International Symposium on Innovation & Sustainability of Structures in Civil Engineering
ISISS-2013
July 6-7, 2013, Harbin, China

Ambient Vibration Analysis for Structural Identification of High-rise Buildings

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ABSTRACT

The performance of the buildings under environment excitation depends on stiffness and mass distributions along the structure especially on the distribution of shear walls and columns. Experience has shown the finite element (FE) models often fail to predict accurately the fundamental natural frequencies. The additional stiffness provided by the in-filled wall and the decreased stiffness caused by the structure-soil interaction will cause the inconsistence of the analytical and experimental results. To understand of the dynamic performance of the structures, a project led by Hunan University together with Laibin Housing and Urban-Rural Construction Committee were conducted. A series of ambient vibration tests were conducted on several high-rise buildings in Laibin city of Guangxi Zhuang Autonomous Region. One building was analyzed in detail for example in this paper. Ambient vibration signals analysis was recorded by rational accelerometer instrumentations. CMIF method was used to identify the lateral and torsional modes after a series of signal pre-processing of data. The analytical analysis was performed by SATWE in PKPM software, which was regarded as the most widely used structural designing software in Chinese Designing Institute. The analytical and experimental modal analysis results were compared.

KEY WORDS: High-rise building; ambient vibration; dynamic signal analysis; PKPM software

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, will reflect the physical parameter characteristic in modal space. The modal parameter set can be identified through the dynamic field test such as ambient vibration test or force 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 measurement 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, quantified in terms of lateral and torsional accelerations, to occupant perception criteria. Such an effort will lead to a more refined definition of criteria strongly impacting structural design of tall buildings. More importantly, full-scale measurements expand existing databases of damping levels [1]. Field measurement results can be used to improve model test techniques and to refine the numerical models for structural analysis as well [2].

A bunch of full scale modal tests were conducted on some super high-rise buildings. Full scale validation of perception can be found in [2-3]. A partnership led by University of Notre Dame in Chicago was established to initiate the Chicago full-scale monitoring program [1], and the actual performance of three tall buildings in Chicago is compared to predictions, both by FE and wind tunnel modes. Li performed health monitoring in 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 [2]. Brownjohn conducted health monitoring measurement on a 18^{th} 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 [4-5]. Shi 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 [6].

In this paper, a Laibin full-scale high-rise building ambient vibration test project led by Hunan University was simply introduced. The actual dynamic performances of ten buildings are systematically measured and analyzed via short-term ambient vibration test. One of the buildings was chosen for example, the dynamic signal analysis was conducted to obtain the modal information, and SATWE in PKPM software was utilized for modal parameter prediction. The first natural frequency was estimated and the performance of the building was evaluated.

DESCRIPTION OF PROJECT

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 10 high-rise buildings in full scale with computer based analytical models for the advancement of the high-rise building design. Such an endeavor requires the selection of several buildings representative of structural systems common to Chinese tall residential building design, all located in the same location of downtown in Laibin city, from which design information and building access are obtainable. The detailed descriptions of the tested buildings were listed in Table 1.

Table 1. Description of Tested High-rise Buildings

Number	Tested Date	Building Name	Height(m)	Storey(n)	Structural Form
Building 1	1/17/2013	Shui Hu Huang Men 2#	98	33	Shear wall
Building 2	1/18/2013	Shui Yang Ren Jia 7#	122	40	Shear wall
Building 3	1/19/2013	Shui Hu Huang Men 1#	116	39	Shear wall
Building 4	1/20/2013	Jin Sui Xiao Qu 1#	99	34	frame-shear wall
Building 5	1/21/2013	Jin Sui Xiao Qu 3#	116	41	frame-shear wall
Building 6	1/22/2013	Xiang Yun Yuan A#	75	24	Shear wall
Building 7	1/23/2013	Xiang Yun Yuan B#	75	24	Shear wall
Building 8	1/24/2013	Bei An Ya Ge 1#	88	29	Shear wall
Building 9	1/25/2013	Bei An Ya Ge 2#	79	26	Shear wall
Building 10	1/26/2013	Xiang Ge Li La 1#	97	32	frame-shear wall

These high-rise buildings all located in downtown Laibin of Guangxi Province, China as shown on the map in Fig.1. Laibin is a developing city in which more than 200 buildings were newly built in the last four years, therefore most of the new buildings have no live loads of residents as well as the furniture. The building owners permit access to their buildings for instrumentation and monitoring provides a good opportunity for researches to perform ambient vibration tests in a short period. These buildings are all based on a concrete frame-shearwall or pure shearwall design, most of which utilizes straight reinforced concrete artificial excavating pile extending to bedrock. Each of the building was designed in accordance with Seismic Provisions of National Building Code of China. The ambient vibration tests for these ten buildings were continuously conducted during Jan. 17, 2013~Jan. 26, 2013, during which the temperature as well as 10 min average wind speed on top of each building were measured utilizing a simple wind speed measurement instrument. The weather conditions for each testing day were listed in Table 2.

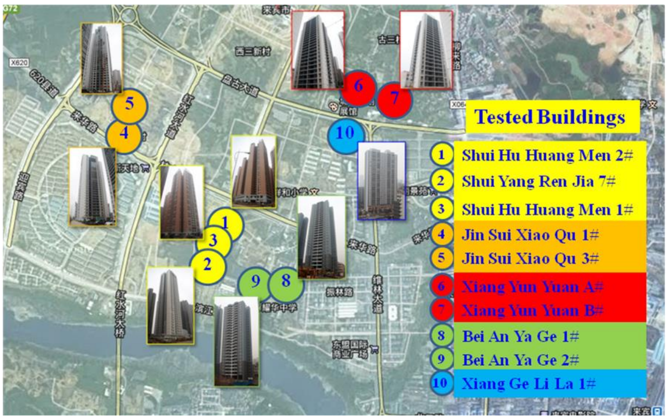


Fig. 1. Distribution of Tested High-rise Buildings in Laibin City

Table 2. Description of Weather Condition for Each Test

Number	Weather	Temperature	Wind Direction	10min Average Wind Speed
Building 1	Overcast to light rain	10.0~11.2	20degree north by west	1.4723m/s
Building 2	Overcast	10.7~11.6	44 degree north by east	1.3229m/s
Building 3	Overcast	16.2~17.9	6 degree west by south	0.8873m/s
Building 4	Overcast	18.2~18.4	South	2.9373m/s
Building 5	Cloudy to sunning	22.5~26.3	16 degree west by south	1.9880m/s
Building 6	Overcast	12.0~12.8	22 degree north by east	2.8490m/s
Building 7	Overcast	14.8~16.5	6 degree north by west	1.7169m/s
Building 8	Overcast to light rain	10.1~10.3	30 degree north by east	1.6856m/s
Building 9	Cloudy to sunning	14.0~15.6	20 degree north by east	2.3767m/s
Building 10	Light rain to overcast	11.7~13.5	20 degree north by east	0.6929m/s

INSTRUMENTATION OVERVIEW

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. A sensitivity of 100V/g and 10V/g for each kind of sensors were selected for this study. These accelerometers are mounted in orthogonal pairs at three opposite corners along two sides of the building, as shown in Fig. 2 (a). 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 will be moved to the bottom first storey in every 3~5 stories. The sampling frequency for capturing ambient signals was set as 204.8Hz, and recorded by LMS Cadax 8 data acquisition (DAQ) system as shown in Fig. 2(b). The DAQ is programmed to continuously capture 15-min time history of these accelerometer outputs.

(a)  (b) 

Fig.2 (a) Four accelerometers setup for one case; (b) Data acquisition test station

AMBIENT VIBRATION SIGNAL ANALYSIS

In the ambient vibration analysis of tested structures, in many of these applications there were a number of 'missing' modes (compared with analytical models) or 'sporadic' modes that 'appeared' or 'disappeared' depending on the various pre- and post-processing techniques used [7]. 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., Averaging of time series data to generate pseudo-impulse response functions (p-IRF) represents a critical step of operational modal analysis. In addition, to prevent leakage, an exponential window was applied to IRF prior to post-processing. This process introduces numerical damping to force the time series to zero within a specific window by multiplying the signal by a time varying function. Complex Mode Indicator Function Algorithm (CMIF) was included in post-processing for modal parameter identification.

FINITE ELEMENT MODELING

Throughout the design stages, structural engineers rely on finite element (FE) models to predict the full-scale behavior of buildings. The survivability level design predicts accelerations that are used to assess the acceptability of the building motions in terms of occupant comfort. Therefore, it is critical that the engineer be able to accurately predict the full-scale behavior of the structure by means of analytical representation through a FE model [8]. A bunch of commercial FE model softwares can be utilized for high-rise building design such as Sap2000 and ETABS. In this study, SATWE in PKPM software is used in FE modeling and dynamic characteristic estimation. SATWE is specially developed for analysis and design of tall buildings, it is a three dimensional FE analysis and design program for composite structures. SATWE is the most popular program in China and widely used in Chinese Design Academies.

JIN SUI XIAO QU 3# TEST

In this paper, a 41 storey residential building with 3 levels of underground parking, name Jin Sui Xiao Qu 3#, was selected for analysis. The objective of the testing was to identify the translational and torsional modes of the building, such as natural frequencies, mode shapes and damping ratios. The identified modes will be compared with the calculated results in SATWE. The instrumentation layout design is shown in Fig.3, in which 4 reference sensors were installed on the 23rd floor, while the rest 4 sensors were installed on roving stories from the 41st floor to the 1st story in every 3~5 stories as shown in Fig.4. The typical ambient vibration signals for point 7 in Case 1 was shown in Fig. 5. It can be found that the maximum lateral acceleration will be less than $2*10^3$g. The correlogram method was used for ambient vibration signal pre-processing analysis, then the CMIF method was utilized for post-processing to analyze the modal information. The overlapped pseudo-FRFs between point 7 and point 3 in Case 1 were shown for example in Fig. 6(a), and the corresponding singular value plot in CMIF method was shown in Fig. 6(b). Peak-picking technique was utilized for mode extraction. The identified first 10 modal frequencies, damping ratios and mode shapes were listed in Table 1 and shown in Fig.7, which was compared with the calculated modes from SATWE as shown in Fig.9.

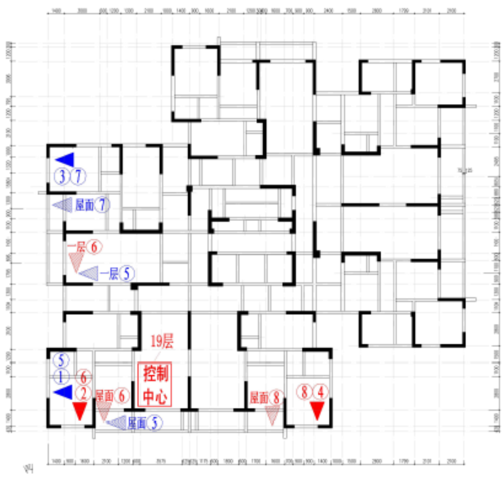


Fig.3 Instrumentation layout for Jin Sui Xiao Qu 3#

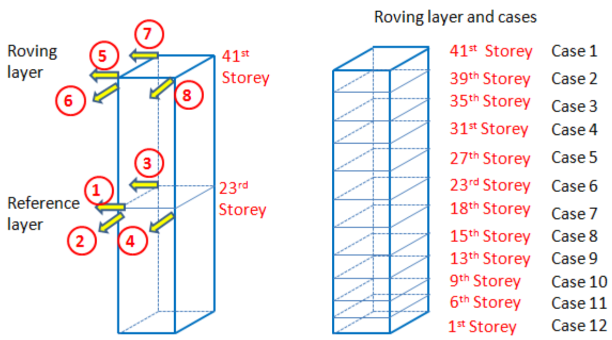


Fig.4 Roving instrumentation cases

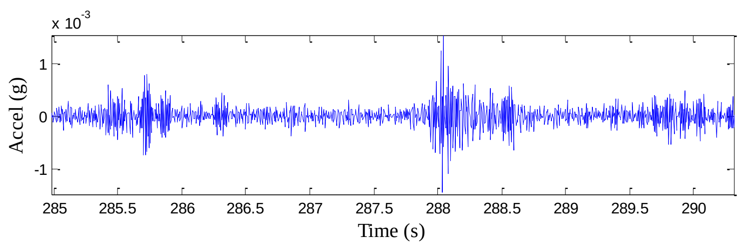
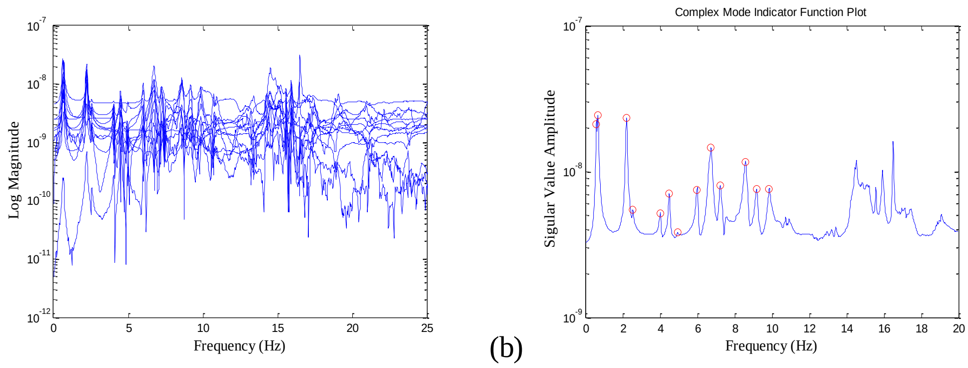


Fig.5 Typical ambient vibration signal of Point 7 in Case 1



(a) (b)

Fig.6 (a) Overlapped P-FRF; (b) Singular value of CMIF method

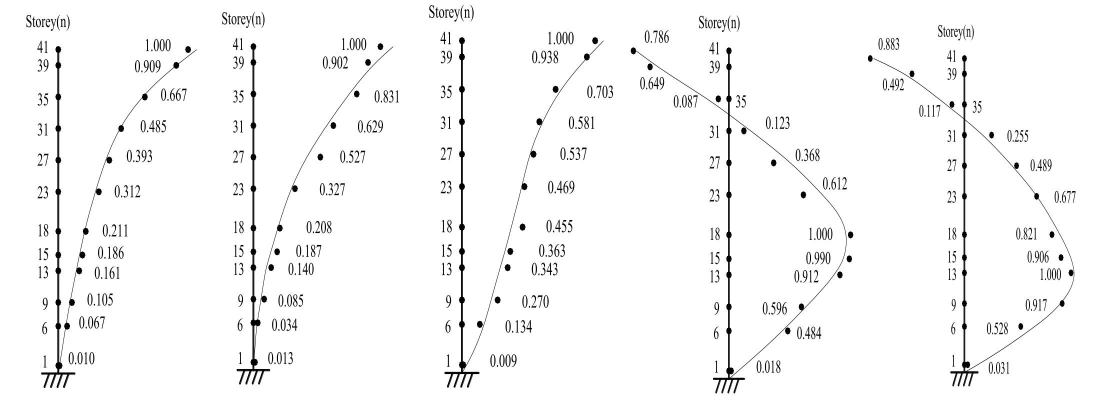
Table 1. Comparison of measured and calculated modes

Mode Number	Measured modes Frequency(Hz)	Measured modes Damping ratio (%)	Calculated modes Frequency (Hz)	Mode description
1st	0.63	6.14	0.28	1st translational in x
2nd	0.64	6.29	0.29	1st translational in y
3rd	0.76	5.39	0.36	1st torsional
4th	2.21	1.53	1.00	2nd translational in x
5th	2.40	2.54	0.96	2nd translational in y
6th	2.54	3.27	1.01	2nd torsional
7th	3.99	1.15	1.84	3rd translational in x
8th	4.00	0.89	1.89	3rd translational in y
9th	4.50	0.12	1.94	3rd torsional
10th	6.49	7.95	2.86	4th translational in x

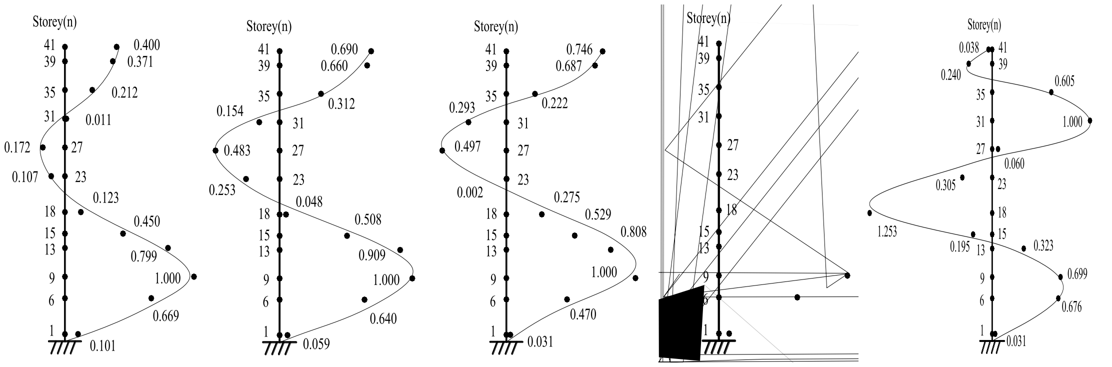
To estimate the fundamental period of the tested building, a simplified calculation equation was recommended in Technical Specification for Concrete Structures of Tall Building (JGJ 3-2010) as T=(0.08~0.1)N for frame-shearwall structure and frame-corewall structure, thus the estimated frequency for the tested building will be 0.24~0.30 Hz, which was close to the calculated modes, but it still has a large difference with the measured mode. To further investigate this issue, another four kinds of natural frequency estimation methods, which were explained in [9], were also utilized for calculation as shown in Table 2. It can be found that the best correlation is the result estimated by USA 1978 equation, but all of the estimations under-estimate the measured frequency, which will be further investigate through analyzing another 9 buildings in the future.

Table 2. Comparison of the natural frequencies by calculation and measurement

Classification	Japan 1977	USA1978	China background material for code	Statistical conclusion	Measured
T_1 Equation	$0.06N$	$0.05H/\sqrt{B}$	$0.33+0.00069\times H^2/\sqrt[3]{B}$	$0.065N$	/
T_1(s)	2.46	1.799	4.77	2.665	1.59
f_1(Hz)	0.41	0.56	0.21	0.375	0.63

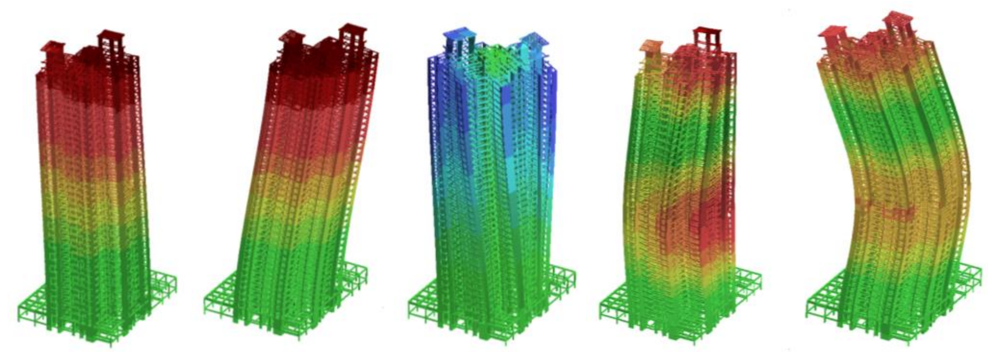


(a) f_1=0.63Hz; (b) f_2=0.64Hz; (c) f_3=0.76Hz; (d) f_4=2.21Hz; (e) f_5=2.40Hz

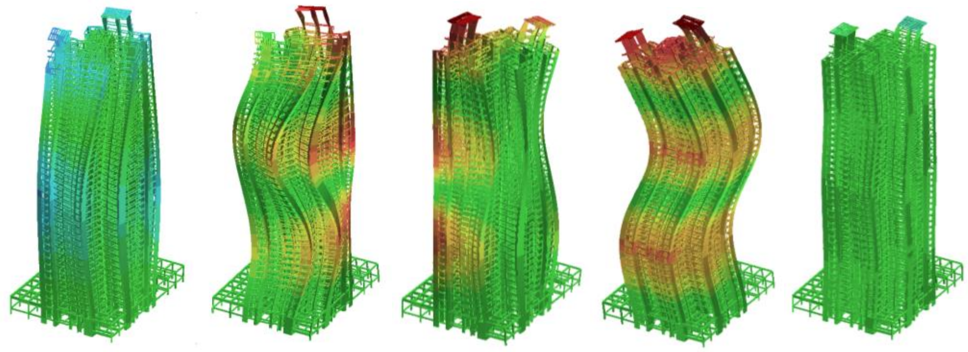


(f) f_6=2.54Hz; (g) f_7=3.99Hz; (h) f_8=4.00Hz; (i) f_9=4.00Hz; (j) f_{10}=6.49Hz

Fig.7. Measured first10 modes



(b) f_1=0.28Hz; (b) f_2=0.29Hz; (c) f_3=0.36Hz; (d) f_4=1.00Hz; (e) f_5=0.96Hz;



(f) f_6=1.01Hz; (g) f_7=1.84Hz; (h) f_8=1.89Hz; (i) f_9=1.94Hz; (j) f_{10}=2.86Hz;

Fig.8. Calculated first 10 modes in PKPM software

CONCLUSIONS

In this paper, a project named Laibin high-rise building full-scale ambient vibration test, which was led by Hunan University and Laibin Housing and Urban-Rural Construction Committee, was simply introduced. The purpose for this project was to correlate the measured structural modes of the high-rise buildings via short-term ambient vibration test with the calculated structural modes via SATWE software. One building was selected to analyze for an example. The pre-processing and post-processing of the ambient vibration signal were conducted to capture the first 10 measured modes, which were compared with the calculated modes. It was found the measured modes were much larger than the calculated modes. Several fundamental period estimation method was utilized, which shows the first period of this building is far beyond the estimation. Further analysis will be conducted on the rest of 9 buildings in the future.

ACKNOWLEGEMENT

The writers 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)

REFERENCES

[1] T.Kijewski-Correa, J.Kilpatrick, and A.Kareem etc. Validating wind-induced response of tall buildings: Synopsis of the Chicago full-scale monitoring Program. *ASCE Journal of Structural Engineering*, 132(10):1509-1523, 2006

[2] Q.S.Li, L.H.Zhi and A.Y.Tuan etc. Dynamic behavior of Taipei 101 tower: field measurement and numerical analysis. *ASCE Journal of Structural Engineering*, 137(1): 143-155, 2011

[3] J.D. Little. The response of a tall building to wind loading. *Ph.D. dissertation*, University of London, London, 1991

[4] J.M.W.Brownjohn and T.C.Pan. Identification loading and response mechanisms from ten years of performance monitoring of a tall building. *ASCE Journal of performance of constructed facilities*, 22(1): 24-34, 2007

[5] J.M.W.Brownjohn. Ambient vibration studies for system identification of tall buildings. *Earthquake Engineering and Structural Dynamics*, 32: 71-95, 2003.

[6] W.X.Shi, J.Z.Shan and X.L.Lu. Modal identification of Shanghai World Financial Center both from free and ambient vibration response. *Engineering Structures*, 36: 14-26, 2012

[7] K.Ciloglu, Y. Zhou, F. Moon and A.E.Aktan. Impacts of epistemic uncertainty in operational modal analysis. *Journal of Engineering Mechanics*, 138(9):1059-1070

[8] Y.G. Li. A CAD Program for tall buildings: SATWE. *Computing in Civil and Building Engineering*, 256-262, 2000

[9] W.J.Yi, Y. Zhou and L.H.Qin. Ambient vibration measurement on a two-tower tall building with enlarged base and model updating research. China Journal of Civil Engineering, 2009, 42(2):65-72 (in Chinese)