Finite Element Analysis Of Mechanical Properties Of Hollow Steel Pipe Ultra High Performance Concrete Composite Column

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Abstract. Ultra high performance concrete (UHPC) is a new type of cement-based composite material with superior mechanical and durability properties, which can reduce the self weight of the structure and prolong its service life. Based on this, a finite element model of 10 composite columns was established to analyze the axial compressive stress process, and to explore the effects of concrete strength, UHPC thickness, and hollow ratio on the mechanical properties of composite columns. The results indicate that UHPC has the highest proportion of load sharing under the ultimate bearing capacity state, while steel pipes have the lowest proportion of load sharing. The ultimate bearing capacity and initial stiffness of composite columns can be improved by increasing the concrete strength, UHPC thickness and decreasing the hollow ratio, and the deformation coefficient of composite columns can be reduced by increasing the hollow ratio.

Keywords: Axial compression; Ultimate bearing capacity; UHPC thickness; Concrete strength

1 Introduction

Ultra high performance concrete (UHPC) is a new cement-based composite material with ultra-high strength, high toughness, high durability, impact resistance and other advantages[1,2], which can reduce the structural weight and improve the service life of the structure. The promotion and application of UHPC is conducive to the sustainable and high-quality development of the construction industry[3]. Concrete-filled Double-skin Steel Tubular Columns (CFDST) has the advantages of high bearing capacity and good seismic resistance, but it has some problems such as poor corrosion resistance[4]. Concrete-filled UHPC Tube Composite Column has good corrosion resistance, but the amount of concrete is large[5]. To improve the shortcomings of the two structures, This paper proposes a new type of hollow steel pipe UHPC composite column, which not only improves the bearing capacity and corrosion resistance of the structure, but also reduces the cross-sectional area and self weight. Subsequently, the

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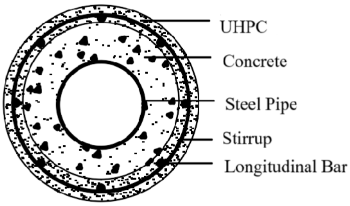
finite element model of the composite column is verified, its stress process under axial compression load is analyzed, and the influence of concrete strength, UHPC thickness, and hollow ratio on its mechanical characteristics is studied.

2 Finite Element Model Building

2.1 Establishment of Finite Element Model

The hollow steel pipe UHPC composite column C1-1 is established, and the cross-section is shown in Figure 1. The diameter of steel pipe and UHPC are 180mm and 430mm respectively, the column length is 1000mm, the thickness of steel pipe, concrete, and UHPC are 4mm, 90mm and 35mm respectively, the diameter of the stirrup and longitudinal bar are 6mm and 8mm respectively.

The plastic damage model (CDP) is used for UHPC and concrete[6], a five-segment linear model is used for the steel pipe[7], and an ideal elastic-plastic stress-strain relationship model is used for stirrups and longitudinal bars[8]. The eight-node linear three-dimensional solid element (C3D8R) is used for UHPC, concrete and steel pipe. The two-node linear three-dimensional truss element (T3D2) is used for Stirrups and longitudinal bars[9]. The loading mode is displacement loading. The finite element model of C1-1 is shown in Figure 2.



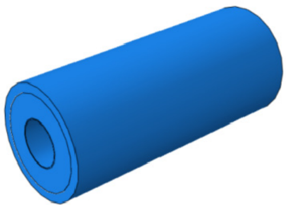
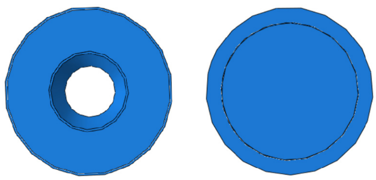


Fig. 1. Cross-section form of C1-1 **Fig. 2.** Finite element model of C1-1

2.2 Verification of Finite Element Model

In order to verify the rationality and accuracy of the above finite element modeling, ABAQUS software is used to establish finite element models numbered CC6a in reference [10] and RUNC-4-60-1 in reference [6]. The cross-sectional form is shown in Figure 3.



(a) CC6a (b) RUNC-4-60-1

Fig. 3. Finite element model of CC6a and RUNC-4-60-1

The comparison results of load-displacement curves are shown in Figure 4. It can be seen from the figure that the load-displacement curves calculated by a finite element model are in good agreement with the experimental results. The ratio of the simulated ultimate bearing capacity of CC6a to the test results is 1.000, and the ratio of the simulated ultimate bearing capacity of RUNC-4-60-1 to the test results is 1.013, respectively. The errors are within a reasonable range.

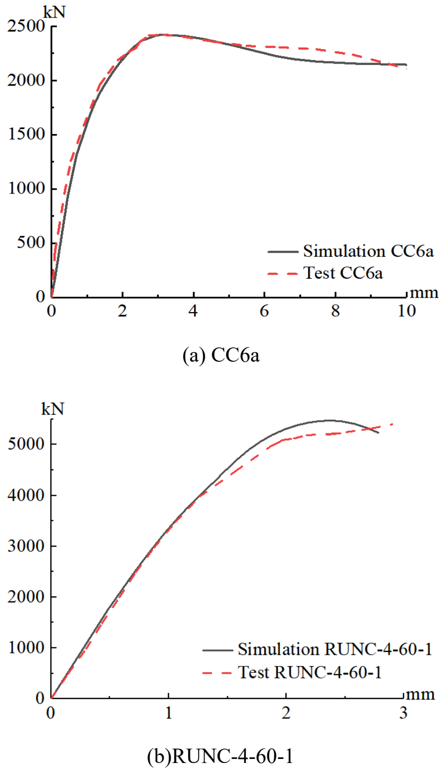


Fig. 4. Comparison of load-displacement curves

3 Axial Compression Process

3.1 Analysis of Load-Displacement Curve

Through the ABAQUS software, the process of axial compression of the hollow steel pipe UHPC composite column (P1-1) is analyzed, and its load-displacement curve is shown in Figure 5. Under the action of axial compression load, the curve is divided into the following five stages: OA section (elastic stage), AB section (plasto-elasticity stage), BC section (plastic strengthening stage), CD section (the stage of rapid decline in bearing capacity), DE section (the stage of slow decline in bearing capacity).

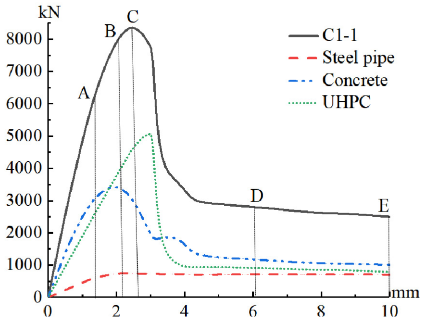


Fig. 5. C1-1 load-displacement curve

OA section: At the initial stage of loading, each component is in an elastic state, the proportional relationship of the curve is linearly increased, and the overall stiffness of the composite column is relatively large; AB section: With the increase of load, the composite column is changed from elastic state to plasto-elasticity state, the curve is changed from linear increase to nonlinear increase, and the slope of the curve slowly is decreased. The concrete is constrained and in a state of three-dimensional stress, and its ability to bear the load continues to be increased; BC section: After entering this stage, all components in the composite column work together, and the peak load point C is gradually reached, the deformation of the composite column is gradually obvious, and the ability of UHPC to bear the load is gradually enhanced; CD section: With the increase of load, the load borne by the composite column begins to significantly decrease, and the overall stiffness of the composite column is gradually decreased. The load borne by UHPC is greatly decreased, and the steel pipe contact pressure stress on the concrete is generated by the steel pipe again. The lateral deformation of the concrete is constrained, and the lateral deformation speed is decreased; DE section: In the later stage of loading, the load bearing capacity of the composite column is decreased slowly, and the residual stress exists in the composite column, which can still bear a certain load. The load value at point E is about 29.9% of the ultimate load value.

3.2 Analysis of Load Sharing Capacity

From Figure. 5 and Table 1, it can be seen that the load sharing of steel pipe, concrete and UHPC in C1-1 during the whole loading process.

Table 1. load sharing capacity

Feature points and Proportion	Composite column	steel pipe	Concrete	UHPC
Point A	6077.79kN	594.19kN	2991.33kN	2492.27kN
N/%	-	9.78%	49.22%	41.00%
Point B	8090.04kN	740.57kN	3372.39kN	3977.08kN
N/%	-	9.15%	41.69%	49.16%

Point C	8359.10kN	745.04kN	3030.73kN	4583.33kN
N/%	-	8.91%	36.26%	54.83%
Point D	2785.33kN	714.27kN	1160.19kN	910.87kN
N/%	-	25.64%	41.65%	32.71%
Point E	2499.42kN	705.36kN	1008.69kN	785.36kN
N/%	-	28.22%	40.36%	31.42%

Before point C, C1-1 had not yet reached its ultimate bearing capacity, and the steel pipe, concrete, and UHPC gradually exerted a synergistic effect. The steel pipe reached the yield stage at point B, and its proportion of load sharing is slowly decreased; in section AB, the hoop effect on concrete is gradually increased, improving its ability to bear longitudinal stress. When concrete undergoes compression failure, its proportion of load sharing is gradually decreased; UHPC has not yet undergone significant plastic deformation, and the longitudinal stress borne by UHPC is gradually increased, and its proportion of load sharing is also gradually increased. At point C, the ultimate bearing capacity of the composite column is mainly borne by UHPC, and the proportions of steel pipe, concrete, and UHPC sharing the load are 8.91%, 36.26%, and 54.83%, respectively. After point C, there is a restraining effect between the steel pipe and the concrete after yielding, and the proportion of its load sharing begins to increase; the concrete is gradually strengthened by the restraint of steel pipe and UHPC, slowing down the internal failure and deformation of concrete, and its proportion of load sharing is slightly decreased after increasing; UHPC undergoes brittle failure, and the longitudinal stress borne by UHPC is gradually decreased, and its proportion of load sharing begins to decrease.

4 Analysis of the Impact of Various Parameters

In this paper, a finite element model of axial compression of 10 hollow steel pipe UHPC composite columns is established to study the effects of concrete strength, UHPC thickness and hollow ratio on the ultimate bearing capacity, initial stiffness and deformation coefficient of the composite columns. The model parameters are shown in Table 2.

Table 2. Model parameter

Composite column number	Concrete strength /MPa	UHPC thickness /mm	Hollow ratio
C1-1	38.5	35	0.42
C1-2	41.5	35	0.42
C1-3	44.5	35	0.42
C1-4	47.4	35	0.42
C2-1	38.5	28	0.42
C2-2	38.5	30	0.42
C2-3	38.5	32	0.42

C3-1	38.5	35	0.00
C3-2	38.5	35	0.32
C3-3	38.5	35	0.52

4.1 Concrete Strength

The load-displacement curves of hollow steel pipe UHPC composite columns with different concrete strengths are shown in Fig. 6. From Figure 6 and Table 3, in the early stage of loading, the influence of concrete strength on the bearing capacity of the composite column is relatively small. In the plasto-elasticity stage, the ultimate bearing capacity is increased with the increase of concrete strength, after reaching the ultimate bearing capacity, composite columns with high concrete strength is decreased faster. The ultimate bearing capacity of C1-1 is 8359.10kN, and the ultimate bearing capacity of C1-2 is about 3.42% higher than that of C1-1, that of C1-3 is about 6.76% higher than that of C1-1, and that of C1-4 is about 10.29% higher than that of C1-1.

Table 3. Influence of concrete strength on composite columns

Composite column number	Ultimate bearing capacity (kN)	Initial stiffness (kN/mm)	Deformation coefficient
C1-1	8359.10	3704.41	1.2511
C1-2	8645.02	3947.04	1.2488
C1-3	8924.39	4067.18	1.2462
C1-4	9219.02	4186.41	1.2454

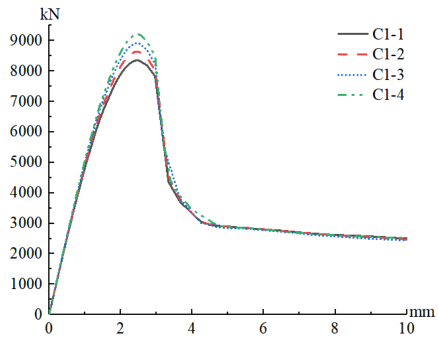


Fig. 6. Load-displacement curves

With the increase of concrete strength, the restraint effect is reduced, and the ultimate bearing capacity of composite column is increased with the increase of concrete strength. The initial stiffness of composite column is increased with the increase of concrete strength. The deformation coefficient of composite column is less affected by the strength of concrete.

4.2 UHPC Thickness

The load-displacement curves of hollow steel pipe UHPC composite columns with different UHPC thickness are shown in Fig. 7. From Figure 7 and Table 4, it can be seen that in the initial stage of loading, the bearing capacity of composite columns is affected slightly by the thickness of UHPC. As the load increases, the bearing capacity of composite columns with larger UHPC thickness is increased rapidly, and the peak load is continuously increased with the increase of UHPC thickness. In the stage of decreasing bearing capacity, the bearing capacity of composite columns with larger UHPC thickness is decreased significantly. The ultimate bearing capacity of C2-1 is 7398.17kN, the ultimate bearing capacity of C2-2 is about 3.58% higher than C2-1, the ultimate bearing capacity of C2-3 is about 7.24% higher than C2-1, and the ultimate bearing capacity of C1-1 is about 12.99% higher than C2-1.

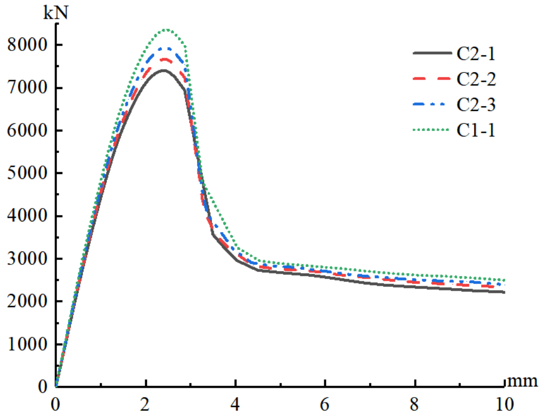


Fig. 7. Load-displacement curves

Table 4. Influence of UHPC thickness on composite columns

Composite column number	Ultimate bearing capacity (kN)	Initial stiffness (kN/mm)	Deformation coefficient
C2-1	7398.17	3185.94	1.2802
C2-2	7662.68	3296.18	1.2782
C2-3	7933.95	3407.53	1.2491
C1-1	8359.10	3704.41	1.2511

Due to the increase in thickness of UHPC, the restraining effect of UHPC on concrete is enhanced, and the supporting effect on concrete is increased. The ultimate bearing capacity of composite column is increased continuously with the increase of UHPC thickness; the initial stiffness of the composite column is gradually increased with the increase of UHPC thickness; when the thickness of UHPC increases from 28mm to 35mm, the deformation coefficient of the composite column first decreases and then slightly increases.

4.3 Hollow Ratio

The load-displacement curves of hollow steel pipe UHPC composite columns with different hollow ratio are shown in Fig. 8. From Figure 8 and Table 5, it can be seen that in the early stage of loading, the bearing capacity of composite column is affected slightly by the hollow ratio. As the load increases, the bearing capacity of the composite column with smaller hollow ratio is increased slightly. In the stage of decreasing bearing capacity, the decline of composite column C3-1 with hollow ratio of 0 is the fastest. The ultimate bearing capacity of C3-1 is 8359.10kN, the ultimate bearing capacity of C3-2 is reduced by about 0.22% compared to C3-1, the ultimate bearing capacity of C1-1 is reduced by about 2.24% compared to C3-1, and the ultimate bearing capacity of C3-3 is reduced by about 5.95% compared to C3-1.

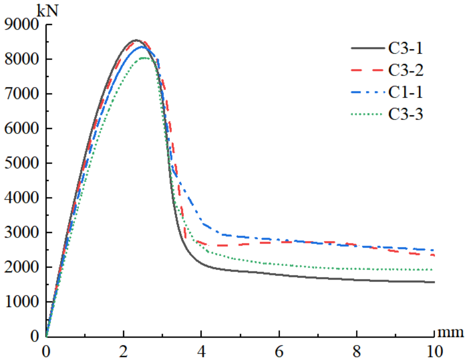


Fig. 8. Load-displacement curves

Table 5. Influence of Hollow ratio on composite columns

Composite column number	Ultimate bearing capacity (kN)	Initial stiffness (kN/mm)	Deformation coefficient
C3-1	8550.90	3843.74	1.2669
C3-2	8531.78	3810.34	1.2583
C1-1	8359.10	3704.41	1.2511
C3-3	8042.22	3525.84	1.1888

The ultimate bearing capacity of the composite column is decreased continuously with the increase of hollow ratio; the initial stiffness of the composite column is gradually decreased with the increase of the hollow ratio; when the hollow ratio increases from 0.42 to 0.52, the deformation coefficient is beginning to decline rapidly, and with the increase of hollow ratio, the plastic deformation ability of composite column is reduced.

5 Conclusions

Based on ABAQUS software, the finite element model of hollow steel pipe UHPC composite column is established and verified in this paper, and analyzes the axial compressive stress process of the composite columns and the influencing factors on the mechanical properties of the composite columns. The results show that:

(1) Under the action of axial compression load, the full stress process of the hollow steel pipe UHPC composite column is divided into: elastic stage, plasto-elasticity stage，plastic strengthening stage, the stage of rapid decline in bearing capacity, the stage of slow decline in bearing capacity.

(2) Before the ultimate bearing capacity, the load is mainly borne by concrete and UHPC; when the ultimate bearing capacity is reached, the load borne by the steel pipe is the smallest, and the load borne by UHPC is the largest; after the ultimate bearing capacity, the load borne by steel pipes is gradually increased, the load borne by concrete first increases and then decreases, and the load borne by UHPC is gradually decreased.

(3) Within the parameter range studied in this paper, under axial compression load, when the concrete strength and UHPC thickness are increased, the ultimate bearing capacity of the hollow steel pipe UHPC composite column is increased, the initial stiffness is increased, and the plastic deformation capacity is less affected; when the hollow ratio is increased, the ultimate bearing capacity of the hollow steel pipe UHPC composite column is decreased, the initial stiffness is decreases, and the plastic deformation capacity is decreased.

Against the backdrop of promoting the large-scale development of green buildings, the advantages of hollow steel pipe ultra-high performance concrete composite structures are obvious. The research on hollow steel pipe UHPC composite structures are still in its early stage by domestic and foreign scholars. This study focuses on the stress process and influencing factors under axial compression loads, which can lay the foundation for future research.

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