On Seismic Design of Composite High-rise Buildings with SRC Column, Steel Beam and RC Core Tube

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SUMMARY:
Composite high-rise building structures with steel reinforced concrete column, steel beam and reinforced concrete core tube are widely adopted in the recent construction market. The seismic performance of such structural systems is one of the key issues for maintaining its seismic safety under the case of earthquake events. In this research, two reduced scale models of the composite high-rise building with steel reinforced concrete column, steel beam and reinforced concrete core tube were designed and tested by using the shake table test technology. The acceleration and displacement of the models were measured during the tests. Dynamical characteristics, cracking pattern and failure mechanism were illustrated. Above the shake table test, the finite element analysis of the test mode was carried out. The main effort of the numerical analysis was focused on the selection of the nonlinear models. Based on the experiment results and the strategy of considering nonlinear property of the beam-column joint and the short beam of the concrete core wall were proposed. It is proved that the proposed strategy is effective and economical for seismic design of such composite high-rise building structure system.

Keywords: Seismic design, Composite structure, High-rise building, Shake table test, Numerical analysis

1. INTRODUCTION

The novation of structural system and material usage has become an efficient measurement to satisfy the requirement of the new constructions. The application of new structural system has always been a common feature of the new development of the high-rise buildings. A composite high-rise building structural system with steel reinforced concrete column, steel beam and reinforced concrete core tube has been adopted in the recent construction activity. The seismic performance of such structural systems is an important aspect for the structure to maintain its seismic safety when it exposes to earthquake events. In this paper, both shake table tests and numerical analyses are carried out to research the seismic performance of such structural system and the seismic design rules for the structural system are presented for engineering application.

In the research, two scale models of the composite high-rise building structure with steel reinforced concrete column, steel beam and reinforced concrete core tube were designed and tested on the shake table at the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, P. R. China. Three earthquake records, El Centro earthquake record, Pasadena ground motion and Shanghai artificial acceleration wave, were engaged for the seismic tests for different seismic intensity levels with increasing magnitudes input to the table. The acceleration and displacement responses of the model were measured during the test. Dynamical characteristics, cracking pattern and failure mechanism were illustrated. The finite element analysis of the model structure was carried out while the main effort was focused on the selection of nonlinear models, and the strategy of considering nonlinear property of the beam-column joint and the short beam of the concrete core wall was proposed. The numerical results were compared with the experimental results and it is proved that the proposed strategy are effective and economical for seismic design of the composite high-rise building structure with steel reinforced concrete column, steel beam and reinforced concrete core tube.

2. DESCRIPTION OF THE STRUCTURE

The target high-rise buildings in this research are T1 and T2 official building which are located in West Nanjing Road in Shanghai, China. Both buildings have the same structural system, with steel reinforced concrete column, steel beam and reinforced concrete core tube, and similar plan layout, which are shown in Fig. 1 and Fig. 2. The higher one T2 is 54-story with a rectangular plan of dimensions as 60.0m×44.7m and total structural height of 242.0m. The typical story height is 4.2m with two strengthen layers, one located in floor 21 and floor 22, the other located from floor 36 to floor 38.

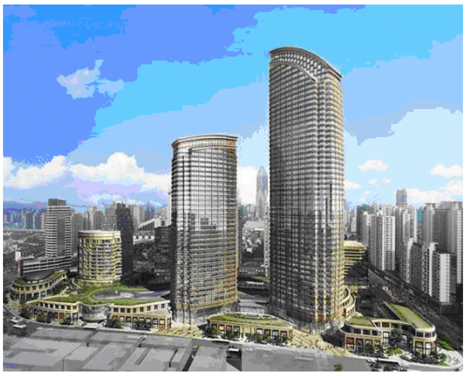


Figure 1. Design sketch of the target building

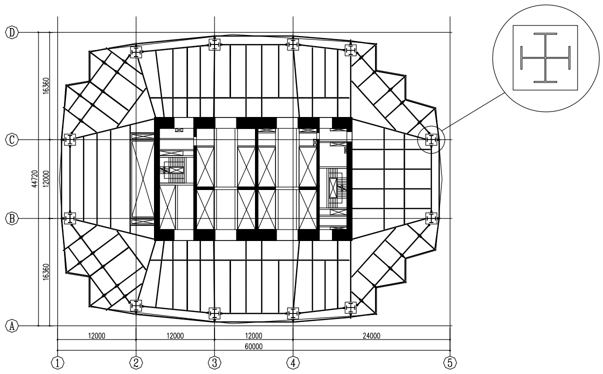


Figure 2. Typical floor plans

3. DESIGN OF THE SHAKE TABLE TESTS

3.1 Model Material and Test Model Design

Fine-aggregate concrete and fine iron wire were used to model concrete and reinforce bar of the prototype structure, while the steel columns and beams were simulated by copper plates. To make sure that the model behaves in a similar manner to the prototype, the model design should accord with dynamic similitude theory. According to the size and load-carrying capacity of the shake table facility, the similitude relationship, as shown in Table 1, was established. The model structure members were designed by the similitude relationship. The mechanical performance of some model material cannot confirm strictly to the similitude relationship, so the sections and reinforcement of model structural members were designed under the principle of obtaining the same or similar stiffness or yield force.

Table 1. Typical similitude parameters for T2 Building

Category	Variable	Expression	Scaling factor
Dimension	Length	S_l	1/30
Material	Strain	S_σ / S_E	1.0
	Elastic modulus	$S_E = S_\sigma$	0.35
	Density	$S_\sigma / (S_a \cdot S_l)$	3.0
Load	Force	$S_\sigma \cdot S_l^2$	3.889E-04
Dynamic behavior	Frequency	$S_l^{-0.5} S_a^{0.5}$	10.25
	Acceleration	S_a	3.50

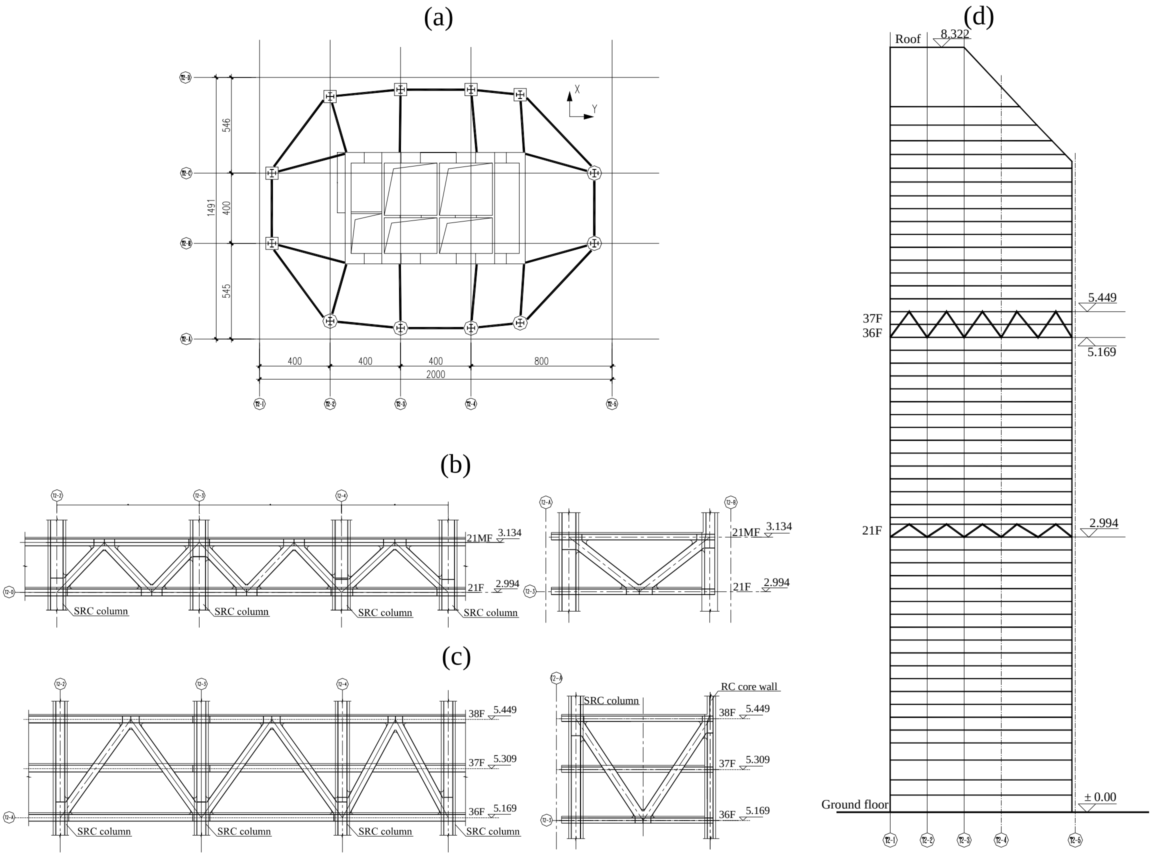


Figure 3. Typical design drawing of model structure. (a) Typical floor, (b) strengthened layer in floor21 and floor22, (c) strengthened layer in floor36, floor 37 and floor 38, (d) elevation

The typical design drawing of the model structure is shown in Fig. 3. The construction of the base, the typical story and strengthened layer are shown in Fig. 4(a), Fig. 4(b) and Fig. 4(c) respectively. An overview of the model after installation on the shake table facility and experimental set-up are shown in Fig. 4(d).

3.2 Instruments and Transducers

In order to monitor the global response as well as the local state of the model structure during the tests, a variety of instrumentation were installed on the model structure before performing the tests. The accelerations, displacements and strain were measured by accelerometers, displacement transducers and strain gauges, respectively. There were a total of 40 accelerometers and 12 displacement transducers installed on the model. The displacements at the measurement points of acceleration can be obtained by integrating the recorded accelerations twice. A portion was placed at the same measurement points with the accelerations can be made to check the precision of these sensors. A total of 15 strain gauges were installed on the truss, bottom of the core wall and column to monitor the variation of their strains.

3.3 Input Waves

Taking Shanghai Type IV soft soil in consideration, three seismic ground motions were chosen for the shake table: (1) El Centro record from the California Imperial Valley earthquake of May 18, 1940; (2) Pasadena record from the California Kern Country earthquake of July 21, 1952; (3) Shanghai artificial wave (SHW2), which is specified for particular soil conditions of Shanghai and can be found in Shanghai Code for seismic Design of Buildings (SHCSDB DGJ08-9-2003).

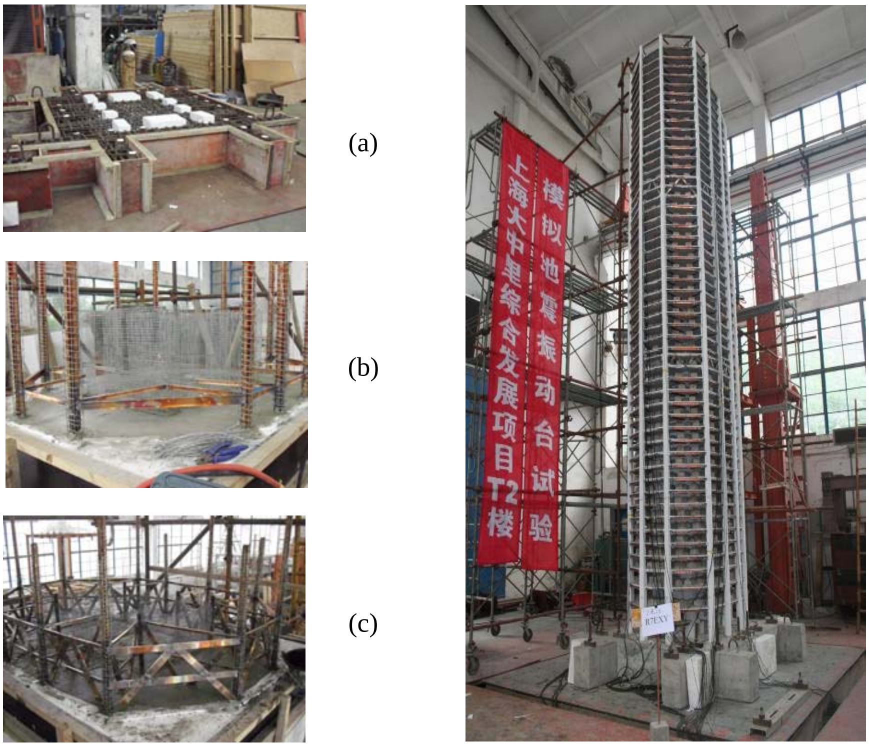


Figure 4. Pictures of the test model. (a) Base, (b) typical story, (c) strengthen layer in floor 36 to floor38, (d) overview of model structure

3.4 Test Program

The construction place Shanghai is located in the seismic region of intensity 7 and earthquakes of frequent, moderate and rare levels with seismic intensity 7 are specified with peak ground acceleration (PGA) of 0.035, 0.100 and 0.220g, respectively. During In the test, code peak acceleration times that the acceleration scaling factor (S_a=3.5) was used to obtain the target input peak value. Before the earthquake test and at the end of each seismic intensity level, a white noise test was performed to measure the mode parameters.

4. TEST RESULTS

4.1 Dynamic Properties

Frequencies of the model at different phases were obtained by inputting a white noise signal before and after the seismic input waves. The variations of frequencies at the end of every occurrence phase are shown in Table 2. Before the input seismic waves, the frequencies of first three modes are 2.989Hz (X direction), 3.239Hz (Y direction) and 5.730 (Torsion) where the longitudinal direction of the model is defined as axis X, the lateral direction as axis Y and the vertical direction as axis Z. After the input seismic waves of Frequent 7 and Moderate 7, the first mode was always in direction X. After the input seismic waves of Rare 7 and Rare 8, the first mode became in direction Y. It means that the lateral stiffness of the model in direction Y degraded rapidly.

4.2 Test Phenomenon and Damage Pattern

After the earthquake simulation tests of Frequent 7, no visible damage appeared on the model structure. Combined with the measured dynamic properties of the model, it can be found that the model structure was still in an elastic state. During the earthquake simulation tests of Moderate 7, there were still no visible damage on the surface of the model structure. But according to the dynamic properties of the

Table 2. Measured first three mode frequencies of T2 building

		mode		
		1	2	3
Initial	Frequency(HZ)	2.989	3.239	5.730
	Damp ratio	0.0270	0.103	0.0393
	Vibration mode	Translation in X	Translation in Y	Torsion
After the inputs of Frequent 7	Frequency(HZ)	2.989	3.239	5.730
	Damp ratio	0.0276	0.109	0.0175
	Vibration mode	Translation in X	Translation in Y	Torsion
After the inputs of Moderate 7	Frequency(HZ)	2.740	2.740	4.733
	Damp ratio	0.0538	0.0467	0.0285
	Vibration mode	Translation in X	Translation in Y	Torsion
After the inputs of Rare 7	Frequency(HZ)	1.744	2.491	3.239
	Damp ratio	0.0788	0.0550	0.0694
	Vibration mode	Translation in Y	Translation in X	Torsion
After the inputs of Rare 8	Frequency(HZ)	0.996	1.346	2.235
	Damp ratio	0.156	0.105	0.0791
	Vibration mode	Translation in Y	Translation in X	Torsion

model, the natural frequencies are reduced which means the model structure was reached in plastic state. Under the simulation of Rare 7, concrete crack became visible and the frequencies were significantly reduced. The deformation of the model became obvious. After the simulation of Rare 8 (test case 22-28), the cracks became wider. New cracks on the concrete element and the buckling of the truss were found in the model. After the tests of Rare 8, the photos of main damage are shown in Fig. 5. There are three kinds of damage on the model structure: Cracks on the bottom of the columns (Damage A); Cracks on the end of connecting short beams (Damage B); Buckling of the truss elements in the strengthen layers (Damage C). Almost all the cracks were concentrated in the beam-column joint and the short beam of the concrete core wall.

(a) (b) (c)

Figure 5. Damage pattern after the test of T2 Building. (a) Damage A, (b) Damage B, (c) Damage C.

4.3 Acceleration Response

The distribution of acceleration-amplifying coefficient K of T2 Building under the simulations of El Centro, Pasadena and SHW2 for the four test phases where K represents the ratio of the measured model acceleration to the corresponding input peak ground acceleration is shown in Fig. 6. The acceleration-amplify coefficient decreased gradually as the intensity of table excitation was increased, which implies that the stiffness of the model structure degraded progressively. The acceleration-

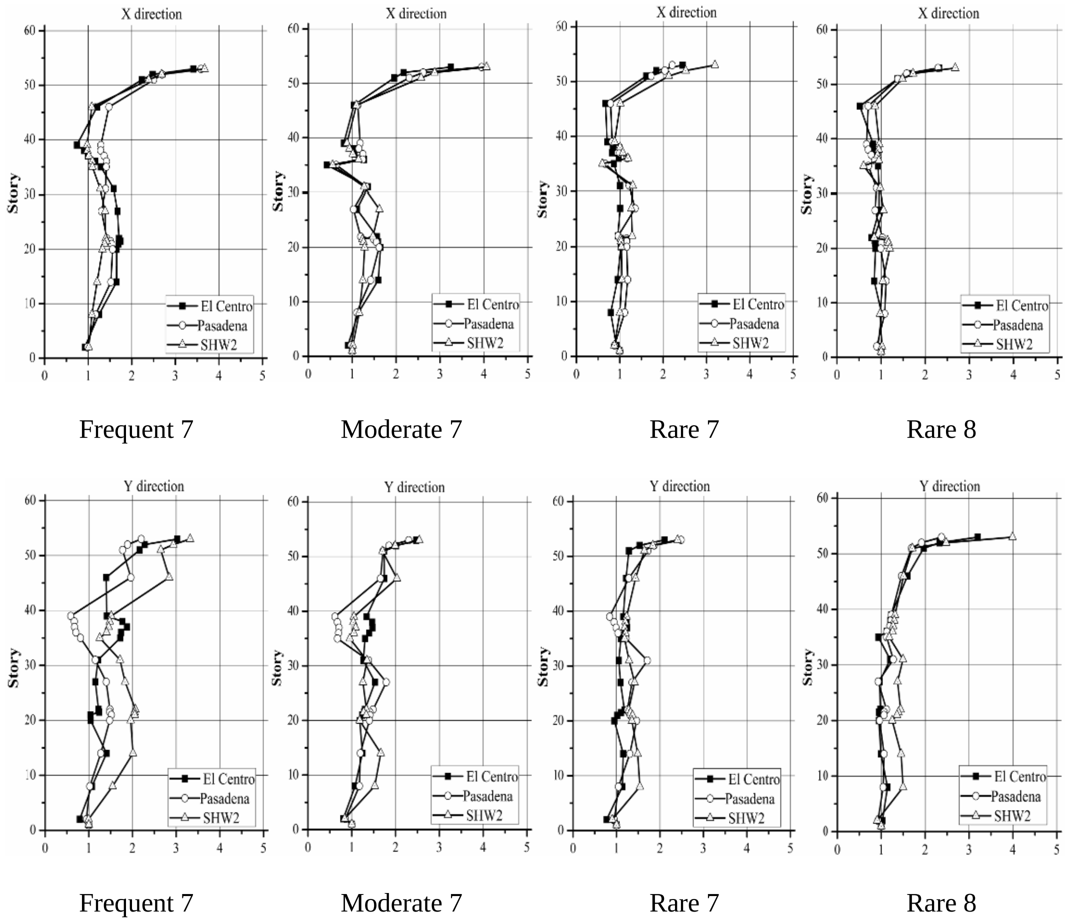


Figure 6. The distribution of acceleration-amplifying coefficient K of T2 building

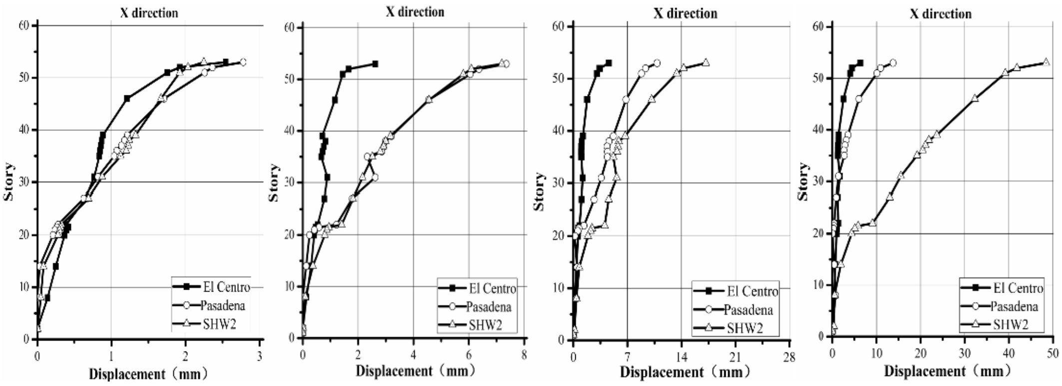
amplify coefficients became much smaller in the strengthen layers (21F and 36F-38F). Because the cross-sectional dimensions reduce from 49F to the roof, the stiffness of these floors degraded and the acceleration-amplifying coefficients became much larger. The acceleration-coefficient on the roof became obviously larger, which means that the whiplash effects of the model structure were remarkable.

4.4 Displacement Response

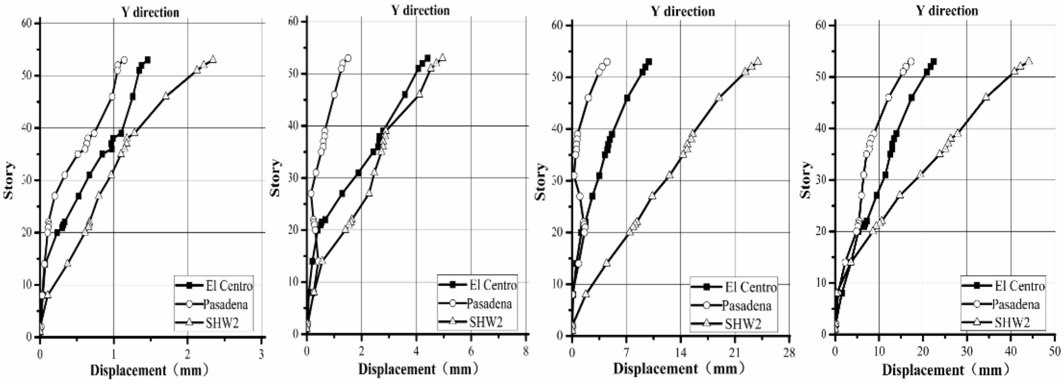
The envelop curves of displacement during different earthquake simulation tests can be obtained by the data measured by accelerometers, displacement gauges, and are shown in Fig. 7. It can be found that the displacement in the roof of the model is larger than the other floor. It means the whiplash effects were remarkable, which presented similar result as the distribution of acceleration. The variation of displacement in strengthened layers (21F and 36F-38F) is smaller than the other stories, which means the stiffness of the strengthen layers are larger than the other stories. Through observation of the envelop curves, during the earthquake simulation of Frequent 7 and Moderate 7, the lateral stiffness of model in direction X is larger than that in direction Y. During the earthquake simulation of Rare 7 and Rare 8, the lateral stiffness of model in direction Y is larger than that in X direction. Combined with the variation of dynamic properties, it means that the degradation of the lateral stiffness in direction Y is more obvious, resulting mainly from the failure of the connecting beam located in direction Y.

5. NONLINEAR FINITE ELEMENT ANALYSIS RESULTS

5.1 Numerical Modelling

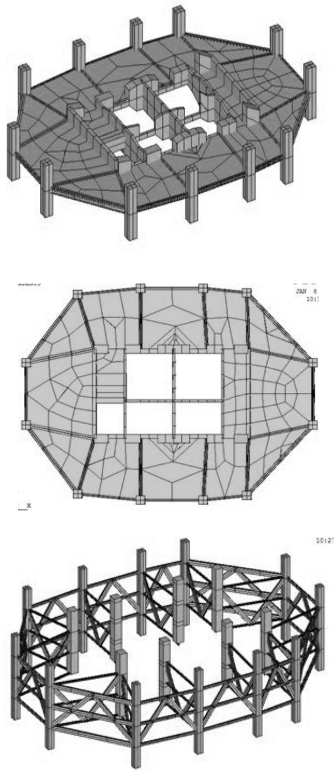


Frequent 7 Moderate 7 Rare 7 Rare 8



Frequent 7 Moderate 7 Rare 7 Rare 8

Figure 7. Envelop curves of displacement of T2 building



(a)

(b)

(c)

(d)

Figure 8. Finite element model of T2 building. (a) and (b) standard floor, (c) strengthen floor, (d) 3D model

Table 3. Material parameters of the model of T2 building

Young's modulus (N/m^2)		Density(kg/m^3)		Poisson' ratio		Total mass(kg)
Fine-aggregate Concrete	copper plate	Concrete	Steel	Concrete	Steel	
2.0×10^{10}	4.0×10^{10}	2400	7800	0.23	0.3	19600

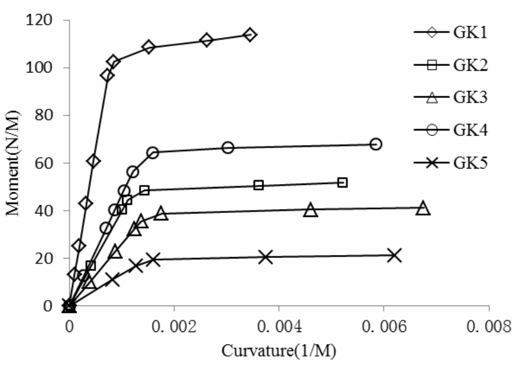


Figure 9. Nonlinear models for the joints

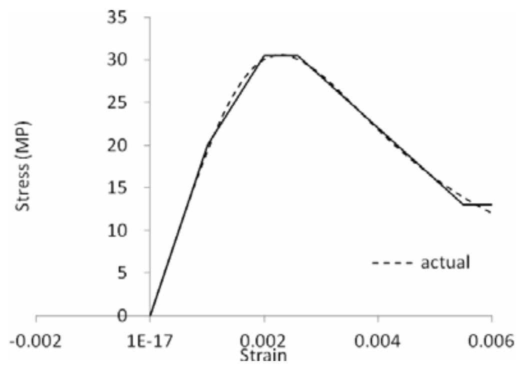


Figure 10. Nonlinear model for core wall beams

The finite element analysis was carried out for better understanding of the seismic performance of the model structure of T2 building. The 3D numerical model is shown as Fig. 8. The input material parameters are listed in Table 3. As mentioned before, almost all the cracks were concentrated in the beam-column joint and the short connecting beam of the concrete core wall during the shake table tests. So following the test results, only the nonlinear property of the beam-column joint and the short beam of the concrete core wall were considered during the analyses for reducing the computation hours. According to the section type of the beam-column joint, 5 types of nonlinear joints which are shown in Fig. 9 as GK1 to GK5 were used for numerical modeling, while the nonlinear model for the reinforced concrete core wall short beam is shown as Fig. 10. Both mode analysis and nonlinear time history analysis were carried out.

5.2 Mode Analysis Results

The natural frequencies of the first three vibration modes of the finite element model are listed in Table 4 and the numerical results are very close to test results with maximum error of 7.29%.

Table 4. Comparison of natural vibration frequencies (Hz) of T2 building

Vibration mode	Numerical analysis	Extrapolated from test	Direction	Error
1	2.771	2.989	Translation in X	7.29%
2	3.285	3.239	Translation in Y	1.42%
3	6.146	5.730	Rotation	7.26%

5.3 Time History Analysis Results

The time history comparison of the displacement at the top of T2 building under Moderate 7 and Rare 7 earthquakes for the selected records, El Centro, Pasadena and SHW2, are given in Fig. 11 and 12. The numerical results show quite well the concordance with the experiment results.

6. CONCLUSIONS

The shake table tests for T1 and T2 building were performed and the results indicate that both building can resist frequent earthquakes without damage, resist moderate earthquake with some structural

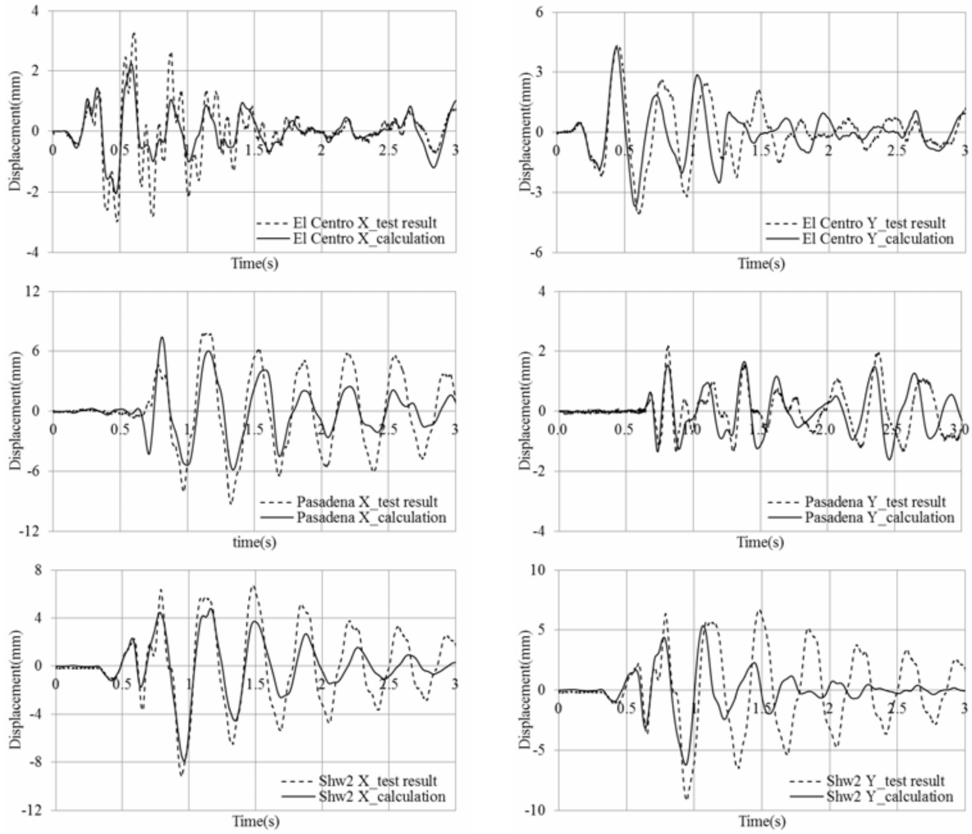


Figure 11. Time history comparison of the displacement at the top of T2 building under Moderate 7

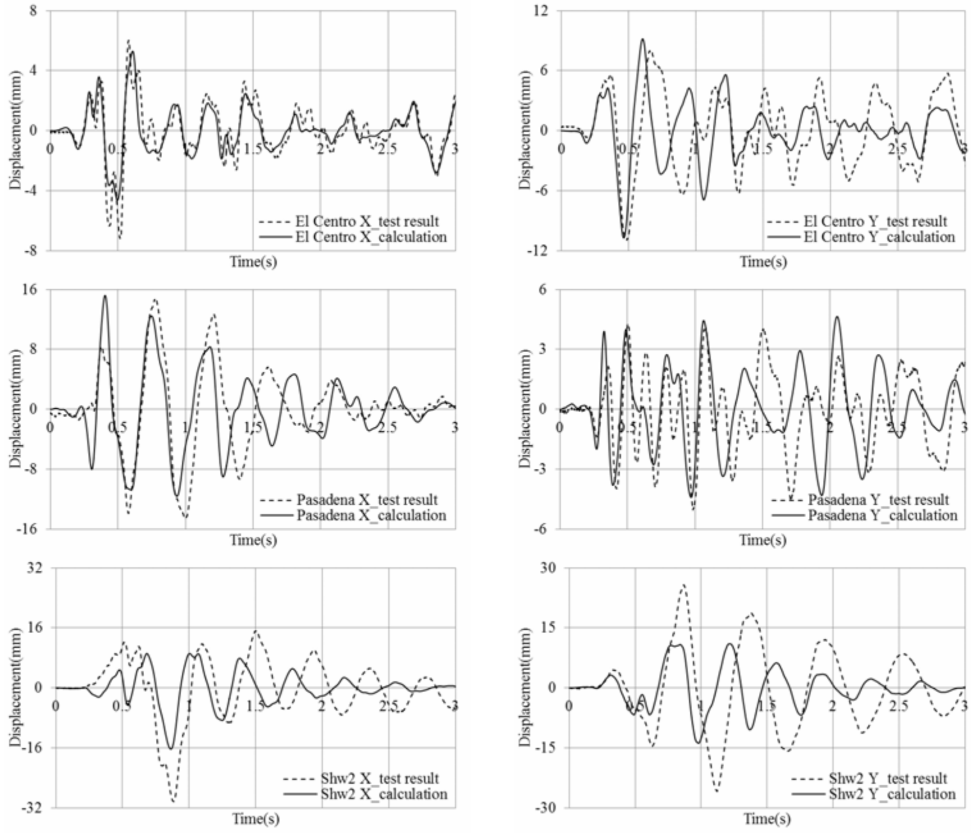


Figure 12. Time history comparison of the displacement at the top of T2 building under Rare 7

damages, and avoid collapse under rare earthquake. Based on the test results, the nonlinear finite element analyses have also been carried out in the research. The main effort was focused on the selection of nonlinear models, and the strategy of considering nonlinear property of the beam-column joint and the short beam of the concrete core wall are proposed. The mode analysis results are very close to the experimental natural frequencies with maximum error of 7.29% for the first three modes, while he time history analysis results show very well concordance with the experiment results. It is proved that the strategy are effective and economical way for seismic design of the composite high-rise building structure with steel reinforced concrete column, steel beam and reinforced concrete core tube.

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