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Research and analysis on seismic performance of steel fiber reinforced concrete box type

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Abstract

On the basis of studying the properties of basic materials of steel fiber reinforced concrete and the failure characteristics of box column members, this paper uses steel fiber reinforced concrete to replace ordinary concrete in order to improve the seismic performance of box column. By designing four steel fiber reinforced concrete box column models and using finite element analysis software ABAQUS to simulate, the seismic performance of fiber reinforced concrete box column under horizontal low cyclic load is studied. By analyzing the hysteretic curve, skeleton curve, ductility coefficient and equivalent viscous damping coefficient of the model, the effect of steel fiber content on the seismic performance of the box column was studied. The results show that steel fiber reinforced concrete box column has better bearing capacity and ductile deformation capacity than ordinary reinforced concrete box column. Steel fiber effectively improves the seismic energy dissipation capacity of box column by preventing the generation and development of cracks. With the increase of steel fiber volume content, the seismic ability of box column is improved.

Keywords

Steel fiber reinforced concrete, Box column, Seismic performance, Finite element analysis.

1. Introduction

The nonlinear finite element analysis method of reinforced concrete structure is an important theoretical research method in the study of civil structure performance. With the development of computer technology and finite element software, this method will be used more widely. Although the mechanical properties and failure characteristics of the structure can be obtained more accurately and reliably through the full-size or downsized structural tests, the structural tests are time-consuming and costly, and many unexpected factors often cause the test deviation and some unexpected conditions, so the cost effectiveness of structural tests is not high. It is a good supplement to the structural test to use limited software to simulate and simulate the structure test. At present, researchers mostly use finite element software to simulate and verify the existing tests, so as to obtain more accurate analysis conclusions. In fact, with the development of basic theories and analysis methods, the cost of simulation can be reduced, and the structural prediction can be more accurate. The multi-angle tentative research and analysis of the structure can be tried, so as to do preliminary prediction research for the structural test, and the cost benefit of the structural test can be improved while exploring the research direction. Compared with other finite element software, the finite element software ABAQUS has more prominent nonlinear analysis ability, so it is more suitable for the mechanical property analysis of reinforced concrete structures. In this paper, ABAQUS software is used to simulate the fiber concrete box column, study the seismic ability of fiber concrete box pier column, and make an exploratory study on the application of fiber concrete to box pier column to improve the existing problems of ordinary box concrete box pier column. However, due to the lack of specific test and simulation results for comparison, in order to ensure the accuracy and reliability of the research results, a certain theoretical basis is needed. For example, the constructed structural model can roughly predict its failure form, and the selected constitutive relation model can accurately and truly reflect the material properties.

2. Box column model design

2.1. Model basic parameter

Through the analysis of the experimental research of concrete box pier column at home and abroad, the test specimen models of Beijing University of Technology, Tongji University, Hunan University and other universities and research institutions are compared, and the final choice of reference to Beijing University of Technology Du Xioli, Han Qiang et al reinforced concrete hollow pier seismic performance test model adopted for the design of the analysis model of this topic. Before the finite element analysis of the seismic performance of the fiber-concrete box column, the original reference model is firstly simulated and restored by some original experimental studies, and good simulation results are obtained to prove that the model is available.

In this paper, a total of four finite element analysis models are designed, numbered A0 -- A3, in which A0 is the reference control model using ordinary concrete matrix material without mixing fiber, A1, A2, A3 are steel fiber concrete box column configuration, see Table 1. All the models adopt the same geometric section size, the outer contour section size is 500mm×360mm, the inner hollow section size is 260mm×120mm, the wall thickness is 120mm, the box column is equipped with solid column head and base at both ends, and the effective loading height is 2880mm. HRB335 reinforcement is used for longitudinal reinforcement and stirrup, among which the diameter of longitudinal reinforcement is 8mm and stirrup is 6mm, and the spacing of stirrup is 40mm and 80mm. The size and reinforcement of box column are shown in Fig 1

Table 1 Specimen number and parameter

Model number	Fiber combination mode	Steel fiber volume content	Axial pressure (kN)	Stirrup spacing (mm)	Stirrup ratio (%)
A0	SF0	0	280	40	0.035
A1	SF0.5	0.5%	280	40	0.035
A2	SF1.0	1.00%	280	40	0.035
A3	SF1.5	1.50%	280	40	0.035

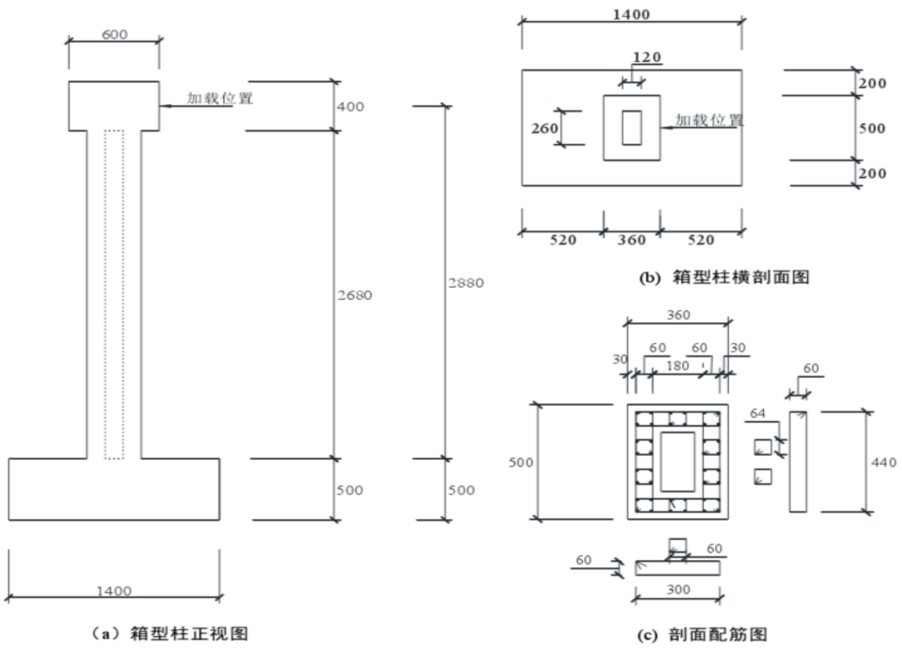


Fig. 1 Size and reinforcement drawing of box column

2.2. Material basic parameter

In the definition of reinforcement material attributes in the model, measured material parameters of reinforcement in the reference test model are used, as shown in Table 2. The mechanical properties of steel fiber are shown in Table 3. The material parameters of fiber are shown in Table 4.

Table 2 Material parameters of reinforcement

Type	Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (N/mm2)	Poisson's ratio
Longitudinal bar	8	393.2	624.0	196600	0.3
Stirrup	6	388.6	609.3	194300	0.3

Table 3 Mechanical property parameters of fiber reinforced concrete

Fiber combination mode	Steel fiber volume dosage	Yield strength (MPa)	Compressive strength (MPa)
SF0	0	46.67	3.03
SF0.5	0.50%	51.47	3.87
SF1.0	1.00%	54.13	4.35
SF1.5	1.5%	53.80	4.41

Table 4 Fiber material parameter

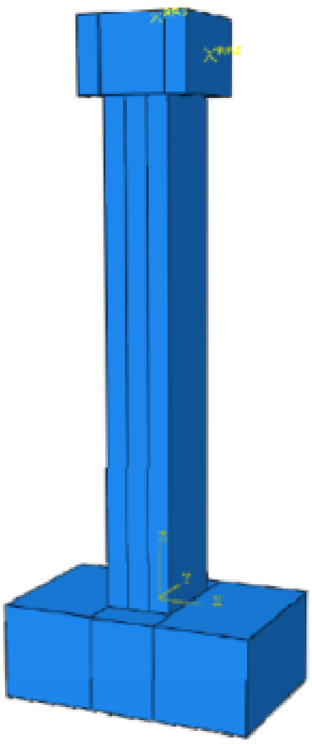
Fibre number	Fiber length-diameter ratio	Fiber type	Tensile strength (MPa)	Elastic modulus (N/mm2)
SF	60	Steel fibre	≥600	220000

3. Finite element analysis of seismic performance of steel fiber reinforced concrete box column

3.1. Establish finite element model

3.1.1. Analysis step setting

The setting of the analysis step will directly affect the solving speed of the model and even determine whether the model solving can proceed smoothly. Based on the initial step, this model sets two more analysis steps, both of which adopt static general analysis step. The initial boundary conditions of the box column were defined in the initial analysis, that is, the lower surface of the pier column base was treated as a fixed support, and the axial load was applied in Step 1 and the horizontal repeated load (horizontal displacement over time) was applied in Step 2 of the subsequent analysis. The setting of the analysis Step mainly includes the setting of the analysis Step time (time period) and the setting of the incremental step. The analysis step time in Step 1 only needs to be set to the default value 1, but the analysis step time in Step 2 must be consistent with the horizontal loading cycle time. If the setting is too small, the calculation will be completed prematurely and the loading will be incomplete. The setting of incremental steps mainly involves the type of incremental steps, the maximum number of incremental steps allowed, the size of initial incremental steps, etc. In this model, the type of incremental steps is set as Automatic, that is, the size of incremental steps will automatically increase or decrease according to the convergence of results. The maximum number of jump steps should be set to a large enough number to ensure that the analysis process is complete and does not end prematurely; The initial increment step size should be appropriately selected according to the model. Too small will increase the calculation process, and too large will lead to non-convergence of the calculation. This model is set as 0.01. Also, be careful to set geometric nonlinearity to on.



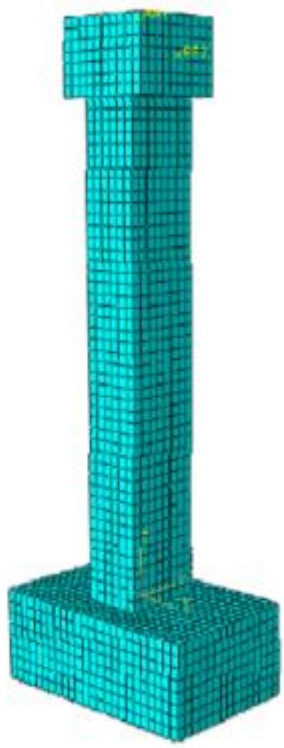


Fig.2 Model cutting Fig.3 Mesh generation of finite element model

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3.1.2. Meshing

The quality of meshing will affect the speed of analysis and calculation process and the precision of simulation results. In the grid division of the model, in order to make the grid division of the model more regular, the concrete parts need to be cut first. As shown in Fig 2, the box column can become a cube with several regular parts after cutting. As for the selection of elements in the model, C3D8R hexahedral reduction integration elements were used for concrete, and the grid division results were all 60mm×60mm, as shown in Fig 3. T3D2 truss element is used for the rebar.

3.1.3. Loading mode

The loading involved in the model includes axial concentrated force and repeated horizontal load, in which the axial concentrated force is applied at the top center of the column of the box column model. Two kinds of axial pressure loading are used in the simulation process, 280k N and 580k N, to compare the influence of different axial pressure ratios on the seismic performance of the box column. The axial force is applied once and remains unchanged until the entire calculation is completed. Horizontal loading adopts displacement control loading method, and the displacement amplitude of each stage is cyclically loaded three times. The loading scheme is shown in Fig 4. In the simulation process, it was found that if the initial loading displacement amplitude was too large, the calculation process and results would be abnormal. Therefore, in the initial loading, a relatively small value displacement without cycling was first adopted as the transition and then a normal cyclic loading scheme was applied. When the horizontal bearing capacity of the box column is reduced to 85% of the ultimate horizontal load, it is considered that the column has been damaged and the loading should be ended. However, since there is no specific test to judge and control the degree of loading in advance, the total duration of all model loading analysis steps is set to 184 in the simulation, that is, the complete displacement loading cycle process is completed. However, in the actual calculation, when the model bearing capacity decreases greatly and the column is completely destroyed, the incremental step changes very little, and the calculation efficiency decreases significantly. It is no longer meaningful to continue the calculation, so some models choose to terminate the calculation after the failure.

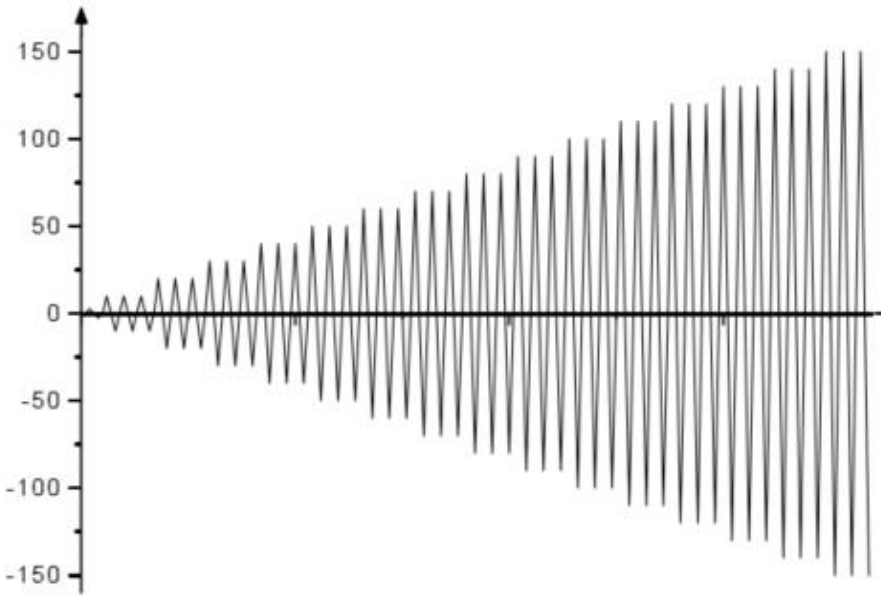

Fig.4 Loading scheme

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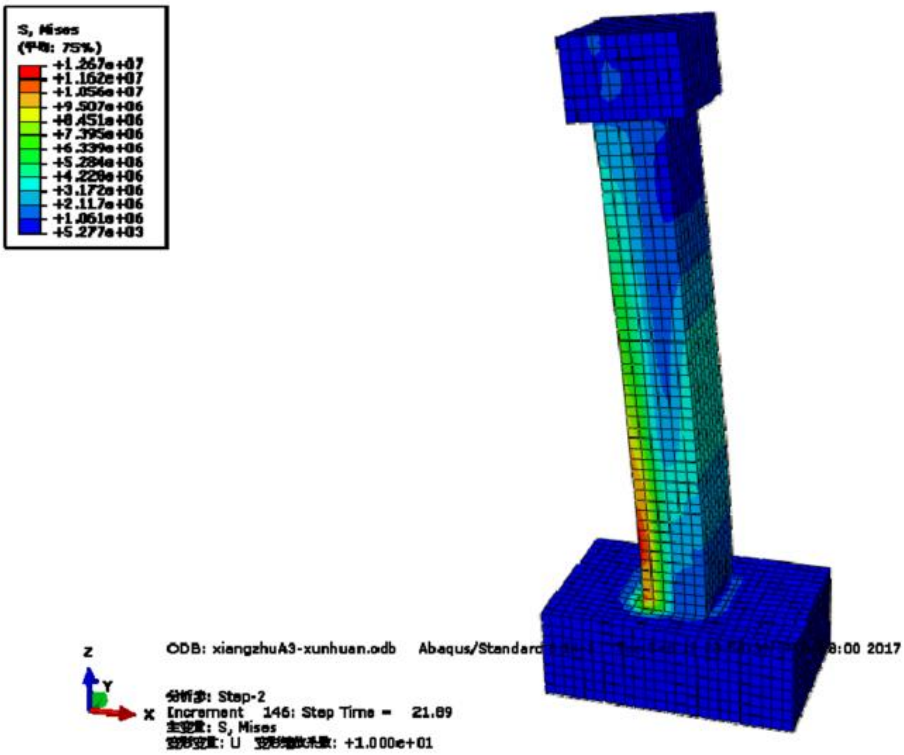
3.2. Summary and analysis of finite element calculation results

3.2.1. Stress nephogram

FIG. 5 and FIG. 6 show the stress moire diagram of fiber concrete box columns simulated by low cyclic horizontal load applied by BAQUS software.



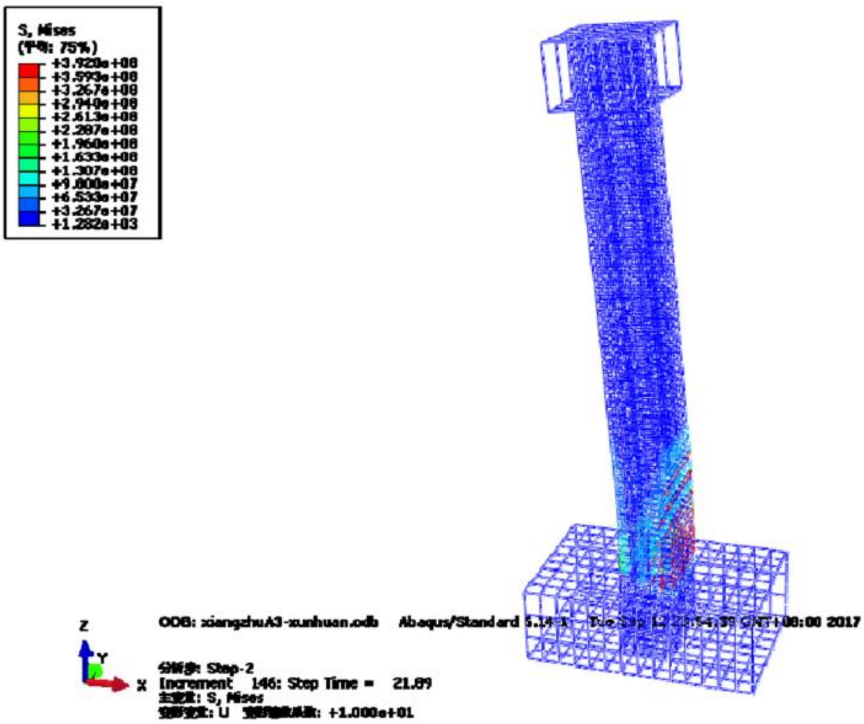


Fig.6 Stress cloud diagram of box column steel bar

According to the stress mobbin diagram of concrete and reinforced skeleton of box column, the load is mainly distributed in the lower part of box column, and the closer the column end is, the less the stress will be, which will also lead to the lower part of the column with greater stress to crack first, which is the weak area of the structure. This conforms to the failure characteristics of box column structure in engineering practice and experimental research. Observation of the change process of concrete stress momograph during the whole loading process shows that as the loading displacement increases, the larger stress area gradually expands and moves upward, the stress in the compression area is obviously greater than the stress in the tension area, the stress at the foot of the column is relatively concentrated, but the stress of the concrete in the thin-walled side area is small. Compared with the stress of concrete, the stress on the steel bar is concentrated and mainly concentrated in the lower part of the box column. By observing the stress moire pattern of concrete and reinforcement at the same time, it is found that the larger stress area is distributed on the opposite two sides.

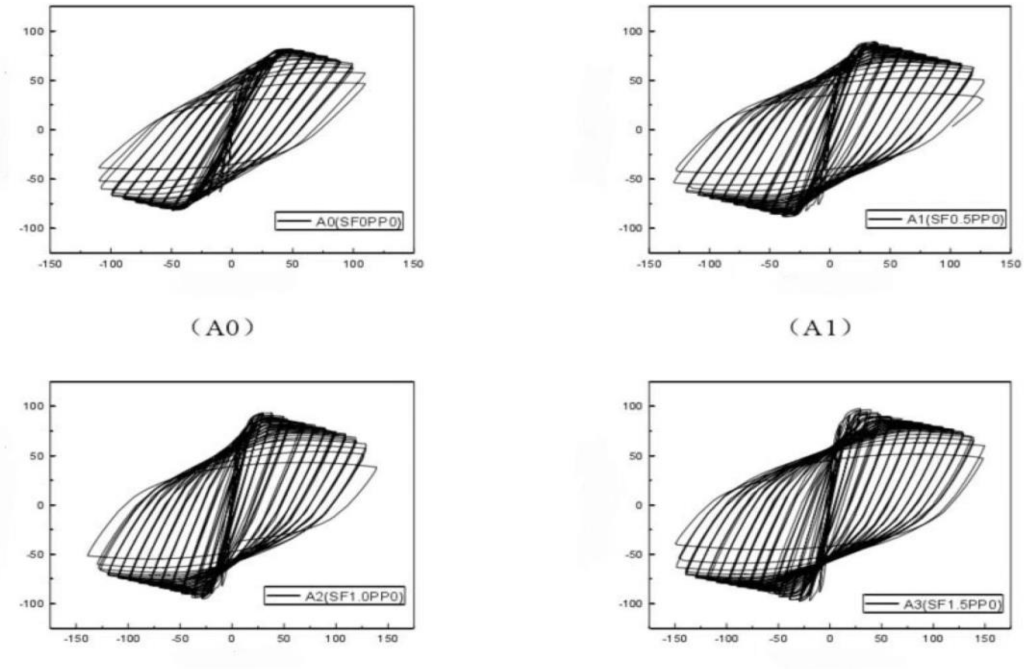
3.2.2. Hysteresis curve

Hysteretic curve refers to the load-displacement curve obtained by the model member under cyclic and repeated loads. It records the whole process of the model member in the whole process of loading, from the elastic stage to the elastic-plastic stage to the plastic stage to the failure stage. It can comprehensively reflect the seismic capacity of the test piece, such as the stiffness, strength, deformation and energy dissipation capacity of the structure. The curve obtained after one week of loading is closed into a loop called the hysteresis loop. The size of the graph area enclosed by the hysteresis loop represents the amount of energy consumption of the specimen. The larger the area enclosed, the fuller the hysteresis curve, indicating the stronger the energy dissipation capacity of the specimen, which is conducive to withstand seismic load. FIG. 18 shows the hysteretic curves of all specimen models in this subject.

According to the obtained hysteretic curve of the model, when the horizontal loading amplitude of the column top of the box column is small, the deformation of the specimen is still in the elastic deformation stage of concrete material. At this time, the loading curve and unloading curve of the model are approximately straight lines, and the area of the hysteresis loop enclosed by them is very small. There is no cracking of the concrete material in the loading process and no deformation residue after loading. As the horizontal displacement amplitude of the top of the column increases, the loading curve and unloading curve gradually change from straight to curved, and the enclosed area gradually becomes larger, forming a spindle shape, which indicates that the material in the model is damaged and consumes a certain amount of energy. Finally, the specimen will retain some residual deformation after unloading, which is reflected in the actual test, the specimen cracks and the material stiffness decreases. When the load continued until the peak value of the model bearing capacity, the model bearing capacity began to decline, and the corresponding hysteretic curve of the model gradually appeared the phenomenon of "pinching".

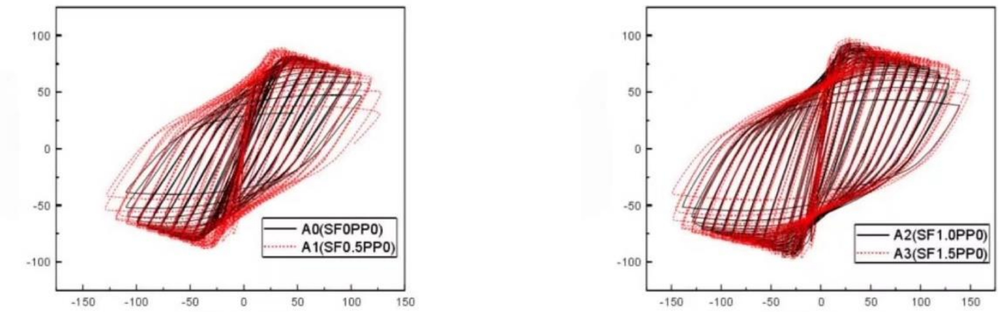
As can be seen from Fig 7, hysteresis curves of each fiber reinforced concrete box column model with fiber added are obviously fuller than that of A0 of the ordinary reinforced concrete box column model without fiber added, indicating that steel fiber reinforced concrete box column has better anti-seismic energy dissipation capacity, and fiber added plays a positive role. The descending section of the bearing capacity of the member becomes more gentle, and the displacement at the top of the column becomes larger when the bearing capacity changes sharply, which indicates that the ductility of the member becomes better. In order to facilitate and accurately compare the hysteretic curves of fiber concrete box column models with different fiber content, the hysteretic curves of two groups of fiber concrete box column models with steel fiber volume content of 0 and 0.5% and 1.0% and 1.5% were drawn in the same coordinate system, as shown in Fig 8. It can be seen from the comparison figure that the hysteretic curves of the box column model with low fiber content are completely wrapped within the hysteretic curves of the box column model with large fiber content, and the initial stiffness of the components increases significantly. It can be seen that the change of steel fiber content has a very large impact on the hysteretic properties of the models, and the increase of fiber volume content makes the energy dissipation capacity of the components stronger.

Analysis of the reason, the increase of fiber content can effectively improve the tensile performance of concrete, inhibit the development of cracks, when the box column bending under horizontal load, and formed a small bending crack on the loading surface, the fiber bridge between cracks can inhibit the development of cracks, and then delay the failure process of components.



（A2） （A3）

Fig.7 Model hysteresis curve



（a） A0、A1 （b） A2、A3

Fig.8 Comparison of hysteresis curves of different fiber content models

3.2.3. Skeleton curve

As shown in Fig. 9, the peak points of each hysteresis loop in the hysteresis curve are connected to form an outsourcing complex line of the hysteresis curve, which is called skeleton curve. Skeleton curve reflects the variation of the relationship between load and deformation in cyclic loading mode, but its curve form is very close to that of load-deformation curve under monotone load. Characteristic parameters such as strength change information, yield load, peak load, failure load and corresponding displacement of specimens can be extracted from skeleton curve. The skeleton curve can also reflect the ductility and seismic capacity of the specimen. In this paper, the peak point of hysteretic curve in the first cycle of each level of load is connected, and the connected track is used as the skeleton curve of the model.

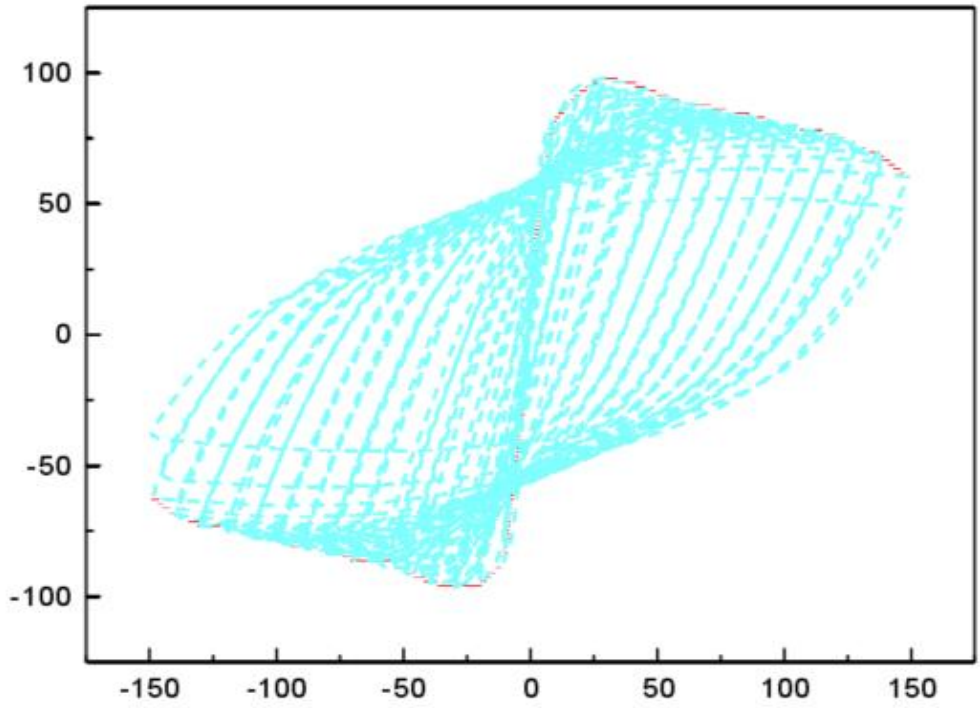


Fig.9 Schematic diagram of skeleton curve

Fig 10 shows the skeleton curves of model A0, A1, A2 and A3. These models are all fiber reinforced concrete box columns with single steel fiber content, and the fiber volume content is 0, 0.5%, 1.0% and 1.5%, respectively. As can be seen from the comparison figure, with the increase of fiber content, the model's bearing capacity and ductility are significantly improved. The stiffness of the ascending section becomes larger, the yield displacement becomes smaller, the descending section becomes more gentle, and the ultimate displacement at the corresponding failure moment becomes larger.

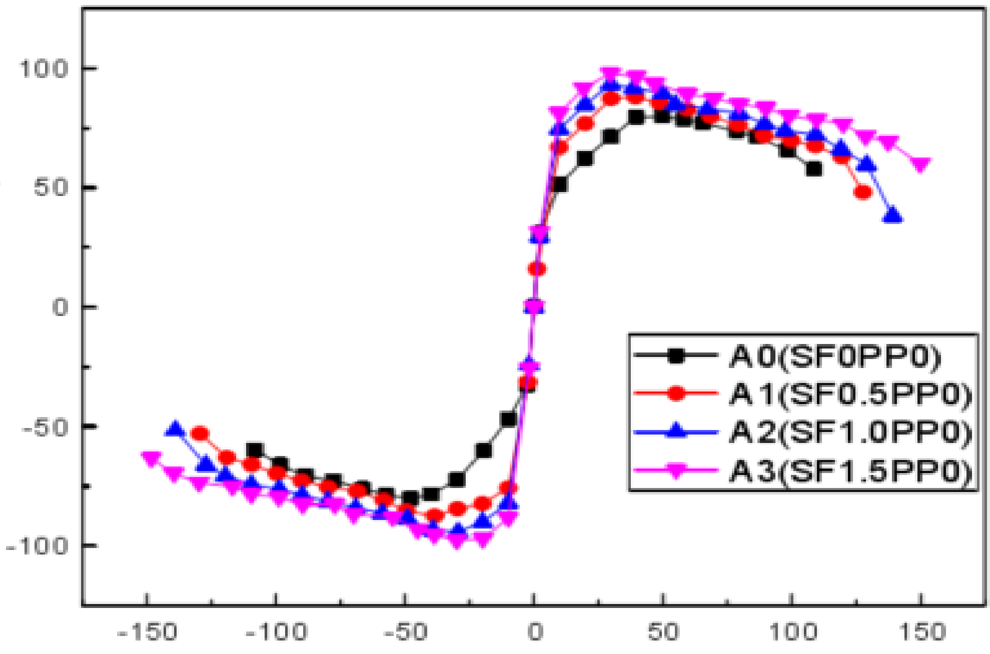


Fig.10 Skeleton curve of fiber concrete box column model

3.2.4. Ductility analysis

The maximum bearing capacity (i.e. peak load) of the model A1, A2 and A3, whose volume content of steel fiber is 0.5%, 1.0% and 1.5%, is about 10.0%, 16.3% and 21.3% higher than that of the A0 model without fiber, respectively. Meanwhile, the displacement ductility coefficients are increased by 15.2%, 27.3% and 29.4%, respectively. It shows that steel fiber reinforced concrete can greatly improve the bearing capacity and ductility seismic capacity of box column members, and the increase is more significant with the increase of fiber content.

As can be seen from Table 7, the steel fiber reinforced concrete box column models show better ductility performance than ordinary reinforced concrete box column models, and the displacement ductility coefficients of all models are between 5.54 and 8.24, indicating that the steel fiber reinforced concrete box column models have good ductility and earthquake resistance.

Table5 Calculation of Displacement Ductility Coefficient

model number	Yield load (kN)	yield Displacement (mm)	Ultimate load (kN)	Ultimate displacement (mm)	Ductility coefficient	Average ductility coefficient
A0	57.16	16.35	67.83	93.71	5.73	5.54
	-59.85	-17.58	-68.11	-93.86	5.34	
A1	69.33	13.21	74.82	82.36	6.23	6.38
	-74.41	-12.91	-74.23	-84.22	6.52	
A2	78.31	12.85	79.33	83.55	6.50	7.05
	-79.02	-11.21	-79.92	-85.24	7.60	
A3	84.32	12.49	83.17	90.16	7.22	7.17
	-84.96	-12.21	-82.99	-86.85	7.11	

3.2.5. Energy dissipation capacity

Under the action of low cyclic loading, the specimen produces unrecoverable plastic deformation and damage along with energy absorption and release. In the hysteresis curve of the model, the graph area enclosed by the loading curve and the horizontal axis represents the energy absorbed by the specimen during the loading process, while the graph area enclosed by the unloading curve and the horizontal axis represents the energy released by the specimen during the unloading process. The area of hysteresis loop enclosed by loading curve and unloading curve represents the energy dissipated by plastic deformation and damage during a loading cycle. In order to accurately describe the energy-dissipation capacity of specimens, equivalent viscous damping ratio is usually used to describe them. As shown in FIG. 11, equivalent viscous damping ratio is the ratio between the energy dissipation in a cyclic loading process and the energy consumed by an equivalent linear elastic system to reach the same displacement, which is calculated as follows:

$$\mathrm{h}_e = \frac{1}{2\pi}\frac{S_{(\mathrm{ABC+CDA})}}{S_{(\mathrm{OBE+ODE})}}$$

Where: is the area enclosed by the hysteresis loop, represents the energy dissipated by the structure during a cyclic loading process, is the sum of the areas of triangle OBE and triangle ODE, represents the energy consumed by the equivalent linear elastic system to reach the same displacement. The hysteresis loop corresponding to the first cycle of each grade load was extracted from the hysteresis curves of each fiber reinforced concrete box column model obtained above to calculate the equivalent viscous damping coefficient of the specimen.

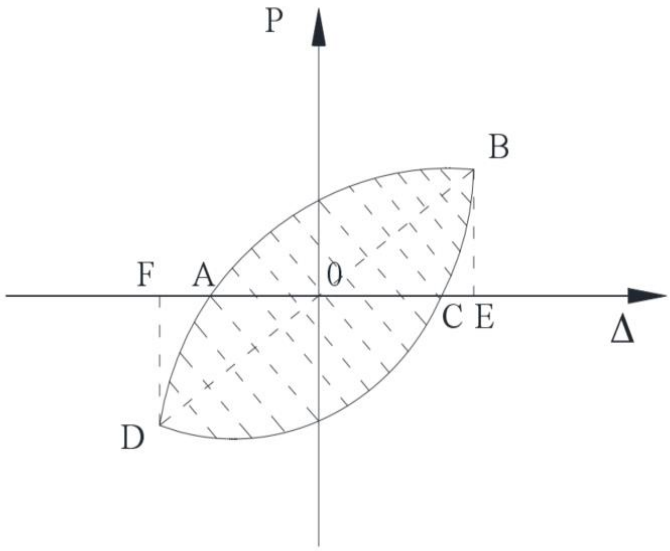


Fig.11 Equivalent viscous damping coefficient calculation sketch map

Figure 12 shows the comparison diagram of the relationship between the equivalent viscous damping coefficient of each fiber reinforced concrete box column and the horizontal displacement of the column top. The equivalent viscous damping coefficient can reflect the fullness of the hysteretic curve of the model and the energy dissipation capacity of the model. The larger the equivalent viscous damping coefficient is, the fuller the hysteretic curve of the model is, and the stronger the seismic energy dissipation capacity of the model is. As can be seen from the curve in Figure 12, the equivalent viscous damping coefficient of all specimen models is above 0.3 at the time of failure, indicating that the box-type column model with this section form has good energy dissipation capacity. The equivalent viscous damping coefficient increases with the horizontal displacement loading of the top, and the dissipated energy increases gradually. Before the cracking of the specimen model, the cylinder deformation is small, the energy absorption and dissipation are small, and the equivalent viscous damping coefficient increases gently. After the failure of the model, the damping coefficient increases rapidly, the hysteresis curve becomes full, and the energy dissipation capacity increases substantially. When the ultimate displacement model is completely destroyed, the curve of equivalent viscous damping coefficient tends to be gentle again.

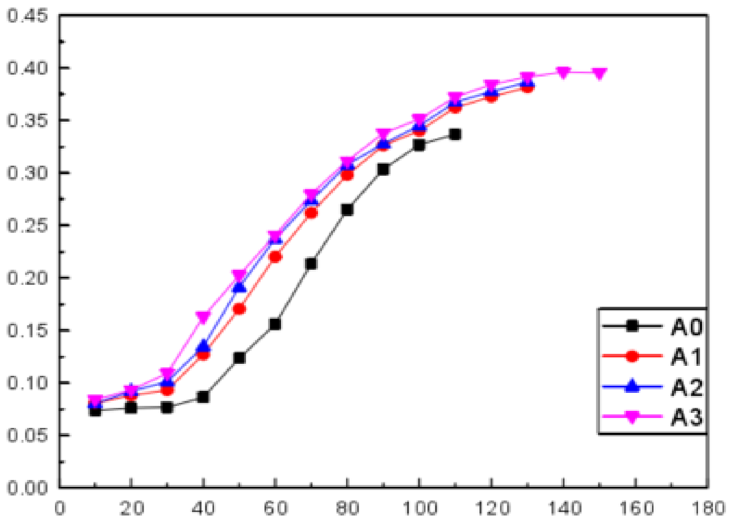


Fig.12 Comparison of equivalent viscous damping coefficients

4. Conclusion

In this paper, four different steel fiber reinforced concrete box column models are designed and the finite element software ABAQUS is used to analyze the seismic performance. After the finite element software simulation calculation results are obtained, the changes of the bearing capacity, deformation, ductility and seismic energy dissipation of the box column models are analyzed through the hysteresis curve, skeleton curve and ductility coefficient of the models. The results are as follows:

1) The seismic ability of fiber reinforced concrete box column is obviously stronger than that of ordinary reinforced concrete box column without fiber. The addition of fiber improves the bearing capacity, deformation, ductility and energy consumption of box columns to varying degrees. The addition of fiber inhibits the generation and development of cracks, and then delays the failure process of the box column. The fiber pulling out and breaking consumes a lot of energy and improves the seismic energy dissipation capacity of the box column.

2) The increase of fiber content has the most significant effect on the performance improvement of box column. The volume content of steel fiber increases from 0 to 0.5%, 1.0%, 1.5%, and the maximum bearing capacity of the model increases by 10.0%, 16.3%, 21.3%, respectively. The displacement ductility coefficients were increased by 15.2%, 27.3% and 29.4% respectively.

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