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Application of Non-Detective Techniques in Traditional Masonry Structures

CHENG Cheng (程　成),　*CHE Ai-lan** (车爱兰),　*CAO Yong-kang* (曹永康)
(School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, China)

Abstract: Study on the non-destructive detection techniques and damage identification method is of great importance in protecting and rehabilitating the ancient architectural structure. In order to identify the location and the grade of structural damages, a multi-point microtremor measurement is performed on carved brick screen walls at Songjiang area in Shanghai, and the observed dynamic parameters (natural frequencies and natural modal) are obtained. On the other hand, the dynamic parameters of the original structure are calculated by finite-element-method (FEM). Normalizing the observed and calculated parameters on unified physical quantity, the damages are located by the variation on vibration modal, and the grade of structural damages is quantitatively evaluated by stiffness losses based on the variation on vibration modal.
Key words: damage identification, microtremor, natural modal, stiffness loss
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0 Introduction

Most of the existing Chinese traditional ancient architectures are masonry structure, which is valuable heritage of Chinese ancient culture. For thousands of years, it has been formed a profound and unique system, and becomes the represents of oriental architectural culture. Most of the well preserved were built in Song, Yuan, Ming, and Qing dynasties, such as Nine-Dragon Wall at Datong and the Great Wall at Beijing. In the long history, it has been endured loads, natural weathering, war and earthquakes, and has caused problem of damages and damage accumulation which could reduce the functional performance of the structure or even cause structural damages[1]. For protecting the traditional ancient architectures and avoiding the disastrous accidents, a convenient and non-destructive detection method is needed to identify the location and the grade of the damage as early as possible.

There are a variety of non-destructive detection techniques for structural damage. Among them, X-ray photographic technology, ultrasonic inspection technique, electromagnetic testing and acoustic detection technology are widely used[2]. Most of them need prior know the approximate damage and detection positions which are easy to approach. It is difficult to apply for the structures whose damages are invisible, not opening, large complex, and not easy to approach. The signal is easy to collect and the sensor can easily be set for the non-destructive detection techniques using the dynamic characteristics of structure. Therefore, a variety of non-destructive detection methods based on dynamic characteristics are used to detect the traditional ancient structures[3], such as stress wave nondestructive testing, resistance detection, resonance method and microtremore which are widely used in Japan and Italy[4].

The source of microtremor is from deep of the Earth, and it has no effect on the structure. Moreover, the equipment of microtremor measurements is lightweight and easy to operate, so it can be applied to large complex structures[5]. The vibration characteristics of the structure like amplitude of vibration, natural frequencies and modal are measured by microtremor technique. The functional performance of the structure is quantitatively evaluated based on the damage identification using the observed dynamic response as damage identification parameters.

1 Damage Identification Method Based on the Varieties of Structural Natural Vibration Modal

It is well known that structural damage causes loss of stiffness or mass which resulting in the variety of structural dynamic characteristics such as natural frequencies, natural modal and damping. In general, the

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∗**E-mail:** alche@sjtu.edu.cn

structural damage would cause a decrease of the natural frequencies and an increase of the damping ratio. Therefore, the structural damage can be identified by the variety of the natural frequencies, damping ratio and modal of vibration. The natural frequencies of structure show the overall performance and it is difficult to identify the local damage of the structure. However, there is more information of structural damage in the natural modal, especially for evaluation of the damage location[6]. Though it is easy to locate the damage of the structure by using the variety of structural modal, the vibration modal is difficult to observe completely, the deviation is inaccuracy, and the damage grade is difficult to evaluate quantitatively[7].

1.1 Analytical Method

The damage of structure is located by observing the mutation of vibration modal, e.g. strain modal and power modal. For the incomplete information of measurements, the quantitative evaluation of damage can be iterated by least square method, or the stiffness losing can be calculated by variance of vibration modal. Analytical procedures are listed as follows.

(1) The natural frequencies and natural modal of the structure are measured using microtremor, while the measurement points are setting all over of the structure according to the structural characteristics.

(2) The dynamic parameters such as natural frequencies and natural modal of the undamaged structure are calculated by finite-element-method (FEM) according to the original design and construction data.

(3) Comparing the calculated natural frequencies and natural modal with the observed results, the damages of the structure are located by evaluating the mutation of response.

(4) As the natural frequencies and modal of the structure are the function of mass and stiffness, the variety of stiffness and mass of the structure can be identified by comparing the analytical dynamic characteristics with the observations:

$$\boldsymbol{K}\boldsymbol{\phi}_i - \omega_i^2 \boldsymbol{M}\boldsymbol{\phi}_i = \boldsymbol{0}, \tag{1}$$

where, $\boldsymbol{M}$ and $\boldsymbol{K}$ are the mass and stiffness matrixes, respectively; ω_i is eigenvalue of the i order; $\boldsymbol{\phi}_i$ is the corresponding eigenvector.

1.2 Stiffness Losing

Generally, the observed structure can be simplified as a system with n number of degrees of freedom (DoFs). The ω_i and $\boldsymbol{\phi}_i$ of damaged structure can be obtained by analyzing the observation data. Suppose n numbers of eigenvectors (natural modal) compose of an $n \times n$ natural modal matrix, i.e. $\boldsymbol{\phi} = [\boldsymbol{\phi}_1 \quad \boldsymbol{\phi}_2 \quad \cdots \quad \boldsymbol{\phi}_n]$, and let $\boldsymbol{\phi}$ be normalized by mass matrix and $\boldsymbol{I}$ is unit matrix, then there is

$$\boldsymbol{\phi}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{\phi} = \boldsymbol{I}. \tag{2}$$

According to

$$\boldsymbol{\phi}^{\mathrm{T}}\boldsymbol{K}\boldsymbol{\phi} = \mathrm{diag}(\omega_1^2, \omega_2^2, \cdots, \omega_n^2), \tag{3}$$

the stiffness matrix of damaged structure can be represented by the natural modal and natural frequencies:

$$\boldsymbol{K} = (\boldsymbol{\phi}^{-1})^{\mathrm{T}}\mathrm{diag}(\omega_1^2, \omega_2^2, \cdots, \omega_n^2). \tag{4}$$

Therefore, the grade of damage of the structure can be identified by analyzing the variation of stiffness matrix and losing of stiffness. Effectively, there would be uncertain for structures with many numbers of DoFs or complex structures, because each natural modal cannot be measured and usually only several low orders of modal can be measured[8].

2 Microtremor Measurements of Traditional Masonry Structure

2.1 Carved Brick Screen Wall at Songjiang Area

Carved brick screen walls at Songjiang area were built in Ming dynasty, 1370 A.D., for over 600 years, located in the west of Shanghai, China. The superstructure is of 14.90 m length and 5.30 m height. The wall is masonry with two types. In 2.43 m height from the ground, the masonry form is one horizontal and three vertical arrays of black bricks with size of 270 mm × 140 mm × 48 mm used to mortar bond, and the thickness of this part is 630 mm. The other part of the wall is masonry with one horizontal and five vertical arrays of black bricks with 230 mm × 85 mm × 40 mm size used to mortar bond, and the thickness of this part is 530 mm. Masonry form is shown in Fig. 1.

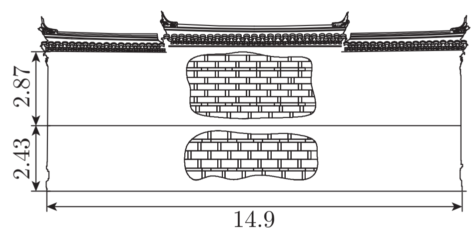

Fig. 1 Carved brick screen walls at Songjiang and masonry form (m)

There are serious damages occurred in the wall, such as weathering on the surface of sidewall in north, cracks on the sidewall in south and edges, and other local damages, leakage and weathering on the tiles of roof. The wall shows protruding to south, especially in the middle part, and the maximum tilting of the wall reaches 33.1‰. Therefore, there are multiple potential dangers in the wall; it is needed to comprehensively evaluate the safety status for ensuring the safety of the large brick-carving artistic works.

2.2 Microtremor Measurements

The measuring equipment consists of one handy seismometer (Geode, 24 channels, distinguishing ability 24 bit, frequency range of 1.75 Hz—20 kHz) and one component high-sensitive velocity detector (the natural frequency is 4.5 Hz). The detectors are connected by cables for simultaneous acquisition of multi-point data. Also a simple device which can be effectively coupled with structure in two directions of east-west (EW) and north-south (NS) is machining, as shown in Fig. 2.

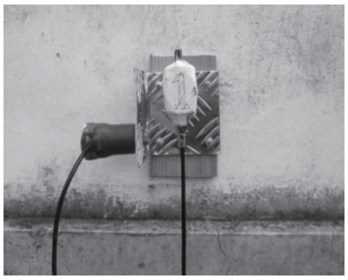

Fig. 2 Machining device for setting sensors

The detectors (two components) are placed on each part of the wall with four measurement points at different heights considering the structural form, masonry style and characteristics of structure components, as shown in Fig. 3. The measured direction of NS is along the long axis and the one of EW is along the short axis of the structure. The interference of human activities should be avoided during measuring, and the surface of the structure should be as flat as possible. The signals of two components (EW and NS) with short-period microtremor are obtained. It is designed to record at a sampling rate of 4 ms for 150 min. Figure 4 shows

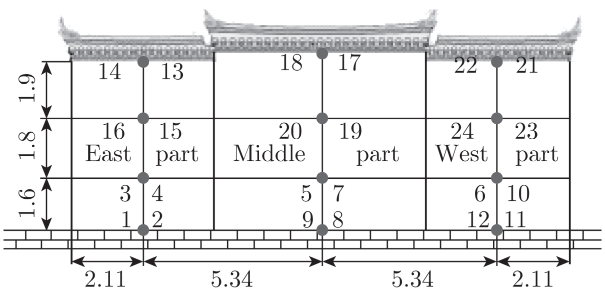

Fig. 3 Multi-point measurement (m)

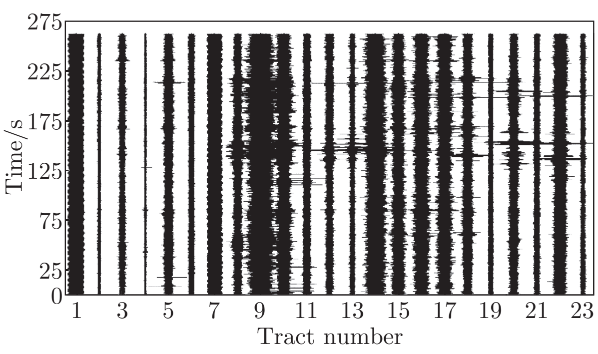

Fig. 4 Recorded velocity waves of 24 channels

the recorded velocity waves of 24 channels (0—250 s). There is a regular interference on the waves from cables by the wind and other natural factors, however the waveform is steady.

2.3 Data Analysis

The frequency characteristics of microtremor can be obtained by a spectral analysis of its signals used fast Fourier transform (FFT), and it can be used to probe into dynamical characteristics of the structure. From the recorded data of microtremor measurements, 10 sets of 60 s digital data avoided the potential noise sources during the measurement time of 150 min are selected to use for FFT analysis. The Fourier spectra of velocity by a period in NS and EW directions, denoted as S, are calculated by averaging the 10 sets of Fourier spectra after smoothing with 10 times Hanning window (frequency band is about 0.1 Hz). The natural frequency, denoted as f, is determined by analyzing the peak values of FFT results. The vibration modal corresponding to each natural frequency can be plotted using the peak amplitude values of Fourier spectra at measuring points.

Figure 5 shows the Fourier spectra of velocity by a period in NS direction with different heights of the eastern side of the wall. The height of the wall is denoted as h. It shows the same resonant characteristics of four measurement points, and the basic three natural frequencies of the wall are 2.43, 3.09 and 4.48 Hz, respectively. The basic three orders of vibration modal can be obtained by plotting the resonant amplitude corresponding to each natural frequency.

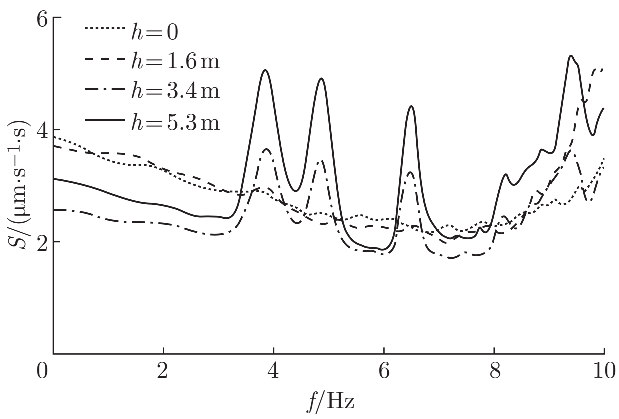

Fig. 5 Fourier spectra of velocity by a period in NS direction of the eastern side of the wall

Figure 6 shows the basic three orders of vibration modal corresponding to each natural frequency distribution considered as the natural modal of the structure. It is shown that the vibration modal in east and west parts of the wall is similar, and the response of modal is different from the middle part. Especially, there is a mutation occurred on the top of the middle part.

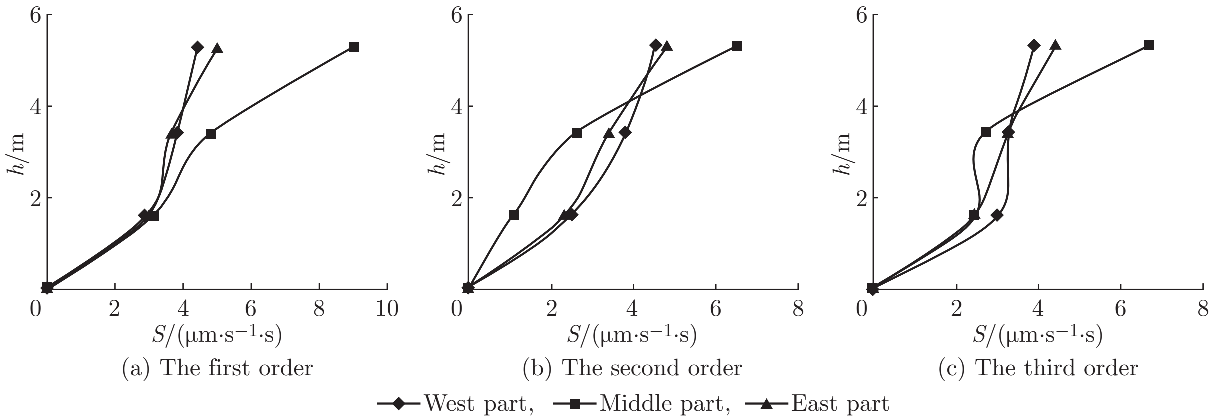

Fig. 6 Natural modal of the structure in NS direction

3 Structural Damage Evaluations Based on the Measured Dynamic Parameters by Microtremor

3.1 Dynamic Characteristic of Undamaged Structure

An undamaged 3D FEM model is established according to the historical records, surveying and original design and construction data, as shown in Fig. 7. The hexahedral solid element is used, and the bottom of the model is fixed. The material parameters of the model are shown in Table 1. Density is ρ, elastic modulus is E, and Poisson's ratio is μ.

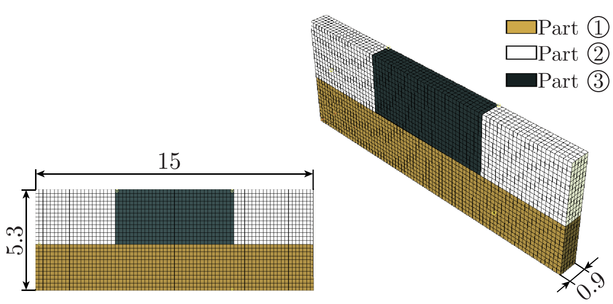

Fig. 7 Three-dimensional FEM Model (m)

Table 1 Material parameters

Part	$\rho/(\mathrm{kg\cdot m^{-3}})$	E/MPa	μ
①	1 700	0.64	0.12
②	1 700	0.80	0.12
③	1 700	1.00	0.12

The modal analysis of the 3D wall model is carried out. As a result, the basic three natural frequencies are 2.45, 3.86 and 6.11 Hz, respectively. Compared with the observed results, it decreases slightly. The calculated modal of the basic three orders is shown in Fig. 8, where U_y is the displacement in y direction. The dynamic response of the undamaged wall model shows symmetric characteristic, the ones of the first and second orders of the vibration modal are predominant mostly, and the maximum response appears at the top of the wall.

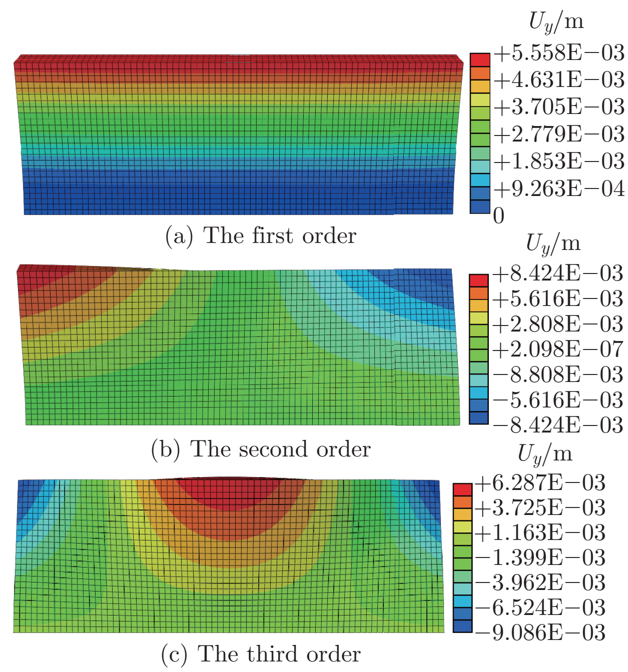

Fig. 8 Natural modal of the 3D wall model

3.2 Damage Location of the Structure

The physical quantities of natural modal in calculation are displacement and spectra of velocity by a period in observation. It is needed to normalize those results into dimensionless quantity. Then we define D-value as positive difference between the observation results and the calculation results. The distribution of damage is located by D-value, as shown in Fig. 9. The variety of variation modal is mainly concentrated on the upper part of the wall, the result of which is consistent with the measuring deformation of the wall. The middle part is protruding to the south, and the maximum tilting of the wall reaches 3.31%.

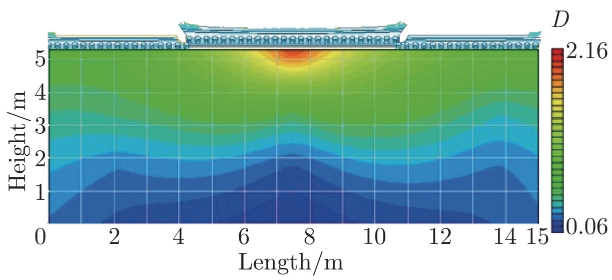

Fig. 9 Damaged location of the wall

3.3 Damage Grade of the Structure

Each part of the observed structure can be simplified to a 3-DoF system according to the structural characteristics and the measurement arrays. In the 3-DoF system, the stiffness (k_1, k_2, k_3) is unknown, the mass (m_1, m_2, m_3) is constant, and the eigenvalue ω and modal Y are observed. Then the stiffness can be calculated by

$$\left.\begin{aligned} k_1 &= \frac{s_1 Y_{11} + s_3 Y_{31} + s_2 Y_{21}}{Y_{11}} \\ k_2 &= \frac{s_3 Y_{31} + s_2 Y_{21}}{Y_{21} - Y_{11}} \\ k_3 &= \frac{s_3 Y_{31}}{Y_{31} - Y_{21}} \end{aligned}\right\}, \qquad (5)$$

$$s_1 = \omega^2 m_1, \quad s_2 = \omega^2 m_2, \quad s_3 = \omega^2 m_3,$$

where Y_{11}, Y_{21} and Y_{31} are the variation modal which can be measured. According to the results of FEM analytical results and microtremor observation results, the damaged stiffness k_{obv} and undamaged stiffness k_{cal} can be calculated by Eq. (5). The stiffness losing is defined as

$$\eta = (k_{\mathrm{obv}} - k_{\mathrm{cal}})/k_{\mathrm{cal}}.$$

Plotting the stiffness losing on the profile of the wall, the distribution of damage grade evaluated by stiffness losing is shown in Fig. 10. It is shown that the west part is more serious than the east part, and the most serious part appears in the upper of the middle part with 62% stiffness losing.

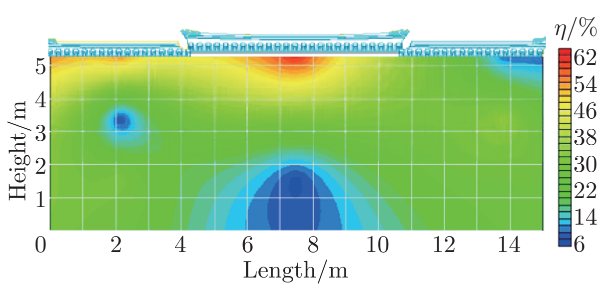

Fig. 10 Evaluation of damaged grade

4 Conclusion

Microtremor technology has low effects on the structure, and can also probe into the dynamic response of the structure. The vibration modal of the structure is regarded as the damage identification parameter. The damage location can be identified by evaluating the variety of variation modal, and the damage grade can be determined by calculating the stiffness losing between the observation results and the FEM analytical results.

Microtremor measurements are conducted on carved brick screen walls at Songjiang area. The measurement points are setting considering the structural form, masonry style and characteristics of structure components, so that the damage status of structure can be adequately grasped. The basic three natural frequencies and vibration modal of the wall are obtained by FFT analysis.

During the practical application, it is needed to normalize the modal as a dimensionless quantity. Comparing the analytical results with the microtremor observation results, the damage location and quantitative grade are evaluated. The most serious damage part appears in the upper of the middle part with 62% stiffness losing, the result of which is consistent with the measuring deformation of the wall. The middle part is protruding to the south, and the maximum tilting of the wall reaches 3.31%.

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