SHAKING TABLE TEST AND ANALYSIS ON SEISMIC BEHAVIOR OF STEEL-CONCRETE HYBRID STRUCTURE FOR HIGH RISE BUILDINGS

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ABSTRACT :

The steel-concrete hybrid structures for high rise buildings combine the advantage of concrete and steel structures. And they may resist large wind and strong earthquake actions. This type structure is more and more popular all over the world. Shaking table test on a 15 storey steel-concrete hybrid structure 1/10 model is conducted. Firstly, experimental study on the mechanical properties of copperplates, iron wires and micro-concrete is carried out. Secondly, the dynamic similitude relationship for steel-concrete hybrid structure is designed. Thirdly, the shaking table test is done. Some payloads are put on the floor to fulfill the acceleration similitude law. The El Centro wave is selected as the seismic motion input. About 40 accelerator transducers and 12 displacement transducers are set up on the model to measure the earthquake response in the shaking table test. The shaking table test is conducted in Tongji University, Shanghai, China. The acceleration response and displacement response are gained and analyzed. The seismic behavior such as vibration shape and distribution of the shear force and failure pattern of model are analyzed based on the shaking table test results. The seismic behavior of the prototype structure is analyzed according to the dynamic similitude relationship. It can be concluded that steel-concrete hybrid structure for high rise buildings may be constructed all over the world because of its good seismic performance.

KEYWORDS: steel-concrete hybrid structure, high-rise building, shaking table test, seismic behavior

1. INTRODUCTION

The steel-concrete hybrid structure is a complex structure for high-rise building and now it is more and more popular in the design of high-rise building. Some experimental investigations of the 1/20 scale model of 23-story steel-concrete hybrid structure model is conducted (GONG Bingnian et.al. 1995). The model was subjected to pulsation vibration, free vibration and hammering tests in order to investigate its flexibility, frequency and damping characteristics. The shaking table test on the 1/20 scale model of 25-story steel-concrete hybrid structure model is conducted (LI Guoqiang et.al. 2001). The behavior of the model subjected to earthquake is discussed and furnishes the basis for the earthquake resistant design and analysis of hybrid structures. A 1/35 scale model of steel-concrete hybrid structure for high-rise building was tested on shaking table to study the seismic behavior of the prototype structure (LU Xilin et.al. 2004). The dynamic characteristics and response of prototype structure were calculated according to the similitude relationship. The failure mechanism and cracking pattern under different earthquake intensities were also discussed. Another shaking table test on a 1/20 scale model based on LG tower was conducted to study seismic resistance of hybrid structures (LU Xilin et.al. 2004). The influence of earthquake spectrum and intensity on the performance of hybrid structures was investigated. The earthquake response and damage characteristics were also studied. Further study on the seismic performance of steel-concrete hybrid structure for high-rise building need to be conducted because more and more these structures will be constructed in China and other countries.

Shaking table test on steel-concrete hybrid structures for high-rise building is conducted to study its seismic performance. In the shaking table test, the micro-concrete, the iron wire and the copperplate are used to simulate the normal concrete, the steel bars and the steel components, respectively. The mechanical performance of micro-concrete, iron wire and copperplate is studied first in this paper. And then the shaking table test on the 1/10 scale model is conducted to study the dynamic properties, the acceleration response and the displacement response. The seismic performance of steel-concrete hybrid structures for high-rise building is analyzed.

2. MECHANICAL PERFORMANCE OF MODEL MATERIAL

2.1. Mechanical Performance of Copperplate

The mechanical performance of copperplate is studied according to some Chinese codes. The relationship between deformation and loading of copperplates with different thickness under different load applying rate is studied. The result is shown in Figure 1. As shown in Figure 1, there is no obvious yielding point and yielding platform and the strengthen phase. So the constitutive equation of copperplate can be simulated by ideal elastic-plastic model. This constitutive equation is not the same with that of the steel bars such as the yielding point, yielding platform and the strengthen phase.

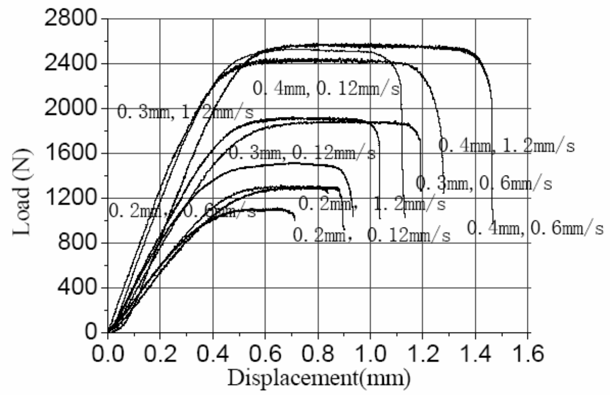


Figure 1: Relationship between displacement and loading of copperplate

The strength of copperplates with the thickness of 0.2mm, 0.3mm and 0.4mm under different load applying rate such as 0.12mm/s, 0.60mm/s and 1.2mm/s is studied. The ultimate strength and young's modulus of copperplate is shown in Table 1 and Table 2.

Table 1. Ultimate strength of copperplates with different thickness

NO.	Load applying rate(mm/s)	Ultimate strength(MPa)			
		0.2mm	0.3mm	0.4mm	average
1	0.12	351.1	317.5	386.3	351.6
2	0.60	415.2	394.3	403.8	404.4
3	1.20	411.4	402.0	400.8	404.7

Table 2. Young's modulus of copperplates

NO.	Load applying rate(mm/s)	Young's Modulus($\times 10^5$MPa)			
		0.2mm	0.3mm	0.4mm	average
1	0.12	2.39	2.21	2.56	2.39
2	0.60	2.53	2.50	2.60	2.54
3	1.20	2.85	2.55	2.74	2.71

As shown in Table 1, the ultimate strength of the copperplates with the same thickness is nearly equal under the load applying rate 0.6mm/s and 1.2mm/s. The ultimate strength of the copperplates with thickness 0.2mm, 0.3mm and 0.4mm under load applying rate 0.60mm/s and 1.20mm/s is larger than that under load applying rate

0.12mm/s by 18%, 20% and 4%, respectively.The average ultimate strength of copperplates with different thickness increases by 15% when the load applying rate increases from 0.12mm/s to 0.60mm/s.As shown in Table 2, the Young's modulus of the copperplates with thickness of 0.2mm, 0.3mm and 0.4mm increases by 6%,13%, 2% and 19%, 15%, 7% when the load applying rate increase from 0.12mm/s to 0.60mm/s and 1.20mm/s, respectively. The average value of Young's modulus increases by 5.9% and 13.4% when the load applying rate increases by 5 times and 10 times.The larger the load applying rate is, the larger the strength of the copperplates is. This effect must be considered when the dynamic similitude relationship is gained. The copperplates with different thickness have different mechanical performance, so the different similitude relationship for different thickness of copperplate will be adopted.

2.2. Mechanical Performance of Iron Wires

The mechanical performance of iron wires with diameter of 2.70mm, 2.22mm and 1.50mm is studied and the results is shown in Table 3.

Table 3. Mechanical performance of iron wires

NO	Diameter (mm)	Elongation rate (%)	Section shrinkage(%)	Yielding strength(MPa)	Ultimate strength(MPa)	Young's modulus(MPa)
1	2.70	20.5	79.6	335.9	436.1	72385
2	2.22	36.7	81.8	256.6	385.5	61745
3	1.50	20.8	77.9	266.5	372.9	77546
average		20.5	79.6	335.9	436.1	72385

The elongation rate of iron wires with different diameter is between 20.5% and 36.7%, and the average elongation rate is 26.0%. The average section shrinkage rate is 79.8%. The yielding strength of the iron wires is between 256.6MPa and 335.9MPa, and the average yielding strength is 286.3MPa. The ultimate strength of the iron wires is between 372.9MPa and 436.1MPa, and the average ultimate strength is 398.2MPa. The yielding strength of the iron wires is about 1.35 times and 0.95 times of that of rebar I and rebar II, respectively. And the Young's modulus of iron wires is about 1/3.5 to 1/2.5 times of that of steel bars. The iron wires with different diameter have different mechanical performance, so the different similitude relationship for different diameter of iron wires will be adopted.

2.3. Mechanical Performance of Micro-concrete

The mechanical performance such as compression strength and Young's modulus of micro-concrete is studied. The micro-concrete which is tested mechanical performance is used to construct the model of steel-concrete hybrid structure for high-rise building. The results are shown in Table 4.

Table 4. Mechanical performance of micro-concrete

Story	**1**	**3**	**5**	**6**	**9**	**11**	**13**	**15**
Compression strength(MPa)	5.20	8.92	8.25	9.59	9.58	11.05	16.02	19.09
Young's modulus ($\times 10^4$MPa)	0.91	1.09	1.15	1.60	1.04	1.43	1.40	1.49

As shown in Table 4, although the designed compression strength of micro-concrete of all the stories is the same, the testing results show that there is some difference between the designed and the real micro-concrete. Usually, the different strength of all stories is averaged, and the result is used to design the similitude relationship. There is some errors of this method. As shown in Table 4, the compression strength and the Young's modulus are not of the same similitude relationship. But usually we think that the compression strength and the Young's modulus are of the same similitude relationship. So much attention must be paid to further research on this problem.

3. DESIGN OF DYNAMIC SIMILITUDE RELATIONSHIP

The dynamic similitude relationship may be designed by theoretical research or experimental research. The main similitude scale factors of these two models are shown in Table 5.

Table 5. Similitude scale factors

Model	Young's modulus	Mass density	Mass	Time	Frequency	acceleration
1/10	2/7	0.9533	0.00095	0.18257	5.47723	3

3.1. Similitude Relationship of Steel Tubular Column

The method we adopted to design the similitude relationship of steel tubular column is that the similitude scale factor of the section dimension must be fulfilled and then the similitude scale factor of the section area and bending rigidity will be satisfied. The thickness of the copperplate must be reduced in order to satisfy the similitude scale factor such as geometrical dimension, section area, and bending rigidity. In fact, there is not copperplate with any thickness for us to choose, so the section dimension will be adjusted in a small scope.

3.2. Similitude Relationship of I Shape Beam

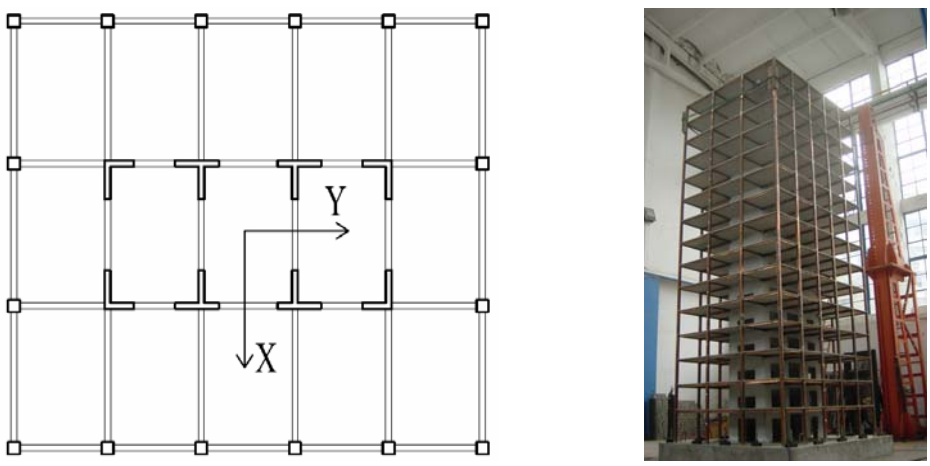
The action applied on the beam mainly is bending moment and shear force. The similitude scale factor of bending rigidity is used to design the model beam. The I shape beam is made by two C shape beam connected by welding.

3.3. Similitude Relationship of Steel Bars in Shear Wall

The similitude scale factors of diameter, Young's modulus, strength, constructional detail and distribution of steel bar are considered in the design of the similitude relationship of steel bars in shear wall. The distribution and constructional detail of the iron wire must fulfill the similitude relationship.

4. CONSTRUCTION OF THE MODEL

The 1/10 scale model is shown in Figure 2.



(a) structural plan view (b) scale model

Figure 2: 1/10 scale model

The concrete core tube is constructed, and then the frame-structure made from copperplate is constructed. The iron wires are connected by welding for the diameter is too small. The foam is used as the formwork for its lower elasticity.

5. SHAKING TABLE TEST

5.1. Description of the Shaking Table

Shaking table test model is carried out using MTS shaking table facility at State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. Its frequency ranges from 0.1Hz to 50Hz and there are 96 channels available for data acquisition during testing process.

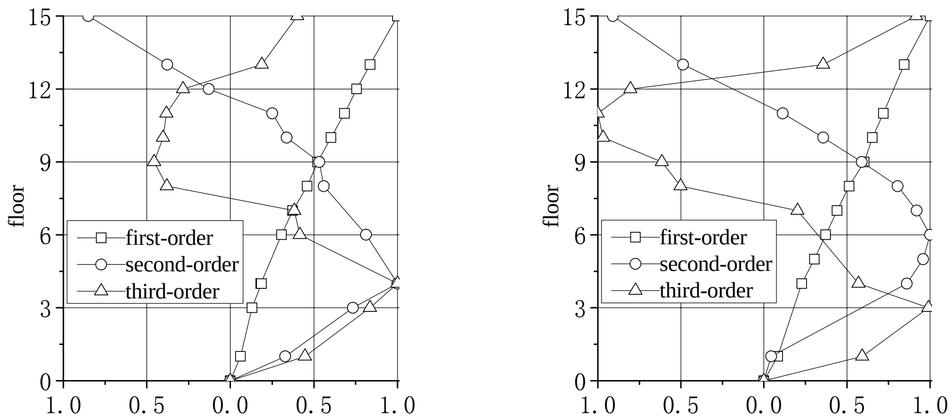
5.2. Test Procedure

To ensure an effective transmission of the table motion to the base of the test structure, the model base plate was firmly mounted on the shaking table through bolt connections. The instrumentation is organized so that dynamic response and dynamic characteristics could be measured.

In order to evaluate the dynamic performance under different seismic motions, El Centro wave (1940,NS) time histories of acceleration is selected as the input data. The test is carried out in frequent, basic and rare occurrences of fortification intensity 7 and rare occurrence of fortification intensity 8. The gradually increasing amplitudes of base excitation is input successively in a manner of time-scaled earthquake waves. After different series of ground acceleration are input, white-noise is scanned to determine the natural frequencies of the model structure. The peak value of the white-noise input is selected to 0.05g in order to keep the model in linear elastic deformation.

6. TEST RESULTS

Modeling scale factors, given in Table 5, can be used for interpreting the model test results to prototype structure. The dynamic properties and dynamic response of the prototype of steel-concrete hybrid structure for high-rise building are shown in the following.



(a) Direction X (b)Direction Y

Figure 3: Vibration mode of the prototype

6.1. Dynamic characteristics of Prototype

The vibration modes the prototype structures are shown in Figure 3. The first-order, second-order and third-order vibration modes are all shown in Figure 3.

6.2. Acceleration Response of the Protype

The acceleration response was obtained from the accelerometers installed on the models. The acceleration amplifier coefficient in direction X and Y are shown in Figure 4.

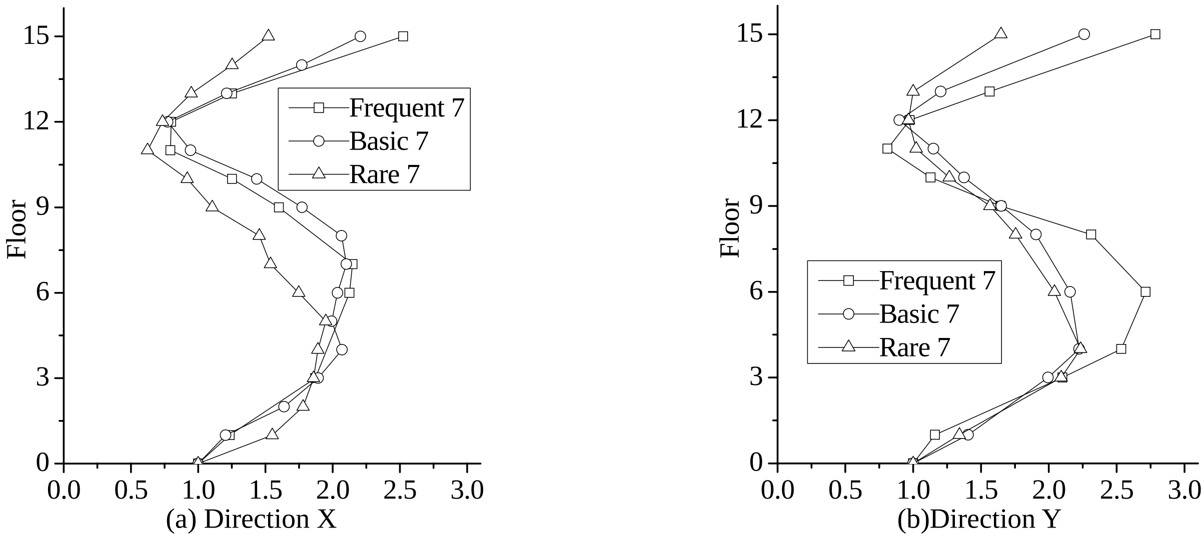


Figure 4: Displacement of the prototype

The acceleration amplifier coefficient in direction X is smaller than that in direction Y. The acceleration amplifier coefficient of the prototype is S shape. The maximum acceleration amplifier coefficient is in the roof storey. The more the earthquake intensity is, the smaller the roof acceleration amplifier coefficient is. The maximum acceleration amplifier coefficient in direction X and Y are 2.52 and 2.78, respectively.

6.3. Displacement Response of the Prototype

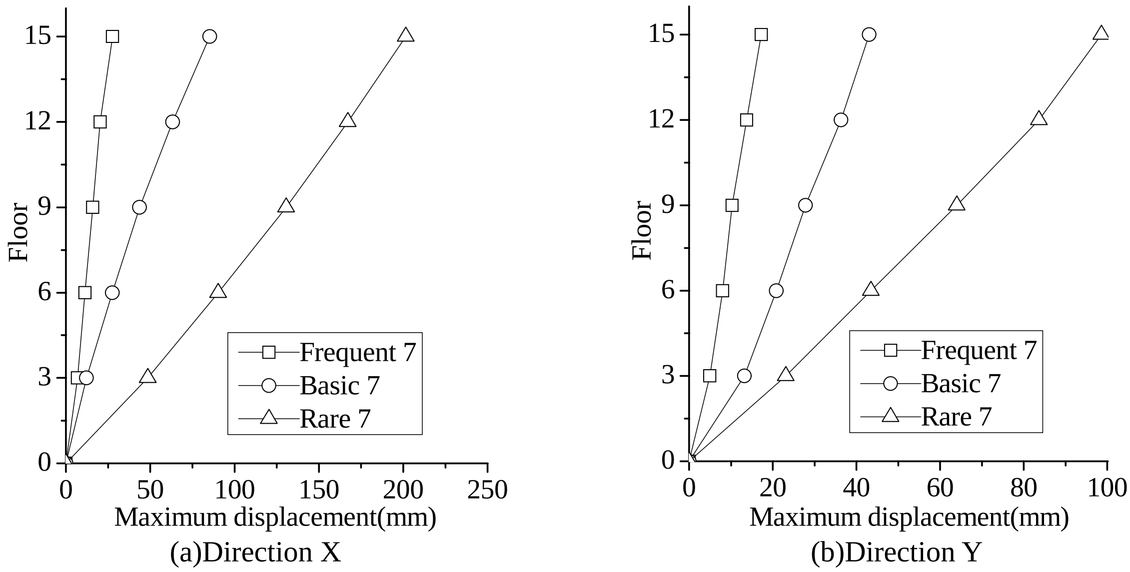
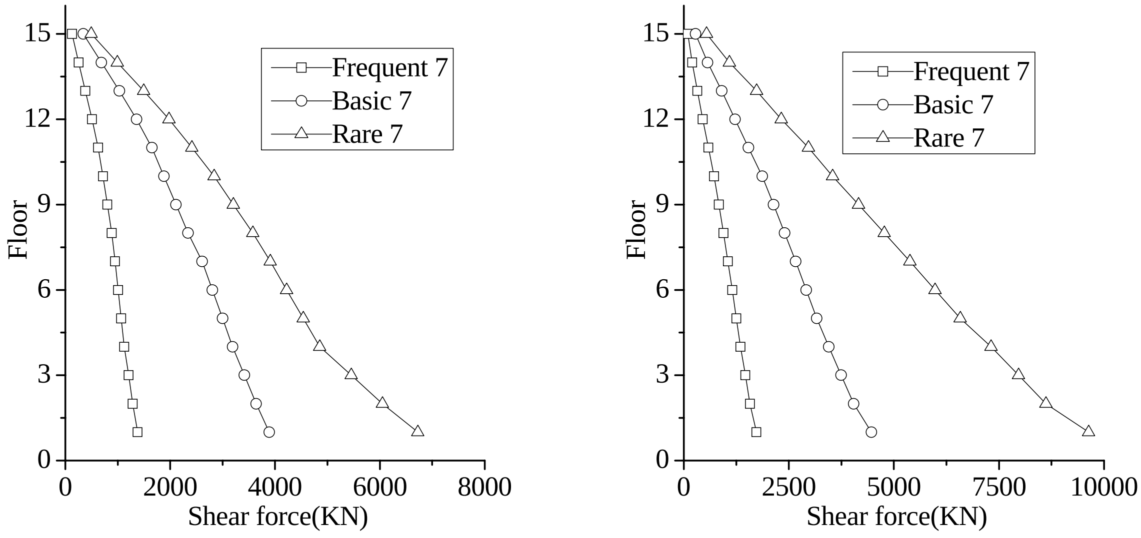


Figure 5: Displacement of the prototype

The maximum storey displacement is shown in Figure 5. Generally, the storey displacement responses in direction X are larger than those of direction Y. The ratios of roof maximum displacement to height in direction X and Y are 1/303 and 1/622, respectively. The maximum storey displacement curves are relatively smooth without obvious inflexions, which mean that the distribution of equivalent rigidities along the structure is well proportioned.

6.4.Inter-storey shear force of prototype

The average storey shear force distributions along the height under three earthquake levels are demonstrated in Figure 6. The inter-storey shear force of protype in direction Y are larger than those of direction X. The distributions of the shear force along the structural height are about triangular. The ratios of the shear force to the weight are approximate uniform.



(a)Direction X (b)Direction Y

Figure 6: Shear force distribution of the prototype

6.5. Cracking and Failure Pattern

The test model survived earthquake waves from frequent intensity 7 to rare 7 without visible damage. Major damages eventually occurred and propagated under rare occurrence earthquake of fortification intensity 8, which are shown in Figure 7.

Figure 7: Concrete crack on the bottom of the shear wall

The main failure patterns under rare intensity 8 ia that obvious cracks occurred horizontally on the core wall at the bottom of floor 1.

7. CONCLUSIONS

Seismic behavior of 1/10 scale model of a 15-storey steel-concrete hybrid structure is tested on a shaking table by subjecting it to a series of simulated seismic ground motions with increased intensity of shaking in each successive test run. The following conclusions can be drawn from the test results.

1) It is difficult to keep the same similitude relationships between the steel components and concrete components, such as strength, modulus, and geometrical dimension. Some equivalent principle is introduced in this paper. The copper plate, iron wires and micro-concrete can be used to construct the shaking table test model for steel-concrete hybrid structures for high rise building.
2) The structure, designed under earthquakes of intensity 7, can resist frequent intensity earthquakes without damage, resist basic earthquakes with some structural cracking, and resist rare earthquakes without collapse. The structural design is deemed to have met the three-stage requirements of the design code provisions.
3) The acceleration amplifier coefficient is S shape and the maximum value in direction X and Y are in the roof storey. The distributions of the shear force along the structural height are about triangular and the shear force in direction Y is larger than those in direction X. The ratios of the shear force to the weight are approximate uniform.
4) The storey maximum displacement in direction X and Y is 201mm and 98mm respectively. And the ratios of roof maximum displacement to height in direction X and Y are 1/303 and 1/622, respectively.
5) The shaking table model test results indicate that the prototype structure of steel-concrete hybrid structure for high-rise building can resist frequent occurrence, basic occurrence and rare occurrence earthquake of fortification intensity 7 without collapse. The steel-concrete hybrid structure demonstrates good performance in resisting earthquakes.

8. ACKNOWLEDGEMENT

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