

SEISMIC MODEL TEST AND ANALYSIS OF MULTI-TOWER HIGH-RISE BUILDINGS

Wensheng LU¹ And Xilin LU²

SUMMARY

This paper summarizes tests of several scaled multi-tower high-rise building models on the shaking table. The assumption of rigid floor is obviously unsuitable for the analysis of multi-tower buildings. A new analytic model considering the effect of flexible transfer floor is put forward. The theoretical dynamic behavior is compared with the test results. The conjunction floors between towers at higher levels, and the stiffness of foundation contribution to structural dynamic behavior is also discussed in this paper. Several suggestions and conceptual guidelines are concluded.

INTRODUCTION

It is well known that high-rise buildings act as very important roles in modern cities. First of all, tall buildings can be effectively used to meet the requirements of modern society and solve the problem of limitation of construction site resources. On the other hand, they are the signals of economic properties and civilization. Nowadays high-rise buildings rise higher and higher, with more and more complex and individual plan and elevation, such as multi-tower buildings.

The multi-tower building mentioned in the paper is refer to two or more towers connected with one large podium or conjunction parts at different levels. It is well known that the podium and conjunction parts shall be designed very carefully to meet the internal force and the deformation between towers. Figure1 shows the typical style of twin-tower buildings.

From the point of structural properties, multi-tower high-rise buildings have the following characteristics,

- the height exceeding the limitation of present codes;
- extremely irregular shape, including in plan and elevation;
- the distribution of mass and lateral stiffness are sharply changed along the height;
- mega-member with huge space and large span,;
- flexible weak connection between towers;
- new construction materials, methods and details.

Multi-tower high-rise buildings appear in recent decades but the researches on this field are not sufficient now. The nonlinear time-history analysis and structural model tests are seldom presented in document. Some perfect software, such as ADINA, SAP, SUPER-SAP, ANSYS, TBSA, SAP84, TAT and SATWE etc. are widely used by designers and researches in this field. Figure 2 shows the traditional calculation models of multi-tower buildings.

The seismic simulation shaking table test is of importance for the earthquake safety research on those kinds of complex structures. More than 10 shaking table facilities are imported or manufactured in China recently. The test abilities can reach to six degree of freedom, 4~6g of acceleration and 15~25 tons of static mass.

¹ Research Institute of Engineering Structures, Tongji University, Shanghai, P. R. China. EMAIL: luloes@mail.tongji.edu.cn

² Research Institute of Engineering Structures, Tongji University, Shanghai, P. R. China. TEL: (86)(21)65982666

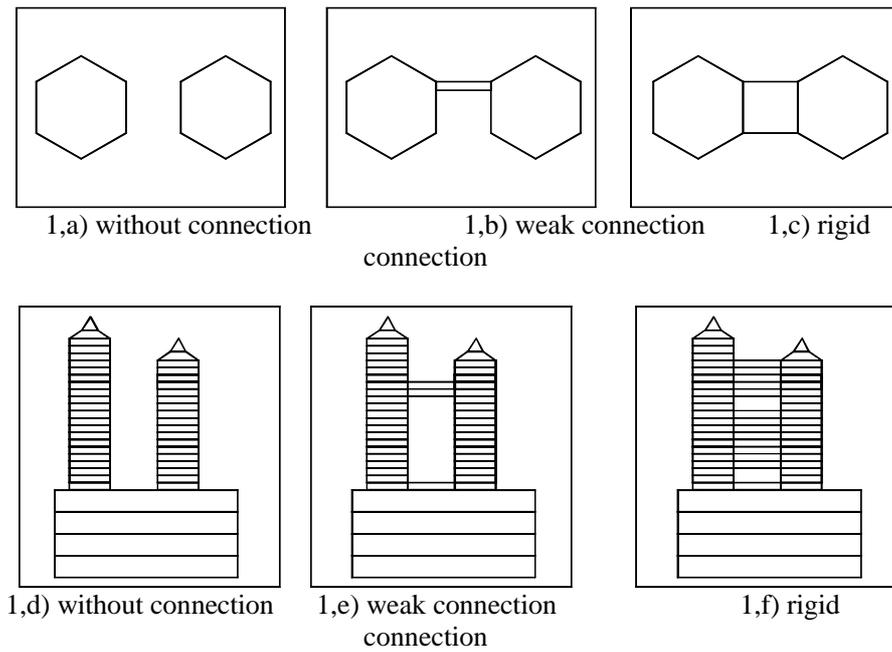


Figure 1. Typical twin-tower buildings

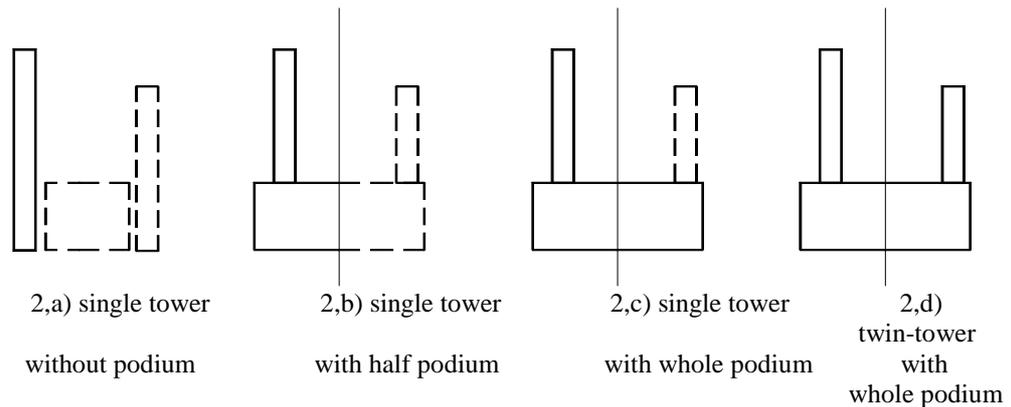


Figure 2. Traditional calculation models of multi-tower buildings

In this paper, the state of art of the present study on the shaking table test and analysis of multi-towers high-rise buildings are presented.

2. SHAKING TABLE TESTS

This section summarizes the tests of several scaled multi-tower high-rise building models on the shaking table which locates at the State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University, Shanghai, China.

2.1 Test purposes

The main purposes of seismic simulation tests are,

- 1) to check the free vibrating modes, and the corresponding frequencies and damping ratios of structural model after different earthquake intensity,
- 2) to study the seismic responses of accelerations, displacements and strains,
- 3) to determine the structural crack positions and the weakness points, to verify or find the collapse styles and failure mechanism,
- 4) to assess the safety reliability of main structures under different earthquake intensity, to verify the rationality and effectiveness of various earthquake-resistant countermeasures.

2.2 Prototype Structures

There are different styles of multi-tower high-rise buildings, such as,

- 1) several towers on one large podium, e.g. five towers on one large podium;
- 2) towers with rigid connection at top;
- 3) towers with flexible connection between towers;
- 4) irregular shape of towers.

Most of multi-tower structures tested at Tongji University are RC structures, with the height from 39m to more than 200m.

2.3 Similitude relationship

Before, during and after designing, constructing and analysis of a structural model for shaking table tests, the most important aspect is to satisfy the similitude relationship. On the other hand, it is very difficulty to meet all the demands exactly. Hence, some main factors shall be determined strictly first. Table 1 is the similitude relationship of some models, which have been tested recently.

Table 1. Similitude coefficients of models

Physics Behavior	Main Factors	Guangzhou Tianwang Center	Guangzhou International Plaza	Shanghai BOCOM Financial Tower	Shanghai Changshou Commercial Plaza	Shanghai Pudong Reception Center
Geometry Property	Length	1/25	1/40	1/33	1/25	1/20
	Elastic modules	1/6	1/2.6	1/2.96	1/6	1/3.8
Material Property	Stress	1/8	1/2.6	1/6.92	1/6	1/8.7
	Mass density	1	2.5	1	1.39	
	Mass	1/11194	1/25600	6.96×10^{-5}	1/11250	1/4800
Dynamic Property	Period	1/8.636	1/15.69	0.107	0.12	6.25
	Acceleration	2.985	6.25	2.64	3	1.9

2.4 Design and construction of model

As stated previously, the focus of shaking table test is on the dynamic behavior and earthquake resistance capacity of the structures. Hence the main similitude factors must be strictly obeyed during design, while the dimension, reinforcement, mass and stiffness are also considered. On the other hand, the capacity of the facilities of laboratory shall be taken into account.

Micro-concrete and fine reinforcement is always used to build a model. These kinds of material and construction methods have been maturely used in Tongji University, which are used to build nearly 50 models during last decades. The main structural members are entirely reproduced similarly, and the dimension and reinforcement ratio is also determined by the similitude factor. Usually it spends 3 to 5 months to build one whole model. Figure 3 a) through e) show several structural models which have been tested on the shaking table during the last five years.

Elastic model can also be made of plastic and other materials. Those model shall keep elastic during test and the linear behavior will be measured by sensors.

2.5 Shaking Table tests

For choosing suitable earthquake waves to input into the shaking table to excite the model, the soil type of construction site and the dynamic behavior of the prototype structure shall be taken into account. During test, the exciting intensities of each earthquake waves vary from the frequently occurred earthquake to the seldom occurred earthquake step by step, and the exciting inputs can be one dimension or three dimensions. Sensors

such as strain gauges, displacement transducers and acceleration transducers are placed at critical and interesting places of the model.

It is found that the responses of multi-tower buildings have very complex behavior during earthquake action. The dynamic properties and the damage area are different if the position and the stiffness of the connection floor between towers are located at different levels.

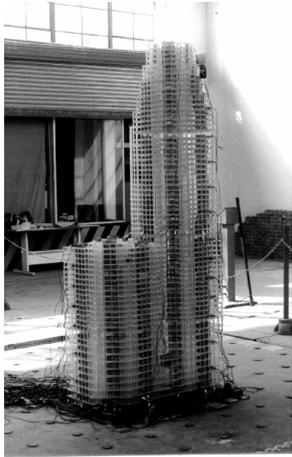


Figure 3,a) Model of Guangzhou International Commercial and Trade Plaza



Figure 3,b) Model of Shanghai Kaixuanmen Mansion



Figure 3,c) Model of Shanghai BOCOM Financial Tower



Figure 3,d) Model of Shanghai Changshou Commercial Plaza

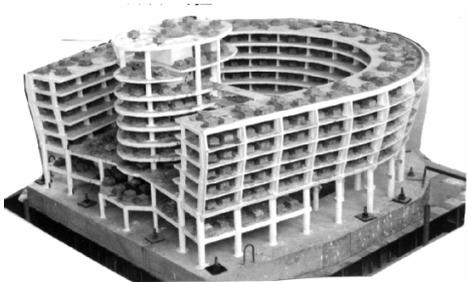


Figure 3,e) Model of Shanghai Pudong Reception Center

3. ANALYSIS

3.1 Theoretic analysis methods

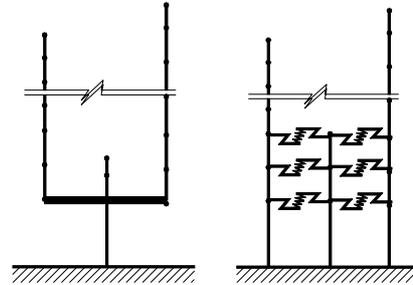
As above mentioned the assumption of the whole floor as one rigid block for analysis of multi-tower building is inappropriate. Several effective methods have been applied in the analysis of high-rise buildings by researchers of Tongji University. Here after are some theoretic models for analyzing these kinds of complex structures.

1) multi-tower with rigid podium⁽³⁾, which is suitable for the analysis of multi-tower building with strong transfer floor and the torsion response is negligible, as shown in figure 4.a)

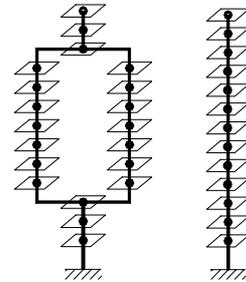
2) Multi-towers with spring element podium⁽³⁾, which is suitable for the analysis of multi-tower building with flexible podium and also the torsion response is negligible. As shown in figure 4.b).

3) Rigid-plate mass spring model⁽⁴⁾, which is suitable for the analysis of complex building. This model uses the master-slave constrain mode for the slab with relative large stiffness in slab plane, i.e. there is usually one master node for each podium floor or conjunction floor and one master node for each floor of separate tower. The torsion of the floor is considered in this model. As shown in figure 4.c)

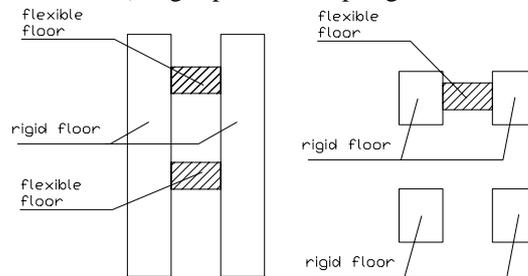
4) A new multi-rigid block model⁽⁴⁾, in which rigid floors of each tower, flexible transform floor, rigid or flexible connection and the elastic floor of large opening are considered, as shown in figure 4.d).



4.a) Multi-tower with rigid podium 4.b) Multi-tower with spring element podium



4.c) Rigid-plate mass spring model



4.d) Multi-rigid block model

Figure 4. Calculation model

3.2 Comparison of test results

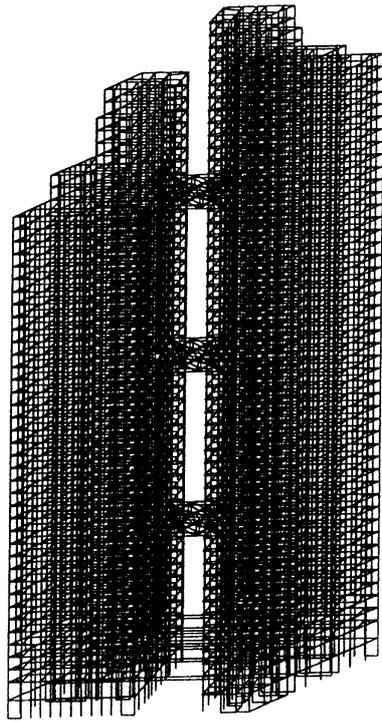
The multi-rigid block model has been applied to analyze several multi-tower buildings, and the calculation models are as shown in figure 5. The theoretical dynamic behavior is compared with the test results. Furthermore, vibration tests at site are also under going.

The error between the results of testing and the results of calculation and site testing are within 10%~30%. Hence the results of shaking table testing are satisfactory.

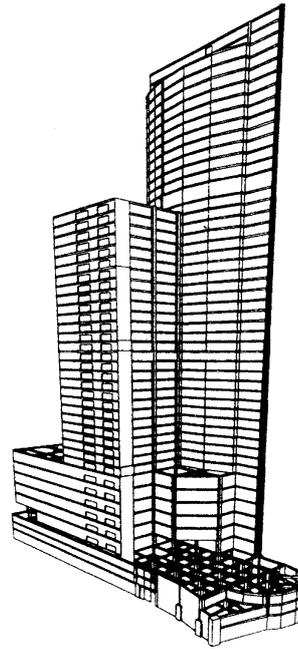
Table 2 and 3 show some compared results of Shanghai Reception Center.

3.3 The conjunction floors

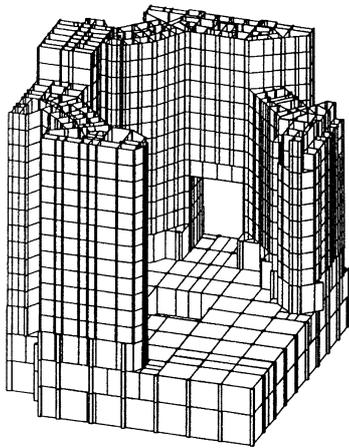
The conjunction floors at higher levels can significantly reduce top drift of the tower. However the higher order vibration modes affect the seismic response, and the internal force in the conjunction floor and the local members are relatively higher. For example, the torsion of each tower and the interaction between towers cause large stress in the conjunction floor and the joint area. The same condition is to the large podium under high-rise towers. Tests and theoretic analysis show that cracking always are at those areas. Even more, the dynamic properties of structures change a lot after cracking, e.g., the frequencies can decrease 30~50%. If the podium floors between twin-tower crack, each tower will have individual dynamic response except collision between each other.



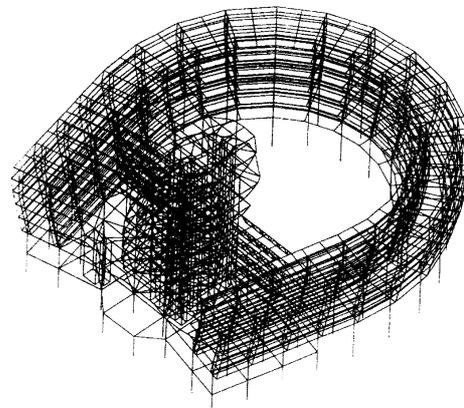
5.a) Shanghai BOCOM Financial Tower



5.b) Guangzhou Tianwang Center



5.c) Shanghai Haiyi Gardern



5.d) Shanghai Pudong Reception Center

Figure 5 Theoretic model of multi-tower buildings

Table 2 Comparison of Frequencies of Shanghai Reception Center

No.	Frequencies(Hz) by calculation	Frequencies(Hz) by test	Error(%)	Vibration mode
1	1.01	1.23	22	Torsion
2	1.32	1.36	3	X
3	1.72	1.67	3	Y
4	2.50	2.24	11	Interaction between towers
5	2.54	2.70	6	Floor vibration
6	2.79	2.80	1	Space vibration

Table 3 Comparison of Maximum Displacement of Shanghai Reception Center

Measured points	Direction	Displacement by calculation (mm)	Displacement by test (mm)	Error(%)
8 th floor	X	28.6	27.6	4
	Y	19.3	17.0	13.5
6 th floor	X	20.9	22.7	8
	Y	15.2	15.3	1
3 rd floor	X	7.7	9.1	15
	Y	8.5	9.8	13

3.4 The stiffness of foundation

The shaking table test and the traditional seismic analysis of high-rise building always neglect the effect of foundation. Unfortunately, the nature frequencies of most multi-tower buildings meet with the dominant frequency of site soil, especially those buildings with irregular shape, which have complex vibration modes, as shown in table 4.

When earthquakes act to multi-tower buildings, the higher order modes such as torsion modes and interaction modes between towers take great affection on the seismic behavior. Tests and analysis both prove that soft soil site may increase the damage intensity of multi-rise buildings.

Table 4 Nature frequencies of multi-tower buildings

Modes	Changshou	Pudong Reception	BOCOM
1	1.042 Hz	0.813 Hz	2.732 Hz
2	0.304 Hz	0.735 Hz	1.931 Hz
3	0.301 Hz	0.599 Hz	0.659 Hz

4. CONCLUSION

Considering the above-mentioned aspects, the following conclusions can be drawn.

- 1) The dynamic behavior of multi-towers high-rise buildings is usually different from traditional high-rise buildings. First of all, the distribution of floor mass and the lateral stiffness change sharply at different level hence the higher order vibration modes are dominant. Secondly, the members near those areas are easily destroyed under earthquake action.
- 2) The door-shaped building structure has bad earthquake resistant ability. Because the rigid and heavy conjunction block is on the top of the building, and the dynamic response of the towers under earthquake action will increase.
- 3) The couple action between transfer floors of multi-tower building with large podium is significant, which will cause the damages near the transfer floors, and each tower works separately if cracks appear after higher intensity earthquake.
- 4) The flexible connections between towers can significantly reduce the drift of multi-tower high-rise buildings, and they will be destroyed and act as energy dissipation members during a moderate earthquake.
- 5) For irregular shape multi-tower buildings, such as Shanghai Reception Center with U-shape, the responses are very complex. Not only the couple actions between towers but also the internal forces in the narrow shape slab are affective to the safety of the building.
- 6) Multi-tower building may be severely damaged when it is subjected to strong earthquakes. However the building will keep in safety if it is appropriately designed and constructed.

Furthermore, suggestions on design, construction and maintenance of multi-tower buildings are put forward.

- 1) It is very important to design and construct multi-tower buildings according to the appropriate conceptions and detailed earthquake resistant measures.
- 2) Simplify the force route of lateral action and vertical weight. It is necessary to avoid applying different axis system to the podium and towers individually.
- 3) The stiffness and mass from the bottom to the top of the whole building shall distribute near one straight line, and the stiffness ratio of the superstructure to the podium shall be adjusted within 0.5~2.0.

- 4) Members near tower bottom and the podium roof must be strengthened, e.g. the reinforcement ratio shall be increased and the performance of concrete beams, slabs, columns and shear walls shall be enhanced. The ductility property of the shear-walls, columns and beams at the critical zone must be designed carefully.
- 5) It is essential to analyze earthquake resistance of the whole structure during and after serious earthquake, and to analyze the dynamic behavior of the separated towers with partial podiums after the podium roof and floors are severely damaged, and to evaluate their earthquake resistance.
- 6) The seismic simulation shaking table test is of importance for the earthquake safety research on multi-tower high-rise buildings. Shaking table test is proved to be a relative effective, economic and figuratively measure for the seismic research of those kinds of complex structures..
- 7) It is essential and helpful for both architectures and engineers to keep well cooperation between each other to solve the problem among beauty scene, function and safety.
- 8) Site tests and sensors embedded in the prototype structures will be helpful to improve the analysis methods and the knowledge in this field.

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