International Journal of High-Rise Buildings
March 2013, Vol 2, No 1, 79-83

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Shaking Table Model Test of Shanghai Tower

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Abstract

Shaking table test is an important and useful method to help structural engineers get better knowledge about the seismic performance of the buildings with complex structure, just like Shanghai tower. According to Chinese seismic design guidelines, buildings with a very complex and special structural system, or whose height is far beyond the limitation of interrelated codes, should be firstly studied through the experiment on seismic behavior. To investigate the structural response, the weak storey and crack pattern under earthquakes of different levels, and to help the designers improve the design scheme, the shaking table model tests of a scaled model of Shanghai tower were carried out at the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. This paper describes briefly the structural system, the design method and manufacture process of the scaled model, and the test results as well.

Keywords: Super tall building, Shaking table test, Model test, Seismic behavior

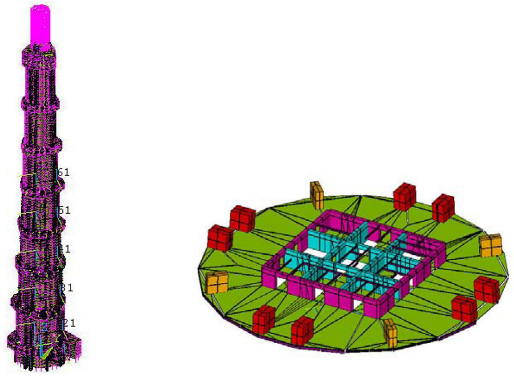
1. Introduction

Shanghai tower will be the largest super high-rise complex located in Shanghai's Lujiazui Financial and Trade Zone. There are going to be two main parts above ground of the complex, which are one 632 m tower and one 38 m podium, with 5-storey basement. The aspect ratio of height to width of the tower is 7. It could be the tallest building in China when completed.

The tower is divided into eight main zones vertically, with a tower crown on the top£¨as shown in Fig. 1. The lateral force resistance of the super tower will be provided by a combined structural system of mega frame-core wall-outrigger. The exterior mega frame consists of four paired concrete super-columns and four diagonal super-columns, and eight 2-storey-height belt trusses at each strengthened/refuge storey. The six outrigger systems located in the strengthened stories of zone 2 and zone 4 to zone 8 are designed to connect the mega frame and core wall, which make them work together to resist the wind load and seismic force efficiently.

The structural design of Shanghai tower has been beyond the limitation of Chinese code in many ways. The structural height of the tower is far beyond the coverage of the Technical Specication for Concrete Structures of Tall Building (TSCSTB, JGJ 3-2002) (Ministry of Construction of China, 2002), which is 190 m for steel reinforced concrete core wall. The elevation design is so complex that the building may be categorized as vertical irregular structure according to the Code for Seismic Design of Buildings (CSDB, GB50011-2001) (Ministry of Construction of China, 2002) due to the existence of the outriggers, the space trusses and 14m cantilever radial trusses.

As mentioned above, the structure is so complex that detailed study is requested according to Chinese regulations. With the special characteristics of this to-be tallest building in China taken into account, the shaking table model test was recommended by the peer review committee. Actually, another shaking table tests for Shanghai Tower had been conducted by China Academy of Building Research in Beijing (Tian et al., 2011) before the structural model was constructed by the research group in the Shaking Table Testing Division of the State Key Laboratory of Disaster Reduction in Civil Engineering (SKLDRCE), Tongji University, Shanghai, China. It was found from the first shaking table test results that some expectant results might not be revealed, like the severe dy-



(a) Elevation of the prototype structure (b) 31th floor layout

Figure 1. Main elevation and typical floor layout of the prototype structure.

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namic amplification effect on the top of the building, the whipping-lash effect and so on. As a result, the second shaking table tests in SKLDRCE, Tongji University were commended by the owner of the building and the peer review committee to compare with the other.

2. Model Design and Materials

With regard to the small-scale model test of the high-rise structure, the model design part becomes very important. The laboratory conditions, the dimension and the mass of the prototype structure are taken into account when establishing reduction scales, as listed in Table 1, based on the similitude laws.

During the model design process, because it is difficult to satisfy all the similitude relationship, it is necessary to meet the dominating similitude rules and simplify or sacrifice some minor relationships. Since the main objective of this test is to study the overall seismic performance of the model, the bending and shearing similitude relationships of the lateral resisting system are satisfied primarily (Lu et al., 2007, 2009). Due to the construction difficulties of the small-scale model and the very little influence of floors on the lateral resisting system, 69 floors of ordinary stories excluding any strengthening stories in all the eight zones are removed in the design of model structure. To keep the consistency between the original design and model design, the dead load of the removed floors and beams are added onto the neighboring floors, and the existing beams and steel columns are revised on the basis of the principle of equivalent flexural rigidity and strength.

Fine-aggregate concrete and fine steel wire are used to model concrete and rebar of prototype structure, respectively. The steel columns and beams are simulated by using copper plates.

3. Model Construction and Test Program

Because the size of every component is quite small, the construction needs to satisfy a high accuracy requirement. The model is totally 13.04 m high with a 0.4 m-high base beam, as shown in Fig. 2. The whole mass of the model is around 25 t, including the artificial mass and the rigid base beam which are 17.1 t and 4.1 t, respectively.

Table 1. Main similitude parameters

Item	Dimension	Similitude factor (model/prototype)
Length	L	0.02
Stress	$ML^{-1}T^{-2}$	0.26
Mass	M	2.99E-5
Acceleration	LT^{-2}	3.478
Force	MLT^{-2}	1.04E-4
Frequency	T^{-1}	12.98
Time	T	0.077

Figure 2. Overview of the model and experimental arrangement.

Three kinds of instrumentation are installed on the model structure before simulation tests, which are accelerometers, displacement gauges and strain gauges. These transducers are installed on the different levels of mega columns and core walls, and some key parts of refuge stories in terms of the numerical analysis results of this complicated structure. There is a total of 59 accelerometers, 19 displacement gauges and 24 strain gauges installed in every zone as well as on the base and the top crown.

Condition of site soil is a significant factor in determining the earthquake inputs for the dynamic test. Type IV site soil in China is defined as soil whose soft layer thickness is more than 80 m and average velocity of shear wave in the soil layer is not more than 140 m/s. According to the CSDB, the site soil in Shanghai belongs to Type IV (soft soil). With the requirement of seismic protection intensity 7 and the spectral density properties of Type IV site soil taken into consideration, four earthquake records of acceleration are selected as input excitations, which are MEX006~008 recorded from Mexico City earthquake (1985), US1213~1215 recorded from Borrego Mountain earthquake (1968), and two artificial records of acceleration, S79010~12 and SHW3. All the earthquake records are input in three orthotropic directions except the Shanghai articial accelerogram, SHW3, which is one-dimensional input.

As specied in CSDB, buildings located in earthquake-prone regions should be able to withstand earthquakes of minor, moderate and major levels, which have 63.2%, 10% and 2% probability of exceedence in 50 years, respectively. Shanghai belongs to the seismic zone of intensity 7. Earthquakes of minor, moderate and major levels with seismic intensity 7 are specified with peak ground acceleration (PGA) of 0.035 g, 0.100 g and 0.200 g, respectively. Thus, the test program should include the three levels, that is, tests for frequently occurring (Frequent 7), basic (Basic 7), rarely occurring earthquake (Rare 7) of intensity 7. In addition, to study the dynamic performance of the structure under extremely strong earthquakes, another phase is added into the test program which is rarely occurring earthquakes of named intensity 7.5 (Rare 7.5), whose PGA is specified as 0.280 g.

4. Test Results

4.1. Crack pattern

During the Frequent 7 and Basic 7 simulation tests, no visible cracks appeared on the model structure. There was also no buckling of steel beams and columns and elements of trusses. After the two phases of the earthquake simulation tests, the natural periods of the model structure did not change compared with the initial natural periods in the first three modes, as shown in Table 2.

During the earthquake simulation tests with rare intensity 7, several horizontal cracks emerged at the super columns of the 3rd floor in Zone 1 and the 11th floor in Zone 2, as shown in Fig. 3. Some horizontal cracks and hairline diagonal cracks were also found on the super-columns of the 79th floor and 82th floor in Zone 6, and of the 90th, 93th, 96th and 99th floors in Zone 7. Most of the cracks that appeared on the super columns were near the location of floor slab. No buckling appeared on the steel elements and trusses.

The earthquake simulation tests with rare intensity 7.5 caused relatively severe damages to the model structure, which included: (1) the cracks on the super-columns of Zone 1, Zone 2, Zone 6 and Zone 7 extended further as shown in Fig. 3(a), and more cracks developed around the ones found first in Rare 7 tests; (2) many cracks emerged on the surface of the core wall of 47th and 50th floor in Zone 4, of 60th floor in Zone 5, of 71th, 79th and 82th floor in Zone6, of 96th and 99th floor in Zone 7, and of 113th and 116th floor in Zone 8. Most of these floors are just one to three stories below the refuge stories of each zones. Furthermore, the end of coupling beams connecting the shear walls, located in the 50th floor of Zone 4, 110th, 113th and 116th floor of Zone 8, produced vertical cracks as shown in Fig. 3(b); (3) numerous local buckling also occurred on the flanges and webs of the lower chord of the belt trusses in Zone 5 and Zone 6, as shown in Fig. 3(c). The flange of the lower chord of the belt truss in Zone 6 even generated fracture between one paired super-columns; (4) as for the top crown, many truss members buckled at the lower part of the crown. Moreover, the shear wall concrete at the corner of 124th floor connecting to the column of the crown spalled off a little.

4.2. Dynamic characteristics

White noise excitation was input to the model structure in the beginning of the tests and after each test phase to record its dynamic performance information. The variations of frequencies and damping ratios at the end of each test phase are presented below as shown in Table 2. The first two modes were of translation in directions X and Y with both initial natural frequencies of 1.69 Hz. The third mode was of torsion with an initial natural frequency of 2.97 Hz. The first frequency in X direction is equal to that in Y direction, which indicated that the overall rigidities of direction X and Y are equivalent. The frequencies of the first three modes remained constant until the end of Basic 7 test phase, which revealed that the model structure was generally behaving in an elastic state without any damage occurring in the first two test phase, Frequent 7 and Basic 7. In the Rare 7 test phase, the structure was subjected to the stronger earthquake inputs resulting in 14.2% decrease in the natural frequency of the first mode and 9.4% decrease in the natural frequency of the second mode. The frequency in X direction dropped faster than that in Y direction. Furthermore, after the Rare 7.5 test, the structure remained the 9.4% decrease of the second mode of natural frequency, which was the frequency in Y direction, while the frequency in X direction decreased 18.9%


(a) Crack distribution on the super-column of Zone 1 (b) Cracks on coupling beams of 113th floor (c) Local buckling of belt truss member

Figure 3. Concrete cracking and local buckling of truss member at Rare 7.5 test phase.

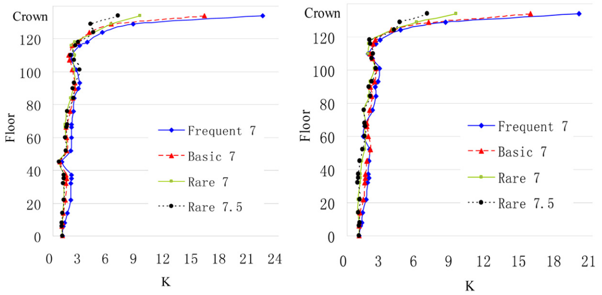
Table 2. Natural frequency, damping ratio and vibration mode of the model

		First mode	Second mode	Third mode
Initial	Frequency (Hz)	1.69	1.69	2.97
	Damping ratio	0.0180	0.0190	0.011
	Vibration mode	Translation of X	Translation of Y	Torsion
Frequent 7	Frequency (Hz)	1.69	1.69	2.97
	Damping ratio	0.0180	0.0180	0.02
	Vibration mode	Translation of X	Translation of Y	Torsion
Basic 7	Frequency (Hz)	1.69	1.69	2.97
	Damping ratio	0.0280	0.0555	0.019
	Vibration mode	Translation of X	Translation of Y	Torsion
Rare 7	Frequency (Hz)	1.45	1.53	2.97
	Damping ratio	0.0350	0.0340	0.016
	Vibration mode	Translation of X	Translation of Y	Torsion
Rare 7.5	Frequency (Hz)	1.37	1.53	2.33
	Damping ratio	0.0340	0.0602	0.027
	Vibration mode	Translation of X	Translation of Y	Torsion

compared to the initial natural frequency. It indicated that the damages occurred in X direction were severer than that in Y direction.

5. Dynamic Response of the Prototype Structure

The first three natural vibration frequencies of prototype structure were derived from test results of the model structure according to the similitude laws, which were 0.130 Hz, 0.130 Hz and 0.229 Hz, respectively. The distribution of dynamic amplification coefficient K under four test phases is shown in Fig. 4. Here K represents the ratio of peak acceleration response measured directly by the accelerometer at one measure point to the one measured at the base. The amplification coefficient decreased as the intensity of table input increased, which implied the progressive degradation of structural stiffness. There are three inflection points in the distribution of K values at floor 52, 85 and 118, which just corresponded with the lateral stiffness degradation at the same floor, where a setback in elevation is designed on the core wall. The whipping-lash effect developed sharply above floor 118, which is Zone 9 and the top crown part.

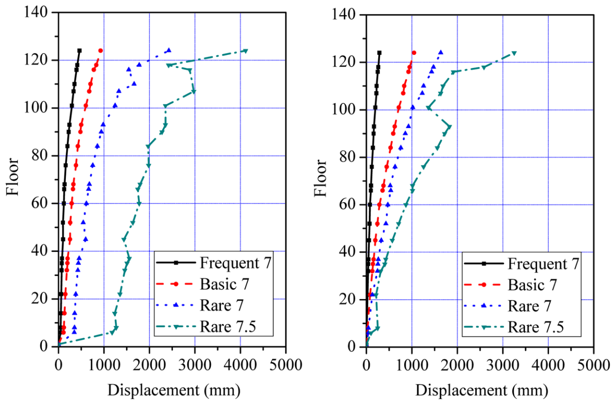


(a) Direction X (b) Direction Y

Figure 4. Distribution of K: (a) Direction X; (b) Direction Y.

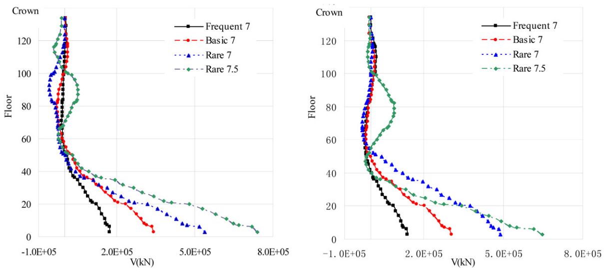
The lateral displacements of prototype structure were calculated by assuming that the displacement was distributed linearly along the structural height between two measured points. Figure 5 gives the maximum lateral floor displacement distribution of the prototype structure during different testing phases. The maximum lateral floor displacements were obtained by comparing the maximum values from the four different earthquake records in different earthquake levels. Generally, the floor displacement responses in direction X are slightly larger than those of direction Y in the same earthquake level, which coincide with the results of the measured natural frequencies in direction X and Y. The maximum floor displacement curves are relatively smooth without obvious inflexions except for the rapidly increasing displacements of the top crown and its connecting level, which demonstrated the whipping-lash effect.

The average storey shear force distributions along the height under four earthquake levels are shown in Fig. 6. In general, storey shear force increase proportionally with the increase of PGA. It is obvious that high order modes



(a) Direction X (b) Direction Y

Figure 5. Maximum floor displacement.



(a) Direction X (b) Direction Y

Figure 6. Average story shear force distribution.

Table 3. Maximum inter-storey drift ratio and average base shear coefficient

	Maximum inter-storey drift ratio		Average base shear coefficient	
Direction	X	Y	*X* (%)	*Y* (%)
Frequent 7	1/510	1/576	2.57	2.04
Basic 7	1/180	1/206	5.05	4.63
Rare 7	1/80	1/129	8.02	7.23
Rare 7.5	1/27	1/56	10.15	10.35

have a relatively serious effect on the structural response, which is consistent with the results of crack pattern observed on the model. Even though the floor displacement above the 120 floor is much larger than the other, especially at the case of Rare 7.5, the story shear at the portion is not accordingly large. The story shear force equals story mass times acceleration. The story mass of stories above 120 is relatively small due to the lack of megaframe and the reduced section of core wall by nearly 40% at this part, which also cause the low story stiffness. So the story displacement would be large while the shear could keep a low value.

The ratios of maximum inter-storey drift and average base shear coefficient (the ratio of base shear to weight of the structure) are listed in Table 3.

6. Conclusions

Shanghai tower is a super tall building with a complex structural system that is beyond the coverage of Chinese design code. To investigate the structural performance under earthquakes of different levels, shaking table model tests were carried out at the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, as suggested by the peer review committee. The following conclusions and corresponding suggestions can be drawn from the test results:

The model test results indicate that the prototype structure is able to withstand frequently occurring, basic and rarely occurring earthquake of intensity 7 without severe damages. According to the test result, all the seismic performance, like the ratio of total displacement/height, the inter-storey drift and the period ratio, meet the requirements of the *TSCSTB* in all the earthquake levels, except for the inter-storey drift of X direction of the floor 117 to floor 124 in basic and rarely occurring earthquake of intensity 7. So one of the design suggestions is that the stiffness of the shear wall at the top stories needs to be improved to avoid the whipping-lash effect.

Some weak stories appeared in the test phase of Rare 7.5, which were one to two stories above and under the refuge stories of Zone 4 to Zone 8. Many cracks emerged on the super columns, core walls and coupling beams of these parts. The cross section sizes of the vertical elements at these stories are suggested to be modified so that the vertical variation of the lateral stiffness would be more equally distributed.

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