFRC and concrete beam occurs and a negligible strengthening effect is observed. The findings indicate that the ability of UHPFRC can be fully utilized only provided that the interface strength is sufficient to prevent premature debonding for the hybrid UHPFRC-concrete structure.

Keywords: Ultra-high performance fiber-reinforced concrete (UHPFRC) · Shear behavior · Bonding tech-niques · Interface strength

1 Introduction

Nowadays, shear failure of aging concrete structures is a major concern worldwide due to its unpredictable brittle behaviour and catastrophic consequences. Therefore, repair or strengthening of the shear-deficient reinforced concrete structures is necessary. Apart from traditional strengthening measures, such as steel/ concrete jacketing and external prestressing, the advent of innovative cementitious material (e.g. UHPFRC) provides another promising alternative.

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The use of ultra-high performance fiber-reinforced concrete (UHPFRC) to reinforce the existing RC bridges draws attention in recent years [1]. Unlike normal concrete (NC), UHPFRC is characterized as dense and low-porosity fiber reinforced cementitious materials with high compressive/ tensile strength as well as superior durability [2]. However, high cost and serious environmental impacts resulting from the steel fibers and large cement content in the mix proportion of UHPFRC still limit its large-scale applications [3]. Therefore, rather than fully reconstruction of structures with UHPFRC, partial replacement of deteriorated concrete layers by using UHPFRC is more favourable for industry and government.

Until now, researches are focused on the application of UHPFRC to improve flexural performance of concrete structures [4]. Results show that the bending capacity and deformational ability are significantly increased when UHPFRC is employed. However, with regard to shear behaviour of RC structures reinforced with UHPFRC, extensive studies and in-depth analysis are still limited [5]. A. Sakr et al. [6] applied precast UHPFRC panels using epoxy to improve the shear capacity of RC beams. The influence of bonding configurations and reinforcement ratios in UHPFRC were investigated. Said et al. [7] carried out extensive experiments to study the strengthening efficiency of concrete beams with UHPFRC. Parameters including UHPFRC thickness, strengthening configurations, the volume of steel fibers in UHPFRC, strengthening length of UHPFRC layers, as well as bonding techniques were considered. These studies all found that UHPFRC is an effective method for shear strengthening of concrete structures.

However, to ensure the strengthening efficiency of concrete structures with UHPFRC, one of the most important prerequisites is a good and durable bond at the interface [8]. Thus, extensive research in recent years focused on bond strength tests to evaluate the interfacial performances between UHPFRC and NC [9]. The influence of surface roughness and moisture degree of concrete substrate [10], the strength of repair material [11], the bonding techniques [12] as well as the bond test methods [13] have been examined. It is concluded that compared to NC, UHPFRC could provide better bonding quality due to the presence of steel fibers, which helps to transfer the stress at the interface [8].

Although lots of studies have focused on the quantification of interface strength through bond tests, experimental investigations for shear performance of UHPFRC strengthened concrete structures are lacking. Therefore, the main aim of this work is to experimentally investigate the role of different bonding methods (i.e. casting fresh UHPFRC in-situ vs. bonding precast UHPFRC laminates with epoxy resin), on the shear performance of UHPFRC-RC composite beams. UHPFRC is first tested to characterize its material properties. Then beams without transverse reinforcement are designed and strengthened with 10 mm thick UHPFRC lamellas on lateral sides. Finally, all the beams are tested under three-point configuration to assess the strengthening efficiency with UHPFRC.

2 UHPFRC Materials

The mixture proportion of the developed UHPFRC is presented in Table 1. In order to form dense microstructure, silica fume is added to fill in the pores between cement particles and maximum aggregate size does not exceed 1 mm. In addition, a 2% volume fraction of straight steel fibers with a diameter of 0.16 mm and a length of 6mm is employed in this study.

Table 1. Mixture proportion of UHPFRC (kg/m^3).

CEM I 52.5	Silica fume	Water	S.P	Aggregate (0.125–1 mm)	Fiber
850.5	100	177	42	1113.2	200

2.1 Mechanical Properties

In order to measure the compressive strength of UHPFRC, 40 × 40 × 40 mm^3 cubes are tested. Subsequently, 100 × 100 × 400 mm^3 prisms are prepared for E-modulus measurement, according to NEN-EN 12390. To determine the tensile properties of UHPFRC, direct tension tests are conducted (Fig. 1 (a)).

Measured stress-strain response from the uniaxial tensile test is shown in Fig. 1 (b). It can be seen that after reaching the initial cracking strength (>6 MPa), the pseudo strain-hardening behavior is activated, followed by reaching the peak strength. The average results for compressive strength, modulus of elasticity and peak tensile strength of the UHPFRC, based on at least three samples and all measured after 28 days, are summarized in Table 2. The high variation in tensile capacity for different tested specimens is in line with earlier studies for UHPFRC [14–16], and fiber reinforced material in general is governed by the fiber distribution and orientation, but also affected by the specific testing method [17].

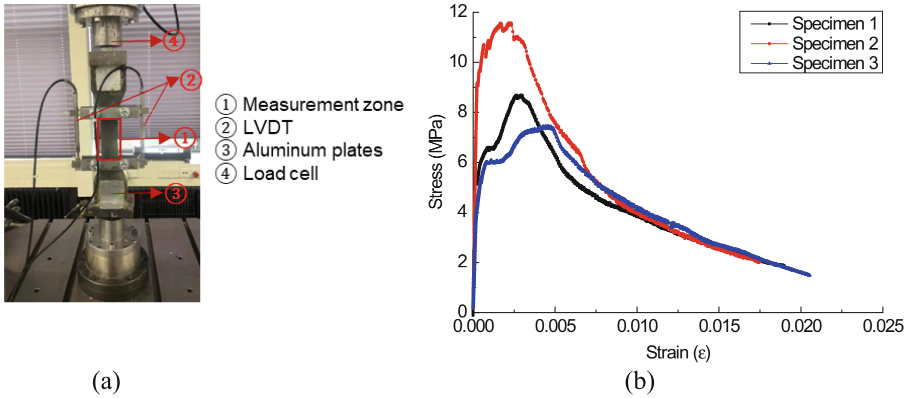

Fig. 1. Experimental set-up (a) and tensile stress-strain behaviour (b) for UHPFRC.

Table 2. Mechanical properties of UHPFRC.

UHPFRC	Cubical compressive strength (MPa)	E-Modulus (GPa)	Peak tensile strength (MPa)
Mean	122.4	45.2	9.2
Standard deviation	5.1	1.1	2.1

2.2 Shrinkage

Due to low water-cement ratio and high amount of binder, UHPFRC has high autogenous shrinkage and is expected to have a higher total shrinkage compared to NC. High shrinkage of UHPFRC might lead to the risk of early age cracking and delamination. Therefore, the free autogenous and total shrinkage of UHPFRC are monitored after unmoulding (at the age of 1 day) with specimens being exposed to controlled curing (temperature of 20 ± 2 °C, and relative humidity of 50%). As shown in Fig. 2, in total, six prisms 40 × 40 × 160 mm^3 are prepared and three of them are sealed to measure the autogenous shrinkage.

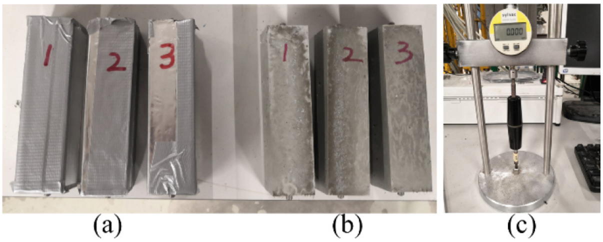

Fig. 2. Specimen and set-up for shrinkage measurement: (a) sealed specimen for autogenous and (b) unsealed specimen for total shrinkage measurement; (c) comparator (accuracy of 0.001 mm).

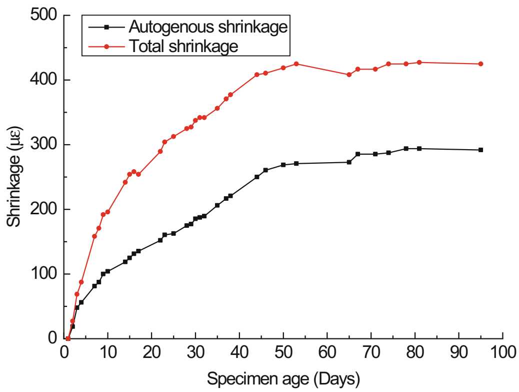

Fig. 3. Average autogenous and drying shrinkage curves of UHPFRC.

Figure 3 shows the average value of autogenous and total shrinkage of UHPFRC. It is observed that autogenous shrinkage occupies a large portion of total shrinkage. However, the total shrinkage of UHPFRC after 90 days is around 400 με, which is nearly similar to that of NC. This is because the initial development of autogenous shrinkage within 24h is not measured [18].

3 Experimental Program

3.1 Specimen Design and Strengthening Technique

Three shear-dominant RC beams with a length of 1400 mm and a rectangular cross section of 100 mm width and 200 mm height are first fabricated. Two longitudinal rebars with a nominal diameter of 16 mm are placed at the bottom side of the RC beams. Moreover, no stirrup is provided in the clear span of the beams to make the specimens fail in shear. The detailed configuration of RC beams is shown in Fig. 4(a).

After curing for more than two months, two of the RC beams are strengthened with UHPFRC using different bonding techniques, namely casting fresh UHPFRC and bonding precast UHPFRC laminates by epoxy resin on the smooth lateral sides of RC beams, as shown in Fig. 4(b). The prefabricated UHPFRC laminates are cured in lab condition for more than one month before the application of epoxy resin. Before casting the UHPFRC layers, the RC beam sides are cleaned with cloth and ethanol to remove the dust. It should be noted that in order to make a better comparison between these two bonding techniques and exclude the influence of additional parameters (e.g. surface roughness), special surface treatments such as water-jetting or sand-blasting, which is generally used for in-situ UHPFRC casting in practice, are not applied. After gluing of UHPFRC laminates, all the strengthened beams are cured in lab conditions.

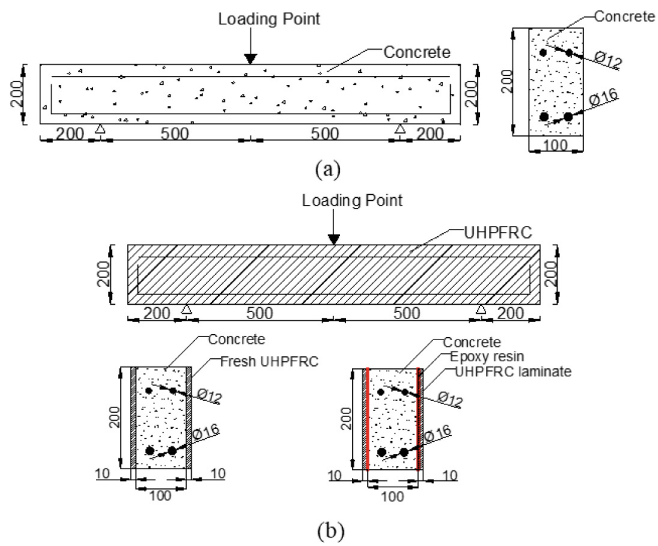

Fig. 4. Specimen configurations: (a) RB beam; (b) ST beam (Unit: mm).

3.2 Measurement Design and Test Setup

Figure 5 shows the test setup. Two different measurement systems are used to obtain deformations: Linear variable differential transducers (LVDTs) and digital image correlation (DIC), which is a non-contact technique for full-field displacement measurement. For RB beam, LVDTs are used to measure the deflection and strain distribution along the height of beam at the mid-span. While for ST beam, LVDTs are attached to obtain mid-span deflection and the interface displacement near the loading points. The deflection could also be recorded and clear visualization of crack pattern could be provided through DIC technique. After test preparation, all beam specimens are tested under three-point bending. Vertical displacement is imposed on top of the beam with a speed of 0.01 mm/sec.

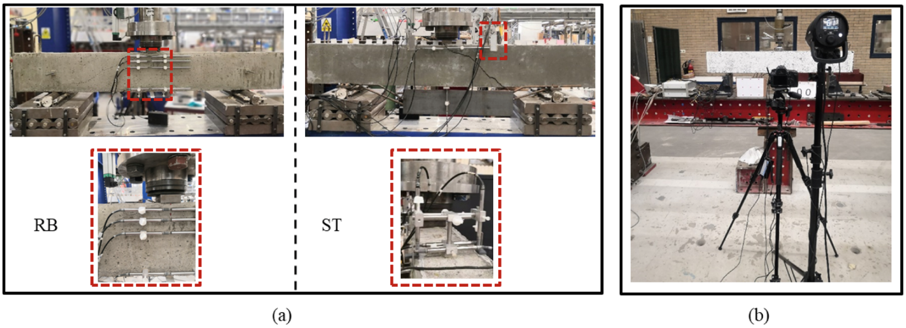

Fig. 5. Measurement system: (a) LVDT configuration, (b) DIC setup.

4 Test Results and Discussion

As shown in Fig. 6, after 14 days of curing in the lab condition, the beam strengthened by in-situ cast UHPFRC seriously delaminates and there is no strengthening efficiency. The delamination might be attributed to stress induced by restrained shrinkage at the interface. Therefore, only the RB beam and ST beam with the epoxy-resin bonding technique are tested.

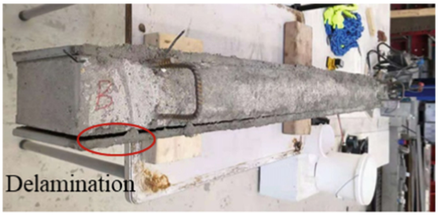

Fig. 6. Interface delamination for cast in-situ strengthened beam.

4.1 Load-Deflection Relationship

Figure 7 shows the force vs. deflection response measured from LVDT and DIC for RB and ST-EB beams respectively and Table 3 summarizes the main experimental results. The DIC results have a deformation resolution of 0.008 mm and major strain resolution of 0.075%. It is observed that for the reference beam the vertical mid-span displacement obtained by DIC analysis agrees well with LVDT measurements. For ST beam, the difference of mid-span deflection between LVDT and DIC occurs mainly due to the incompatible deformation between UHPFRC and concrete. Furthermore, a considerable effect of UHPFRC laminates is observed. By using 10 mm precast UHPFRC bonded on lateral sides of RC beams, both the peak load and ductility significantly increase. The UHPFRC plates enable the beam to achieve an ultimate load of 126 kN and corresponding deflection of 3.94 mm (2.17 times the ultimate capacity and 1.57 times the ductility of unstrengthened beam). While for beams strengthened with same type of normal concrete, as estimated by Eurocode formula [19], the shear capacity improves only around 20% due to an increase of cross-section area. This demonstrates that bonding precast UHPFRC plates with epoxy-resin is a prosperous technique for strengthening shear critical concrete beams. However, this strengthening method is not able to enhance the initial stiffness of RC beams. In contrast, UHPFRC plays a more role in mitigating the stiffness degradation as applied load increases due to high tensile strength and “bridging effect” of steel fibers to limit crack initiations and propagations.

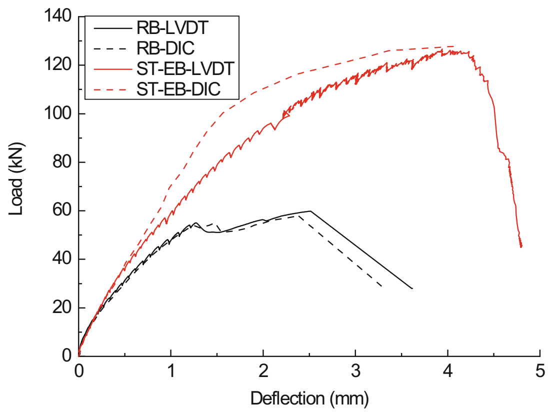

Fig. 7. Load-deflection relationship for test specimens.

4.2 Fracture Pattern and Cracking Behaviour

In order to capture the fracture pattern and damage process, DIC analysis is conducted and principal strain contour in three different cracking stages is plotted in Fig. 8, namely shear crack initiation, peak load and post-peak cracking stages. As depicted in Fig. 8, shear failure is observed for both tested specimens after the formation of main diagonal crack in shear span zone. Before the initiation of shear crack, flexural cracks have

Table 3. Average mechanical properties of UHPFRC.

Beam	Bonding technique	Shear cracking load (V_{cr})/ kN	Peak load (V_u)/ kN	Deflection at peak load Δ/ mm	Failure patterns
RB	-	42	58	2.51	Shear
ST-EB	Epoxy-resin	100	126	3.94	Shear

already developed at the bottom of the specimen. And fewer flexural cracks appeared on the ST-EB specimen. After that, the major shear crack initiates and propagates towards the loading point and support. With the use of 10 mm UHPFRC, the load when the critical shear crack is formed is increased by 138% compared to the RB specimen. As expected, if the thickness of UHPFRC is increased to enable the shear capacity of specimen to exceed its bending resistance, which is governed by the longitudinal reinforcement in tension zone, the failure mode will shift from shear to flexure failure. However, although theoretically the shear capacity will continue to increase with the increase of UHPFRC thickness, an added UHPFRC thickness will pose a challenge to the bond at the interface, as insufficient bond might lead to early delamination in hybrid beams prior to the full exploitation of UHPFRC in shear strengthening [6]. Finally, as the specimens fail, concrete spalling occurs around the loading point area. Subsequently, in post-peak stage, the stress starts to release due to the significant opening of diagonal shear crack and therefore, leads to the closure of flexural cracks.

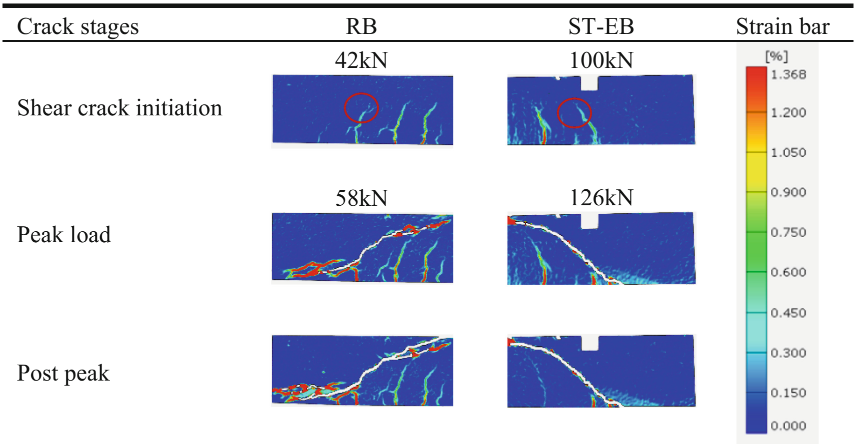

Fig. 8. Damage process of test beams (left RB, right ST-EB).

4.3 Interface Displacement

The interface strength between UHPFRC and normal concrete is a major factor that determines the composite behaviour of concrete structures strengthened with UHPFRC. To monitor the interface behaviour between concrete and UHPFRC, LVDTs are used to detect the interface displacement at four measurement points near the loading point (Fig. 5(a)). The average interface displacement from four symmetric measurement points is displayed in Fig. 9. As can be seen in Fig. 9, the interface opening and slip grow as applied load increases. However, when the load increases to around 100 kN, it alters the growth trend and interface displacement starts to decrease, which might be attributed to stress relaxation and incompatible deflection resulting from initiation of major shear crack. Moreover, the opening of interface develops faster than sliding but the maximum interface displacement is less than 8 μm, which meets the requirement specified in fib Bulletin 43 that the slip should not exceed 2 mm at ultimate stage [20]. Therefore, the use of epoxy resin is an effective bonding method to provide good bond quality at the interface and keep the specimen intact under mechanical load. Nevertheless, since epoxy resin is susceptible to humidity and temperature, the efficiency of this technique under harsh environmental conditions needs further investigation.

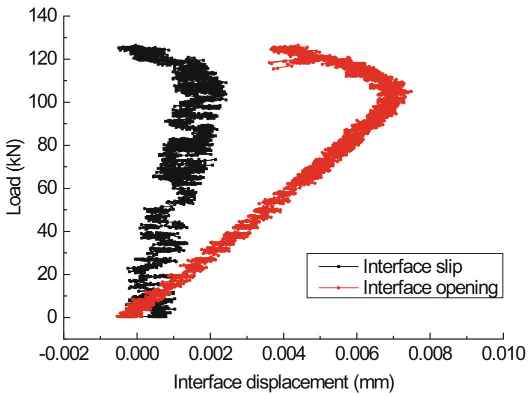

Fig. 9. Average results of interface displacement for ST-EB specimen.

5 Conclusion

This paper presents an experimental investigation of the shear strengthening effectiveness by adding UHPFRC on shear-critical RC beams. Different bonding techniques (Bonding precast UHPFRC laminates with epoxy resin and casting UHPFRC in-situ) are examined. The strengthening efficiency is mainly discussed in terms of load-deflection response, cracking behaviour and failure mode, as well as interface displacement. Based on the current study, several conclusions are drawn:

(1) Compared to unstrengthened beam, the application of precast UHPFRC panels with the use of epoxy resin can significantly increase the shear capacity of the RC beams and hinder the crack development in concrete.

(2) For casting in-situ technique, the effect of shrinkage cannot be ignored. The composite specimen will delaminate even under the effect of restrained shrinkage if proper interface preparation and curing conditions are not provided.
(3) The interface behaviour is one of the major factors to govern the performance of composite UHPFRC-RC specimens. With the use of epoxy resin, only minor interface displacement is observed during the loading process, proving that the epoxy resin can provide a strong bond at the interface between UHPFRC and NC, which could guarantee the efficiency of UHPFRC strengthening application.

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