Shaking Table Test of an External Prestressed Self-centering RC Frame

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Abstract

External Prestressed Self-centering Frame (EPSCF) is a new type of vibration control structure, the main structural features of EPSCF are adopting pure hinged column-beam joints, external prestressed strands are used to provide lateral stiffness of the frame and dampers are used to control the displacement responses. Under earthquakes, the acceleration and shear responses of EPSCF are reduced by weakening the overall stiffness of the structure, and the lateral displacement responses are controlled by the energy-dissipation dampers. The shaking table test of a 1/3-scale 3-story-2-span EPSCF model is described, including model design and fabrication, input earthquake records, arrangement of measuring points, and seismic responses analysis. The experimental results show that EPSCF structure has smaller acceleration and inter-story shear responses than the conventional RC frame, and the displacement responses can be controlled effectively. The shaking table test revealed that no damage occurred in the main structure and the residual deformation was very small under major earthquakes. Based on the test results, a conclusion can be reached that EPSCF is a damage-free resilient structure and it has excellent seismic performance.

Keywords: self-centering, external prestress, seismic performance, RC frame, shaking table test

1. Introduction

Resilient structure refers to a structure that can not only protect life safety by preventing structural failure under an earthquake but also restore its structural function immediately afterward [1]. Priestley and Tao [2] proposed the concept of a rocking frame by allowing frame beams to rotate in a prefabricated concrete frame. El-Sheikh et al. [3] performed a pushover analysis and a time history analysis for a six-story unbonded prestressed self-centering reinforced concrete frame. Lu Xilin et al. [4] conducted a shaking table test research for a new type of self-centering reinforced concrete frame which uses prestressed tendons arranged in the joints to provide restoring force. The research results showed that the self-centering concrete frame structure remains after the earthquake and the residual deformation is small.

Lu et al.[5] proposed the Controlled Rocking Reinforced Concrete Frame (CR-RCF) structure. The column-base joints and column-beam joints in CR-RCF use pure hinges, and the elastic restoring force of the structure is provided by the unbonded prestressed tendons arranged in the beam and column. In the process of studying the seismic performance of CR-RCF structure, the author found that the prestressed tendons would weaken the cross-sectional area of the beam and column members, and the construction accuracy was difficult to control. Therefore, Lu et al. [6] proposed a new vibration control structure External Prestressed Self-Centering Frame (EPSCF). The main structural features of EPSCF are as follows: (1) the pure hinged beam-column joints are used to make the frame have enough rotation capacity while weakening its overall stiffness and reducing the earthquake action on the structure. (2) externally prestressed steel strands are arranged between the upper and lower beams to provide self-centering capability under the earthquakes, and the number of prestressed tendons determines the lateral stiffness of the structure. (3) inter-story dampers are installed to dissipate the earthquake energy and control the displacement response of the structure. The pseudo-static test of a single-frame external prestressed self-resetting frame showed that EPSCF has an excellent seismic performance [7].

Based on the above research, a 1/3-scale 3-story-2-span EPSCF model was designed for shaking table tests, and the dynamic characteristics, dynamic responses, and possible damage under different levels of earthquakes were investigated. In combination with the design method and performance targets, the seismic performance and self-centering capability of the EPSCF structure are evaluated.

2. Design of the shaking table test model

2.1 Model overview

The prototype of the EPSCF structure is a 3-story-2-span reinforced concrete frame. The design parameters of the prototype and the 1/3 scale test model are shown in Table 1, and the dynamic similarity relationships of the shaking table test are shown in Table 2.

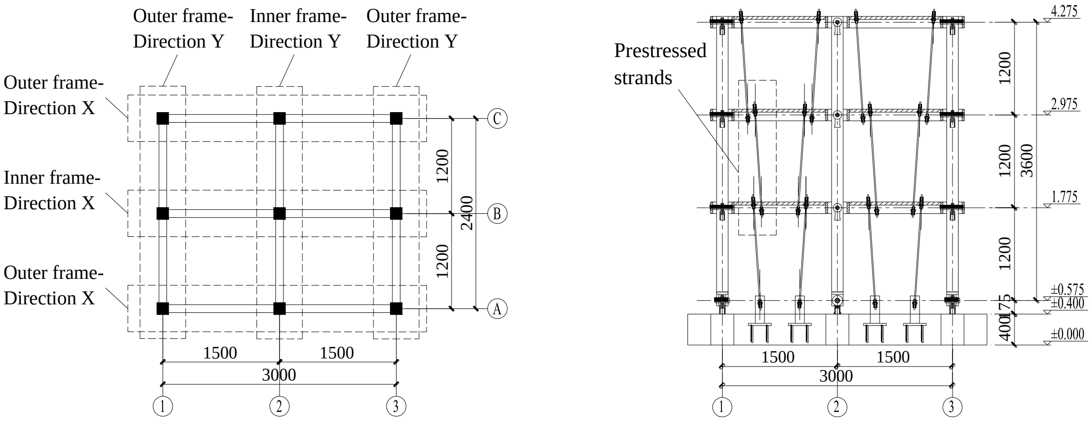
Table 1 – Design parameters of the 1/3 scale shaking table model

Item	Model	Prototype
Number of stories	3	3
Number of spans	2× 2	2× 2
Height of floor	1.2 m	3.6 m
Total height	3.6 m	10.8 m
Plane dimension	3.0 m × 2.4 m	9.0 m × 7.2 m
Cross-section of beam	100 mm × 200 mm	300 mm × 600 mm

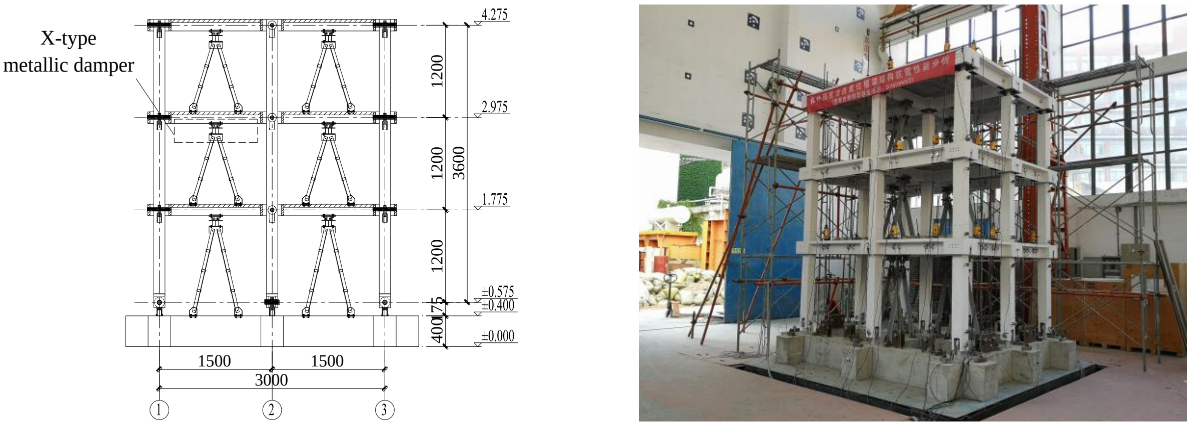
Cross-section of column	150 mm × 150 mm	450 mm × 450 mm
Thickness of slab	40 mm	120 mm
Concrete strength	19.1 MPa	19.1 MPa

Table 2 – Dynamic similitude relationships of the shaking table test

Parameters	**Similitude relationships**	**Similitude ratios**
Length	S_l	1/3
Strain	$S_\varepsilon=1$	1
Modulus of elasticity	S_E	1
Stress	$S_\sigma=S_E$	1
Density	$S_\rho=S_E/(S_\sigma S_l)^{1/2}$	3/2
Concentrated force	$S_p=S_\sigma S_l^2$	1/9
Frequency	$S_f=(S_a/S_l)^{1/2}$	$\sqrt{6}$
Stiffness	$S_K=S_\sigma S_l$	1/3
Time	$S_t=(S_l/S_a)^{1/2}$	$1/\sqrt{6}$
Damping	$S_c=S_\sigma S_l^{2/3}/S_a^{1/2}$	$1/\sqrt{54}$
Acceleration	S_a	2



(a) Layout of model plane (b) Layout of prestressed steel strands



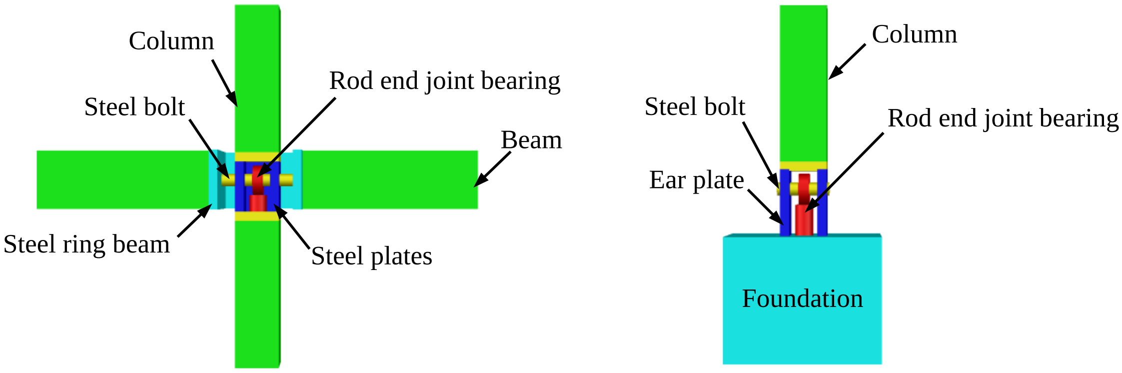
(c) Layout of dampers (d) Photo of the test model

Fig. 1 – Overview of the shaking table test model

The layout of the EPSCF test model is shown in Fig.1(a). Externally prestressed steel strands are arranged on the outer frames in both the long-span direction (X direction) and the short-span direction (Y direction) to provide lateral stiffness for the structure under earthquakes, as shown in Fig. 1(b). Inter-story dampers are arranged in inner frames to control the inter-story displacement of structure, as shown in Fig.1(c). The photo of the test model is shown in Fig.1(d). The test model was designed to satisfy the seismic requirements stated in the *Code for Seismic Design of Buildings of China* [8].

2.2 Design of EPSCF joints

Unlike the conventional frame structure, three-dimensional pure hinges are used for the column-base and column-beam joints of EPSCF as shown in Fig.2. The column-beam joints are hinged through rod-end joint bearings, steel bolts and steel connectors so that the column can rotate in two directions respectively around the center of the joint during the rocking process. The rod end joint bearings which placed in the columns would weaken the cross-section, therefore, at the same height, four steel plates are enclosed and reinforced with bolts to reinforce the column. The column-base joints adopt joint bearings, steel bolts, and embedded steel components to achieve three-dimension hinging.



(a) Column-beam joint (b) Column-base joint

Fig. 2 – Details of EPSCF joints

2.3 Design of external prestressed steel strands and dampers

The overall lateral stiffness of the EPSCF structure is much smaller than that of the conventional frame structure because of the hinged joints, therefore, it is necessary to install prestressed steel strands between beams to provide lateral resistance restoring forces. In order to ensure that the EPSCF structure is always in an elastic state, the tensile stress of the steel strand in the initial state is 0.35 f_{ptk} (f_{ptk} is the standard strength of the prestressed steel strand) and the maximum allowable stress is 0.70 f_{ptk} when the inter-story displacement angle reaches limit value of 1/20 [9] .According to the calculation, 1×7 type $Ø^s$15.2 steel strand was selected for the test model corresponding to the cross-section area A_s=140mm^2, the limit strength f_{ptk}= 1860 MPa, and the modulus of elastic E=1.95×105MPa. The horizontal distance between the upper and lower anchor points of the prestressed steel strand is 80mm, and the initial angle between steel strand and the vertical direction is 3.81°. As a design result, the initial tensile force of a single steel strand is F_{po}= $0.35 \times f_{ptk} \times A_s$= 91.14 kN, and the maximum tensile force is F_p= $0.7 \times f_{ptk} \times A_s$= 182.28 kN under the rare earthquake.

The displacement response of the EPSCF structure is relatively increased compared to the conventional frame under earthquakes. In order to effectively control the inter-story displacement responses and dissipate the input energy of the earthquakes, X-type mild steel plate dampers were installed between the stories of the test model through herringbone braces. As shown in Fig.3, the yield force and yield displacement of X-type mild steel plate damper are 3.34 kN and 4.85 mm respectively.

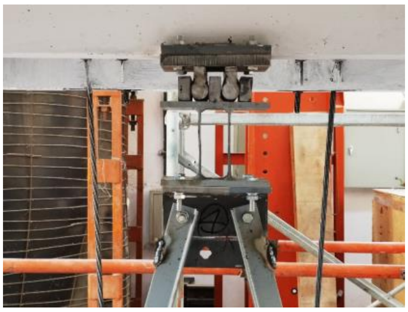
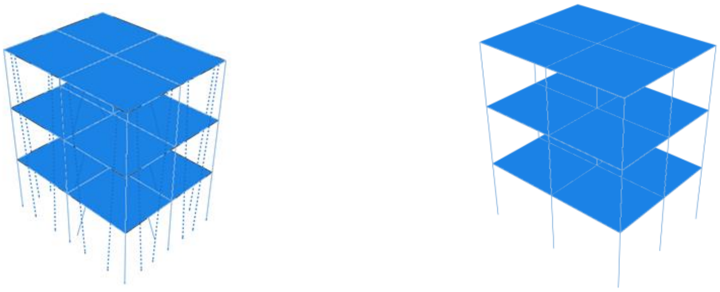


Fig. 3 – Energy dissipation device of EPSCF

3 Numerical modeling of EPSCF

3.1. FEM elements

The finite element software ABAQUS was used to perform the numerical modeling work, and the parameters of the EPSCF model are shown in Table 1. The connection element type *Joint* and *Rotation* was adopted to simulate hinged joints. The connection element type *Axial* was used to simulate the spring performance of prestressed steel strands. The connection element *Cartesian* was used to simulate inter-story dampers. Beam and column members were modeled by element *B31* and slabs were modeled by element *S4R*. The constitutive material model of the reinforced concrete is based on a fiber element in ABAQUS and uses a group of uniaxial hysteresis constitutive models called *TJ-Fiber* [10]. For comparative research, a numerical model of the conventional RC frame was established and the size and cross-sections of which were the same as the EPSCF model. The diagrams of the two models are shown in Fig.4.



(a) EPSCF

(b) Conventional frame

Fig. 4 – FEM models

3.2 Time history analysis

The El Centro wave was selected as the input ground motion time history for the ABAQUS finite element models. The dynamic time history analysis of the EPSCF model and the conventional frame model were performed to calculate the acceleration, inter-story displacement, and other dynamic responses under different earthquakes. Due to the limitation of space, only part of the comparison results of experiment and simulation are presented here. As an example, the time history curves of the dynamic response of the third floor in EPSCF model are shown in Fig.5 and Fig.6. It can be observed that the time history curves of the accelerations and inter-story drifts obtained from the numerical analysis correspond well with the results obtained from the shaking table test. It can be verified that the finite element model can accurately simulate the hinged joints, external prestressing and damping of the EPSCF structure.

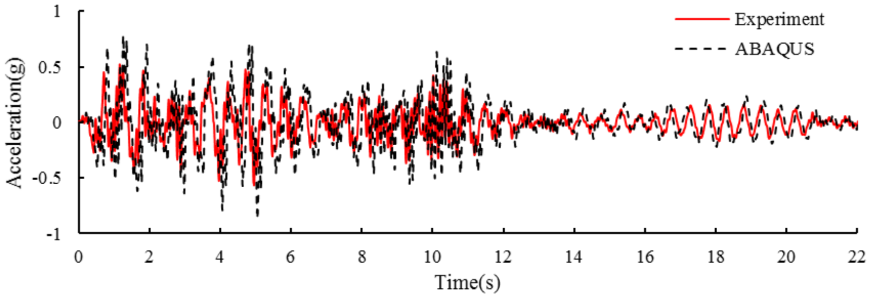


Fig. 5 – Time history curves of acceleration response under PGA=0.40g (X direction)

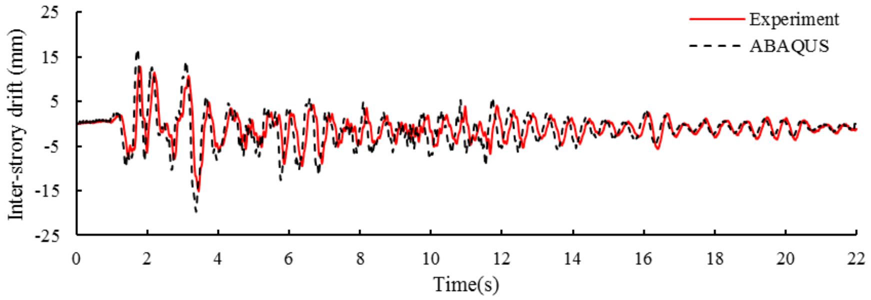


Fig. 6 – Time history curves of inter-story drift response under PGA=0.80g (X direction)

4. Shaking table test

4.1 Test method and test phenomenon

The El Centro wave which commonly used in shaking table tests as the ground motion input, and it was input in both directions of X (long-span direction of test model) and Y (short-span direction of test model). The seismic wave input in the X direction corresponds to the E-W direction of the natural seismic wave while the seismic waveform input in the Y direction corresponds to the N-S direction. The PGA of the input waves exerted on the model sequentially were 0.15 g, 0.40 g, 0.60 g, 0.80 g, and 1.00 g, respectively. The ratio of the peak input acceleration is adjusted to X/Y = 1/0.85. Eight acceleration sensors and eight displacement sensors were evenly arranged on the test model to measure the acceleration responses and overall displacement responses of two directions respectively. The test run cases were divided into two types: the EPSCF model with dampers and the EPSCF model without dampers.

Under the rare earthquakes, the main components of the EPSCF model without dampers remained intact, but the displacement responses were relatively large. The main components of the EPSCF model with dampers remained intact except that the dampers yielded under the rare earthquakes, as shown in Fig.7. The test results showed that although the EPSCF model undergo a large deformation during the earthquake, it returned to its original position after the earthquake with very small residual deformation. Test results revealed that the EPSCF structure has superior damage-free and self-centering performance.

Fig. 7 – EPSCF model with dampers remained intact except dampers

4.2 Dynamic characteristics and seismic responses

Before each earthquake wave exerting, white noise excitation tests were performed to measure the natural vibration periods of the model. Table 3 shows the first three orders of the natural frequencies of the EPSCF model with dampers and without dampers in the initial state and after going through all test cases.

Table 3 – Natural frequencies of the EPSCF model

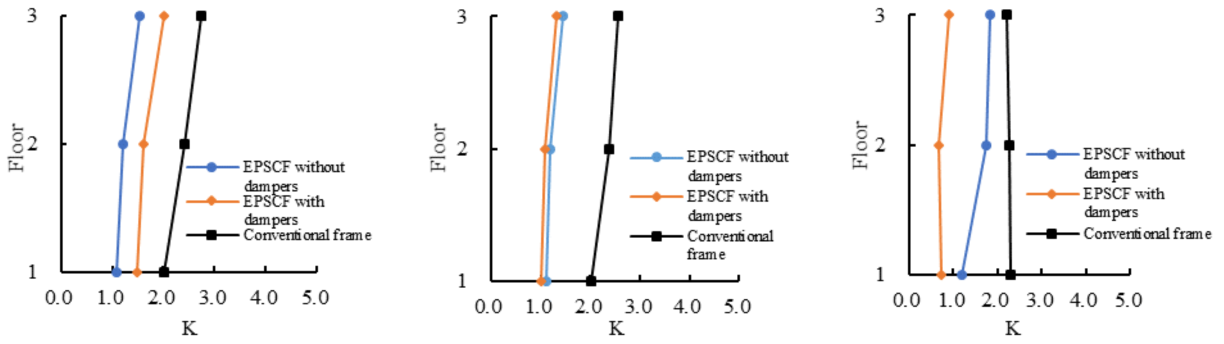
Natural frequencies (Hz)	**Vibration mode**	**EPSCF without dampers**		**EPSCF with dampers**	
		Initial	**End of the test**	**Initial**	**End of the test**
f_1	X-direction translation	1.375	1.375	1.937	1.688
f_2	Y-direction translation	1.381	1.381	1.938	1.750
f_3	Y-direction translation	8.813	8.188	10.125	8.812

From Table 3, it can be obtained that the first-order natural vibration period of the EPSCF model without dampers is 0.727s, and the EPSCF model with dampers is 0.516s. The first-order natural vibration periods of the two prototype structures are 1.781s and 1.264s respectively which derived from the similitude ratio listed in Table 2. The first-order natural vibration period of the prototype conventional frame structure obtained from finite element calculation is 0.316s. It is shown that the conventional frame has a shorter period but larger stiffness compared to EPSCF. According to the seismic response spectrum theory, the floor acceleration response and inter-story shear response of EPSCF would become smaller compared to the conventional frame. After experiencing all test cases, the natural frequencies of the EPSCF model without dampers are basically the same, which shows that the stiffness has not changed, and the prestressed steel strands are always in the elastic state. It means that the EPSCF structure has the feature of being damage-free under earthquakes.

The envelope values of acceleration and inter-story displacement response of the EPSCF model with dampers and without dampers were obtained from the shaking table test as shown in Table 4 and Table 5. The envelope values of acceleration and inter-story displacement response of the conventional frame as shown in Fig. 4(b) were obtained from the finite element calculations. The comparison of the envelope acceleration response between the EPSCF structures and the conventional frame structure is shown in Fig.8, and the dynamic amplification factor K is defined by the ratio of the maximum floor acceleration response on the model base. The envelope values of the inter-story displacement response are shown in Fig.9.

Table 4 – Acceleration responses of the EPSCF model

PGA	EPSCF model	Direction	F1		F2		F3	
			a_{max1}	K_1	a_{max2}	K_2	a_{max3}	K_3
0.15g	without dampers	X	0.16 g	1.08	0.18 g	1.21	0.24 g	1.55
		Y	0.16 g	1.18	0.10 g	0.72	0.12 g	0.86
	with dampers	X	0.22 g	1.50	0.24 g	1.62	0.40 g	2.68
		Y	0.14 g	1.10	0.18 g	1.44	0.24 g	1.88
0.40g	without dampers	X	0.48 g	1.12	0.51 g	1.19	0.62 g	1.45
		Y	0.36 g	1.03	0.45 g	1.28	0.56 g	1.60
	with dampers	X	0.44 g	1.02	0.47 g	1.09	0.57 g	1.32
		Y	0.30 g	0.88	0.41 g	1.18	0.48 g	1.42
0.80g	without dampers	X	1.10 g	1.18	1.62 g	1.75	1.69 g	1.82
		Y	0.63 g	0.91	0.59 g	0.85	0.65 g	0.93
	with dampers	X	0.61 g	0.73	0.57 g	0.68	0.77 g	0.91
		Y	0.63 g	0.87	0.70 g	0.98	0.69 g	0.96



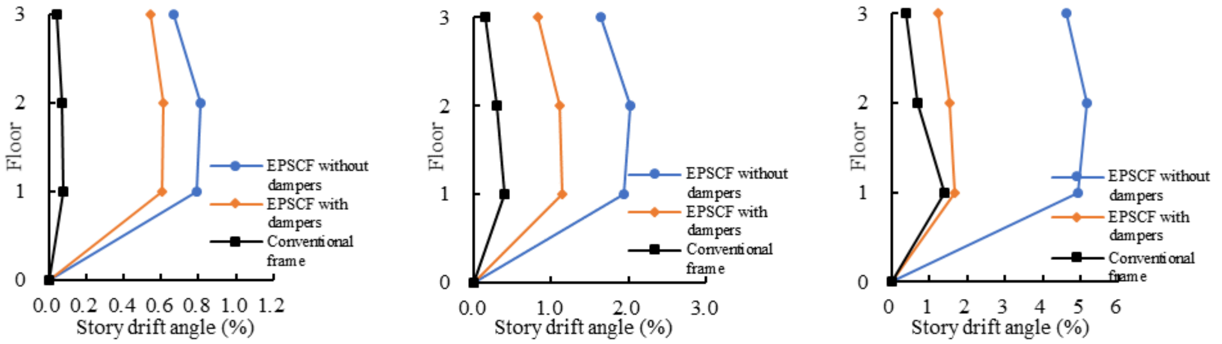
(PGA=0.15g) (PGA=0.40g) (PGA=0.80g)

Fig. 8 – Comparison of acceleration responses between EPSCF and conventional frame (X direction)

Table 5 – Story drift responses of EPSCF model

PGA	EPSCF model	Direction	Peak story drift (mm)			Peak story drift angle (%)		
			F1	F2	F3	F1	F2	F3
0.15g	without dampers	X	9.5	9.7	8.0	0.79	0.81	0.67
		Y	5.4	4.3	3.9	0.45	0.36	0.32
	with dampers	X	7.2	7.4	6.6	0.60	0.61	0.55

		Y	5.6	2.7	2.9	0.47	0.23	0.25
0.40g	without dampers	X	23.3	24.3	19.6	1.94	2.03	1.63
		Y	14.2	14.6	13.0	1.18	1.22	1.09
	with dampers	X	13.8	13.4	9.8	1.15	1.12	0.82
		Y	14.0	6.3	5.9	1.17	0.52	0.49
0.80g	without dampers	X	59.0	61.8	55.6	4.91	5.15	4.63
		Y	34.4	35.9	33.6	2.87	2.99	2.80
	with dampers	X	19.9	18.6	15.0	1.66	1.55	1.25
		Y	18.4	13.2	14.5	1.53	1.10	1.21



(PGA = 0.15g) (PGA = 0.40g) (PGA = 0.80g)

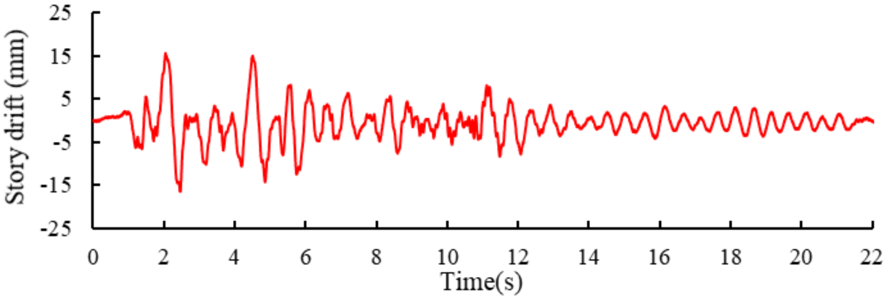
Fig. 9 – Comparison of story drift responses between EPSCF and conventional frame (X direction)

It can be seen from the data in Fig.8 that: (1) the acceleration seismic response *K* values of EPSCF structure with and without dampers are about 1.0, which are smaller than the *K* values of conventional RC frame structure, and the *K* values of conventional RC frame structure are larger than 2.0; (2) under the PGA = 0.15g earthquake, the acceleration response of EPSCF with dampers is larger than that of EPSCF without damper, because the dampers of EPSCF structure provides additional initial stiffness; (3) under the PGA = 0.80g earthquake, the acceleration response of the EPSCF with dampers is smaller than that of the EPSCF without damper, because the metal dampers have yielded, the additional stiffness provided is small, and the equivalent damping provided is relatively large; (4) under the action of PGA = 0.40g earthquake, the acceleration response of EPSCF with and without damper in the figure is little different, mainly because the additional stiffness provided by the dampers increases the acceleration response of the structure, while the additional damping provided by the dampers reduces the acceleration response of the structure.

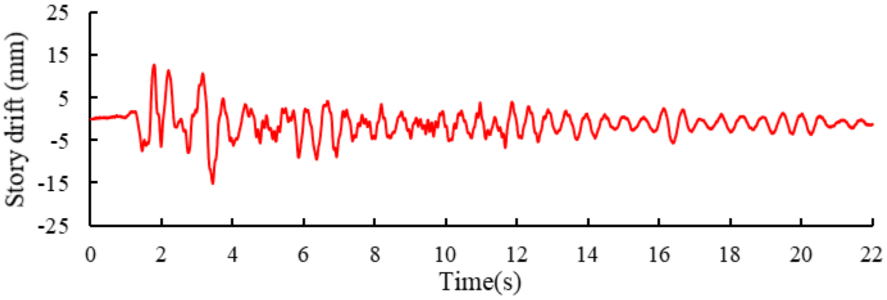
The story drift responses of the EPSCF model with dampers in the X and Y directions are smaller than that of the EPSCF model without dampers. Taking the X direction as an example, the peak inter-story displacement of the top floor of the EPSCF model with dampers decreased by 17.5%, 50%, 73% respectively compared to the EPSCF model without dampers under different seismic waves. It shows that the dampers in the EPSCF structure can significantly control the displacement response and the maximum inter-story displacement angle of the EPSCF model with dampers is only 1/60 under PGA = 0.80g earthquake.

Therefore, compared with the conventional frame structure, the EPSCF structure can greatly reduce the acceleration response, while the displacement response is effectively controlled, and EPSCF has a superior seismic performance.

Fig.10 shows the time-history curves of the top floor story drift response of the EPSCF model with dampers in the X and Y directions under the PGA = 0.4g seismic wave. Although large deformations occurred in both directions of the structure during the earthquake, the structure almost recovered to the original position after the earthquake, and the residual deformation was small, showing its excellent self-centering performance.



(a) X direction



(b) Y direction

Fig. 10 – The top floor story drift responses

5. Conclusions

(1) In the EPSCF structure system, three-dimensional hinged connections are adopted and the rotation constraint between column and beam is released. Structural lateral stiffness and restoring force are provided by externally prestressed steel strands. Compared with the conventional RC frame, EPSCF has smaller lateral stiffness but better deformation capacity. Furthermore, its natural vibration period is relative larger and earthquake response of acceleration and base shear decrease.

(2) Arranging inter-story dampers in EPSCF can control its displacement response and increase energy dissipation under earthquakes. Owe to prestressed steel strands, this structure system can recover to the initial position which achieves structural self-centering. Compared with the conventional RC frame, the EPSCF structure system not only can decrease the energy input of earthquakes but also control structural displacement responses.

(3) After earthquakes, the main structural components of EPSCF keep intact when dampers yield. Utilizing changing yielded dampers, this structural system can remain in service immediately. In general, EPSCF possesses clear energy dissipating mechanism and excellent self-centering capacity, which conforms to the requirements of resilient structures.

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