Title: **Shaking Table Model Test of a HWS Tall Building**

Authors:
Xilin Lu, Professor, Tongji University
Jianbao Li, Lecturer, Tongji University
Wensheng Lu, Associate Professor, Tongji University
Bin Zhao, Associate Professor, Tongji University

Subjects:
Building Case Study
Seismic
Structural Engineering

Keywords:
Seismic
Structure

Publication Date: 2004

Original Publication: CTBUH 2004 Seoul Conference

Shaking Table Model Test of a HWS Tall Building

Xilin Lu [1], Jianbao Li [2], Wensheng Lu [3], Bin Zhao [3]

[1] Professor, State Key Laboratory for Disaster Reduction in Civil Engineering
Tongji University, Shanghai 200092, China
[2]Lecturer, State Key Laboratory for Disaster Reduction in Civil Engineering Tongji University
[3]Associate Professor, State Key Laboratory for Disaster Reduction in Civil Engineering Tongji University

Abstract

A model of HWS tall building, undergone several different simulated earthquake excitations, is studied in this paper. The responses of acceleration and deformation of the model are measured and investigated. Its dynamic behavior, cracking pattern and failure mechanism are discussed as well. And at the end of this paper, some suggestions for the design of the structure are put forward.

Keywords: hybrid wall system; building model, shaking table test, seismic behavior

1. Introduction

The Hybrid Wall System (HWS) building is composed of center core RC walls and exterior steel frame or SRC frame. For its advantages of light weight, small section, rapid construction and cost savings, it is desirable and widely used. However, common knowledge about its seismic behavior is not achieved yet. Thus, it is very necessary to completely understand its overall structural behavior under moderate and strong earthquakes, when designing such buildings in high seismic region. In this regard, a shaking table model test of a of HWS building is carried out in this paper, which attempts to study its seismic responses, failure mechanism and accumulates experimental evidences for design improvement.

2. Description of the structure

The target building is one of the LG Beijing twin Tower, which is a commercial square located at Changan Avenue, Chaoyang District, Beijing, China (as shown in Fig.1), and composed of two HWS towers and a steel frame podium separated by settlement joints. Each tower has an approximately elliptical standard plan with the dimension of 44.8m along the long axis and 43.7m the other (Fig.2). With 31 stories above the ground, the tower has a total structural height of 149.479m and a typical story height of 3.96m.

The primary lateral load resisting elements for the Towers consist of the steel reinforced concrete core wall, the steel beams and the steel RC columns. Simple connections are employed for beam-wall joints and moment connections for beam-column joints. The floor of the tower is steel-RC composite floor.

Fig. 1. LG Beijing Twin Tower

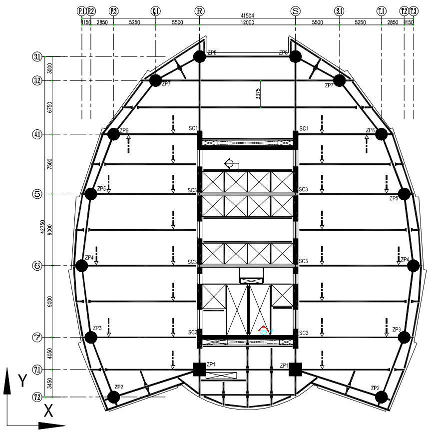

Fig. 2. Standard Floor Plan of the Tower

Contact Author: Xilin Lu, Disaster Reduction in Civil Engineering Tongji University, Shanghai 200092, China
Tel: +86+021+65983430, Fax: +86+021+65982668
e-mail: lxlst@mail.tongji.edu.cn

3. Model experiment

3.1. Model similitude and materials

The test model is designed by scaling down the geometric and material properties from prototype structure according to dynamic similitude theory. The similitude relationships of the test are listed in Table.1. When constructing model, micro-concrete, fine wires, and red copper were chosen to simulate concrete, reinforcing bars and steel respectively.

Table 1. Similitude Relationships

Physical	Physical	Equation	Scaling	Note
Dimension	Length	S_l	1/20	Controlling Parameter of Dimension
Material	Strain	S_σ / S_E	1.00	Controlling Parameter of Material
	Young's Modulus	$S_E = S_\sigma$	0.30	
	Stress	$S_\sigma = S_E$	0.30	
	Density	$S_\rho = S_\sigma / S_a$	6.00	
Load	Force	$S_\sigma \cdot S_l^2$	7.50E-04	
Dynamic Behavior	Frequency	$S_l^{-0.5}.Sa^{0.5}$	7.75	Controlling Parameter of Testing
	Acceleration	S_a	3.00	

The accomplished model structure is about 7.025m high and 20.86t weigh. It is located at a rigid RC base with height of 0.3m and weight of 4.6t. As shown in Fig.3.

Fig.3. Elevation of the Model

3.2. Description of the Shaking table

Shaking table test was carried out using MTS shaking table facility at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, and Shanghai, China. The table has a dimension of 4m by 4m with a maximum payload of 25,000kg and can input three-dimensional and six degree-of-freedom motions. The maximum acceleration, with a 15,000kg payload, for the two horizontal directions is 1.2g and 0.8g while 0.7g for the vertical, respectively. Its frequency range is from 0.1Hz to 50Hz and there are 96 channels available for data acquisition during testing [2].

4. Test program

There are 38 accelerometers, 6 LVDTS and 18 electric resistance strain gages used in this test program. Among all these 38 accelerometers, four were set in both X and Y directions at 5, 11, 23 , and 30 floor, two at base, 1, 3, 11, 16, 17, 20, 29 and roof floor respectively. Six LVDTS were arranged evenly to 10, 20 and roof floor in direction X and Y. Electric resistance strain gages were mainly distributed on some key steel beams.

Table. 2 Test Program

Series	Signal	Peak Acceleration (g)			
		Direction X		Direction Y	
		Prog	Ach	Prog	Ach
White Noise		0.07	-	0.07	-
Freq 8	El-Centro	0.21	0.205	0.179	0.148
	El-Centro	0.179	0.172	0.21	0.162
	Taft	0.21	0.195	0.179	0.157
	Taft	0.179	0.143	0.21	0.185
	GB11	0.21	0.18		
	GB11			0.21	0.156
White Noise		0.07	-	0.07	-
Basic8	El-Centro	0.588	0.544	0.50	0.398
	El-Centro	0.50	0.512	0.588	0.520
	Taft	0.588	0.735	0.50	0.610
	Taft	0.50	0.553	0.588	0.685
	GB11	0.588	0.655		
	GB11			0.588	0.533
White Noise		0.07	-	0.07	-
Rare 8	El-Centro	1.20	1.447	1.02	0.859
	El-Centro	1.02	1.404	1.20	0.821
	Taft	1.20	1.292	1.02	0.762
	Taft	1.02	1.222	1.20	0.757
	GB11	1.20	1.244		
	GB11			1.20	0.711
White noise		0.07	-	0.07	-

Notes: **Prog** means Programmed and **Ach** means Achieved

The following three seismic ground motion records were used as the testing input acceleration to the shaking table: (1) El-Centro record from the California Imperial Valley earthquake of May 18, 1940; (2)Taft record from Kern County earthquake of

July 21, 1952; (3) Beijing artificial accelerogram (GB11,ξ =0.04, α_{max}=70cm/s^2), which is specified for the particular soil condition of the construction site in Beijing. Before the inputs of every occurrence, a 2D white noise was firstly input to acquire the dynamic behaviors of the model. Then, simulations of El-Centro record, Taft record and GB11 were input to the model in turn. As listed in Table.2.

5. Test results

5.1. Overall behavior of the model

For earthquake simulations of intensity eight with a high rate of occurrence no visible cracks were observed from the outside of the model after all the cases were executed. The second white noise scanned the model to find that the frequency of the model in both directions X and Y were decreased slightly, which indicated that micro-cracks of the model structure had developed, but the building model still kept in elasticity at the frequent occurrence of the intensity eight.

Under earthquakes with basic intensity concrete cracking started to be visible and the natural frequencies clearly reduced. Small horizontal cracks were first observed to appear on columns in the 11th and 12th floor. The deformation of the model became obviously and its rigidity decreased greatly.

Under the simulation of seldom occurred earthquakes previously observed cracks kept developing and many new cracks appeared on other columns. An obvious feature of the cracks is that most of them distributed on exterior SRC columns at the beam top and bottom faces horizontally, seeing in Fig.4. After the test, there is no failure of the structural component occurred despite of much damage.

5.2. Variations of model dynamics properties

The variations of frequencies at the end of every occurrence phase can be seen in Fig.5 and their values are listed in Table.3.

From Table.3, the model's initial frequency of direction X lightly differs from that of direction Y, which indicates that the equivalent rigidities in the two directions are somewhat different. The first mode of vibration is translation in direction X and the second in direction Y. The third is overall torsion. Thus the ratios of the first two translation modes to the first torsion mode are 0.65 and 0.73 respectively, which both meet the requirement of Chinese Technical Specification for Concrete Structure of Tall Building (JGJ3-2002) that the ratios should be within 0.85 in order to avoid excessive torsion portion of the whole structure vibration.

Table 3. Natural Frequency, Damping Ratio and Vibration Models

Dynamic property		No.1	No.2	No.3	No.4
Initial	Frequency (Hz) $_M$	4.319	4.883	6.761	16.714
	Damping ratio	0.043	0.046	0.026	0.042
	Frequency (Hz) $_P$	0.557	0.630	0.872	2.157
	Vibration Modes	Translation of X	Translation of Y	Overall torsion	Translation of X
After the Inputs of Frequent Event	Frequency(Hz) $_M$	4.132	4.695	6.197	15.587
	Damping ratio	0.065	0.065	0.039	0.031
	Frequency (Hz) $_P$	0.533	0.606	0.800	1.987
	Vibration Modes	Translation of X	Translation of Y	Overall torsion	Translation of X
After the Inputs of Basic Event	Frequency(Hz) $_M$	3.668	3.852	12.019	13.146
	Damping ratio	0.062	0.086	0.046	0.038
	Frequency (Hz) $_P$	0.473	0.497	1.551	1.696
	Vibration Modes	Translation of X	Translation of Y	Translation of Y	Overall torsion
After the Inputs of Rare Event	Frequency(Hz) $_M$	2.817	3.005	9.202	10.517
	Damping ratio	0.085	0.052	0.065	0.078
	Frequency (Hz) $_P$	0.363	0.388	1.187	1.357
	Vibration Modes	Translation of Y	Translation of X	Translation of Y	Overall torsion

Note: **Frequency** $_M$ and **Frequency** $_P$ refer to frequency of model structure and prototype structure, respectively

Fig. 4. the Typical Cracks on the SRC Columns

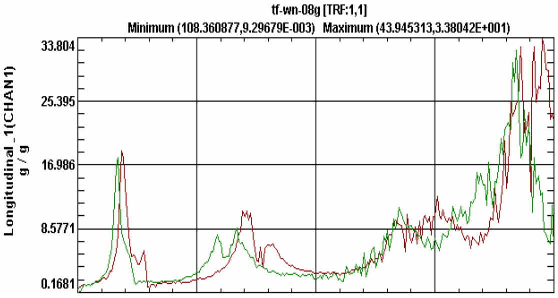

Fig. 5a. Variations of Frequencies after Frequent Occurrence Inputs in Direction X

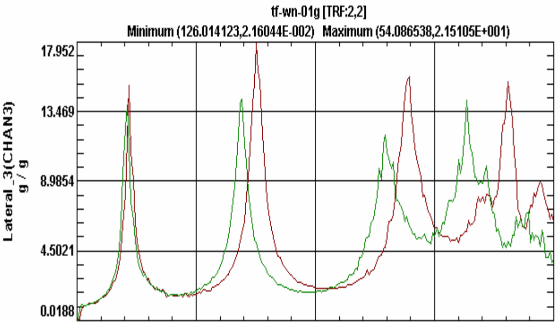

Fig. 5b. Variations of Frequencies after Frequent Occurrence Inputs in Direction Y

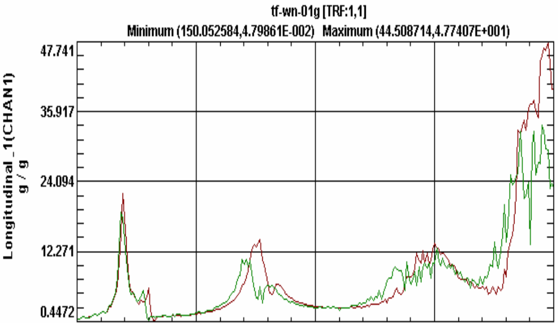

Fig. 5c. Variations of Frequencies after Basic Occurrence Inputs in Direction X

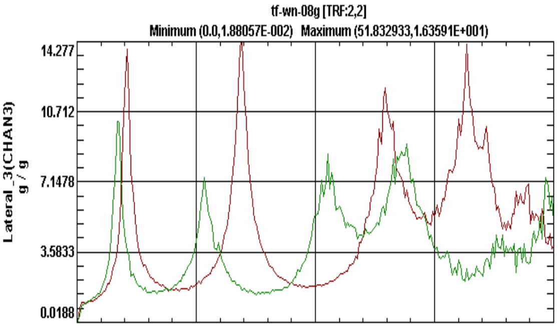

Fig. 5d. Variations of Frequencies after Basic Occurrence Inputs in Direction Y

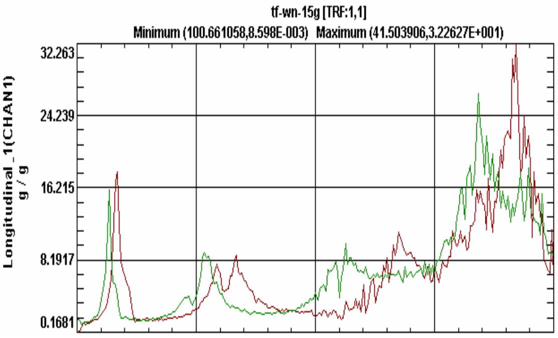

Fig. 5e. Variations of Frequencies after Rare Occurrence Inputs in Direction X

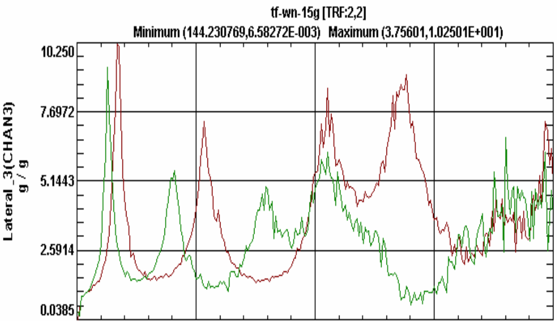

Fig. 5f. Variations of Frequencies after Rare Occurrence Inputs in Direction Y

6. Seismic behavior evaluation of the Prototype Structure

6.1. Natural frequencies

The first three natural frequencies of the prototype structure derived from the model test results are listed in Table.3.

6.2. Amplification coefficients of the acceleration (K)

The distributions of K along the structural height under different occurrences are shown in Fig.6. The curves in Fig.6 show that with the seismic intensity going up, the value of K of the same floor became smaller. This variation probably indicates that the structure damaged more seriously and became softer.

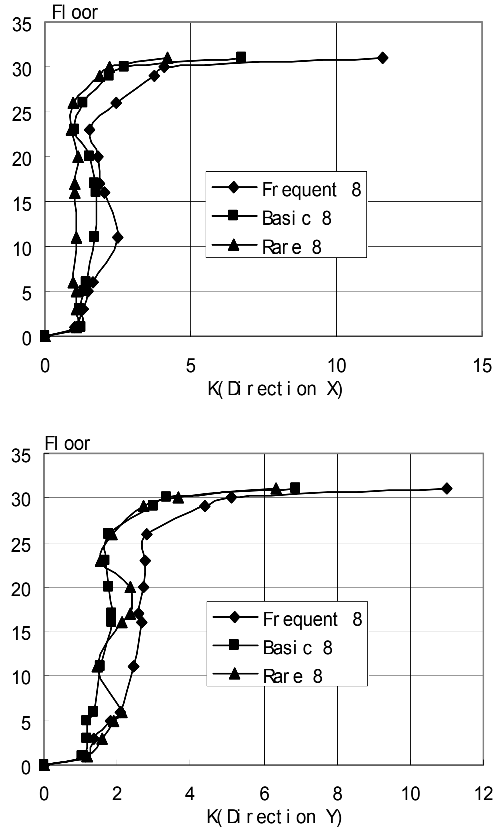

Fig. 6. the Distributions of K along the Structural Height

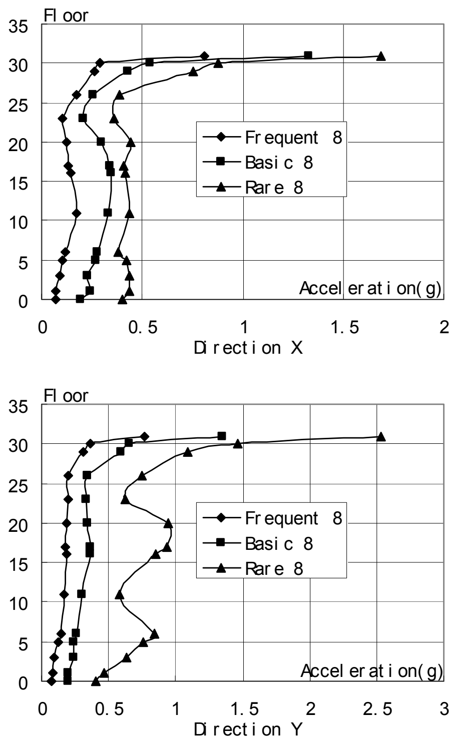

Fig. 7. the Distributions of the Maximum Acceleration

6.3. The response of the acceleration

The distributions of the maximum acceleration along the structural height are shown in Fig.7. Fig.7 illustrates that the accelerations under different occurrences changed evenly along the structural height in despite of the whiplash effect of the roof floor.

6.4. Displacement response of the prototype

Through integrating corresponding acceleration twice, we can get the structural displacement response of prototype. Table.4 lists the values of maximum displacement, total displacement/height and maximum inter-story drift.

From Table.4, the maximum inter-story drift under frequent occurrence is 1/1008 in direction X and 1/1005 in direction Y, both meet the code (JGJ3-2002) requirement of 1/800. Under rare occurrence, the maximum inter-story drift is 1/120 in direction X and 1/101 in direction Y, also meet the code (JGJ3-2002) requirement of 1/100.

Fig.8 shows the maximum story displacement and Fig.9 shows the distribution of the maximum inter-story drift of the prototype along the structural height.

Table 4. Maximum Displacement, Total Displacement/Height and Maximum Inter-story Drift

Occurrence Events	Frequent		Basic		Rare	
Direction	X	Y	X	Y	X	Y
Maximum Displacement (mm)	92.63	71.06	204.55	269.12	619.43	835.45
Total Displacement/Height	1/1488	1/1939	1/674	1/512	1/222	1/165
Maximum Inter-story Drift	1/1008	1/1005	1/188	1/262	1/120	1/101

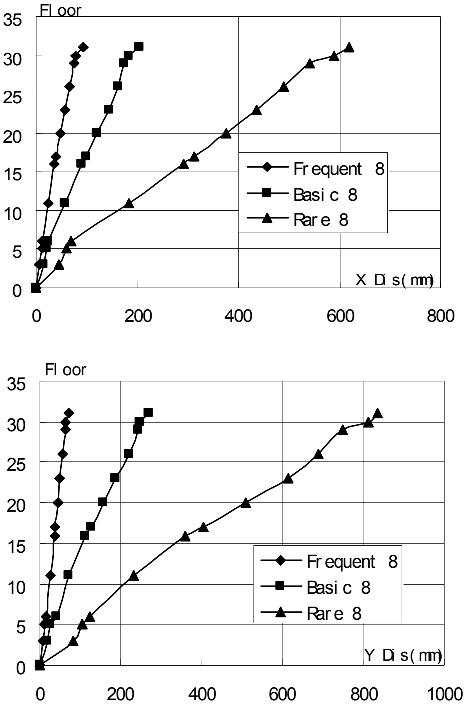

Fig. 8. Maximum Story Displacement

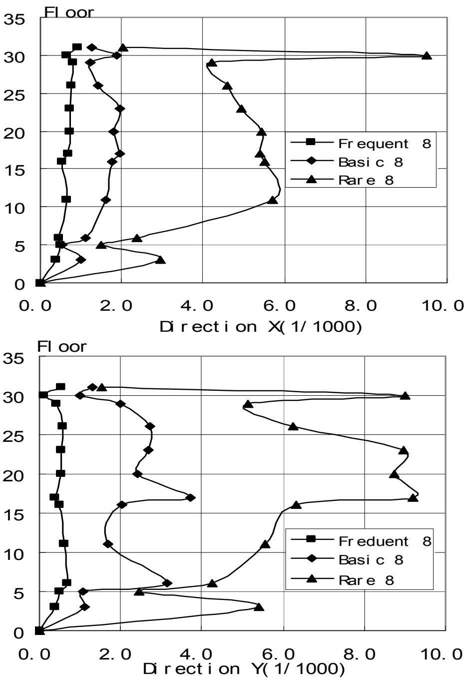

Fig. 9. Distribution of the Maximum Inter-story Drift along the Structural Height

7. Conclusions

From the shaking table model test, the following conclusions can be drawn.

1.The prototype structure, designed under earthquake of intensity eight, is able to resist frequent earthquakes without damage, resist basic earthquakes with some structural cracks and resist rare earthquakes without collapse, which indicates that the structure system employed in the design meets the three-stage requirements of the Chinese design code provisions.

2. The test results shows that the exterior SRC frame of the tower synergizes well with the RC core wall and the simple beam-wall joints can transfer shear and axis force efficiently.

3. Under frequent earthquakes the maximum elastic inter-story drifts of the prototype structure is 1/1008 in direction of X and 1/1005 in direction Y. The maximum inelastic inter-story drift is 1/120 in direction of X and 1/101 in direction Y under rare earthquakes. These parameters both meet the relative requirements of the Chinese design code provisions and show that the structure has enough lateral rigidity to resist seismic intensity designed.

4. The ratio of the first translation mode in the direction X to the first torsion mode is 0.65 and the ratio of the first translation mode in the direction Y to the first torsion mode is 0.73, which both meet the requirement of Chinese Technical Specification for Concrete Structure of Tall Building (JGJ3-2002) and indicate that the torsion portion of the whole structure vibration is controlled properly.

5. The crack patterns of the model test illustrate that the sections of SRC columns near by beam-column joints could be weak positions and should be strengthened.

6. Though there is no collapse happened in the model test, the curves in Fig.8 indicate that the maximum inter-story drifts of 17~23 and 30 floors approach the restriction of Chinese code (JGJ3-2002) very closely, some measures should be taken to strengthen the lateral rigidity between those floors properly.

Acknowledgement

The financial support of National Natural Science Foundation of China through Grant 50025821 and Grant 50321803 is gratefully acknowledged.

References

1) Tongji University. Report on shaking table testing of LG Beijing Tower model. (2002). Research Institute of Structural Engineering and Disaster Reduction, Shanghai, China.
2) Tongji University. Introduction of Shaking Table Testing Division. (2003). State Key Laboratory for Disaster Reduction in Civil Engineering, Shanghai, China.
3) China Ministry of Construction. Technical Specification for Concrete Structure of Tall Building (JGJ3-2002). China Architecture & Building Press, Beijing, China.
4) China Ministry of Construction. Code for seismic design of building (GB50011-2001). China Architecture & Building Press, Beijing, China.
5) Sabis G M, et al. Structural Modeling and Experimental Techniques [M]. Prentice-hall Inc., Englewood Cliffs, N. J., 1983.
6) Krawinkler, H. and Zhu, B.L.U.S./P.R.C Workhop on experimental methods in earthquake engineering. Report No. U.S./P.R.C, July 1993; The John A. Blume Earthquake Engineering Center, Departmengt of Civil Engineering, Stanford, California.