ISSN: 2688-8645

Orthogonal Analysis of Axial Bearing Capacity of Long Columns Reinforced by Circular Steel Tube and Ultra High Performance Concrete with Coarse Aggregate

Weidong Zhang, Guanyu Zhu, Jiajun Tang *

School of Civil Engineering, Changchun Institute of Technology, Changchun Jilin, 130012, China

* Corresponding author: Jiajun Tang

Abstract

The influence of steel pipe wall thickness, steel pipe length, ultra high performance concrete with coarse aggregate (UHPC-CA) strength, and steel grade on the axial compressive bearing capacity of round steel pipe UHPC-CA long columns was analyzed using orthogonal experimental method. The results indicate that the influence of various factors on the axial compressive bearing capacity of round steel tube UHPC-CA long columns is in the order of steel grade>steel tube wall thickness>steel tube length>UHPC-CA strength. The axial compressive bearing capacity increases with the increase of steel pipe wall thickness, UHPC-CA strength, and steel grade, and decreases with the increase of steel pipe outer diameter. When the aspect ratio is 8 and 10, the axial compressive bearing capacity increases with the increase of the hoop coefficient. When the aspect ratio is 12, the axial compressive bearing capacity first decreases and then increases with the increase of the hoop coefficient.

Keywords

Ultra High Performance Concrete with Coarse Aggregate (UHPC-CA); Circular Steel Tube; Axial Bearing Capacity; Hoop Coefficient.

1. Introduction

It is generally believed that Ultra high performance concrete (UHPC) includes two types: reactive powder concrete (RPC) without coarse aggregates, and Ultra high performance concrete with coarse aggregates (UHPC-CA) with compressive strength higher than 100 MPa. Previous studies have shown that the addition of coarse aggregates can reduce the shrinkage deformation and cost of UHPC [2]; Coarse aggregate has a significant effect on improving the residual compressive strength of UHPC after high temperature [3]; Coarse aggregate is beneficial for improving the high-temperature cracking performance of UHPC [4]. Due to its excellent mechanical and durability properties, the research on UHPC-CA has become a hot topic in the field of concrete research.

Compared with reinforced concrete columns, steel reinforced concrete columns have advantages such as high bearing capacity, good ductility, fatigue resistance, impact resistance, and fast construction speed [5]. Yan Zhigang et al. [6] studied the interfacial bonding performance of RPC short columns made of circular steel pipes through axial push tests. The results indicate that the experimental phenomena, failure modes, and load slip curves of RPC short columns made of round steel tubes have similar patterns to those of ordinary steel-concrete columns. Wang Yifeng et al. [7] analyzed the effects of loading methods (axial compression and eccentric compression) and hoop coefficient ξ on the compressive performance of RPC short columns made of circular steel pipes using ABAQUS software. The results indicate that with the increase of ξ, the ultimate bearing capacity of circular steel tube

RPC short columns under both loading modes is improved to varying degrees. Luo Hua [8] plotted the measured data of 96 sets of circular steel tube RPC short columns into a $N_u/(f_cA_c)$ - ξ scatter plot, and used Qrigin software to perform linear fitting and polynomial fitting. Finally, he proposed the calculation formulas for the linear and quadratic functions of the axial compressive bearing capacity of circular steel tube RPC short columns. Rong Qin et al. [9] found that with the increase of ξ, the failure type of RPC short columns with round steel pipes changed from shear failure (ξ between 0.63-0.88) to waist drum failure ($\xi \geq 1$). It can be seen that there is currently more research on circular steel tube RPC columns, but a lack of research on circular steel tube UHPC-CA columns.

Therefore, this article takes the steel pipe wall thickness, steel pipe length, strength of ultra-high performance concrete containing coarse aggregates, and steel grade as factors, and the axial compressive bearing capacity of round steel pipe UHPC-CA long columns as indicators. Through intuitive analysis, range analysis, analytic hierarchy process, factor index analysis, and bearing capacity hoop coefficient analysis, the changes in axial compressive bearing capacity are studied, providing reference for subsequent experimental research on round steel pipe UHPC-CA long columns.

2. Experimental Overview

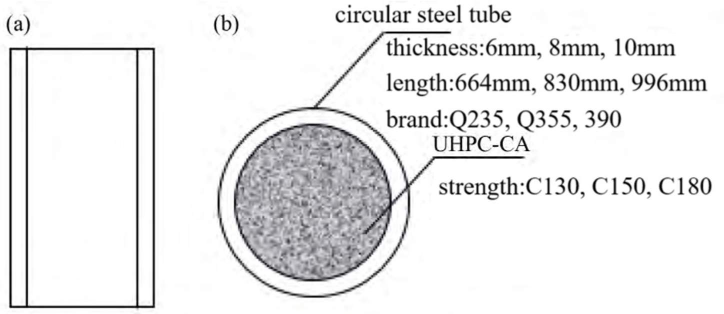
2.1. Experimental Plan Design

Table 1. Experimental factors and levels

Level	Factor			
	A/mm	B/mm	C	D
1	6	664	C130	Q235
2	8	830	C150	Q355
3	10	996	C180	Q390
4	6	664	C130	Q235

Table 2. Experimental plan design

No.	Orthogonal combination	Factor			
		A/mm	B/mm	C	D
No.1	A1B1C1D1	6	664	C130	Q235
No.2	A1B2C2D2	6	830	C150	Q355
No.3	A1B3C3D3	6	996	C180	Q390
No.4	A2B1C2D3	8	664	C150	Q390
No.5	A2B2C3D1	8	830	C180	Q235
No.6	A2B3C1D2	8	996	C130	Q355
No.7	A3B1C3D2	10	664	C180	Q355
No.8	A3B2C1D3	10	830	C130	Q390
No.9	A3B3C2D1	10	996	C150	Q235



(a)Vertical view (b)Sectional view

Fig 1. Vertical and sectional views of columns

The L_9 (3^4) orthogonal experimental scheme was designed to determine four factors: steel pipe wall thickness (factor A), steel pipe length (factor B), strength of ultra-high performance concrete containing coarse aggregates (factor C), and steel grade (factor D). Each factor corresponds to three levels, and the experimental factors and levels are shown in Table 1. Among them, factor A includes three types: 6mm, 8mm, and 10mm; There are three levels of factor B: 664 mm, 830 mm, and 996 mm; The three levels of factor C, C130, C150, and C180UHPC-CA, are derived from data in papers by Peng Gaifei [10], Yang Juan [11], and Huang Zhengyu [12], respectively. The standard compressive strength values of UHPC-CA cubes at 28 days of age are 130.3 MPa, 154.3 MPa, and 180.1 MPa, respectively. The three levels of factor D are Q235, Q355, and Q390. A total of 9 sets of round steel pipe UHPC-CA long columns were designed, with an outer diameter of 83 mm and a length to diameter ratio controlled between 8 and 12. The test plan design is shown in Table 2, and the column elevation and section are shown in Fig. 1.

2.2. Calculation of Axial Compressive Bearing Capacity

The calculation of the axial compressive bearing capacity of UHPC-CA long columns with round steel pipes adopts the calculation method in reference [13]. Based on the axial compressive bearing capacity of short columns, a slenderness ratio reduction factor is introduced, and the ultimate bearing capacity calculation formula is shown in Equations (1-4).

$$N_{\mathrm{cr}} = \varphi N_{\mathrm{u}} \tag{1}$$

$$\varphi = 1 - 0.115\sqrt{L/D - 4} \tag{2}$$

$$N_{\mathrm{u}} = f_{\mathrm{c}} A_{\mathrm{c}} \left(1 + 1.188\xi\right) \tag{3}$$

$$\xi = f_{\mathrm{s}} A_{\mathrm{s}} / f_{\mathrm{c}} A_{\mathrm{c}} \tag{4}$$

Where: N_{cr} is the axial compressive bearing capacity of UHPC-CA long columns made of round steel pipes; φ is the slenderness ratio reduction factor; N_u is the axial compressive bearing capacity of UHPC-CA short columns made of round steel pipes; L is the length of the steel pipe or column; D is the outer diameter of the steel pipe; f_c is the design value of the axial compressive strength of UHPC-CA; A_c is the cross-sectional area of the core UHPC-CA inside the steel pipe; ξ is the hoop coefficient; f_s is the design value of compressive strength of steel; A_s is the cross-sectional area of the steel pipe.

3. Analysis of Test Results

3.1. Visual Analysis

Table 3. Calculation results of axial compressive bearing capacity

No.	Capacity/kN	No.	Capacity/kN	No.	Capacity/kN
No.1	569.3	No.4	894.0	No.7	948.5
No.2	691.2	No.5	671.5	No.8	883.6
No.3	744.9	No.6	682.3	No.9	627.0

Table 3 shows the calculation results of the axial compressive bearing capacity of UHPC-CA long columns made of circular steel pipes in each orthogonal experimental group. According to the table, the axial compressive bearing capacity of the first group of specimen columns is the lowest, at 569.3 kN, and the orthogonal combination at this time is A1B1C1D1; The maximum axial compressive bearing capacity of the 7th group of column specimens is 948.5 kN, and the orthogonal combination at this time is A3B1C3D2. Comparative analysis shows that when the length of the steel pipe is 664 mm, while increasing its wall thickness (from 6 mm to 10 mm), UHPC-CA strength (from C130 to C180), and steel grade (from Q235 to Q355), the axial compressive bearing capacity of the round steel pipe UHPC-CA short column increases by 379.2 kN, an increase of 66.6%, and the growth effect is significant.

3.2. Range Analysis

Table 4 shows the range values of the influence of four factors, including steel pipe wall thickness, steel pipe length, UHPC-CA strength, and steel grade, on the axial compressive bearing capacity of round steel pipe UHPC-CA long columns. It can be seen that the range values corresponding to factors A, B, C, and D are 151.3, 119.2, 76.6, and 218.3, respectively. The order of the influence of each factor on the axial compressive bearing capacity is D>A>B>C, that is, steel grade>steel pipe wall thickness>steel pipe length>UHPC-CA strength.

Table 4. Range analysis of axial compressive bearing capacity

Parameter	Range/kN			
	Factor A	Factor B	Factor C	Factor D
k1	668.5	803.9	711.7	622.6
k2	749.3	748.8	737.4	774.0
K3	819.7	684.8	788.3	840.9
R	151.3	119.2	76.6	218.3
Note: ki is the average value of the experimental results at the level of each factor i; R is extremely poor.				

3.3. Hierarchical Analysis

In order to obtain the influence weights of various factor levels on the axial compressive bearing capacity of UHPC-CA short columns made of round steel pipes, a hierarchical analysis was conducted on the research indicators. Based on the method described in reference [14], the range analysis 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 axial compressive bearing capacity were listed in Table 5. According to the table, among the three levels of steel pipe wall thickness, A3 has the highest weight on the axial compressive bearing capacity of round steel pipe UHPC-CA long columns, with a weight value of 0.0981; Among the three levels of steel pipe length, B1 has the highest weight on the axial compressive bearing capacity, with a value of 0.0758; Among the three levels of UHPC-CA strength, C3 has the highest influence weight, with a value of 0.0477; Among the three levels of steel strength, D3 has the highest influence weight, with a value of 0.1451. Therefore, when combined as A3B1C3D3, the axial compressive bearing capacity of the round steel tube UHPC-CA long column will reach its maximum value. At this time, the corresponding steel tube wall thickness is 10 mm, steel tube length is 664 mm, UHPC-CA strength is C180, and steel strength is Q390.

Table 5. Hierarchical analysis of axial compressive bearing capacity

Factor level	Weight value	Factor level	Weight value
A1	0.0800	C1	0.0431
A2	0.0896	C2	0.0447
A3	0.0981	C3	0.0477
B1	0.0758	D1	0.1075
B2	0.0706	D2	0.1336
B3	0.0645	D3	0.1451

3.4. Factor Indicator Analysis

Fig. 2 shows the variation of axial compressive bearing capacity of UHPC-CA long columns made of round steel pipes with the level of factors. As shown in the figure, with the increase of factors A, C, and D, the axial compressive bearing capacity of UHPC-CA long columns with round steel pipes gradually increases; As factor B increases, the axial compressive bearing capacity gradually decreases. When the wall thickness of the steel pipe increased from 6mm to 10mm, the axial compressive bearing capacity increased by 22.6%; When the strength of UHPC-CA increases from C130 to C180, the axial compressive bearing capacity increases by 10.8%; When the steel grade changes from Q235 to Q390, the axial compressive bearing capacity increases by 35.1%; When the length of the steel pipe increased from 664 mm to 996 mm, the axial compressive bearing capacity decreased by 17.4%. It can be seen that the steel grade has the greatest impact on the axial compressive bearing capacity of round steel tube UHPC-CA long columns, while the impact on UHPC-CA strength is the smallest. The above analysis results are consistent with the range analysis results.

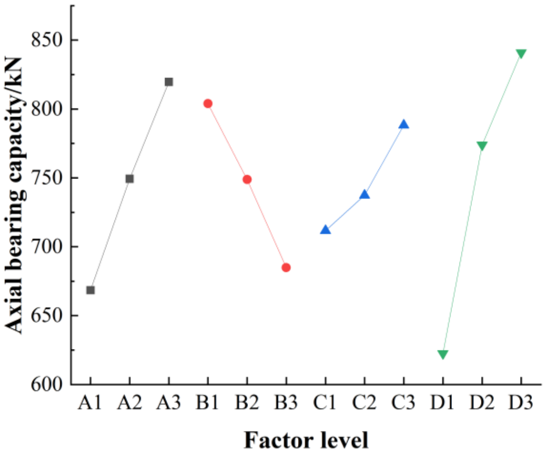


Fig 2. The variation of axial compressive bearing capacity with factor level

3.5. Analysis of Bearing Capacity and Hoop Coefficient

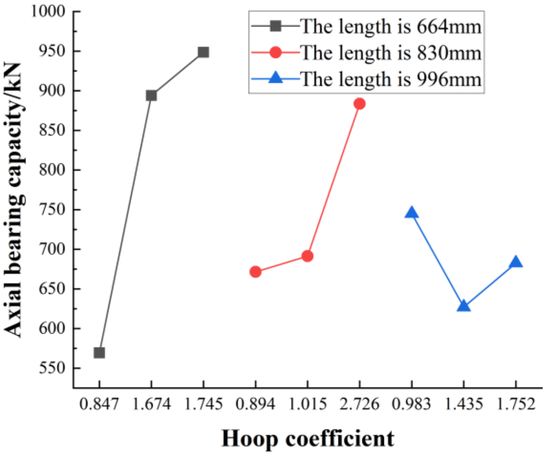


Fig 3. The variation of axial compressive bearing capacity with hoop coefficient

The hoop coefficient ξ changes with the variation of factors A, C, and D. The variation law of the axial compressive bearing capacity of UHPC-CA long columns with different steel pipe lengths (factor B) is shown in Fig. 3. As shown in the figure, when the length of the steel pipe is 664 mm (corresponding to a length to diameter ratio of 8) and 830 mm (corresponding to a length to diameter ratio of 10), the axial compressive bearing capacity increases by 66.7% and 31.6% respectively with the increase of ξ; When the increment of ξ is the same, the increase in axial compressive bearing capacity of UHPC-CA long columns with round steel pipes decreases with the increase of steel pipe length (or length to diameter ratio). At this point, the larger the hoop coefficient ξ, the stronger the lateral constraint effect of the round steel pipe on UHPC-CA, and the more the compressive strength and deformation capacity of the maximum principal stress axis are improved [15]. When the length of the steel pipe is 996 mm and the aspect ratio is 12, the axial compressive bearing capacity decreases by 18.8% as ξ increases from 0.983 to 1.435; When ξ increased from 1.435 to 1.752, the axial compressive bearing capacity increased by 8.9%. It can be seen that the axial compressive bearing capacity of UHPC-CA long columns with round steel pipes does not necessarily increase with the increase of the hoop coefficient ξ, and its relationship is influenced by the range of hoop coefficient and length to diameter ratio values.

4. Conclusion

(1) From intuitive analysis, it can be seen that when the orthogonal combination is A3B1C3D2, the axial compressive bearing capacity of the round steel tube UHPC-CA long column is relatively high; When the orthogonal combination is A1B1C1D1, the axial compressive bearing capacity is relatively small.

(2) According to the range analysis, the influence of various factors on the axial compressive bearing capacity of round steel tube UHPC-CA long columns is ranked in descending order as follows: steel grade>steel tube wall thickness>steel tube length>UHPC-CA strength.

(3) According to hierarchy analysis, among the three levels of each factor, A3 (10 mm), B1 (664 mm), C3 (Q390), and D3 (C180) have the highest influence weight on the axial compressive bearing capacity. When the orthogonal combination is A3B1C3D3, the axial compressive bearing capacity of the round steel tube UHPC-CA long column will reach its maximum value.

(4) According to the analysis of factor indicators, with the increase of steel pipe wall thickness, UHPC-CA strength, and steel grade, the axial compressive bearing capacity increases by 22.6%, 10.8%, and 35.1%, respectively; As the length of the steel pipe increases, the axial compressive bearing capacity decreases by 17.4%.

(5) According to the analysis of bearing capacity and hoop coefficient, when the aspect ratio is 8 and 10, the axial compressive bearing capacity of UHPC-CA long columns of round steel pipes increases with the increase of sleeve coefficient; When the aspect ratio is 12, the axial compressive bearing capacity first decreases and then increases with the increase of the sleeve coefficient.

Acknowledgments

2025 Innovation and Entrepreneurship Training Program for College Students of Changchun Institute of Technology (Project number: 202511437045).

References

[1] Peng Gaifei, Teng Yan, Huang Yanzhu, etc. Research on High Temperature Performance of Ultra High Performance Concrete with Coarse Aggregate in Fire [J]. Journal of North China University of Water Resources and Electric Power, 2013, 34 (1): 1-6.

[2] Yang Fengling, Ji Bank, Liu Wei, etc. Experimental study on ultra-high performance concrete containing coarse aggregates [J]. Concrete, 2018 (12): 110-113.

[3] Peng Gaifei, Yang Juan, Shi Yunxing. Experimental study on residual mechanical properties of ultra-high performance concrete after high temperature [J]. Journal of Civil Engineering, 2017, 50 (4): 73-79.

[4] Peng Gaifei, Yang Juan, Shi Yunxing, etc. Experimental Study on High Temperature Burst Resistance of Ultra High Performance Concrete [J]. Journal of Building Materials, 2017, 20 (2): 229-233+238.

[5] Zhu Yanpeng, Shao Yongjian. Basic Principles of Concrete Structures [M]. Beijing: China Architecture& Building Press, 2012.

[6] Yan Zhigang, Luo Hua, An Mingzhe. Research on the Interface Bonding Performance of Steel Tube Reactive Powder Concrete Columns [J]. Journal of Civil Engineering, 2010, 43 (8): 57-62.

[7] Wang Yifeng, Xu Fenghua, Xu Zhuangzhuang. Analysis of compressive performance of circular steel tube active powder concrete short columns based on ABAQUS [J]. Low temperature Building Technology, 2019, 41 (10): 41-43.

[8] Luo Hua. Research on the Axial Compression Performance of Activated Powder Concrete Short Columns with Circular Steel Tubes [D]. Beijing: Beijing Jiaotong University, 2011.

[9] Rong Qin, Zeng Yusheng, Hou Xiaomeng, etc. Experimental study on axial compression performance of steel fiber reinforced concrete short columns with circular steel tubes [J]. Journal of Building Structures, 2019, 40 (3): 247-253.

[10] Peng Gaifei, Yang Juan, Gao Yuxin, etc. Factors affecting the compressive strength of ultra-high performance concrete containing coarse aggregates [J]. Journal of North China University of Water Resources and Electric Power, 2012, 33 (6): 5-9.

[11] Yang Juan. Experimental Study on High Temperature Mechanical Properties, Bursting and Improvement Measures of Ultra High Performance Concrete with Coarse Aggregate [D]. Beijing: Beijing Jiaotong University, 2017.

[12] Huang Zhengyu, Li Shigen. Research on the Mechanical Properties of Ultra High Performance Concrete with Coarse Aggregate [J]. Journal of Hunan University (Natural Science Edition), 2018, 45 (3): 47-54.

[13] Luo Hua. Experimental and theoretical study on compressive performance of steel tube activated powder concrete columns [D]. Beijing: Beijing Jiaotong University, 2015.

[14] Tang Jiajun, Pei Changchun. Research on Optimal Selection of Mechanical Properties of Multi index Recycled Concrete Based on Queuing Scoring Method and Matrix Analysis Method [J]. Journal of Yanbian University (Natural Science Edition), 2019, 45 (3): 279-282.

[15] Wang Qiuwei, Wang Yang, Zhang Chunyao, etc. Research on the Axial Compression Performance of Steel Tube Activated Powder Concrete Short Columns Based on ABAQUS [J]. Journal of Disaster Prevention and Reduction Engineering, 2019, 39 (3): 421-429.