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Orthogonal Analysis of Shear Capacity of Ultra High Performance Concrete Beams with High Strength Reinforcement and Coarse Aggregate

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Abstract

The influence of seven factors, including shear span ratio, reinforcement grade, reinforcement diameter, reinforcement spacing, section width, section height, and concrete strength, on the shear bearing capacity of Ultra high performance concrete with coarse aggregate (UHPC-CA) beams containing high-strength steel bars was analyzed using orthogonal experimental method. The results show that the influence of various factors on the shear bearing capacity of high-strength steel reinforced UHPC-CA beams, from large to small, is in the order of section width>concrete strength>shear span ratio>section height>hoop diameter>hoop spacing>hoop grade. The shear capacity of high-strength reinforced UHPC-CA beams decreases with the increase of shear span ratio and hoop spacing, and increases with the increase of hoop grade, hoop diameter, section width, section height, and strength of ultra-high performance concrete containing coarse aggregates.

Keywords

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

1. Introduction

Ultra high performance concrete with coarse aggregate (UHPC-CA) refers to ultra-high performance concrete (UHPC) containing coarse aggregates (CA), basalt, limestone, etc., with a compressive strength greater than 100 MPa. It belongs to the category of UHPC along with reactive powder concrete (RPC). Due to its ultra-high strength, toughness, and durability, UHPC-CA has received widespread attention from scholars both domestically and internationally. Cheng Jun et al. [2] analyzed the effect of different CA content on the compressive strength and elastic modulus of UHPC. The results indicate that CA has little effect on compressive strength, but has a significant effect on improving elastic modulus. When the CA content increased from 0 to 480 kg/m3, the compressive strength only decreased by 3.7 MPa and the elastic modulus increased by 7.3%. Research by Peng Gaifei et al. has shown that the residual compressive strength of UHPC-CA is higher than that of RPC at different target temperatures, and CA has a significant effect on improving the residual compressive strength of UHPC [3]; Under different moisture contents, the burst temperature range of UHPC-CA is smaller than that of RPC, the duration is shorter, the number of burst sounds is fewer, the internal temperature difference of the specimen is smaller, and the cumulative sieve residue of 90mm sized fragments is larger. UHPC-CA has better high-temperature burst performance than RPC, and CA is beneficial for improving the high-temperature burst performance of UHPC [4].

The application of high-strength steel bars in structures can save steel consumption, increase structural span, and improve safety reserves. Combining high-strength steel bars with UHPC can fully utilize their excellent mechanical properties [6]. Sun Mingde et al. [7] studied the bond performance between HRB400, HRB500 grade steel bars and RPC under multiple factor conditions. The results show that the ultimate bond stress τ u between the two decreases with the increase of steel bar diameter and bond length, and increases with the increase of curing age and steel bar strength. Properly thickening the protective layer and configuring stirrups can improve τ u. Jin Lingzhi et al. [8] conducted flexural performance tests on five sets of high-strength steel reinforced RPC beams with different reinforcement ratios and forms. The results showed that when the reinforcement ratio was the same, the deflection value of HRB400 grade reinforced RPC beams was lower than that of HRB500 grade reinforced RPC beams, and the bearing capacity of the former was significantly lower than that of the latter. The crack development of the two was similar; When the longitudinal reinforcement strength is the same, the increase in the average crack spacing of RPC beams is inversely proportional to the increase in reinforcement ratio; Finally, it is suggested that the coefficient of the equivalent rectangular stress diagram in the tensile zone in the calculation formula for the flexural bearing capacity of high-strength reinforced RPC beams be 0.3. The shear performance test of high-strength reinforced RPC beams by Zhang Meng et al. [9] showed that the inclination angle of shear diagonal cracks decreases with the increase of shear span ratio λ, and the cracking load has no significant relationship with λ, while the ultimate load decreases with the increase of λ. Fu Qiang et al. [10] found that when calculating the deflection of high-strength reinforced RPC beams using the method in GB 50010-2010, the deflection test value was about 16% lower than the calculated value. Therefore, it is recommended to introduce a deflection reduction factor of 0.84. It can be seen that there is currently more research on high-strength reinforced RPC beams, but a lack of research on high-strength reinforced UHPC-CA beams.

Based on this, this article takes high-strength steel reinforced UHPC-CA beams as the research object, analyzes the influencing factors of the shear bearing capacity of high-strength steel reinforced UHPC-CA beams, including shear span ratio, stirrup grade, stirrup diameter, stirrup spacing, section width, section height, and strength of ultra-high performance concrete containing coarse aggregates, in order to provide reference for the theoretical research of high-strength steel reinforced UHPC-CA beams.

2. Experimental Overview

2.1. Experimental Plan Design

The L_8 (2^7) orthogonal experimental scheme was designed to determine seven factors: shear span ratio (factor A), reinforcement grade (factor B), reinforcement diameter (factor C), reinforcement spacing (factor D), section width (factor E), section height (factor F), and concrete strength (factor G). Each factor corresponds to two levels, and the experimental factors and levels are shown in Table 1. Among the two levels of factor G, C130UHPC-CA was selected from the 0.18UHPC-HF3 experimental group in Yang Juan's doctoral thesis [11]. The steel fiber (SF) had a length of 30 mm, a diameter of 1 mm, a dosage of 1.15%, an end hook type, and a tensile strength of 1800-2000 MPa; C150UHPC-CA is selected from the 0.18UHPC-RSFR test group in reference [11]. The SF length is 40 mm, the diameter is 1.1 mm, the dosage is 1.15%, the type is corrugated, and the tensile strength is 1800-2000 MPa. The experimental plan design is shown in Table 2.

Table 1. Experimental factors and levels

Level	Factor						
	A	B	C/mm	D/mm	E/mm	F/mm	G/MPa
1	1.5	HRB400	10	150	200	500	C130
2	2.0	HRB500	12	200	250	550	C150

Table 2. Experimental plan design

No.	Orthogonal combination	Factor						
		A	B	C/mm	D/mm	E/mm	F/mm	G/MPa
No.1	A1B1C1D1E1F1G1	1.5	HRB400	10	150	200	500	C130
No.2	A1B1C2D1E2F2G2	1.5	HRB400	12	150	250	550	C150
No.3	A1B2C1D2E1F2G2	1.5	HRB500	10	200	200	550	C150
No.4	A1B2C2D2E2F1G1	1.5	HRB500	12	200	250	500	C130
No.5	A2B1C1D2E2F1G2	2.0	HRB400	10	200	250	500	C150
No.6	A2B1C2D2E1F2G1	2.0	HRB400	12	200	200	550	C130
No.7	A2B2C1D1E2F2G1	2.0	HRB500	10	150	250	550	C130
No.8	A2B2C2D1E1F1G2	2.0	HRB500	12	150	200	500	C150

2.2. Test Piece Design

According to the orthogonal combination scheme, there are four situations for the section width b x section height h of the beam: 200 mm x 500 mm, 200 mm x 550 mm, 250 mm x 500 mm, and 250 mm x 550 mm. The calculated length L of the beam varies with the shear span ratio and section height. When the shear span ratio is 1.5, L=2070 mm (h=500mm) or 2295 mm (h=550mm); When the shear span ratio is 2.0, L=2760mm (h=500mm) or 3060mm (h=550mm). The two ends of the beam are simply supported and adopt a two-point symmetrical concentrated loading method, with the loading point acting at the three-point position. HRB500 grade steel bars with a diameter of 20mm and 2 pieces are selected for longitudinal tensile reinforcement; HPB300 grade steel bars with a diameter of 10mm and 2 pieces are selected for the erection reinforcement; There are HRB400 and HRB500 grades of stirrups, with diameters of 10mm and 12mm, spacing of 150mm and 200mm, and a total of 2 stirrups, namely double leg stirrups.

2.3. Calculation of Shear Capacity

On the basis of the truss arch model, Jin Lingzhi et al. [12] considered the softening coefficient of UHPC-CA, the bridge action of SF, and the bolt action of longitudinal reinforcement. Based on the measured data of the shear bearing capacity of the beam, a calculation method for the shear bearing capacity of high-strength reinforced UHPC-CA beams was constructed, as shown in Equations (1-3).

$$V_u = 0.465\left(\sqrt{\lambda^2 + m^2} - \lambda + 0.035\beta_v\lambda_f\right)f_c bh \tag{1}$$

$$m = 1 + 1.637\frac{\rho_{sv}f_{yv}}{f_c}\lambda^2 \tag{2}$$

$$\lambda_f = \rho_f\frac{l_f}{d_f} \tag{3}$$

Where: V_u represents the shear capacity of high-strength reinforced UHPC-CA beams; λ is the shear span ratio; m is the coefficient; β_v is the coefficient of influence of SF on shear capacity; λ_f is the characteristic value of SF content; f_c is the design value of the axial compressive strength of UHPC-CA; b is the cross-sectional width; h is the height of the cross-section; ρ_{sv} is the coupling ratio; f_{yv} is the design value of the tensile strength of steel bars; ρ_f is the SF content; l_f is the length of SF; d_f is the diameter of SF.

3. Analysis of Test Results

3.1. Visual Analysis

Table 3 shows the calculation results of the shear bearing capacity of UHPC-CA beams with high-strength steel bars in each experimental group. According to the table, when the orthogonal combination is A1B1C2D1E2F2G2, the shear bearing capacity of the high-strength steel bar UHPC-CA beam is the highest, at 2466.5 kN; when the orthogonal combination is A2B1C2D2E1F2G1, the shear bearing capacity of the beam is the lowest, at 1479.7 kN. Comparative analysis shows that when the stirrup grade is HRB400, the stirrup diameter is 10 mm, and the section height is 550 mm, changing the shear span ratio (from 2.0 to 1.5), the stirrup spacing (from 200 mm to 150 mm), the section width (from 200 mm to 250 mm), and the concrete strength (from C130 to C150) simultaneously increases the shear bearing capacity of the beam. 986.8 kN, an increase of 66.7%, with a significant growth effect.

Table 3. Calculation results of shear capacity

Orthogonal combination	Shear capacity/kN	Orthogonal combination	Shear capacity/kN
A1B1C1D1E1F1G1	1524.5	A2B1C1D2E2F1G2	1748.3
A1B1C2D1E2F2G2	2466.5	A2B1C2D2E1F2G1	1479.7
A1B2C1D2E1F2G2	1922.6	A2B2C1D1E2F2G1	1805.3
A1B2C2D2E2F1G1	1916.1	A2B2C2D1E1F1G2	1720.7

3.2. Range Analysis

Table 4 shows the range values of the influence of seven factors, including shear span ratio, stirrup grade, stirrup diameter, stirrup spacing, section width, section height, and concrete strength, on the shear bearing capacity of high-strength reinforced UHPC-CA beams. It can be seen that the range values corresponding to factors A, B, C, D, E, F, and G are 268.9, 36.4, 145.6, 112.6, 322.2, 191.1, and 283.1, respectively. The order of the influence of each factor on shear bearing capacity is E>G>A>F>C>D>B, that is, section width>concrete strength>shear span ratio>section height>hoop diameter>hoop spacing>hoop grade.

Table 4. Range analysis of shear capacity

Parameter	Range/kN						
	Factor A	Factor B	Factor C	Factor D	Factor E	Factor F	Factor G
k1	1957.4	1804.8	1750.2	1879.3	1661.9	1727.4	1681.4
k2	1688.5	1841.2	1895.8	1766.7	1984.1	1918.5	1964.5
R	268.9	36.4	145.6	112.6	322.2	191.1	283.1

Note: ki is the average value of the experimental results at the level of each factor i; R is extremely poor.

3.3. Matrix Analysis

Based on the method in reference [13], the range analysis calculation results in Table 4 were written in matrix form and input into MATLAB software for solution. The weight values of the influence of factor levels on shear bearing capacity were listed in Table 5. According to the table, in the two levels of shear span ratio, A1 has a greater weight on the shear bearing capacity of high-strength reinforced UHPC-CA beams, with a weight value of 0.1062; Among the two levels of hoop reinforcement grade, hoop reinforcement diameter, and hoop reinforcement spacing, B2, C2, and D1 have a greater weight on the shear bearing capacity of the beam, with values of 0.0135, 0.0557, and 0.0427, respectively; In the two levels of section width and section height, E2 and F2 have a relatively large influence weight, with values of 0.1289 and 0.0739, respectively; Among the two levels of concrete strength, the influence weight of G2 is relatively large, with a value of 0.1122. Therefore, when the orthogonal combination is A1B2C2D1E2F2G2, the shear bearing capacity of high-strength reinforced UHPC-CA beams will reach its maximum value. At this time, the shear span ratio is 1.5, the reinforcement grade is HRB500, the reinforcement diameter is 12 mm, the reinforcement spacing is 150 mm, the section width is 250 mm, the section height is 550 mm, and the concrete grade is C150.

Table 5. Matrix analysis of shear capacity

Factor level	Weight value	Factor level	Weight value
A1	0.1062	A2	0.0916
B1	0.0132	B2	0.0135
C1	0.0514	C2	0.0557
D1	0.0427	D2	0.0401
E1	0.1080	E2	0.1289
F1	0.0666	F2	0.0739
G1	0.0960	G2	0.1122

3.4. Factor Indicator Analysis

In order to obtain the variation law of the shear bearing capacity of high-strength reinforced UHPC-CA beams with the level of factors, the average values of the research indicators at each factor level in Table 4 were plotted as point graphs, as shown in Fig. 1. As shown in the figure, the shear bearing capacity of high-strength reinforced UHPC-CA beams increases with the increase of factors B, C, E, F, and G, and decreases with the increase of factors A and D. The magnitude of the change in shear bearing capacity is shown in Table 6, where+represents improvement and - represents decrease. For example, when the shear span ratio increases from 1.5 to 2.0, the decrease in bearing capacity is 15.9%; When the reinforcement level is increased from HRB400 to HRB500, the increase in bearing capacity is 2.0%; Other similar categories will not be further elaborated.

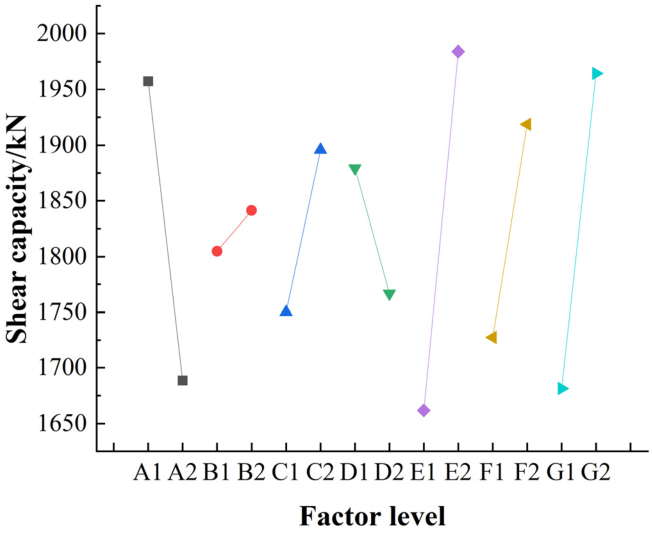

Fig 1. The variation of shear capacity with factor level

Table 6. Change amplitude of shear capacity

Factor	A	B	C	D	E	F	G
Change amplitude/%	-15.9	+2.0	+8.3	-6.4	+19.4	+11.1	+16.8

3.5. Analysis of Capacity and Stirrup Ratio

The reinforcement ratio is equal to the ratio of the total cross-sectional area of each limb of the reinforcement to the product of the cross-sectional width and the spacing between the reinforcement [14]. In this study, the reinforcement ratio of each specimen beam varies with the simultaneous changes of factor C (reinforcement diameter), factor D (reinforcement spacing), and factor E (cross-sectional width). Fig. 2 shows the variation of the shear bearing capacity of high-strength reinforced UHPC-CA beams with the reinforcement ratio when the shear span ratio is 1.5. As shown in the figure, when the reinforcement ratio increases from 0.52% to 0.60%, factors F (section height) and G (concrete grade) also increase correspondingly. At this time, the bearing capacity value increases by a total of 61.8%. If the contributions of factors F and G are deducted by 11.1% and 16.8%, the bearing capacity value increases by 33.9%. Similarly, it can be calculated that when the reinforcement ratio increases from 0.39% to 0.45%, the shear bearing capacity of high-strength steel reinforced UHPC-CA beams increases by 27.6%.

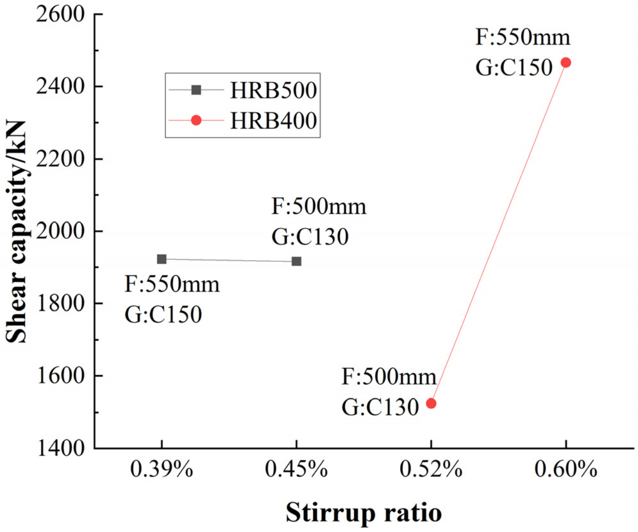

Fig 2. The variation of shear capacity with stirrup ratio

4. Conclusion

(1) From intuitive analysis, it can be seen that when the orthogonal combination is A1B1C2D1E2F2G2, the shear bearing capacity of high-strength reinforced UHPC-CA beams is relatively high; When the orthogonal combination is A2B1C2D2E1F2G1, the shear bearing capacity is relatively small.

(2) According to the range analysis, the order of the influence of various factors on shear bearing capacity from large to small is section width>concrete strength>shear span ratio>section height>hoop diameter>hoop spacing>hoop grade.

(3) According to matrix analysis, among the two levels of each factor, A1 (1.5), B2 (HRB500 level), C2 (12 mm), D1 (150 mm), E2 (250 mm), F2 (550 mm), and G2 (C150) have a greater weight on the influence of shear bearing capacity. When the orthogonal combination is A1B2C2D1E2F2G2, the shear bearing capacity of high-strength reinforced UHPC-CA beams will reach its maximum.

(4) According to the analysis of factor indicators, with the increase of shear span ratio and hoop spacing, the decrease in shear bearing capacity of high-strength steel reinforced UHPC-CA beams is 15.9% and 6.4%, respectively; With the increase of reinforcement grade, reinforcement diameter, section width, section height, and concrete strength, the growth rates are 2.0%, 8.3%, 19.4%, 11.1%, and 16.8%, respectively.

(5) According to the analysis of bearing capacity and reinforcement ratio, when the reinforcement ratio increases from 0.39% to 0.45% and from 0.52% to 0.60%, the shear bearing capacity of high-strength reinforced UHPC-CA beams increases by 27.6% and 33.9%, respectively.

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