SHAKING TABLE MODEL TEST OF A SUPER HIGH-RISE BUILDING WITH SETBACKS IN ELEVATION

Ningfen Su[1], Xilin Lu[1], Ying Zhou[1], Kun Ding[1], Wensheng Lu[1]

ABSTRACT

Standing 260m above the ground, the tower employs a complex structure system that involves the use of a steel reinforced concrete core, a belt truss storey and a number of SRC columns to resist vertical and lateral loads. The design includes two setbacks in elevation and two sets of inclined columns which contribute to its irregularity and complexity. To investigate the validity of the design, a 1/35 scale model was made and tested on shaking table, which is introduced in this paper, including the model material selection, similitude relationship and the simplification of the model design. By analyzing the dynamic property, acceleration and displacement responses of the model structure, the failure mode and the dynamic responses of the model structure and the prototype structure are investigated. The conclusions drawn from this investigation show that the structure can meet the design requirements of no damage under frequent earthquake and no collapse under rare earthquake.

INTRODUCTION

In order to make the design a unique one, many new buildings take on novel faces to make the city diverse and beautiful. However, this is at the expense of the appropriate structural system and element arrangement. Thus, irregularities and complexities are developed during the structural design, which have brought great challenges to structural engineers since their structural behaviors are difficult to predict and analyze. Although substantial progress has been made in computer-based procedure for structure analysis these years, it is still hard to predict analytically the seismic performance and view the dynamic response of a building when the earthquake attacks.

It is well-known that the shaking table model test is one of the most effective ways to study the performance of complex buildings, which can provide a real dynamic process of the earthquake. Not only can engineers study the damage mechanism, the failure pattern and the dynamic response of the structure, weak points in the structure can be exposed also.

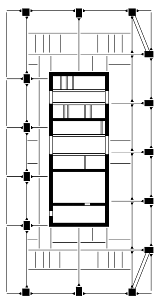
In this paper, a shaking table model test of a 1/35 scale model of a super high-rise building with setbacks in elevation is introduced, including the structural system characteristics, model material selection, similitude relationship and simplification of the model design. By analyzing the dynamic property, acceleration and displacement responses of the model structure, the failure mode and the dynamic responses of the model structure and the prototype structure are investigated.

---

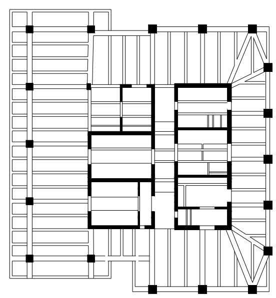
[1] *State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China*

DESCRIPTION OF THE STRUCTURE

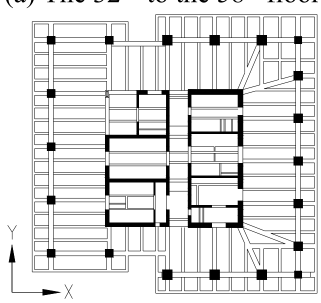
The target high-rise building is a multifunctional building located at Yanan road in Shanghai, China, which has 58 stories above the ground including a 24-storey hotel part and a 23-storey office part and 4 stories basement underneath. It has a total structural height of 244.8m and the architectural height is 260m. The typical plan of the office part in the bottom of the building is 60m by 60m, 52.5m by 54.0m in the middle, and 28.5m by 54.0m in the top hotel part. Figure 1 shows the typical plans of each part.



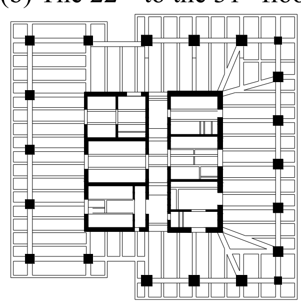
(a) The 32nd to the 58th floor



(b) The 22nd to the 31st floor



(c) The 14th to the 21st floor



(d) The 1st to the 13th floor

Fig. 1 Typical plan layouts of each part

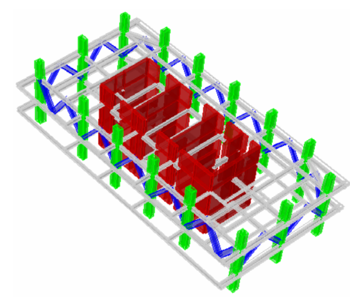


Fig. 2 Belt truss in the 47th floor

The structure employs the steel reinforced concrete (SRC) frame and the reinforced concrete (RC) core system to resist the lateral and the vertical loads. Owing to the weak connection between the frame and the tube in the upper hotel part, a belt truss storey is arranged in the middle to serve as the strengthened storey (Fig. 2). The height of the setback is 101.9m, which is about 41.7% of the overall structural height. With the alteration of the plan, the elevation takes on two setbacks at the 21st and 31st storey respectively, which is shown in Figure 3. Besides, there are two sets of inclined columns (Fig. 4), which tilt from the 16th floor to the 21st floor and from the 21st floor to the 22nd floor. The angles of the inclined columns to the vertical direction are 11.5 degree and 13.2 degree respectively.

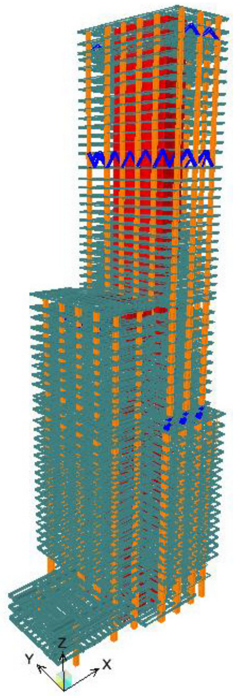


Fig. 3 Setback elevation

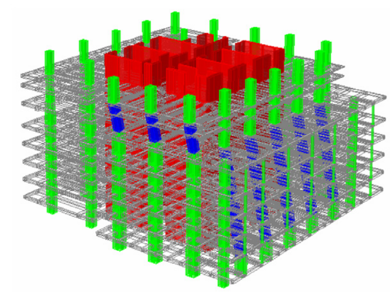


Fig. 4 Inclined columns

According to the Chinese Code for Seismic Design of Building (CCSDB, GB 50011-2001) and Technical Specification for Concrete Structures of Tall Building (TSCSTB, JGJ3-2002), the height of the building exceeds the stipulated maximum height of 190m for a SRC frame and RC core system. The two setbacks make it difficult to the appropriate arrangement of the vertical structural elements. All those characteristics mentioned above contribute to the vertical and horizontal irregularity and complexity of the building. Given these irregularities and complexity of the structure, it is significant to study its seismic behavior and evaluate its capacity to withstand earthquake, especially the response of the elements near the setbacks, inclined columns and the strengthened storey.

MODEL DESIGN AND CONSTRUCTION

Shaking Table Facility

The test was conducted at the State Key Laboratory of Disaster Research in Civil Engineering at Tongji University, Shanghai, China. The specifications of the shaking table facility are shown in the Table 1.

Table 1 Specifications of the shaking table facility

Item		Performance
Maximum Payload		25tons
Table Size		4m×4m
Excitation Control		X, Y and Z Simultaneously with 6 DOF
Maximum Stroke		X: ±100mm, Y and Z: ±50mm
Maximum Velocity		X: 1000mm/s, Y and Z: 600 mm/s
Maximum Acceleration	X	4.0g (bare table), 1.2g~0.8g (15~25tons)
	Y	2.0g (bare table), 0.8g~0.6g (15~25tons)
	Z	4.0g (bare table), 0.7g~0.5g (15~25tons)
Frequency Range		0.1～50Hz
DAS Channel		96/STEX3

Material of the Model

Based on the past experience, fine-aggregate concrete with fine wires was chosen to construct the RC building model. The red copper was used to simulate the steel.

Similitude Relationship

Generally, to make sure that the model behaves in a similar manner to prototype, the model design should conform to the dynamic similitude theory. It requires five similitude conditions: the physical similitude condition, the geometrical similitude condition, the boundary similitude condition, the similitude of dynamic equilibrium equations and the initial movement condition. However, it is impractical to meet all of them. Considering the aim of the test is to study the overall structural behavior, priority was given to similarity of the main lateral force resisting members between the model and the prototype structure.

According to the dynamic similitude equilibrium equation, there are three major controlling scaling factors in the model similitude relationship design. They are scaling factors of dimension, elastic modulus, and acceleration.
Based on the capacity and the size of the shaking table, the scaling factor of dimension S_l was chosen as 1/35. Therefore the model was built with a total height of 7.429m.

Since the materials of the prototype structure include concrete and steel, the overall scaling factor of elastic modulus S_E should be determined by the two-component material. Besides, the similitude of physical condition requires the same relationship of stress S_σ and elastic modulus S_E. In general, the two scaling factors are first considered as equal and between 1/5 and 1/3. These parameters were then determined to be 0.3 according to the material test results.

The third scaling factor for the test is that of the acceleration S_a. Theoretically, the acceleration scaling factor should be 1.0 since the acceleration due to gravity remains constant. However, if that is the case, low-strength and high-density material would be needed which is practically impossible. Another problem is that the peak value of the noise might be greater than the amplitude of earthquake inputs under small input. Considering the capacity of the shaking table and to avoid the disturbance of the noise, the scaling factor of acceleration was set to be 3.0 and additional mass blocks were then evenly distributed on the model to ensure the similitude of vertical load.

After all the three controlling scaling factors are determined, others can be obtained by the similitude theory. The main similitude relationships are shown in the Table 2.

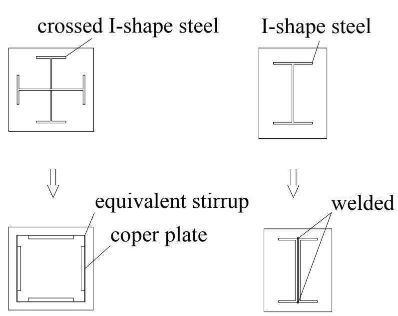
Table 2 Similitude relationships

Parameters	Relationships	Model/prototype
Length	S_l	1/35
Elastic modulus	S_E	0.30
Stress	S_σ	0.30
Strain	S_σ/S_E	1.00
Density	S_ρ	3.50
Force	S_F	2.45E-04
Frequency	S_f	10.25
Acceleration	S_a	3.00

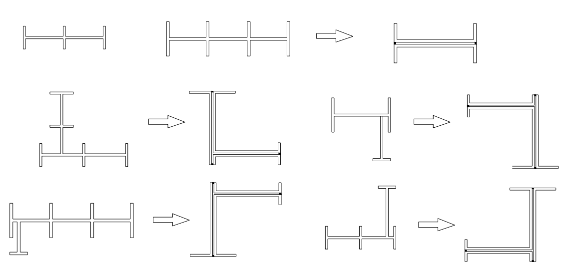
The Member Design and Simplification

For the RC members, the design should be based on the principle of bending capacity equivalent of normal section and shearing capacity equivalent of the diagonal section, while for the steel in the SRC members, it is based on the equivalent of stiffness. Since the truss member is compressive or tensile alternatively, the equivalent of axial force was employed when model design.

During the process of model design, some simplifications were involved for it is rather difficult to design the model abide by the prototype for the sake of the operability. The lateral stiffness is mainly provided by the SRC frame and the core tube, so the secondary beams which have little contribution to the lateral stiffness were excluded. In order to compensate the weight and loads of the excluded beams, the thickness of the floor slab was modified on the principle of bending resistance stiffness equivalent. In the prototype, complex steel section pattern was used, which is hard to accomplish in the model construction. For this reason, the steel in the SRC members and the shear walls were simplified on the basis of bending and shearing capacity equivalent principles. As shown in Figure 5, the crossed I-shape steel was divided into two parts, that is, four copper plate and additional stirrups. The I-shape steel was simulated by two C-shaped copper plate side by side considering the construction convenience. The complex steel in the shear walls was simplified to a composite shape which contains a T-shape part and an I-shape part.



(a) steel in the columns and beams

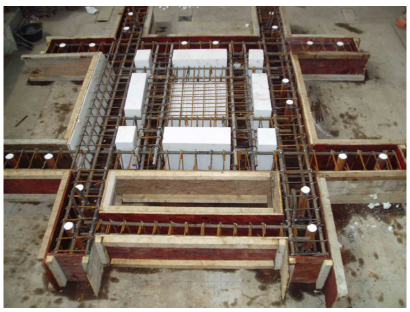


(b) steel in the shear walls

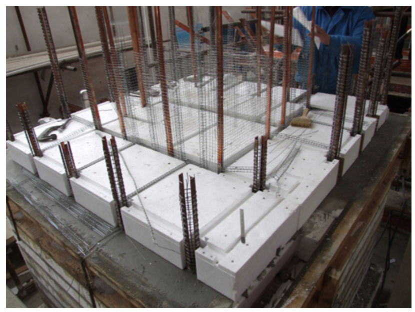
Fig. 5 Simplification of steel section

Model Construction

The model structure was made of micro concrete and fine wires. Wood forms were used outside for slip-form construction and cellular plastic was applied inside for its easy removal and little influence to the structure property. The process of the model construction is illustrated in Figure 6. The total height of the model structure is 7.729m, which contains the height of the base.



(a) base of the model



(b) typical floor construction

(c) model panorama

Fig. 6 The process of model construction

TEST PROGRAM

Instruments and Transducers

According to the structural characteristics of the building, thirty five accelerometers were installed on the key stories along the height of the model including the roof, the strengthened storey, the setback stories, and the base in three directions. Twelve displacement transducers were installed at the roof, the 47^{th} floor, the 31^{st} floor, the 21^{st} floor and the base respectively.

Ground Motion Input

Condition of site soil is an important 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 80m and the average shear wave velocity in the soil layer is not more than 140m/s. Taking Shanghai type IV soft soil into consideration, three seismic ground motions were selected as the input signal in the test: (i) El Centro record from California Imperial Valley earthquake of May 18, 1940; (ii) Pasadena record from the California Kern County earthquake of July 21, 1952; (iii) Shanghai artificial wave SHW1, which can be found in the Shanghai Code for Seismic Design of Buildings (DGJ08-9-2003).

Test Program

Regulated by CCSDB, the seismic design area of Shanghai belongs to the zone of intensity 7. That is to say, the design basic acceleration of ground motion is 0.1g. The test was carried out in four phases representing the frequent, the moderate and the rare occurrence of seismic design intensity 7 and the rare occurrence of seismic design intensity 8. The corresponding acceleration of ground motion is 0.035g, 0.10g, 0.20g and 0.36g. When testing, the specified peak acceleration times the scaling factor (here S_a=3.0) was used to obtain the target input peak value. After each phase, a white noise test was conducted to investigate the change in natural periods of the model. The test program is listed in Table 3. Note that, when earthquake input, the Shanghai artificial wave was in one direction, while the other two were in two directions at the first three phases. In the white noise test cases and the last phases, the ground motions were inputted in three directions. The peak accelerations in X, Y and Z direction are in the proportion of 1:0.85:0.65 which is specified in CCSDB. In the Table 3, the design value means the code specified peak acceleration value of input ground motion adjusted by the similitude relationship. The achieved value means the measured real peak acceleration value of the shaking table.

Table 3 Test program

Test case	Case name	Earthquake Occurrence Frequency	Input Signal	Peak value of input acceleration (g)						Note
				Direction X		Direction Y		Direction Z		
				Design	Achieved	Design	Achieved	Design	Achieved	
1	W1	White noise 1		0.05		0.05		0.05		3D
2	F7EXY	Frequent 7	El Centro	0.11	0.128	0.09	0.097			2D
3	F7EYX			0.09	0.101	0.11	0.152			
4	F7PXY		Pasadena	0.11	0.129	0.09	0.073			2D
5	F7PYX			0.09	0.126	0.11	0.163			
6	F7SHX		SHW1	0.11	0.123					1D
7	F7SHY					0.11	0.155			
8	W2	White noise 2		0.05		0.05		0.05		3D
9	B7EXY	Moderate 7	El Centro	0.30	0.342	0.26	0.276			2D
10	B7EYX			0.26	0.261	0.30	0.264			
11	B7PXY		Pasadena	0.30	0.349	0.26	0.281			2D
12	B7PYX			0.26	0.299	0.30	0.348			
13	B7SHX		SHW1	0.30	0.436					1D
14	B7SHY					0.30	0.304			
15	W3	White noise 3		0.05		0.05		0.05		3D
16	R7EXY	Rare 7	El Centro	0.60	0.713	0.51	0.418			2D
17	R7EYX			0.51	0.526	0.60	0.508			
18	R7PXY		Pasadena	0.60	0.741	0.51	0.573			2D
19	R7PYX			0.51	0.552	0.60	0.593			
20	R7SHX		SHW1	0.60	0.803					1D
21	R7SHY					0.60	0.471			
22	W4	White noise 4		0.05		0.05		0.05		3D
23	R8EXY	Rare 8	El Centro	1.08	1.407	0.92	0.803	0.70	0.716	3D
24	R8EYX			0.92	1.227	1.08	1.33	0.70	0.654	
25	R8PXY		Pasadena	1.08	1.716	0.92	1.119	0.70	1.012	
26	W5	White noise 5		0.05		0.05		0.05		3D

TEST RESULTS

Cracking and Failure Pattern

During the first two phases, no visible damage in appearance was identified. After the third white noise test case, it was found that the frequencies of the model structure in both X and Y directions reduced slightly. That is to say, fine cracks had already developed inside. After the third phase, several cracks were observed and the natural frequency reduced continually. After the forth phase, existing cracks further propagated, crossing cracks appeared in the columns of stories above and under the setbacks and concrete crushed locally, especially in the setback storey. The diagonal cracks run through the whole walls of the concrete tube in the setback storey. It indicates that the setbacks in the elevation which in turn lead to the stiffness alteration have an effect on the structure performance. The columns above the inclined columns of the 22nd floor cracked horizontally and vertically which is the result of complex load transfer from inclined columns to the vertical ones. No damage was observed in the bottom shear walls and the truss members in the strengthened storey. Figure 7 shows the typical damage of the model structure.

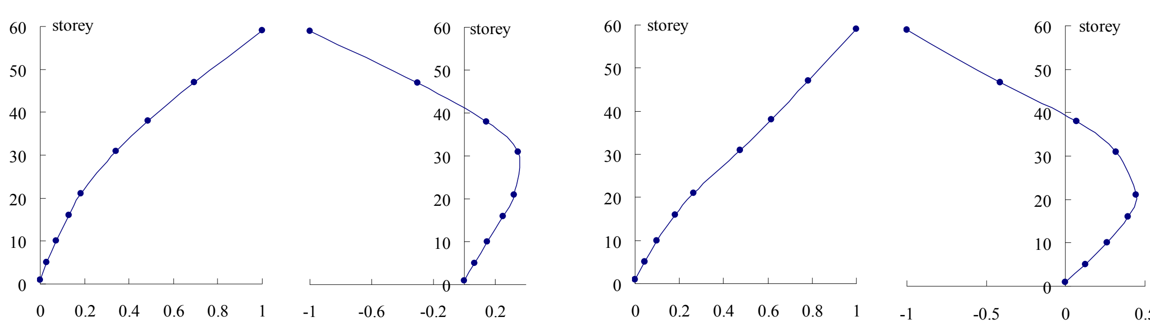
(a) shear wall diagonal crack in the 30th storey (b) column diagonal crack in the 31st storey (c) column crossing crack in the 32nd storey

Fig. 7 Failure pattern of the model structure

Dynamic Property of the Model Structure

Before and after every test phase, white noise test was conducted which provided great information about of alteration of the structural dynamic property. By analyzing the response time history and the transfer function, the natural frequency and the mode shape were derived. The first three frequency of the model structure is 3.418 Hz (translation vibration in X direction), 3.418Hz (translation vibration in Y direction) and 6.347Hz (torsion vibration). With the increase of the input peak acceleration value of ground motion, the frequency of the structure decreased. After the rare occurrence of seismic design intensity 7 phase, the first three frequency of the model structure is 2.930Hz (translation vibration in X direction), 2.930Hz (translation vibration in Y direction) and 5.371Hz (torsion vibration). The decrease of the frequency is 14.3%, 14.3% and 15.4% respectively.

The first two mode shapes in the two directions are shown in Figure 8.



(a) the first two mode shape in the X direction (b) the first two mode shape in the Y direction

Fig. 8 The first two modal shapes in the two directions

The Displacement Response of the Model Structure

Figure 9 shows the maximum displacement response envelops in two directions under different level of ground motion input. The displacement above the setback storey takes on an increasing trend which results from the sudden alteration in stiffness.

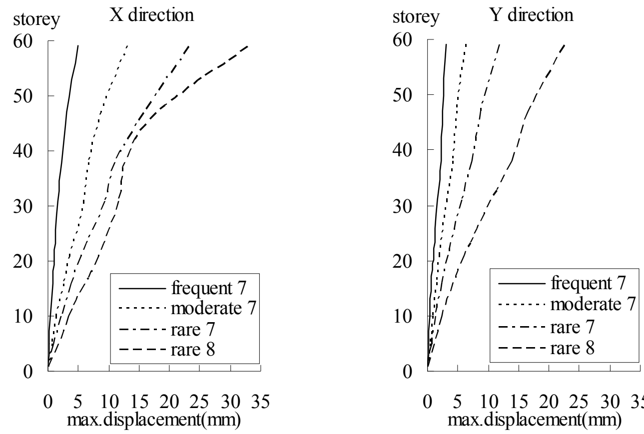


Fig. 9 Displacement response envelopes of the model structure

DYNAMIC RESPONSE OF THE PROTOTYPE STRUCTURE

Dynamic Property of the Prototype Structure

The natural frequency of the prototype structure can be derived according to the similitude relationship. The first three frequencies of the prototype structure are 0.333Hz、0.333Hz and 0.619Hz respectively. Their mode shapes are translational vibration in X direction, translational vibration in Y direction and the torsional vibration correspondingly. The frequency ratio between the first translational mode to the first torsional mode is 0.538, which is less than the stipulated value 0.85 in the TSCSTB.

Displacement Response and the Inter-Story Drift Angle of the Prototype Structure

Similarly, the displacement response of prototype structure can be obtained by applying the similitude relationship to the model test result. Then, the inter-storey drift and the inter-storey drift angles can be calculated. In the frequent occurrence of seismic design intensity 7 phase, the maximum inter-storey drift angles are 1/838 and 1/1611 in X and Y direction, which are much less than the limitation of 1/500 by the TSCSTB. In the rare occurrence of seismic design intensity 7 phase, the maximum inter-storey drift angles are 1/207 and 1/308 in X and Y direction, which satisfy the limitation of 1/100 by the TSCSTB.

Storey Shear Force Distribution and Overrunning Moment of the Prototype Structure

Figure 10 and 11 show envelops of shear force and the overturning moment of prototype structure under different occurrence level of seismic design intensity. It indicates that the storey shear force and overturning moment evenly distributed. In the frequent occurrence of seismic design intensity 7 phase, the maximum base shear in the X and Y direction are 69027kN and

95543kN respectively. The base shear coefficient (ratio of base shear to the weight) of the structure is 2.62% and 3.63%.

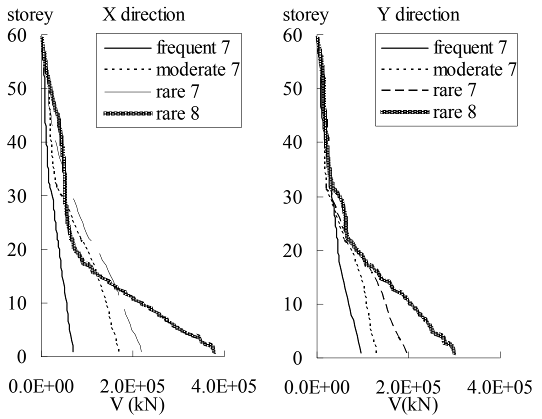


Fig. 10 Envelopes of the shear force

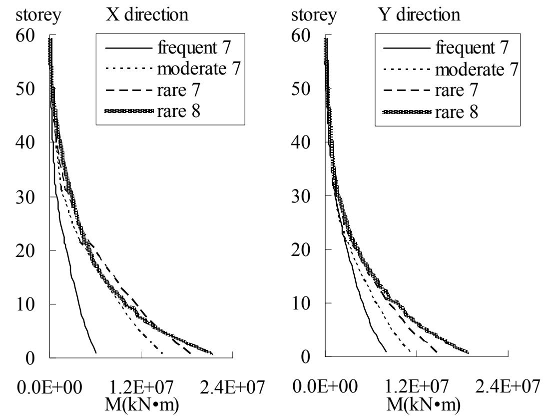


Fig. 11 Envelopes of the overturning moment

CONCLUSIONS

From the shaking table model test and result analysis, the following conclusions were drawn:
(1) Under the frequent occurrence of seismic design intensity 7, no visible damage can be observed. The natural frequencies remained unchanged. Under the moderate occurrence of seismic design intensity 7, it decreased very slightly, which indicates that the prototype structure can behave elastically when attacked by those levels of earthquakes. Under the rare occurrence of seismic design intensity 7 and 8, the structure damaged locally but still could survive and keep stable, which indicate that the targeted high rise building could meet the design criteria of no damage under frequent earthquake and no collapse under rare earthquake;

(2) The maximum inter-storey drift angles are 1/838 and 1/1611 in X and Y direction under frequent earthquake 7 phase, which are less than the limitation of 1/500 by the TSCSTB. In the rare occurrence of seismic design intensity 7 phase, the maximum inter-storey drift angles are 1/207 and 1/308 in X and Y direction, which satisfy the limitation of 1/100 by the TSCSTB;

(3) When a very rare earthquake attacks, the setback storey damaged severely due to the sudden change in stiffness, which may leads to the weak point of the structure. It is suggested that appropriate improvement on ductility should be made to the stories adjacent the setbacks;

(4) The angle between the inclined columns in the 21st to the 22nd storey and the vertical direction should be decreased to improve the seismic performance of the structure.

ACKNOWLEDGEMENTS

The authors are grateful for financial support from the National Natural Science Foundation of China (NSFC) (Grant No. 90815029) and National Key Technology R&D Program (Grant No. 2006BAJ13B01).

REFERENCES

China Ministry of Construction 2001. *Code for Seismic Design of Buildings (GB 50011-2001)*, Beijing, China.

China Ministry of Construction 2002. *Technical Specification for Concrete Structures of Tall Buildings (JGJ3-2002)*, Beijing, China. (in Chinese)

Shanghai Government Construction and Management Commission 2003. *Code for Seismic Design of Buildings (DGJ08-9-2003)*, Shanghai, China. (in Chinese)

Lu X. L. 2007. *Earthquake resistant theory and application of complex high-rise building*, Science Press, Beijing. (in Chinese)

Lu X. L., Zhou Y., Lu W. S. 2007. Shaking table model test and numerical analysis of a complex high-rise building, *The Structural Design of Tall and Special Buildings* **16**(2):131-164.

Lu X. L., Zou Y., Lu W. S., Zhao B. 2007. Shaking table model test on Shanghai World Financial Center Tower, *Earthquake Engineering and Structural Dynamics* **36**:439-457.

Huang Z. H., Lu X. L., Zhou Y., Chen L. Z. 2007. Shaking table model test of an irregular high-rise building, *Proceedings of the 2nd International Conference on Advances in Experimental Structural Engineering*, Shanghai, China.