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# AMBIENT MODAL IDENTIFICATION AND LONG TERM MONITORING OF TWO ADJACENT STRUCTURES SEPARATED BY AN EXPANSION JOINT

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To determine the effects of separation joint on the dynamic characteristics of as-built adjacent structures, ambient vibration tests were conducted in two adjacent reinforced concrete frame-shear wall structures separated by an expansion joint. The first four modes including natural frequencies, damping ratios and mode shapes were identified using the recently proposed fast Bayesian FFT method. Long-term monitoring for the vibrations of the adjacent structures was conducted. The trends of the first four natural frequencies varying with the temperature were obtained. The finite element modelling method for the adjacent structures taking into account of the expansion joint under different temperatures was proposed. The results show that the dynamic characteristics of the adjacent structures are the same due to the continuous floor paving bricks across the expansion joint. The two adjacent structures form a system. The natural frequencies of the first three modes which are global modes of the system almost have no change with the increase of the temperature. The natural frequency of mode four in which the torsional vibrations for the two structures are in the opposite directions increases significantly with the increase of the temperature. Slabs with the same width as the separation gap are used to simulate the link between the adjacent structures due to the expansion joint. The fourth natural frequency of the structural system increases with the increase of the elastic modulus of the slabs.

*Keywords*: Ambient vibration test, expansion joint, adjacent structures, dynamic characteristics, long-term monitoring.

## 1 Introduction

A separation joint separates two parts of a building with a gap which allows the adjacent structures to move independently. Damage to facilities crossing the joint is a common type of seismic damage in buildings. Dynamic characteristics of the adjacent structures are the key factors which influence their seismic pounding responses.

At the design stage, the adjacent structures are usually assumed to be independent without considering the separation joint. However, after completion of the adjacent structures, separation joint apparatus is usually adopted for convenience of usage and aesthetics. Separation joints constructed as designed may induce dynamic interactions between the adjacent structures, which makes the modal parameter identification more complex (Liu 2017). During the service life of the structures, the cover to the joint may be subjected to alteration due to decoration. Architectural finishes of the floor and ceiling continuing across the joint may reduce its efficiency. Hence, it is necessary to study the dynamic characteristics of adjacent structures with these characteristics.

An increasing number of ambient vibration field tests have been performed on structures (Au 2012, Foti 2012, Ni 2016, Rainieri 2012, Liu 2016) to obtain their actual dynamic characteristics. In addition, through long-term vibration monitoring effects of temperatures on the dynamic characteristics of structures could be determined. The main purpose for designing an expansion joint is to decrease cracking of a long building caused by temperature changes. Hence, in this case it is essential to conduct long-term monitoring to study the changes of dynamic characteristics with temperatures.

In this paper, ambient vibration tests, modal parameter identification, long-term monitoring and finite element modeling of two adjacent structures with an expansion joint were conducted. Effects of the expansion joint with architectural finishes continuing across it on the dynamic characteristics of the adjacent structures were evaluated.

## 2 Ambient Vibration Tests of Two Adjacent Structures with an Expansion Joint

The studied building is divided into two reinforced concrete frame-shear wall structures by an expansion joint. It has eight stories with a total height of 29.3m. There is one basement level only in the eastern structure. The structural layout of the fourth floor is shown in Fig.1. The expansion joint is covered by the terrazzo and rubber strips or floor paving bricks. The floor paving bricks are continuous on top of the expansion joint from the sixth to eighth stories. The ceiling runs continuously across the expansion joint at each story.

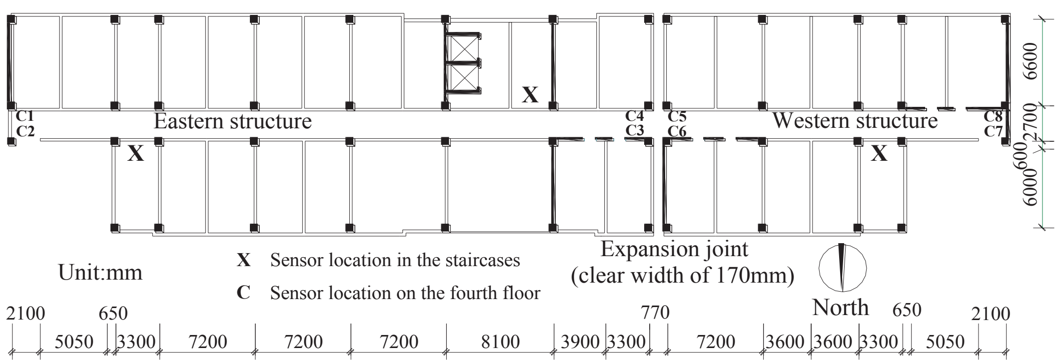


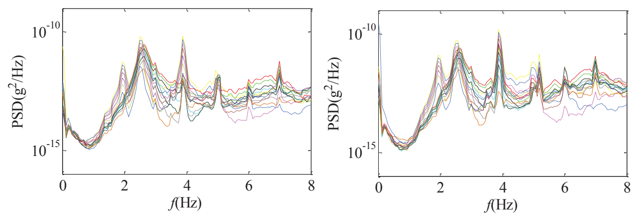

Figure 1 Structural layout of the fourth floor of the studied building

To evaluate the effects of the expansion joint on the dynamic characteristics of adjacent structures, ambient vibration field tests were conducted. Data acquisition and signal processing systems INV3018C with 8 channels (by Beijing Eastern Vibration and Sound Research Center) and sensors of type 941B (by Institute of Engineering Mechanics of China Earthquake Administration) were used for collecting the dynamic responses. Data were recorded with a sampling frequency of 512Hz in all the tests. Due to the limitation of 8 active channels, measurements in the tests were performed in multiple setups with reference sensors.

Ambient vibration tests 1 to 3 were conducted in the eastern, western and middle staircases separately. Sensors were installed eastward and northward on floors 1 to 8. Test 4 was conducted on the aisle of the fourth floor with sensors installed eastward and northward at 8 corners. Locations of the sensors are denoted by notation ‘X’ and ‘C’ in Fig.1. Acceleration data in the horizontal direction were recorded for 20min in all the tests.

## 3 Modal Identification Results of the Studied Adjacent Structures

The PSD spectra obtained in the tests conducted in the eastern and western staircases are shown in Fig.2. They roughly indicate the dominant modes and their frequencies.




(a) Eastern staircase (b) Western staircase

Figure 2 PSD spectra of the measured data for the eastern and western staircases

The fast Bayesian FFT method (Au 2011) is employed to identify the modal parameters. Four vibration modes are identified in the four field tests. Table 1 summarizes the most probable values of natural frequency and damping ratio. The most probable mode shapes for the DOFs measured on the aisle in the middle of the fourth floor are shown in Fig.3.

**Table 1.** Most probable values of natural frequency (Hz) and damping ratio (%)

| Test | Mode 1 | | Mode 2 | | Mode 3 | | Mode 4 | |
|---|---|---|---|---|---|---|---|---|
| | Natural frequency | Damping ratio | Natural frequency | Damping ratio | Natural frequency | Damping ratio | Natural frequency | Damping ratio |
| 1 | 1.95 | 2.32 | 2.50 | 2.21 | 2.63 | 3.83 | 3.89 | 0.39 |
| 2 | 1.95 | 2.06 | — | — | 2.64 | 4.97 | 3.90 | 0.22 |
| 3 | 1.95 | 2.29 | 2.51 | 1.81 | 2.61 | 2.51 | 3.90 | 0.20 |
| 4 | 1.96 | 1.95 | 2.54 | 1.96 | 2.61 | 4.06 | 3.88 | 1.84 |

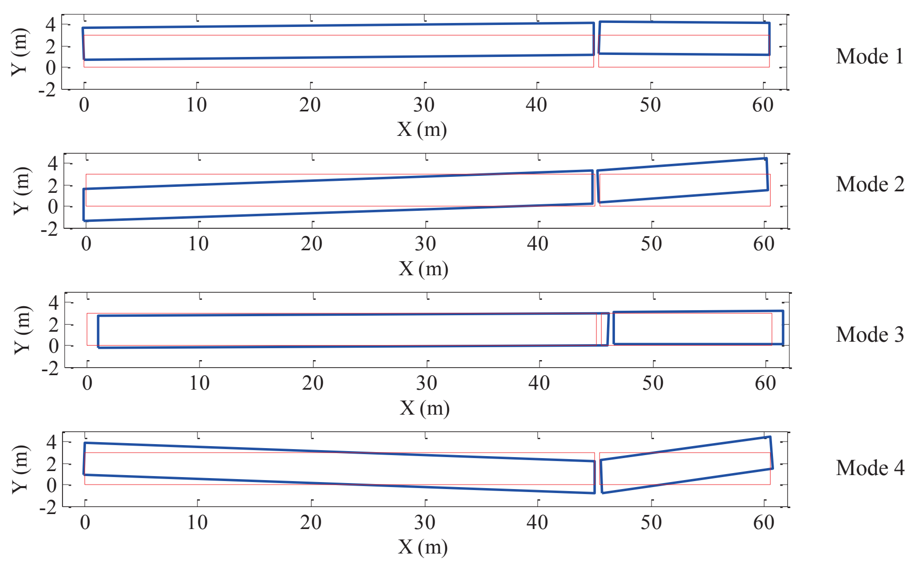



Figure 3 Most probable mode shapes for the DOFs measured on the aisle in the middle of the fourth floor

From Fig.3 it can be seen that mode 1 is the first transverse direction bending mode for both structures. Mode 2 is the first global torsional mode where the torsional direction of the eastern structure is the same as that of the western structure. Mode 3 is the first longitudinal direction bending mode for both structures. Mode 4 is the first local torsional mode where the torsional direction of the eastern structure is opposite to that of the western structure.

The spectra of the western structure have consistently revealed the same peaks as the ones from the eastern structure shown in Fig.2. Inspection of the natural frequencies in Table 1 and the mode shapes in Fig.3 shows that the four modes of the western structure are the same as those of the eastern structure. This shows that the western structure vibrates together with the eastern structure. They form a single structural system. Strong dynamic interactions exist between the two structures for linear performance. Although there is an expansion joint, the false ceilings and the paving bricks on the floors across the joint are continuous in the refurbishing work in the many years of operation.

## 4 Long Term Monitoring of the Studied Adjacent Structures

Long term vibration monitoring was conducted to study the effects of temperature on dynamic characteristics of the studied adjacent structures. Sensors were installed on both sides of the joint synchronously on the aisle of the fourth floor. Acceleration data in two horizontal directions were recorded for 20min each time. The measurement was conducted every two weeks from October 2016 to November 2017.

According to the long term monitoring acceleration data, trends for the MPVs of natural frequency of the first four modes varying with the temperature for the eastern structure are shown in Fig.4. Similar trends for the western structure can also be found.

From Fig.4, it can be seen that with the increase of the temperature the natural frequencies of the first three modes remain almost unchanged. However, the fourth natural frequency increases. It increases by 18% from -1ºC to 30ºC. Because the first three modes are all global modes of the structural system, the temperature has almost no effects on them. However, the fourth mode is a local torsional mode where the torsional vibrations of the eastern and western structures are opposite. With the increase of the temperature, dynamic interactions between the eastern and western structures are enhanced and the natural frequency of this mode increases. The linear relationship between the fourth natural frequency and the temperature through regression analysis is shown in Fig.4.

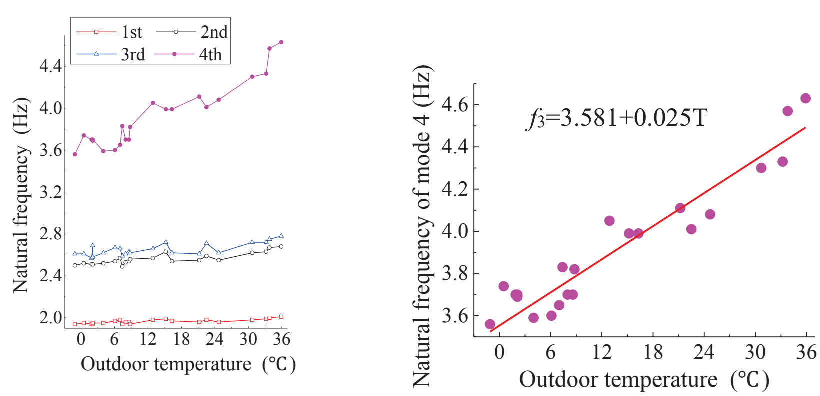



Figure 4 Trends of the natural frequencies varying with the temperature for the eastern structure

## 5 Finite Element Modal Analysis of the Studied Adjacent Structures

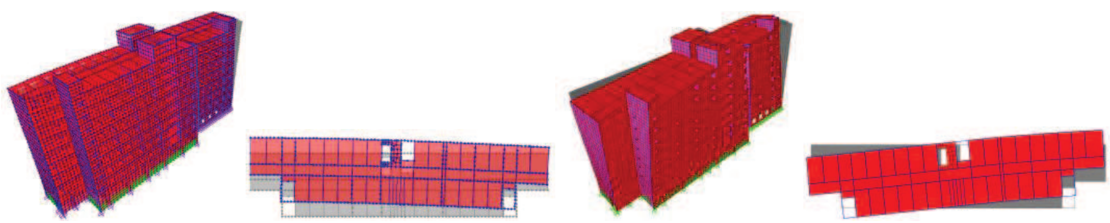
The FEM of the building is developed with SAP2000® software using available structural drawings. The stiffness of nonstructural elements such as infilled walls is considered because the structure is elastic when performing the modal analysis. The one-dimensional structural elements (columns and beams) are modeled by frame elements. The two-dimensional structural elements (floor slabs, shear walls, infilled walls and stairs simulated by inclined slabs) are modeled by shell elements.

The thickness of the RC walls is 200mm. The typical cross-section of the RC columns is 600mm×600mm. The concrete grade in all the structural members is C30. The infilled external walls are construction from hollow bricks of slag with thickness of 240mm, whose elastic modulus and mass density are $2.5\times10^3$MPa and 1700kg/m$^3$, respectively. The infilled internal walls are construction from aerated concrete blocks with thickness of 200mm, whose elastic modulus and mass density are $2.5\times10^3$MPa and 850kg/m$^3$, respectively. The distributed load assigned to the floors is 2.5kN/m$^2$. The one basement level in the eastern structure is considered.

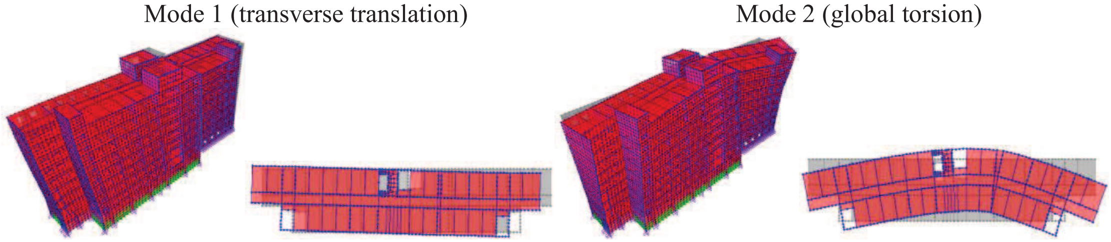
To simulate the strong link between the western and eastern structures, a floor slab across the expansion joint with thickness of 40mm and elastic modulus of 5.7GPa is used to connect the floors of the adjacent structures. The natural frequencies of the structural system are shown in Table 2, which are approximately equal to the identified ones (average MPVs). The first four mode shapes of the structural system are shown in Fig.5. The mode shapes of the FEMs are consistent with the identified ones.

**Table 2.** Natural frequencies from the FEM (Hz)

| | Mode 1 | Mode 2 | Mode 3 | Mode 4 |
|---|---|---|---|---|
| FEM | 2.08 | 2.50 | 2.80 | 3.89 |
| Identified | 1.95 | 2.52 | 2.62 | 3.89 |



Mode 1 (transverse translation) Mode 2 (global torsion)



Mode 3 (longitudinal translation) Mode 4 (local torsion)

Figure 5 Mode shapes from the finite element model

Natural frequencies of the structural system varying with the elastic modulus of the slab across the expansion joint are shown in Fig.6. It can be seen that the elastic modulus of the slab only affects the fourth natural frequency and has little effects on the first three natural frequencies. With the increase of the elastic modulus of the slab, the forth natural frequency increases. The same trend is found when the temperature increases during the long term monitoring. For example, the fourth natural frequency from the FEM with the elastic modulus of the slab equal to 20GPa is almost equal to the identified one with the temperature of 30°C.

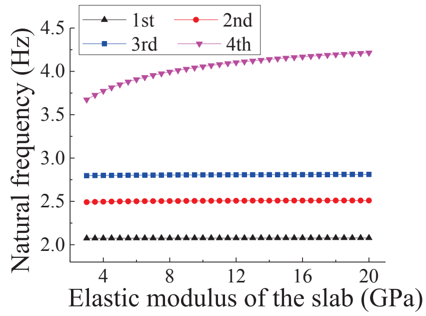



Figure 6 Effects of the elastic modulus of the slab across the joint on the natural frequencies of the system

## 6 Conclusion

Ambient vibration tests and modal parameter identification of two adjacent structures with an expansion joint have been conducted. Results show that the identified natural frequencies and mode shapes of the first four modes for the western and eastern structures are almost the same. The two structures connected via the joint in the floor slab behave as one structural system due to the continuous false ceilings and floor paving bricks across the joint.

Long-term vibration monitoring of the two adjacent structures has been conducted. Results show that with the increase of the temperature, the natural frequencies of the first three modes which are global modes of the structural system vary little. The natural frequency of mode four which is the local torsional mode for the two structures increase significantly because the link between the adjacent structures is enhanced.

The joint can be simulated by a slab across it in a FEM. With the increase of the elastic modulus of the slab, the fourth natural frequency of the FEM increases significantly, which is consistent with the monitoring results.

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