Periodica Polytechnica Civil Engineering

61(2), pp. 300–312, 2017
https://doi.org/10.3311/PPci.9243

RESEARCH ARTICLE

Shaking Table Test and Time-history Analysis of High-rise Diagrid Tube Structure

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Received 27 March 2016; Accepted 11 September 2016

Abstract

As a new type of high-rise building structure system, diagrid tube in tube structure is increasingly applied in high-rise building. Guangzhou West tower is the first high-rise diagrid tube in tube structure in China. To study seismic performance of the structure, elastic time-history analysis and shaking table test were conducted. The results of elastic time-history analysis and shaking table test were in a good agreement, which verified the validity of the elastic time-history analysis. Dynamic characteristics and responses of the model structure's acceleration, displacement and strain under different intensity earthquake action were obtained through analysis and test. Dynamic responses of prototype structure were deduced based on similarity law and shaking table test results. Research shows that diagrid tube structure has a small deformation under earthquake actions; the main vibration mode is translation, while torsional effect is not obvious; whiplash effect has less influence on the structure; diagrid members, diagrid nodes and shear walls at the bottom of the structure are weak parts.

Keywords

Diagrid structure; Plexiglas; Shaking table test; Time-history analysis; Seismic performance

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1 Introduction

West tower in Guangzhou Zhujiang new city is a new type of tube structure system as shown in Fig. 1 and Fig. 2, which has total floor area of 247000 square meters. Outer tube of this structure consists of diagonal members which are concrete-filled steel tube columns, while inner tube consists of shear walls and steel frames. Shear walls of inner tube are cancelled above 67th floor and replaced by steel frames. Elevation for the underground fourth floors is -18.7meters, and elevation for the top of structure is 432 meters. Because the height of West tower is higher than code limit value and shear walls of inner tube change into oblique steel frame at 67th floor, which leads to vertical irregular arrangement of the structure. Thus, West tower belongs to a complex super high-rise structure [1] .

At present, researches on high-rise diagrid structures are still not very mature. Moon [2] proposed preliminary design method for diagonal members. Han [3] researched deflection, stress and failure mode of diagonal nodes by conducting model test of concrete filled steel tubular joint. Tian [4] conducted a shaking table test on West tower by using micro-concrete and brass tube, and destructed form of West tower was obtained. Kim [5] obtained hysteresis curve of steel diagonal nodes by experiment. Kim [6] evaluated the seismic performance of diagrid structure by finite element method.

Structural type of diagrid structure makes the force-mechanism become complicated, and it also makes mechanical property calculation of diagrid structure difficult. Therefore, it is necessary to carry out further experimental study on seismic performance of whole structure. For this reason, a shaking table test of a plexiglas model in scale 1:80 was carried out to study the seismic performance of the structure. In further, an elastic time-history analysis by finite element software was carried out on the structure, the mechanical characteristics and weak parts of the diagrid tube structure were obtained by comparing the results of analysis and shaking table test. In this paper, the research also expects to provide the basis for the reasonable design of diagrid tube structure.

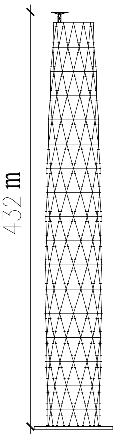

Fig. 1 Elevation of West tower

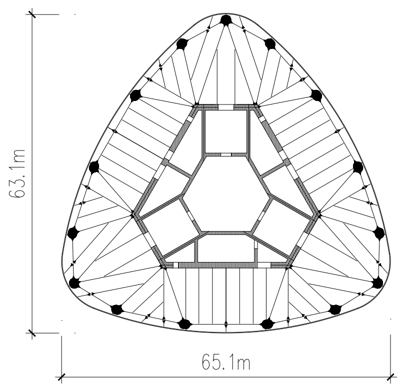

Fig. 2 Planar shape of West tower

2 Model design and Fabrication

2.1 Material performance test on plexiglas

Plexiglas was used to simulate all materials of the prototype according to similarity law [7]. Test parameters are shown in Table 1, and constitutive-curve of plexiglas is shown in Fig. 3.

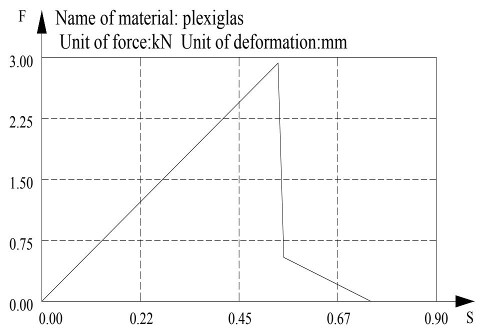

Fig. 3 Constitutive-curve of plexiglas

2.2 Similarity law

According to similarity relation between inertia force and elastic force in dynamic test, the following equation can be obtained:

$$S_t^2 = S_l^2 \cdot S_\rho \cdot S_E^{-1} \tag{1}$$

Where S_l, S_t, S_ρ, S_E are geometry similarity coefficient, time similarity coefficient, density similarity coefficient and elastic modulus similarity coefficient of model respectively. When the model geometry similarity coefficient and the material of model are selected, rest similarity coefficient of physical quantities can be obtained.

The artificial mass added to the model can be obtained by following equations:

$$S_m = S_\rho \cdot S_l^3 \tag{2}$$

$$M^m = S_m \cdot M^p \tag{3}$$

Where S_m is mass similarity coefficient of model, M^m is total mass of model (including the model structure mass and artificial mass) and M^p is total mass of prototype structure. The similarity coefficients of whole model are shown in Table 2.

2.3 Model fabrication

In order to simulate and research the prototype structure accurately, the whole prototype structure including basement was selected to fabricate test model [8]–[13] . Parts of beams, columns and walls were simplified in a normalized method to ensure success of model fabrication. To ensure test model reflecting the mechanical characteristics of the prototype structure as far as possible, contributions of rebar and steel tube were converted according to its certain stiffness proportion.

Walls and columns at the bottom of model were consolidated with a fiberglass baseboard of 40 mm thick, and then the fiberglass baseboard was fixed on shaking table through reserved hole at baseboard. In order to ensure the verticality of the assembled model, the error of processing and assembling was strictly limited within 1/3000. Details of fabrication and completion of model are shown in Fig. 4–Fig. 6. Fig. 6 shows whole model with artificial mass. Total mass of model is 1.73 tons, and the height of model is 5.70 meters.

Table 1 Test parameters of plexiglas

Acceleration of test	Measuring range	Width of specimen	Thickness of specimen	Peak load	Peak stress	Elasticity modulus	Peak strain
1mm/min	50mm	21.42mm	5.4mm	2.93kN	25.3MPa	2.46GPa	0.01028

Table 2 Similarity coefficients of whole model

Physical ratio	Length	Linear displacement	Equivalent elastic modulus	Density	Mass	Frequency	Acceleration
Similarity formulae	1/80	1/80	0.060	2.300	4.44×10^{-6}	12.658	2.000

Fig. 4 Marking number

Fig. 5 Node details

Fig. 6 The whole model

3 Shaking table test

3.1 Transducer arrangement

According to the structure characteristics of Guangzhou West tower, corresponding transducers were assigned successively at the key parts of the structure, such as the transfer plate, diagonal nodes, shear walls and interior columns of the shear walls, main girder at node layer etc., as shown in Fig. 7 and Fig. 8.

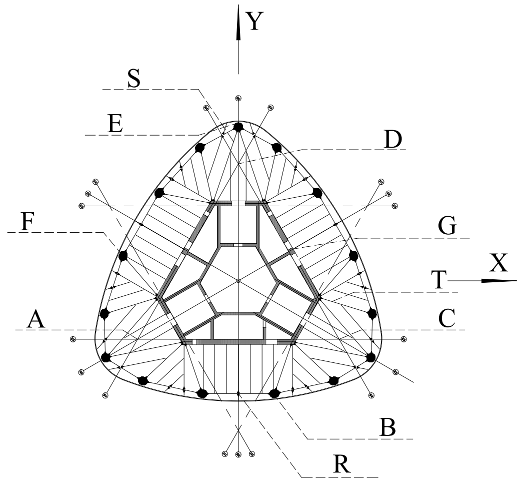

Fig. 7 Plane arrangement of transducers at node layer

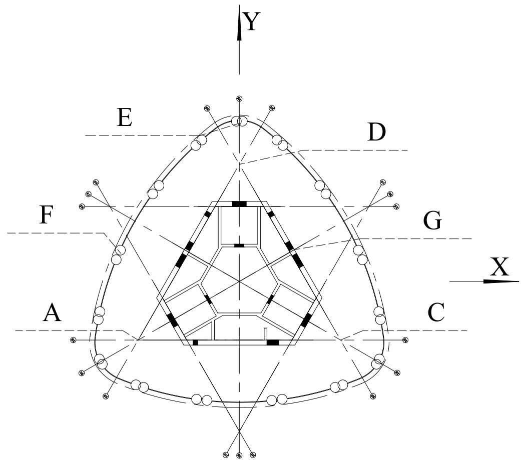

Fig. 8 Plane arrangement of transducers at non-node layers

Twenty-three strain gauges were assigned on the model; fourteen displacement gauges were assigned at measuring point B and D in X and Y direction respectively; and thirty acceleration gauges were assigned at measuring point A and C. The details of the position of the transducers are shown in Table 3.

3.2 Testing Procedure of the Shaking Table Test

According to the requirements of Chinese seismic code [14], El Centro record, Taft record and the artificial seismic record (GZ record) were regarded as the table excitation of the shaking table. The artificial seismic record was generated according to the code for seismic design.

Test loadings were conducted in four sequential stages including frequent earthquake of intensity 7, basic earthquake of intensity 7, rare earthquake of intensity 7 and rare earthquake of intensity 8, which meant that the original time history records were multiplied by factors which were increasing the effective intensities (PGA) shown in Table 4. In order to obtain frequencies of the test model, white noise excitation was carried out on the test model before and after inputting different level seismic records. El Centro record, Taft record and GZ record were input to the shaking table respectively. Based on

Table 3 The position of the transducers of the shaking table test

Floor	Transducers position	Floor	Displacement gauges position	Direction	Floor	Displacement gauges position	Direction
101	N,M	Parking apron	C,A,A	X ,Y ,X	Parking apron	D,B	Y,X
97	G,G,G,E	Top floor	C,A,A	X ,Y ,X	Top floor	D,B	Y,X
72	L,H	99	C,A,A	X ,Y ,X	97	D,B	Y,X
71	K,J	97	C,A,A	X ,Y ,X	69	D,B	Y,X
69	G,G,G,R	73	C,A,A	X ,Y ,X	55	D,B	Y,X
67	E	69	C,A,A	X ,Y ,X	19	D,B	Y,X
55	T,R,S	37	C,A,A	X ,Y ,X	Baseboard	D,B	Y,X
19	T,S	19	C,A,A	X ,Y ,X	-	-	-
7	E,F	7	C,A,A	X ,Y ,X	-	-	-
1	G	-	-	-	-	-	-

Table 4 Test conditions of shaking table test for the model of Guangzhou west tower

SN	Earthquake excitation	MD	PAC	M	SX(g)	AX(g)	SX(g)	AY (g)
1	The first white noise frequency sweep					0.05		0.05
2	El Centro frequent earthquake of intensity 7	X	0.035	2	0.07	0.066	0.06	0.057
3		Y	0.035	2	0.06	0.061	0.07	0.080
4	Taft frequent earthquake of intensity 7	X	0.035	2	0.07	0.067	0.06	0.051
5		Y	0.035	2	0.06	0.051	0.07	0.144
6	Artificial seismic records frequent earthquake of intensity 7	X	0.035	2	0.07	0.073	0.06	0.124
7		Y	0.035	2	0.06	0.066	0.07	0.089
8	The second white noise frequency sweep					0.05		0.05
9	El Centro basic earthquake of intensity 7	X	0.1	2	0.20	0.194	0.17	0.199
10		Y	0.1	2	0.17	0.170	0.20	0.187
11	Taft basic earthquake of intensity 7	X	0.1	2	0.20	0.214	0.17	0.145
12		Y	0.1	2	0.17	0.165	0.20	0.225
13	Artificial seismic records basic earthquake of intensity 7	X	0.1	2	0.20	0.219	0.17	0.199
14		Y	0.1	2	0.17	0.213	0.20	0.181
15	The third white noise frequency sweep					0.05		0.05
16	El Centro rare earthquake of intensity 7	X	0.22	2	0.44	0.467	0.37	0.411
17		Y	0.22	2	0.37	0.346	0.44	0.483
18	Taft rare earthquake of intensity 7	X	0.22	2	0.44	0.430	0.37	0.369
19		Y	0.22	2	0.37	0.377	0.44	0.431
20	Artificial seismic records rare earthquake of intensity 7	X	0.22	2	0.44	0.460	0.37	0.382
21		Y	0.22	2	0.37	0.350	0.44	0.483
22	The fourth white noise frequency sweep					0.05		0.05
23	El Centro rare earthquake of intensity 8	X	0.4	2	0.80	0.863	0.68	0.675
24		Y	0.4	2	0.68	0.674	0.80	0.759
25	Taft rare earthquake of intensity 8	X	0.4	2	0.80	0.866	0.68	0.677
26		Y	0.4	2	0.68	0.673	0.80	0.824
27	Artificial seismic records rare earthquake of intensity 8	X	0.4	2	0.80	0.831	0.68	0.668
28		Y	0.4	2	0.68	0.710	0.80	0.764
29	The fifth white noise frequency sweep					0.05		0.05

SN: Sequence number; SX: Set values in X direcion; MD: Main direction of main shock; AX: Actual values in X direction; PAC: peak accelerations from codes; SY: Set values in Y direction; M: Multipliers obtained from Similarity law; AY: Actual values in Y direction

Table 5 The change of the first frequency in X and Y direction

white noise excitation	First		Second		Third		Fourth		Fifth	
Direction	X	Y	X	Y	X	Y	X	Y	X	Y
Frequency (Hz)	1.545	1.584	1.545	1.584	1.545	1.584	1.545	1.584	1.545	1.584

the similarity law, the duration of seismic records were compressed to 1/12.658 of original seismic records, and the inputting directions were divided into X and Y direction. In order to simulate the effect of various earthquake levels, peak accelerations that were input to the shaking table were modified according to the relative codes [14] and similarity law. Test conditions of shaking table test for the model of Guangzhou West Tower are shown in Table 4.

3.3 Test execution

The test model showed no sign of damage in the test and kept in elastic stage all the time, which proved that shaking table test was accomplished well. Table 5 illustrates that first frequency of the test model in X and Y direction is constant which means the test model keeps elastic and meets the requirement of similar design.

4 Time-history analysis of the model structure

4.1 Finite element model

Finite element model based on the test model and consisted of 103 floors on the ground, the parking apron and four-floor basements; Four-floor basements were set as fixed ends in structural analysis.

Beam element was used to simulate the beams and columns; shell element was used to simulate the shear walls; as for floor slabs, considering the influence of their rigidity, shell element was used too. 6716 beam elements and 18277 shell elements were used in finite element model, and the total number of elements was 24993. Fig. 9 shows the finite element model of diagrid outer tube; Fig. 10 shows the finite element model of stiffness mutation part, where shear walls in inner tube change into oblique steel frames on the 67th floor; Fig. 11 shows the whole finite element model.

Fig. 9 Finite element model of diagrid outer tube

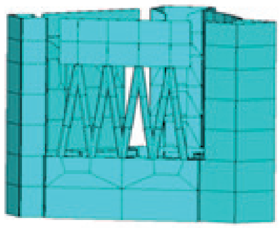

Fig. 10 Stiffness mutation of inner tube

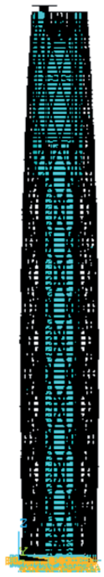

Fig. 11 Stiffness mutation of inner tube

4.2 Comparison of the modal analysis

Before the time-history analysis for the model was carried out, the modal analysis of the finite element model was carried out in elastic state, and the first nine order natural vibration frequencies and modal types were obtained. Table 6 illustrates that the first nine frequencies obtained from time-history numerical calculation has a good agreement with the shaking table test results, and directions of vibration mode are the same, which shows rationality of time-history analysis results. Because nodes in the test model cannot entirely achieve rigid connection due to craftsmanship, while nodes in finite element model can realize ideal rigid connection, which leads to finite element model has lager stiffness, thus the first two frequencies obtained from FEM are overestimated to some degree when compared with measuring frequency. Finite element method could be used as a powerful auxiliary tool of shaking table test analysis to assist judging rationality of each frequency and vibration model. Fig. 12 and Fig. 13 show the first three vibration mode shapes of X-direction and Y-direction for the model structure respectively.

Table 6 One to nine order natural frequency of calculating and the measuring model /Hz

Order	One	Two	Three	Four	Five	Six	Seven	Eight	Nine
Calculated frequency	1.701	1.729	4.131	5.037	5.106	6.197	6.500	6.568	7.644
Calculated direction	X	Y	Torsion	X	Y	Y	X	Y	Y
Measured frequency	1.545	1.584	4.636	5.254	5.872	6.490	7.031	7.108	8.344
Measured direction	X	Y	Torsion	X	Y	Y	X	Y	Y
Damping ratio of measuring	3.03%	3.26%	3.41%	2.9%	1.21%	1.11%	4.0%	2.7%	2.9%
Frequency error	-10.1%	-9.14%	10.90%	4.13%	13.05%	4.52%	7.55%	7.60%	8.39%

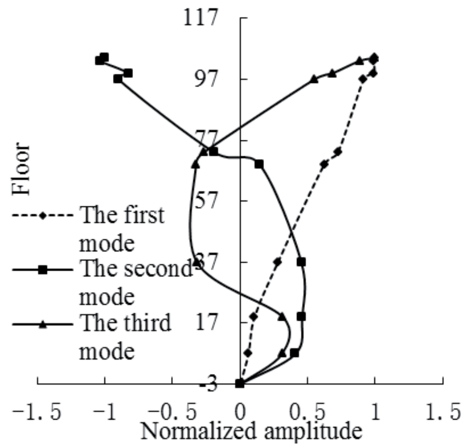

Fig. 12 The first three vibration modes of the model in X direction

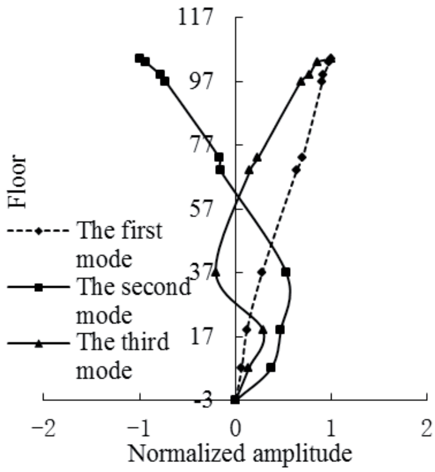

Fig. 13 The first three vibration modes of the model in Y direction

4.3 Comparison of the acceleration responses

The comparisons of the acceleration magnification coefficients between time-history analysis results and the shaking table test results are shown in Fig. 14–Fig. 21. The marks in the Fig. 14–Fig. 21 are stated as follows: "Expe-elx" represents shaking table test results of the model in the X direction under the El-Centro record; "Feam-elx" represents finite element analysis results of the model in the X direction under the El-Centro record; and the remaining marks in the same way.

The results from time-history analysis and shaking table test results were in a good agreement. The acceleration response of model was given priority to the first and second vibration mode, while the influence of the torsional vibration mode was not significant. Due to stiffness mutation of the model's main structure was not serious, the influence of whiplash effect on the model is small and the values of acceleration magnification coefficients were not large. Under the earthquake action, the amplitude of high-rise buildings or other buildings' top protruding slender part were increasing dramatically, which was called whiplash effect. Acceleration magnification coefficient was determined by seismic records' characteristics and model characteristics, so it was reasonable that some acceleration magnification coefficients were less than one. Because the shaking table test model and the finite element model were both elastic models, acceleration magnification coefficients did not have obvious changes along with the increase of seismic intensities.

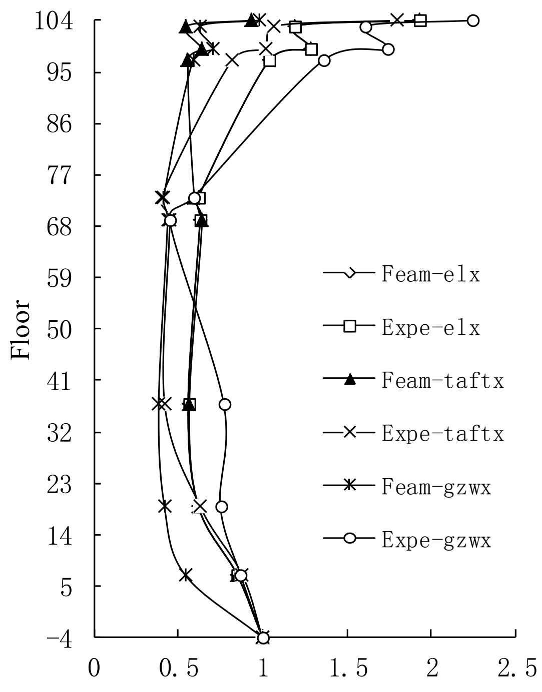

Fig. 14 Acceleration magnification coefficients envelope of model structure in frequent intensity7 in X direction

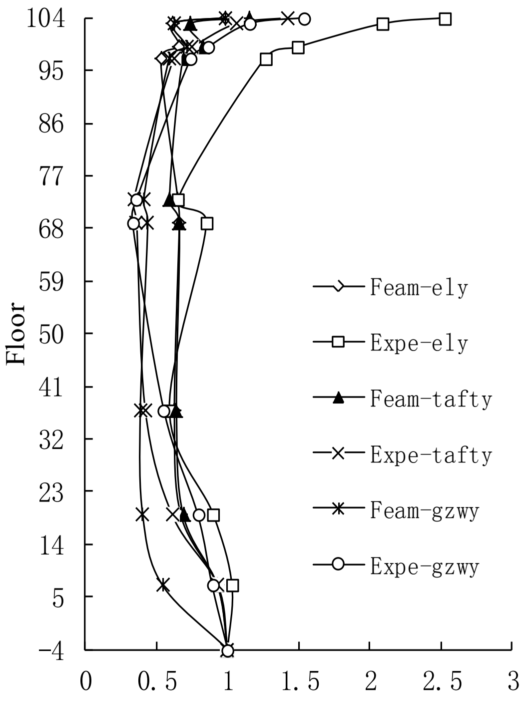

Fig. 15 Acceleration magnification coefficients envelope of model structure in frequent intensity 7 in Y direction

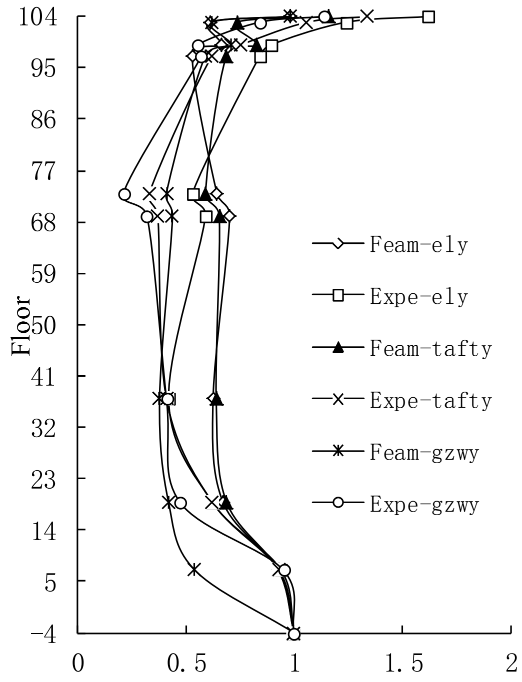

Fig. 17 Acceleration magnification coefficients envelope of model structure in basic intensity 7 in Y direction

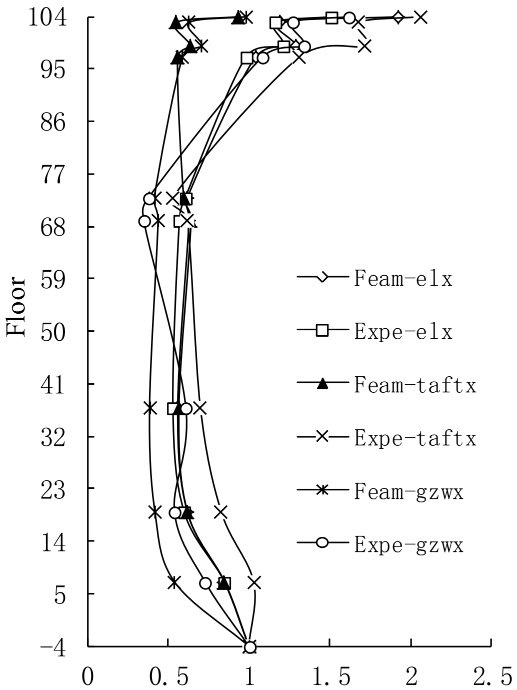

Fig. 16 Acceleration magnification coefficients envelope of model structure in basic intensity 7 in X direction

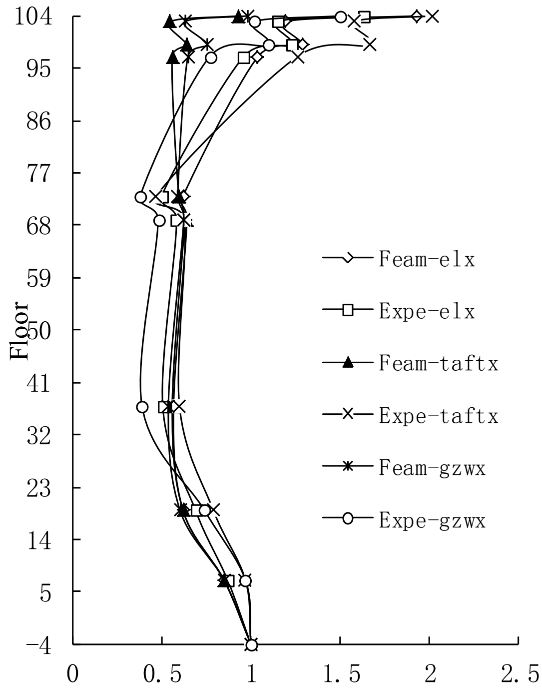

Fig. 18 Acceleration magnification coefficients envelope of model structure in rare intensity 7 in X direction

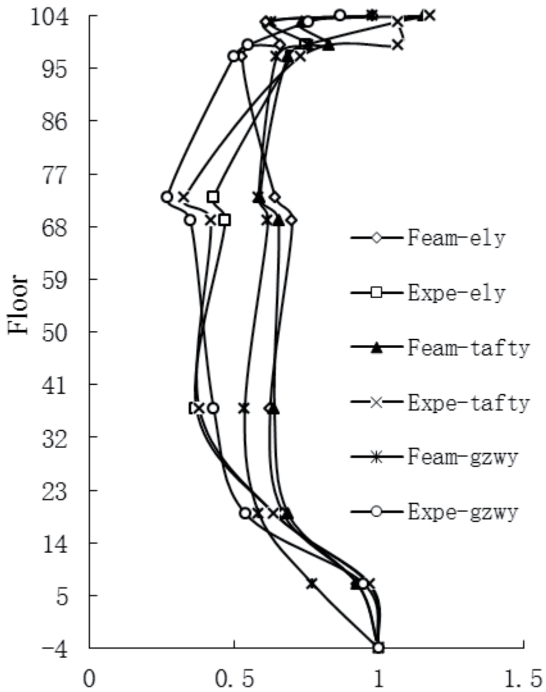

Fig. 19 Acceleration magnification coefficients envelope of model structure in rare intensity 7 in Y direction

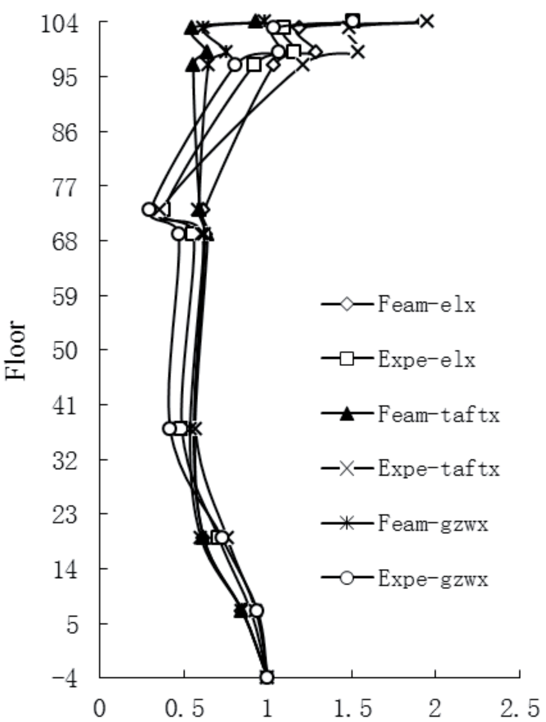

Fig. 20 Acceleration magnification coefficients envelope of model structure in rare intensity 8 in X direction

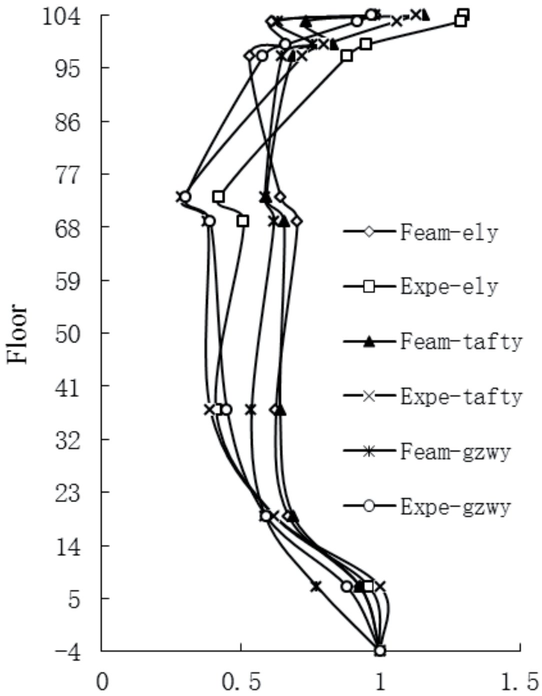

Fig. 21 Acceleration magnification coefficients envelope of model structure in rare intensity 8 in Y direction

4.4 Comparison of displacement responses

The comparisons between displacement responses obtained from time-history calculation and the shaking table test results are shown in Fig. 22–Fig. 29. Displacement envelopes obtained from time- history analysis and shaking table test were in a good agreement. Figures illustrates that the effect of different kind of seismic records on the structure model are different even on the same intensity. Generally speaking, under the same seismic record intensity, displacement in X-direction is sensitive to Taft record, and displacement in Y-direction is sensitive to El Centro record. With seismic intensity increasing, the displacement of model structure became more significant. Because of mutation of the vertical stiffness at the 67th floor and 98th floor, there is mutation of displacement curves near the 67th floor and 98th floor.

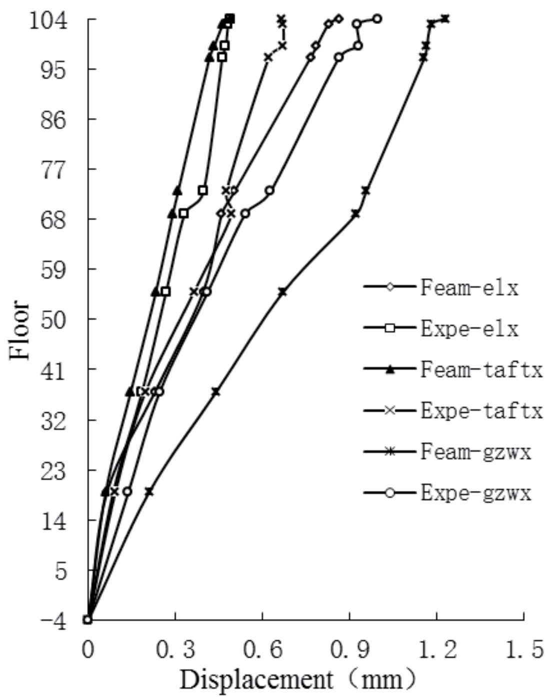

Fig. 22 Displacement envelope of model structure in frequent intensity 7 in X direction

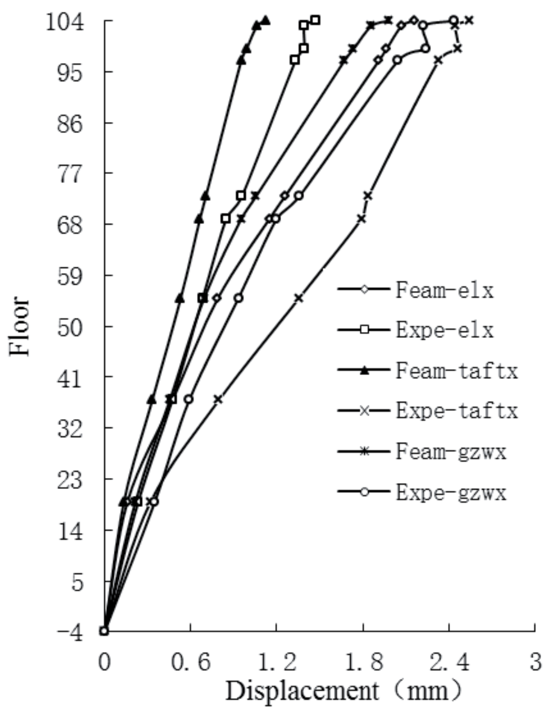

Fig. 24 Displacement envelope of model structure in basic intensity 7 in X direction

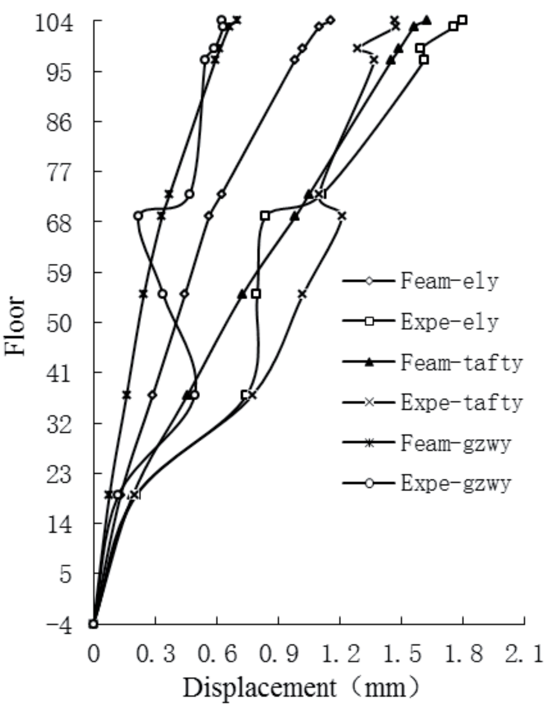

Fig. 23 Displacement envelope of model structure in frequent intensity 7 in Y direction

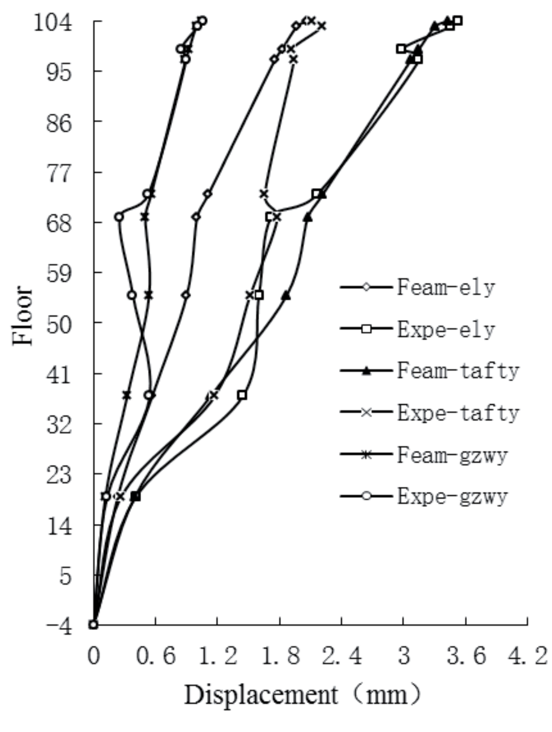

Fig. 25 Displacement envelope of model structure in basic intensity 7 in Y direction

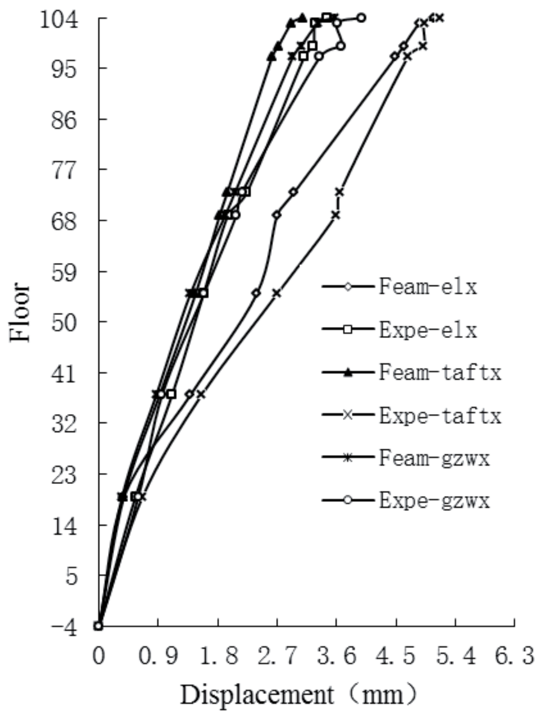

Fig. 26 Displacement envelope of model structure in rare intensity 7 in X direction

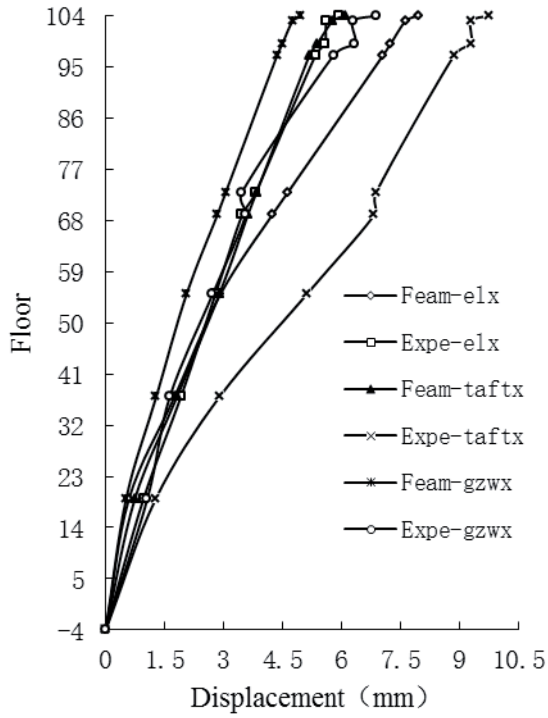

Fig. 28 Displacement envelope of model structure in rare intensity 8 in X direction

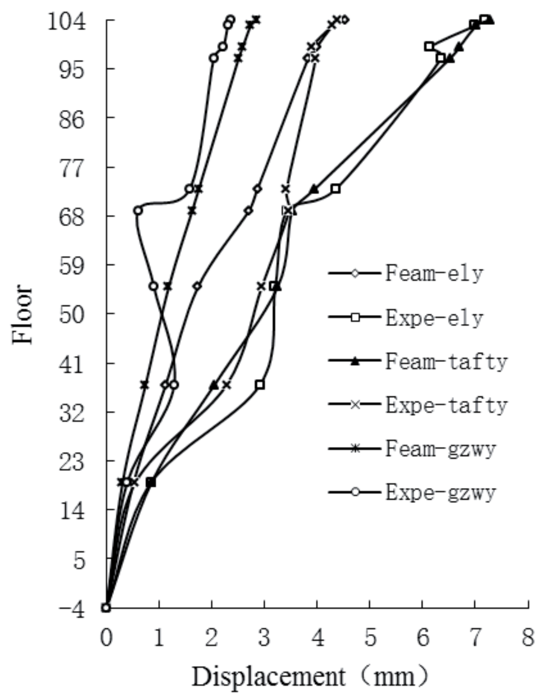

Fig. 27 Displacement envelope of model structure in rare intensity 7 in Y direction

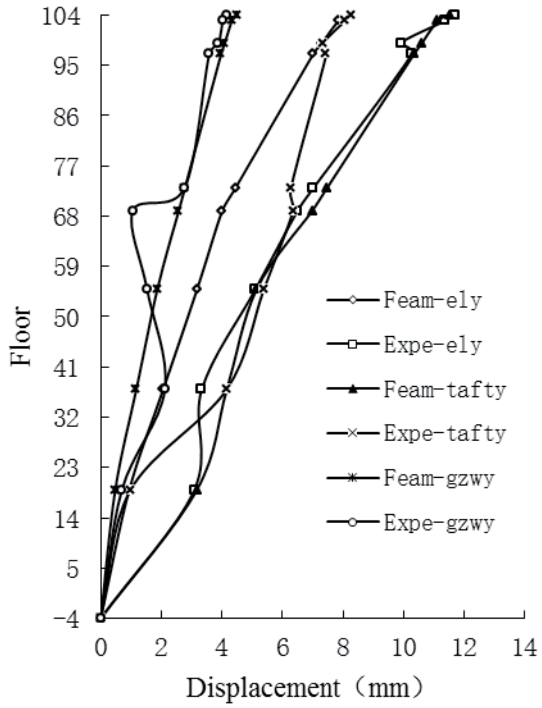

Fig. 29 Displacement envelope of model structure in rare intensity 8 in Y direction

Table 7 Natural vibration frequencies of the prototype structure

Order	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Direction	X	Y	Torsion	X	Y	Y	X	Y	Y	X
Frequency (Hz)	0.122	0.125	0.366	0.415	0.464	0.513	0.555	0.562	0.659	1.047
Period (Sec)	8.197	8.000	2.732	2.410	2.155	1.949	1.802	1.779	1.517	0.955

5 Seismic performance analysis of the prototype structure

5.1 Natural vibration frequency

According to the similar law, natural vibration frequencies and natural vibration periods of the prototype structure could be obtained, as shown in Table 7.

5.2 Acceleration responses

According to similarity law, the equation to calculate maximum acceleration response of the prototype structure is shown as follows:

$$a_i = K_i a_g \tag{4}$$

Where a_i represents maximum acceleration response of the ith floor in the prototype structure;

K_i represents the maximum acceleration magnification coefficient of the ith floor in the model under the corresponding intensity level;

a_g represents the maximum acceleration of the ground under the corresponding intensity level.

Under the earthquake actions with different intensity levels, the maximum accelerations in the X and Y direction of the prototype structure are shown in Fig. 30 and Fig. 31. Maximum acceleration magnification coefficient is 2.52 m/s^2, and as for the prototype structure, there is whiplash effect which has no significant effect.

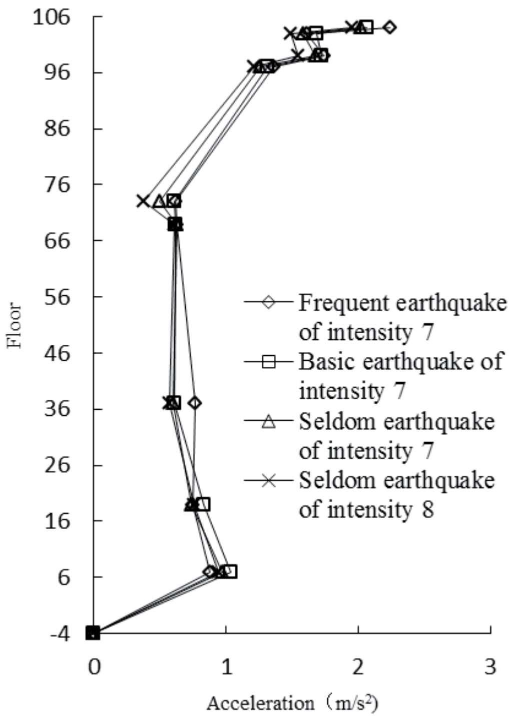

Fig. 30 The acceleration response envelope in X direction of the prototype structure

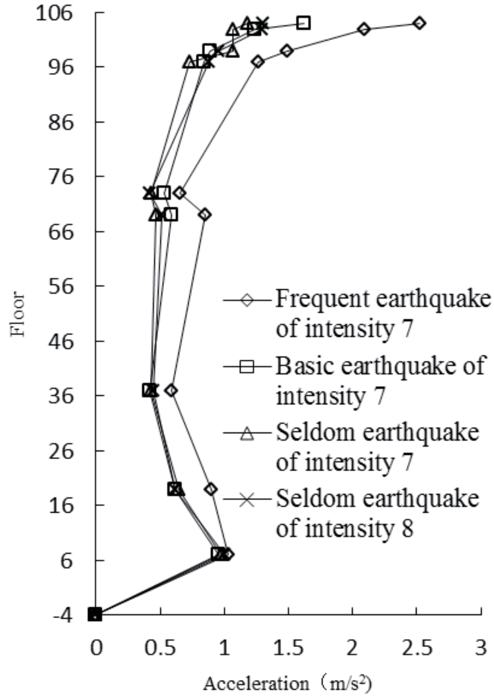

Fig. 31 The acceleration response envelope in Y direction of the prototype structure

5.3 Displacement responses

According to similarity law, the equation to calculate maximum displacement response of the prototype structure is shown as follows:

$$D_i = \frac{a_{mg}}{S_d a_{tg}} D_{mi} \tag{5}$$

Where: D_i represents the ith floor displacement response of the model (mm)

D_{mi} represents the ith floor maximum displacement response of the model structure (mm)

a_{mg} represents maximum acceleration of the shaking table, which is obtained by similarity law (m/s^2)

a_{tg} represents measured maximum acceleration of the shaking table corresponding to (m/s^2)

S_d represents displacement similarity relation of the model structure;

When the prototype structure is under the earthquake action, the maximum displacement responses of the prototype structure are shown in Table 8.The figures of the average inter-story displacement angle of prototype structure under frequent earthquake of intensity 7 and basic earthquake of intensity 7 are shown in Fig. 32–Fig. 35

Table 8 The maximum displacement response of the prototype structure (mm)

Floor	Frequent intensity 7		Basic intensity7		Rare intensity 7		Rare intensity 8	
	X	Y	X	Y	X	Y	X	Y
Top floor	79.8	125.8	203.5	296.7	422.7	526.2	716.9	984.8

When the prototype structure is under the frequent earthquake of intensity 7, the maximum inter-story displacement angle is 1/891, which appears in 100–103 floors with an effect of the whiplash effect. If the whiplash effect is ignored, the maximum inter-story displacement angle is 1/1241 which appears in 70–73 floors. The maximum inter-story displacement angel satisfies the current code [14].

When the prototype structure is under the basic earthquake of intensity 7, the maximum inter-story displacement angle is 1/458, which appears in 70–73 floors and the prototype structure is in the elastic state.

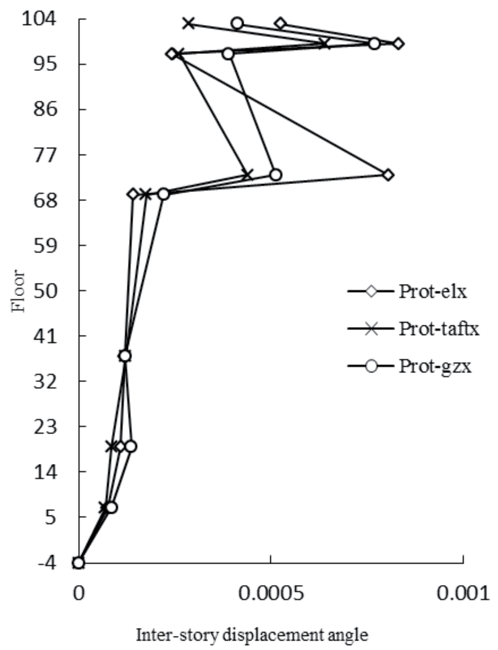

Fig. 32 Inter-story displacement angle in frequent intensity 7 in X direction

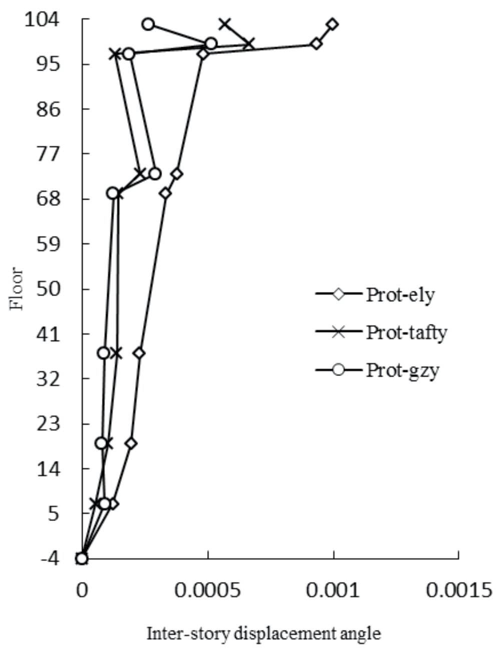

Fig. 33 Inter-story displacement Angle in frequent intensity 7 in Y direction

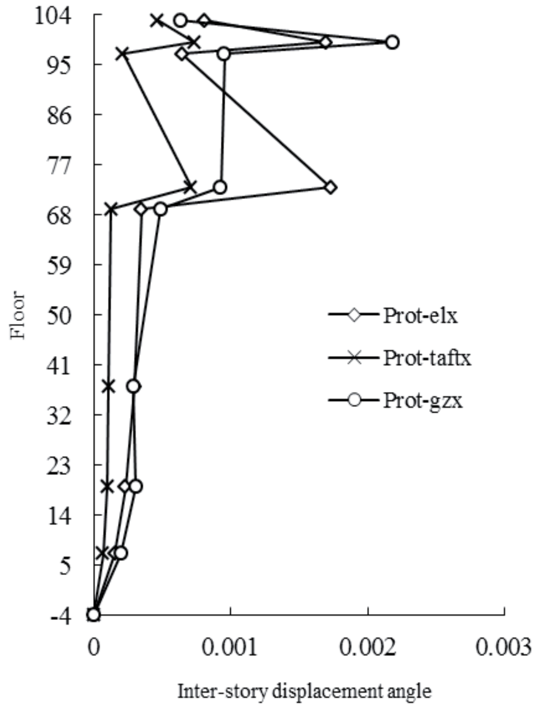

Fig. 34 Inter-story displacement Angle in basic intensity 7 in X direction

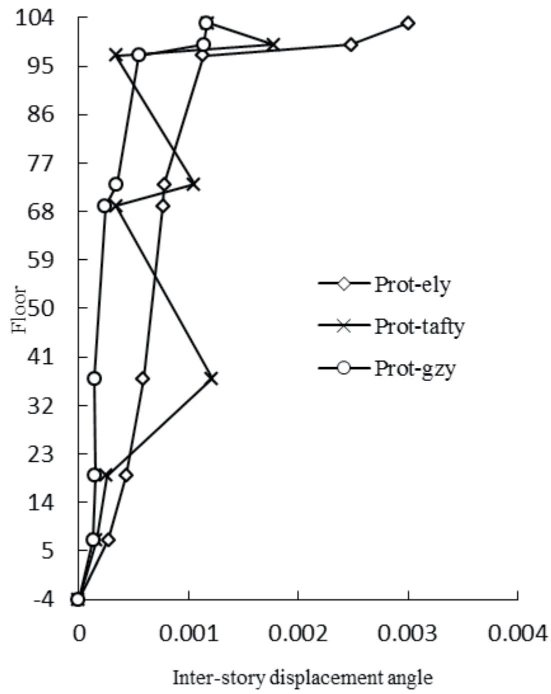

Fig. 35 Inter-story displacement angle of basic intensity 7 in Y direction

5.4 Stress responses

According to maximum strain of components, weak parts including the bottom of the inner tube, diagrid members and nodes at the bottom of diagrid outer tube of diagrid tube structure were obtained. In further, based on the similar law, the total stress of the prototype structure could be obtained. When the prototype structure was under the frequent earthquake of intensity 7, the maximum additional pressure stress (the stress was only caused by earthquake action) of the steel pipe of the diagrid node was 11.32 MPa, and the maximum additional tensile stress was 10.82MPa. The maximum pressure stress of the rebar in the shear wall was 4.24 MPa, and the maximum tensile stress was 3.71 MPa. The maximum compressive stress of the concrete was 0.73MPa, and the maximum tensile stress was 0.64 MPa.When the prototype structure was under the basic earthquake of intensity 7, the maximum additional compressive stress of the steel pipe of the diagrid node was 26.41 MPa, and the maximum additional tensile stress was 27.07 MPa. The maximum compressive stress of the rebar in the shear wall was 13.06 MPa, and the maximum tensile stress was 11.08 MPa. The maximum additional compressive stress of the concrete was 2.25 MPa, and the maximum tensile stress was 1.91 MPa. When the prototype structure was under the rare earthquake of intensity 7, the stress of key components of the prototype structure was still in the elastic range.

6 Conclusions

Based on the shaking table test and time-history analysis of a typical high-rise diagrid tube in tube structure, following conclusions could be obtained:

Diagrid tube in tube structure possesses a good seismic performance. This kind of structure could satisfy requirements of the seven intensity earthquake.

Translational mode is taken as the main mode of diagrid tube in tube structure. The first and second modes have a significant influence on structure, while the torsional vibration mode has little influence on structure.

Stiffness mutation of diagrid tube in tube structure is not serious, so the influence of the whiplash effect is not significant and the value of acceleration amplification coefficient is not large. Increasing the stiffness at the top of the floor appropriately could decrease the whiplash effect and the inter-story displacement angle.

The bottom of the inner tube, diagrid members and nodes at the bottom of diagrid tube are weak parts of diagrid tube structure. Diagrid members and shear walls at the bottom of the structure should be enhanced.

Acknowledgement

The supported by the National Natural Science Foundation of China (No.51278428) is very appreciated.

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