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UHPC Reinforcement of Damaged RC Beams under Load Conditions Cracking and Bending Performance

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Abstract: In order to study the mechanical properties of damaged reinforced concrete (RC) beams reinforced with ultra-high-performance concrete (UHPC), a four-point bending test was conducted to systematically investigate the influence of factors such as the number of reinforcement surfaces and the degree of damage. The results indicate that single-sided repaired beams have certain advantages in crack resistance performance, but are more disadvantageous in ultimate bearing capacity, with obvious debonding phenomenon before the end of loading. Compared with single-sided reinforcement, the cracking load of the three-sided reinforced beam increased by an average of 1.85 times, the ultimate bearing capacity increased by an average of 177.5%, and a good UHPC-RC combination effect could be formed, which could work synergistically until the end of loading. The degree of pre damage has a significant impact on the crack resistance performance of reinforced beams, while its impact on the ultimate bearing capacity is relatively limited. When the pre splitting width of the RC beam increases from 0.2 mm to 0.4 mm, the ultimate bearing capacity decreases by 28.33%.

Keywords: UHPC reinforcement; Three-sided repair; Bending performance: Cracking characteristics; Ultimate bearing capacity

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1. Introduction

As the service life of reinforced concrete (RC) structures increases, the problems of damage and performance degradation become prominent, especially after repeated loading, environmental erosion, or sudden events, the components are prone to damage, affecting safety and durability. In recent years, ultra-high-performance concrete (UHPC) has great potential in the field of structural repair and reinforcement due to its excellent mechanical properties and durability. As a cement-based composite material with high density, strength, and toughness, its compressive strength usually exceeds 150 MPa. In terms of durability, the dense microstructure formed by low porosity has excellent impermeability, and the chloride ion diffusion coefficient is reduced by more than 90% compared to ordinary concrete. It can serve stably in harsh environments [1]. After high-temperature curing, the shrinkage coefficient and creep degree of UHPC are lower, and it is widely used in bridge engineering, high-rise buildings, marine structures and other fields.

In recent years, scholars have conducted extensive research on the mechanical properties of UHPC reinforced RC beams. Previous study revealed the regulatory mechanism of UHPC layer thickness on the flexural performance of RC beams through experiments and finite element simulations [2]. They found that for every 10 mm increase in thickness, the flexural stiffness can be increased by 18% to 25%. The experimental results of Yang Zhang et al. showed that the synergistic improvement of strain hardening ability of UHPC layer by reinforcement ratio and steel fiber content can significantly enhance the cracking load and ultimate bearing capacity of reinforced beams [3]. Zhang Jianrui three-point loading test showed that the thickness of UHPC reinforcement had an impact on the shear strength of RC beams, and the effect was significant when the thickness was ≥ 20 mm [4].

In terms of reinforcement methods and interface treatment, Zhu Jingwei conducted bending tests and finite element analysis on steel UHPC-NC composite beams, which showed that the UHPC layer can significantly improve the flexural bearing capacity [5]. The interface chiseling and shear reinforcement can achieve complete combination (without slip), and the plastic failure characteristics are obvious. Al Osta used two different reinforcement techniques (sandblasting on the surface of RC beams and bonding with epoxy adhesive), and the results showed that both techniques had good bonding strength at the interface, ensuring the integrity of the composite structure [6]. Meanwhile, some scholars are also concerned about the improvement of fatigue performance and durability. Tohru verified the effectiveness of UHPC layer in controlling the damage of RC components through bending fatigue tests, and proposed a numerical model considering the pre damage of RC beams, the fracture characteristics of RC and UHPC, and the elastic-plastic behavior of steel bars for fatigue life prediction [7]. Research has shown that UHPC reinforcement of damaged RC structures can effectively improve crack resistance and durability, and extend their service life.

Based on this, this article focuses on the reinforcement of damaged RC beams with UHPC. Through four point bending tests, the influence of the number of reinforcement surfaces and the degree of damage on RC beams was explored, and the role of both in resisting bending capacity was further analyzed. This study aimed to provide theoretical support and technical reference for the efficient repair and performance prediction of damaged RC structures in engineering.

2. Material and methods

2.1. Overview of the experiment

A total of four reinforced concrete (RC) beams were fabricated in this experiment. One of them served as the control beam without any damage or strengthening treatment (denoted as BC-0). The remaining three beams were repaired and strengthened using ultra-high-performance concrete (UHPC) with variables including the number of strengthened surfaces and the degree of damage. Details of the specimens are shown in **Figure 1**. The RC part of each test beam has a height of 400 mm, a width of 200 mm, and a length of 2600 mm, with a calculated span of 2400 mm. A four-point loading scheme was adopted for the test beams, resulting in a pure bending segment of 640 mm. For longitudinal reinforcement (LR), 3 bars of Φ18 mm were arranged on the tensile side of the cross-section, and 2 bars of Φ10 mm on the compressive side. As for stirrups (HR), Φ10 mm bars were placed at a spacing of 80 mm in the bending-shear segments and 160 mm in the pure bending segments. Except for the control beam, the other test beams were repaired and strengthened with a 50 mm thick UHPC layer, which contained a layer of Φ3

× Φ3 steel mesh (MR) with a mesh size of 30 mm × 30 mm. Detailed information of the test beams is provided in **Table 1**. The letters in the table have the same meanings as defined above. For example, B1-0.2 refers to the test beam that was pre-cracked to a maximum crack width of 0.2 mm at the bottom and then repaired on the single bottom surface; while B3-0.2 represents the test beam that was pre-cracked to 0.2 mm at the bottom and then repaired on three surfaces (the bottom and two sides).

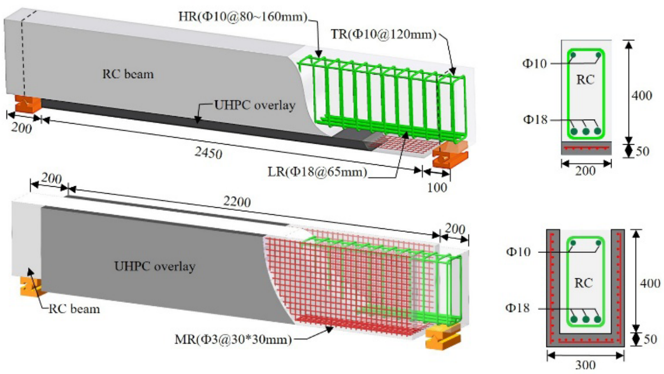

Figure 1. Detailed Scheme of Test Piece.

Table 1. Detailed information of test beams

Serial Number	Member Number	Repaired Surface	Pre-damage
1	BC-0	-	-
3	B1-0.2	1	0.2 mm
5	B3-0.2	3	0.2 mm
7	B3-0.4	3	0.4 mm

1.2. Test piece material

In the experiment, the normal concrete (NC) was designed as C50 strength grade concrete, composed of cement, sand, gravel, water, and water reducer, with its mix proportion given in **Table 2**. The ultra-high-performance concrete (UHPC) used was a commercial dry-mix product of Xingguli U120-2% type, whose main components include cement, silica fume, fly ash, quartz powder, quartz sand, high-performance plasticizer, and steel fibers. Among them, the steel fibers are straight ones with a diameter of 0.2 mm and a length of 13 mm, with a volume content of 2%. Their tensile strength is higher than 2000 MPa, and elastic modulus is 200 GPa. Basic mechanical parameters of NC and UHPC were obtained through material performance tests on concrete mechanics, as shown in **Table 3**. The test beams adopted HRB400 reinforcement, where the yield strength of Φ10 mm steel bars is 472.5 MPa, and that of Φ18 mm steel bars is 465 MPa.

Table 2. Mix Proportion of NC (Unit: kg/m^3)

Component	Cement	Crushed Stone	Sand	Water	High-Efficiency Water Reducer	Water-Cement Ratio
Mass (kg/m³)	470	1048	771	122	4	0.26

Table 3. Mechanical Properties of Concrete Materials

Type of Concrete	Curing Condition	Compressive Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)
C50	Natural Curing	46.5	8.9	38.6
UHPC	Natural Curing	144.3	25.6	47.1

1.3. Sample production process

The fabrication process of pre-damaged RC beams strengthened with UHPC layers is illustrated in Figure 2, which mainly includes the following steps: (a) Casting of RC beams: After casting, the RC beams were cured at room temperature for 28 days, followed by further curing at room temperature for more than 90 days. (b) Pre-damage introduction: The RC beams were first pre-loaded and then strengthened. The degree of pre-damage was evaluated by the maximum crack widths introduced in the RC beams under pre-loading, which were set to 0.2 mm and 0.4 mm respectively. (c) Interface treatment before strengthening: After the pre-damage degree was reached, the test beams were unloaded, and the surfaces of the RC beams to be strengthened were chiseled. (d) Casting of UHPC layers: For the beams with completed interface treatment, the steel meshes were positioned, and UHPC was used for repair. The formwork was removed after standard curing for 28 days. (e) Destructive testing: After the repair of the test beams was completed, a four-point bending loading test was carried out from the initial state until failure.

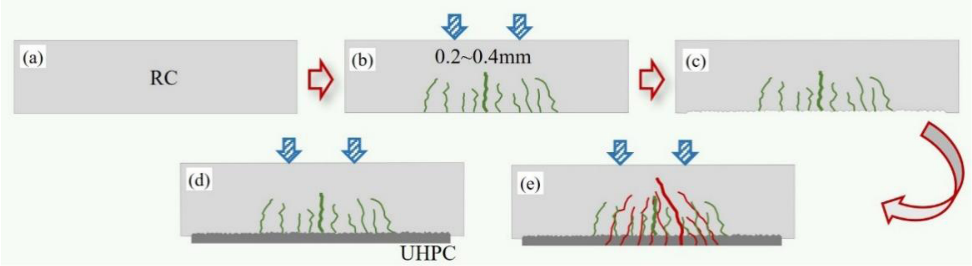

Figure 2. Preparation of experimental beam.

1.4. Test setup and instruments

In the pre-cracking stage, all test beams except the control beam were loaded according to the pre-damage conditions specified in **Table 1**. The initial load increment was set to 5 kN per step to compact the beam body, preventing damage to the loading device and the beam due to excessive load increments, which could affect the test accuracy. Subsequently, pre-damage loading was conducted with a load increment of 10 kN per step, and a crack observer was used to continuously monitor the development of major cracks. When approaching the pre-damage value, the load increment was adjusted to 5 kN per step to obtain the accurate load corresponding to the target damage value. Loading was stopped once the beam reached the pre-damage value, and relevant data were recorded before unloading at an increment of 2 kN per step. During formal loading, the initial load increment was 10 kN per step, which was reduced to 5 kN per step when approaching the cracking load. After the RC beam cracked, the load increment was restored to 10 kN per step. When the load reached 80% of the theoretical peak value, displacement-controlled loading was adopted at a rate of 1 mm/min, with a mid-span deflection increment of 1 mm per step. After maintaining the load, cracks were observed until the specimen lost its load-bearing capacity. In terms of measuring points: Dial gauges were installed at the top of the beam-end supports, mid-span, and the supports of the distribution beam to measure settlement and deflection; Dial gauges were mounted at the interface between the UHPC and RC layers to measure slip and debonding; Strain gauges were attached to the side surfaces of the test beam and the surface of tensile reinforcement to measure strain; An extensometer was installed at the bottom of the beam to record the tensile deformation of the UHPC layer after cracking. The arrangement of measuring points and strain gauges for single-sided and three-sided repaired beams was similar as shown in **Figure 3**.

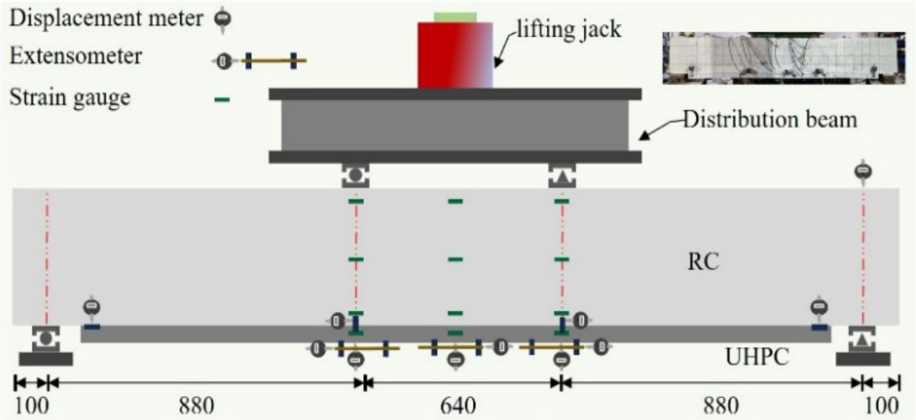

Figure 3. Test set up and lay out of measuring points.

2. Failure modes and crack distributions

The failure modes and crack development patterns of the test beams are shown in **Figure 4**. For the single-sided repaired beam, when loaded to 0.7 Pu (Pu is the ultimate load of the test beam), debonding occurred at the UHPC-NC interface, causing the UHPC to gradually disengage from load-bearing, and the RC beam had to bear the load alone, leading to crushing of the NC at the top. Compared with the control beam BC-0, the crack resistance of the single-sided strengthened test beam was significantly improved, with the cracking load reaching 1.85 times that of the control beam (**Table 4**), while the flexural load-bearing capacity was comparable to that of the undamaged control beam. The three-sided repaired beam exhibited good cooperative force-bearing and overall performance throughout the loading process. Compared with the control beam, the cracking load increased by 1.69–2 times, and the flexural load-bearing capacity increased by 1.63–1.92 times. As shown in **Figure 4**, there were significant differences in crack development and distribution among the test beams. The control beam BC-0, an unrepaired RC beam, showed typical characteristics of flexural failure in RC beams: cracks in the pure bending segment developed vertically upward, slightly inclined near the supports, and the cracks were sparsely and uniformly distributed overall. At failure, most cracks penetrated the beam height with widths exceeding 0.2 mm, and crushing occurred in the upper part of the beam. For the single-sided repaired beam B1-0.2, obvious debonding at the UHPC-NC interface was observed. The crack distribution on the RC surface was similar to that of the control beam. Due to the disengagement of UHPC from load-bearing in the later loading stage, crushing also occurred in the upper part of the RC.

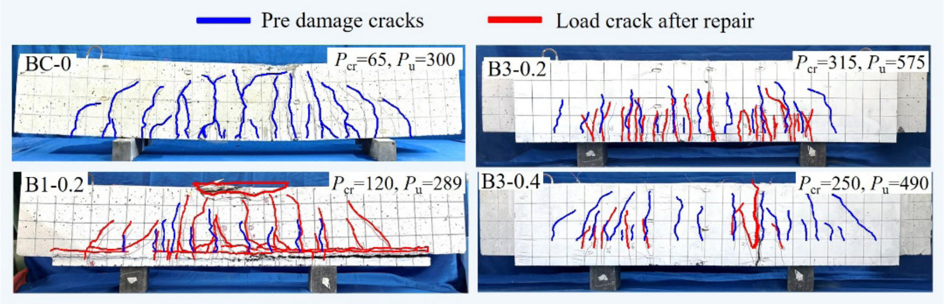

Figure 4. Experimental beam failure mode and crack distribution.

3. Load-deflection response

The load-midspan deflection curves of the test beams are shown in **Figure 5**, and their load-displacement responses can be divided into four stages: (i) Elastic stage (0–0.54 Pu for three-sided repaired beams, 0–0.43 Pu for single-sided repaired beams): The stiffness of the beams was close to that of the control beam, and the UHPC remained uncracked, resulting in linear curves. The slope of the curve for the single-sided repaired beam was very close to that of the control beam; the elastic stage of the three-sided repaired beam was significantly longer, with a notably improved stiffness. (ii) Working stage with cracks (0.54–0.93 Pu for three-sided repaired beams, 0.43–0.76 Pu for single-sided repaired beams): For the three-sided repaired beam, the UHPC layer cracked first, accompanied by multiple fine and dense cracks. The stiffness degradation was not obvious; although the slope of the curve was lower than that in the elastic stage, it still increased approximately linearly within a relatively large load range, performing better than the control beam. In this stage, the repaired layer of the single-sided repaired beam deboned, and the curve slope was close to that of the control beam, with its stiffness significantly lower than that of the three-sided repaired beam. This indicates that mere chiseling treatment is insufficient to achieve collaborative work at the interface. (iii) Yield stage (0.93 Pu–Pu for three-sided repaired beams, 0.76 Pu–Pu for single-sided repaired beams): The steel bars in the beam gradually yielded, and the deflection and crack width developed rapidly. The curve of the three-sided repaired beam dropped sharply, with a significant decrease in stiffness; for the single-sided repaired beam, as the load increased, the UHPC layer deboned and eventually ceased to work, leading to intensified deformation and an approximately straight curve. (iv) Failure stage (≥ Pu): The load dropped suddenly, the deflection increased sharply, and the cracks expanded significantly. The curve of the three-sided repaired beam entered the descending segment, with the slope tending to flatten in the later stage, and it still maintained good flexural capacity after failure; due to the debonding of the UHPC layer, the failure process and curve change of the single-sided repaired beam were close to those of the control beam, similar to conventional RC beams.

In summary, the stiffness advantage of the three-sided repaired beams stems from the composite effect between UHPC and the RC beam, as well as the synergistic constraint of multiple interfaces.

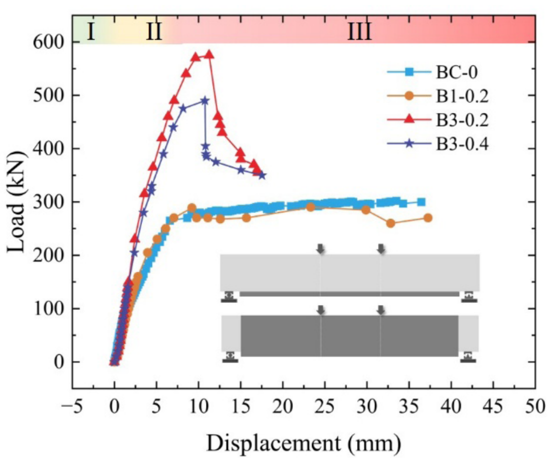

Figure 5. Load-Midspan deflection curves.

4. Conclusions

In this paper, a study on pre-damaged RC beams strengthened with UHPC was conducted. Through four-point bending tests, the effects of factors such as the number of strengthened surfaces and different damage degrees on the RC beams were investigated, and the following conclusions were drawn:

(1) In terms of the number of strengthened surfaces, compared with single-sided strengthened beams, the three-sided strengthened beams showed an average increase of 1.13 times in cracking load and an average increase of 183.92% in ultimate bearing capacity. Moreover, they could form a good UHPC-RC composite effect, maintaining collaborative work until the end of loading.

(2) The degree of pre-damage had a significant impact on the crack resistance of the strengthened beams, but a relatively limited effect on the ultimate bearing capacity. When the pre-crack width of the RC beams increased from 0.2 mm to 0.4 mm, the cracking load decreased by 13.79%-34.92%, and the ultimate bearing capacity decreased by 6.09%. The above rules were more obvious for the beams repaired after unloading.

Disclosure statement

The authors declare no conflict of interest.

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