TORSIONAL VIBRATION CHARACTERISTICS AND ANALYSIS OF EARTHQUAKE RESPONSE OF YINGXIAN WOODEN PAGODA

YAN Xu[1] LI Tie-ying[2] ZHANG Shan-yuan[2] QIN Hui-min[1]

[1] *Ph D candidate, College of Civil and Environmental Engineering, Taiyuan University of Technology, Shanx, China*

[2] *Professor, College of Civil and Environmental Engineering, Taiyuan University of Technology, Shanxi，China*

ABSTRACT: Measuring on Yingxian wooden pagoda demonstrates that the torsional component of the residual deformation is distinct. After the two historic earthquake periods, the traces of broken damages become evident. The trials by conducting micro-tremor measurements of the tower, obtained the time-history curves of measuring points of each upper floor. Also, horizontal modes of vibration corresponding to different predominant frequencies of every upper floor are obtained from frequency spectrum analysis. Study on the horizontal mode discovers that translation-torsion coupling response of the floors is distinct, as well as relative torsion between layers. The phenomena are consistent with the residual torsional deformation. The torsional elastic earthquake response of each upper layer of the tower under different seismic waves is also calculated and analyzed.

KEY WORDS: Yingxian Wooden tower, torsional dynamic characteristics, seismic response, micro-tremor measurements

1. INTRODUCTION

The “Yingxian Wooden pagoda”, being of 65.84 meters high, located in the northwest of Yingxian city, Shanxi province of China, was built in 1056. It is an octagonal tower of nine stories with five upper stories clearly visible outside and four mezzanine stories not apparent from the outside. Each upper story is underpinned by a mezzanine story. [1] Constructed with the timber, the structure has two rings of columns, and the diameter of the exterior ring is 33.15M at the bottom. In each ring of every layer, partitions are built between two adjacent columns, which formed an octagonal surrounding in plane. The structure, being well preserved, is the oldest tower in China, and the only pavilion-like wooden Buddhist pagoda in the world.

In the history, the structure has experienced numerous strong earthquakes and bombardments, together with weakened material, which caused damages to some components and the whole structure in different degree.[2] From 1970s, the team led by Li shiwen surveyed damages of the tower in detail, compartmentalized the grades of the wood damages of the ancient timber components, and analyzed the earthquake history of the tower and the relationship between the damages and earthquakes. The dislocations of columns on each layer in the horizontal and vertical direction and the horizontal distortion of the whole body have been summarized and analyzed. The phenomena show that the bearing columns have the distinct residual dislocations in the horizontal direction, which cause relatively obvious horizontal deformation of the whole structure. [3]

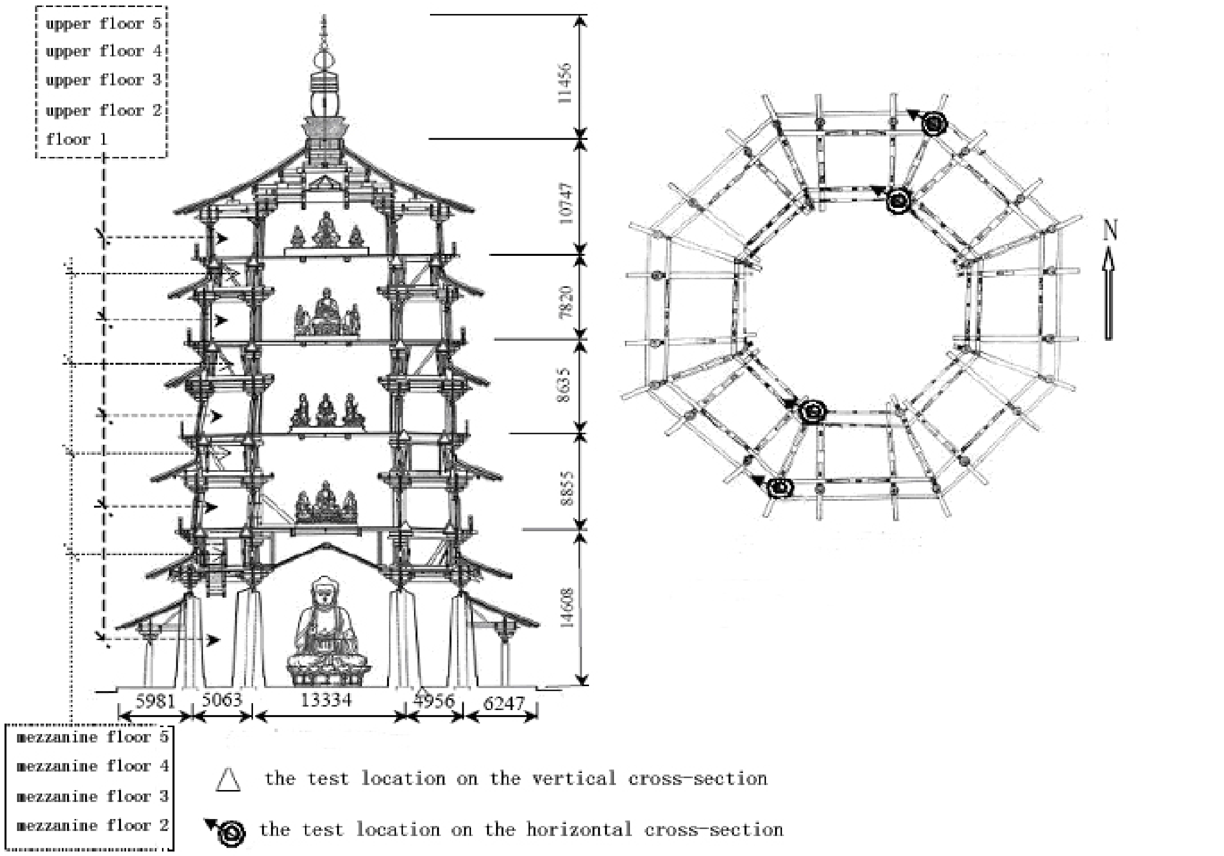
In order to have a better understanding of the torsional vibration characteristics of the wooden structure under the seismic action, micro-tremor measurements have been carried out in the present paper. Horizontal vibration modes of each upper floor corresponding to different predominant frequencies have been obtained from frequency spectrum analysis. Based on transfer function method, elastic seismic displacements of every measuring points on each upper story have been calculated. By comparison and analysis of torsional displacement response of each upper layer under different seismic waves, torsional vibration characteristics of the pagoda have been concluded as a basis for researching and protecting the ancient building.

2 MICRO-TREMOR MEASUREMENTS ON YINGXIAN WOODEN PAGODA

2.1 Measuring Points Arrangements

To determine the dominant frequencies and the corresponding modes in the horizontal direction，micro-tremor signals can be recorded by displacement sensors. In view of avoiding disturbing effects, the periods of time are selected at nights with small wind speed and weak circumstance influence.

It is designed to place the points at the bottoms of the columns on 2-5 upper floors which stand on the northeast and southwest direction of the two rings, and a point as the reference point at the foot of the northeast column on the first floor of the interior ring (figure 1). For the limited number of the pick-ups, torsional vibration tests are classified two groups: 4 points on the 2nd or the 3rd upper floor as group one, 4 points on the 4th or the 5th upper floor as group two.



(a) The vertical cross-section of the tower (b)The horizontal cross-section of the tower

Figure 1 Measuring points arrangements of Yingxian wooden pagoda

The apparatus are mainly DRA-101C dynamic measurement system, nine cd-7-s horizontal displacement pick-ups, two CD-7-C vertical displacement pick-ups and supplementary instruments. The calibration instruments include ZS-COD vibration table and CMT5105A electronic universal testing machine. Test flow chart is shown in Figure 2.

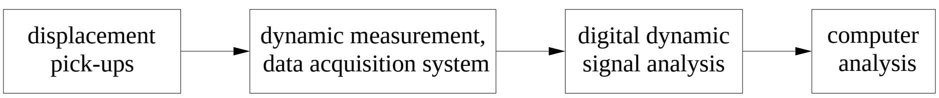


Figure 2 signal analysis process

2.2 Analysis of the Test Results

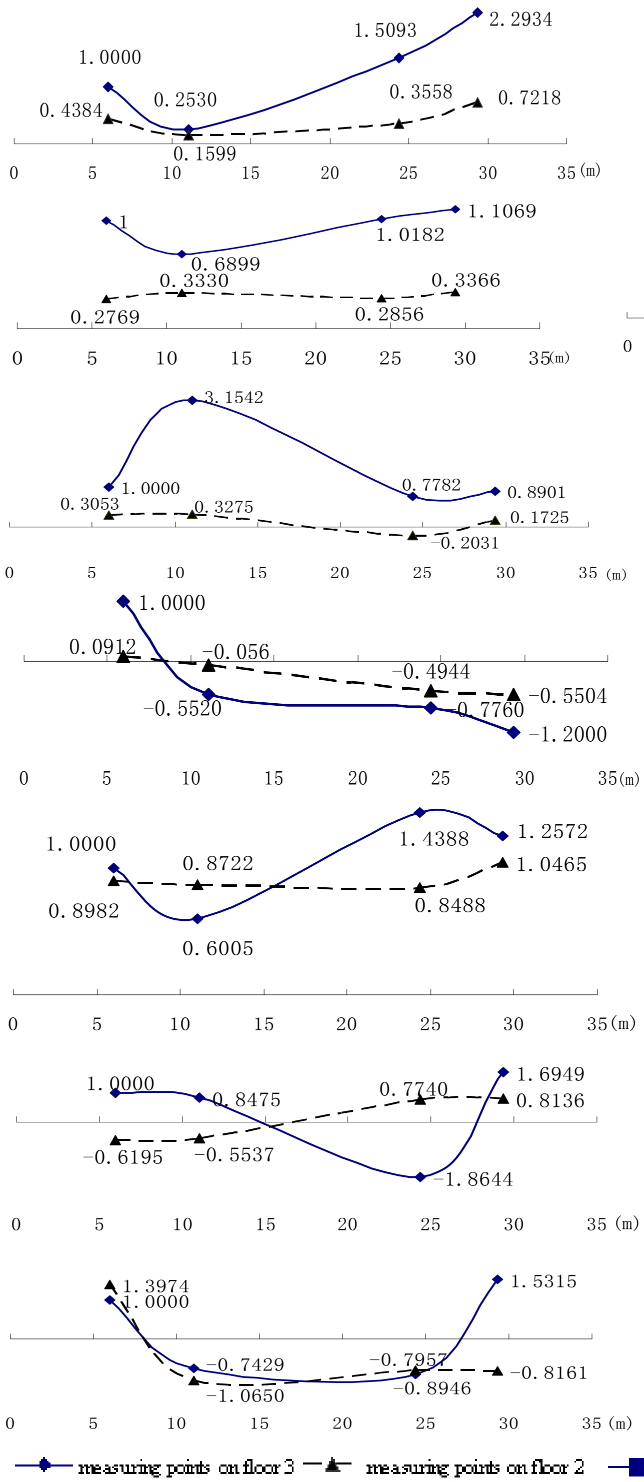


Figure 3 Horizontal vibration modes of upper floor 2 and upper floor 3 (from mode 1 to mode 7)

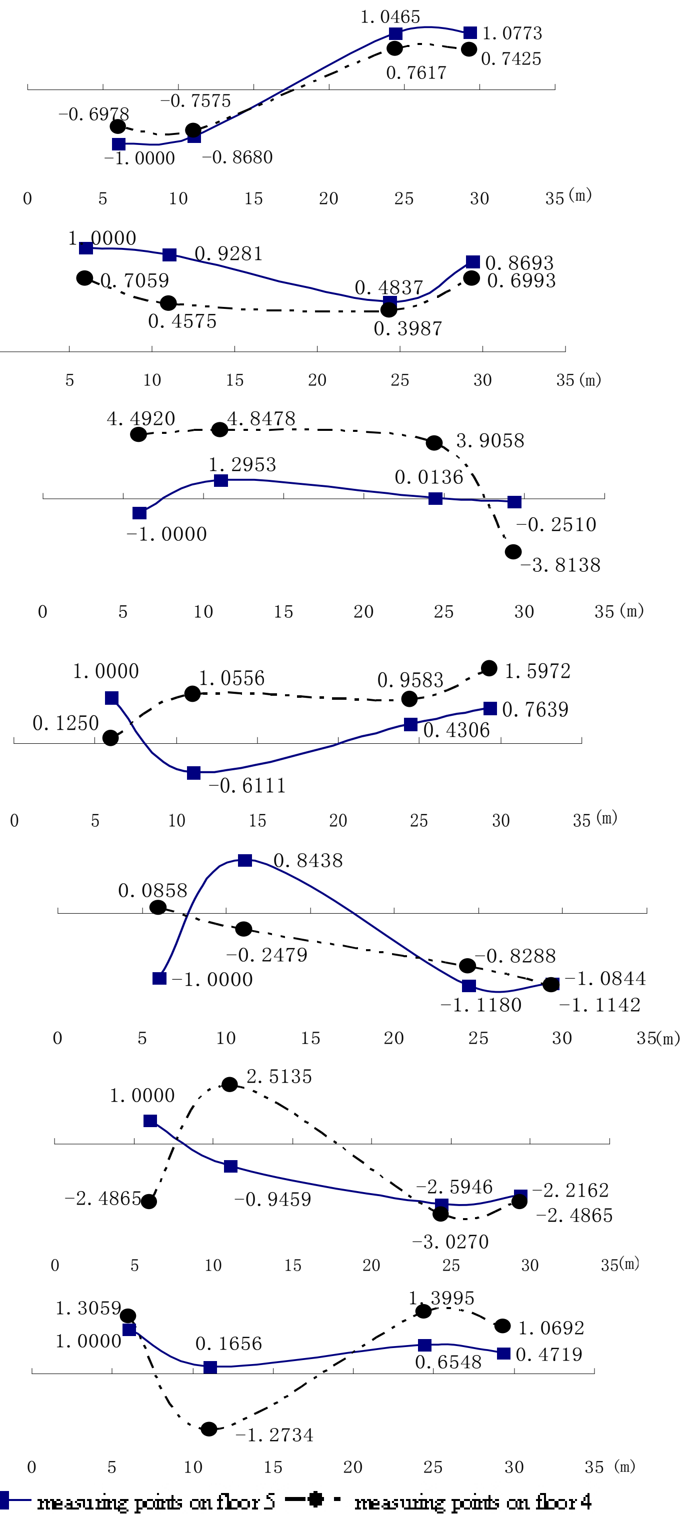


Figure 4 Horizontal vibration modes of upper floor 4 and upper floor 5 (from mode 1 to mode 7)

It is designed to record 4096 digital data with the sampling rate of 100HZ. By observing from the power spectrum, resonance points and displacement amplitudes at peaks can be obtained. Phase spectrum shows relative vibration direction of measuring points. From the above comprehensive analysis, it is drawn that the first seven frequencies are 0.63Hz, 0.98Hz, 1.76Hz, 2.34Hz, 2.88Hz, 3.13Hz, 3.61Hz. According to the two test groups, horizontal vibration modes corresponding to different predominant frequencies of every floor are classified into two groups through frequency spectrum analysis. (figure.3, figure.4)

The figures of horizontal vibration modes demonstrate that when the frequency is between 0.63 Hz and 1.76Hz, the vibration of the upper floor 2 and upper floor 3 mainly shows translational characteristics with no distinct torsional phase change; while it is between 2.34 Hz and 3.13Hz, relative torsion is distinct. And with the frequency becomes larger in the domain, the phase difference becomes larger, even leading the two floors to the reverse direction. Then with the further growing of the frequency, the vibration of the two floors shows translational trend. In addition, by comparison on horizontal vibration modes of upper floor 4 and upper floor 5, it is found that in the low-frequency part, the vibration is mainly torsional. With the growing of the frequency, the vibration shows the transit from torsion to translation. The vibration of each upper floor presents alternative and recycling characteristics with translation, translation-torsion coupling and torsion with the frequencies variation, but different with each floor, which demonstrate the complexity of the wooden pagoda’s dynamic characteristics.

3 TORSIONAL ELASTIC EARTHQUAKE RESPONSE CALCULATED BY TRANSFER FUNCTION METHOD

3.1 Transfer Function Method

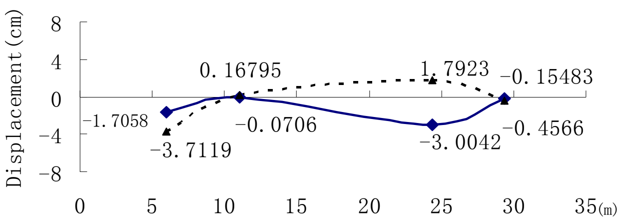
The input-output relationship of the linear system in the laplace domain is called the transfer function. In this paper, transfer function method can been interpreted as follows: Micro tremor input on the ground and micro response of a measuring point j are transferred by fast Fourier transform method (FFT) in the frequency domain, the ratio of which as the transfer function. Similarly, input time history of earthquake on the ground has also been transferred by FFT, and by means of multiplying by the transfer function, the corresponding J seismic response spectrum can be gained. Furthermore, by inverse FFT transform, the displacement-time history curve and the acceleration-time history curve of j point under corresponding earthquake can be obtained. This progress is realized by MATLAB program.

But input signals of the structure in this paper is unknown, the signals of the reference points on the bottom of the wooden pagoda were taken as input signals. Here, reducing the external disturbance of the testing signals should be paid attention to.

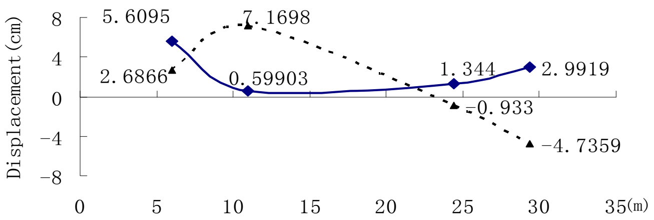
3.2 Elastic Maximum Displacements of Measuring Points under Earthquakes

The seismic response of 16 measuring points between upper floor 2 and upper floor 5 has been calculated. The acceleration peak on the ground of the three seismic waves, (EL Centro wave、Ning he wave and the artificial wave) based on the amplitude modulation as the rate of 110cm/s^2 , reached the conclusion of the time history curve of linear displacement response on each measuring point by transfer function method, from which maximum displacement of each point and the displacements of other points at the same time under earthquakes can be gained.

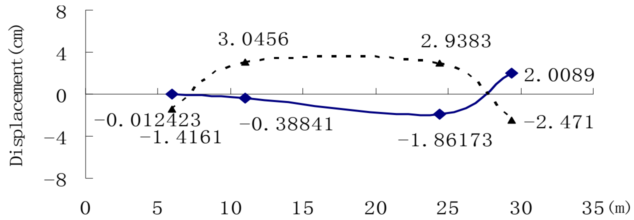
Through calculation and comparison, it is found that the displacements of the measuring points on upper floor 2 and upper floor 3 are larger than those on upper floor 4 and upper floor 5 under the three seismic waves. When the maximum displacement of every point between upper floor 2 and upper floor 3 happens, relatively distinct torsional vibration is generated. The centers of the two layers deviate owing to the vibration. Time history curve of maximum displacement response of each measuring point on upper floor 2 produced by El Centro wave is shown in Figure 5. From the phenomena, it is known that greater damages would be generated on upper floor 2 and upper floor 3, which corresponds with the current damages of the tower.



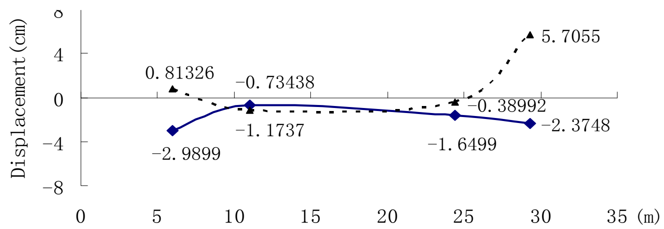
Maximum displacement of the 2rd upper story 's column in the northeast direction of exterior ring（t=8.44s）



Maximum displacement of the 2rd upper story 's column in the northeast direction of interior ring（t=5.95s）



Maximum displacement of the 2rd upper story 's column in the southwest direction of interior ring（t=3.73s）

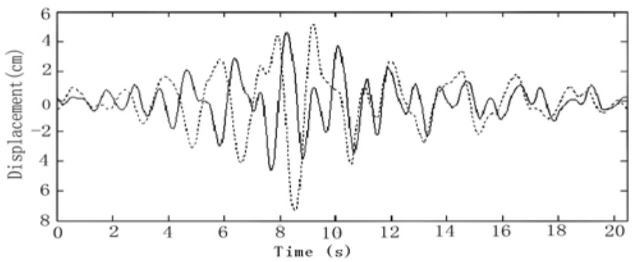


Maximum displacement of the 2rd upper story 's column in the southwest direction of exterior ring（t=6.88s）

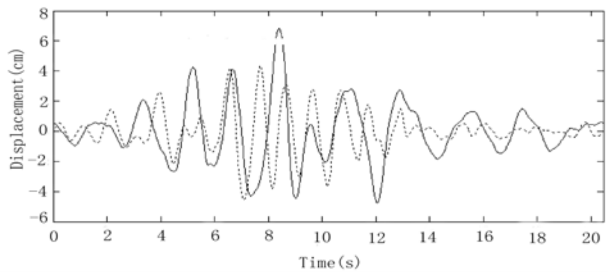
measuring points on floor 3 measuring points on floor 2

Figure 5 The displacements of the measuring points on upper floor 2 and upper floor 3

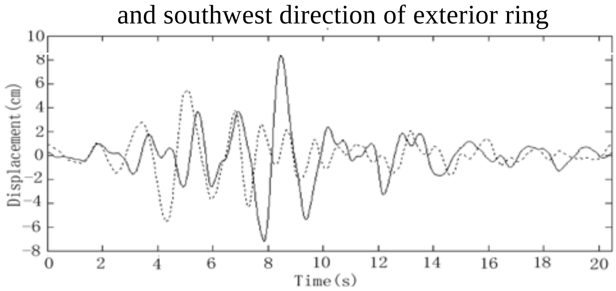
3.3 Time-history Analysis of the Measuring Points on the Same Upper Floor



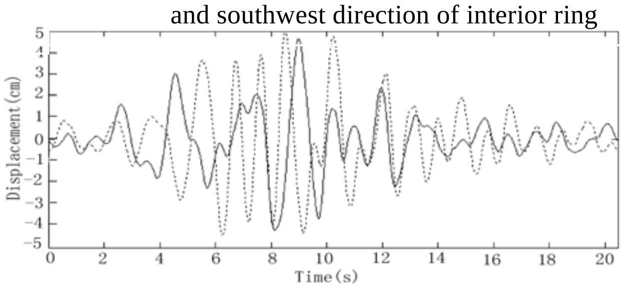
The 2rd upper story 's columns in the northeast direction and southwest direction of exterior ring



The 2rd upper story 's columns in the northeast direction and southwest direction of interior ring



The 3rd upper story 's columns in the northeast direction and southwest direction of exterior ring



The 3rd upper story 's columns in the northeast direction and southwest direction of interior ring

Figure 6 The torsional vibration of upper floor 2 and upper floor 3 under Ning he wave

In the horizontal direction, the columns and brackets are connected just by the wooden floors with small stiffness, so the torsional stiffness of the tower is weak to resist earthquakes and other external forces. In order to make clear of the torsional vibration of the tower, the time history curves of the displacement response generated on the symmetrical two points of the internal ring on each story are placed in the same figure; it is the same with the symmetrical two points of the external ring. From which the reverse phases of displacement response about the two points show obvious torsional vibration. The figures of every floor show that the vibrations generated under three seismic waves have translation-torsion coupling phenomena. Time history curves of displacement response of each measuring point on upper floor 2 and upper floor 3 caused by Ning he wave are shown in Figure 6.From which we can see that in the time period of 3.87 s-5.92s, the phase differences between two external (internal) columns on the same floor close to ±180,which show obvious torsional vibration.

4． Conclusions

(1)In this paper, the trials conducted by micro tremor measurements on the tower obtain the time-history curves of measuring points on each upper floor. Also, horizontal modes of vibration corresponding to different predominant frequencies of every upper floor are gained from frequency spectrum analysis.
(2)Study on the horizontal modes discovers that translation-torsion coupling responses of each floor are distinct, as well as with the frequency variation, the vibration presents alternative and recycling characteristics with translation, translation-torsion coupling and torsion, which demonstrates the complexity of the wooden pagoda's dynamic characteristics.
(3)The pagoda's elastic seismic displacements of measuring points of each upper layer under three seismic waves are calculated by transfer function method. It is found that the displacements of measuring points on upper floor 2 and upper floor 3 are larger by contrasting the displacements of other floors, as well as torsional vibrations are distinct on the two floors, which are in accordance with the current damages of the structure.
(4)By contrasting displacement time history curves of measuring points on the same upper floor, it is manifested that the vibration of the structure takes on translation-torsion coupling phenomena, which is related to the construction of the structure. The components（such as column cap, column foot, floors etc.） connected by mortise and tenon joints lead to weak integrity and compatibility of deformation of the wooden tower. Under the external forces, the deformation and displacement of the tower are restricted by the friction and pressure between mortise and tenon, From the above reasons, distinct deformation is generated on each layer of the pagoda under seismic performance.

5. Acknowledgement

The project was funded by the National Natural Science Foundation of China(NSFC)under grant no.50308016 and 50678111.The supports are gratefully acknowledged.

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