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Nonlinear finite element analysis of PVA fiber reinforced high strength concrete columns under low cyclic loading

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Abstract. In this paper, four PVA fiber reinforced super-high-strength concrete columns under the low cyclic reciprocating load were studied by using the finite element analysis software OpenSEES and their hysteretic curves and skeleton curves were studied. The energy dissipation capacity of PVA fiber were analyzed to evaluate the effect of PVA fiber on the seismic performance of concrete columns. The results show that the restoring force curve of the finite element analysis software OpenSEES simulation agrees well with the experimental curve, which can fully reflect the hysteretic behavior of fiber reinforced concrete columns under low cyclic loading. The incorporation of PVA fiber can obviously improve the energy dissipation capacity of ordinary concrete columns.

1 Introduction

In this paper, finite element analysis software-Open System for Earthquake Engineering Simulation (OpenSEES) was used to simulate four super-high-strength concrete short columns under axial pressure and low cyclic loading. Through analyzing its energy dissipation capacity, it is proved that the PVA fiber can improve the seismic performance of concrete short columns and it provides effective design method and idea for the structural design compared with the experimental results.

2 The basic parameters of the test

The dimensions of the specimens used in the test are shown in Figure 1. It is that column height is 1500mm, the size of cross-sectional is 200mm× 200mm, the specimen shear span is 2.0, longitudinal reinforcement is the 4 Φ 14 HRB400 grade steel, stirrups is the Φ 8 HRB400 grade steel and the volume with the hoop rate(ρ_V) is 2.2% [1]. PVA fiber used Kuraray REC15 × 12 produced by Kuraray Co., Ltd. In the test, all the four specimens were loaded into the failure state and the specimen parameters are shown in Table 1.

Table 1. Specimen design parameters

Specimen Number	Compressive strength f_{cu} / MPa	Splitting tensile strength $f_{t,s}$ / MPa	PVA fiber content ρ_f / %	Test axial compression ratio n_t
RC	103.6	5.05	0	0.35
PFRC-0.17	108.1	6.16	0.17	0.35
PFRC-0.33	105.7	6.86	0.33	0.35
PFRC-0.50	112.1	7.41	0.5	0.35

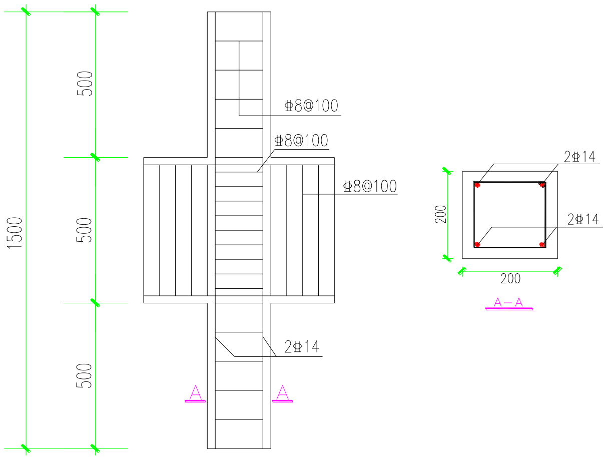


Figure 1. Dimensional drawings of test pieces

3 Numerical simulation based on OpenSEES

3.1. Stress-strain Relationship Model of Fiber Reinforced Concrete

As the number of dividing units is relatively large, the damage constitutive model with relatively simple form is selected under the premise of meeting the requirements of calculation. The constitutive model of each unit of PVA fiber concrete is defined as concrete in order to reflect the brittle performance mainly. A constitutive model of elastic-brittle damage with residual strength is adopted [2]. The corresponding damage evolution equation is expressed as follows:

$$D = \begin{cases} 0 & (\varepsilon \le \varepsilon_{t_0}) \\ 1 - \mu \frac{\varepsilon_{t_0}}{\varepsilon} & (\varepsilon_{t_0} \le \varepsilon \le \varepsilon_{tu}) \\ 1 & (\varepsilon > \varepsilon_{tu}) \end{cases} \tag{1}$$

Where: μ represents the residual strength coefficient of concrete; ε_{t0} represents the maximum tensile stress corresponding to the concrete strain; Where ε_{tu} is the ultimate tensile stress of concrete, $\varepsilon_{tu} = \xi\varepsilon_{t0}$, ξ represents the ultimate strain coefficient of concrete.

PVA fiber using the ideal elastic-plastic stress-strain relationship, namely:

$$\begin{cases} \varepsilon_s = E_s \cdot \varepsilon & (\varepsilon_s \le \varepsilon_y) \\ \varepsilon_s = f_y & (\varepsilon_s > \varepsilon_y) \end{cases} \tag{2}$$

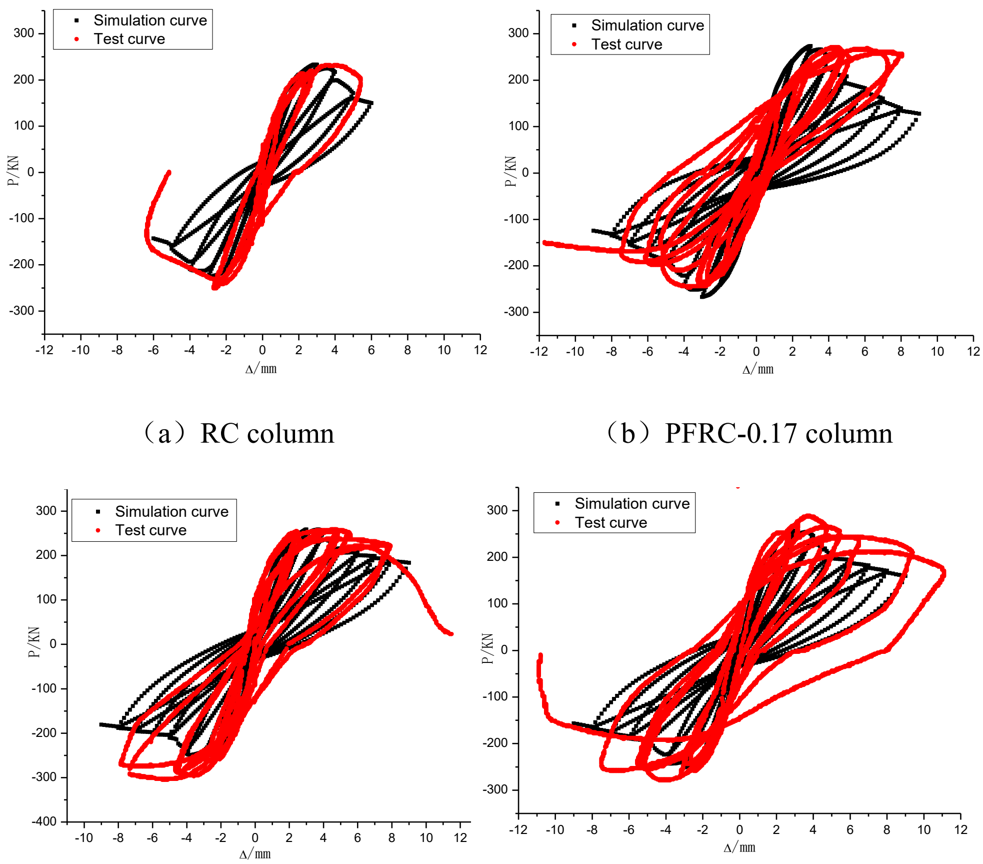
Where: E_s represents the ideal elastic modulus of concrete; f_y represents the ideal stress of concrete.

3.2. Constitutive Model of Steel Bar

The expression of strain explicit function is adopted in this model and its computational efficiency is high while keeping the consistency with the repeated loading test results of steel bars. Therefore, the steel model selected by the paper is isometric stress hardening [3].

3.3. Comparison of Simulation Results and Test Results

3.3.1. Hysteresis Curve. The hysteresis curve is the load-deformation curve obtained by cyclic loading. It reflects the deformation of structural members in the process of deformation characteristics, stiffness degradation and energy dissipation [4], which is the basis for nonlinear seismic response. The hysteresis curves obtained from the quasi-static tests of four PVA super-high-strength reinforced concrete short columns are compared with the hysteresis curves obtained from the corresponding loading tests, which is shown in Figure 2:



（a）RC column （b）PFRC-0.17 column

（c）PFRC-0.33 column （d）PFRC-0.5 column

Figure 2. Hysteresis curve

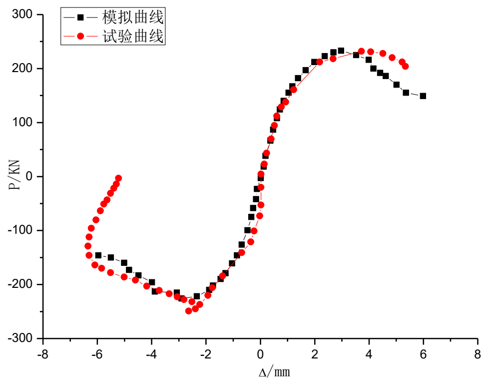
Figure 2 shows that under the low cyclic loading, the finite element analysis software OpenSEES was used to simulate the super-high-strength concrete (HPC) concrete column with PVA fiber. Compared with the experimental results, the hysteresis curve is represented. At the initial stage of loading, the simulated hysteretic curves of RC columns and PFRC columns coincide with the test curves when the load is not at the peak load, indicating that the components are in the elastic stage.

When the load exceeds the peak load, RC column and PFRC column show different hysteresis characteristics. The hysteresis curve of the RC column becomes narrower, the bearing capacity declines rapidly, and the rigidity degrades. The hysteresis curve of the FRC column becomes fuller, the frequency of the load increases and the sign of the stiffness degradation tends to be slow.

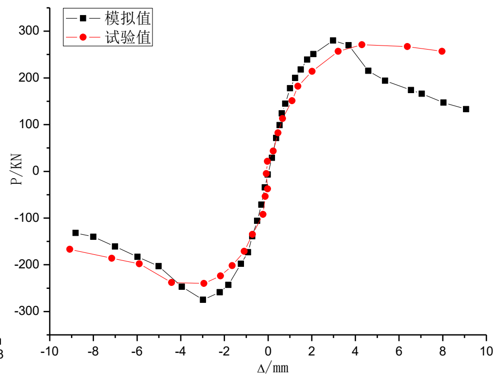
The hysteresis curve of concrete column with PVA fiber content shows: with the increase of fiber content, the fullness of hysteresis curve is better. After peak load, the trend of curve descending is not so obvious. Stiffness degeneration tends to be slow and the plastic property and energy dissipation capacity are also strengthened.

3.3.2. Skeleton Curve. The skeleton curve is a curve formed by connecting the peak points of positive and negative loading cycles in turn. The skeleton curves of each specimen were drawn according to the maximum horizontal forces and displacements obtained by the bending test of each loading cycle. When the tensile strength of PVA fiber reinforced concrete columns is yielded, the stiffness and P-Δ curve of the specimens decrease with the increase of load. When the bearing capacity of the specimen is reduced, the specimen undergoes four stages: cracking, yielding, ultimate bearing capacity and failure [5]. For commonly used flexural members, the yielding of the members is the yield strength. The ductility coefficient can be calculated from the yield and the ultimate load and displacement of the member according to the skeleton curve. Skeleton curve reflects the relationship between load-deformation, which is the main basis for seismic-inelastic dynamic reflection of structures [6].

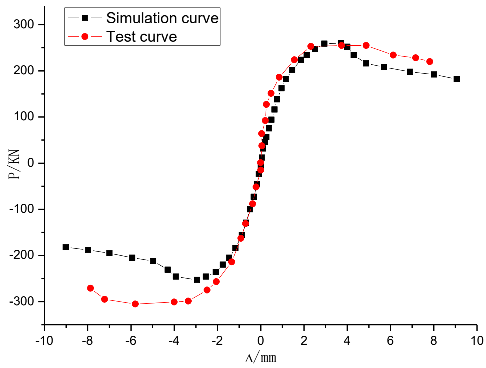
The skeleton curves of the RC and PFRC columns are shown in Figure 3.



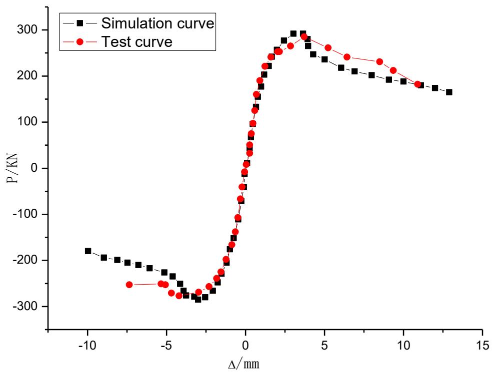
（a）RC column



（b）PFRC-0.17 column



（c）PFRC-0.33 column



（d）PFRC-0.50 column

Figure 3. Skeleton curve

4 Energy dissipation analysis

The energy dissipation capacity [1] reflects the energy consumption of building structure under seismic load. The stronger the consumption power is, the better the seismic effect of the structure is. At present, we often use energy consumption ratio, the cumulative energy consumption and the equivalent viscous damping coefficient to represent.

The equivalent viscous damping coefficients of the PVA super-high-strength concrete columns calculated under low cyclic loading are shown in Table 2.

Table 2. PVA fiber ultra-high-strength concrete column equivalent viscous damping coefficient

Component Number	Equivalent Viscous Damping Coefficient h_{e1}			Equivalent Viscous Damping Coefficient h_{e3}			Equivalent Viscous Damping Coefficient h_{e5}		
	Test Value	Analog Value	Error	Test Value	Analog Value	Error	Test Value	Analog Value	Error
RC	0.0426	0.0467	9.62	0.0842	0.0835	-0.83	0.1785	0.1826	2.30
PFRC0.17	0.0512	0.0494	-3.52	0.1096	0.1200	9.49	0.1956	0.2130	8.90
PFRC0.33	0.0585	0.0540	-7.69	0.1200	0.1255	4.58	0.2096	0.2147	2.43
PFRC0.50	0.0602	0.0576	-4.32	0.1502	0.1393	-7.26	0.2131	0.2308	8.31

From the analysis of Table 2:

(1) The error of the equivalent viscous damping coefficient between RC column, PFRC-0.17 column, PFRC-0.33 column and PFRC-0.5 column was 9.62%, 3.52% 7.69% and 4.32% respectively when the first cycle was loaded; The errors were 0.83%, 9.49%, 4.58% and 7.26% at the third cycle; In the fifth cycle, the errors are 2.30%, 8.90%, 2.43% and 8.31% respectively. The results show that the finite element analysis software OpenSEES can accurately analyze the PVA fiber reinforced concrete frame columns quantitatively.

(2) Both the experimental and simulated values show that the equivalent viscous damping coefficient increases with the increase of PVA content under the same conditions. For example, the experimental values of the equivalent viscous damping coefficients of PFRC-0.17, PFRC-0.33 and PFRC-0.50 were 20.2%, 37.3% and 41.3% higher than those of RC column. The simulated values increased by 5.8%, 15.6% and 23.3%. The results show that with the increase of volume fraction of PVA fiber, the energy dissipation capacity of frame column is enhanced, and the deformation ability of the structure is improved effectively.

5 Conclusion

Based on OpenSEES, the numerical simulation of PVA fiber reinforced concrete short columns was carried out. The energy dissipation capacity of PVA fiber reinforced concrete columns were analyzed to verify the effect of PVA fiber on the seismic performance of concrete short columns. Compared with the experimental results, the following conclusions can be drawn:

(1) The finite element analysis software OpenSEES can be applied to the numerical simulation of seismic performance of fiber reinforced concrete structures. Compared with the experimental results, it is found that the error values of the hysteresis curve, the skeleton curve and the equivalent viscous damping coefficient calculated by numerical simulation are within the effective range. It shows that the finite element analysis software OpenSEES is able to analyze the seismic performance of PVA fiber reinforced concrete members.

(2) Through experiment and numerical simulation can be found that the incorporation of PVA fiber can improve the seismic capacity of concrete frame columns. Compared with the RC column, the experimental value of the equivalent viscous damping coefficient of the PFRC column increased by 41.5% and the simulated value was 26.4%. The results show that the incorporation of PVA fibers can improve the ultimate elastic-plastic displacement angle of ordinary concrete columns. With the increase of the volume fraction of PVA fibers, the energy dissipation capacity were enhanced.

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