Structures and Buildings

Use of non-destructive techniques in Chinese traditional timber structures
Che, Ge and Li

ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/stbu.10.00019
Paper 1000019
Received 17/02/2010 Accepted 19/09/2012
Keywords: field testing & monitoring/health & safety/timber structures

ice
Institution of Civil Engineers
publishing

Use of non-destructive techniques in Chinese traditional timber structures

Ailan Che PhD
Associate Professor, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiaotong University, Shanghai, P.R. China

Xiurun Ge BA
Professor, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiaotong University, Shanghai, P.R. China

Yueming Li PhD
Professor, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an, P.R. China

The study of structural damage detection in ancient Chinese timber buildings is very important in the protection and rehabilitation of the ancient architectural culture. The purpose of structural damage detection is to identify the location and grade of structural damage based on the variation in characteristics of the structure, which is dependent on positioning techniques and quantitative analysis of structural damage detection. These elements are studied thoroughly by introducing microtremor measurements and using the finite-element method. Multi-domain microtremor measurements are performed to detect the tilting and twisting of the structure. From the observational data, the natural frequencies and vibration modes of the structure are evaluated, and these are compared with numerical results. In the numerical analysis, the changes in dynamic characteristics of the structure, such as natural frequencies and natural modes, are obtained, with special attention paid to the characteristics of brackets. Comparing the natural frequencies and natural modes from microtremor measurements with those from three-dimensional numerical analysis, the location and form of the damage is qualitatively delimited. Through continued reduction of the stiffness of the damaged layer in different directions, until the natural frequencies and natural modes from the simulation are shown to be consistent with those of the microtremor measurements, the severity of damage to the structure is quantitatively evaluated.

1. Introduction

Ancient Chinese wooden architecture is a valuable heritage of ancient Chinese culture; over thousands of years it has formed a profound and unique system, and become representative of oriental architectural culture (Su, 1999). In the 1920s and 1930s, a lot of pioneering research, excavation and measurements on Chinese ancient wooden architecture was performed by Liang Sicheng, Lin Huiyin, and so on. In the 1950s, structures with large roofs were criticised, and a number of ancient buildings were destroyed; research studies and investigations of ancient Chinese architecture were halted (Liang, 1984). Work was only restarted again in the 1990s.

The wooden material used in ancient Chinese wooden architecture is quite soft and shows serious evidence of destruction and complex behaviours after several hundred or even thousands of years, through aging and damage by natural or human activities. Examples of this include uneven settlement of the platform, incompetence of columns, loss of mortise–tenon joints, and breaking or excessive deformation of the bracket–tenon joints and beams. In addition, most of these buildings are rich in terms of pictures and historical researches, but there is generally less information available in terms of specific structural size records and other data; also it is not possible to perform relatively destructive tests on protected architectural heritage. It has been shown that the structural characteristics of Chinese ancient architecture, such as brackets, tenons and column foundations, differ greatly from other structures; their mechanical characteristics, including material non-linearity, geometric non-linearity and structural non-linearity, are not well known, so it is difficult to perform damage detection evaluation. Therefore, systematic study combining numerical simulation and modern experimental methods is of particular importance.

The Yingxian wooden pagoda is a flat-form, tall building, which was formed by the superposition of monolayer temples. The pagoda forms the external layer of a tube in a tube structure, and its seismic performance is excellent. It was built in the Liao dynasty, 1056 A.D., it is 65·86 m high and it is located in the northwest of Shanxi Province, P.R. China. The tower, an octagonal structure with five storeys, is made entirely of wood without any steel nails (Cheng, 1966). It is composed of more than 10 000 components, and its complexity and importance can be compared with the Leaning Tower of Pisa. The significant damage caused by violent earthquakes and bombardment, together with weakened material and some components (wooden columns) continuously cause threat to its safety (Li and Wang, 1996). The weakened performance of the wooden components, the actions of strong external forces, effects of environmental change and factors attributable to unfavourable human activities have accelerated damage to the tower. A recent assessment of the damage condition showed that the total height of the Pagoda has dropped by 88·8 cm from observation data recording of 67·3 m in 1962. It has tilted from the axis of the tower towards the north, by 29 cm at the first layer, 34 cm at the second layer, 36 cm at the third layer, 36 cm at the fourth layer and 54 cm at the fifth layer. The overall building is tilted to the northwest by 65 cm and compressed by nearly 90 cm, and there are over 90 damage locations on the tower. Therefore, there is an urgent requirement to repair and reinforce the Pagoda (Lam *et al.*, 2008). As part of the repair, protection and reinforcement project of the Yingxian wooden pagoda, a series of studies, including in situ tests monitoring stress, displacement and vibration, and numerical analysis of the dynamic response and wind load effects, were implemented by Li *et al.* (2005); also, microtremor measurements and seismic analysis have been performed by Che and co-workers since 2006 (Che *et al.*, 2006, 2007).

Based on a large number of historical records, survey data, observational data and previous studies, the damage evaluation is discussed in the present paper using non-destructive observation (microtremor) combined with numerical simulation. The changes of dynamic characteristics of the structure, such as natural frequencies, damping ratio and natural modes, are obtained. Special attention is given to simulation of the brackets, as well as sensor array arrangement and data analysis. The final result could be regarded as a basis of reference in the protection of ancient structures.

2. Damage detection using microtremor measurements

In natural conditions, there is always vibration at the earth's surface, with an amplitude of approximately 10^{-8} cm in the bedrock of a quiet mountain and 10^{-4} cm in the city; the period is 0·05∼10 s; this is called microtremor. It is generally considered to be the result of 'micro-causes' such as transportation, machinery operation and other human activities, or from deep formations, weather changes, rivers, lakes, ocean waves or other natural excitation. It is well known that microtremor observation is one of the most convenient methods for investigating the dynamic characteristics (natural frequency, damping constant and vibration mode) of surface ground and structures (Hattori and Kobayashi, 2001; Maekawa and Kawai, 1989; Uchida *et al.*, 1989). Considering the dynamic response as the damage identification parameter, the damaged structure is quantitatively assessed.

2.1 Measurements

The measuring equipment consisted of a type of handy seismometer (SPC-35F, distinguishing ability of 16 bit, frequency range of 0∼70 Hz) and a three-component high-sensitivity detector (VSE-15D velocity detector, with a natural period of 1 s). Any interference by human activities were to be avoided during the investigation and sites were to be as flat as possible. The records of two horizontal components (east–west (EW) and north–south (NS)) and a vertical one up down (UD) with short-period microtremors were obtained. The set-up was designed to record at a sampling rate of 100 Hz for 5 min, with a total of 30 000 values recorded for each point.

The measurement step was divided into two parts as follows:

(*a*) a layered two-dimensional observation, with one set of detectors (three components) placed on each floor (1∼5 layers) at the same time
(*b*) a three-dimensional observation, with eight detectors (one component at each time, three times for NS, EW and UD) placed on eight sidewalls of each floor (2∼5 layers) at the same time (Figure 1).

2.2 Data analysis

The frequency characteristics of microtremor can be obtained by spectral analysis of its signals using fast Fourier transform (FFT), which can be used to probe the dynamic characteristics of the structure (Che *et al.*, 2006; Jiang, 1997; Peng *et al.*, 2000). From the recorded data of microtremor measurements, five sets of 2048 digital data which avoided potential noise sources – such as machinery, vehicle traffic or pedestrians – near the seismometer during the measurement time of 5 min were selected to use for FFT analysis. The velocity Fourier amplitude spectra, spectra ratio and relative variation amplitude were calculated (Uchida *et al.*, 1999). The natural frequencies were determined by the peak values of the FFT analytical results. The vibration modes corresponding to each natural frequency were plotted using the values of Fourier amplitude at the measuring points.

2.3 Measurement results and discussion

Based on the layered two-dimensional observation, the Fourier amplitude spectra and vibration modes were obtained as shown in Figures 2 and 3. The first three natural frequencies of the pagoda obtained were 0·6, 1·66, 2·93 Hz, respectively, and the vibration modes in the NS and EW directions were asymmetric. From the vibration mode deformation, it could be considered that the relative horizontal displacement under dynamic loading would concentrate on the second floor. Based on the three-dimensional observation, the response on each of the eight sidewalls of the pagoda was obtained, as shown in Figure 4. It can be seen that the dynamic response (Fourier amplitude spectra) between floor 2 and floors 3, 4 and 5 presents torsional deformation. This result from observation is consistent with the measured deformation of the tower, in which the second floor is seriously damaged.

3. Three-dimensional finite-element model of the pagoda and its dynamic characteristics

3.1 Modelling and parameters

The ancient wooden structure can be divided into three parts: base, body and roof. The base is mainly rammed earth. The structure is supported by a wooden frame composed of

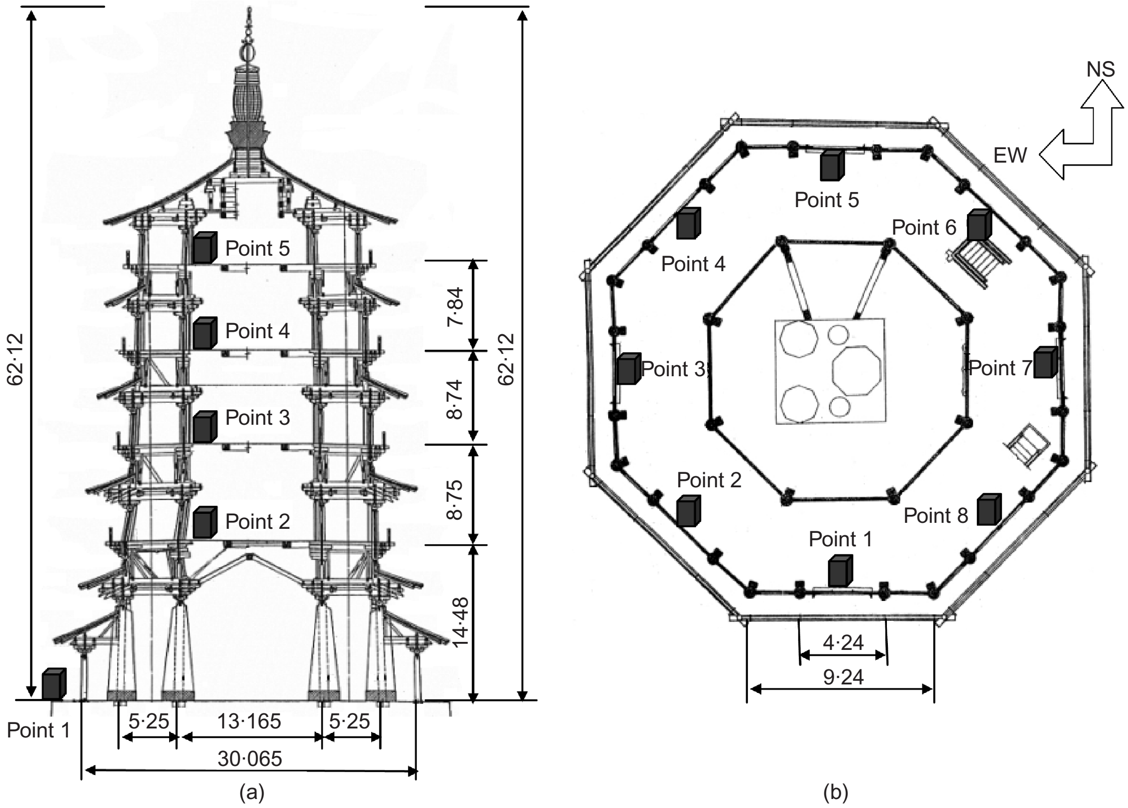


Figure 1. Structural damage detection method using microtremor measurements (dimensions in m): (a) layered measurements; (b) three-dimensional measurements

beams and columns, with wooden doors, windows or walls around it constituting filling and support. A simple and effective way was needed to establish the finite-element model for the structure, which could simulate structural and mechanical characteristics. The finite-element model includes several components, as described in the following subsections.

3.1.1 Beam element system

Yingxian wooden pagoda is a structure with five apparent storeys and four hidden storeys. There are similarities to a modern core-in-core structure; considerable fixed bracing makes each hidden floor appear to have rigid reinforced connections, and the oblique support causes the horizontal and upright frames to integrate tightly. Overall, the pagoda as is composed of by the apparent storeys, brackets layer and the hidden storeys, where the stiffness of those layers is great. The wooden frame structure mainly consists of columns, beams, plates and brackets, which can be regarded as a beam structure system. As shown in Figure 5, a detailed finite-element model is created to be as similar as possible to the Yingxian wooden pagoda. The beams and columns are simulated as interconnected horizontal and vertical beam elements, and connected by the brackets. A rigid connection between the beam and the column is assumed in the analytical model. As the connection between floor and beams is loose and the stiffness is not great, the floor is ignored in the calculation.

3.1.2 Mechanical properties of brackets

A bracket is a connection element comprising various components that connect the pillars and roof of the structure. The behaviour of brackets is complex; they not only bear a large force in the overall structure, but they also provide a damping effect, absorbing more energy of dynamic and seismic forces owing to their flexibility characteristics. A mortise and tenon connection possesses characteristics somewhere between rigid and hinge, and is called a semi-rigid connection. The deformation is larger than for a rigid connection and smaller than for a hinge; it is not only able to withstand tension and compression, but also has considerable bending and torsion capacity. To simulate different types of nodes transfer bending (twisting) moment, a variable-stiffness unit is used (Zhao *et al.*, 1999); this differs greatly from the brackets, being composed of many short components, and the parameters of the semi-rigid connection unit must be inverted for purposes of calculation, so it represents an uncertainty.

Based on the above experience, two kinds of detailed finite-element model for mortise and tenon joints composed of beams

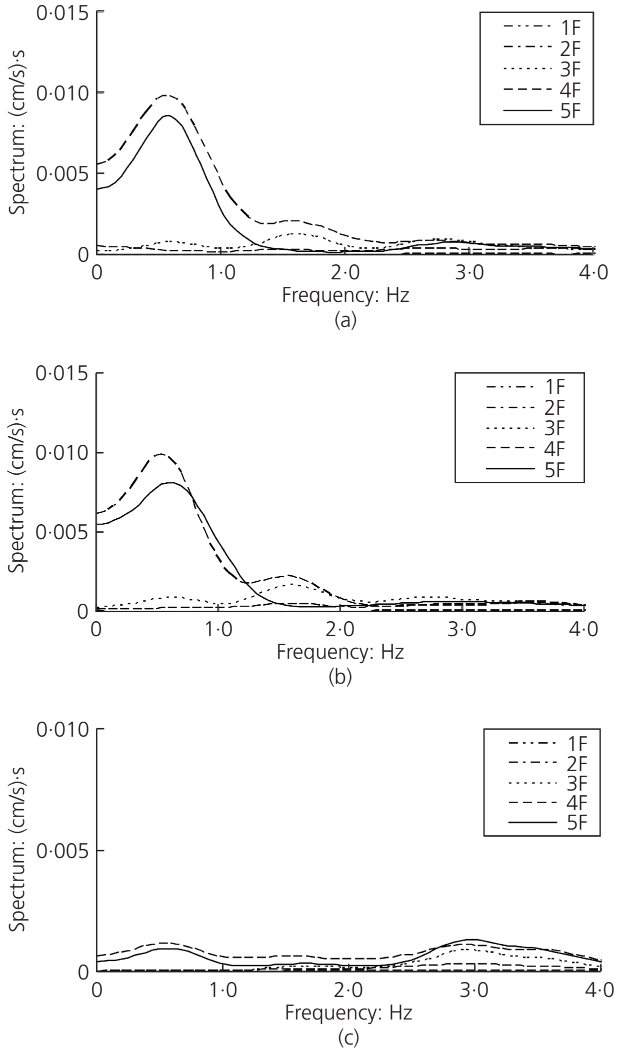


Figure 2. Fourier amplitude spectra at (a) NS; (b) EW; (c) UD

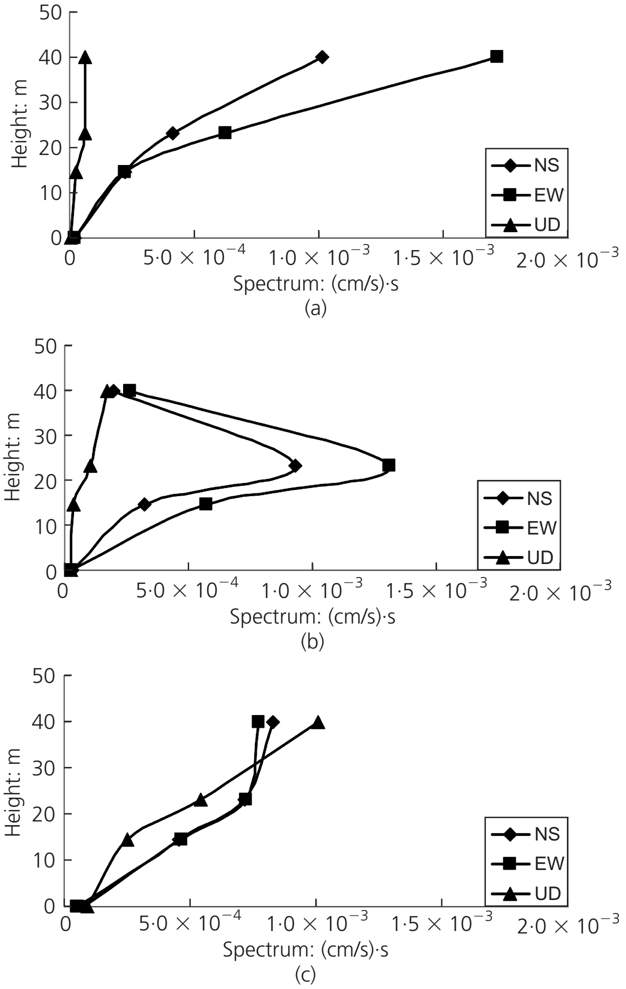


Figure 3. The first three vibration modes of the tower: (a) first mode; (b) second mode; (c) third mode

and columns are established, where the geometry is consistent with the pagoda. Beam elements are used in the finite-element model, where type-1 is on the octagonal side and type-2 is in the octagonal corner (Figure 6). Its flexible connection is simulated by changing the stiffness (I_{zz}, I_{yy}) of the connecting column element, which can transfer tensile and compression forces and torque and bending moments and the dynamic characteristics of the bracket model are shown in Figure 7, where the stiffness (I_{zz}, I_{yy}) of connecting column element is reduced to 20%.

In the calculation of the overall model, the mortise and tenon joints of the structure are replaced by a special beam element (bracket element), the dynamic properties of which are shown in Figure 7. For equivalent stiffness it is assumed that the force and displacement acting on the node at the top centre of the three-dimensional bracket model is equal to that of the one-dimensional bracket element, so $E_1' = E/180$ (type-1), $E_2' = E/220$ (type-2), where $E = 9{\cdot}0 \times 10^9$ GPa (Young's modulus) and the equivalent diameters are $d_1 = 0{\cdot}88$ m (type-1), $d_2 = 1{\cdot}04$ m (type-1), considering the total volume of brackets to be the same as that in the overall model.

3.1.3 Parameters

An elastic material model is used for the beam elements and a plastic material model is used for the bracket elements. According to the experimental results (Fang *et al.*, 2001), the elastic constants of the model are as follows: Young's modulus = $9{\cdot}0 \times 10^6$ kN/m^2 (beam elements); $5{\cdot}0 \times 10^4$ kN/m^2 (bracket elements – type-1); $4{\cdot}0 \times 10^4$ kN/m^2 (bracket elements – type-2), Poisson ratio = 0·1, density = 4·5 kN/m^3. The non-linear relationship of the bracket beam elements is shown in Figure 7.

3.1.4 Adobe walls

The bottom layer of the pagoda is packed with adobe around the columns, so the stiffness is very great and it is not easily deformed under load. This is represented by increasing the

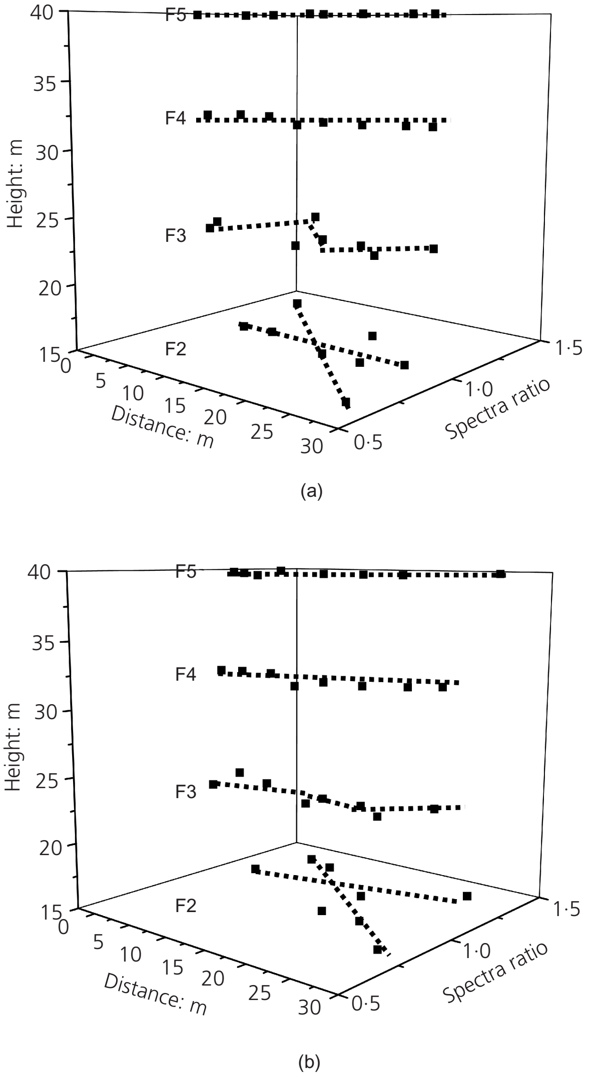


Figure 4. Spectra ratio of the first floor between floor 2 and floors 3, 4 and 5: (a) NS direction; (b) EW direction

stiffness of the bottom beam element to simulate the adobe walls in the calculation model.

3.1.5 Concentrate quality

A concentrate quality is instated of the added mass, which includes eaves' tiles, statues and top temple. The concentrate quality element is uniformly distributed at the top of the columns.

3.1.6 Foundation

The wooden structure has good flexibility in relation to the foundation, so it is assumed to be rigid between the structure and the foundation.

3.2 Analytical results

The modal analysis of the Yingxian wooden pagoda is carried out by means of the finite-element method, and the first three natural frequencies are 0·65, 1·956, 3·196 Hz, respectively. The first three modes are shown in Figures 8 and 9. The dynamic response of the tower shows that the second and third floors of the tower are mostly predominant in the response.

4. Evaluation method comparing measurements results with analytical results

Structural damage detection methods based on dynamic analysis are widely studied; they can detect damage comprehensively (Kim and Barkowicz, 1997). For large-scale structures it is very difficult to identify simultaneously the location and the grade of structural damage by using limited modal measurements, and this often leads to mistaken results in damage identification (Kim, 1995). An effective approach is to identify the structural damage in complex structures using location identification and grade identification. A multi-domain structural damage detection method using microtremor measurements was investigated in the present study. Comparing the natural frequencies and their multiple modes from microtremor measurements with those of the three-dimensional numerical model, the location and damage formation are qualitatively delimited. By combining the existing measurement information with those results, a three-dimensional numerical model of damage is established. By continued reduction of the stiffness of the damaged layer in different directions, until the natural frequencies and their multiple modes from the simulation are shown to be consistent with those of the microtremor measurements, the severity of the damage to the structure is quantitatively evaluated.

4.1 Evaluation of location of structural damage

The first three natural frequencies and the first three vibration modes of the tower at two mutually orthogonal horizontal directions (NS and EW) are obtained by finite-element method modal analysis of the three-dimensional model and microtremor measurements of the damaged tower (Figure 9). Comparing the first three natural frequencies of the numerical results with the microtremor measurements, results of 0·65, 1·956 and 3·196 Hz are decreased to 0·6, 1·66 and 2·93 Hz, respectively. It is shown that there is significant weakness in the whole structure. The natural modes of the numerical model show a symmetrical response, whereas the natural modes of the damaged model show an asymmetrical response, where the mode in the EW direction is greater than for the NS direction. This was considered to be because the tower is tilted to the northwest. The maximum relative horizontal displacement is between floors 2 and 3 (Figure 4). Therefore, the horizontal stiffness of the tower is deduced and great horizontal stiffness between the two floors is discovered, which causes a concentration loading during earthquake. These results are consistent with the current deformed state of the tower.

4.2 Evaluation of severity of structural damage

Based on the experimental studies and the survey results, which showed that the maximum tilting of the tower was 1·2% and the top of the tower had deviated from its central axis by over 0·5 m,

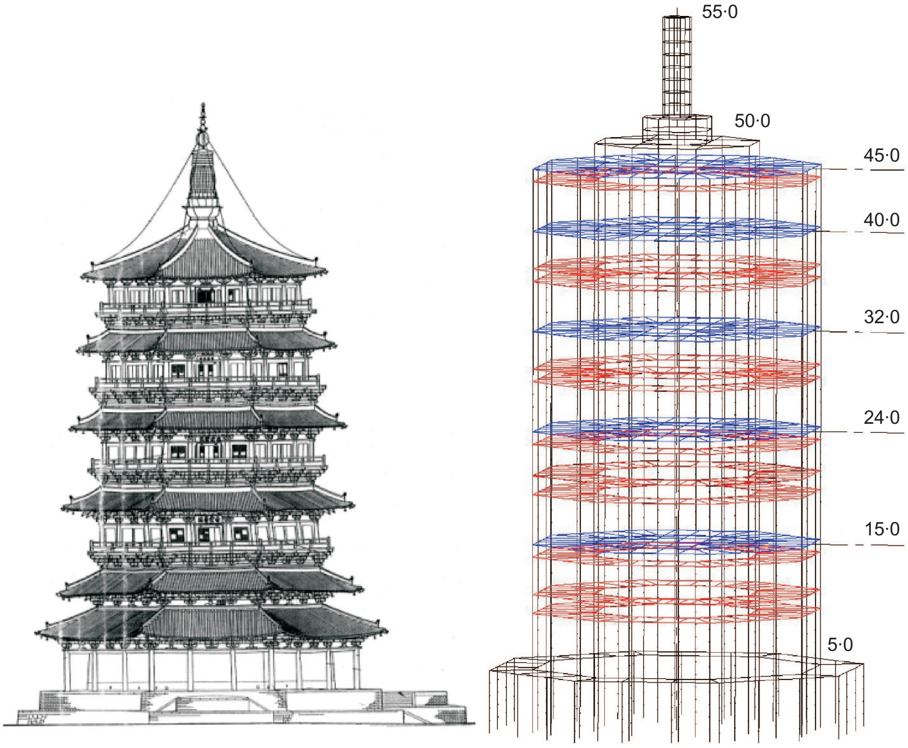


Figure 5. Three-dimensional finite-element model of the Yingxian wooden pagoda (dimensions in m)

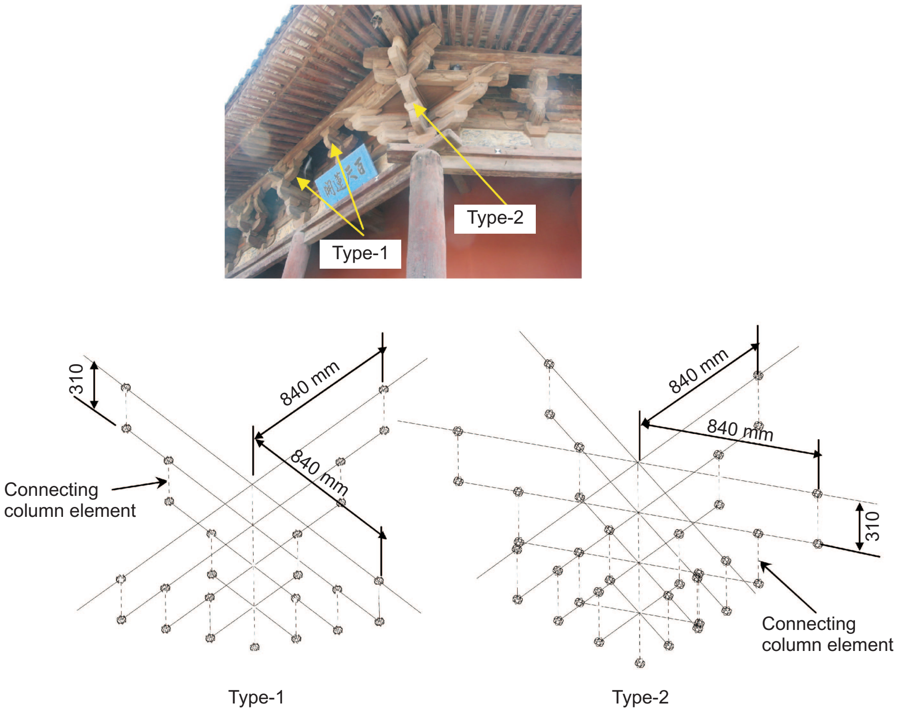


Figure 6. Finite-element model of mortise and tenon joints (dimensions in mm)

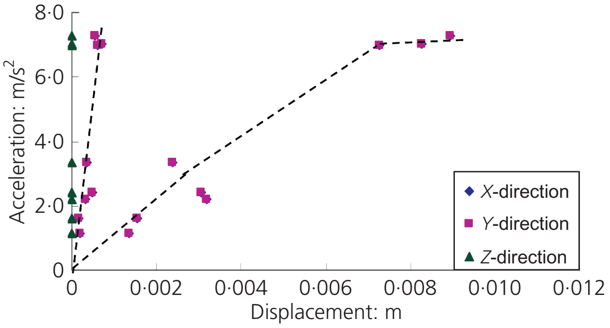


Figure 7. Non-linear characteristics of the brackets element

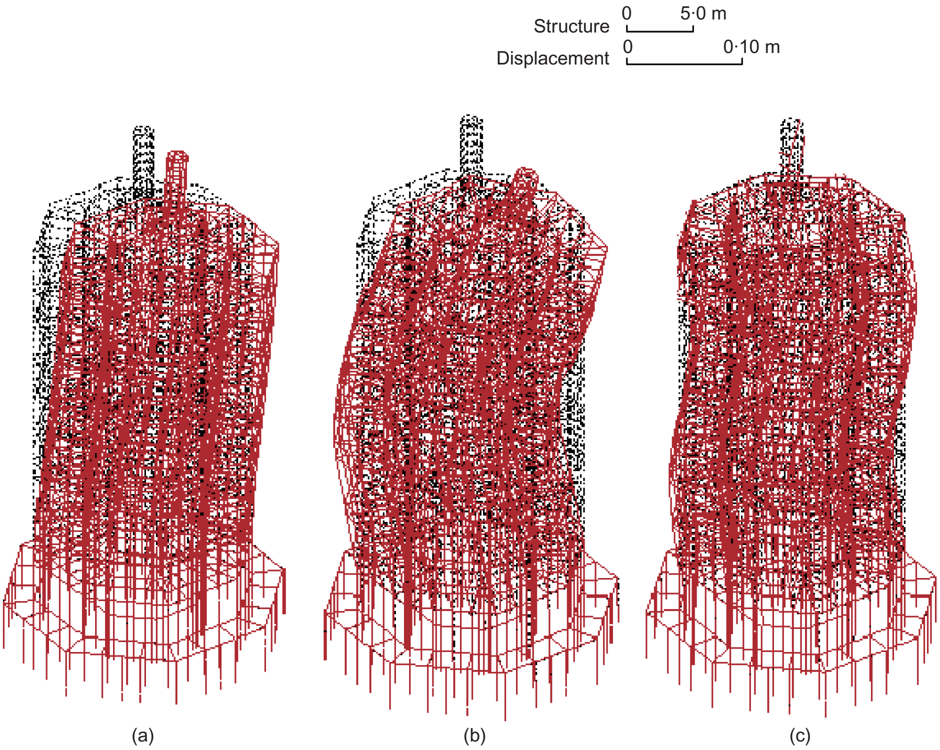
a three-dimensional finite-element tilting model was established. The simulation was based on an existing horizontal relative displacement of the tower of 0·3 m between the first and second floors, and 0·6 m between the first and third floors. Initially, during continued reduction of the stiffness of the damaged layer, with a reduction ratio of 10%, the natural frequencies and natural modes from the simulation remained basically consistent with the microtremor measurements. Then the layer rigidity of the second floor was decreased to 60%, according to the results showing the location of structural damage, with the reduction of layer rigidity of the tower concentrated at the second floor, and the dynamic characteristics of the damaged model mostly corresponded to the microtremor measurements (Figure 10).

5. Conclusion

For an ancient wooden structure with damage, a simplified damage detection method has been proposed based on the results of microtremor measurements. A layered two-dimensional and three-dimensional observation was performed to obtain the predominant frequencies and vibration modes of the structure. The symmetry, tilt and torsion of the structure were clarified.

By comparing the natural frequencies and natural modes from the microtremor measurements with those obtained by three-dimensional numerical analysis, the location and damage formation were qualitatively delimited. Combining the existing information with those results, a three-dimensional numerical model of the damages was established. Through continued reduction in the stiffness of the damaged layer in different directions until the natural frequencies and natural modes from the simulation showed consistency with the microtremor measurements, the severity of damage to the structure was quantitatively evaluated.

In this case, modal analysis of the structure showed that the element on the second and third floors supports a heavy burden and takes on large deformation under loading. The decrease of the tower's energy dissipation ability, as a result of these



(a) (b) (c)

Figure 8. Vibration modes of a comprehensive model of Yingxian wooden pagoda: (a) first mode; (b) second mode; (c) third mode

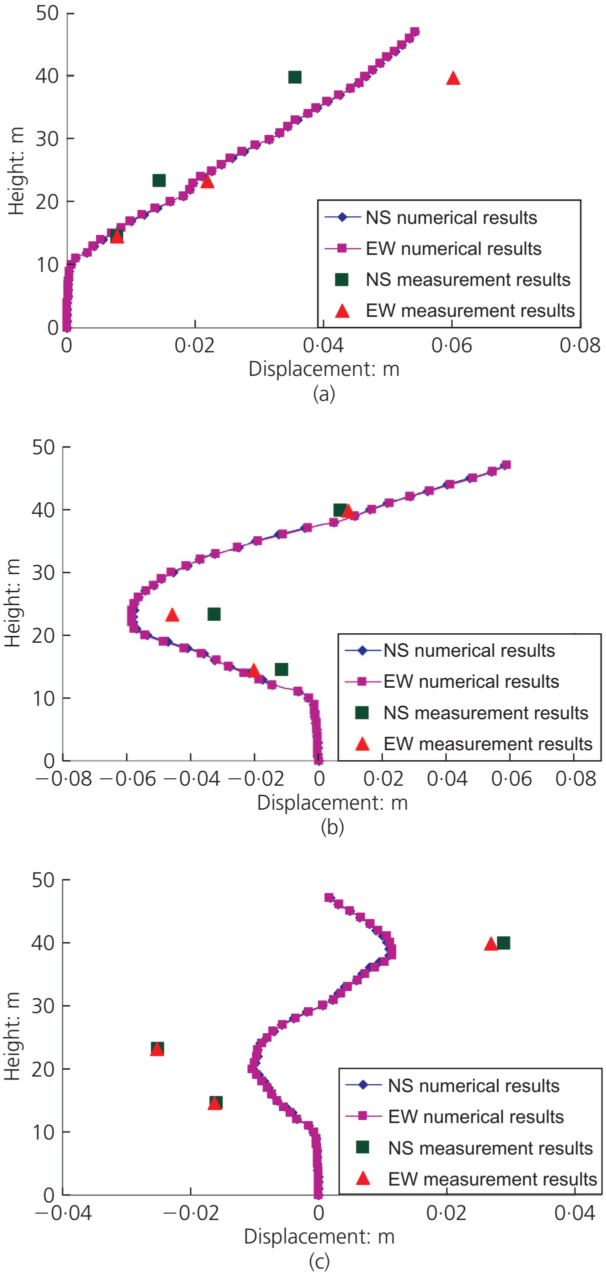


Figure 9. Comparing the natural modes of the numerical model with microtremor measurements: (a) first mode; (b) second mode; (c) third mode

damaged parts and the remaining displacements, is the main factor causing weakness in the tower's seismic resistance ability. Reinforcement should be carried out first at the second and third floors, since the problem appears to be located there according both to the present study and to other monitoring data. In addition, any reinforcement should be considered carefully in order to retain the original characteristics of the structure according to the tower's individuality.

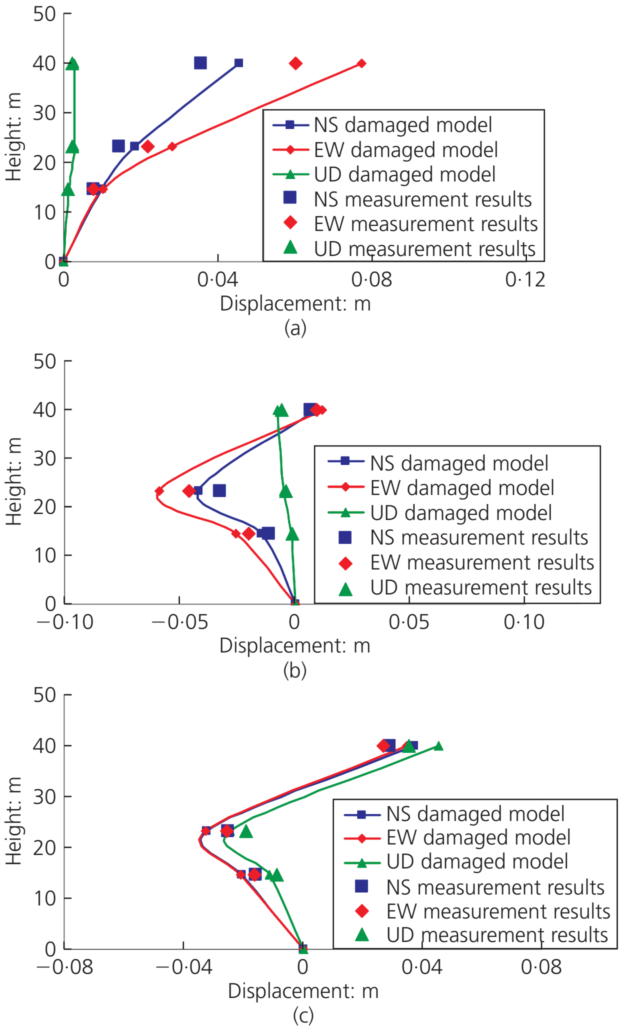


Figure 10. Comparing the vibration modes of the damaged model with microtremor measurements: (a) first mode; (b) second mode; (c) third mode

Acknowledgement

This project is financially supported by the fund of the National Natural Science Foundation of China (no. 40974070).

REFERENCES

Che A, Iwatate T and Ge X (2006) Study on the applicability of frequency spectrum of micro-tremor and dynamic characteristics of surface ground in Asia area. *Journal of Zhejiang University, Science* **7(11)**: 1856–1863.

Che A, Ge X and Iwatate T (2007) Evaluation of dynamic behaviors and damage mechanism of ancient timber architectures. *Key Engineering Materials* **340–341(1)**: 277–282.

Cheng M (1966) *Yingxian Wooden Tower*. Cultural Relic Press, Beijing, China.

Fang DP, Iwasaki M and Yu MH (2001) Ancient Chinese timber architecture, A: Experimental study. *Journal of Structural Engineering, ASCE* **127(11)**: 1348–1357.

Hattori H and Kobayashi K (2001) The dynamic characteristics of an ancient timber structure (3-storied pagoda of Shinrakuji (Miyota, Nagano)). *Proceedings of the 56th JSCE Symposium*, pp. 1–9.

Jiang T (1997) Study on microseism and its application to earthquake engineering. *World Earthquake Engineering* **13(4)**: 41–46 (in Chinese).

Kim HM and Barkowicz TJ (1997) A two-step structural damage detection approach with limited instrumentation. *Journal of Vibration and Acoustics* **119(2)**: 258–264.

Kim HM (1995) Health monitoring of large structures. *Sound and Vibration* **29(4)**: 18–21.

Lam F, He M and Yao C (2008) Example of traditional tall timber buildings in China – the Yingxian pagoda. *Structural Engineering International* **18(2)**: 126–129.

Li S and Wang J (1996) *Anti-seismic Research on Yingxian Wooden Tower*. Taiyuan Engineering University, Shanxi, China.

Li T, Wei J, Li S and Zhang S (2005) Appraisal of the structure of the Yingxian wooden tower. *China Civil Engineering Journal* **38(2)**: 51–58.

Liang S (1984) *A Pictorial History of Chinese Architecture: A Study of the Development of Its Structural System and the Evolution of Its Types*. MIT Press, Cambridge, MA, USA.

Maekawa H and Kawai N (1989) Dynamic characteristics in Japanese traditional timber buildings. *Proceedings of the World Conference on Timber Engineering (WCTE)*, vol. 1, pp. 40–47.

Peng Y, Lu Z, Li X *et al.* (2000) The application for the pulsant predominant period of the subsoil in engineering seismics. *North China Earthquake Sciences* **18(4)**: 61–68 (in Chinese).

Su B (1999) *Effects on China City and Architecture from Japan*. China Water Power Press, Beijing, China.

Uchida A, Naohito K and Maekawa H (1989) Dynamic characteristics in Japanese traditional timber buildings. *Proceedings of the World Conference on Timber Engineering (WCTE)*, vol. 2, pp. 34–41.

Uchida A, Kawai N and Maekawa H (1999) Non-destructive diagnosis for Japanese traditional timber buildings. *Proceedings of the 1st Internatural RILEM Symposium on Timber Engineering, Stockholm*. RILEM, Bagneux, France, pp. 295–304.

Zhao J, Yu M, Sun JJ and Song T (1999) The testing of dynamic behavior of a wooden structure ‘Dougong’. *Proceedings of the 3rd International Symposium on Test and Measurement (ISTM-99)*, pp. 784–787.