AMBIENT VIBRATION ANALSIS AND STRUCTURAL MODELING OF THE HIGH-RISE BUILDINGS

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ABSTRACT

The frequencies and mode shapes, obtained from on-site ambient vibration test and operational modal analysis for high-rise building, are very important for structural dynamic property design and seismic design. In this paper, the Guangxi Laibin high-rise building ambient vibration test project was introduced, in this project 8 buildings were selected for ambient vibration test to obtain the accelerations in time domain, then the cross correlation analysis and fast Fourier transform were utilized to generate cross power spectrum, from which the modal parameters can be obtained by operational modal analysis. Finite element (FE) models were constructed in PKPM and Sap2000 softwares to calculate modal frequencies and mode shapes, in order to research the influence of mass and stiffness of the in-filled wall to the dynamic properties, 3 models were built in Sap2000 to estimate mode frequencies and mode shapes. It was found that the measured fundamental frequency is almost twice larger than PKPM software estimation frequency, and the shell element was verified to rationally estimate the stiffness of the in-filled wall. At last, the frequencies tested from 8 high-rise buildings were compared with the empirical equation estimation results from four countries code.

KEYWORDS

High-rise building; Ambient vibration; Operational modal analysis; In-filled wall stiffness; Modeling analysis; Fundamental period estimation.

INTRODUCTION

Performance of a high-rise building subjected to seismic, wind and other dynamic loads depends on its structural physical properties such as mass, stiffness and their distribution. While modal parameters, such as frequency, mode shape and damping ratio, will reflect the physical parameter characteristic in modal space. The modal parameter set can be identified through the ambient vibration test, and the valuable information is not just for calibration of analytical model but also for other applications, such as the evaluation of prototypes, structural health monitoring and structural vibration control etc. Full-scale measurements can produce limited but accurate results of dynamic characteristics of the buildings and structures. It is recognized as the most reliable way for evaluating dynamic behavior of tall buildings. To a high-rise building, full-scale monitoring provides the opportunity to directly correlate actual building performance to occupant perception criteria. Field measurement results can be used to improve model test techniques and to refine the numerical models for structural analysis as well.

A lot of full scale dynamic tests were conducted on some super high-rise buildings. In 1998 and 2003, Brownjohn *et al* (1998, 2003) conducted health monitoring measurement on a 18th story of a 65-story office tower named Republic Plaza for 12 years, a comprehensive ambient vibration survey and FE model updating exercise provided a thoroughly validated analytical model of the structure. In 2004, Li *et al.* (2004) conducted field measurements to investigate the dynamic characteristics of Di Wang Tower in Shenzhen. Seven FE models have been established to model the multi-outrigger-braced tall building and to analyse the effects of various arrangements of outrigger belts and vertical bracings. In 2004, Wu *et al.* (2004) researched an eigensensitivity-based FE model updating procedure for FE model updating of an existing 310m tall Nanjing TV Tower based on ambient vibration measurements. Detailed comparative study is conducted with consideration of six FE model cases with selecting different groups of updating parameters and constructing the eigensensitivity matrix with various methods. In 2005, a partnership led by University of Notre Dame in Chicago (Kareem *et al*, 2005) was established to initiate the Chicago full-scale monitoring program, and the actual performance of three tall buildings in Chicago is compared to predictions, both by FE and wind tunnel modes. In 2009, Ni et al. (2009) designed a sophisticated structural health monitoring (SHM) system consisting of over 600 sensors on Guangzhou New TV Tower for in-service real-time monitoring. In 2011, Li *et al* (2011) performed health

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monitoring on Taipei 101 Tower and analyzed the data recorded during three typhoons as well as a seismic event to investigate the effects of wind and seismic on the supertall building. In 2012, Shi *et al*. (2012) conducted a set of dynamic field tests on Shanghai World Financial Center, and the modal frequencies obtained from the FE model analysis and the shaking table test are further studied with the results of field test. In 2013, Kareem et al. (2013) initiated a program to monitor the full-scale response of representative tall buildings and compare this to the predicted response from wind tunnels and FE models used commonly in design.
In this paper, a Laibin full-scale high-rise building ambient vibration test project led by Hunan University was simply introduced. The actual dynamic characterises of eight buildings were systematically measured and analyzed. Xiang Yun Yuan A# building was chosen for an example, and the dynamic signal analysis and spectrum analysis were conducted to obtain the modal information. PKPM software and Sap2000 software were utilized for modal parameter predictions, especially three models considering the mass or the stiffness were built in Sap2000 for comparison. Finally the measured first three natural frequencies were compared with the calculation results predicted by different FE models. The measured first frequencies of different buildings were compared with the empirical equation estimation result.

LAIBIN HIGH-RISE BUILDING TEST PROJECT

Project Introduction

A partnership led by Hunan University and Laibin Housing and Urban-Rural Construction Committee was established to initiate Laibin high-rise building full-scale ambient vibration test project. The primary purpose of this project is to correlate the in-situ measured dynamic response of eight high-rise buildings in full scale with computer based analytical models for the improvement of the high-rise building seismic design and optimization. The detailed descriptions of the tested buildings were listed in Table 1. Most of the new buildings have no live loads of residents and the furniture. These buildings are all designed as concrete frame-shear wall or pure shear wall structure, most of which utilized straight reinforced concrete artificial excavating pile extending to bedrock.

Table 1. Introduction of Tested High-rise Buildings

Building Name	Height(m)	Storey(n)	Structural form	Temp. (℃)	10min average wind speed (m/s)
Shui Hu Huang Men 2#	98	33	Shear wall	10.0~11.2	1.4723
Shui Hu Huang Men 1#	116	39	Shear wall	16.2~17.9	0.8873
Jin Sui Xiao Qu 1#	99	34	frame-shear wall	18.2~18.4	2.9373
Jin Sui Xiao Qu 3#	116	41	frame-shear wall	22.5～26.3	1.9880
Xiang Yun Yuan A#	75	24	Shear wall	12.0～12.8	2.8490
Xiang Yun Yuan B#	75	24	Shear wall	14.8～16.5	1.7169
Bei An Ya Ge 1#	88	29	Shear wall	10.1～10.3	1.6856
Bei An Ya Ge 2#	79	26	Shear wall	14.0~15.6	2.3767

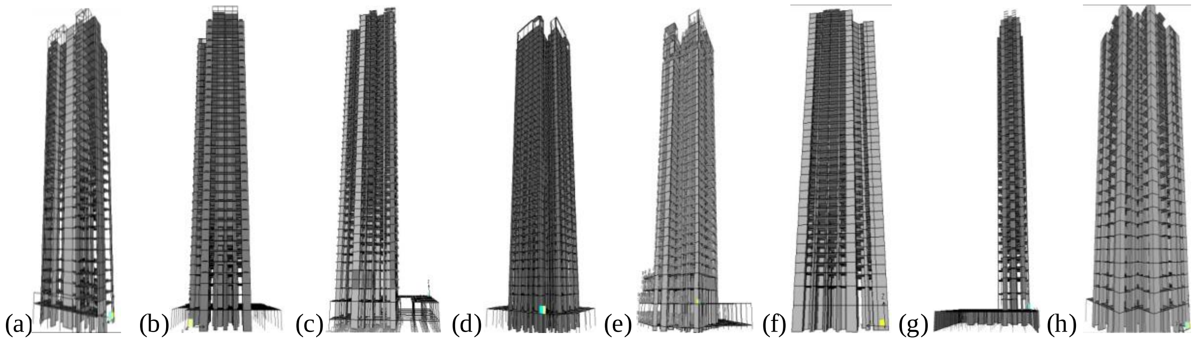
In-situ Dynamic Test Introduction

Each building is equipped with almost the same instrumentation system and layout that features four US Wilcoxon 731A high sensitivity accelerometers and four Chinese KD12000L accelerometers, capable of accurately measuring accelerations in low frequencies with high sensitivity, making them well suited for measuring these high-rise buildings. These accelerometers are mounted in orthogonal pairs at three opposite corners along two sides of the building. The reference layout was arranged in the middle height of the building for saving cable length, and the roving layer was set on the top of the building, then it was moved to the bottom storey in every 3~5 stories in each case. The sampling frequency for capturing ambient signals was set as 204.8Hz, and recorded by LMS Cadax 8 data acquisition (DAQ) system. The DAQ is programmed to continuously capture 15-min time history of these accelerometer outputs. The correlogram method, computed the correlation functions in the time domain before transferring them into the frequency domain by Discrete Fourier Transform (DFT), was used for pe-processing method. Complex Mode Indicator Function Algorithm (CMIF) was included in post-processing for modal parameter identification.

FINITE ELEMENT MODELING

Modeling in PKPM and Sap2000 Software

Two different softwares were utilized to build the FE models for eigenvalue analysis. Firstly SATWE module in PKPM software designed by China Academy of Building Research was utilized in modal analysis. In this software, only the mass of the in-filled wall was loaded on the corresponding beam without considering the stiffness of the wall. In addition, the foundation and the substructure analysis were belong to two modules in the software, and the loading acting on the superstructure were transferred from the substructure to the foundation, and at the footing of the substructure were considered to be fully fixed without considering the interaction of the substructure and the soil foundation. Due to the limitation of PKPM software, another software Sap2000 was used for modelling. SAP2000 was designed by Computer and Structures Inc. (CSI) and was widely used in engineering. Eight high-rise buildings used for Sap2000 modelling was shown in Figure 1.



(a)Shui Hu Huang Men 2# (b) Shui Hu Huang Men 1# (c) Jin Sui Xiao Qu 1# (d) Jin Sui Xiao Qu 3# (e)Xiang Yun Yuan A# (f) Xiang Yun Yuan B# (g) Bei An Ya Ge 1# (h) Bei An Ya Ge 2#

Figure 1. Sap2000 models for tested eight high-rise buildings

In-filled Wall Modeling

To evaluate the influence of different modeling approaches of the in-filled wall to the dynamic properties of the high-rise buildings, three different models were built in Sap2000 for comparison. They are listed in the following,

(a) Model 1: The FE model without considering the mass and stiffness;
(b) Model 2: The FE model considering only the mass of the in-filled wall;
(c) Model 3: The FE model considering both the mass and the stiffness.

Model 1 simulation is an idealized situation, and it was built only for comparison as baseline reference. The mechanism of Model 2 is consistent with PKPM modeling approach, in which the mass of the in-filled wall was loaded on the corresponding floor beams. Due to the existence of the window and the door on the infilled wall, reduction coefficient 0.75 for permanent loading was chosen when considering the modeling process. As for model 3, the compressive strength standard value was chosen as 2.4 MPa for the construction of MU10 bricks and M5 mortar. The Possion ratio was selected as 0.2 and the elastic modulus was chosen as 1.85×10^4 N/mm^2. FE modelling of Xiang Yun Yuan A# building in Sap2000 was shown in Figure 2.

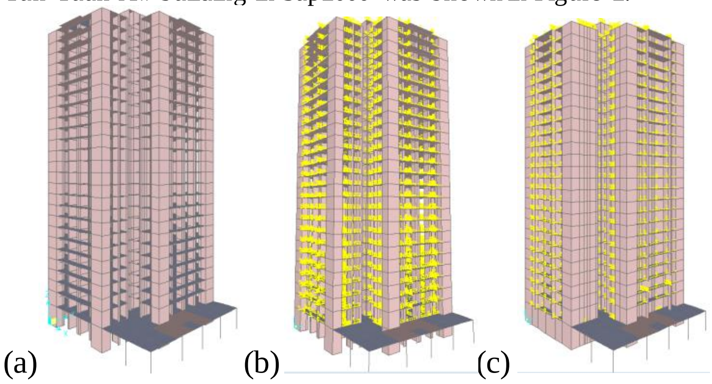


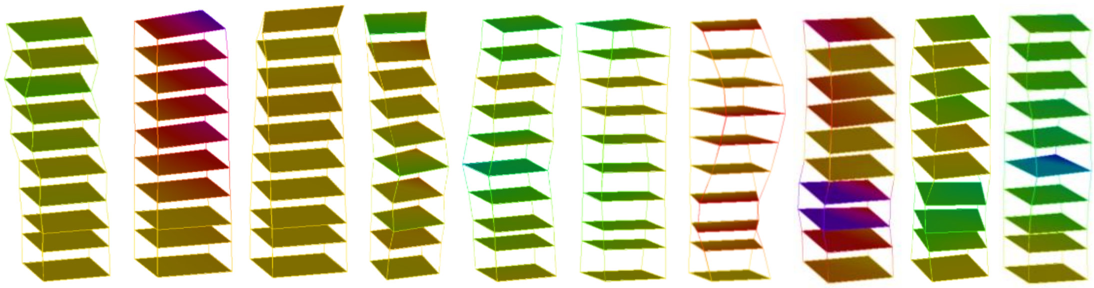
Figure 2. Three modeling method for Xiang Yun Yuan A# Building in Sap2000 (a) Model 1; (b) Model 2; (c) Model 3

Comparison of Tested and Calculated Results

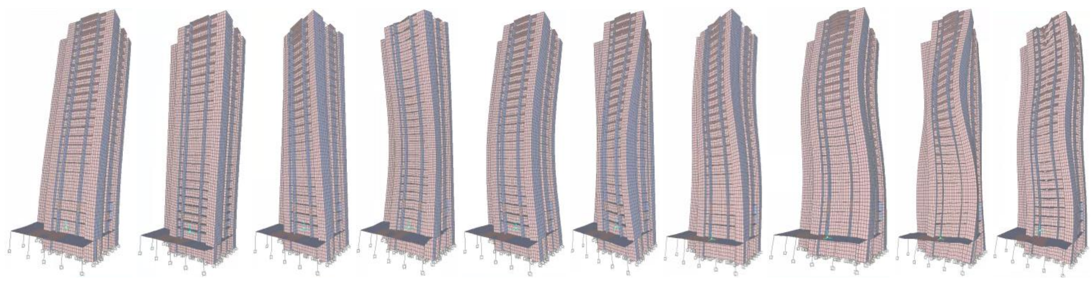
Xiang Yun Yuan A# building was analyzed in detail as an example, and measured modal frequencies via LMS, calculated modal frequencies via PKPM and calculated modal frequencies via Sap2000 were listed in Table 2. It can be found that the measured 1st frequency was 1.09Hz while the analytical value via PKPM was only 0.44 Hz, so the measured value was 2.48 times of calculated mode, thus the differences will result in inaccuracy in seismic design of the building. In model 3, shell element was chosen for the infilled wall modelling in Sap2000, so the calculated frequency was increased to 1.33Hz, which was quite close to the measured value. The measured and calculated 10 modes were shown in Figure 3 and Figure 4.

Table 2. Comparison of tested and calculated frequencies for Xiang Yun Yuan A building (Hz)

Method	1	2	3	4	5	6	7	8	9	10
Measured	1.09	1.16	1.25	3.85	3.93	4.18	7.22	7.56	7.81	10.84
PKPM calculated	0.44	0.51	0.53	1.51	1.81	1.84	3.11	3.64	3.81	5.14
SAP(Model 1)	0.63	0.71	0.73	2.23	2.54	2.63	4.61	5.30	5.53	7.54
SAP(Model 2)	0.51	0.59	0.60	1.82	2.12	2.16	3.75	4.37	4.60	6.13
SAP(Model 3)	1.33	1.49	1.98	5.06	5.11	6.18	10.01	10.05	10.46	11.18



(a) f_1=1.091Hz; (b) f_2= 1.156Hz; (c) f_3=1.250Hz; (d) f_4=3.852Hz; (e) f_5=3.927Hz;
(f) f_6=4.181Hz; (g) f_7=7.221Hz; (h) f_8=7.555Hz; (i) f_9=7.807Hz; (j) f_{10}=10.835Hz
Figure 3. Measured modal frequencies and mode shapes for Xiang Yun Yuan A# building



(a) f_1=1.334Hz; (b) f_2=1.487Hz; (c) f_3=1.980Hz; (d) f_4=5.057Hz; (e) f_5=5.110Hz;
(f) f_6=6.178Hz; (g) f_7=10.014Hz; (h) f_8=10.457Hz; (i) f_9=11.183Hz; (j) f_{10}=11.183Hz
Figure 4. Model 3 calculated modal frequencies and mode shapes for Xiang Yun Yuan A# building

Measured and calculated first three frequencies for all the tall buildings were listed in Table 3, and it was found the variation trend of the other 7 buildings was nearly the same as Xiang Yun Yuan A# building, in which the calculated results of model 3 were almost the same as the tested results via LMS software, so in the actual engineering, model 3 will be more accurate than model 1 and model 2 for seismic performance evaluation.

FUNDAMENTAL PERIOD ANALYSIS

Fundamental period, which was highly related to the distribution of the stiffness and mass, was the basic dynamic property of the high-rise building and it was the most important parameter related to seismic design. In Chinese seismic design process, the seismic effect can be evaluated by two basic approaches, which are equivalent base shear method and mode-superposition response spectrum method. In the analyzing process, seismic influence coefficient was highly related to the fundamental period. There are quite a few factors have influences on the fundamental period, for example the distribution of the planar structure form, the mass and stiffness distribution of the structure, the properties of the material and non-structure distribution etc, among which the stiffness distribution of the in-filled wall has the largest influence on the fundamental period. Empirical equation was concluded and proposed to analyze the dynamic properties of the tested on-site buildings. In this paper, the measured values were compared with US code (1997), Europe code (2003), Japanese code(1994) and Chinese code(2012). The tested frequencies and the frequencies estimated by different codes are shown in Table 4. It can be found that the US code and Chinese code overestimated the actual fundamental period of the structures, but the Europe and Japanese Code underestimated them.

Table 3. Calculated three measured and calculated modes (Hz)

Building and mode number		LMS Test results	PKPM Calculated results	SAP2000 Model1 1	SAP2000 Model 2	SAP2000 Model 3
Bei An Ya Ge 1#	1st	0.71	0.28	0.48	0.37	0.86
	2nd	0.84	0.29	0.50	0.38	1.13
	3rd	0.96	0.37	0.58	0.45	1.79
Bei An Ya Ge 2#	1st	0.80	0.28	0.48	0.35	0.98
	2nd	0.89	0.30	0.53	0.39	1.28
	3rd	1.05	0.38	0.64	0.47	1.96
Jin Sui Xiao Qu 1#	1st	0.76	0.29	0.40	0.33	0.92
	2nd	0.83	0.30	0.44	0.36	1.01
	3rd	0.84	0.43	0.46	0.38	1.47
Jin Sui Xiao Qu 3#	1st	0.62	0.28	0.37	0.30	0.67
	2nd	0.68	0.29	0.38	0.31	0.82
	3rd	0.78	0.36	0.41	0.34	1.43
Xiang Yun Yuan A#	1st	1.09	0.44	0.63	0.52	1.33
	2nd	1.16	0.51	0.71	0.60	1.49
	3rd	1.25	0.53	0.73	0.60	1.97
Xiang Yun Yuan B#	1st	1.09	0.43	0.64	0.52	1.33
	2nd	1.16	0.51	0.71	0.60	1.49
	3rd	1.27	0.54	0.74	0.61	1.97
Shui Hu Huang Men 1#	1st	0.56	0.23	0.31	0.25	0.63
	2nd	0.64	0.24	0.32	0.26	0.72
	3rd	0.98	0.28	0.35	0.28	1.15
Shui Hu Huang Men 2#	1st	0.70	0.27	0.38	0.31	0.74
	2nd	0.71	0.28	0.44	0.35	0.77
	3rd	0.82	0.32	0.46	0.37	1.46

Table 4. Comparison of the tested frequencies with frequencies estimated by empirical equations (Hz)

Items	Shui Hu Huang Men 1#	Shui Hu Huang Men 2#	Jin Sui Xiao Qu 1#	Jin Sui Xiao Qu 3#	Xiang Yun Yuan A#	Xiang Yun Yuan B#	Bei An Ya Ge 1#	Bei An Ya Ge 2#
Measured	0.708	0.803	0.76	0.618	1.091	1.087	0.563	0.703
US Code	1.218	1.437	1.375	1.118	2.051	1.978	1.069	1.301
Europe Code	0.652	0.702	0.599	0.542	0.707	0.707	0.526	0.599
Japan Code	0.521	0.575	0.466	0.407	0.581	0.581	0.391	0.466
China Code	1.059	1.146	0.991	0.862	1.187	1.188	0.866	0.903

CONCLUSIONS

In this paper, the Laibin high-rise building ambient vibration test project was introduced in detail, and eight high-rise buildings in 4 different districts were tested under the environmental excitation. Operational modal analysis was successfully conducted to generate modal frequencies and mode shapes of the building. PKPM and Sap2000 software were utilized in tall building analysis. By comparison of first three models, it was found that shell element modeling the in-filled wall was quite close to the measured results. Finally by comparing the measured fundamental frequency with the empirical equation estimation results, it was found US code and Chinese code were overestimated the actual 1st frequency, while Europe and Japanese code underestimated it.

ACKNOWLEDGMENTS

The authors are grateful for the support provided to this research by NSFC (No.51208190), Hunan Provincial Natural Science Foundation of China (No.12JJ4053) and Research Fund for the Doctoral Program of Higher Education (No. 20120161120028).

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