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Shaking Table Test and Seismic Performance Evaluation of Shanghai Tower

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Abstract

Shanghai Tower is a super high-rise building of 632 m height with 'mega frame-core- outrigger truss' structure system. Due to the complexity and irregularity of structure, shaking table test was carried out to investigate its seismic performance. A 1/40 scaled test model was designed, built and tested on shaking table under earthquake of small, moderate and large levels. The experimental results showed that the structure can meet the requirements of Chinese codes and reach scheduled performance objectives. Elastic and plastic time-history analysis on the structure were carried out and the results were compared to experimental results. Based on the research results some suggestions were proposed to contribute favorable effect on the seismic capacity of the structure.

Key words: super high-rise building, shaking table test, scaled model, seismic performance

1. Introduction

In recent years, several super high-rise buildings have been constructed in China, including Shanghai Tower, Ping-An Finance Center and Goldin Finance 117, with height over 600 m. These buildings do not follow traditional structural design concepts due to the height and new structure system. A thorough investigation of their seismic performance is thus necessary to verify safety of these buildings.

In the past several decades, substantial progress has been made in the development and use of computer-based procedures for seismic analysis of structures. However, it is still difficult to accurately predict the seismic performance of a given structure due to the differences between analysis model and real structure. To overcome this limitation, shaking table model testing is adopted to investigate the seismic performance of building structure. The use of shaking table model tests in civil engineering began in the 1980s. Sabnis et al. (1983) systematically introduced and discussed the principles of structural model testing particularly for civil engineering applications, based on the similitude theory. The ACI publication edited by Harris (1982) introduced several important papers presenting the state-of-the-art in dynamic model testing for concrete structures, which advanced the theory of similitude. By the end of the 20th century, shaking table test has been increasingly used to study the dynamic responses of different structures, including energy dissipation systems, new types of structures, dams, and high-rise buildings. For high-rise buildings, Li et al. (2006) conducted shaking table test of a 1:20 scaled model of a typical reinforced concrete (RC) residential building in Hong Kong. Ko and Lee (2006) performed a series of shaking table tests on a 1:12 scale model to investigate the seismic performance of a 17-story RC high-rise structure, with a high degree of torsional eccentricity and soft-story irregularities in the bottom two stories. Ye et al. (2004) do shaking table to test on a RC structure. Jiang et al. (2005) carried out shaking table test on an irregular hybrid structure. Lu et al. (2007, 2008, and 2009) performed shaking table test on tall buildings with various structure including RC high-rise building, hybrid high-rise building and so on. Tian et al. (2010) performed shaking table test on Zhujiang New City Tower, a structure composed of SRC inner core and weaved CFST outer tube. Considering its advantages, several shaking table facilities have recently been constructed in different countries, including E-defense in Japan, EU Center in Italy, Montreal Structural Engineering Laboratory in Canada, China Academy of Building Research, etc.

For Shanghai Tower, shaking table test was done on the structure to investigate its seismic performance because of its complexity and irregularity. A 1/40 scaled test model was designed and tested on shaking table of China Academy of Building Research. Based on the experimental results some suggestions were proposed to contribute favorable effect on the seismic capacity of the structure. The research results can provide reference for seismic design of similar super high-rise buildings.

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2. Description of the Building Structure

Shanghai Tower is a super high-rise building of 632 m height including shopping mall, office and hotel, located at Shanghai, as shown in Fig. 1. The building has 124 levels over ground. The building structure mainly consist of mega frame including twelve mega SRC columns and eight steel belt trusses, SRC core, and six steel outriggers connecting the mega frame and core. The structure is divided into nine parts by belt trusses on elevation as shown in Fig. 2. Main structure of one typical part is shown in Fig. 3. Except for main structure there are secondary structure including secondary-frame and floor system bearing gravity loads, as shown in Fig. 4. Plan of the structure is an approximate round with 83.6 m diameter at ground level and 42 m diameter at top level. The core plan is a square with 30 m side length at ground level and changed to a cross at top level by cutting the corners. The typical plan is shown in Fig. 5.

The building is located at seismic area and design basic acceleration of ground motion is 0.1 g. In order to ensure safety of this super-high-rise building, detailed seismic design and analysis were done on the structure, including performance-based seismic design, elastic and plastic time-history analysis and so on. Then a shaking table test was carried out to revealed the seismic performance and verify that if the designed structure can meet the requirements of codes and reach scheduled performance objectives.



Figure 1. Shanghai Tower.

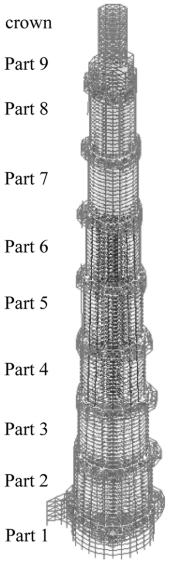


Figure 2. Structure system.

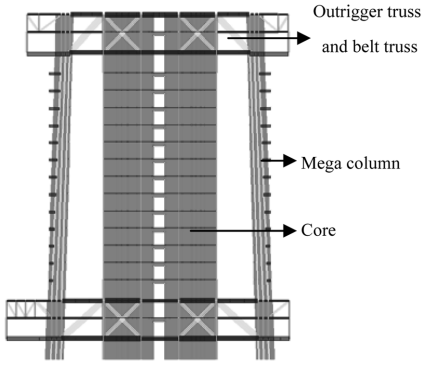


Figure 3. Main structure elevation of one typical part.

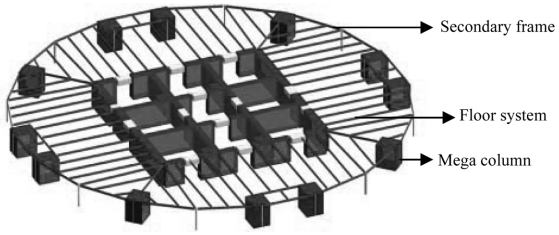


Figure 4. Secondary structure of one typical floor.

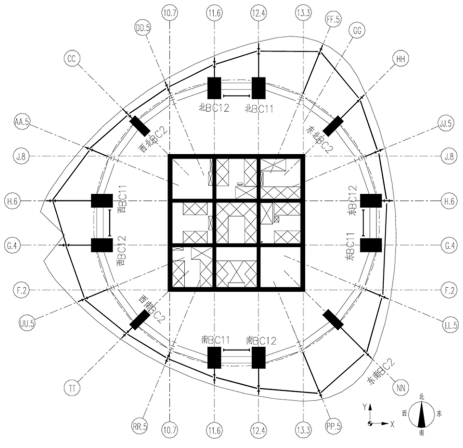


Figure 5. Typical structure plan.

3. Test Model Design and Construction

3.1. Model materials

Based on past experience, brass were used to simulate the steel structural members and fine-aggregate concrete with ne steel wires was chosen to construct the RC components in the test model. The strength and elastic modulus of the material are listed in Table 1, which forms the basis of the scaling factor for the materials.

3.2. Model scaling factor

Scaling factors of dimension, elastic modulus, acceleration, and density is most important in a shaking table test. By simulated theory of dynamics test, only three among the four model quantities can be arbitrarily selected (Sabnis et al., 1983). The test was carried out on the shaking table of China Academy of Building Research, which is the biggest shaking table in China with dimension of 6 m × 6 m and bearing capacity of 80 ton. According to the dimension of structure and shaking table, length scale of 1/40 was adopted. Based on the model material properties, the scale of materials elastic modulus were 1/3.2. According to bearing capacity of shaking table, scale of mass density was selected as 1/5.2. Then scaling factors of other parameters of the test model to prototype were conducted and listed in Table 2.

3.3. Model design

The test model included the tower form B1 floor to roof and part of podium connected to tower. The crown on top of structure was also included in the model. The prototype structure is very huge and complex. There are too many members to simulate all of them strictly according to the scaling factor in the test model. So the structure was simplified while designing test model for convenience of model construction and test. Main measures are listed as following.

1) Key structure members, including core wall, mega columns, out trigger trusses and belt trusses were kept and simulated strictly according to the scaling factors in the test model.
2) The secondary structure including secondary-frame and floor system were simplified. The beams and columns of secondary frame were kept and simulated approximately. Floors were deleted alternately except for the floors adjacent to belt truss as shown in Fig. 6. The masses of floors being deleted were distributed to adjacent floors. The kept floors consisting of H steel beam and composite slab were simulated by reinforced flat slab in test model. The in-plane and out-plane rigidity of flat slab and prototype floor system meet the scaling factors.
3) The rigidity and mass of top crown structure were simulated, while the steel structure was simplified and some small members were deleted.
4) Curtain wall structure was not included in the test model and its weight was simulated and applied at edge of floor.

Seismic analysis was done on the simplified test model and the results were compared with that of prototype structure. The main results including period, story shears and displacements are listed in Table 3 and Figs. 7~8. In these tables and figures the analysis results of test model have been scaled up according to the scale factors. The analysis result show that the simplified measures have little influence on the dynamic characteristics and seismic performances of structure. The designed test model was reasonable and the test results of this scaled model can reveal the seismic performances of prototype structure.

3.4. Model construction

The construction procedure of test model is similar with real structure. The brass members in SRC wall, frame and trusses were installed firstly, then the reinforcement in SRC and RC members was installed, at last concrete of floor slab and vertical members were cast in site. During construction polyfoam was taken as mould of concrete

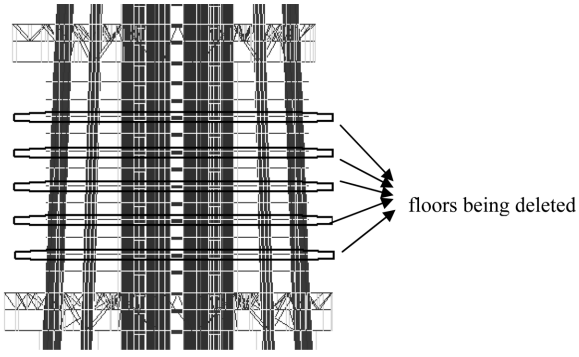


Figure 6. Position of floors being deleted in test model of one typical part.

Table 1. Model material properties

material	Elastic modulus (MPa)	Compressive strength (MPa)
fine-aggregate concrete	11570	11.63~12.5
Brass plate	83860	89~95

Table 2. Scale factors of model to prototype structure

parameter	Length	Elastic modulus	Strain	Mass density	Time	Stress	Acceleration	Frequency
Scaling factors	1:40	1:3.2	1:1	5.2:1	1:0.102	1:3.2	1:2.4	9.81:1

Table 3. Dynamic characteristics of test model and prototype structure

	Period (s)		Model participating mass ratios					
	Test model	Prototype structure	Test model			Prototype structure		
			X	Y	RZ	X	Y	RZ
T1	8.96	8.87	47.24	0.12	0.01	47.27	0.11	0.01
T2	8.89	8.80	0.12	46.63	0.00	0.11	46.72	0.00
T3	4.57	4.16	0.03	0.00	51.11	0.05	0.00	51.80
T4	3.17	3.11	24.70	0.08	0.01	24.77	0.09	0.04
T5	3.07	3.03	0.09	23.67	0.00	0.10	23.79	0.00
T6	2.22	2.05	0.00	0.00	20.05	0.00	0.00	20.36
T7	1.59	1.56	8.62	0.00	0.00	8.68	0.00	0.01
T8	1.54	1.51	0.00	8.74	0.00	0.00	8.76	0.00
T9	1.41	1.30	0.02	0.00	7.10	0.00	0.00	7.16

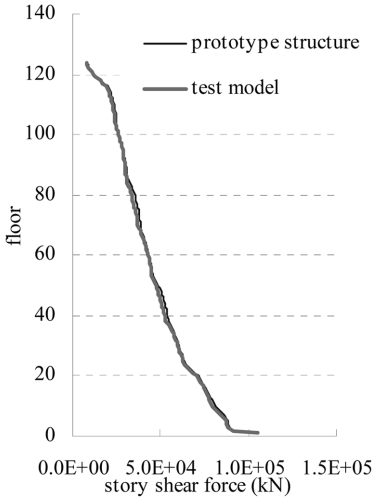


Figure 7. Compare of story shear force at X direction.

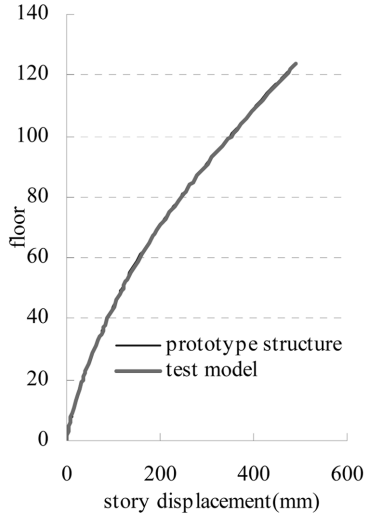


Figure 8. Compare of story displacement at X direction.

members. The procedure of model construction is shown in Fig. 9.

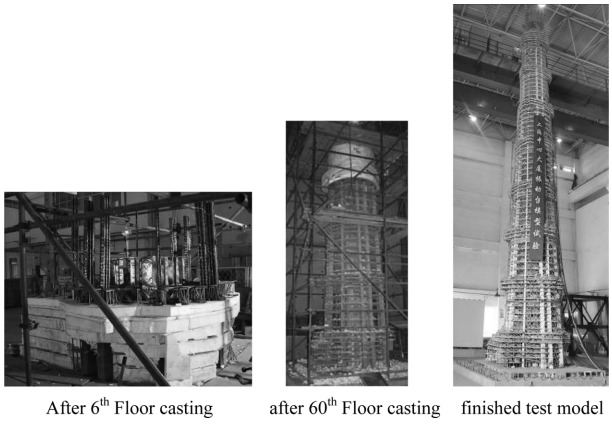


Figure 9. Test model construction procedure.

4. Test Programme and Instruments

According to the Chinese code (CMC, 2010), buildings in a seismic region must sustain earthquakes of small, moderate and large levels, whose probability of exceedance is 63.2%, 10% and 2% within 50 years of the design period and the return period in years is 50, 475 and 2475, respectively. A building will not be damaged, or will be only slightly damaged and will continue to be serviceable without repair when subjected to a frequent (small) earthquake with an intensity of less than the design intensity. The building may be damaged but will still be serviceable after ordinary repair or without repair when subjected to an earthquake equal to the design intensity (moderate earthquake). The building will neither collapse nor suffer damage that would endanger human lives when subjected to a rare (large) earthquake with intensity higher than the design intensity. Shanghai is assigned to an earthquake zone of intensity 7. The peak ground accelerations corresponding to the small, moderate and large levels of seismic intensity 7 are specied as 0.035 g, 0.10 g, 0.22 g, respectively. The peak acceleration times and the acceleration scaling factor of 2.4 were used to obtain the target input

Table 4. Test programme

Stage	Input seismic records	Direction	Peak acceleration (cm/s^2)
small earthquake of intensity 7	All three records	X,	84.1
		Y	84.1
		X+Y+Z	84.1+71.5+54.7
Moderate earthquake of intensity 7	All three records	X	240.4
		Y	240.4
		X+Y+Z	240.4+204.3+156.3
Large earthquake of intensity 7	MEX record	X+Y+Z	480.8+408.7+312.5
large earthquake of intensity 7.5	MEX record	X+Y+Z	745.2+633.4+484.4

peak value in the tests. A summary of the test inputs is listed in Table 4.

Three ground motions were selected as the input motions during the test: (i) MEX record from Mexcity earthquake of Sep. 19, 1985; (ii) Borrego record from the Borrego mountain earthquake of Apr. 8, 1968; and (iii) Shanghai articial accelerogram, which is specied for the type IV soft soil conditions found in Shanghai. These earthquake acceleration time histories were scaled to have the same target input peak value for each intensity level. The structure was designed to be almost elastic at small and moderate earthquake, so all of three seismic records were inputted one by one form X, Y and X+Y+Z directions. While some damage will happen at large earthquake, so only one seismic record was inputted at X+Y+Z directions to avoid accumulated damage. In the three-direction excitations in the test, the peak acceleration ratio of the X, Y and Z direction is designated to be 1:0.85: 0.65.

70 acceleration sensors were installed on the floors of model. 40 strain gauges were installed on key structure members, including core and mega columns, outrigger trusses and belt trusses.

5. Experimental Results

5.1. Seismic behavior of the model structure

For small earthquakes of intensity 7, no visible damage was observed. After test it was found that the frequencies were slightly reduced. This reveals that micro-cracks had already developed in the model.

For moderate earthquakes of intensity 7, some diagonal cracks were found at ends of several spandrels of core wall at parts 4~7. No crack or damage happened on mega columns, outrigger trusses and belt trusses. Strain test results showed that these members all keep elastic.

For large earthquake of intensity 7, more cracks on spandrels of core wall were found. Some horizontal cracks happened on mega columns at parts 6. No crack or damage happened on outrigger trusses and belt trusses. Strain test results showed that these members almost keep elastic. For large earthquake of intensity 7.5, the structure rigidity decreased obviously. More cracks on columns, spandrels and piers of core walls were found. No damage happened on outrigger trusses and belt trusses. The structure keeps standing and shows enough margin of seismic capacity. Typical cracks on core walls and mega columns are showed in Fig. 10.

5.2. Dynamic characteristics

Frequencies of the model at different phases were measured by inputting a white noise signal and the period of test model was listed in Table 5. With increasing of inputting earthquake magnitude, the period of model decreased and damp ratio increased due to more damage and cracks of model.

5.3. Acceleration results

Acceleration amplication factor β is usually dened as the ratio of the peak value of oor accelerations to the peak ground acceleration (PGA). Value of β reects by the dynamic amplication effect of different oors in the structure. Figure 11 shows the distribution of the horizontal acceleration amplication factor. Most values of β under 117th story are between 1.0 and 2.0. The maximum value



Cracks on spandrel cracks on core wall crack on mega columns

Figure 10. Typical cracks on core walls and mega columns.

Table 5. Period and damp ratio of test model

Phrase	X direction		Y direction	
	Period (s)	Damp ratio	Period (s)	Damp ratio
Before test	0.98	2.12%	0.90	2.32%
After small earthquake of intensity 7	1.00	2.64%	0.96	3.10%
After moderate earthquake of intensity 7	1.03	3.80%	0.97	4.08%
After large earthquake of intensity 7	1.10	4.08%	1.02	4.24%
After large earthquake of intensity 7.5	1.11	5.11%	1.35	5.36%

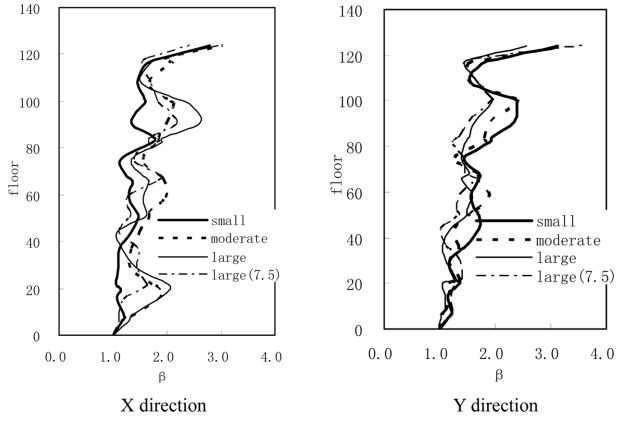


Figure 11. Envelope of horizontal acceleration amplication factor at different phrases.

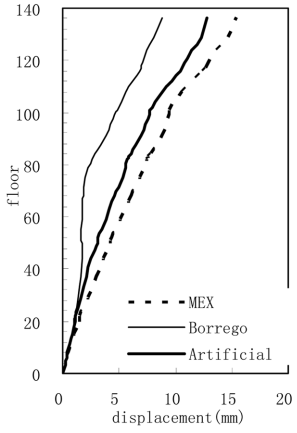


Figure 12. Peak story horizontal displacement at X direction for small earthquake.

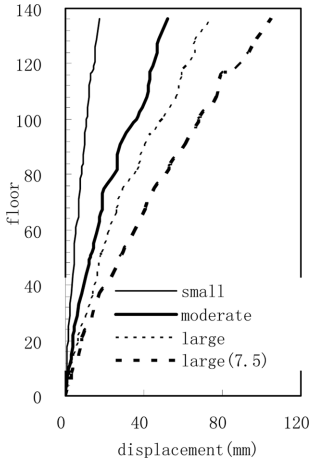


Figure 13. Peak story horizontal displacement at X direction at different phrases for MEX wave.

of β reaches 3.5 at top of structure. There is obvious whipping effect due to reduction of rigidity and concentrated mass of crown at structure top. Special attention should be paid in designing top of structure.

5.4. Displacement results

The peak story horizontal displacement at X direction relative to shaking table at various test phases are showed in Figs. 12~13. The displacement at Y direction was similar to X direction and not listed. The displacement increased form bottom to top gently and there is no abrupt change. The results show that different input records with same peak acceleration will lead to different shape and value of model deformation. For same input record, displacement increases with peak acceleration.

The envelope of story drift at various test phases are showed in Fig. 14. The results showed that the story drift increased obviously above 68th story, where four mega corner columns were cut and thickness of shear wall was decreased. The reduction of vertical member lead to sudden decrease of rigidity and capacity. So the story drift increased significantly and more cracks occured here. Special attention should be paid in designing this part. Maximum story drift and corresponding location during small and large earthquake were listed in Table 6 and all the

Table 6. Maximum story drift

Phrase	X direction		Y direction	
	Maximum story drift	location	Maximum story drift	location
small earthquake	1/482	108th story	1/545	124th story
large earthquake	1/99	118th story	1/91	124th story

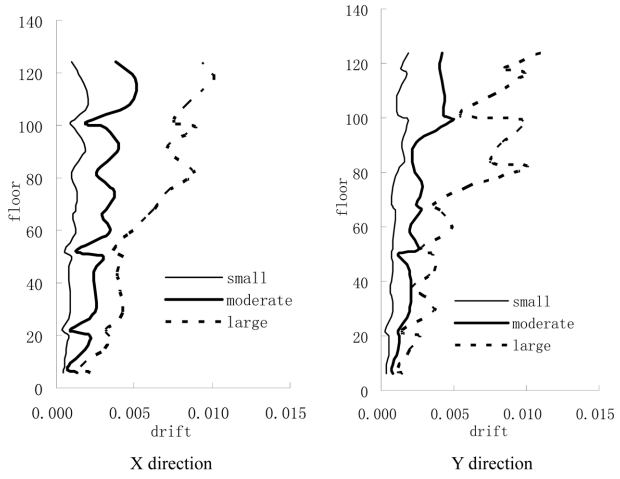


Figure 14. Envelope of story drift at various test phases.

values approximately meet requirement of Chinese code.

6. Compare of Experimental and Analysis Results

Dynamic elastic and plastic time-history analysis on the prototype structure were carried out by SAP2000 and ABAQUS and the analysis results were compared with experimental results. All experimental results have been scaled up according to the scale factors. Table 7 shows the experimental and analysis frequency results. The error is within 10%. The compare of experimental and analysis results of story displacement and drift at some test cases are listed in Figs. 15~16. For small earthquake experimental result were approximately consistent to corresponding analysis results. For large earthquake, the experimental results were larger than analysis results by about 10~40%.

Table 7. experimental and analysis frequency results

Model shape	Experimental result	Analysis result	error
1st order at X direction	0.104	0.110	6.2%
2h order at X direction	0.316	0.302	9.5%
1st order at Y direction	0.113	0.112	9.8%
2h order at Y direction	0.344	0.313	9.1%

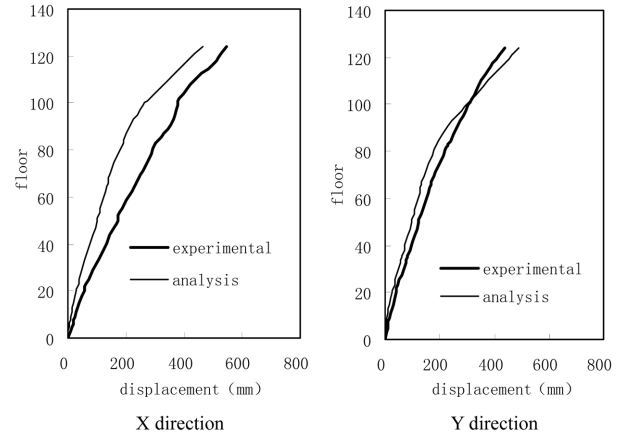


Figure 15. Experimental and analysis results of story displacement for small earthquake with MEX record.

7. Conclusions

Shanghai Tower is a super high-rise building of 632 m height with 'mega frame- core- outrigger truss' structure system. Shaking table model test was carried out at China Academy of Building Research to investigate its seismic performance. A 1/40 scaled test model was designed and tested for small, moderate and large earthquake levels. The dynamic responses of the model structure and prototype structure were analyzed. The following conclusions can be drawn.

1) The Shanghai Tower structure system is feasible and reasonable to resist earthquake action. It would not be damaged by a small earthquake and would have some minor structural cracking under a moderate earthquake. For large earthquake, more cracks occurred but most key members almost keep elastic. The structure shows enough margin of seismic capacity.
2) Experimental results show that the structure can meet the requirements of Chinese codes and reach scheduled performance objectives.
3) Above 68th story, where four corner columns were cut and thickness of shear wall were decreased, the story drift increased abruptly and more cracks occurred. It is suggested to keep thickness of shear wall unchanged at 68th story and change it at 71st story to avoid concentrated reduction of structure rigidity and shear capacity. Top of structure showed obvious whipping effect. It is suggested to amplify seismic force of this part during seismic design. These suggestions in this paper have been accepted by the design institute and the Shanghai Tower building is under construction.

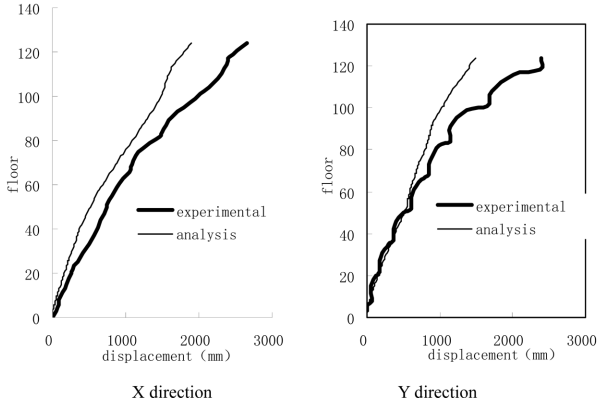


Figure 16. Experimental and analysis results of story displacement for large earthquake with MEX record.

4) For the scaled model test, reasonable design and fine construction of test model is very important. Throughout analysis should be carried out during model design to verify that the test model and prototype structure are in conformity with the similitude theory and the experimental results on the scaled model can revealed the seismic performances of prototype structure.

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