

Orthogonal Analysis of Flexural Capacity of Beams Reinforced by High Strength Reinforcement and Ultra High Performance Concrete with Coarse Aggregate

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Abstract

In order to study the influencing factors of the flexural capacity of ultra high performance concrete with coarse aggregate (UHPC-CA) beams with high strength reinforcement, the orthogonal test method was used to analyze the influence of reinforcement grade, reinforcement diameter, section effective height and concrete strength grade on the flexural capacity of UHPC-CA beams with high strength reinforcement. The results show that the diameter of reinforcement is an important significant factor affecting the flexural capacity of UHPC-CA beams with high-strength reinforcement, and the grade of reinforcement and the effective height of section are general significant factors. With the increase of the three factors, the flexural capacity of the beam is gradually improved. The influence of concrete strength grade on the flexural capacity of UHPC-CA beams with high-strength reinforcement is small. With the increase of concrete strength grade, the flexural capacity first decreases slightly and then increases slightly. The effect of reinforcement ratio on flexural capacity of UHPC-CA beams with ordinary strength reinforcement is greater than that of UHPC-CA beams with high strength reinforcement.

Keywords

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

1. Introduction

Ultra high performance concrete with coarse aggregate (UHPC-CA) and reactive powder concrete (RPC) belong to the category of ultra high performance concrete (UHPC) [1-3]. Previous studies have shown that under different target temperature environments, the residual compressive strength of uhpc-ca is higher than that of RPC, and coarse aggregate plays a significant role in improving the residual compressive strength of UHPC [4]; Under the condition of different moisture content, the burst temperature range of uhpc-ca is smaller than that of RPC, the duration is shorter, the number of burst sounds is less, the internal temperature difference of the test piece is lower, and the accumulated sieve residue of fragments of 90 mm size is larger. The high-temperature burst performance of uhpc-ca is higher than that of RPC, and coarse aggregate is conducive to improving the high-temperature burst performance of UHPC [5].

The use of high-strength reinforcement can save the total steel consumption of the project. When HRB400 is used to replace HRB335 and HRB500 is used to replace HRB400, the steel saving rates are 12% ~ 14% and 5% ~ 7% respectively [6]. The combination of high-strength reinforcement and uhpc-ca can give full play to their excellent mechanical properties. Sun Tao [7] designed the pull-out test and analyzed the effect of reinforcement bonding length, protective layer thickness and curing age on the bonding performance between HRB400 reinforcement and UHPC-CA. The results show that when the bonding length increases from 4d

(d is the diameter of reinforcement) to $6d$, the ultimate bonding stress τ_u decreases by 5.95 MPa; When the protective layer increases from 10 mm to 35 mm, τ_u increases by 6.64 MPa; When the age increases from 7 days (D means days) to 28 days, τ_u increases by 10.46 MPa. Deng Zongcai et al. [8] tested the flexural performance of six groups of HRB500 reinforced UHPC-CA beams (the parameters are reinforcement ratio and section form). The test found that the loading experience of high-strength reinforced UHPC-CA beams is similar to that of ordinary concrete beams, but the existence of steel fiber significantly improves the stiffness of UHPC-CA beams. Xu Haibin et al. [9] studied the moment amplitude modulation of high-strength reinforced UHPC-CA continuous beam, and calculated the moment amplitude modulation coefficient under the limit state of bearing capacity and the limit state of normal use based on the analysis of nonlinear theory. Jin Lingzhi et al. [10] analyzed the influence of web reinforcement and shear span ratio on the shear performance of high-strength reinforced UHPC-CA beams.

Considering that there are few studies on the mechanical performance of high-strength reinforced UHPC-CA beams at present, this paper takes the reinforcement grade, reinforcement diameter, effective height of section and concrete strength grade as the factors, and the flexural capacity of high-strength reinforced UHPC-CA beams as the index, analyzes the variation rules of the index with various factors, the influence size and significance of various factors on the index, so as to provide reference for the theoretical research of high-strength reinforced UHPC-CA beams.

2. Test Overview

2.1. Test Scheme Design

Table 1. Test factors and levels

Levels	Factors			
	A	B/mm	C/mm	D/MPa
1	HRB400	14	143	C130
2	HRB500	16	162	C150
3	HRB600	18	181	C180

Table 2. Test scheme design

Test serial number	Orthogonal combination	Factors			
		A	B/mm	C/mm	D/MPa
1	A1B1C1D1	HRB400	14	143	C130
2	A1B2C2D2	HRB400	16	162	C150
3	A1B3C3D3	HRB400	18	181	C180
4	A2B1C2D3	HRB500	14	162	C180
5	A2B2C3D1	HRB500	16	181	C130
6	A2B3C1D2	HRB500	18	143	C150
7	A3B1C3D2	HRB600	14	181	C150
8	A3B2C1D3	HRB600	16	143	C180
9	A3B3C2D1	HRB600	18	162	C130

$L_9(3^4)$ orthogonal test scheme is designed, and four factors are selected: reinforcement grade (factor A), reinforcement diameter (factor B), effective height of section (factor C) and concrete strength grade (factor D). Factor A includes three levels of HRB400, HRB500 and hrb600 reinforcement. The level of factor B includes 14 mm, 16 mm and 18 mm. The section height is 180 mm, 200 mm and 220 mm. Assuming that the thickness of the protective layer is 20 mm

and the diameter of the stirrup is 10 mm, the horizontal values of the corresponding factor C are 143 mm, 162 mm and 181 mm. The three levels of factor D include C130, C150 and C180. The intensity data of C130UHPC-CA is from the doctoral dissertation of Yang Juan [11], C150UHPC-CA is selected from the conference papers of Chen Feixiang et al. [12], and C180UHPC-CA is the data in the master's thesis of Li Shigen [13]. See [Table 1](#) for test factors and levels and [Table 2](#) for test scheme design.

2.2. Specimen Design

[Figure 1](#) shows the section size and reinforcement structure of the beam specimen. In addition to the reinforcement information and section height mentioned above, it can be seen from the figure that the section width of the beam is 120 mm, the longitudinal tensile reinforcement is 2, and the stirrup is selected $\phi 10@100$. The diameter of the erection bar is 10 mm.

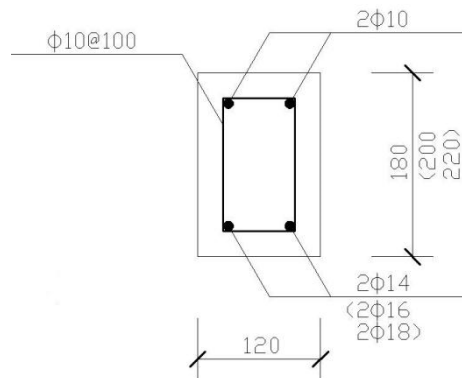


Figure 1. Section size and reinforcement structure of beam specimen

2.3. Calculation of Bending Capacity

Due to the high tensile strength of UHPC-CA, it is necessary to consider the contribution of concrete in the tensile zone when calculating the flexural capacity of the normal section of UHPC-CA beam with high-strength reinforcement. The following calculation method of Zheng Wenzhong et al. [14] is adopted in this study:

$$\alpha f_c b x = f_y A_s + k f_t b \left(h - \frac{x}{\beta} \right) \tag{1}$$

$$M_u = \alpha f_c b x \left(h_0 - \frac{x}{2} \right) - k f_t b \left(h - \frac{x}{\beta} \right) \left[0.5 \left(h - \frac{x}{\beta} \right) - a_s \right] \tag{2}$$

Where: M_u is the flexural capacity of normal section of UHPC-CA beam with high-strength reinforcement; f_c is the design value of axial compressive strength of UHPC-CA; f_t is the design value of axial tensile strength of UHPC-CA; f_y is the design value of tensile strength of longitudinal reinforcement; A_s is the sectional area of longitudinal tensile reinforcement; a_s is the distance from the resultant force point of longitudinal reinforcement to the tensile edge of the section; α 、 β is the equivalent rectangular stress diagram coefficient of the compression zone, $\alpha= 0.9$, $\beta= 0.77$; k is the equivalent rectangular stress diagram coefficient in the tensile zone, $k=0.25$; x is the height of compression zone; b is the section width; h is the section height; h_0 is the effective height of the section.

3. Analysis of Test Results

[Table 3](#) shows the test calculation results of bending capacity of uhpc-ca beams with high-strength reinforcement in each test group.

Table 3. Test calculation results

Test number	Bearing capacity/kN·m	Test number	Bearing capacity/kN·m	Test number	Bearing capacity/kN·m
1	17.40	4	25.28	7	32.22
2	26.13	5	33.10	8	31.26
3	36.84	6	31.98	9	41.13

3.1. Visual Analysis

According to the analysis of [Table 3](#), the bending bearing capacity of beam specimens in group 9 is the largest, which is 41.13 kN·m. At this time, the orthogonal combination is A3B3C2D1, that is, the reinforcement grade is HRB600, the reinforcement diameter is 18 mm, the effective height of the section is 162 mm, and the UHPC-CA strength grade is C130; The bending capacity of the first group of specimen beams is the lowest, which is 17.40 kN·m. At this time, the orthogonal combination is A1B1C1D1, that is, the reinforcement grade is HRB400, the reinforcement diameter is 14 mm, the effective height of the section is 143 mm, and the UHPC-CA strength grade is C130. According to the comparative analysis, for C130UHPC-CA, the bending capacity of the beam increased by 23.73 kN·m, or 136.4%, with the reinforcement grade (from HRB400 to hrb600), the reinforcement diameter (from 14 mm to 18 mm) and the effective height of the section (from 143 mm to 162 mm) increased at the same time.

3.2. Range Analysis

[Table 4](#) shows the extreme value of the influence of four factors, namely, reinforcement grade, reinforcement diameter, effective height of section and UHPC-CA strength grade, on the bending capacity of UHPC-CA beams with high strength reinforcement. It can be seen that the range values corresponding to factors A, B, C and D are 8.08, 11.68, 7.18 and 1.02 respectively. The influence of each factor on the bending capacity is B> A> C> D from large to small, that is, the reinforcement diameter > reinforcement grade > effective height of section > UHPC-CA strength grade.

Table 4. Range analysis of bending capacity

Parameter	Range/kN·m			
	Factor A	Factor B	Factor C	Factor D
k1	26.79	24.97	26.88	30.54
k2	30.12	30.17	30.85	30.11
k3	34.87	36.65	34.06	31.13
R	8.08	11.68	7.18	1.02

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 variation law of the research index with the factor level, the average value of the bending capacity under each factor level in [Table 4](#) is drawn into a point diagram, as shown in [Figure 2](#). It can be seen from [Figure 2](#) that with the increase of factors A, B and C, the bending capacity of UHPC-CA beam with high-strength reinforcement gradually increases; With the increase of factor D, the flexural capacity first decreases slightly and then increases slightly. When the reinforcement grade is changed from HRB400 to HRB600, the flexural capacity is increased by 30.2%; When the diameter of steel bar increases from 14 mm to 18 mm, the flexural capacity increases by 46.8%; When the effective height of the section increases from 143 mm to 162 mm, the flexural capacity increases by 26.7%. When the strength grade of UHPC-CA is increased from C130 to C150, the flexural capacity is reduced by 1.4%; When C150 is strengthened to C180, the flexural capacity increases by 3.4%; The bending capacity of

C180UHPC-CA is 1.9% higher than that of C130UHPC-CA. It can be seen that the increase of UHPC-CA strength grade does not significantly enhance the flexural capacity of the beam, while the increase of reinforcement grade, reinforcement diameter and effective height of section has a significant effect on the flexural capacity of the beam. Due to the lack of UHPC-CA strength grade data selected in this study, the variation of bending capacity of high-strength reinforced UHPC-CA beams with UHPC-CA strength grade needs to be further studied.

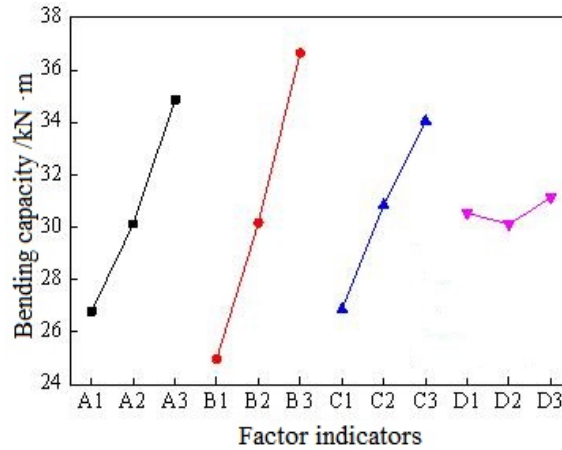


Figure 2. Variation of flexural capacity with factor level

3.4. Matrix Analysis

In order to calculate the influence weight of each factor on the horizontal bending capacity, the research index is analyzed by matrix. Compile the range analysis and calculation results in Table 4 in the form of matrix according to the method in literature [15] and input them into the MATLAB software window for operation. The final matrix calculation results are listed 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 the bending capacity, and the weight value is 0.1098; Among the three levels of reinforcement diameter, B3 has the largest influence weight, which is 0.1668; Among the three levels of section effective height, C3 has the largest influence weight, which is 0.0953; Among the three levels of UHPC-CA strength grade, D3 has the largest influence weight, with a value of 0.0124. Therefore, the combination is A3B3C3D3, that is, when the reinforcement grade is hrb600, the reinforcement diameter is 18 mm, the effective height of the section is 181 mm, and the UHPC-CA strength grade is C180, the bending capacity of the UHPC-CA beam with high-strength reinforcement will reach the maximum.

Table 5. Matrix analysis of bending capacity

Factor level	Weight value	Factor level	Weight value
A1	0.084 4	C1	0.075 2
A2	0.094 8	C2	0.086 3
A3	0.109 8	C3	0.095 3
B1	0.113 7	D1	0.012 1
B2	0.137 3	D2	0.012 0
B3	0.166 8	D3	0.012 4

3.5. Variance Analysis

In order to obtain the significance of the effect of each factor on the bending capacity, the variance analysis of the research indicators is carried out. The variance analysis results of the bending capacity are shown in Table 6. It can be seen from Table 6 that factors A, B and C have a significant impact on the bending capacity, while factor D has no significant impact. The diameter of steel bar is an important significant factor, which has the greatest impact on the

flexural capacity; The grade of reinforcement and the effective height of the section are generally significant factors, and the influence of the grade of reinforcement on the flexural capacity is higher than that of the effective height of the section; The influence of concrete strength grade is the least. It can be seen that the above analysis results are consistent with the range analysis.

Table 6. Variance analysis of bending capacity

Factor	Sum of squared deviations	Freedom	Mean square	F value	Critical value	Significance
A	98.9	2	49.4	63.4	$F_{0.01}(2,2)=99.0$	*
B	205.5	2	102.8	131.8		**
C	77.5	2	38.8	49.7	$F_{0.05}(2,2)=19.0$	*
D	1.6	2	0.8	1.0	$F_{0.10}(2,2)=9.0$	

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.

3.6. Bearing Capacity-Reinforcement Ratio Analysis

The reinforcement ratio of longitudinal reinforcement is equal to the ratio of the total sectional area of longitudinal reinforcement to the effective sectional area [16]. In this study, the reinforcement ratio of each specimen beam changes with the simultaneous change of factor B (reinforcement diameter) and factor C (effective height of section). From the above analysis, it can be seen that factor D (UHPC-CA strength grade) has little effect on the bending capacity of UHPC-CA beam with high-strength reinforcement. If this factor is ignored, the change of bending capacity with reinforcement ratio under different reinforcement grades (factor A) can be obtained, as shown in [Figure 3](#).

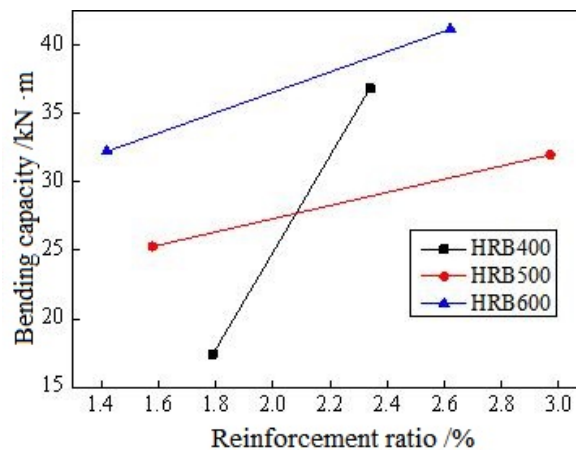


Figure 3. Variation of flexural capacity with reinforcement ratio

It can be seen from [Figure 3](#) that for HRB400 reinforced series beams, when the reinforcement ratio increases from 1.79% to 2.34%, the flexural capacity of UHPC-CA beams with high-strength reinforcement increases by 111.7%; For the HRB500 reinforced series beams, when the reinforcement ratio increases from 1.58% to 2.97%, the flexural capacity of the beams increases by 26.5%; For HRB600 reinforced series beams, when the reinforcement ratio is increased from 1.42% to 2.62%, the flexural capacity is increased by 27.7%. It can be seen that

the increment of reinforcement ratio (0.55%) of HRB400 reinforced series beams is the lowest, while the bearing capacity is increased the most; The increment of reinforcement ratio of HRB500 and HRB600 reinforced series beams is close, which is 1.39% and 1.20% respectively. The increase of bearing capacity is close, and both are lower than that of HRB400 reinforced series beams. The results show that the ratio of longitudinal reinforcement has a great influence on the flexural capacity of UHPC-CA beams with ordinary reinforcement (HRB400), while it has a relatively small influence on the flexural capacity of UHPC-CA beams with high-strength reinforcement (HRB500, HRB600).

4. Conclusion

- 1) It can be seen from the visual analysis that the orthogonal combination is A3B3C2D1, that is, when the reinforcement grade is HRB600, the reinforcement diameter is 18 mm, the effective height of the section is 162 mm, and the concrete strength grade is C130, the bending bearing capacity of the beam is high.
- 2) According to the range analysis, the influence of various factors on the bending capacity of UHPC-CA beams with high-strength reinforcement is in the order of reinforcement diameter > reinforcement grade > effective height of section > concrete strength grade.
- 3) According to the factor index analysis, with the increase of reinforcement grade, reinforcement diameter and effective height of section, the flexural capacity increases by 30.2%, 46.8% and 26.7% respectively; With the increase of UHPC-CA strength grade, the flexural capacity first decreased slightly and then increased slightly.
- 4) According to the matrix analysis, among the three levels of respective factors, A3 (HRB600), B3 (18 mm), C3 (181 mm) and D3 (C180) have the largest influence weight on the bending capacity.
- 5) According to the analysis of variance, the diameter of steel bar is an important significant factor of bending capacity, the grade of steel bar and the effective height of section are generally significant factors, and the strength grade of concrete is not significant factor.
- 6) From the analysis of bearing capacity reinforcement ratio, it can be seen that with the increase of reinforcement ratio, the flexural capacity of HRB400 reinforced series beams is significantly improved, while the increase of flexural capacity of HRB500 and HRB600 reinforced series beams is relatively small.

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