AMBIENT VIBRATION MEASUREMENT AND EARTHQUAKE RESISTANT BEHAVIOR ANALYSIS ON A TWO-TOWER TALL BUILDING WITH ENLARGED BASE

Y. Zhou[1] and W.J. Yi[2]

[1] *PhD student, College of Civil Engineering ,Hunan University, Changsha, P.R.China*
[2] *Professor, College of Civil Engineering, Hunan University, Changsha, P.R.China*
Email: zhouyun05@gmail.com, hunuyi2006@gmail.com

ABSTRACT :

The two-tower building with enlarged base is a high-rise building form favored by the architect. In this paper the ambient vibration measurement was conducted on a 86-meters-high frame-wall tall building. This building consists of two towers connected by air corridors and an enlarged base. Translational and torsional modes are measured. SATWE module in PKPM software is used to model the structure and the analytical modes are calculated. It is found that due to the eccentricity of the air corridors, each mode shape in the structure has component of torsional vibration, and the higher modes are all torsional modes. In comparison with the experiential formulas used in calculating fundamental period of tall building in different country, it is found that the measured fundamental period of the structure is higher than the results by calculation. It shows that the measured stiffness of the structure is higher than that of the analytical model. At last the designed ground motions are used in the elastic dynamic time history analysis by using Newmark-β method, and the results show that the response forces concentrate on the transfer story and the highest air corridor on the top of the tower, and the shear forces have greatly changed. Due to the connection of the air corridor, the bending moments and lateral displacements are approximately equal to each other in X and Y direction.

KEYWORDS: two-tower tall building with enlarged base; ambient vibration measurement; experimental modal analysis; earthquake resistant behavior analysis

1. INTRODUCTION

With the rapid development of high rise building, the multi-tower structure with enlarged base is favored by the people. The lower part of the structure is designed as enlarged podium, the upper structure is designed as two or more towers, which can be connected by the air corridors. The modal experiments of the high rise buildings have been researched by Bownjohn et al. (2000, 2003), they conducted modal experiment on Republic Plaza building in Singapore and analyzed the influences of several factors on the modal analysis results. Li et al. (2004) have made field measurements on Di Wang Tower in Shenzhen to investigate the dynamic characteristics of the super tall building, seven finite element models have been built to analyze and model the multi-outrigger-braced tall building. Wu et al. (2004) presented an eigensensitivity-based finite element (FE) model updating procedure and used for an existing 310m Nanjing TV Tower based on ambient vibration measurements, it is found that the FE model updating procedure based on the weighted least squares method is the most effective approach for the FE model updating. Chassiakos et al.(2005) presented an overview of the ambient vibration data collected before, during, and after the structural retrofit, a FE model of the building was developed and used to estimate the dominant frequencies and mode shapes before and after the retrofits.

In this paper, the modal experiments on realistic field condition were done on two tower commercial high-rise building in Shenzhen city. By using ambient vibration measurement method, the global modal information of the structure has been measured, SATWE software has been used to build a model, and the measured results and calculated results are compared and analyzed. Newmark- β method has been used in elastic time history analysis, the dynamic characters of the building has been analyzed.

2. MODE EXPERIMENT OF THE TWO-TOWER TALL BUILDING WITH ENLARGED BASE

2.1. Introduction of Ruihua Building

Ruihua Building is established in Shenzhen, China, as shown in Figure1 (The crane has been removed when testing.). It is a reinforced concrete frame-supported shear wall tall building. Its total area and height are 27577m^2 and 86.35m, respectively. The main tower has 27 stories. The underside structure has 3 stories. The concrete strength grades are between C35~C45. The bearing capacity standard value of the foundation is 2800kN/m^2 and the pre-stressed tube pile has been used. The two towers are symmetry along the axes. The air corridors are set eccentricly on the 7th, 9th, 11th, 13th, 15th, 17th, 19th, 21st, 23rd and 25th story (in Figure2). The 27th story is set as the larger air corridor, which can be used as the active region and prevent the rain. In each tower there is a concrete core tube made of elevators and stairs. The core tube is extended out of the upper story to be defensive tower.

Figure 1 The panorama of Ruihua Building

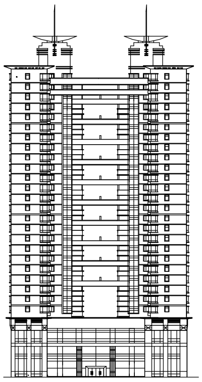


Figure 2 The front view of Ruihua Building

2.2. Modal Identification Method under Ambient Excitation

The ambient excitations include the wind and the earth pulsation. By using structural frequency response spectrum, the amplitudes of transfer function can be used to judge the structural modes. The limited bands white noises are assumed as input signals, the power spectrum $S_{xx}(\omega)$ can be considered as constant value a and shown as follows:.

$$\left|H(\omega)\right|^2 = S_{yy}(\omega)/S_{xx}(\omega) = S_{yy}(\omega)/a \tag{2.1}$$

In the process of analysis, the input of the system can be set as unknown and the response signal can be used to identify part of parameters in the system. The peak value appears on natural frequencies location in auto spectrum and cross spectrum. The coherence function of the two measuring points is close to 1 when natural frequency appears in the spectrum, and the phase angle is nearly 0° or 180° . By comparing the different points of the frequency function, the mode shapes can be obtained.

2.3.Modal Experiment Arrangement

The ambient vibration measurement was carried out in February, 2004. The building had been finished constructing and was on sale at this time. The preliminary decoration work had been completed but service load was not applied. INV303 DASP dynamic signal analysis instrument and two INV-9898 accelerometers (frequency range is 0-100 Hz) were used. The torsional and translational modal measurements are considered and the arrangements of measure points are shown in Figure 3~5, the measurement method is as follows:

(1) X and Y direction are shown in Figure3. In torsional mode measurement, two accelerometers are calibrated in point A. Measurements were conducted on A-B points in X direction and A-C points in Y direction, 64 blocks (512 points in each block) of data were collected. Torsional modes were also measured on the 14th story (in Figure 4), the accelerometers are placed on E-F points in X direction and F-G points in Y direction.

(2) In translational mode measurement, D point on the 24th story was selected as the reference point, another accelerometer was placed on the D point on the 4th, 8th, 12th, 16th, 20th and 28th story (in Figure 4-5). Translational modes in the X direction and Y direction are measured.

The measured cross power spectrums are shown in Figure 6-8, the identified several modes are shown in Figure 9. The measured fundamental natural frequency is about 0.684 Hz, a translational mode in X direction.

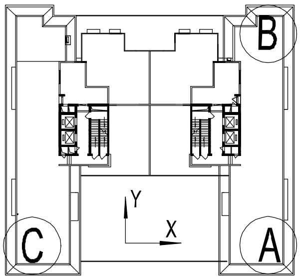


Figure 3 Measurment point on the top story

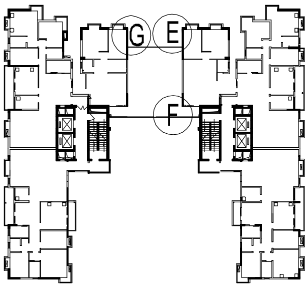


Figure 4 Measurment point on the 14th story

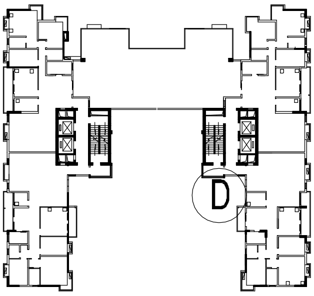
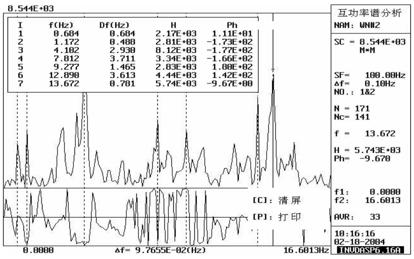


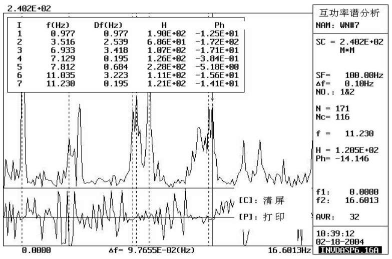
Figure 5 Measurment point on the standard story



```
I      f(Hz)      Df(Hz)       H          Ph
1      0.684      0.684     2.17E+03   1.11E+01
2      1.172      0.488     2.81E+03  -1.73E+02
3      4.102      2.930     8.12E+03  -1.77E+02
4      7.812      3.711     3.34E+03  -1.66E+02
5      9.277      1.465     2.83E+03   1.80E+02
6     12.890      3.613     4.44E+03   1.42E+02
7     13.672      0.781     5.74E+03  -9.67E+00
```

```
互功率谱分析
NAM: WN#2
SC = 8.544E+03
     M*M
SF=   100.00Hz
Δf=   0.10Hz
NO.: 1&2
N = 171
Nc= 141
f =   13.672
H = 5.743E+03
Ph=  -9.670
f1:    0.0000
f2:   16.6013
AVR:   33
10:16:16
02-18-2004
```

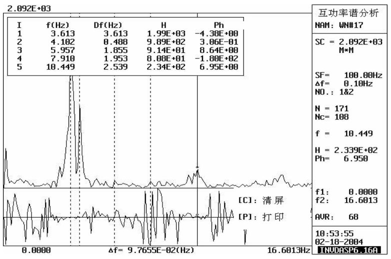
Figure 6 Cross power spectrum on A-B point in X direction



```
I      f(Hz)      Df(Hz)       H          Ph
1      0.977      0.977     1.90E+02  -1.25E+01
2      3.516      2.539     6.86E+01  -1.72E+02
3      6.933      3.418     1.07E+02  -1.71E+01
4      7.129      0.195     1.26E+02  -3.84E-01
5      7.812      0.684     2.28E+02  -5.18E+00
6     11.035      3.223     1.11E+02  -1.56E+01
7     11.230      0.195     1.21E+02  -1.41E+01
```

```
互功率谱分析
NAM: WN#7
SC = 2.402E+02
     M*M
SF=   100.00Hz
Δf=   0.10Hz
NO.: 1&2
N = 171
Nc= 116
f =   11.230
H = 1.205E+02
Ph= -14.146
f1:    0.0000
f2:   16.6013
AVR:   32
10:39:12
02-18-2004
```

Figure 7 Cross power spectrum in Y direction between 20and 24 story



```
I      f(Hz)      Df(Hz)       H          Ph
1      3.613      3.613     1.99E+03  -4.38E+00
2      4.102      0.488     9.89E+02   3.06E-01
3      5.957      1.855     9.14E+01   8.64E+00
4      7.910      1.953     8.08E+01  -1.80E+02
5     10.449      2.539     2.34E+02   6.95E+00
```

```
互功率谱分析
NAM: WN#17
SC = 2.092E+03
     M*M
SF=   100.00Hz
Δf=   0.10Hz
NO.: 1&2
N = 171
Nc= 108
f =   10.449
H = 2.339E+02
Ph=   6.950
f1:    0.0000
f2:   16.6013
AVR:   68
10:53:55
02-18-2004
```

Figure 8 Cross power spectrum in Y direction on F-G point on 14 story

3. NUMERICAL MODAL ANALYSIS AND COMPARISON

3.1. Numerical Modal Analysis

PKPM software is used to build the structure model and shown in Figure 10. SATWE module in PKPM software adopt spatial member element to model beam, column and spatial member, the wall elements condensed based on the shell element are used to model shear walls. The calculated first 12 modes are listed in Table 3.1. By numerical modal analysis it can be found that the natural frequencies only have some relationships with the amounts and locations of the structural column and shear wall, the other factors have little influences on it. The higher modes are all torsional modes, it is due to the concave shape of the building dimension, also the characteristic and weak link of the building.

3.2. Comparison with the Empirical Equation

According to the simplified equation suggested in Chinese code (JGJ3-2002), the fundamental period of the frame-shear wall structure and frame-tube structure is T=(0.08-0.1)N (N is the story number). By using this equation, the fundamental periods of this structure is between 2.16s-2.7s and the fundamental frequency is between 0.37-0.46Hz, the measured results are out of this range.

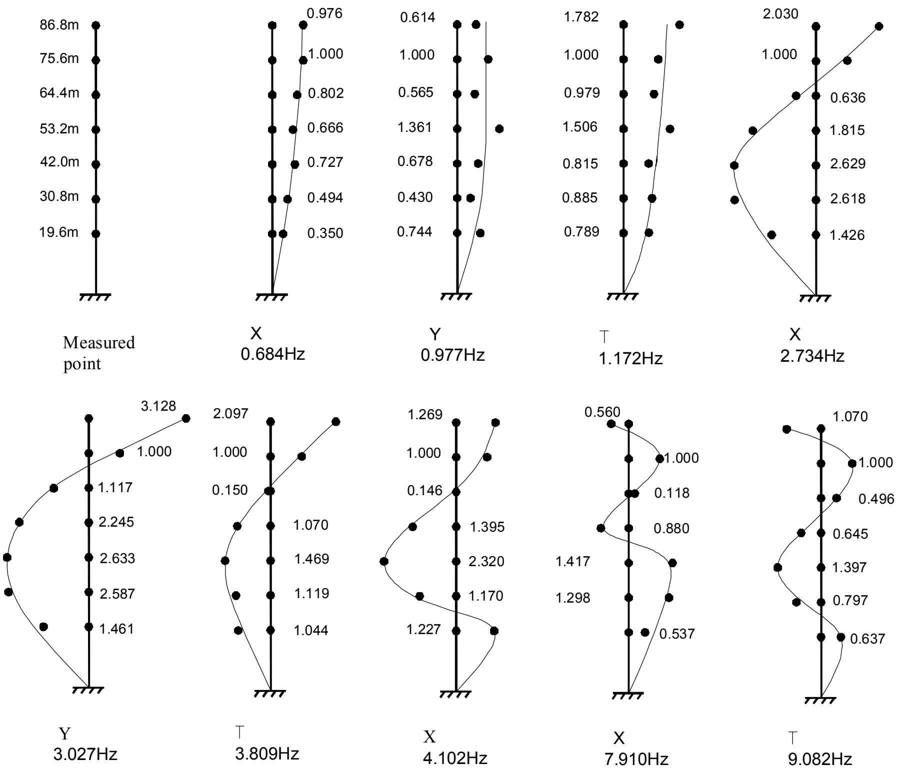


Figure 9 Vibration shapes by measurement (X means translational mode in X direction, Y means translational mode in Y direction, T means torsional measurement)

Table 3.1 Frequencies by calculating modal analysis (Unit: Hz)

Case	f_1(Y)	f_2(X)	f_3(T)	f_4(Y)	f_5(T)	f_6(X)	f_7(Y)	f_8(T)	f_9(X)	f_{10}(Y)	f_{11}(Y)	f_{12}(Y)
Baseline	0.402	0.496	0.518	1.537	1.698	1.763	2.954	3.159	3.489	4.482	4.843	5.666

Note: X means translational mode in X direction, Y means translational mode in Y direction, T means torsional mode

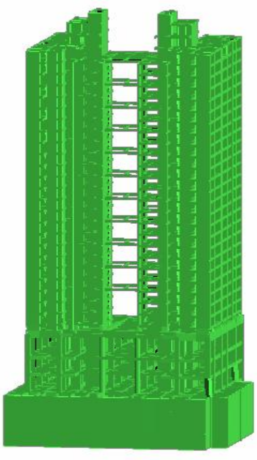


Fig. 10 Calculating model in SATWE

In order to estimate the fundamental periods, Engineering aseismic research department (1982) concludes the Japanese Aseismic Designing Method (Draft) in 1977, American Building Aseismic Temporary Byelaw in 1978 and the Chinese background materials of Code for Seismic Design of Buildings. The fundamental periods of building measured by ambient vibration measurement reflects the dynamic character in small deflection. Some nonstructural members are also partaken in the vibration which makes the building's fundamental period lower. The building has large displacement under the earthquake and some small cracks could make the structure's stiffness decrease. Damage in some nonstructural member could also make the fundamental period longer. As indicated that in 1971 San Fernando earthquake, 70 high-rise buildings' fundamental periods were recorded in Los Angeles. The recorded data indicated that the high-rise building's fundamental periods are 1.1-2.0 times of that before earthquake, and they will be recovered about 1.0-1.4 times after the earthquake. The comparison of the natural frequency results by empirical equation and the measurement is shown in Table 3.2.

It is indicated that in the process of estimating the fundamental periods of new tall building, the measured fundamental period by ambient vibration can not be used directly, 1.5 amplified factors should be multiplied on it. The measured natural frequency of this building is 0.684Hz, which is 1.7 times higher than 0.402Hz by numerical calculation, so it can be concluded that the real stiffness of this tall building is higher. (It has some relationship with the stiffness of the infill wall, and it also has the relation with the underestimating the slab's stiffness by using shell element in SATWE.) The engineer is more interested in the problem that the ratio of the calculated fundamental frequency to the measured one, so the rational period reduction factor can conveniently be used in calculating earthquake force.

Table 3.2 Fundemantal periods and frequencies by using empirical equation

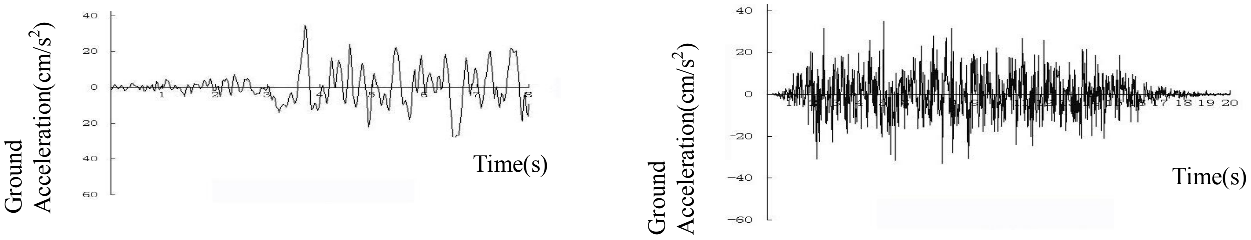
Classification	Japan 1977	American 1978	China background material of Code	Computer Conclusion	Measurement
T_1 equation	$0.06N$	$0.05H/\sqrt{B}$	$0.33+0.00069\times H^2/\sqrt[3]{B}$	$0.065N$	/
T_1 (s)	1.620	1.237	1.601	1.755	1.460
f_1 (Hz)	0.617	0.808	0.625	0.570	0.684

4. NUMERICAL SEISMIC RESISTANT ANALYSIS ON THE TWO TOWER STRUCTURE WITH ENLARGED BASE

Horizontal sismic motions mainly casuse translational vibration in symmetry structure. The horizontal seismic forces distribute according to the structure's vertical stiffness distripution. Due to the mass center and rigid center are not superposed in the non-symmetry structure, the torsional vibration can also be excited under the horizontal seismic motions. The structural member far away from the rigid center often share in larger horizontal shear force, it easily causes serious destroy and exceeds the limits of translational displacement. The seismic dynamic time history analysis is done according to the former numerical model.

According to the numerical two-tower structure model in this paper, Newmark-β method is used in seismic analysis. Taft wave (TAFT-2 duration 8 seconds), Lanzhou Wave(LAN1-2 duration 20 seconds) and Lanzhou Wave(LAN6-2 duration 17 seconds) are selected as the input waves, the maximum base acceleration is set as 35cm/s^2 and the time step is set as 0.02s, the structure damping is set as 0.05%. The figures of seismic waves and structure response forces are shown in Figure11-13. Due to the deflection-torsion coupled vibration exist in it, CQC seismic force composition method has been used. The 50 year's basic wind pressure is set as 0.75kN/m^2, the displacements under the wind and seismic action are compared in Figure14-15 and Table 4.3-4.4.

By numerical elastic time history analysis, the response force curves and shear force curves concentrate on the transfer story, and large changes also have taken place on the top air corridor's place. It is indicated that these places are weak link and should be strengthened. The moment and displacement value are close in the X and Y direction, it is found that the structure in the two directions have the similar stiffness due to the action of air corridors. The response deflections have the similar values in the wind and earthquake actions.



(a) TAFT-2 seismic acceleration history (b) LAN1-2 seismic acceleration history

Figure 11 Time history of the earthquake

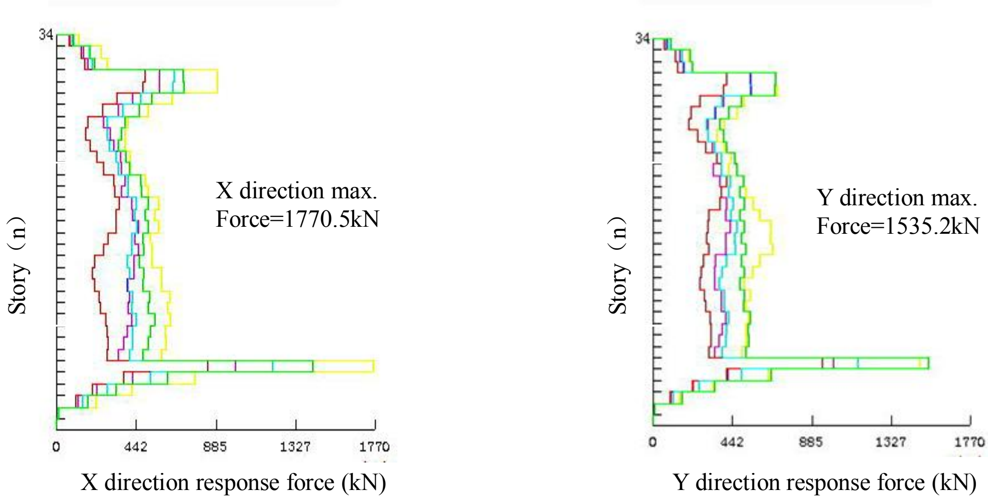


Figure 12 X and Y direction response force curves of the story under the earthquake
(Curves in the figure from left to right are respectively LAN6-2, LAN1-2, response average, CQC method, TAFT-2)

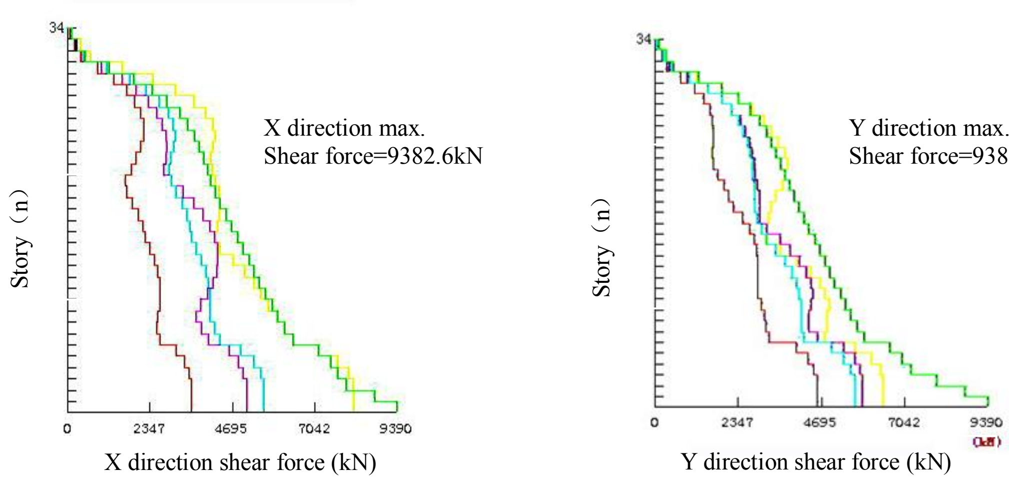


Figure 13 X and Y direction shear force curves of the story under the earthquake
(n=0, Curves in the figure from left to right are respectively LAN6-2、LAN1-2、response average、TAFT-2、CQC method)

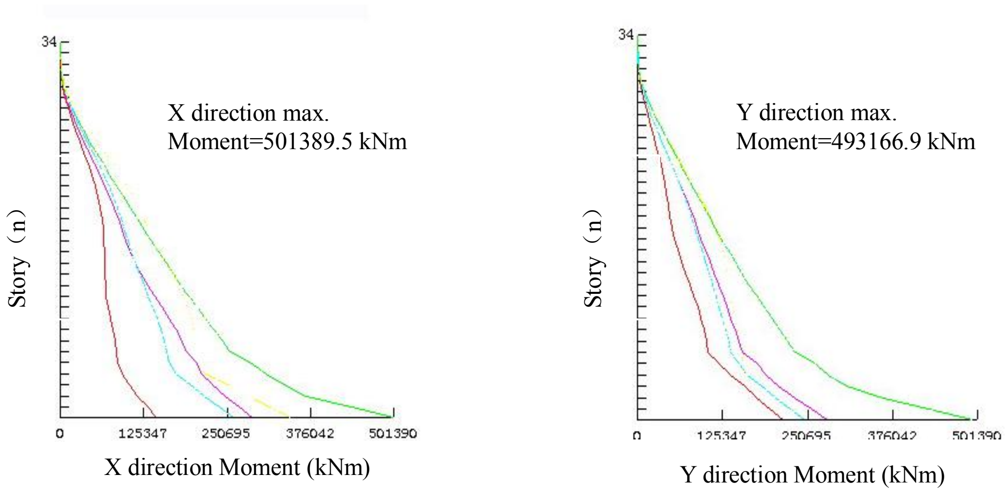


Figure 14 X and Y direction deflection curves of the story under the earthquake
(n=34, Curves in the figure from left to right are respectively LAN6-2,response average, LAN1-2, TAFT-2, CQCmethod)

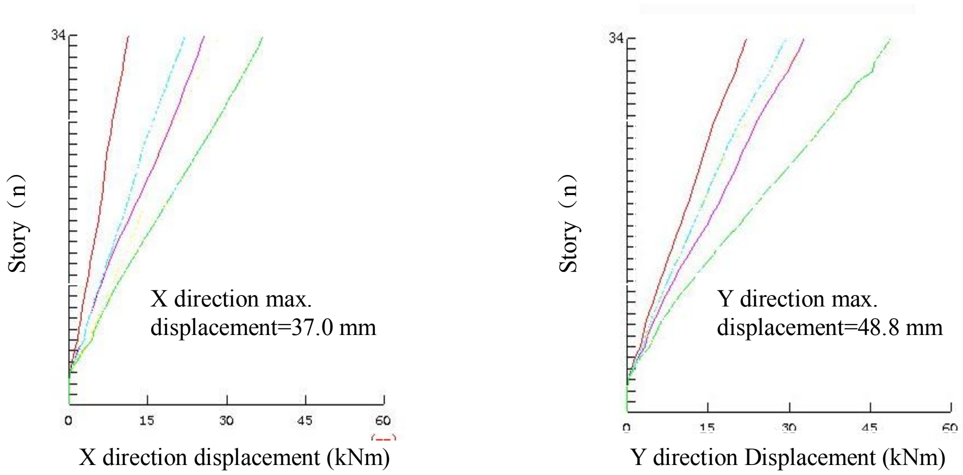


Figure 15 X and Y direction deflection curves of the story under the earthquake
(n=34, Curves in the figure from left to right are respectively LAN6-2、response average、LAN1-2、TAFT-2、CQC method)

Table 4.3 Relative displacement by the force of wind and earthquake

Force		Ratio of Max. inter story displacement to story height△u/h	Ratio of Max. horizontal displacement of the vertical member to the story's average value	Ratio of Max. inter-story's displacement of the vertical member to the story's average value
Wind	X direction	1/1951	1.52	1.54
	Y direction	1/1364	1.53	1.55
Seismic	X direction	1/2028	1.52	1.54
	Y direction	1/1184	1.50	1.52

Table 4.4 Comparison of the maximum displacement and acceleration, the horizontal force of the transfer story

Items	TAFT-2	LAN1-2	LAN6-2	Average
X direction top story max. deflection(mm)	29.14	26.5	11.08	22.24
Y direction top story max. deflection (mm)	33.35	32.96	18.54	28.28
X direction top story max. acceleration(mm/s^2)	937.1	821.3	582.3	780.3
Y direction top story max. acceleration (mm/s^2)	907.4	697.7	561.9	722.4
X direction top story transfer story horizontal force (kN)	1770.5	992.6	842.2	1201..8
Y direction top story transfer story horizontal force (kN)	1480.8	994.1	948.7	1141.2

5. CONCLUSIONS

Ambient vibration measurement has been done on a frame-shear wall structure, which is a two-tower connected commercial dwelling high-rise building with enlarged base. Several modes are measured, SATWE module in PKPM software has been used in the numerical modal analysis, the measured and calculated modes are compared. Newmark-β method has been used in structural seismic analysis, the main conclusions are as follows:
(1)Modal experiment based on ambient vibration was done on Rui-hua building in Shenzhen, translational and torsional modes are measured. Due to the eccentricity of the air corridors, each modes of the structure has the component of torsional vibration. The measured fundamental frequency is 0.684Hz, the calculated fundamental frequency is 0.402Hz. The measured results are compared with the results by empirical equation, it is found that the fundamental period is little than the results by using the codes in other countries, so it can be inferred that the stiffness of the structure is large, and it has some relations with the stiffness provided by infilled wall and other facilities, it also has some relations with the modeling method on air corridors.
(2) Three seismic waves are used in structural elastic seismic analysis by using Newmark-β method. It can be found that the response force and shear force concentrate on the structural transfer story and the top story, and it is indicated that it is the weak link. The bending moments and displacements are close in the X and Y direction, it is also shown that the structure has the same stiffness due to the action of air corridors.

ACKNOWLEDGEMENTS

Financial support provided by the National Natural Science Foundation of China (NSFC) under Grant No.50678064 and Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT)under Grant No. IRT0619.

REFERENCES

Brownjohn, J.M.W., Pan, T.C., Deng, X.Y. (2000). Correlating dynamic characteristics from field measurements and numerical analysis of a high-rise building. *Earthquake Engineering and Structural Dynamics* **29**, 523-543.
Brownjohn, J.M.W. (2003). Ambient vibration studies for system identification of tall buildings. *Earthquake Engineering and Structural Dynamics* **32**, 71-95.
Li, Q.S., Wu, J.R. (2004). Correlation of dynamic characteristics of a super-tall building from full-scale measurements and numerical analysis with various finite element models. *Earthquake Engineering and Structural Dynamics* **33**, 1311-1336.
Wu, J.R., Li, Q.S. (2004). Finite element model updating for a high-rise structure based on ambient vibration measurements. *Engineering Structures* **26**, 979-990.
Chassiakos, A.G., Masri, S.F., Nayeri, R.D., Caffrey, J.P., Tzong, G., Chen, H.P. (2005). Use of vibration monitoring data to track structural changes in a retrofitted building. *Structural control and Health Monitoring*, **14:2**, 219-238.
Engineering aseismic research department in design institute of central research institute of building and construction of MIMI. (1982). Compilation of nine countries aseismic design code, China Architecture and Building Press, P.R.China (in Chinese)