DYNAMIC TEST ON A MULTI–TOWER CONNECTED BUILDING STRUCTURE

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ABSTRACT

A multi-tower connected building, with large floor slab openings in plan and long-span truss in elevation, was studied because of its structural irregularity. First, a 1/25 scaled model structure was tested on the shake table under minor, moderate, and major earthquake levels. Then, the dynamic responses of the model structure were interpreted to those of the prototype structure according to the similitude laws. The experimental results were also compared with the numerical analysis of the irregular structure. Both results demonstrate that, despite its structural complexity, the responses of the building meet the requirements of the Chinese code and the torsion of the structure is not remarkable. It is suggested that the strength and stiffness of the long-span connecting truss should be improved due to the potentially large vertical acceleration under strong earthquakes.

INTRODUCTION

In recent years, a large number of aesthetically pleasing high-rise buildings has been constructed throughout China. Most of these buildings are irregular and do not follow traditional structural design concepts. From past experiences, structural irregularities could directly or indirectly cause the collapse or severe damage of these structures under strong earthquakes. A thorough investigation of their seismic performance is thus necessary to verify the safety of these irregular buildings. In China, irregular structures are investigated prior to construction through a series of steps, including preliminary analysis and review, shake table model testing, and static testing of weak joints identified through the model testing, resulting in a refined analysis of the overall structure (Zhou and Lu, 2008).

In the past several decades, substantial progress has been made in the development and use of computer-based procedures for analysis of structures. However, it is still difficult to accurately predict the seismic performance of a given structure using one analytical method. This is particularly true for earthquake-resistant design of irregular structures, since there are not very many applications of analytical and numerical simulations for them. To overcome this limitation, shake table model testing can be conducted to examine the seismic performance of a given structure. The use of shake table model tests in civil engineering began in the 1980s. By the end of the 20th century, shake table testing has been increasingly used to study the dynamic responses of new types of structures and high-rise buildings. Shake table testing on innovative structures and dams were introduced in the work (Lu and Wu, 2000; Tinawi et al., 2000; Morin et al., 2002; Midorikawa et al., 2006; Wight et al., 2007; Ghaemmaghami and Ghaemian, 2008). Shake table testing of high-rise buildings has also increased (Li et al., 2006; Ko and Lee, 2006; Lu et al., 2007a, 2007b, 2008a, 2008b; Zhou et al., 2009). It can be seen that shake table testing

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has been a useful means to study the seismic performance of various innovative structures. Considering its advantages, several shake 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. (Zhou and Lu, 2008). The construction of these shake tables will help advance research and application of dynamic testing.

In this paper, a high-rise multi-tower connected hybrid structure is used as a representative irregular structure not currently included in Chinese codes. Detailed shake table model testing was performed by a working group at the State Key Laboratory of Disaster Reduction in Civil Engineering at Tongji University, China. Experimental responses such as frequency and displacement were analyzed and compared with those of the numerical analysis. Finally, conclusions for evaluating the seismic performance of this type of structure are drawn.

DESCRIPTION OF THE BUILDING STRUCTURE

Building Structure

The Zhoushan Eastern Port Business Center (ZEPBC) is an office building located at the people's square of the eastern port, Zhoushan city. To bring the visual impact to the people on the square, ZEPBC is designed as a multi-tower building connected by a long-span corridor at its top. A round opening is included in the architectural design of ZEPBC corridor to symbolize the "round-sky-and-square-earth" concept in the Chinese tradition (see Figure 1). Two towers are 18 stories with the height of 81.4m. The corridor has an axial span of 60.4m and a clear span of 58m from story 17 to story 18. The hybrid structural system, with two reinforced concrete (RC) tower connected by a steel truss, was employed in ZEPBC as shown in Figure 2.

Fig. 1. Architectural rendering

#1 Tower #2 Tower

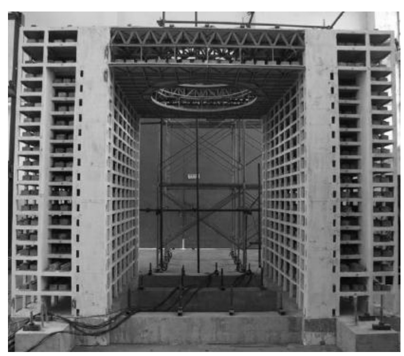

Fig. 2. Structural elevation

Structural Irregularities

According to the Chinese Code for Seismic Design of Buildings (GB50011-2001) (CMC, 2001) and the Technical Specification for Concrete Structures of Tall Building (JGJ3-2002) (CMC, 2002), the main characteristics of the ZEPBC are summarized as follows.
1. In the plan layouts, there are large openings that have a floor area of over 30% in six consecutive stories of the #1 Tower, which is beyond the limits specified in the Chinese Code. Second, the span of the corridor totals 58m and is located 69.1m above the ground, which may potentially induce severe vibration during a strong earthquake.

2. In the elevation, ZEPBC is a two-tower-connected hybrid structure. China has built a multi-tower structure connected by a rigid truss (Zhou et al., 2009); however, it has no experiences to build such a structure connected by a semi-rigid truss.

Given the above irregularities and complexity of the structure, it is necessary to study the seismic behaviour of the ZEPBC in detail and evaluate its capacity to resist strong earthquakes.

SHAKE TABLE TESTING OF THE ZEPBC MODEL STRUCTURE

Shake Table Facility

The MTS shake table at State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University is capable of generating six-degree-of-freedom motions. It has a dimension of 4 m × 4 m with a maximum payload of 250 kN. With a 150 kN payload, the maximum accelerations are 1.2 g, 0.8 g and 0.7 g for the horizontal, transverse and vertical directions, respectively. The working frequency ranges from 0.1 Hz to 50 Hz and 96 channels are available for data acquisition (SLDRCE, 2008).

Building Model Material

Material properties are very important in dynamic model tests. Depending on the purpose of the experiment, shake table models can be classified into two categories: elastic model and strength model. The former is usually used to verify new methods and parameters for design, while the latter is often employed to obtain the overall performance of the structure beyond elastic limits. The material of the elastic model does not need to be exactly the same as the prototype, provided that it remains elastic during testing and has the same distribution of mass and rigidity. However, similarity of the elastoplastic material between the model and the prototype is essential in the strength model.

Thus, based on past experiences, copper plates were used to simulate the steel structural members and fine-aggregate concrete with fine wires was chosen to construct the RC components in the ZEPBC model. The maximum aggregate size was 4 mm, and its grading was scaled to the extent possible.

Model Design

Considering that the dynamic behavior of a structure is fully identified by means of three basic quantities, i.e., mass, stiffness and restoring force, and these three quantities are in turn related with to mass density, elastic modulus, time and length. It is easy to derive their relationship as given in Equation (1), where S_l, S_E, S_a, and S_ρ are scaling factors of dimension, elastic modulus, acceleration, and mass density, respectively. Only three among the four model quantities can be arbitrarily selected in dynamic problems (Harris and Sabnis, 1999).

$$\frac{S_E}{S_\rho \cdot S_a \cdot S_l} = 1 \tag{1}$$

First, based on the capacity and the size of the shake table, the scaling factor of dimension S_l was chosen to be 1/25. The ZEPBC model was thus built with a height of 3.6 m. Second, since the prototype structure was made of concrete and steel, the overall scaling factor of elastic modulus S_E should be determined by two kinds of materials. It should also be noted that there is a distinct decrease in the elastic modulus when the copper is welded. According to the material test results, the overall scaling factor of the elastic modulus was determined to be 0.25. Third, theoretically, the acceleration scaling factor S_a should be 1.0 since the acceleration due to gravity remains constant. If that is the case, however, low-strength and high-density material would be needed, which is practically impossible for a high-rise building model. Another problem is that the peak value of the noise might be greater than the amplitude of the earthquake inputs under small input (such as 0.035 g) and the seismic input pattern would be distorted. In the test discussed here, S_a was set to be 2.5 and additional iron blocks were evenly distributed on the model to compensate for the difference in vertical load. The total weight of the model was estimated to be 178 kN, including iron blocks with a weight of 144 kN. All the other scaling factors could be derived and the typical factors are listed in Table 1.

Table 1. Typical scaling factors of ZEPBC model

Parameter	Relationship	Model/prototype
Length	S_l	1/25
Elastic modulus	S_σ	0.25
Density	$S_\sigma/(S_a \cdot S_l)$	2.50
Force	$S_\sigma \cdot S_l^2$	4.0E–04
Frequency	$S_l^{-0.5} \cdot S_a^{0.5}$	7.91
Acceleration	S_a	2.50

To be certain that the model behaves in a similar manner to the prototype, the model design should be in accordance with dynamic similitude theory. Similitude requirements include equilibrium, compatibility, material laws, boundary and initial conditions. However, meeting all these requirements is not possible. Considering that the primary purpose of the study is to determine the overall seismic response of the building, priority is given to the lateral force resisting members. Furthermore, it is difficult to have the same stress scaling factor for both aggregate and steel bars. Therefore, strength alternation in the structural members should be considered in the model design, as shown in Equations (2) and (3) (Lu et al., 2007a). Different strength scaling factors for concrete materials and steel materials are considered and are used to calculate the model reinforcement.

$$A_s^m = A_s^p \cdot \frac{S_\sigma \cdot S_l^2}{S_{f_y}} \tag{2}$$

$$A_{sv}^m = A_{sv}^p \cdot \frac{S_\sigma \cdot S_l \cdot S_s}{S_{f_{yv}}} \tag{3}$$

where "m" refers to the model structure and "p" corresponds to the prototype structure. A_s is a cross section area of the longitudinal reinforcement in tension; A_{sv} is a cross section area of stirrups with different legs; and S_σ, S_{f_y}, $S_{f_{yv}}$ and S_s are scaling factors of stress, tensile strength of reinforcement, tensile strength of stirrups and spacing of stirrups, respectively.

An overall facade of the ZEPBC test model is shown in Figure 2.

Instruments and Transducers

There were a total of 75 sensors installed on the ZEPBC model structure, which included 40 accelerometers on the ground, 3rd, 9th, 14th, 17th, and 18th floors, respectively; 25 displacement transducers on the ground, 3rd, 9th, 14th, 17th and 18th floors, respectively; and 10 strain gauges on the surface of a few structural members such as the lower shear walls and connecting trusses.

Earthquake Selection and Test Program

According to the Chinese code (CMC, 2001), buildings in a seismic region must sustain earthquakes of minor, moderate and major 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. That is to say, when a building is designed to be subjected to a minor (frequent) earthquake with an intensity of less than the design intensity, the building will not be damaged, or will be only slightly damaged and will continue to be serviceable without repair. When it is subjected to an earthquake equal to the design intensity (moderate earthquake), it may be damaged but will still be serviceable after ordinary repair or without repair. Finally, when it is subjected to a major (rare) earthquake with intensity higher than the design intensity, it will neither collapse nor suffer damage that would endanger human lives. Zhoushan city 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. The peak acceleration times and the acceleration scaling factor (here S_a=2.5) were used to obtain the target input peak value in the tests.

According to the soil condition and design intersity of Zhoushan, the following 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) Pasadena record from the California Kern County earthquake of July 21, 1952; and (iii) Shanghai artificial accelerogram, which is specified 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 test was carried out in four stages. The first three stages represented minor, moderate and major levels of intensity 7, respectively. The last one represented a major earthquake of intensity 8, which was applied for further investigation of the ZEPBC structure subjected to extremely strong earthquakes. In the two-direction excitations in the test, the peak acceleration ratio of the principle direction to the other direction is designated to be 1 to 0.85, as specified in Chinese design code.

EXPERIMENTAL OBSERVATION OF ZEPBC MODEL STRUCTURE

For minor earthquakes of intensity 7, no visible damage was observed. After the white noise 2 was used to scan the model, 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 in the RC connecting beam ends of the #1 Tower at story 5, while the #2 Tower remained uncracked. Steel members at the connecting corridor worked well. The results of the white noise showed the stiffness of the structure had noticeably decreased.

For major earthquakes of intensity 7, existing cracks were extended. In the #1 Tower, cracks appeared at the RC coupling beam ends from story 4 to story 6, as shown in Figure 3. No damages were observed in the #2 Tower and at the connecting truss.

For a major earthquake of intensity 8, existing cracks were remarkably extended. In the #1 Tower, more cracks spread at the coupling beam ends. New cracks were also found on the shear walls of both #1 and #2 Towers. Most members of the connecting truss buckled (see Figure 4 and 5).

The following conclusions are drawn from the test observations:
1. The #2 Tower, which has no large openings in the plan, remained undamaged until it was subjected to a major earthquake of intensity 8, while the #1 Tower cracked at the moderate earthquake stage.
2. The connecting truss and the rigid joints between the truss and towers worked well to keep two towers deform together under three earthquake levels of intensity 7, however, steel truss members buckled under a major earthquake of intensity 8.

Fig. 3. Cracks of the connecting beam at 5th floor

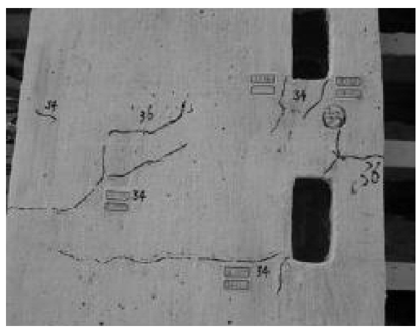

Fig. 4. Cracks of the shear walls

Fig. 5. Bulking of the truss member

EXPERIMENTAL RESULTS OF ZEPBC STRUCTURE

Experimental Dynamic Characteristics

Frequencies of the model at different phases were measured by inputting a white noise signal before further seismic input simulations. Model frequencies can be extrapolated from the test results to the periods of the prototype structure by similitude relationships, i.e., Equation (4). The variations of frequencies and stiffness at the end of every earthquake level are listed in Table 2.

$$f^p = f^m / S_f \tag{4}$$

where f_p and f_m are the frequencies of the prototype structure and the model structure, respectively. S_f is the scaling factor of the frequency.

Table 2. Frequencies under different stages

Dynamic property		Mode 1	Mode 2	Mode 3
Initial	Frequency (Hz)	0.496	0.496	0.623
Minor level	Frequency (Hz)	0.496	0.447	0.602
	Variation of frequency (%)	0	-10	-3
	Variation of stiffness (%)	0	-19	-7
Moderate level	Frequency (Hz)	0.447	0.447	0.595
	Variation of frequency (%)	-10	-10	-4
	Variation of stiffness (%)	-19	-19	-9
Major level	Frequency (Hz)	0.347	0.397	0.523
	Variation of frequency (%)	-30	-20	-16
	Variation of stiffness (%)	-51	-36	-30
Major level (intensity 8)	Frequency (Hz)	0.248	0.298	0.481
	Variation of frequency (%)	-50	-40	-23
	Variation of stiffness (%)	-75	-64	-40
Vibration modes	Vibration modes	Translation in *Y*	Translation in *X*	Torsion

In Table 2, the first three vibration modes represent translation in Y, translation in X, and torsion, respectively. In the Chinese code (CMC, 2002), the period ratio between the first torsional mode and the first translational modes is required to be less than 0.85 to prevent excessive structural torsion. In the structure, these ratios were calculated as

$$T_3/T_1 = f_1/f_3 = 0.496/0.623 = 0.80 \tag{5}$$

where T_1 and T_3; and f_1 and f_3 denote the first and third periods and the corresponding frequencies, respectively. Note that the period ratios of the structure meet the requirements of the code and the overall torsion of the multi-tower connected ZEPBC is not obvious.

Table 2 also shows that all three frequencies decreased as the earthquake input level increased. In the elastic range, the frequency of the structure, f, is calculated by the well known Equation (6), where K and m denote the stiffness and the mass of the structure, respectively.

$$f \propto \sqrt{K/m} \tag{6}$$

During the shake table tests, the responses of the model gradually become nonlinear once damage begins. However, it is still assumed that the relationship between $\sqrt{\overline{K}}$ and f is valid in a modal sense, where $\overline{K}$ is the equivalent stiffness of the model structure. Accordingly, after the minor earthquake level, the frequency decrease in X direction is 10% and the decrease of the corresponding $\overline{K}$ is 19%. At the moderate earthquake level, the decrease of frequencies in both X and Y directions was up to 10%, indicating that cracking of the model developed from inside to outside and the global structure entered the elastoplastic state. Under the major earthquake level, the frequency in both directions decreased more rapidly. The stiffness in direction Y decreased by 51%, which showed that serious cracking of the model developed but no collapse occurred.

Experimental Displacement

Envelops of the peak floor displacements of two towers are plotted in Figure 6. Note that from the minor level to the major earthquake level, the deformation curve at the top of the building gradually bends toward the axis. That is to say, the existence of the steel truss at the top prevents the two towers from excessive deformation under strong earthquakes. One should also note that, in direction *X*, the displacement of #2 Tower is larger under minor level and the two towers gradually deform together under moderate and major levels. However, this is not the case in the other direction. In direction *Y*, the initial stiffness of the shear walls keep two towers work together under minor earthquakes. While their displacement differences become manifest with the cracking of shear walls when suffering strong earthquakes. Thus, the horizontal wall elements of #1 Tower in direction *Y* should be strengthened to keep two towers work together to prevent possible structural torsion.

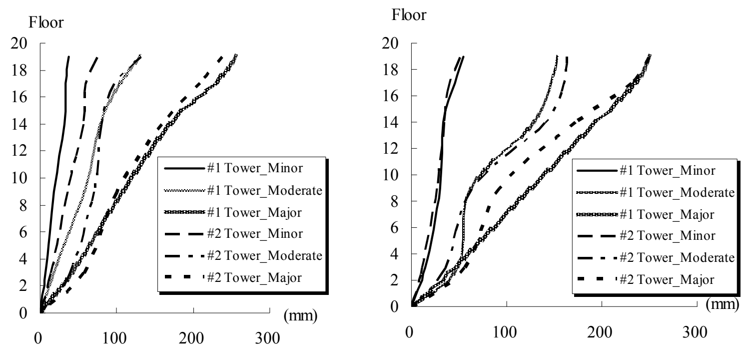

Fig. 6. Envelops of the peak floor displacements of two towers: (a) Direction X; (b) Direction Y

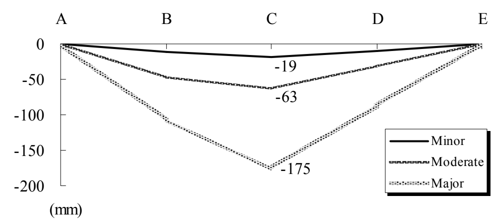

Fig. 7. Envelops of the vertical displacement of the steel truss

Figure 7 shows envelops of the vertical displacement of the steel truss under different earthquake levels. It can be seen that the multiples of the deflection at the mid-span increase faster than those of the peak ground acceleration (PGA). Say PGA increases 6 times from 0.035g to 0.22g, then the deformation at point C becomes 175mm (1/331 of the 58m truss span), which is over 9 times to 19mm (the value under minor earthquake). Accordingly, the stiffness reduction due to the existence of the round opening is obvious especially under the major earthquake level.

ANALYTICAL RESULTS OF ZEPBC STRUCTURE

Analytical Model

To gain a better understanding of the dynamic behavior of the building, 3-dimensional finite element analysis software (ANSYS) was used to analyze the ZEPBC structure. 3-dimensional beam elements were selected for the beams and columns, and shell elements were used for the shear walls and floor slabs. Totally, the model has 12945 nodes, 16196 beam elements, and 6172 shell elements. The longitudinal direction is defined as axis *X* and the lateral direction as axis *Y*.

Analytical Dynamic Characteristics

The first three frequencies are 0.49Hz, 0.53Hz, and 0.56Hz, respectively and the corresponding modes are translation in Y, translation in X, and torsion, as shown in Figure 8. It is shown that the frequency difference between the dynamic test and the numerical analysis is within 10%. The experimental modal shapes agree well with the analytical results.

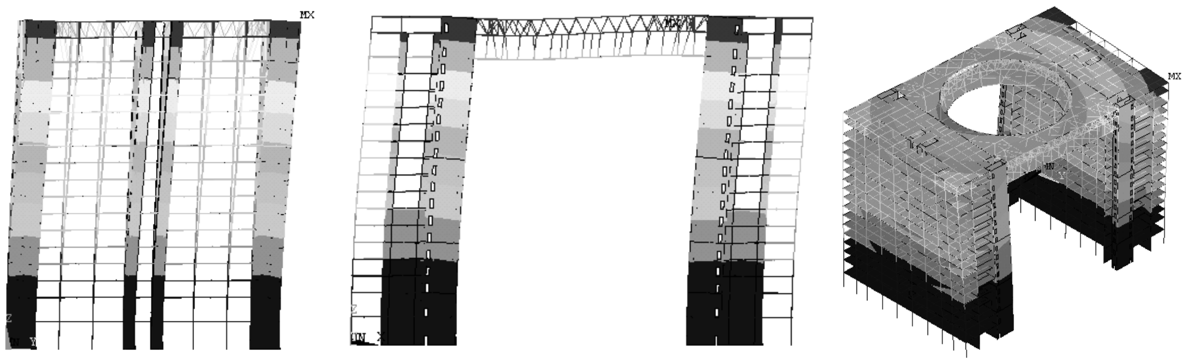

Fig. 8. First three vibration modes: (a) first vibration mode (translation in Y); (b) second vibration mode (translation in X); (c) third vibration mode (torsion)

Time History Analysis

The prototype structure was also analyzed using the Shanghai accelerogram discussed above. The ground motion input was one-dimensional and peak acceleration was set to be 0.035 g corresponding to minor earthquake. In the analysis, the slab was assumed to be elastic and the damping ratio to be 0.05. Figure 9 shows inter-story drift at four typical nodes of each story. It can be found that the maximum inter-story drifts are 1/971 (1.03‰) in direction X and 1/957 (1.04‰) in direction *Y*, both of which are smaller than the elastic inter-story drift limitation of 1/800 (CMC, 2002) for hybrid systems.

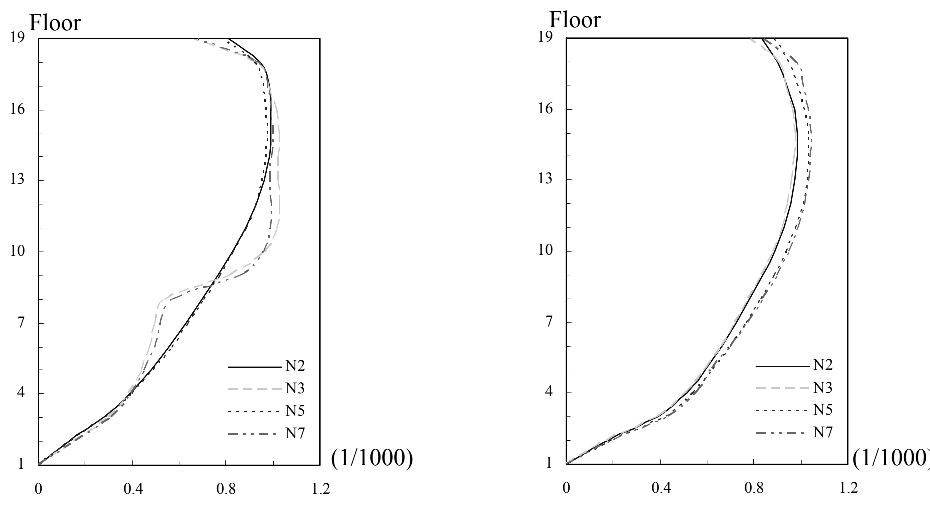

Fig. 9. Analytical inter-story drift of ZEPBC structure: (a) Direction X; (b) Direction Y

CONCLUSIONS

The Zhoushan Eastern Port Business Center (ZEPBC) is a tall hybrid building with two towers connected by a corridor at their tops. A round floor opening is introduced in the corridor architectural design to symbolize the "round-sky-square-earth" concept of Chinese tradition, which results in the stiffness reduction in the structural design. According to Chinese codes, ZEPBC structure is extremely irregular in both plan and elevation. Suggested by the review panel, shake table model testing was carried out at the State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China. A series of earthquakes simulating minor, moderate and major intensity levels were used to investigate the seismic performance of the irregular structure. The extrapolated responses of the prototype structure and the analytical responses of the numerical simulation were compared in the paper. The following conclusions can be drawn.

1. The ZEPBC irregular structure would not be damaged by a minor earthquake. It would have some visible structural cracking under a moderate earthquake, and would be damaged under a major earthquake, but would not suffer a catastrophic collapse.
2. The overall torsion of the multi-tower connected building is not remarkable. When the structure is subjected to minor earthquakes, the maximum inter-story drifts in the directions X and Y are smaller than the allowable value of 1/800 according to the Chinese code.
3. The connecting truss and the rigid joints between the truss and towers worked well to keep two towers deform together under three earthquake levels, however, the stiffness reduction due to the existence of the round opening is obvious especially under the major earthquake level. Thus, the strength and the stiffness of the long-span truss should be improved due to the potentially large vertical acceleration under strong earthquakes.

The suggestions in this paper have been accepted by the design institute and the ZEPBC building is under construction.

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