Shaking Table Model Test of a Super High-Rise Building with CFT frame and Core Wall

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SUMMARY:
In order to study the seismic performances of structures which employ the composite system consisting of a concrete filled steel tube (CFT) frame and a steel plate reinforced concrete core wall, a 1/30-scaled model was made and shaking table tests under a series of one or two-dimensional base excitations with gradually increasing magnitudes was conducted. The model simulated a 264 m high building. This paper presents the process of model construction and testing. Through the observation of seismic performance of the model under frequent, basic, rare earthquake of 8 degree and rare earthquake of 9 degree, the natural frequencies, seismic responses and the failure patterns of the model was studied. Combined with the simulation results by the software PERFORM-3D, the conclusions are drawn that the design of the structural system is able to ensure the life safety even when subjected to strong earthquake with peak ground acceleration up to 0.40g.

Keywords: shaking table test; seismic performance; CFT frame; steel plate reinforced concrete shear wall

1. INTRODUCTION

Recent years, a great number of new buildings have taken on novel faces to make the city diverse and beautiful, which renders the shapes of those buildings increasingly unique and complicated, and bring new challenges to structural engineers. In order to completely understand the overall structural behaviours under moderate and strong earthquakes, shaking table model testing is always carried out as a common approach to acquiring knowledge about new structural systems. The failure pattern and dynamic response of the structure can be studied according to the test results.

Beijing Fortune Plaza Office Building II is a 265m high 62-storey super high-rise building which will be built in Beijing, China. The building employs three parallel structural systems, the concrete filled steel tube perimeter frame, the composite core wall, and the outrigger trusses to resist vertical and lateral loads. When completed, the building will become the tallest building in Beijing employs such complex type of structural system.

According to the Chinese code Technical Specification for Concrete Structures of Tall Building (TSCSTB, JGJ 3-2002), the structural height of the prototype building is beyond the limitation of 150m for a composite frame-reinforced concrete core wall building. The aspect ratio (width/height) of 6.41 exceeds the limitation of 6.0 for the buildings located at seismic zone of intensity 8. In order to capture the seismic performances of this type of complex structural system, a 1/30 scaled model was made and shaking table tests were conducted in the Shaking Table Testing Division of the State Key Laboratory of Disaster Reduction in Civil Engineering (SKLDRCE), Tongji University, Shanghai, China. By analyzing the dynamic property, acceleration and displacement responses of the model structure, the failure mode and the dynamic responses of this type of complex structure were investigated.

2. DESCRIPTION OF THE STRUCTURE

The plan of the building is about 64.0 m×41.5m. Main characteristics of this building are: (1) The composite steel plate shear wall locates at the lower levels from story 1 to story 19; (2) Two strengthened stories in the structure are spaced throughout the height of the building; (3) Thirty-two concrete filled steel tube columns are regular positioned to form the perimeter frame.

3. MODEL DESIGN AND CONSTRUCTION

3.1. Shaking Table Facility

The 25-t triaxial shaking table of SKLDRCE was used for the experiment. The dimension of the table is 4m×4m and its working frequency ranges from 0.1 Hz to 50 Hz. 96 channels are available for data acquisition.

3.2. Material of the Model

Fine aggregate concrete and fine iron wire were used to simulate the concrete and the rebar of the prototype structure, respectively. The shaped steels of the prototype were simulated by red copper plates to meet the similitude requirement.

3.3. Similitude Relationship

In order to make sure that the model behaves in a similar manner to prototype, the model design should conform to the dynamic similitude theory. The dynamic similitude equilibrium is given in Eqn. 3.1, where S_l = scaling factor of dimension, S_E = scaling factor of elastic modulus, S_a = scaling factor of acceleration and S_ρ = scaling factor of material density. When three of the four factors in the equation are decided, other scaling factors can be derived according to the similitude theory.

$$\frac{S_{\mathrm{E}}}{S_\rho \cdot S_{\mathrm{a}} \cdot S_{\mathrm{l}}} = 1 \tag{3.1}$$

Based on the capacity and the size of the shaking table, the scaling factor of dimension S_l was chosen as 1/30. Therefore the model was built with a total height of 9.093m including the 0.3m high base. The overall scaling factor of elastic modulus S_E was determined to be 0.34 according to the material test results, and the acceleration scaling factor was set to be 3.0 after several times of adjustment. The finial scaling factors are listed in Table 3.1.

Table 3.1. Similitude Relationships

Variable	Length	Elastic modulus	Stress	Strain	Density	Force	Frequency	Acceleration
Expression	S_l	S_E	S_σ	S_σ/S_E	S_ρ	S_F	S_f	S_a
Scaling factor	1/30	0.34	0.22	0.66	2.24	2.49E-04	11.66	3.00

3.4. Member Design and Construction

The model is designed by scaling down the geometric and material properties from prototype structure. For RC members, the design is based on the principle of bending capacity equivalent of normal sections and shearing capacity equivalent of diagonal sections. For the shaped steel in 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 to some members on the basis of bending and shearing capacity equivalent principles. Less importance members, such as perimeter beams, secondary beams as well as smaller holes in the floors were also omitted.

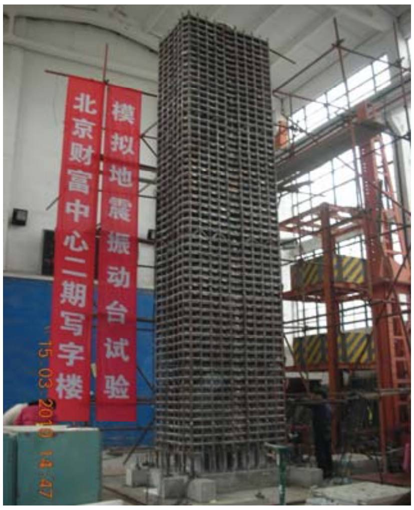

Figure 3.1. Overview of model and experimental set-up

Model construction of each story was repeated using following steps: (1) assemble and weld copper members; (2) carve foam plastic as the internal form and located them at the cast site; (3) fix the wood forms outside; (4) place the fine iron wire; and (5) cast the fine aggregate concrete. When finished, additional mass blocks were evenly distributed on the model to ensure the similitude of vertical load. The total weight of the model was 23.747 tonnes, which contains the base and the additional mass.

An overview of the model after installation on the shaking table facility and the experimental set-up are shown in Figure 3.1.

4. TEST PROGRAM

4.1. Instruments and Transducers

According to the structural characteristics of the building, 39 accelerometers, 12 displacement sensors and 17 strain gauges were installed on the key stories in two orthogonal directions along the height of the model including the roof, the strengthened stories, the setback stories, and the base, that makes 68 in all.

4.2. Ground Motion Input

The construction site belongs to Type Ⅱ which is defined by the Chinese code. With the spectral density properties of site taken into consideration, the design company suggested three one-dimensional seismic ground motions, two of which are natural earthquake records, and one is artificial ground motion. Additionally, two two-dimensional waves: the El Centro earthquake record from Imperial Valley California of May 18 1940, and the Taft earthquake record from Kern County California of 21 July 1952 were also selected as the input shaking table waves.

4.3. Test Program

As specified in Code for Seismic Design of Building (GB 50011-2001), 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 being exceeded in 50 years, respectively. Roughly speaking, that is: (1) buildings will not be damaged or only slightly damaged with continued service without repair when subjected to frequently occurring earthquakes of intensity lower than design one; (2) buildings may be damaged, but still be serviceable after ordinary repair or without any repair when subjected to earthquakes with design intensity; and (3) buildings will neither collapse nor suffer damage that would endanger human lives when subjected to rarely occurring earthquakes with intensities higher than design one. Beijing belongs to the seismic zone of intensity 8. Thus, earthquakes of minor, moderate and major levels with seismic intensity 8 are specified with peak ground acceleration of 0·07g, 0.20g and 0.40g, respectively.

In summary, the test program consists of four phases, that is, tests for frequently occurring (Frequent 8), basic (Basic 8), rarely occurring earthquakes (Rare 8) of intensity 8 and rarely occurring earthquakes of intensity 9 (Rare 9). The Rare 9 phase was conducted for further investigation of the dynamic responses of the targeted structure under quite strong earthquakes.

The acceleration amplitudes of the tests were adjusted to 0.21g, 0.60g, 1.20g and 1.86g corresponding to the four test stages, and ratio of acceleration amplitude in the first main direction to that in the second direction was 1:0.850. After each phase, a white noise test was conducted to investigate the change in natural periods of the model. The four phases contained 45 test cases in all.

5. TEST RESULTS

5.1. Cracking and Failure Pattern

Each state of damage inflicted by the strong motion excitations was followed by an inspection and careful documentation of the eventual cracks.

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 *Y* direction reduced slightly. That is to say, fine cracks had already developed inside. After the third phase, several cracks were observed in the coupling beam of the shear wall, local buckling was observed in some certain steel beams. After the forth phase, existing cracks further propagated, steel beams supporting the floor slabs and the perimeter steel beams in different floors buckled in varying degrees. Figure 5.1 shows the typical damage of the model structure.

Figure 5.1. Failure pattern of the model structure

5.2. Dynamic Responses

By analyzing the response time history and the transfer function, the natural frequency and the mode shape were derived. The first two modes were translations in *X* and *Y* directions with initial natural frequencies of 2.27 Hz and 2.84 Hz, respectively for intact model. The third mode is of torsion with an initial natural frequency of 4.54 Hz. the ratios of the first-order torsional period to the first two translation periods in two horizontal directions are 0.500 and 0.625 respectively, less than 0.900 which is defined by TSCSTB to prevent the excessive torsional effect in the whole structural vibration. With the forth phase completed, the basic frequency in *X* direction reduced to 1.66 Hz, which is 27% smaller than the initial one. For the direction *Y*, natural frequency decreased to 1.70 Hz.

The first two mode shapes in the two directions are shown in Figure 5.2. *X*-1 and *X*-2 are the first two mode shapes in *X* direction respectively; *Y*-1 and *Y*-2 are that in *Y* direction.

Figure 5.3 shows the distribution of maximum values of acceleration-amplifying coefficient *K* under the four earthquake levels. *K* represents the ratio of measured acceleration of different stories to the corresponding input acceleration. In both of the two directions, the whipping-lash effect develops sharply at the top stories. As a result of the stiffening action brought by the outrigger trusses, several turning points appear along the height of the building. The acceleration-amplifying coefficient decreases gradually as the intensity of table excitation increases, implying the progressive degradation of structural stiffness.

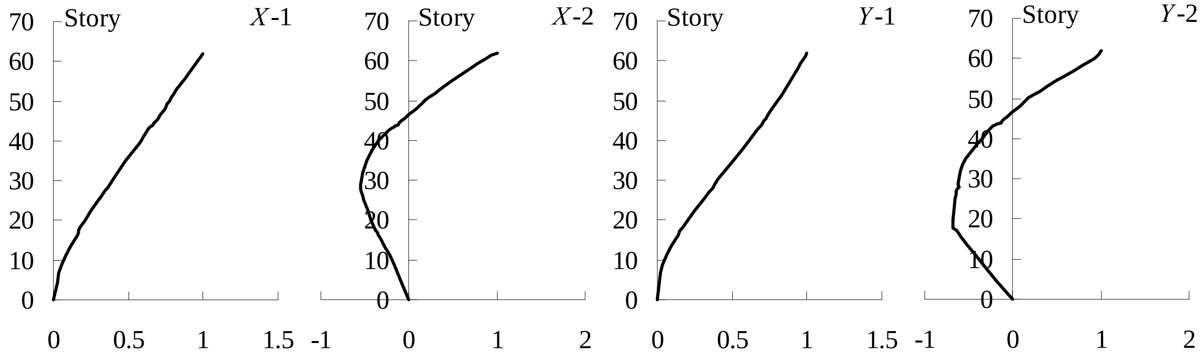

Figure 5.2. Mode shapes of two directions

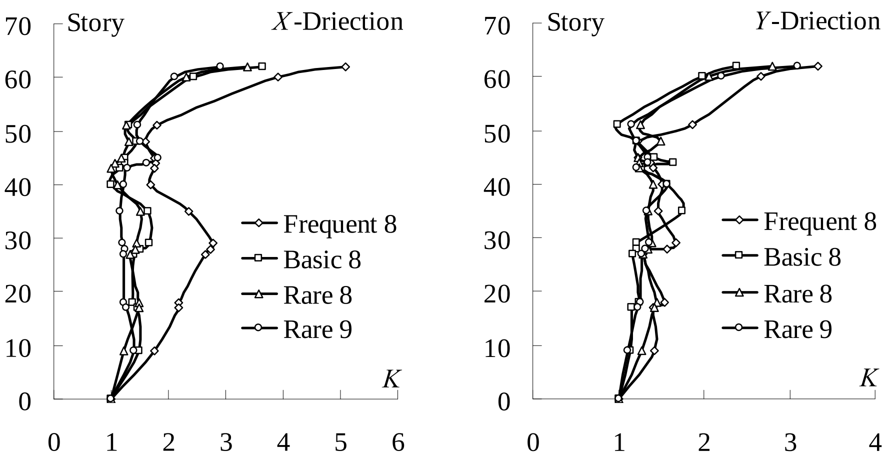

Figure 5.3. Distribution of maximum *K*

6. ANALYSIS MODEL IN PERFORM-3D

6.1. Material Model

Non-bulking bilinear steel model is used to model the reinforcement and steel in the analysis model. Mander (Bai et al., 2002) and Han concrete models are used to describe working condition of concrete confined by stirrup and steel tube respectively. The models are transferred in the standard force–deformation relationship (Computer and Structures Inc., 2006) which can be used in PERFORM-3D.

Parameters of energy degradation for Mander model are taken as 1, 0.9, 0.7, 0.4 and 0.3 at the Y, U, L, R and X points respectively, while for Han model are 1, 0.7, 0.55, 0.45 and 0.35 . Parameters of reinforcement and steel in all strength regions are taken as 1.0.

6.2. Beam-Column Element Model

Plastic hinge model is adopted in beam element. The plastic deformation assumes concentrated only at the element ends. Besides, a shear hinge is added to consider nonlinear shear deformation and shear failure induced by large shear forces acting on the coupling beam component. Fiber model is adopted in column element which using the fiber section properties for bending about both axes, and account for P-M-M interaction. Inelastic fiber cross section and shear material are used to define axial-bending and shear properties for shear wall compound component. Out-of-plane bending is assumed to be elastic.

General Wall element is used in the coupling beams in the bottom, strengthened and adjacent stories, while others adopt beam element. All the beams including the perimeter and interior girders consider the inelastic properties. Shear materials of shear wall in story 1 to story 19, strengthened and adjacent stories are inelastic. Elastic shear materials are used in other shear walls.

Table 6.1 shows the first six natural frequencies of the prototype structure which are derived from the test and PERFORM-3D. In the table, T_T and T_P are the results derived from the shaking table test and PERFORM-3D model respectively. The test results approach the analytic results.

Inter-story drift ratio is the relative horizontal displacement of two adjacent floors divided by the story height, and the maximum value is limited by Chinese code according to different earthquake levels. The Maximum inter-story drift ratios of *X* and *Y* direction under different ground motions are listed in Table 6.2 and Table 6.3 respectively.

Table 6.1. Initial Natural Periods And Modes Of Prototype Structure

Mode	1	2	3	4	5	6
T_T/s	5.128	4.098	2.571	1.712	1.323	1.208
T_P/s	5.319	4.355	3.264	1.431	1.386	1.062
T_T/T_P	0.964	0.941	0.788	1.196	0.955	1.137
Mode shape	Translation in *X*	Translation in *Y*	Torsion	Translation in *Y*	Translation in *X*	Torsion

Table 6.2. Maximum Inter-Story Drift Ratio Of *X* Direction

Ground Motion	Test			PERFORM-3D		
	Frequent 8	Basic 8	Rare 8	Frequent 8	Basic 8	Rare 8
El Centro	1/926	1/310	1/212	1/665	1/241	1/131
User 1	1/1279	1/541	1/125	1/867	1/315	1/178
User 2	1/842	1/426	1/124	1/741	1/274	1/144
User 3	1/665	—	1/125	1/795	1/290	1/144
Average	1/878	1/404	1/139	1/760	1/277	1/148

Table 6.3. Maximum Inter-Story Drift Ratio Of *Y* Direction

Ground Motion	Test			PERFORM-3D		
	Frequent 8	Basic 8	Rare 8	Frequent 8	Basic 8	Rare 8
El Centro	1/1336	1/789	1/213	1/885	1/319	1/189
User 1	1/2155	1/697	1/209	1/1273	1/449	1/224
User 2	1/1961	1/467	1/187	1/790	1/329	1/144
User 3	1/1835	1/587	1/191	1/1019	1/389	1/197
Average	1/1764	1/611	1/199	1/961	1/365	1/184

7. CONCLUSIONS

The super high-rise building consisting of the CFT frame and composite core wall can exhibit good capacity in resisting earthquakes. Even when subjected to extremely strong earthquake, no severe structural damage occurred in this structural system.

1. The first two vibration modes of the model are of translation in direction *X* and *Y*, respectively. The period of the first torsion mode is less than 0.9 times that of the first two translational modes, which indicate the influence of torsion is not remarkable in this building.

2. As a result of significant stiffening action brought by the outrigger trusses in direction *X*, the stiffness decrease of this direction was not distinct. The outrigger trusses were not buckled during the teats.

3. Whipping-lash effect develops sharply on top stories of the structure due to the sudden change in lateral stiffness. Appropriate improvement should be made to the top stories to avoid severe damages under extremely strong earthquakes.

4. After the fourth phase test finished, all the concrete filled steel tube columns remained in the elastic state. The design of the columns is able to ensure the life safety even when subjecting extremely strong earthquake.

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