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Effect of freeze-thaw cycles on shear resistance of reinforced concrete beams strengthened with UHPFRC

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Abstract

Ultra-high performance fiber-reinforced concrete (UHPFRC) has emerged as one of the promising materials for strengthening of concrete structures. For the strengthening application of UHPFRC, one of the primary concerns is to evaluate the degradation of bond behavior and structural response of strengthened elements under harsh environmental conditions. Therefore, an experimental program has been carried out to investigate the interfacial behavior between UHPFRC and normal concrete, as well as the shear performance of UHPFRC-concrete hybrid beams subjected to combined freeze-thaw cycles and mechanical load. In this study, two groups of shear-deficient reinforced concrete beams were first strengthened by UHPFRC precast panels using epoxy resin. Then, the specimens subjected to 0 and 30 freeze-thaw cycles were loaded to failure under three-point bending. The results indicate that the utilization of epoxy resin is an effective bonding technique to ensure the integral performance of the composite beams and the shear capacity is greatly enhanced with the application of UHPFRC. In addition, it is observed that the effect of applied freeze-thaw regime on the UHPFRC-concrete interfacial bond strength and shear resistance of unstrengthened and strengthened beams is negligible.

1 Introduction

Reinforced concrete (RC) is the most widely used construction material. However, in recent decades, existing RC structures suffer serious damage or even fail before reaching their design service life due to increase of loads and/or environmental deterioration. Especially for concrete structures exposed to aggressive environments such as chlorides, sulfates, and freeze-thaw, one of the primary challenges is to provide sufficient durability. Furthermore, some of these structures might not be damaged, but due to upgraded, more stringent design codes they do not meet performance requirements anymore. In order to restore the performances and improve the durability of damaged RC structures, repair or strengthening work might be necessary.

Ultra-high performance fiber-reinforced concrete (UHPFRC), one of the novel superior cement-based materials, is a promising material for both new construction and repair applications. Given its characteristics such as low water-to-binder ratio (normally < 0.25), use of only fine particles, and addition of steel fibers [1], UHPFRC shows better properties compared to conventional concrete. Typically, compressive strength of UHPFRC is more than 150MPa and its tensile strength can reach over 5MPa [2]. Moreover, UHPFRC has a dense microstructure, which is suitable to prevent the ingress of carbon dioxide, chloride, sulfate, etc, contributing to its excellent durability [3]. For example, in terms of its freeze-thaw resistance, UHPFRC can suffer more than 800 freeze-thaw cycles without obvious damage [4], unlike concrete which typically shows damage already after 300 cycles.

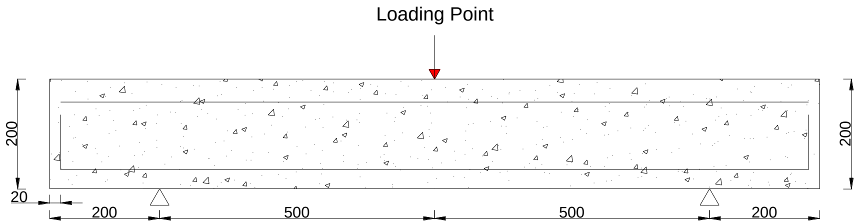
Since UHPFRC has a lot of advantages mentioned above, recently many studies have been conducted to investigate the efficiency of UHPFRC application in repairing existing concrete structures. As summarized in [5], [6], UHPFRC can enhance the performance of deteriorated concrete structures at the laboratory scale. However, some remaining issues need to be addressed before the large-scale on-site application of UHPFRC. Firstly, most studies are limited to structural response with the application of UHPFRC under mechanical loading. However, in this way the behavior of concrete structures reinforced with UHPFRC in real conditions is not reflected. In reality, structures are subjected to combined action of external loads and environmental effects [7]. Thus, the mechanical performance of UHPFRC strengthened structures under harsh environmental exposure effects requires further investigation. In addition, another critical concern is the bond performance between the concrete substrate and UHPFRC [8]. A weak bond might lead to debonding phenomenon prior to the full exploitation of

UHPFRC material strength. So far, various kinds of bond strength tests have been performed to analyze the interfacial behaviour between UHPFRC and normal concrete and test results show that UHPFRC can produce good bond performance due to the reinforcement effect of steel fibers [9]–[15]. The fact that debonding rarely happens at the interface for concrete beams repaired with UHPFRC in structural tests also supports the previous finding [16], [17]. However, the long-term bond behavior between the UHPFRC and the existing structure under harsh environmental conditions is not sufficiently investigated, which may impede the widespread strengthening application of UHPFRC. Therefore, in view of insufficient studies on the mechanical performance of RC structures strengthened with UHPFRC under harsh environmental conditions, this study is devoted to investigating the effectiveness of UHPFRC strengthening technique exposed to the freeze-thaw (FT) cycles and applied load. Three-point bending is carried out and both the strengthening effect and the bond performance are evaluated.

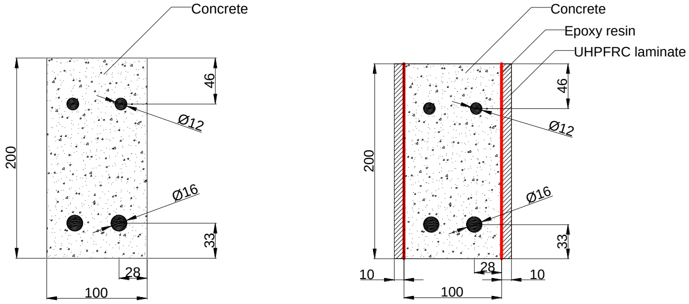
2 Experimental program

2.1 Specimen preparation

In this test, a total of four RC beams with a dimension of 100x200x1400mm are fabricated. Each beam is reinforced with 2 rebars with diameter ϕ16 in tensile and 2 rebars with diameter ϕ12 in compressive zone. All the beams are designed to fail in shear and no stirrups are used in the effective span region. Two beams without strengthening are served as reference beams while another two beams are strengthened with prefabricated UHPFRC panels on lateral sides using epoxy resin. The strengthening procedures are as follows. First, the beams' lateral surfaces are cleaned using cloth and ethanol. Secondly, epoxy resin is applied on both sides of concrete beams to enable bonding with the two precast 10mm thick UHPFRC panels. Finally, the panels are clamped and tightened. The geometric details of the reference, normal concrete (NC) and strengthened beams are shown in Fig. 1. The beams are divided into two groups, namely the control group preserved in lab conditions, and the environmental group exposed to 30 FT cycles. Each group consists of two beams: one beam is reference beam and another one is strengthened beam reinforced with UHPFRC, as presented in Table 1.



(a) Longitudinal view of the beam



(b) Cross-sectional view of the reference beam (Left) and strengthened beam (Right)

Fig. 1 Geometry of reference and strengthened beams (unit: mm).

Table 1 Details of test beams.

Group	Beam	Dimension (mm)	Bonding method	Environmental exposure
Control group	RB	100×200×1400	-	-
	ST-EB	120×200×1400	Epoxy resin	-
Environmental group	RB-30	100×200×1400	-	30 FT cycles
	ST-EB-30	120×200×1400	Epoxy resin	30 FT cycles

2.2 Freeze thaw protocol

Fig. 2 illustrates the freeze thaw protocol. The duration of one FT cycle is 24h. Freezing is done in cold room with temperature of -20 ℃ for 16h and thawing process is conducted in climate room at 20 ℃ for the remaining 8h. In order to follow the real environment exposure condition of existing concrete structures, the FT test is conducted with relative humidity ranging from 50% to 70%. Due to the limitation of experimental setup, the rate of temperature change was not predetermined. However, a sudden drop or increase of temperature will induce an even harsher condition than present in practice, being on safe side when predicting the residual capacity. After 30 FT cycles, compressive strength of NC and UHPFRC are measured, and beam tests are conducted to assess the deterioration of material properties and structural performance subjected to combined load and FT effects. Three NC and UHPFRC cubical specimens with dimension of 100mm and 40mm, respectively, are tested in compression.

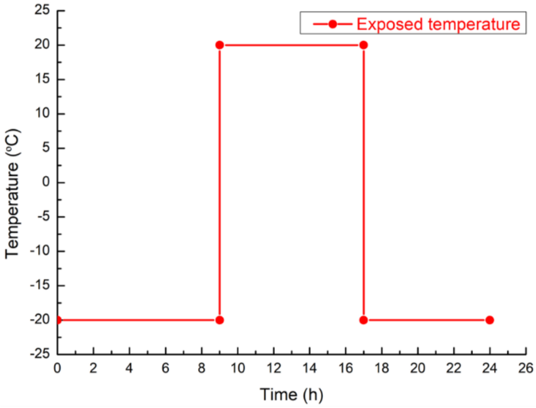
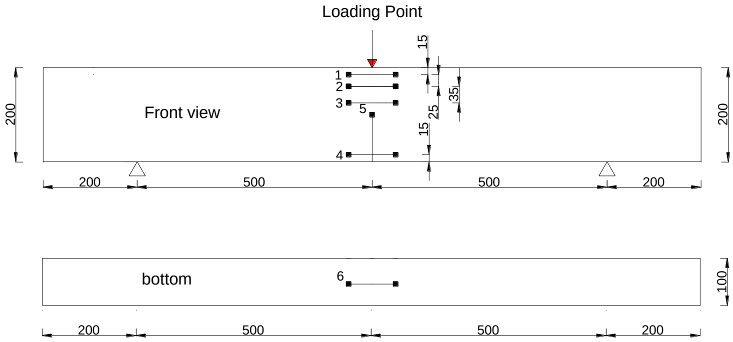


Fig. 2 Freeze thaw protocol on specimens.

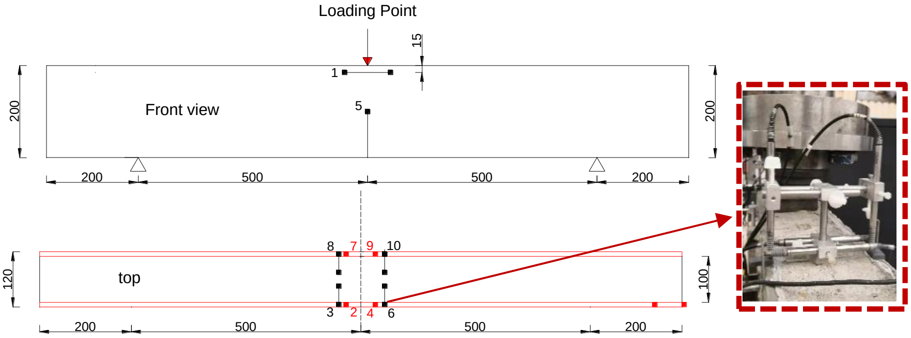
2.3 Mechanical test setup and procedure

All beam specimens are tested under three-point bending configuration and loaded under deformation control at a constant rate of 0.01 mm/sec. To simulate the loading condition for on-site strengthening application with UHPFRC, in the strengthened beam both the supports and loading plates only act on the concrete part. Fig. 3a and 3b show the linear variable differential transducers (LVDT) measurement configuration for reference and strengthened beams respectively. For reference beams, LVDTs are used to measure the deflection and strain distribution along the height at the mid-span. For strengthened beam, eight LVDTs are attached on top of strengthened beam to measure the interface displacement (slip and opening) at four measurement locations close to the loading point, from which the bond quality between UHPFRC and normal concrete can be evaluated during the loading process. Similar to the reference beam, another two LVDTs are used to measure the mid-span deflection and strain level in compression zone respectively.

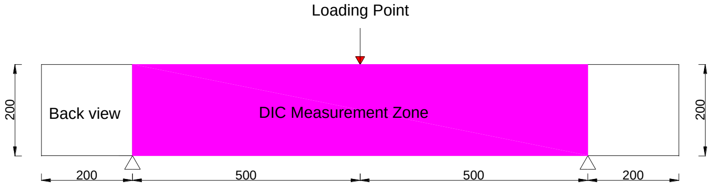
Apart from the LVDT measurement system, Digital Image Correlation (DIC), a non-contact image-based measurements technique, is also used to capture the crack development on the lateral side of the tested beams (Fig. 3c).



(a) LVDT arrangement for reference beam (Unit: mm)



(b) LVDT arrangement for strengthened beam (Unit: mm)



(c) DIC arrangement for reference and strengthened beam (Unit: mm)

Fig. 3 LVDT and DIC arrangement for reference and strengthened beams.

3 Results and discussion

3.1 Material deterioration after FT process

Compressive strength reduction is an important parameter to reflect the possible damage of material after FT cycles. In this study, the compressive strengths of NC and UHPFRC are measured on reference samples and samples exposed to 30 FT (Table 2). For normal concrete, there is a minor decrease of average compressive strength (around 4%), whereas for UHPFRC there is slight increase (2.5%), both falling within one standard deviation. Note that exposure conditions in the freeze thaw test were not harsh since the test is conducted in dry condition with a humidity ranging from 50% to 70%, and the number of FT cycles is limited.

Table 2 Compressive strength of cement-based material without and with 30 FT cycles.

Mixture	Compressive strength	
	0 FT cycle	30 FT cycles
Concrete	35.2±1.5 MPa	33.8±5.3 MPa
UHPFRC	122.4±5.1 MPa	125.4±8.7 MPa

3.2 Structural behaviour

3.2.1 Load-deflection relationship

To evaluate the shear capacity under coupled action of load and FT environment, reference beam (RB) and strengthened epoxy bonded beams (ST-EB) with and without freeze-thaw exposure are tested. The load-displacement relationship of all test beams is shown in Fig. 4. Table 3 summarizes the test results, namely peak load, deflection at peak load and failure modes. Compared to RB beam, ST-EB beam shows by 112% increase in ultimate capacity and around 57% higher deflection at peak load. Although the shear strengthening efficiency might be reduced with increasing beam size due to the size effect, these studies confirm that the contribution of UHPFRC to shear resistance improvement is still considerable [18], [19].

For RB-30 and ST-EB-30 which were subjected to 30 FT cycles, negligible influence of freeze-thaw cycles is observed from load-deflection response. Compared to that of RB and ST-EB, the ultimate shear capacity of RB-30 and ST-EB-30 reduce by 4.5% and 5.5% respectively. In terms of deformation capacity after FT action, the deflection at peak load of ST-EB-30 is nearly the same as that of ST-EB. However, compared to RB beam, the deformation of RB-30 is 41% lower.

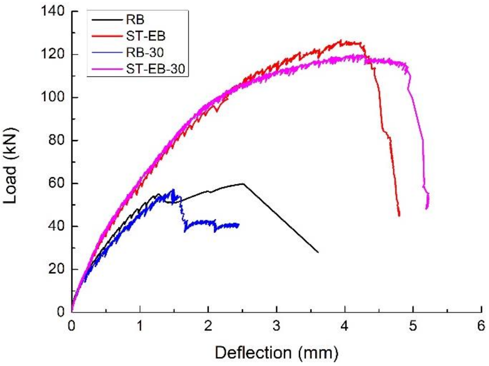


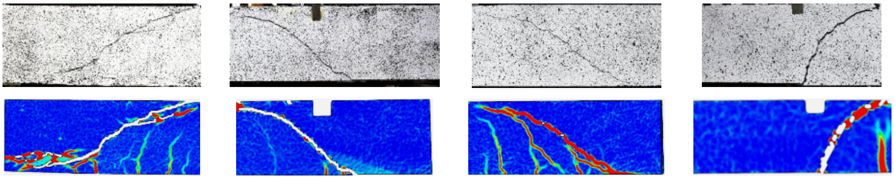
Fig. 4 Load-displacement relationship of all test beams.

Table 3 Results in terms of load, deflection, and failure modes.

Beam	Peak load (kN)	Deflection at peak load Δ_{exp} (mm)	Failure mode
RB	59.8	2.51	Shear compression failure
ST-EB	126.7	3.94	Flexural shear failure
RB-30	57.3	1.48	Shear compression failure
ST-EB-30	119.7	4.19	Flexural shear failure

3.2.2 Fracture modes

Failure modes of all test beams from visual observation and DIC analysis are presented in Fig. 5. The deformation and major strain resolution of DIC results are 0.008mm and 0.075% respectively. From Fig. 5, as expected, all beams fail in shear. The comparison of failure mode between RB, RB-30 and ST-EB, ST-EB-30 shows that the failure mode shifts from shear compression to flexural shear when beams are strengthened with UHPFRC panels. RB beam fails as the dominant shear crack propagates to the top flange of the specimens, eventually followed by the concrete crushing, while ST-EB collapses when the diagonal crack develops through the whole cross section of members. For RB-30 and ST-EB-30, due to negligible damage after the freeze thaw action, similar failure modes to RB and ST-EB are observed.

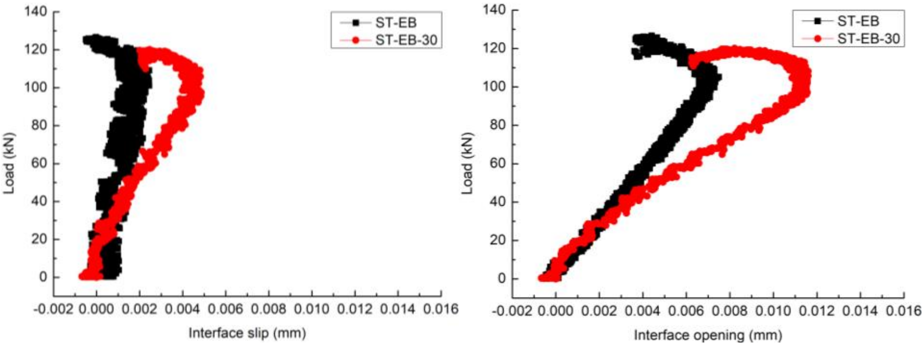


RB ST-EB RB-30 ST-EB-30

Fig. 5 Failure modes of all test beams.

3.2.3 Interface displacement

For ST-EB and ST-EB-FT beams, the average interface slip and opening between UHPFRC and NC are shown in Fig. 6. Since the interface displacement is of the same order of magnitude as the resolution of LVDT (1 µm), the measurement is accompanied by substantial noise. As shown in Fig. 6, the maximum value for both interface slip and opening does not exceed 0.015mm and is much lower than the requirement specified in *fib* Bulletin 43 [20], confirming that a good bond quality between UHPFRC and NC could be obtained by employing the epoxy resin. Similar trend of load-interface displacement curve is observed for all specimens. In the initial stage, the interface displacement increases with increasing load. However, it is found that the interface displacement decreases rapidly after the initiation of shear crack, which might be ascribed to stress relaxation between UHPFRC and normal concrete. In addition, in comparison with ST-EB specimen, larger interface displacement is recorded for beam ST-EB-30 exposed to 30 FT cycles. A possible reason might be that freeze thaw action weakens the bond quality between UHPFRC and normal concrete. Due to complex behaviour at the interface, further investigation is required.



(a) Interface slip (b) Interface opening

Fig. 6 Interface displacement (slip and opening) measurement for strengthened beams.

4 Conclusion

In this study, shear performance of reinforced concrete beam strengthened with UHPFRC under coupled load and FT action is experimentally studied. Compressive strength tests are conducted to evaluate the deterioration of UHPFRC and normal concrete after 30 FT cycles. The effect of UHPFRC application and freeze thaw cycles on the load-deflection, failure modes and interface behaviour were analyzed. Based on the experimental results, the main conclusion of this study are as follows:

1. The application of prefabricated UHPFRC plates using epoxy resin can significantly improve the shear capacity of concrete beams, which shows that UHPFRC application is an effective strengthening method. The maximum load and deformation capacity of strengthened beam is 112% and 57% higher than the reference beam respectively. Owing to the minor frost damage of concrete, the effects of freeze thaw on the shear resistance of RB-30 and ST-EB-30 are negligible as merely 5% decrease of load capacity is observed.

2. In terms of the bond between UHPFRC and normal concrete, the imposed freeze thaw damage is not severe and epoxy resin could still provide sufficient bond strength to prevent the interface debonding.

Acknowledgments

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