Experimental study on seismic behavior of an irregular high-rise building

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SUMMARY:
An office building with height of 112.4m was designed to have very irregular plan and elevation. Shaking table test was carried out on the structure to investigate its seismic performance. A 1/20 scaled test model was designed and built, then tested on the shake table of China Academy of Building Research under small, moderate and large earthquake levels. Test results show that main seismic performance objectives of the structure can be achieved. However, the irregularities lead to some severe damage under strong earthquakes. Based on the research results some suggestions were proposed to contribute favorable effect on the seismic capacity of the structure.

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

1. GENERAL INSTRUCTION

In recent years, a large number of high-rise buildings have been constructed throughout China. Some of these buildings were irregular and do not follow traditional structural design concepts. From past experience, it has been shown that structural irregularities could directly or indirectly cause the collapse or severe damage of these structures under strong earthquakes. A thorough investigation of their performance under seismic loads is thus necessary to verify the safety of these irregular 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. By the end of the 20th century, shaking table test has been increasingly used to study the dynamic responses 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. 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 Guangzhou west tower, a structure composed of SRC inner core and weaved CFST outer tube.

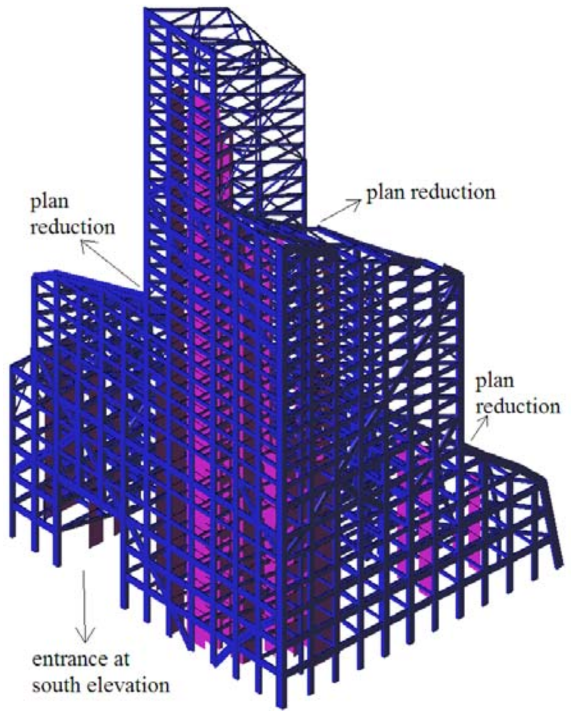
In this paper, a high-rise building adopts a representative irregular structure not currently included in Chinese codes. Detailed shaking table model test was performed on the structure to investigate its seismic performance. Based on the experimental results some suggestions were proposed to improve seismic performance of the structure.

2. DESCRIPTION OF BUILDING STRUCTURE

The Chengdu Raffle Plaza is a high-rise office building, including five towers, as shown in Fig.2.1. Steven Holl Architect was invited to design it. Among these towers, T4 tower with height of 112.4m was designed to have very irregular plan and elevation due to requirements of sunshine duration, ventilation and other reasons, as shown in figure 2.2, which created a challenge for structural engineers to realize the design. There was a big entrance at south elevation and many columns are incontinuous and transferred by beams and braces, as shown in Fig.2.3. The building plan changes form first floor of ‘L’ shape with dimension of 36mX70m to triangle shape with dimension of 16mX15m by three abrupt reduction of plan, as show in Fig.2.4. Previous seismic hazards and study results both show that this kind of structure was easy to be damaged during earthquake. A reinforced concrete core wall-composite braced frame hybrid structure system was employed.

The building is located at Chengdu, Sichuan province, which is only about 90 kilometers apart from the epicenter of Wenchuan earthquake at 2008. The design basic acceleration of ground motion is 0.1g. The building has high seismic risk. In order to ensure safety of this irregular high-rise building under earthquake, detailed seismic design and analysis were done on the structure, including performance-based seismic design, dynamic elastic and plastic time-history analysis and so on. Then a shaking table test was carried out to reveal the performance of structure subjected earthquake and verify that if the designed structure can satisfy the requirements of codes and reach scheduled performance objectives.

Figure 2.1. Chengdu Raffle Plaza



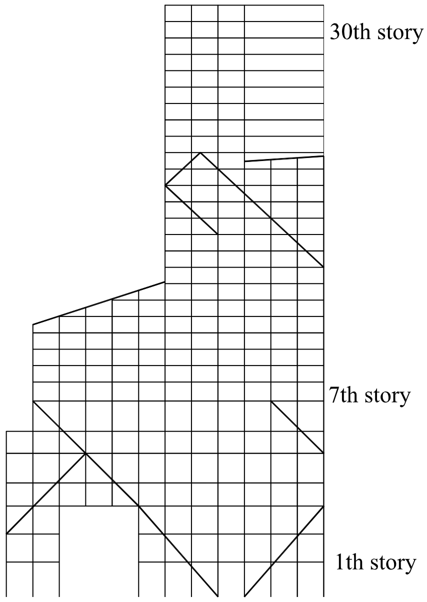
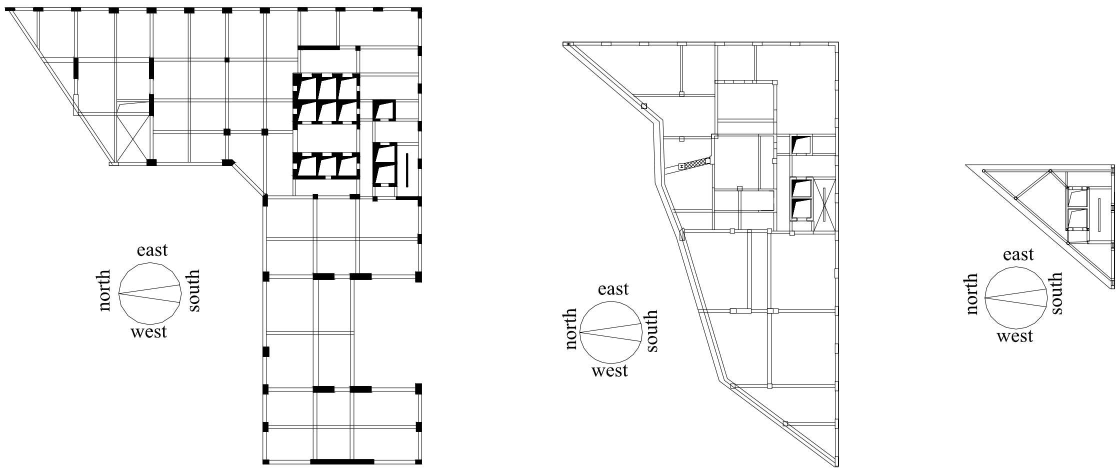


Figure 2.2. Structure of T4 tower

Figure 2.3. South elevation of T4 tower



1st story plan 10th story plan 30th story plan

Figure 2.4. Typical plan of T4 tower

3. TEST MODEL DESIGN AND CONSTRUCTION

3.1. Model materials

Based on past experience, brass plates were used to simulate the steel structural members and fine-aggregate concrete with fine 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 3.1, which forms the basis of the scaling factor for the materials.

Table 3.1. Model material properties

material	Elastic modulus (MPa)	Compressive strength (MPa)
fine-aggregate concrete	12300	13.91
Brass plate	83860	89

3.2. Model design

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). Firstly, the acceleration scaling factor was taken as 1.0 since the acceleration due to gravity remains constant. Based on the model material properties, the scale of materials elastic modulus were 1/2.5. 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 6mX6m and bearing capacity of 80 ton. According to the dimension of structure and shaking table, length scale of 1/20 was adopted. Then scaling factors of other parameters of the test model to prototype were conducted and listed in table 3.2.

Table 3.2. 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

Before shaking table test, seismic behavior of scaled RC and SRC beam and column specimens made of brass, fine-aggregate concrete with fine steel wires were tested. The rigidity and capacity of scaled members and prototype member were approximately in conformity with the similitude theory. So the model design should be in accordance with dynamic similitude theory and the experimental results on the scaled model can revealed the seismic performances of prototype structure.

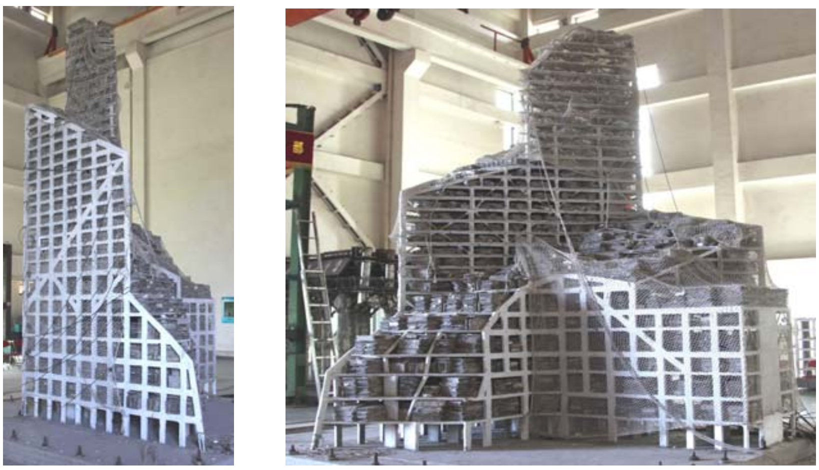


Figure 3.1. Test Model

3.3. Model construction

The construction procedure of test model is similar with real structure. The brass members were installed firstly, secondly the reinforcement in SRC and RC members were installed, and then the floor slab and RC members were cast in site. During construction polyfoam was taken as mould of concrete members. The finished test model is shown in Figure.3.1.

4. TEST PROGRAM 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. Chengdu is assigned to an earthquake zone of intensity 7. The peak ground accelerations corresponding to the minor, moderate and major levels of seismic intensity 7 are specified as 0.035 g, 0.10 g, 0.22 g, respectively. A summary of the test inputs is listed in table 4.1.

Three ground motions were selected as the input motions during the test: (i) El Centro record from the California Imperial Valley earthquake of May 18, 1940; (ii) Taft record from the California Kern County earthquake of July 21, 1952; and (iii) Chengdu artificial accelerogram, which is specified for the type Ⅱ soil conditions. 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 under small earthquake, so all of three seismic records were inputted one by one form X, Y and X+Y directions. Under moderate earthquake, all of three seismic records were inputted one by one from X+Y directions. Only one seismic record was inputted from X+Y directions to avoid accumulated damage. In the two-direction excitations in the test, the peak acceleration ratio of the X, Y and Z direction is designated to be 1: 0.85.

Table 4.1. Test program

phrase	Input seismic records	Direction	peak acceleration
small earthquake of intensity 7	All three records	X,	35
		Y	35
		X+Y	35+29.8
Moderate earthquake of intensity 7	All three records	X+Y	104+88.4
Large earthquake of intensity 7	El Centro record	X+Y	183+155.6
large earthquake of intensity 8	El Centro record	X+Y	400+340

60 acceleration sensors were installed on the floors of model. 32 strain gauges were installed on key structure members, including transfer members, shear wall and braces.

5. EXPERIMENTAL RESULTS

5.1. Experimental 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, cracks first appeared at the internal corner joint of 23rd floor where the plan was reduced. There were cracks at several beam-column-brace joint at 11th floor, several beams' ends at south and north facade, and shear wall at west facade. Most columns and braces hade no crack or damage.

For large earthquake of intensity 7, existing cracks were extended. Many cracks appeared at the internal corner joint of 7th, 15th and 23rd story where the plan was reduced (figure 5.1). Tension cracks were found on some braces (figure.5.2). The transfer beam and column at entrance of south facade have slight cracks (figure.5.3). An obvious damage was observed at the corner column at 11th story, where a brace was connected to this column (figure.5.4). The littler tower above 23rd story shakes obviously.

For large earthquake of intensity 8, existing cracks were remarkably extended. The littler tower above 23rd story shakes violently. Cracks were found on most members of the little tower. Tension cracks were found on many columns and braces. Most beams' ends have cracks. The structure keeps standing and has margin of seismic capacity.

(a) 7th story (b) 15th story (c) 23rd story

Figure 5.1 Cracks appeared at the internal corner joint where the plan was reduced

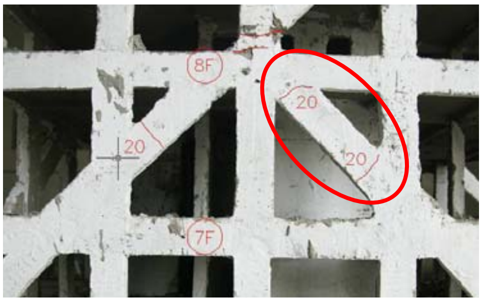


Figure 5.2 Tension cracks on braces **Figure 5.3** Cracks on transfer beam

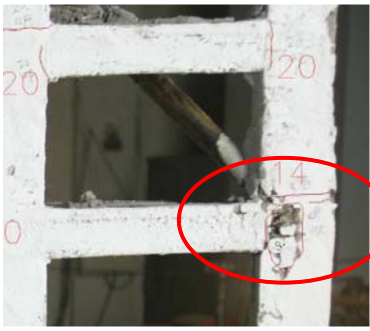


Figure 5.4 Damage of column-brace joint at 11th story

5.2. Dynamic characteristics

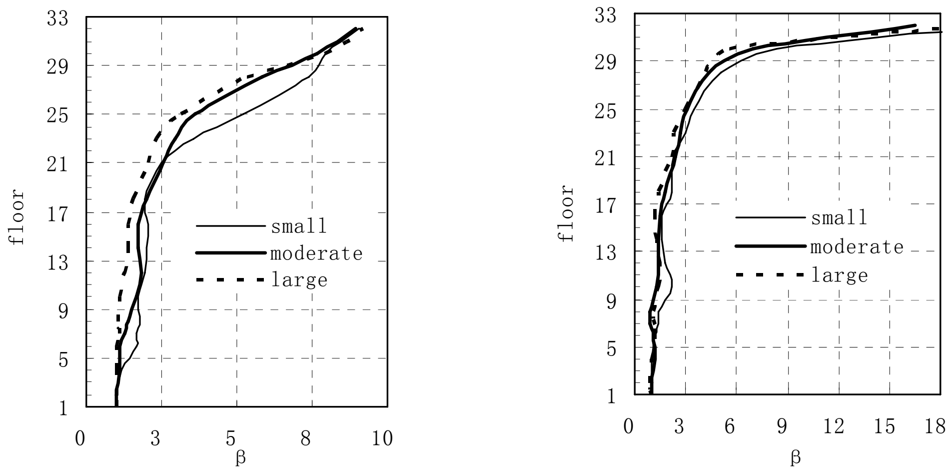
Dynamic characteristics of the model at different phases were measured by inputting a white noise signal and the results were listed in Table 5.1. With increasing of inputting earthquake magnitude, the frequency of model decreased and damp ratio increased due to more damage and cracks of model.

Table 5.1. Period and damp ratio of test model

Phrase	X direction		Y direction	
	frequency (Hz)	Damp ratio	frequency (Hz)	Damp ratio
Before test	3.06	6.8%	3.92	5.6%
After small earthquake of intensity 7	2.94	6.9%	3.81	5.8%
After moderate earthquake of intensity 7	2.68	7.5%	3.38	6.6%
After large earthquake of intensity 7	2.56	8.1%	3.12	8.2%
After large earthquake of intensity 8	1.81	12.5%	2.18	9.0%

5.3. Acceleration results

Acceleration amplification factor β is usually defined as the ratio of the peak value of floor accelerations to the peak ground acceleration (PGA). Value of β reflectes the dynamic amplification effect of different floors in the structure. Figure 5.5 shows the distribution of the horizontal acceleration amplification factor when inputting El Centro record. Values of β under 23rd story are between 1.0 and 3.0 and decrease rapidly above 23rd story. The little top tower has obvious whipping effect. Special attention should be paid in designing the little top tower.



X direction Y direction

Figure5.5. Envelope of horizontal acceleration amplification factor at different phrases under El Centro record

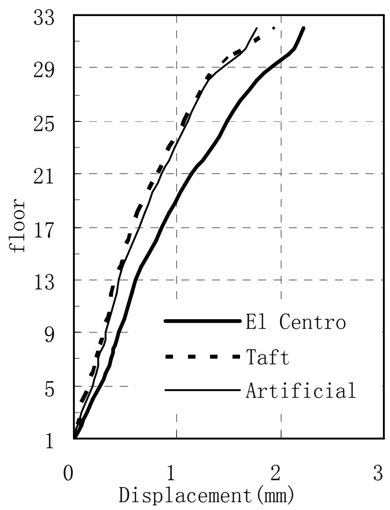


Figure5.6. Peak story horizontal displacement at X direction under small earthquake

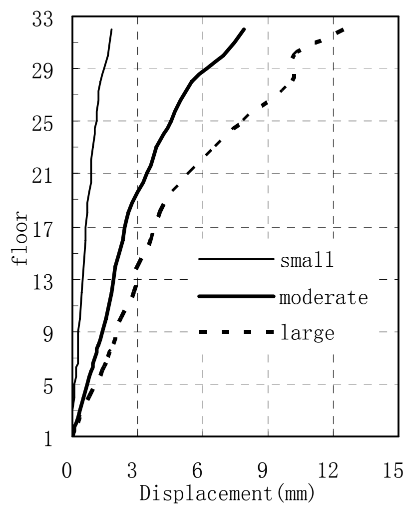
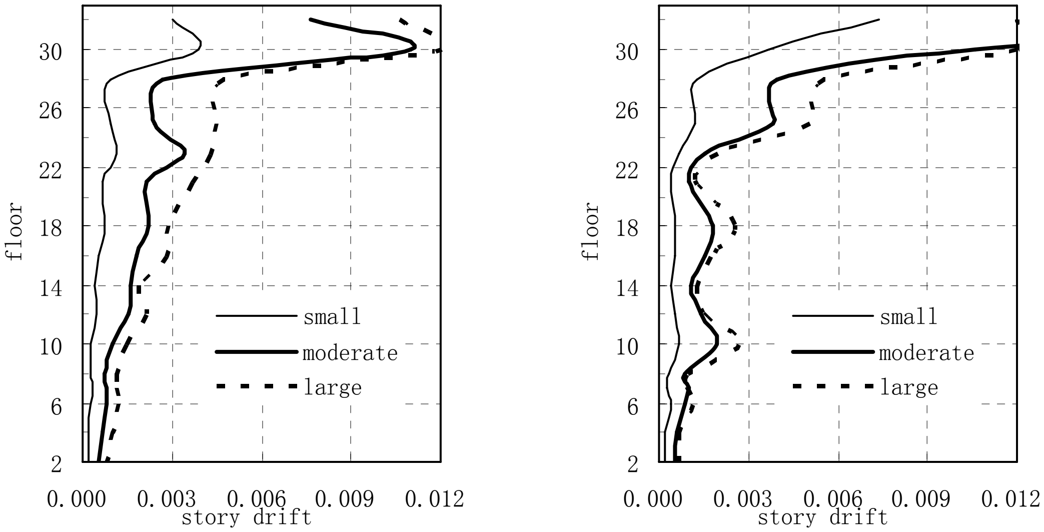


Figure5.7. Peak story horizontal displacement at X direction at different phrases under El Centro record

5.4. Displacement results

The peak story horizontal displacement at X direction relative to shaking table at various test phases are showed in figure5.6~figure5.7. The displacement at Y direction was similar to X direction and not listed. The results show that different input records with same peak acceleration will lead to different shape and value of model deformation. With same input record, displacement increases with peak acceleration.

The envelope of story drift at various test phases is showed in figure5.8. The results showed that the story drift increased obviously above 23rd story after moderate level earthquake. Special attention should be paid in designing the structure above 23rd story. Maximum story drift and corresponding location during small and large earthquake were listed in table5.2 and all the values meet requirement of Chinese code.



X direction Y direction

Figure5.8. Envelope of story drift at various test phases

Table 5.2 Maximum story drift

Phrase	X direction		Y direction	
	Maximum story drift	location	Maximum story drift	location
small earthquake	1/1288	28^{th} story	1/1086	28^{th} story
large earthquake	1/213	28^{th} story	1/182	28^{th} story

6. CONCLUSIONS

Chengdu Raffle Plaza T4 tower is an irregular high-rise building. Shaking table model test was carried out at China Academy of Building Research to investigate its seismic performance. A 1/20 scaled model was designed and tested for small, moderate and large earthquake levels. According to experimental results following conclusions can be drawn.

1) Experimental results show that the structure can meet the requirements of Chinese codes. The structure would not be damaged by a small earthquake. It would have some minor structural cracking under a moderate earthquake, and would be damaged under a large earthquake, but would not suffer a catastrophic collapse.

2) The structural irregularities, including plan reduction, little top tower and uncontinous columns, cause some obvious damage under large earthquakes. The little top tower has obvious whipping effect. In the structure design some measures had be taken to ensure its safety.

3) It was suggested to strengthen the internal corner joint at 7^{th}, 15^{th} and 23rd story and the corner column-brace joint at 11th story by adding steel shape in beam and columns around the joint, and adding reinforcement in the floor slab connected to these joints.

These suggestions in this paper have been accepted by the design institute and the building had been finish and come into service.

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