

Analysis of Flexural Capacity of High Strength Reinforced UHPC-CA Beams based on Orthogonal Test

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Abstract

The effects of the cross-sectional area of the reinforcement, the cross-sectional size of the specimen and the strength of ultra high performance concrete with coarse aggregate (UHPC-CA) on the flexural capacity of UHPC-CA beams with HRB500 grade high-strength reinforcement are analyzed by orthogonal test. The results show that the influence of various factors on the flexural capacity of high-strength reinforced UHPC-CA beams is in the order of specimen section size > reinforcement section area > UHPC-CA strength. With the increase of the three factors, the bending bearing capacity is improved in different degrees. The section size of the specimen is a general significant factor of the bending capacity, while the section area of the reinforcement and the UHPC-CA strength are not significant factors.

Keywords

Ultra High Performance Concrete with Coarse Aggregate (UHPC-CA); High Strength Reinforcement; Flexura Capacity.

1. Introduction

In the 1990s, French scholars proposed a new cement-based composite material with ultra-high strength, ultra-high toughness and ultra-high durability, namely "ultra-high performance concrete" with water, cement, silica fume, ultra-fine fly ash, ultra-fine slag powder, quartz powder, fine aggregate, steel fiber and high-efficiency water-reducing agent as the main raw materials [1]. However, due to the high production cost, large shrinkage deformation and complex mixing process [2], this has largely limited its implementation and use in practical projects. Huang Weirong et al. [3] added diabase macadam coarse aggregate into ultra-high performance concrete to study the influence of coarse aggregate content and coarse aggregate size on hydration temperature, micro-deformation and shrinkage performance of ultra-high performance concrete. The results show that when the particle size of coarse aggregate is 5-8mm and the content of coarse aggregate increases from 0 kg/m³ to 485 kg/m³, the maximum strain value of the matrix of ultra-high performance concrete with coarse aggregate (UHPC-CA) decreases by 9.1% and the shrinkage value of the matrix decreases by 29.0%. Su Jie and other scholars from Hunan University [4-5] studied the influence of coarse aggregate content on UHPC-CA compressive strength and flexural tensile strength in 2021 and 2022 respectively. The results show that when the content of coarse aggregate increases from 0 kg/m³ to 600 kg/m³, the compressive strength of UHPC-CA increases first and then decreases, while the flexural strength decreases gradually. Shi Jinhua [6] studied the influence of basalt content on the UHPC-CA elastic modulus. When the basalt content is 400 kg/m³, 600 kg/m³, 800 kg/m³, 1000 kg/m³ and 1200 kg/m³, the growth range of UHPC-CA elastic modulus is 7.6%, 10.2%, 13.6%, 20.7% and 23.4% respectively. Han Chaorui [7] carried out the durability test of UHPC-CA, and the test results showed that when the content of coarse aggregate was 15%, the

strength loss and mass loss of UHPC-CA after 100 freeze-thaw cycles were the lowest, and the 7d and 14d compressive strength corrosion resistance coefficients were the highest. According to the analysis of the above documents, it is feasible to use coarse aggregate to prepare ultra-high performance concrete (UHPC-CA), which has low production cost, small shrinkage deformation and excellent mechanical properties, is a new research hotspot in the field of concrete research.

HRB500 steel bar is a high-strength hot-rolled ribbed steel bar with excellent performance. Replacing HRB400 steel bar with HRB500 steel bar can save steel consumption, increase structural safety reserve and reduce construction difficulty [8]. The tensile strength of ordinary concrete is low, which is restricted by the crack width of concrete under the limit state of normal use. It is difficult for HRB500 high-strength reinforcement to give full play to its strength. However, the combination of HRB500 high-strength reinforcement and UHPC-CA can give full play to their excellent mechanical properties. Based on this, this paper takes the reinforcement section area, the specimen section size and the UHPC-CA strength as the test factors, and takes the bending bearing capacity of the UHPC-CA beam with HRB500 high-strength reinforcement as the test index to design the orthogonal test, and analyzes the influence and significance of each factor on the test index, the change rule of indicators with the level of factors, and the change rule of flexural bearing capacity of UHPC-CA beams with high strength reinforcement with reinforcement ratio.

2. Test Overview

2.1. Orthogonal Test Scheme Design

Table 1. Test factors and levels

Levels	Factors		
	A/mm ²	B/(mm×mm)	C
1	308	120×180	C100
2	402	150×250	C150
3	509	200×300	C200

Table 2. Test scheme design

Test serial number	Orthogonal combination	Factors		
		A/mm ²	B/(mm×mm)	C
1	A1B1C1	308	120×180	C100
2	A1B2C2	308	150×250	C150
3	A1B3C3	308	200×300	C200
4	A2B1C2	402	120×180	C150
5	A2B2C3	402	150×250	C200
6	A2B3C1	402	200×300	C100
7	A3B1C3	509	120×180	C200
8	A3B2C1	509	150×250	C100
9	A3B3C2	509	200×300	C150

Three factors and three levels $L_9(3^3)$ orthogonal test scheme is designed. The test factors and levels are shown in Table 1. Factors A, B and C are the sectional area of reinforcement, the sectional size of specimen (width $b \times$ height h) and strength of ultra-high performance concrete containing coarse aggregate. The three levels of the cross-sectional area of the reinforcement contain 308 mm² (2 ϕ 14), 402 mm² (2 ϕ 16) and 509 mm² (2 ϕ 18), the horizontal dimension

of the section is 120 mm × 180 mm, 150 mm × 200 mm and 200 mm × 300 mm, three levels of factor C include C100, C150 and C200. Among them, the strength data of C100UHPC-CA is from the B4 test group (steel fiber content is 0.5%, coarse aggregate content is 40%) in the master's thesis of Han Chaorui [7] of Wuhan University of Engineering, C150UHPC-CA is selected from the 0.18UHPC-HF3 test group in the doctoral dissertation of Yang Juan [9] of Beijing Jiaotong University, and C200UHPC-CA is the data of HS-UHPC (CA) test group (curing method is 90 °C hot water curing+250 °C dry heat curing for 3 days) in the doctoral dissertation of Niu Xujing [10] of Beijing Jiaotong University. The specific test scheme design is shown in Table 2.

2.2. Other Information

The section size and tensile reinforcement of 9 groups of test pieces are different. Figure 1 shows the structural drawing of the second group of beams, that is, the section size is 150 mm × 250 mm, longitudinal reinforcement is 2 φ 14. The length of each group of test beam is set as 1500 mm, the clear span is 1200 mm, the shear span is 400 mm, and the pure bending section is 400 mm. Under the action of two symmetrical concentrated loads, the stirrup is selected φ 10@100 (HPB300 grade, double leg hoops), the erection reinforcement is 2 φ 10 (HPB300), tensile reinforcement shall be HRB500 high-strength reinforcement.

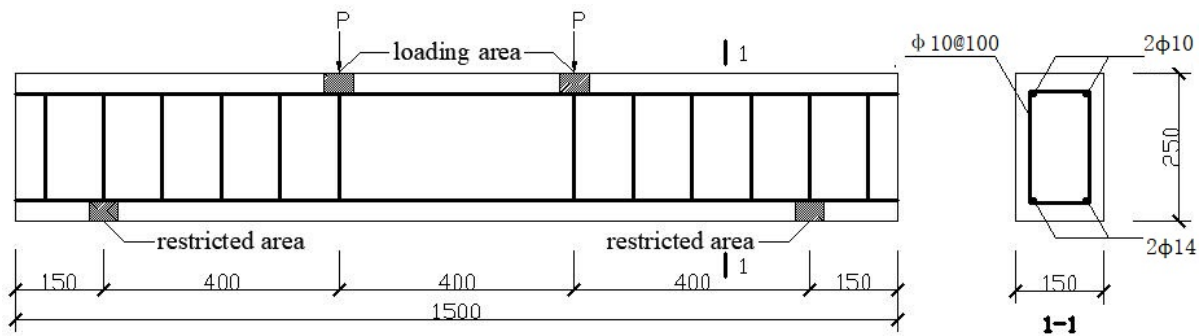


Figure 1. Structural drawing of beam specimen of the second group (unit: mm)

3. Analysis of Test Results

In this study, the bending capacity of UHPC-CA beams with high-strength reinforcement in each test group is calculated using the calculation method in Hou Changgui's [11] master's thesis "Experimental and Theoretical Research on Flexural Performance of UHPC Rectangular Beams", and the calculation results are shown in Table 3.

Table 3. Test calculation results

Test number	Bearing capacity/kN·m	Test number	Bearing capacity/kN·m	Test number	Bearing capacity/kN·m
1	19.5	4	25.7	7	35.1
2	34.2	5	50.8	8	48.6
3	63.9	6	54.2	9	69.2

3.1. Visual Analysis

It can be seen from Table 3 that the flexural bearing capacity of the ninth group of beam specimens is the largest, 69.2 kN·m. At this time, the orthogonal combination is A3B3C2, that is, the sectional area of reinforcement is 509 mm², the sectional size of the specimen is 200 mm × 300 mm, and the UHPC-CA strength is C150. The flexural bearing capacity of the third group of beam specimens takes the second place, 63.9 kN·m. At this time, the orthogonal combination is A1B3C3, that is, the sectional area of the reinforcement is 308 mm², the sectional size of the

specimen is 200 mm × 300 mm, and the UHPC-CA strength is C200. The bending bearing capacity of the beam of the first group of test pieces is the lowest, 20.8 kN·m. At this time, the orthogonal combination is A1B1C1, that is, the sectional area of reinforcement is 308 mm², the sectional size of test pieces is 120 mm × 180 mm, and the UHPC-CA strength is C100. Comparative analysis of the third and ninth group of test pieces shows that when the section size of the test piece is 200 mm × 300 mm, the bending bearing capacity of the beam is only increased by 5.3 kN·m with little change by increasing the sectional area of the reinforcement (from 308 mm² to 509 mm²) and reducing the strength of UHPC-CA (from C200 to C150). Comparative analysis of the first group and the third group of specimens shows that the reinforcement is 2 φ 14 series beam, and increase its section size (from 120 mm × 180 mm to 200 mm × 300 mm) and UHPC-CA strength (from C100 to C200), the bending bearing capacity of the beam increased by 44.4 kN·m, an increase of 227.7%, with a significant increase effect.

3.2. Range Analysis

By analyzing the range of the test results, we can get the order of the degree of influence of each factor on the test index [12]. Through calculation, the extreme difference value of the influence of three factors, namely the reinforcement section area, the specimen section size and the UHPC-CA strength, on the flexural bearing capacity of the high-strength reinforcement UHPC-CA beam can be obtained, as shown in Table 4. It can be seen that the range values corresponding to factors A, B and C are 11.7, 35.6 and 9.2 respectively, and the influence of each factor on the bending capacity is B>A>C from the largest to the smallest, that is, the section size of the specimen>the section area of the reinforcement>the UHPC-CA strength.

Table 4. Range analysis of bending capacity

Parameter	Range/kN·m		
	Factor A	Factor B	Factor C
K1	39.2	26.8	40.8
K2	43.6	44.5	43.0
K3	51.0	62.4	49.9
R	11.7	35.6	9.2

Note: K_i is the average value of the test results under the level i of each factor, R is the range.

3.3. Factor Index Analysis

In order to obtain the change rule of the research index of flexural bearing capacity of UHPC-CA beams with the factor level, the average value of the test results under each factor level in Table 4 is plotted as a point chart, as shown in Figure 2. It can be seen from Figure 2 that with the increase of factor A, B and C, the flexural bearing capacity of UHPC-CA beams with high-strength reinforcement has been improved by different degrees. When the sectional area of reinforcement is increased from 308 mm² to 509 mm², the flexural bearing capacity increases by 29.8%. When the section size of the test piece is 120 mm × 180 mm to 200 mm × 300 mm, the bending bearing capacity increased by 132.8%. When the strength of UHPC-CA increases from C100 to C200, the bending capacity increases by 22.5%. It can be seen that the increase of the section size of the specimen has the most significant effect on strengthening the flexural bearing capacity of the high-strength reinforced UHPC-CA beam, followed by the section area of the reinforcement, and the strength of UHPC-CA is the smallest, and the latter two have relatively close effects.

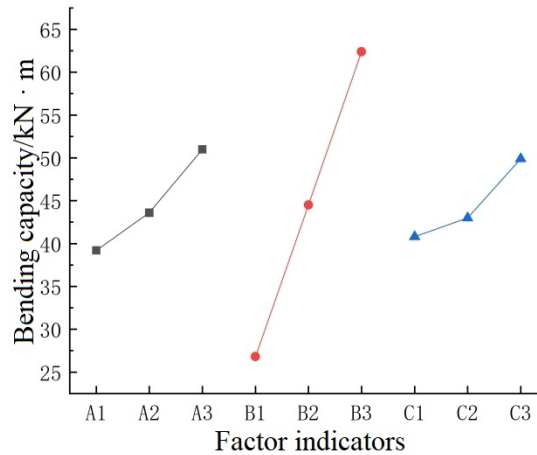


Figure 2. Variation of flexural capacity with factor level

3.4. Hierarchical Analysis

The influence weight of each factor level on the bending bearing capacity can be obtained through the hierarchical analysis of the research indicators [13], and the results are shown in Table 5. It can be seen from Table 5 that among the three levels of reinforcement grade, A3 has the largest influence weight on bending bearing capacity, with the weight value of 0.079 2. Among the three levels of the section size of the test piece, B3 has the largest influence weight, with a value of 0.294 1. Among the three levels of UHPC-CA strength, C3 has the largest influence weight, with a value of 0.060 5. Therefore, the combination is A3B3C3, that is, the sectional area of reinforcement is 509 mm², the sectional size of test piece is 200 mm × 300 mm, and the UHPC-CA strength is C200, the bending bearing capacity of UHPC-CA beams with high-strength reinforcement will reach the maximum value.

Table 5. Hierarchical analysis of flexural bearing capacity

Factor level	Weight value	Factor level	Weight value	Factor level	Weight value
A1	0.060 9	B1	0.126 2	C1	0.049 4
A2	0.067 6	B2	0.209 9	C2	0.052 2
A3	0.079 2	B3	0.294 1	C3	0.060 5

3.5. Variance Analysis

Table 6. Variance analysis of bending capacity

Factor	Sum of squared deviations	Freedom	Mean square	F value	Critical value	Significance
A	211.8	2	105.9	4.1	F0.01(2,2) =99.0 F0.05(2,2) =19.0 F0.10(2,2) =9.0	*
B	1905.5	2	952.8	36.5		
C	136.8	2	68.4	2.6		
Error	52.2	2	26.1	1.0		

Note: 1) When $F > F_{0.01}(2,2)$, it means that the factor is an important significant factor, which is recorded as **; 2) When $F_{0.01}(2,2) > F > F_{0.05}(2,2)$, it means that the factor is a general significant factor, which is recorded as *; 3) When $F_{0.05}(2,2) > F > F_{0.10}(2,2)$, it means that the factor is a significant factor, which is recorded as (*); 4) When $F < F_{0.10}(2,2)$, it means that the factor is not significant.

In order to obtain the significance of the influence of factors A, B and C on the flexural bearing capacity of UHPC-CA beams with high-strength reinforcement, the analysis of variance was conducted on the research indicators [14], and the results are shown in Table 6. It can be seen from Table 6 that the F value of factor B is 36.5, which is between the critical value of 19.0 and 99.0. Therefore, the section size of the test piece is the general significant factor of the flexural

bearing capacity of UHPC-CA beams with high-strength steel bars. The F value of factor A and factor C is less than the critical value of 9.0, which is not a significant factor. The F value of factor A is slightly larger than that of factor C, indicating that the influence of reinforcement section area on the bending capacity of beam is greater than UHPC-CA strength. It can be seen that the above analysis results are consistent with the range analysis results.

3.6. Bearing Capacity-Reinforcement Ratio Analysis

The reinforcement ratio of longitudinal reinforcement (the ratio of the section area of longitudinal reinforcement to the effective area of the section) is an important index that affects the flexural bearing capacity of the beam [15]. In this study, the reinforcement ratio of each specimen beam changes with the simultaneous change of factor A (reinforcement section area) and factor B (specimen section size). Table 7 lists the reinforcement ratio calculation results and corresponding bearing capacity values of some test groups. Comparative analysis of the first and seventh groups of specimens shows that the level of factor B is the same. With the simultaneous increase of factor, A and factor C, the flexural bearing capacity of the beam has increased by 80.0%. If the contribution of factor C is deducted by 22.5%, it can be concluded that when the section size of the specimen is 120 mm × 180 mm, when the reinforcement ratio increases from 1.83% to 3.03%, the flexural bearing capacity of UHPC-CA beams with high-strength reinforcement increases by 57.5%. Similarly, the comparative analysis of the fifth and eighth group of test pieces shows that when the section size of the test piece is 150 mm × 250 mm, when the reinforcement ratio increases from 1.28% to 1.62%, the bending bearing capacity of the beam increases by 18.2%. Comparative analysis of the third and sixth group of test pieces shows that when the section size of the test piece is 200 mm × 300 mm, when the reinforcement ratio increases from 0.59% to 0.77%, the flexural bearing capacity of the beam increases by 7.3%. For the section sizes of B1, B2 and B3 specimens, the bearing capacity increases by 4.8%, 5.4% and 5.6% respectively for each 0.1% increase in reinforcement ratio. It can be seen that when the reinforcement ratio increases by the same extent, the increase in flexural bearing capacity of UHPC-CA beams with high-strength reinforcement increases with the increase of the section size of the specimens.

Table 7. Bearing capacity-reinforcement ratio analysis

Test serial number	Orthogonal combination	Bearing capacity/kN·m	Reinforcement ratio/%
1	A1B1C1	19.5	1.83
5	A2B2C3	50.8	1.28
3	A1B3C3	63.9	0.59
7	A3B1C3	35.1	3.03
8	A3B2C1	48.6	1.62
6	A2B3C1	54.2	0.77

4. Conclusion

- ① According to the intuitive analysis, the orthogonal combination is A3B3C2, and the bending bearing capacity of UHPC-CA beams with high-strength steel bars is high. When the orthogonal combination is A1B1C1, the bending bearing capacity is small.
- ② From the range analysis, it can be seen that the influence of various factors on the flexural bearing capacity of UHPC-CA beams with high-strength reinforcement is in the order of specimen section size > reinforcement section area > UHPC-CA strength from large to small.

③ According to the factor index analysis, with the increase of reinforcement section area, specimen section size and UHPC-CA strength, the bending capacity increased by 29.8%, 132.8% and 22.5% respectively.

④ According to the hierarchical analysis, in the three levels of each factor, A3 (509 mm²) and B3 (200 mm × 300 mm), C3 (C200) and anti-bending bearing capacity have the largest influence weight. When the orthogonal combination is A3B3C3, the flexural bearing capacity of UHPC-CA beams with high-strength reinforcement will reach the maximum value.

⑤ According to the analysis of variance, the section size of the specimen is the general significant factor of the flexural bearing capacity of the UHPC-CA beam with high-strength reinforcement, while the section area of the reinforcement and the UHPC-CA strength are the non-significant factors.

⑥ From the analysis of bearing capacity-reinforcement ratio, it can be seen that when the reinforcement ratio increases by the same amount, the increase of flexural bearing capacity of UHPC-CA beams with high-strength steel bars gradually increases with the increase of the section size of the specimen.

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