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Finite Element Analysis on Seismic Behavior of Ultra-High Toughness Cementitious Composites Reinforced Concrete Column

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/66808>

Abstract

In order to study the seismic behavior of ultra-high toughness cementitious composites reinforced concrete column, the concrete columns were simulated based on the finite element program OpenSees. The simulated hysteresis curves and skeleton curves were in good agreement with the test curves. The results well reflected the seismic performance of ultra-high toughness cementitious composite (UHTCC) reinforced concrete columns under earthquake and showed that the constitutive relation and the related parameters had good applicability for the simulation of fiber concrete columns. The UHTCC reinforced concrete column had higher bearing capacity and energy dissipation capacity.

Keywords: ultra-high toughness cementitious composites, concrete column, low cyclic loading, finite element analysis

1. Introduction

In the earthquake, reinforced concrete columns often lead to plastic hinge under compression, bending, and shear. Shear failure occurs frequently, such as protection layer spalling, reinforcement exposed, concrete crushing, deformation of steel bars, and even overall collapse. In the Seismic code GB50011 (2010), shear stirrups are allocation at the end of column and the diameter, spacing and reinforcement length are stipulated. But, due to the construction factors, the connection between confined concrete and protective layer cannot be guaranteed and leading to hidden danger.

Ultra-High toughness cementitious composite (UHTCC) is a kind of high performance cement matrix composite based on micromechanics and fracture mechanics (Xu and Li, 2008).

It shows the obvious characteristic of strain hardening and high toughness under tension and shearing force and it strengthens the softening performance of traditional cementitious material. Moreover, the characteristics of stable cracking effectively improved the durability and make the deformation coordinate with the steel bar. In view of this, based on the test research, this chapter uses OpenSees to simulate and analyze the seismic behavior of UHTCC reinforced concrete columns and provide reference for engineering application.

2. Numerical model of OpenSees

Concrete column adopted the flexibility-based fiber model in OpenSees program, for every root fibers only consider the axial constitutive relation, and every fiber can be defined different constitutive relations.

Concrete constitutive relation used the Concrete 02 model (Based on the Kent and Park (1971) uniaxial concrete constitutive model), which reflects the restriction of the stirrup by considering the peak stress, peak strain, and the softening curvature of compressive concrete.

A steel constitutive model adopted the Steel 02 material provided by OpenSees. This model considers the double broken line constitutive relation to reflect the Bauschinger effect and have good stability (Liu et al., 2012).

As the constraint effect of stirrups, the section is divided into cover concrete and core concrete according to the different stress-strain relations of the protective layer and confined concrete. **Figure 1** shows the column fiber section. The core concrete is divided into 10×10 , a total of 100 grids, and adopted the confined concrete constitutive model.

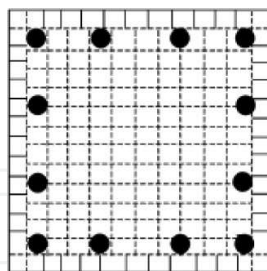


Figure 1. Sketch of column section fiber model.

3. Model validation

The quasistatic test of side and middle columns under low cyclic loading was provided in the study by Tang (2011). The column specimens were numbered Za1, Za2, Zb1, and Zb2: a represented the middle column and b represented the side. The remaining parameters are given in **Table 1**. Comparison of hysteretic curves and skeleton curves between the test and OpenSees is shown in **Figures 2** and **3**. **Table 2** shows the peak load.

Specimens	Dimension (mm ²)	Length (mm)	Strength (MPa)	Longitudinal reinforcement	Hoop reinforcement
Za1	200 × 200	850	30.1	8Φ8	Φ6/70
Za2	200 × 200	850	30.1	8Φ8	Φ6/70
Zb1	200 × 200	850	30.1	4Φ10 + 4Φ8	Φ6/70
Zb2	200 × 200	850	30.1	4Φ10 + 4Φ8	Φ6/70

Table 1. Specimen size and reinforcement.

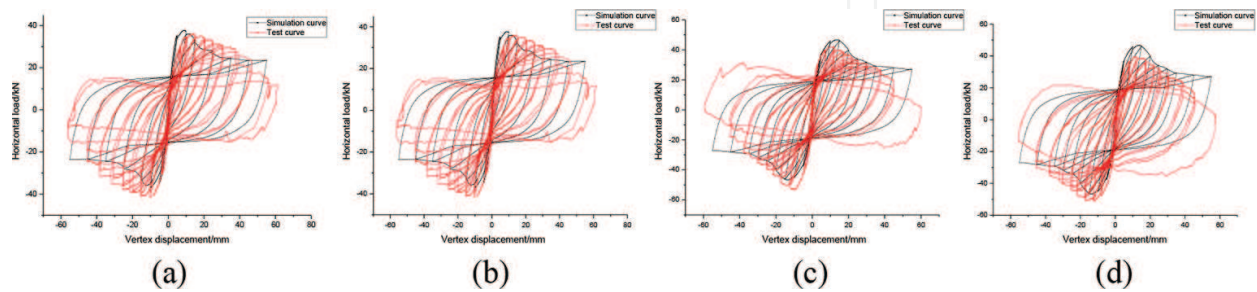


Figure 2. Comparison of Hysteresis curve. (a) Za1, (b) Za2, (c) Zb1, (d) Zb2.

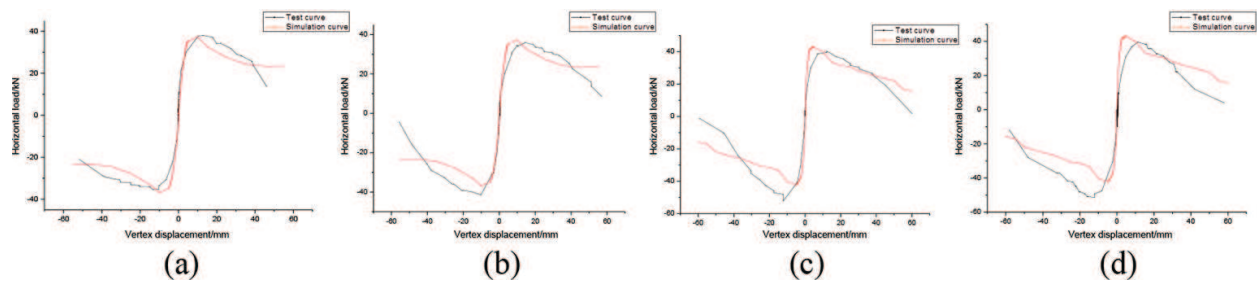


Figure 3. Comparison of Skeleton curve. (a) Za1, (b) Za2, (c) Zb1, (d) Zb2.

Figure 2 shows that the hysteresis curves based on OpenSees were in good agreement with the test results in initial stiffness, pinch degree, and trend. The hysteresis curves showed linear change before Za, Zb yield, and the stiffness degradation was not obvious. But, in the processes of loading and unloading, the stiffness degradation increased gradually. Finite element simulation could well reflect the phenomenon of column crack open and close, develop, and pinch. There are some differences during the late period of the loading process, and the simulation curves were very full. The main reasons were as following: generally, the column specimens were loaded to 85% limit load, but this specimen was loaded to collapse. It is difficult to accurately reflect the stiffness degradation and cumulative damage in the later stage of loading. In the stress-strain model, the parameters of the descending segment and the strength coefficient of steel bars were not very reasonable.

Specimens	Test value (kN)		Simulation value (kN)		Error (%)	
	Positive	Negative	Positive	Negative	Positive	Negative
Za1	38.003	-35.446	37.600	-36.828	1.06	3.90
Za2	36.002	-41.465			4.44	11.18
Zb1	42.059	-53.081	46.650	-46.673	10.92	12.12
Zb2	39.613	-51.435			17.76	9.26

Table 2. Peak load of simulation and test.

4. Numerical simulation of UHTCC reinforced concrete column

4.1. Design of column specimen

According to the size and reinforcement shown in Table 1, the model of UHTCC reinforced column was established and numbered UZ1 and UZ2.

The characteristic value of cube strength took $f_{cu} = 40$ MPa, and the elastic modulus was $E_c = 17,000$ MPa, stiffness decreased to $0.1 E_c$ when unloading. As the confinement effects from hoop steels, the strength increasing coefficient K took 1.1. The longitudinal reinforcement used HRB335 and strength variable coefficient took $\delta = 0.07$, the modulus of elasticity was 2.00×10^5 N/mm² according to the specification. The specific parameters are summarized in Tables 3 and 4.

Areas	f_c /N/mm ²	ϵ_c	ϵ_u	f_t /N/mm ²	E_c /N/mm ²
Cover concrete	40	0.005	0.034	5.98	1.7×10^4
Core concrete	44	0.00517	0.0577	5.98	1.7×10^4

Note: ϵ_c , ϵ_u are peak strain and ultimate strain, respectively. f_t represents the ultimate tensile strength.

Table 3. UHTCC column parameters.

Diameter	f_y /N/mm ²	E_s /N/mm ²	b	R_0	cR_1	cR_2	a_1 - a_4
6	441	2.00×10^5	0.01	12	0.800	0.13	0
8	582	2.00×10^5	0.01	12	0.800	0.13	0
10	481	2.00×10^5	0.01	12	0.800	0.13	0

Table 4. Reinforcement parameter.

4.2. Finite element simulation and analysis

The comparisons of UZ1 and UZ2 with ordinary column are shown in Figure 4.

Bearing capacity. The yield and ultimate load of UHTCC column were significantly higher than that of ordinary column. The average yield load of concrete column was 35.31 kN, the

average ultimate load was 40.25 kN, and the UHTCC column was 40.53 and 47.93 kN, respectively, which was increased by 14.8 and 19.1%.

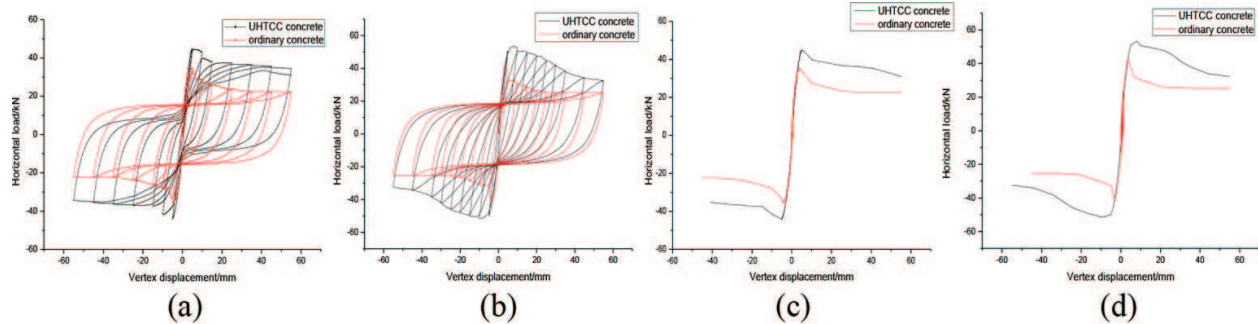


Figure 4. Comparisons of hysteresis curves and skeleton curves. (a) Za1, UZ1. (b) Zb1, UZ2. (c) Za1, UZ1. (d) Zb1, UZ2.

Hysteresis curves and skeleton curves. The hysteresis loops of UHTCC columns (UZ1 and UZ2), in contrast to that of ordinary column, was fuller. Its linear stage was longer, the deformation of elastic stage was slight and the slope change was not obvious. Although the stiffness and strength in the late stage were gradually reduced, the degradation became flat.

Deformation and energy dissipation. The yield points P_y and Δ_y was calculated by the energy method, meanwhile, defined the vertex of curves as the ultimate load P_{max} and ultimate displacement Δ_{max} . The failure load P_u equaled $0.85 P_{max}$ and the corresponding displacement was Δ_u . The ductility coefficient was defined as the ratio of the ultimate displacement to the yield displacement; **Figure 5** shows the method. The equivalent viscous damping coefficient h_e was used to evaluate the capacity of energy dissipation. In **Figure 6**, $h_e = (S_{BEF} + S_{EDF}) / 2\pi(S_{AOB} + S_{COD})$. The simulation results are shown in **Table 5**.

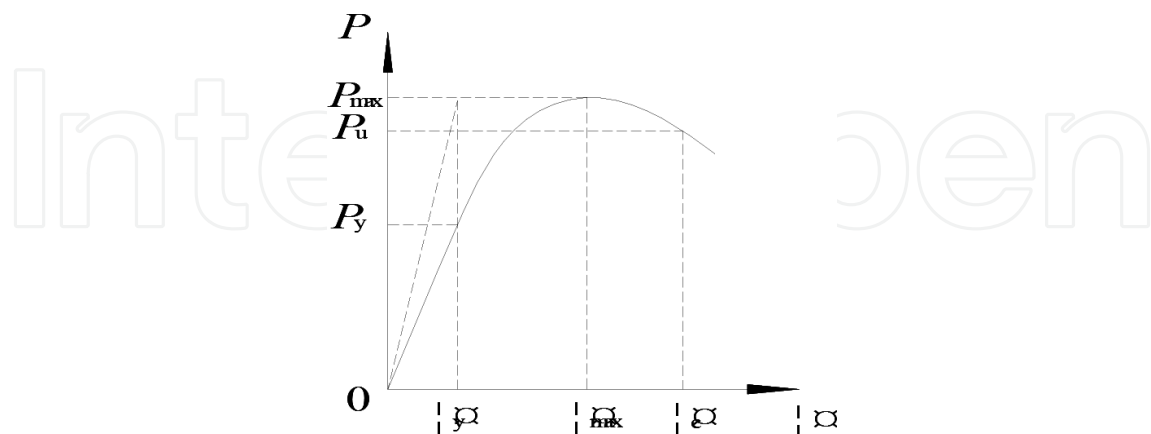


Figure 5. Determination of characteristic points damping.

As shown in **Table 5**, the ductility coefficient of UHTCC column is higher than that of ordinary column. With the cycle of load, the decline of the hysteresis curve of UHTCC columns occurred slowly. Compared with Za1 and Zb1, the viscous damping coefficients of UZ1 and

UZ2 were increased by 14.1 and 18%, respectively. It indicated that the high toughness of UHTCC can effectively improve the deformation and energy dissipation capacity of concrete columns.

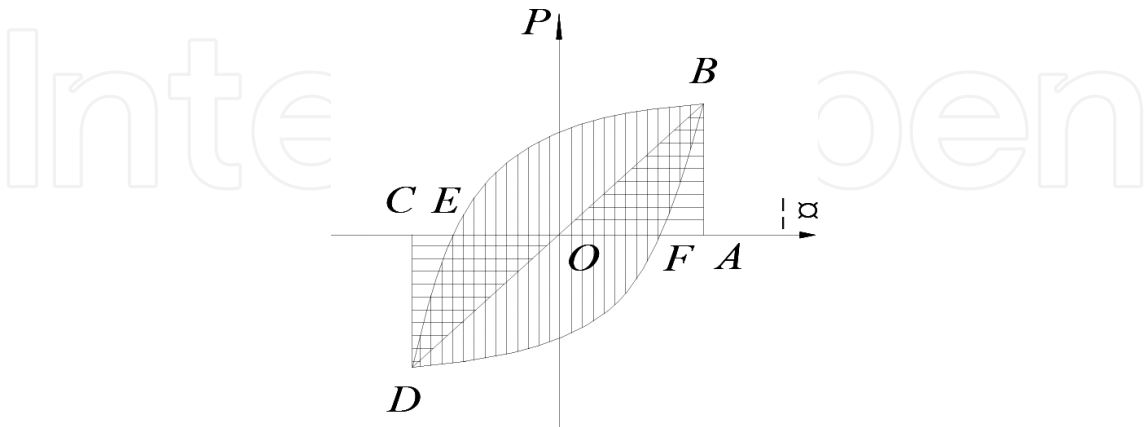


Figure 6. Determination of equivalent viscous coefficient.

Specimen	Δu Positive	Negative	Δy Positive	Negative	$\Delta u/\Delta y$ Positive	Negative	h_e
Za1	11.4	-11.2	4.0	-4.1	2.85	2.73	7.34
UZ1	20.6	-19.3	4.8	-4.7	4.29	4.11	8.37
Zb1	10.6	-10.2	4.1	-3.9	2.59	2.62	7.21
UZ2	28.3	-29.1	5.1	-5.3	5.55	5.49	8.51

Table 5. The ductility coefficient and energy dissipation of each specimen.

4.3. Analysis of influence factor

Axial compression ratio. In the case of other factors remained constant, changed the vertical axial force, and calculated the bearing capacity of UHTCC columns under different axial compression ratios. The results are shown in Figure 7. In the range of axial compression ratio less than 0.7, the horizontal bearing capacity and ultimate displacement increased with the increase of the axial compression ratio.

Volume-stirrup ratio. If the axial compression ratio remains constant then it can be seen than calculated bearing capacity of UHTCC columns is influenced by changing volume-stirrup ratios. It can be seen that, in the case of other factors unchanged, the horizontal bearing capacity of the specimens increased little with the increase of the volume-stirrup ratio (Figure 8).

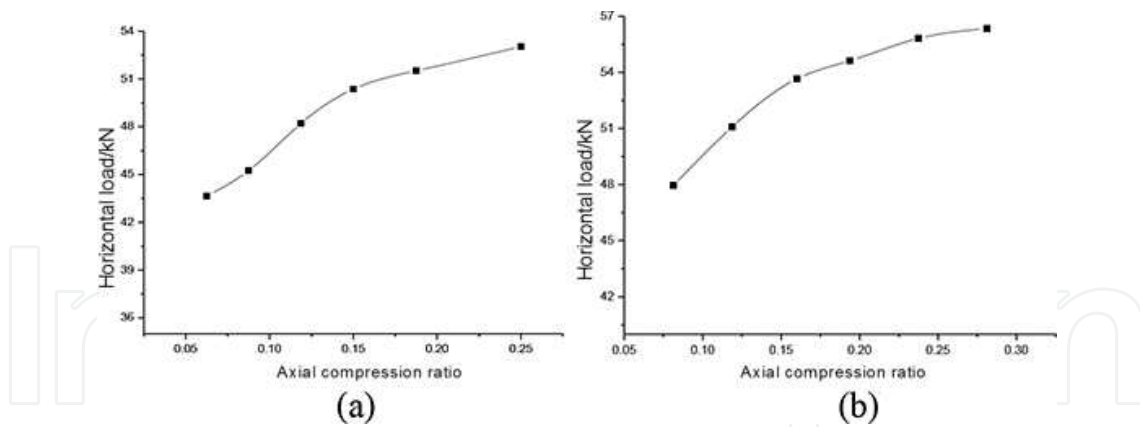


Figure 7. Relation curve of bearing capacity and axial compression ratio. (a) UZ1 and (b) UZ2.

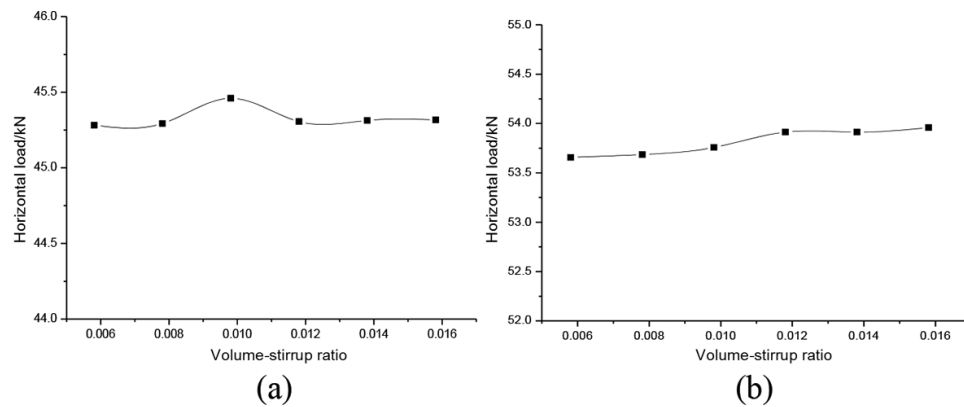


Figure 8. Relation curve of bearing capacity and volume-stirrup ratio. (a) UZ1 and (b) UZ2.

5. Main conclusions

The seismic behavior of UHTCC reinforced concrete column based on OpenSees finite element program was analyzed in this chapter, and the conclusions were as follows:

The flexibility-based fiber model, the Concrete 02 model, and the Steel 02 material can exactly simulate the hysteresis characteristic and energy dissipation of columns under low cyclic loading, and it verified the reliability of OpenSees.

The stiffness of hysteretic curves of the test degenerated obviously, but the simulated curves declined relatively flat at the later stage. On the one hand, it was because the model did not fully take the interaction of various parameters into consideration, on the other hand, although the Steel 02 material considered the Bauschinger effect, the fatigue effect of steel bar under low cyclic loading had not been embodied, so that the decline became flat.

Compared with the ordinary column, the UHTCC column had higher yield strength and ultimate strength, and the UHTCC can effectively improve the ductility. With the cycles increased, the stiffness degradation became flat. The higher viscous damping coefficient also indicates that its energy dissipation capacity was better than that of ordinary column.

The finite element simulation results of the lower axial compression ratio were closer to the test results. With the increase of the axial compression ratio, the horizontal-bearing capacity increased and the specimens under the lower axial compression ratio had better deformation performance. Under the same conditions, the bearing capacity has no significant change with the increase of the volume-stirrup ratio.

Acknowledgements

The research reported in this chapter was made possible by the financial support from the School of Civil Engineering and Architecture, Hubei University of Technology. The authors would like to express their gratitude to this organization and Mr. Su for the support.

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