TEST DESIGN OF A SHAKING TABLE MODEL FOR A SUPER TALL-BUILDING WITH HIGN LEVEL TRANSFER STORY

Chen Yue [1] Lu Xilin [2] Lu Wensheng [3] Zhou Ying [4]

[1] *Doctoral student, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China and Lecturer, Zhejiang Wanli University, Ningbo, China*

[2、3] *Professor,* [4] *Lecturer, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China*

Email:chezailaile@163.com, lxlst@mail.tongji.edu.cn, wenshenglu@vip.163.com, yingzhou@mail.tongji.edu.cn

ABSTRACT :

A shaking table test was carried out for a 53-story super tall-building with high level transfer story in State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University. The height of the super tall-building is 250m above ground, and the central RC tube and peripheral SRC frame with two outrigger trusses are employed to resist vertical and lateral loads. According to the Technical Specifications for Concrete Structures of Tall Building (JGJ3-2002), the height of building clearly exceeds the stipulated maximum height of 190m for a composite frame/reinforced concrete core building. Besides, it belongs to B grade complex tall building due to the strengthened story and high level transfer story. A scaled model (1/30) was designed and manufactured in order to study its dynamic characteristics, seismic responses and to evaluate its capacity to withstand earthquake. The paper mainly focuses on the design work for shaking table model test and illustrates the structural system characteristics of the super tall-building in detail, model material selection, similitude-scaling relationship, model manufacture, sensors' setup and test program. And main test results are given at last. The conclusion is that the test design of this shaking table model recommended in this paper is feasible in the test. The test design applied in model and test program design of this super-tall building will be helpful to other experimental studies.

KEYWORDS: shaking table test, scaled model, super-tall building, similitude-scaling relationship, transfer story

1. INTRODUCTION

The tower is a super tall-building with 53 stories above ground consisting of office building and hotel. The height of the tower is 250m from terrace to main roof. The structural plan of the tower is a rectangle, whose longitudinal length is 46.6m and lateral length is 54m. The tower is used as hotel above 39th story, and as office below the 39th story. The central RC tube and peripheral SRC frame with two outrigger trusses are employed to resist vertical and lateral loads and there are two mega-columns in every side of office stories. This tower has a transfer story in 37～38th story, a strengthened story in 21～22nd story and corner truss in 5～6th story, respectively. The strengthened and transfer story consist of ring belt steel trusses and outrigger steel trusses. In addition, due to the demand of architecture, the four corners of the structure can not contact with the floor, corner truss is set to bear the load of corner columns. The tower's typical structural floor plan and high level transfer story axonometric drawing are shown in Fig.1 and Fig.2.

As totally mentioned above, the tower's structural system is composed by following three parts:

（1）RC tube structure;
（2）Mega-frames below the transfer story consisting of mega-columns and ring belt trusses and frames above the transfer story consisting of upper-close columns and frame beams.
（3）Horizontal outrigger trusses used to connect（1）and （2）.

According to the Technical Specifications for Concrete Structures of Tall Building (JGJ3-2002), the height of the tower clearly exceeds the stipulated maximum height of 190m for a composite frame-reinforced concrete core building. So, it belongs to B grade tall building. Moreover, because the building comprises strengthened story and high level transfer story, which makes it belong to B grade complex tall building. The elevation view of the building is shown in Fig.3.

Due to its height and complexity, a scaled model was made and tested on the shaking table in State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University to study its dynamic characteristics, seismic responses and evaluate its capacity to withstand earthquakes.

2. MODEL DESIGN AND MANUFACTURE

2.1. Model Materials Selection

The selected materials are requested to hold the features of lower Young's modulus and higher specific weight. In addition, their stress-strain relationship should be similar to prototype materials (Sabnis GM, 1983). Owing to the better similarity of mechanical property between microconcrete and prototype concrete, microconcrete is used to simulate the concrete in prototype structure. Model test can simulate concrete crack even its failure, which has the advantage of visibility. Bigger sand grain in microconcrete is adopted as coarse aggregate to replace reduced stone in concrete, and the smaller sand grain is adopted as fine aggregate to replace sand and gravel in concrete. Its job practice, vibrating method and curing condition are same as the prototype structure concrete.

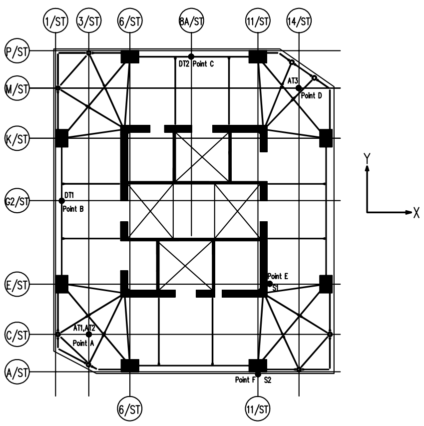
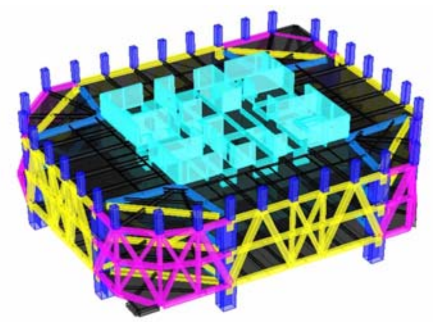


Fig.1. typical structural floor plan



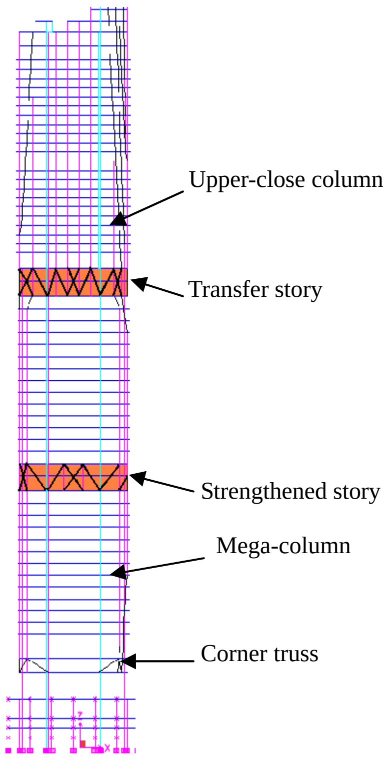


Fig.2. high level transfer story axonometric drawing Fig.3. structural elevation view

In addition, galvanized sheet iron, aluminum alloy and red copper are used to simulate reinforcing bars. By comparing of the three kinds of materials' Young's modulus and strength, we can find that sheet iron and aluminum alloy's Young's modulus is higher, but red copper's Young's modulus is about half of the former. Consequently, red copper is selected to simulate rolled steel in the test. In addition, it can be cut down, joint and welded arbitrarily. Galvanized iron wire and welded iron gauze are used to simulate reinforcing bars and stirrup respectively in prototype structure.

2.2. Similitude Relationship

The design of similitude relationship plays an important role in shaking table tests. Inertia force, restoring force and gravity will be simulated in the test (Xilin Lu, Ying Zhou et al, 2007). So, Young's modulus and density of modeling material are required strictly, the essence is :

$\left(\frac{E}{\rho \cdot a \cdot l}\right)_m = \left(\frac{E}{\rho \cdot a \cdot l}\right)_p$, that is:

$$\frac{S_E}{S_\rho \cdot S_a \cdot S_l} = 1 \qquad (2.1)$$

Table 2.1. structural model similitude relationship

length （S_l）	1/30	mass density （S_ρ）	2.00
elastic modulus （S_E）	0.37	acceleration （S_a）	2.50
Time （S_T）	0.085	gravity acceleration （S_g）	1

The three controllable similarity coefficient S_E、S_l and S_a should be determined firstly ,then , S_ρ can be determined by equation（1）. At last, other similarity coefficients can be determined by dimensional analysis methods. Performance parameter of shaking table, lifting ability and construction condition should all be considered to determine similitude relationship. Since the tower is a super tall-building, and the height of prototype structure reaches 250m, in order to make the height of scaled model satisfy requirement of experimental laboratory, geometrical ratio of similitude（S_l）is adopted as 1/30 firstly in the test. Secondly, according to properties of selected modeling materials and considering Young's modulus of red copper and microconcrete, preliminary ratio of similitude of Young's modulus（S_E）is determined as 0.2. The third parameter is acceleration ratio of similitude （S_a）, which is the main controlling parameter used to apply dynamic load in dynamic test. According to noise of shaking table, bearing capacity of base and former test experience, its value is generally between 2 and 3, S_a is taken as 2.5 in the test. Finally, based on S_E、S_l and S_a, other similitude relationship can be gotten (Seung-Eock Kim et al, 2007). In order to make the similitude relationship exact, after construction was finished, a material test was carried out for concrete specimen. In addition, because property of metal material is comparatively stable, material property of red copper can be referred to former test results (Xilin Lu et al, 2007). Main similarity coefficients in the test are shown in table 1.

In dynamic similitude relationship, the ratio of similitude of horizontal acceleration of shaking table is 2.5, but ratio of similitude of gravitational acceleration is 1. In order to solve this problem, gravitational similitude relationship was met by setting balance weight. When setting balance weight for the model, we can firstly calculate the attached mass, then, pieces of iron slabs with heavier specific weight were fixed on floorslab to act as the attached mass. The advantage is that the method only increases weight of structure and doesn't increase strength and rigidity of structure. Typical attached mass plan is shown in Fig.4. The specimen made for material test is shown in photo 1.

In addition, referring to former research results (Xilin Lu, Yun Zou et al, 2007), we design model structural members according to similarity principle of structural members. Bending resistance equivalent principle was used to control cross-section bearing capacity of reinforced concrete structural members, and shear resistance equivalent principle was used to simulate oblique section bearing capacity of structural members. On the basis of literature (Xilin Lu, Ying Zhou et al, 2007), similarity calculation formulas were deduced to design shape steel beam and members of structural steel truss by equivalent principle. Corresponding calculation formulas are shown in Eqn. 2.2～2.5:

Reinforced concrete beams and columns:

Prototype structure: $M^p = f_y^p A_s^p h_0^p$, $V^p = f_{yv}^p \frac{A_{sv}^p}{s^p} h_0^p$

Model structure: $M^m = f_y^m A_s^m h_0^m$, $V^m = f_{yv}^m \frac{A_{sv}^m}{s^m} h_0^m$

Bending similitude constant: $S_M = \frac{M^m}{M^P} = \frac{f_y^m A_s^m h_0^m}{f_y^p A_s^p h_0^p} = \frac{A_s^m}{A_s^p} \cdot S_{fy} \cdot S_l$

$$A_s^m = A_s^p \cdot \frac{S_M}{S_l \cdot S_{fy}} = A_s^p \cdot \frac{S_\sigma \cdot S_l^2}{S_{fy}} \qquad (2.2)$$

Shearing force similitude constant: $S_V = \frac{V^m}{V^P} = \frac{f_{yv}^m \frac{A_{sv}^m}{s^m} h_0^m}{f_{yv}^p \frac{A_{sv}^p}{s^p} h_0^p} = \frac{A_{sv}^m}{A_{sv}^p} \cdot S_{fyv} \cdot \frac{S_l}{S_s}$

$$A_{sv}^m = A_{sv}^p \cdot \frac{S_V \cdot S_s}{S_{fyv} \cdot S_l} = A_{sv}^p \cdot \frac{S_\sigma \cdot S_l \cdot S_s}{S_{fyv}} \qquad (2.3)$$

Shape steel beams and columns:

Prototype structure: $\sigma^p = \frac{M^p}{W^p}$, $\sigma_{\max}^p = f_y^p = \frac{M_{\max}^p}{W^p}$, $W^p = \frac{M_{\max}^p}{f_y^p}$

Model structure: $\sigma^m = \frac{M^m}{W^m}$, $\sigma_{\max}^m = f_y^m = \frac{M_{\max}^m}{W^m}$, $W^m = \frac{M_{\max}^m}{f_y^m}$

$$W^m = W^p \cdot \frac{S_\sigma \cdot S_l^3}{S_{fy}} \qquad (2.4)$$

Members of steel trusses:

prototype structure: $\sigma^p = \frac{F^p}{A^p}$, $\sigma_{\max}^p = f_y^p = \frac{F_{\max}^p}{A^p}$

Model structure: $\sigma^m = \frac{F^m}{A^m}$, $\sigma_{\max}^m = f_y^m = \frac{F_{\max}^m}{A^m}$

$$A^m = \frac{S_F}{S_{fy}} \cdot A^p = \frac{S_\sigma \cdot S_l^2}{S_{fy}} \cdot A^p \qquad (2.5)$$

2.3. Simplification of Test Model

The SRC frame and RC tube structural system were adopted to bear horizontal loads in the super tall-building. According to the experience of other engineering model tests (Seung-Eock Kim et al, 2007;Xilin Lu, Yun Zou et al, 2007), in order to make model construction easy and the whole structural characteristic to be satisfied, the building should be simplified as following aspects:（1）Main beams and secondary beams in some stories would be simplified. Because the main application of them is only to bear the vertical loads transmitted through slab and they would produce little contribution to horizontal global stiffness of structure. The stiffness of main beams and secondary beams was transformed into slab according to stiffness equivalence.

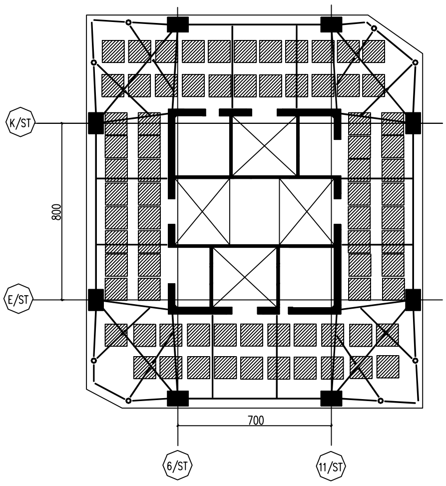


Fig. 4. attached mass floor plan

Photo. 1. material testing specimen

（2）Inner walls of core tube would be regularized. Due to the irregularity of them in prototype structure, construction of the model becomes much more difficult. So, in the design of model structure, inner walls were regularized based on the premise of considering the same contribution of horizontal stiffness.（3）The cross section of steel in SRC columns and main and secondary beams are simplified. For example, channel steel was used to replace I beam.（4）All the holes in the slab were normalized. The distribution of holes in prototype structure is complicated, so, in order to make construction more convenient and easy, they were normalized in model design. （5）some interlayers were simplified. Because the 20th interlayer in prototype structure had little influence to global horizontal stiffness of structure, it was deleted in the model design and its weight and bearing loads were added to the 20th story in the form of balance weight.（6）Accessory non-structural elements would not be considered in the model design. For example, steel framework used to install glass curtain wall was ignored.

2.4. Design and Construction of High Level Transfer Story of Model

One of obvious characteristics of the tower is that there is a high level transfer story, which should be paid more attention in calculation and design.

Owing to importance of transfer story, members of trusses and upper-close columns are without any simplification. In addition, in order to assure the construction speed of model structure and the precision of trusses of transfer story, two-stage construction method was applied.（1）Structural members were consolidated on the ground according to structural vertical plane firstly. It has following advantages: its convenience of manipulation on the ground; the easiness to find the problems of welding and assure the quality of make-up; comparing with work high above the ground, it can accelerate the construction speed.（2）consolidation of trusses on high altitude. After the single truss was consolidated, they were hoisted to the location of transfer story and would be welded as a whole. It is convenient to consolidate a big truss on high altitude. In addition, it can accelerate speed and assure the quality. The shape steels in steel-concrete structure located on the top of transfer story were connected rigidly with corresponding parts of top chords of trusses. After reinforcing bars are assembled around shape steel and form plastic mother plates were installed, microconcrete can be poured. Truss construction of transfer story and the story location of upper-close columns are shown in photo 2～5.

2.5. Model Construction

Because the scaled model is smaller and the requirement of precision is high, model construction is required strictly. Plastic foam is used as mother plate because of its easiness of molding and removal of shuttering. Comparing with concrete, the density, flexural modulus and shearing modulus of plastic foam is much smaller. So, mother plate of plastic foam has little influence to model rigidity. Before model construction, mother plates were incised according to needed shape, and iron wire used to simulate reinforcing bars were assembled, then, copper sheets used to simulate shape steel were consolidated at last. After the reliable connection was assured, microconcrete was poured accompanying vibrating until it became compact. This process was repeated until the

Photo 2 consolidation of single piece of truss

photo 3 consolidation of truss

Photo 4 the connection of upper-close columns and truss

photo 5 the relative location of transfer story and upper-close column story

whole model was finished. In the whole process of construction, the size and verticality of members should be checked out. In addition, the height of the model is 8.63m and exceeded the range of lifting, so the construction process is divided into two stages: The model was constructed out of the shaking table and on shaking table. After the model was constructed out of the shaking table to the 41st story（6.5m）, it was lifted to shaking table and constructed until all the work was finished. The construction relationship of two stages is shown in Fig.5. The total height of the model is 8.63m, and height of base plate is 0.3m and the height of model is 8.33m. The full view of the finished structural model is shown in photo 6. The total mass of model is 22.0t, among them, the model mass and attached mass accounts for 19.0t and the mass of base plate is 3.0t, respectively. After the model attached mass was fixed, model natural frequency of vibration was obtained by fluctuating testing. The relative location between model and shaking table is shown in Fig.6.

3. SHAKING TABLE TEST PROGRAM

3.1. Earthquake Motion Input

According to the requirements of 7 degree seismic fortification and IV site, El Centro waves, Pasadena waves and Shanghai artificial earthquake waves SHW2 were used as excitations. The duration of earthquake motion was scaled to 1/11.79 of original waves. The input directions were classified as one-dimension and two-dimension. The peak value of acceleration of every level was determined according to the Code for Seismic Design of Buildings (GB50011-2001) and dynamic similitude relationships listed in Table 1.

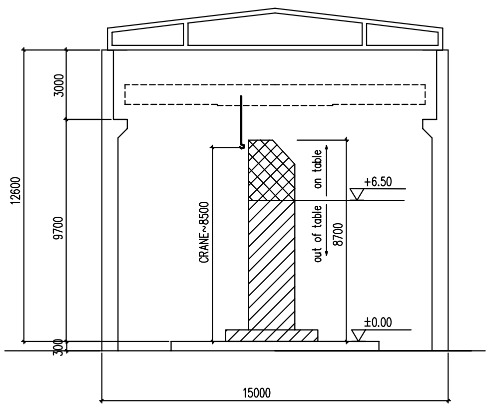


Fig.5. the construction relation of two stage

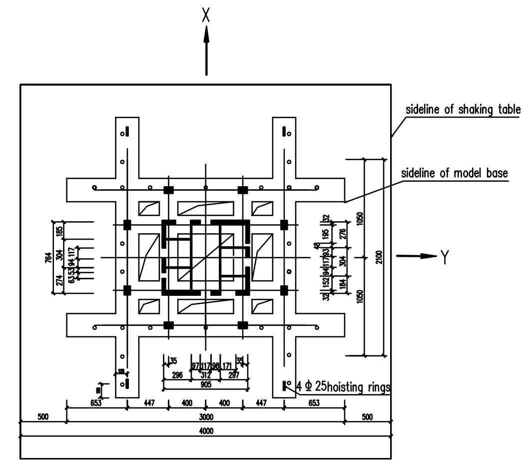


Fig.6. The relative location between model and shaking table

3.2. Sensor Setup

Three kinds of sensors were used in the testing: CA-YD piezoelectric acceleration transducer, whose range of frequency is 0.3～200Hz; ASM displacement transducer, whose measuring range is 0～±375mm; Electrical resistance strain gauge, whose measuring range is 0～20000 $\mu\varepsilon$.

According to the properties of the tall super-building, sensors were arranged at the structural special, typical stories and key parts, such as strengthened story, transfer story, mega- columns, tube wall and the like, to obtain the seismic responses. Sixteen displacement sensors were set up at B and C measuring points located in the plan （Fig. 1）to measure the displacement response of the structure under earthquakes. In order to measure the change of stress under every kind of earthquake, 20 strain gauges were set up at the tube wall, mega-columns, upper-close columns, corner truss, truss of strengthened story, and truss of high level transfer story. Thirty-four acceleration sensors were set up at the first story, typical floor, strengthened story, high transfer story and point A and B located in the plan（Fig. 1）are measuring points for acceleration sensors. Seventy sensors were used totally in this test.

3.3. Test Program

Owing to the requirements of architectural arrangement, there were no columns at the corners of architectural plan, and web frames and flange frames are only connected by two ring belt steel truss to form effective bending resistance connection. In this case, the structural lateral stiffness became weak, which brought about apparent influence to the whole building. So 7 degree frequent earthquake intensities of $+45^0$ and -45^0 direction were increased to check the structural lateral stiffness of 45^0 and -45^0. In addition, in order to research the structural dynamic response under extraordinarily severe earthquake, 8 degree rare earthquake intensity was carried out.

According to the sequence of 7 degree frequent earthquake intensities of X and Y direction, 7 degree frequent earthquake intensities of $+45^0$ and -45^0 direction, 7 degree basic earthquake intensities of X and Y direction, 7 degree rare earthquake intensities of X and Y direction and 8 degree rare earthquake intensities of X and Y direction, Testing Program was divided into five stages to simulate the structural response under different earthquakes. White noise was carried out for the model structure in order to measure the dynamic characteristic parameters of the structure, such as natural frequency of vibrations, modes and damping ratios. The duration of earthquake motion and inputted acceleration peak value were calculated according to acceleration similitude relationship to simulate seismic excitations under different levels of seismic fortification intensity.

4. MAIN TEST RESULTS

(1) The model test results indicate that the prototype structure is able to withstand frequently occurring, basic intensity and rarely occurring earthquakes of intensity 7 without severe damage. The structural system of this building demonstrates good quality in resisting earthquakes.

(2) Under rare occurrence of intensity 8, concrete spalled in mega and upper close columns at transfer story, and some of outrigger truss members buckled at transfer story. These damages indicate that the transfer story is a weak level. Designed measures to increase the ductility of the upper close columns and strength of joints connecting the upper close-columns and the mega-columns at transfer story are needed to avoid extensive deformation and damages.

(3) Although shaking table is more often used in the test of the overall structural models, some limitations still exist in this method, such as size effect and some dynamic similitude requirements that could not be satisfied. These limitations of scale model tests should be improved in the future.

5. CONCLUSION

It is obvious that experimental research on a shaking table model should experience a series of process, such as confirmation of test program, construction preparation, model construction, doing experiment and dealing with experimental data. The whole process will cost lots of time. This paper focused on special characteristics of the tower, and introduced mainly preliminary work about the shaking table test. In addition, the selection of material, confirmation of dynamic similitude relationship, simplicity of model and design of test program were all particularly analyzed. Apparently, in order to accomplish the test successfully, it is important to understand and grasp the whole process of shaking table test in detail. The methodology in this paper can be used as reference for future experimental research. The test results have been applied to engineering design of this building.

ACKNOWLEDGEMENT

The authors are grateful for the financial support in part from the National Key Technology R&D Program (Grant No. 2006BAJ13B01).

REFERENCES

Sabnis GM, Harris HG, White RN, Mirza MS. (1983). Structural Modelling and Experimental Techniques, Prentice-Hall: Englewood Cliffs, NJ.

Xilin Lu, Ying Zhou, Wensheng Lu. (2007). Shaking Table Model Test and Numerical Analysis of a Complex High-rise Building. *The Structural Design of Tall and Special Building,* 16: pp.131~164.

Seung-Eock Kim, Dong-Ho Lee, Cuong Ngo-Huu. (2007). Shaking Table Tests of a Two-Story unbraced Steel Frame. *Journal of Constructional Steel Research. Journal of Constructional Steel Research,* Volume 63, Issue 3, pp. 412-421.

Xilin Lu, Yun Zou, Wensheng Lu, et al. (2007). Shaking table model test on Shanghai World Financial Center Tower. Earthquake Engineering and Structural Dynamics, 36 (4).