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Seismic Model Test of a Hybrid High-rise Building in Shanghai

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Abstract

Abstracts: Shanghai Shimao International Square will be one of the highest buildings at downtown of Shanghai. The superstructure for the main tower of SSIS is RC core and SRC mega columns, the large podium is composite structures of RC shear-wall frame and CFRT column with steel space-truss roof, i.e. hybrid structures are adopted and expected to have the capabilities to resist all imposed wind and seismic lateral loads. It is under construction at present.

The height of the tower is far beyond the limitation for RC shear-wall structure in contemporary Technical Specification, and its elevation is also beyond the limitation of the specification, i.e. the plane and the elevation of the tower are both irregular. On the other hand, the plane of the podium is also far beyond the limitation. The conjunction members between the podium and the tower were supposed to be energy-dissipation linkers.

A micro-concrete structural model with scale of 1/33 was constructed, to validate the calculation results and to find out possible weak regions, moreover to ensure the reliability and safety of the structural design. With the results of the tests, the structure was designed to satisfy the seismic fortification criterions of contemporary Technical Specification. And the weak regions of the building were seriously considered based on the analysis during the phase of the construction drawing design.

Keywords: hybrid structure, seismic behavior, shaking table test.

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1. Introduction

Shanghai Shimao International Square is located at the street corner of famous Nanjing Road and Xizang Road, with multi-functions of hotel, restaurant, entertainment, conference and commerce. The total area of the comprehensive building is 110,000m^2, and it is combination of main tower and a complex large podium. The height of main tower is 246.160m (60-storey above the ground, 3-storey basement), which plane is right-angle triangular. The podium is composite of a hollow entrance and a shear-wall frame building, with the area of height of 48.430m (10-storey above the ground). SSIS will be one of the highest buildings at downtown of Shanghai, as is shown in fig.1 and fig.2.

The complexities of SSIS structural system are summarized as followings,

1. The hybrid superstructure for the main tower of SSIS is RC core and SRC mega columns. Three SRC mega columns are arranged at the corner of the triangular plane, with irregular special shapes,
2. the dimension of 11th floor plane of the main tower stretches 1.5 m out from lower floors, in other words, the mega columns are subjected to significant eccentric loadings from the upper portion of 50 storey at the level above podium roof,
3. the upper-portion of main tower has two incline-planes. The first incline-plane is formed by the withdrawing of floor planes from 37 storey to 46 storey, and the second is from 51 storey to 60 storey,
4. there are three strengthen storey along the main tower, i.e. three steel out-rig are set at 11 storey, 28 storey and 47 storey, which corresponding to the level of 54.840m, 118.30m and 188.880m,
5. the hollow entrance of the podium is composite of `concrete-filled tubular` column with steel space-truss roof, and the free length of CFT column is 29m,
6. the conjunction members between the podium and the tower were supposed to be energy-dissipation linkers, and
7. two slender masts with length of 83.350m will be arranged at top of the main tower.

As above mentioned, the super-structure is very complex, and the mass center is deviate away from the lateral stiffness center. Either the tower or the

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podium, the torsion responses may be significant if it is subjected to earthquake, as well as the relative deformations between tower and podium.

All the above-mentioned problems were challenges to the designers. Specific research and analysis were carried out, and several structural problems were taken into account. The hybrid structure system is adopted and expected to have the capabilities to resist all imposed wind and seismic lateral loads.

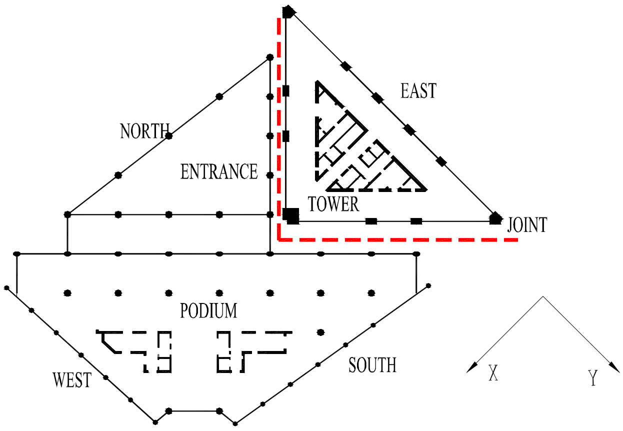


Fig. 1. The Typical Plane.

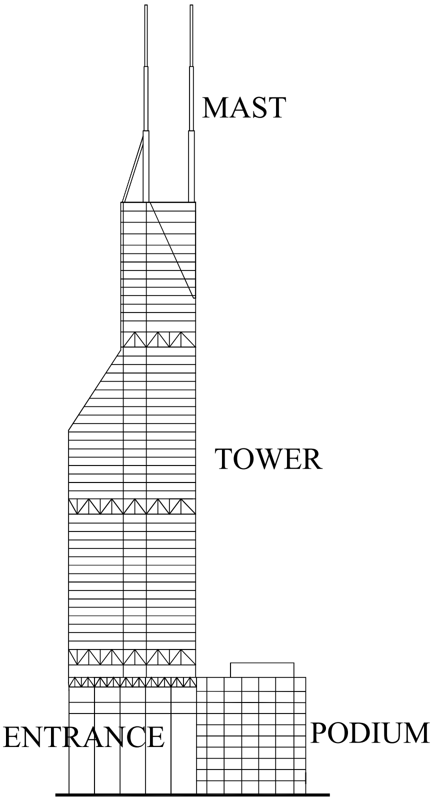


Fig. 2. The Elevation.

2. Seismic Simulation Model Tests via Shaking Table

The main purposes of seismic simulation model tests for SSIS are,

1. to check the free vibrating modes, and the corresponding frequencies and damping ratios of structural model after different earthquake intensities,
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 to find the collapse styles and failure mechanism,
4. to evaluate the whip effect of the masts on the top of the tower, and
5. to assess the safety reliability of main structures subjected to different earthquake intensities, to verify the rationality and effectiveness of various earthquake-resistant countermeasures.

3. Simulation Relationship for Dynamic Model

As mentioned previously, the focus of the seismic proving test was on the dynamic behavior and earthquake resistance capacity of the structures. Hence the main similitude factors were strictly obeyed during design, i.e. the dimension, reinforcement, mass and stiffness were considered. On the other hand, the capacity of the facilities in SKLDRCE were taken into account. For designing, constructing and analysis of a small-scaled structural model of SSIS, the most important aspect was to find reasonable similitude relationship.

However, it did be very difficulty to meet all the similitude demands exactly. Some predominate similitude factors were determined first, and then other factors can be revised to an appropriate region. Table 1 shows the similitude factors for SSIS model test.

Table 1. Similitude Factors of Model.

Length	1/35	Period	0.0976
Elastic	1/4	Frequency	10.25
Stress	1/4	Acceleration	3
Mass density	2.92	Velocity	0.293
Mass	6.80E-05	Force	2.04E-04

4. Design and Construction of 1/33 Scaled Model

Model materials shch as micro-concrete, fine reinforcement, Aluminum alloy and copper were used to construct SSIS model. The skills of using those material and the construction details are mature in SKLDRCE of Tongji University, which have been used to construct nearly 70 high-rise building models for last decades.

A 1/33 scaled model was design and constructed by use of micro-concrete and fine reinforcement. The main structural members are entirely reproduced similarly, and the dimension and reinforced ratio are considered. The test strength and elastic modulus of micro-concrete of the model are well fitted to theoretic data. Both of the tower and the podium structural members were entirely reproduced, and the dimensions and reinforcements were reproduced carefully.

It took 8 months to construct the whole structural model of SSIS. The height of the model is 9.514m, and the total mass is 13.3t, which includes additional mass of 7.0t, shown as fig. 3.

Fig. 3. Structural Model in SKLDRCE.

5. Earthquake Simulation Test on Shaking Table

For choosing suitable earthquake waves to excite SSIS model, the soil type of construction site and the dynamic behavior of the prototype structure were taken into account. Three kinds of earthquake accelerogrames were chosen as exciting inputs of the shaking table, which were El Centro (1940), Pasadena (1952), SHW2 (Artificial accelerogram of Shanghai).

During the test, the exciting intensities of each earthquake waves varied from the frequently occurred earthquake to the seldom-occurred earthquake step by step, and the exciting inputs can be one dimension or three dimensions simultaneously. The angle between the main direction of the excitation and X direction of shaking table was chose along 0º, 90º and 120º. Several white noises served as excitation to the model between different earthquake intensities, so that the changes of the dynamic behaviors of the model were detected.

The testing procedures of the earthquake simulation test for SSIS are listed in table 2.

6. The Arrangement of Sensors

Sensors such as strain gauges, displacement transducers and acceleration meters were placed at critical and interesting points of models.

Six displacement transducers were arranged at the base of the model, the roof of the podium, and the 10th, 37th, 48th floors, roof of the tower.

16 strain gauges were distributed at columns of shear-wall frame structure and the members of strengthen out-rig trusses.

33 accelerometers were mounted at the base of the model, the 8th, roof of the podium, and the 12th, 29th, 37th, 48th floors, roof of the tower.

The summary of the sensors are listed in table 3.

Table2. Testing Procedures.

Case	Intensity	Waves	Main	Excite
1		1st WN		2 dir
2	Freq. 7	El Centro	X	2 dir
3		El Centro	Y	2 dir
4		Pasadena	X	2 dir
5		Pasadena	Y	2 dir
6		SHW2	X	1 dir
7		SHW2	Y	1 dir
8		SHW2	120º	1 dir
9		2nd WN		2 dir
10	Basic 7	El Centro	X	2 dir
11		El Centro	Y	2 dir
12		Pasadena	X	2 dir
13		Pasadena	Y	2 dir
14		SHW2	X	1 dir
15		SHW2	Y	1 dir
16		3rd WN		2 dir
17	Rare 7	El Centro	X	2 dir
18		El Centro	Y	2 dir
19		Pasadena	X	2 dir
20		Pasadena	Y	2 dir
21		SHW2	X	1 dir
22		SHW2	Y	1 dir
23		4th WN		2 dir

Table 3. Summary of Sensors

Sensor Type	Number
Displacement Transducer	6
Strain Gauge	16
Accelerometer	33
Total	55

7. The Dynamic Characteristics of SSIS

The natural frequencies and damping ratios of SSIS model were obtained by white noise excitation, as shown in table 4. The corresponding main modal shapes are illustrated as figure 4.

8. The Seismic Behavior of SSIS

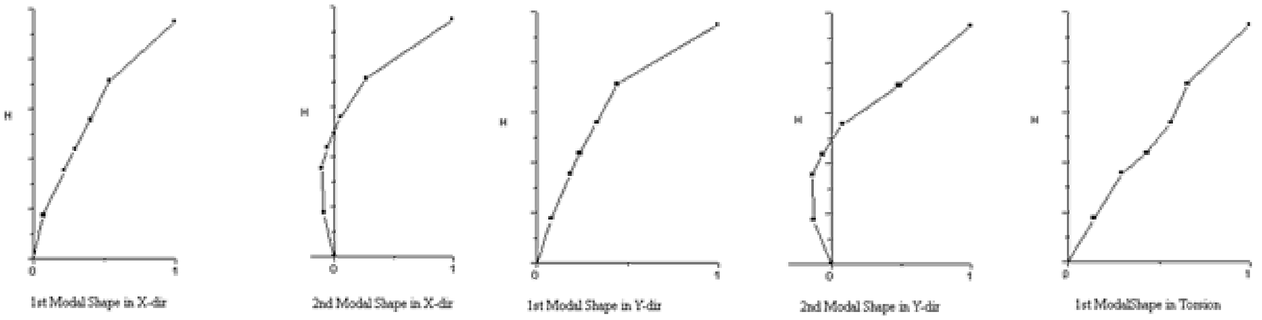
It was observed that the torsion response of the model was much larger subjected to main earthquake excitation of 120º direction than other directions, while the dynamic response subjected to Pasadena was larger than other excitations. Partial test results are shown in table 5.

The possible weak regions of the tower were analyzed before test by means of numerical analysis, which might be the top storey of the shear-wall frame, the conjunction members between main tower and the podium, the mega SRC columns of the tower, and the mast at the top of the tower, etc.

The acceleration response of each floor was gradually increasing with height level, and it is also decreased corresponding to the increasing of earthquake intensities. Strains and the damages are investigated and analyzed during and after the test as well.

Table 4. The Dynamic Characteristics of SSIS Model

Modal Order		1	2	3	4	5	6	7	8	9
1st WN	f (Hz)	2.740	3.737	6.851	10.837	12.954	16.193	18.933	22.297	28.525
	ζ	0.036	0.051	0.024	0.035	0.031	0.021	0.023	0.028	0.007
	Modes	X	Y	Torsion	X	Y	Torsion	X	Y	Torsion
2nd WN	f (Hz)	2.616	3.737	6.228	10.588	12.705	15.197	18.684	21.674	
	ζ	0.050	0.045	0.060	0.034	0.043	0.061	0.016	0.022	
	Modes	X	Y	Torsion	X	Y	Torsion	X	Y	
3rd WN	f (Hz)	2.491	3.363	5.356	10.214	10.837	14.947	18.560	18.684	
	ζ	0.052	0.050	0.062	0.030	0.033	0.007	0.022	0.036	
	Modes	X	Y	Torsion	X	Y	Torsion	X	Y	
4th WN	f (Hz)	2.118	2.740	4.111	8.097	8.470	10.339	14.574	15.446	
	ζ	0.062	0.049	0.033	0.039	0.055	0.030	0.031	0.019	
	Modes	X	Y	Torsion	Y	X	Torsion	Y	X	



1st Modal Shape in X-dir 2nd Modal Shape in X-dir 1st Modal Shape in Y-dir 2nd Modal Shape in Y-dir 1st ModalShape in Torsion

Fig. 4. The Modal Shapes.

9. The Acceleration Responses

The acceleration responses of SSIS model were acquired via accelerometers and MTS data acquisition system, which listed as followings,

1. the acceleration responses of the mast were much larger than the roof's, which showed considerable whip effects,
2. the structural lateral stiffness was deteriorated under earthquake motions, while the damping ratios were increased, and the dynamic amplitude factors were decreased, as shown in table 5,
3. both the tower and the podium showed obvious torsion motions subjected to earthquake.

Table 5. The Dynamic Amplitude Factors of Acceleration.

Position		Freq. 7		Basic 7		Rare 7	
		X	Y	X	Y	X	Y
M	Top	40.5	42.3	44.4	32.9	23.2	21.6
	Roof	8.7	5.7	10.1	4.9	7.7	4.0
	48F	3.0	2.4	3.5	3.4	2.9	1.8
T	37F	3.5	2.5	2.8	2.3	2.0	1.5
	29F	2.9	2.9	2.7	1.4	1.8	1.1
	12F	3.9	2.0	4.4	1.8	3.4	1.5
P	Roof	6.0	4.0	4.2	3.5	3.6	2.7
	Roof	5.2	5.8	4.0	5.7	3.3	6.1
E	8F	3.6	4.2	3.8	6.0	2.7	6.4

M:Mast, T:Tower, P:Podium, E:Entrance

10. The Displacement Responses

The displacement responses of SSIS model could be acquired from two resource data. The first was from the displacement transducers, while the second was from the integrating of the acceleration data. The analysis showed either displacement transducers or acceleration transducers were satisfied each other.

The max inter-storey drifts of SSIS are listed in Table 6.

Table 6. Max Inter-storey Drifts subjected to Earthquake Motions.(1/x)

Position		Freq. 7		Basic 7		Rare 7	
		X	Y	X	Y	X	Y
	M-R	147	195	80	106	46	54
T	R-48F	968	1467	353	462	169	233
	48-37F	984	1120	399	493	201	161
	37-29F	1032	1169	395	506	188	218
	29-12F	1384	2145	535	847	212	351
	12F-B	2433	3281	816	1081	305	501

M:Mast, T:Tower, R:Roof, B:Base

11. The Torsion Responses

The torsion responses were acquired from a couple of sensors at symmetry sides of the model. The max torsion responses of the model were observed under earthquake motions, and became more serious while the earthquake intensity increased. For example, the max torsion angles of the tower were 1/1830 subjected to frequently-occurred earthquakes, 1/450 subjected to basic earthquakes, and 1/150 subjected to rare-occurred earthquakes.

On the other hand, the torsion responses of podium were different from the tower, which means the wide of the joint between the tower and podium was changed during earthquake motions. It was observed that some conjunction linkers of the joint were gradually out of function during basic earthquakes, as illustrated in figure 5.

While the model subjected to rare-occurred earthquakes, most of the conjunction linkers were out of function, and the podium was separated from the tower. The torsion response of podium was becoming more and more serious, which was nearly three times of the tower.

Fig. 5. Conjunction Linkers.

12. The Weak Regions of SSIS Structure

The possible weak regions of SSIS model during the seismic experiment were investigated, as shown in figure 6~8.

1. masts on the top of the tower,
2. the frame columns of the podium ,
3. roof structure of the podium,
4. the mega columns of the tower at the level of 6~10 storey,
5. the slender columns at the entrance.

Suggestions to improve the structural behavior of the previous weak members were put forward.

Viscous dampers were expected to be used as the linker between the tower and the podium. Further study on time viscous dampers are in processing by researchers of Tongji University recently.

13. Conclusions

The model test method is one of the economic, tangible, useful and reliable methods to assess the seismic safety and reliability of high-rise buildings.

As above-mentioned, the factors concerning the structural safety of Shanghai Shimao International Square were seriously considered. The dynamic characteristics of SSIS were investigated.

Several structural problems were taken into account, and countermeasures were investigated and adopted during design and construction process. Even thought it's beyond the limitation of the specifications, the structure of SSIS is proved to be safe subjected to earthquake.

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Fig. 6. Masts Curved.

Fig. 7. Cracks of Podium Frame

Fig. 8. Collapse of Roof Frame of the Podium

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