SHAKING TABLE EXPERIMENTAL STUDY OF REINFORCED CONCRETE HIGH-RISE BUILDING

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SUMMARY

them can not meet the current Chinese Earthquake Design Code. According to Chinese Earthquake Design Code, those buildings must be special studied. Shaking table experiment is the best method to study the seismic behavior of those buildings.

The similarity design is the key to obtain the good test results. Firstly, this paper discusses the similarity theory of high-rise building model for shaking table experiment. Micro-concrete high-rise building model is a big and heavy model. But the carrying capacity of the shaking table is limited. So the scale of the high-rise building model must be less than 1/20. Therefore the gravity acceleration has to ignore. The similarity coefficient of acceleration is about 2 to 4. The model can be designed as a strength model that ignores gravity acceleration.

Secondly, some high-rise building models are designed with similarity theory presented above. Then shaking table experiments of those models are introduced. The experimental results compared with analytical results of the prototype building. The results show that the analytical results of complex structures such as body connecting structure have large errors. So, this paper tests those prototypes of complex structures. The test results approach the shaking table experimental result

INTRODUCTION

exceed the requirements of current design code in height and regularity. The design parameters for the special buildings are chosen according to current design code. The calculating model and damping are given based on assumption and model experiment. All above will cause the difference between real structure and calculating structure. In fact, design parameters in the codes are different from real buildings.

Some shaking table experiments of reinforced concrete high-rise buildings have been done since 1993. This paper studies the shaking table experimental method of reinforced high-rise building. As an example, the model test of Shanghai Kai Xuanmen Building is introduced. In order to prove the correctness of shaking table experiment, the prototype was measured after it was completed. The results are compared with the results of shaking table mode test and calculated values. It proves that the results of shaking table tests are more close to the results of site measuremen

NORMAL PRINCIPLE OF SHAKING TABLE MODEL EXPERIMENT

under earthquake load, determine the calculation model of restoring force, judge the earthquake resistance behavior of structure, study failure mode of the structure and improve current code. In order to realize the purpose, the similarity condition of the model must be studied firstly.

The model and prototype must meet the following condition that the model and prototype perform same physic

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phenomenon. Therefore, the model must simulate the prototype in size, material behavior, initial condition, and boundary condition and load effect.

The method founding the similar relationship between model and prototype is called dimensional analysis method. The base of this method is that any physic phenomenon can be described as dimensional homogeneity. For dynamic model, the dimensional homogeneity formula is as follows:

$$s = f(\vec{r}, t, r, E, a, g, l, s_0, \vec{r}_0) \tag{1}$$

According to *p* theorem, every dimensional homogeneity formula with n variables can be simplified as a function of (*n*-*N*) variables. For dynamic model, the formula is as follows:

$$\frac{s}{E} = f\left(\frac{\vec{r}}{l}, \frac{t}{l}\sqrt{\frac{E}{r}}, \frac{a}{g}, \frac{alr}{E}, \frac{s_0}{E}, \frac{\vec{r}_0}{l}\right) \tag{2}$$

Type of Dynamic Model:

Dynamic model can be divided as strength model, artificial mass strength model, ignoring gravity model and strain fuzzy model. The similarity condition is shown in Table 1.

Table 1: Similarity condition

	Strength model	Artificial mass model	Ignoring gravity model	Strain fuzzy model
Length S_l	S_l	S_l	S_l	S_l
Time S_t	$S_l^{1/2}$	$S_l^{1/2}$	$S_l\, S_r^{1/2}\, S_E^{-1/2}$	$S_l^{1/2}\, S_e^{1/2}$
Frequency S_f	$S_l^{-1/2}$	$S_l^{-1/2}$	$S_l^{-1}\, S_E^{1/2}\, S_r^{-1/2}$	$S_l^{-1/2}\, S_e^{-1/2}$
Gravity Acceleration S_g	1	1	Ignoring	1
Acceleration S_a	1	1	$S_E\, S_l^{-1} S_r^{-1}$	1
Velocity S_v	$S_l^{1/2}$	$S_l^{1/2}$	$S_E^{1/2}\, S_r^{-1/2}$	$S_l^{-1/2}\, S_e^{-1/2}$
Displacement S_d	S_l	S_l	S_l	$S_l\, S_e$
Elastic modulus S_E	S_E	S_E	S_E	S_E
Stress S_s	S_E	S_E	S_E	$S_E\, S_e$
Strain S_e	1	1	1	S_e
Force S_F	$S_E\, S_l^2$	$S_E\, S_l^2$	$S_E\, S_l^2$	$S_E\, S_l^2\, S_e$
Density S_r	$S_E\, S_l^{-1}$	S_r ‘	S_r	$S_E\, S_e S_l^{-1}$
Energy S_N	$S_E\, S_l^3$	$S_E\, S_l^3$	$S_E\, S_l^3$	$S_E\, S_l^3 S_e^2$

Strength model:

The model that satisfies Eq.(2) is called strength model or real model. When we do a model test on earth, the gravity acceleration is normally equal 1g. So, the model’s elastic modulus should be smaller than prototype’s, or the density of model material should be larger than prototype’s. This condition limits the selective field of model material. It is very difficult for steel model.

Artificial mass model:

This model is using the material, which do not influence the strength and stiffness of the model, to add the efficient density of the model material.

Ignoring gravity model:

The gravity acceleration may be ignored when the stress created by gravity force is rather smaller than that created by earthquake force. This model is called ignoring gravity model. Sometimes, this kind of model can be designed as strength model, and at other time this kind of model can be designed as elastic model.

Strain fuzzy model:

When the stress-strain curve of model is different from that of prototype, the model is strain fuzzy model. For steel material, the elastic modulus is same, but the yield strength is often different, for example, the strength of A3 is smaller than the strength of Mn16. This kind of model is called strain fuzzy model.

Similarity Factor Determination:

The similarity factor is not unique. Therefore, the capacity of the experimental equipment must be considered before determining similarity factor. The specimen is usually fixed on the table with bolts. So the sizes of the specimen have to meet the requirements of the table. Height is the second condition we must consider. If the model higher than the crane height, the model could not be lifted from constructing site to the table. Although the model's weight must lighter than the capacity of the table, and the natural frequency must be in the table's working frequencies.

Similarity Design of Reinforced Concrete High-rise Building:

Reinforced concrete high-rise buildings are very high and very heavy. So the weight and height are the very important conditions. The scale that is often used is 1/25~1/50. The most of the shaking table test of high-rise building is to check the design. The acceleration chosen in design is very low. For example, the acceleration is 0.035~0.2g in Shanghai. The noise acceleration of shaking table is about 0.01~0.05g. If the model is designed as a strength model, the earthquake wave couldn't appear on the table because of the noise acceleration. Therefore, acceleration similarity factor is often equal to 2~5. The model is an ignoring gravity mode

SHAKING TABLE EXPERIMENT EXAMPLE

been done in State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, see Table 2. As an example, the model experiment of Shanghai Kai Xuanmen Building is introduced in this paper. The object of this experiment is to study the natural frequencies, acceleration and strain responses of the structure, the earthquake force and failure position of the model.

Table 2: Shaking table experiments

Name	Height (m)	Length S_l	Acceleration S_a
Hainan Futong High-Rise Building	175	1/25	3.125
Chinese Finance Building	138	1/25	8.29
Shanghai Kai Xuanmen Building	100	1/25	5.0
Shanghai Xinghai Building	84	1/25	7.11
Shenzheng Jing Guang Centre	128	1/25	4.0
Guangzhou International Trade Square	249	1/100	6.02
Yuexiu Tower	204	1/28	4.67
Shanghai Changshou Square	114	1/25	3.0
Shang Long Tower	175	1/25	4.0
BOCOM Financial Tower	230	1/33	2.64

Structural System of Shanghai Kai Xuanmen Building:

Shanghai Kai Xuanmen Building is 100m high, 31-stories. The structure consists of two huge door-columns in outside, and a huge girder at the top of the structure to connect two huge door-columns (see Figure 1). It looks like triumphal arch. Some of the floor plates are uncontinuous in their floor level. The structure couldn't be designed using structure analysis software at that time. So, shaking table test on this building model was done before it constructed in 1993.

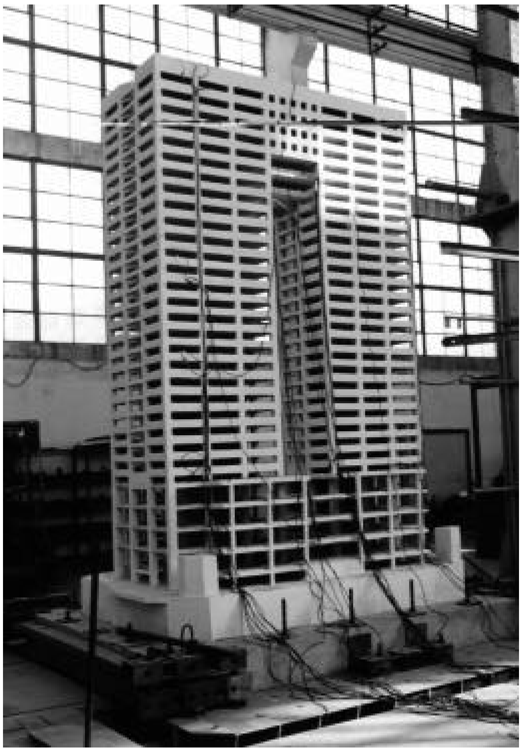

Figure 1: The model of Kai Xuanmen Building

Similarity Factor:

According to the capacity of the shaking table, and the elastic modulus of model's material, the model is designed as an ignoring gravity model. The similarity factors are shown in Table 3.

Table 3: Similarity factor

	Model/Prototype
Length S_l	1/25
Elastic modulus S_E	1/5
Stress S_s	1/5
Acceleration S_a	5
Displacement S_d	1/25
Time S_t	0.0894
Frequency S_f	11.19
Strain S_e	1
Density S_r	1

Model Material:

The model is made of micro-concrete and steel mesh. The strength and elastic modulus are shown in Table 4.

Table 4: Strength and elastic modulus

Floor	Compression strength (MPa)		Elastic modulus (MPa)	
	Test	Design	Test	Design
-2~6	11.3	12.0	9738	7200
7~12	8.71	10.0	7002	6900
13~roof	6.79	8.0	6593	6500

Earthquake Wave and Experiment Program:

In order to study the earthquake response of the model in different earthquake, El-Centro record, Pasadena record and Shanghai artificial waves are chosen as the input waves. Firstly, the uniaxial earthquakes are done.

Secondly, the triaxial earthquakes are input. The proportion of input acceleration amplitude in x, y, z-axes is 1.0:0.8:0.6.

Measurement:

In this experiment, acceleration and strain are measured. The 21 acceleration transducers are installed at bottom, 7th, 14th, 20th, 26th floor, and roof. The 25 strain gauges are stuck at the columns of 1st, 6th, 25th, 26th, 27th floor. The displacement is calculated from acceleration using FFT method.

Experiment Results:

The first cracks appear at the columns of 6th, 7th, 8th, 10th, 11th floor when the 0.5g 3D El-Centro input. The concrete break and the steel bar yield after the 1.0g artificial wave excited.

The amplification factors of acceleration decrease when then earthquake amplitude increase, because the damping increase with the earthquake intensity increasing. On other hand, the model has different response in different earthquake, because different earthquake waves have different frequency characteristic. The response will be very strong while the frequency of earthquake is approaching the natural frequency of model.

Comparing with Model Test and Calculation Results:

The structure has been analyzed with SAP84 software. The structure member is simulated by beam element. But it doesn't consider the restriction effect in beam-column joint. The calculated results and model test results are listed in Table 5. The calculated periods are less than the measured value. That means the stiffness of real structure is larger than the calculating structure. In fact, because the beam depth is high, it restricts the deformation of column. So, the real deformation in the structure is less than calculated value.

Table 5: Comparison of period

Mode type	Measurement (s)	Model test		Calculation	
		Period (s)	Error (%)	Period (s)	Error (%)
NS	1.795	1.577	-12.14	2.985	66.30
EW	1.383	1.082	-21.76	2.004	44.90
Torque	1.066	0.932	-12.57	1.441	35.18
NS	0.447	0.387	-13.42	0.770	72.26
Torque	0.303	0.293	-3.30	0.562	85.48
EW	0.302	0.289	-4.30	0.530	75.50
EW	0.269	0.294	9.29	0.383	42.38
Torque	0.224	0.269	20.09	0.365	62.95

Site Measurement Results:

The mass of high-rise buildings is huge. It is therefore difficult to excite the building using a vibration machine. In fact, the buildings vibrate at all time due to ground micro-vibration. This micro-vibration is created by earthquake, vehicle moving, people walking and wind. Any of the building has micro-vibration response, which can be measured by sensitive equipment and can be used to obtain the dynamic parameters of the structure.

The vibration frequency of high-rise buildings is very low. Therefore, the measuring system must have good low frequency response and high sensitivity. In this paper, the following measurement system is used to measure the micro-vibration, see Figure 2. This system includes sensors, amplifier, recorder, data processor, and computer. The velocity sensors are used for Shanghai Kai Xuanmen Building. The recorded data is analyzed with FFT software. The FFT frame is 1024, and interval is 0.1 second.

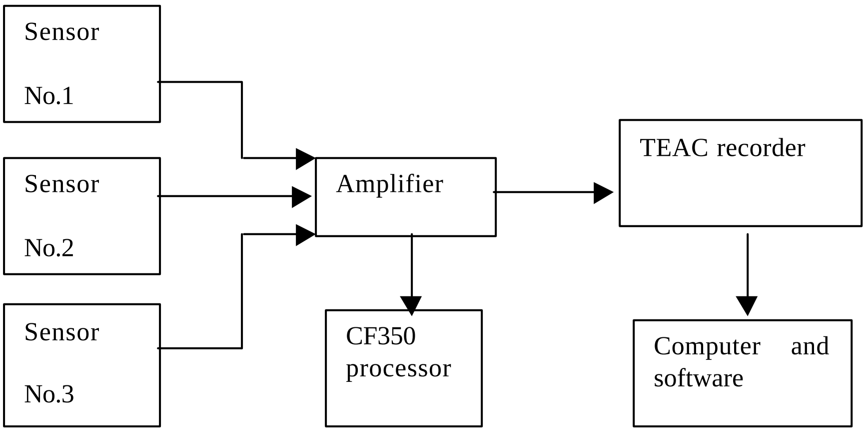

Figure 2: Measurement system

The building is measured on July 7, 1998 while it is in service condition. The measurement results are listed in Table 6. The power spectra in NS and EW direction are shown in Figure 3 and Figure 4, respectively. NS direction is out of plan, and EW is in the plan of the huge door. The huge door likes a huge frame, therefore the frequency in EW direction is larger than that in NS.

Table 6: Vibration Frequency and Damping

No.	Mode type	Frequency (Hz)	Period (s)	Damping
1	NS	0.557	1.795	0.01359
2	EW	0.723	1.383	0.01780
3	Torque	0.938	1.066	0.01569
4	NS	2.236	0.447	0.00452
5	Torque	3.301	0.303	0.00072
6	EW	3.310	0.302	0.01249
7	EW	3.711	0.269	0.01237
8	Torque	4.463	0.224	0.08289

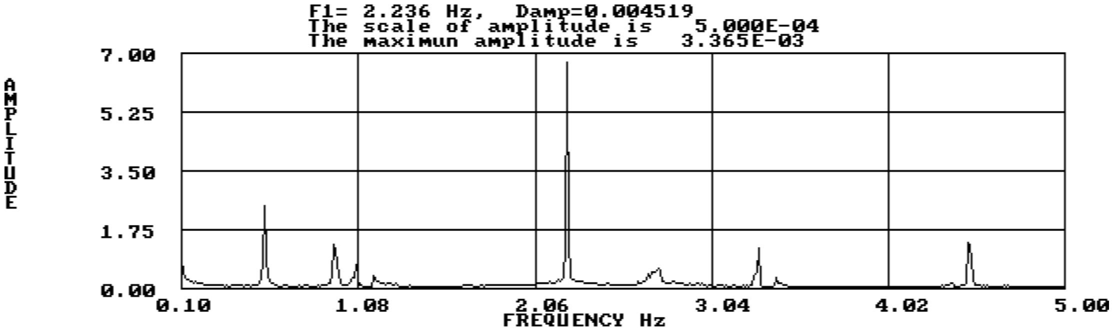

Figure 3: Power spectrum of Shanghai Kai Xuanmen Building in NS

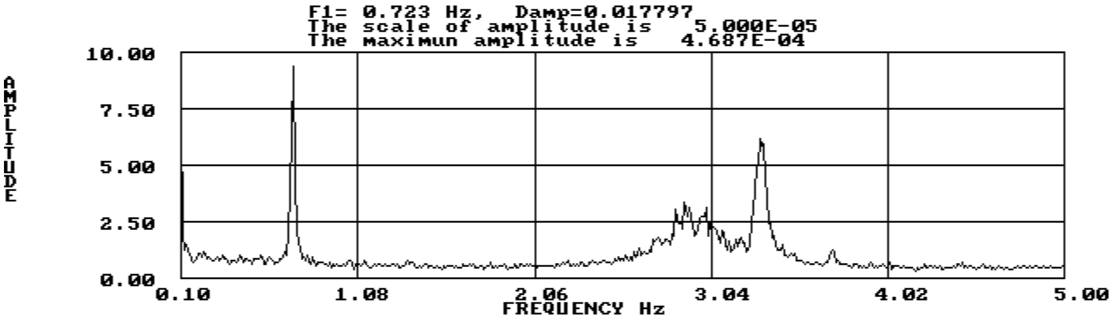

Figure 4: Power spectrum of Shanghai Kai Xuanmen Building in EW

The testing model used in shaking table test is made of reinforced micro-concrete. The natural characteristics are tested by white noise excitation. The results are also listed in Table 5 and Table 7. The period of model test approaches the measured value. The damping ratio is larger than the measured value. The exciting acceleration in site measurement is very low (about 0.001g), and the exciting acceleration in shaking table test is large (about 0.1g), which causes the nonlinear or micro-crack in reinforced concrete members. The nonlinear or micro-crack will increase the damping ratio.

Table 7 Comparing of Damping

Mode type	Damping	
	Measurement	Model test
NS	0.01359	0.0345
EW	0.01780	0.0542
Torque	0.01569	0.0238
NS	0.00452	0.0276
Torque	0.00072	0.0221
EW	0.01249	0.0222
EW	0.01237	0.0179
Torque	0.08289	0.0122

CONCLUSIONS

The models that are usually used in shaking table experiment are strength model, artificial mass model, ignoring gravity model, and strain fuzzy model. The ignoring gravity model is adopted for reinforced concrete high-rise building because of the weight and high of the building. The scale that is often used is 1/25~1/50. The acceleration similarity factor is often equal to 2~3.

There are large errors between the calculated value and measured value. Therefore, the analysis model of high-rise building should be improved. The restriction of beam and column should be considered if the depth of the beam is large.

The design methods suggested by Chinese current design codes are adaptable for most high-rise buildings if the structure is simple and regular. But special study is suggested for complex and irregular structures.

Shaking table model test is a good method to investigate the natural vibration characteristics and seismic behavior of irregular structure. The current similitude principle is applicable for high-rise building model test if one carefully designs and constructs the model. The test results of micro-concrete model test are useful for engineering desig

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