Determining Structural Damage of Stone Curtain Walls by Dynamic Method

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Abstract. Dry hanging stone curtain wall is widely used in the building envelopes, but it was of ten deemed as a safety risk. The damage of the back anchorage structure may result in the urban disaster accident due to the falling down of the tone panel. There is no yet effective detection method because the damage part is hidden behind the panel. In this paper, a dynamic detection method is presented to monitor the damage degree of the anchorage structure on the back of the panel and to determine the damage location. Experiments indicate that the first three steps of natural frequency of the stone panel declined, with the increase of the damage degree of the anchorage structure. The degradation of the natural frequency can be used to identify the degree of back connection damage. In addition, the relationship between the damage position of the back connection and the modal parameters of the stone was investigated. It was found that the change of the damaged location significantly affected the modal vibration of the stone panel and the relative discriminant method is proposed to determine the damage position.

1. Introduction

Architects are interested in using stone curtain walls as the facade decoration layer of buildings because of its magnificence, beauty and energy efficiency. The annual production of building curtain wall in China has increased from 16 million square meters in 2001 to 1.3 hundred million square meters in 2014, according to the reports of Chinese Construction Metal Structure Association. China has become the largest producer of architectural curtain walls and 30% of the curtain walls are stone curtain walls \cite{1}. Dry hanging stone curtain wall is a kind of building peripheral protection structure, and it is composed of stone panel, stainless steel metal pendant and keel\cite{2}. Metal pendants are bolted to the keel on the one hand and cemented to the grooved stone panel on the other. But the anchorage structure on the back of the stone panels is vulnerable to be damaged due to long-term exposure to the complex environments. As a result, the stone panels would fall without warning, which is a serious threat to people's life and public safety. Especially this kind of exterior wall decoration is mostly concentrated in central business districts, so the consequence is serious once the accident occurs. For example, in Hong Kong, there has been a stone decoration plate falling off, resulting in serious injuries to pedestrians \cite{3}.

Previous studies have focused on the overall reliability evaluation of building curtain walls under external loads such as thermal stress and seismic force \cite{4-9}. However, few studies have paid attention to predict the risk of falling of the curtain wall panels. There is no reliable and efficient method to detect the safety of stone curtain walls. Fang et al. \cite{3} summarized the safety problems of building curtain wall, and concluded that the failure of the anchorage structure and the bending of thin marble
plate caused the falling of stone curtain wall panels. The latter rarely occurs when the thickness of the marble plate exceeds 50 mm. At present, the main testing methods used at home and abroad are: observation, drawing and percussion [10-13]. The observation method uses the endoscope to observe the pendant and the keel on the back of the curtain walls, which can only be used in partial positions of the curtain walls. Pull-out method belongs to destructive testing, and the sampling quantity is limited. Percussion method relies heavily on the experience of the inspectors and cannot achieve quantitative detection.

In view of the shortcomings of various traditional detection methods, Liu et al. [14,15] used dynamic method to study the glass curtain wall safety performance assessment. They found the looseness of the boundary support of the four-side supporting glass curtain wall sample will cause its natural frequency decline. Therefore, the reduction of natural frequencies of curtain wall glass is used to identify the level of loose damage of the four side support of glass. But the study did not involve stone curtain walls. Huang et al. [16] used the Laser Doppler Vibrometer to measure the first-order natural frequency of the blind frame glass curtain wall to evaluate its safety performance, but this study did not involve stone curtain wall. Wang et al. [17] measured the first-order frequency of the stone panels and found that the first-order frequency of defective stone panels was significantly lower than that of better stone panels. However, there is no relevant research on the damage detection of back anchorage structure. Above all, there are relatively few and insufficient researches on the detection of structural damage of dry-hung stone curtain wall. Therefore, there are certain technical difficulties in the field inspection of the safety of dry hanging stone curtain wall, and an accurate and non-destructive inspection method for dry hanging stone curtain walls is urgently needed.

The damage of the back connection of stone is the key factor causing the stone panel to fall off, but the traditional detection method is not good. Combining the theory of modal analysis and finite element simulation, the natural frequency and modal vibration mode of the stone curtain wall under different damage degree of connection were obtained by dynamic method. The research results will provide reference for the detection of the structural damage of stone curtain wall.

![Figure 1. Diagram of the measuring points layout.](image-url)
2. Experimental
The stone curtain wall structure connected by metal pendant at four corners was used in this study. In order to simulate the actual service status of stone panel, the related test device was designed and developed specially. Rectangular steel frame welded with angle steel was used to simulate real curtain wall keel structure. Four T-shaped metal pendants are bolted to the steel frame. So the metal pendants can be loosened or detached by unscrewing the bolts. The pendants are connected to the stone panel at the slot and the two parts are fixed in the groove with dry hanging stone adhesive. So the stone panels are connected to the steel frame keel by metal pendant. Starting at the top left corner, mark the four metal pendants A, B, C and D clockwise. The back connection damage forms of dry hanging stone are divided into the following 9 types: ABCD, BCD, ACD, ABD, ABC, AC, BD, AD and BC. ABCD means that the four-angle connection is tight. BCD means that the pendant at point A is removed, while the pendants at triangle B, C and D are firmly connected. AC means that the two pendants B and D have been removed, while the two pendants A and C have been well connected and so on.

The stone panel size is 600 mm × 800 mm × 20 mm, with the elastic modulus $E = 48$ GPa, Poisson’s ratio $\nu=0.3$, the density $\rho = 2800$ kg/m$^3$. Ansys 15.0 was used for finite element simulation. Shell 3D 4node 181 was chosen for the element type. The first three steps of natural frequency of the stone panel under the above nine conditions can be obtained by modal analysis. The theoretical values obtained by finite element simulation were compared with the natural frequencies determined by the dynamic tests.

As shown in Figure 1, in order to conduct experimental modal analysis, the stone panel is divided into 4 equal parts in the length direction and 3 equal parts in the width direction, forming 20 test points. Figure 2 shows the test process. In the test, the metal pendants of different parts were removed by loosening bolts and the natural frequency and modal vibration patterns of the stone panels were obtained under 9 kinds of different conditions. DASP software and related hardware facilities developed by China Orient Institute of Noise & Vibration were used for modal test. A force hammer with a rubber head was used to stimulate the stone panel. Type INV9822 acceleration sensors were used to collect the vibration signal of the stone panel.

![Diagram of the test process](image)

**Figure 2.** Diagram of the test process.
3. Results and Discussion
The first three natural frequencies of the stone panel can be calculated by finite element analysis. Also, the first three natural frequencies of the stone panel can be measured by modal analysis. The calculated and measured results are shown in Table 1. As can be seen from Table 1, there is no significant difference between the measured stone frequencies and the finite element calculation results. And the change trend is consistent.

| Table 1. The first three natural frequencies determined by finite element simulation and dynamic tests [Hz] |
|---------------------------------------------------------------|
| Finite element calculation | Experimental |
| | First | Second | Third | First | Second | Third |
| ABCD | 79.687 | 152.13 | 193.93 | 71.166 | 144.764 | 210.969 |
| BCD | 38.317 | 97.356 | 152.74 | 33.811 | 88.656 | 160.63 |
| ACD | 38.317 | 97.356 | 152.74 | 40.677 | 89.343 | 170.137 |
| ABD | 38.317 | 97.356 | 152.74 | 31.993 | 99.499 | 173.226 |
| ABC | 38.317 | 97.356 | 152.74 | 44.383 | 85.182 | 156.575 |
| AC | 31.096 | 44.127 | 138.45 | 26.492 | 36.386 | 155.213 |
| BD | 31.096 | 44.127 | 138.45 | 20.088 | 42.824 | 148.199 |
| AD | 21.806 | 70.855 | 119.05 | 23.391 | 81.381 | 90.983 |
| BC | 21.806 | 70.855 | 119.05 | 25.22 | 89.785 | 113.345 |

The back connection damage of dry hanging stone is divided into three cases according to the degree of damage: four corners firmly connected (including ABCD), one corner damaged (including BCD, ACD, ABD, ABC) and two corners damaged (including AC, BD, AD, BC). The mean values of the natural frequencies under different damage conditions were calculated, and the change of natural frequencies of the stone panel under different connection damage conditions was shown in Figure 3. Figure 3 shows that the first three steps of the natural frequency of the stone decrease gradually with the increase of the damage degree of the back connection damage of the stone.
In order to explore the influence of connection damage location on natural frequencies and mode shapes of the stone panel, four conditions with one corner damaged were chose. The first three natural frequencies are shown in Figure 4. The first three order mode shapes are shown in Figure 5. The darker color means the greater amplitude. Figure 4 and Figure 5 tell that, under the condition of the same degree of damage, the first three order frequencies of stone panel with different damage position are not much different, but the first three order mode shapes of the stone panel are quite different. Moreover, in each vibration mode, the relative amplitude of the stone panel at the damaged position is large, while the relative amplitude at the stable position is small.

Taking all nine conditions into account, the amplitudes at each connection point of the first three order vibration modes under each damage condition are added as the total amplitude value of each point, as shown in Figure 6. As shown in Figure 6, the amplitude of stone panel under the condition where four corners are stable (ABCD) is small, but the amplitude of the stone under other conditions is relatively large. For four-point fixed dry hanging stone, stone panel will lose solid connections with the keel at the damage positions. As a result, the amplitude of stone panel at these damage points will
increase relatively when the panel is stimulated by the hammer. Theoretically, the amplitude at the undamaged point should be zero. However, the deformation of the test steel frame under external excitation will lead to the displacement of the stone panel at the undamaged point during vibration. This is consistent with the actual situation of the stone curtain wall, because the keel of the curtain wall will also produce displacement due to vibration in the actual situation.

![Figure 6. The amplitude of four corners under 9 damage conditions.](image)

The position of the connection damage on the back of the stone directly affects the amplitude of the panel after excitation. On the contrary, the position of damage on the stone back can be located by comparing the amplitude value at each joint. The relative R value discrimination method is given as followed.

The amplitude of the stone panel at the joint point can be obtained from the data matrix of the mode shapes. Adding the amplitudes in first three mode shapes, the amplitude index at each point can be expressed as the following equation:

\[
Z_A = Z_{A1} + Z_{A2} + Z_{A3}
\]  

(1)

Where \(Z_{A1}, Z_{A2}, Z_{A3}\) are first three natural frequencies respectively. \(Z_B, Z_C, Z_D\) can also be obtained in this way. So the average \(Z_M\) can be calculated by the following equation.

\[
Z_M = \frac{Z_A + Z_B + Z_C + Z_D}{4}
\]  

(2)

Comparing the amplitude index at each point with \(Z_M\), the relative R value can be obtained by the following equation.

\[
R_A = \frac{Z_A - Z_M}{Z_M}
\]  

(3)

\(R_B, R_C, R_D\) can also be obtained in this way.

The relative R values of each joint under different damage conditions are shown in Figure 7. As shown in Figure 7, the relative R values at the damage joints are higher than 1.5 when there is one corner damaged on the back of the stone panel and the values are higher than 0.85 when there are two corners damaged. On the contrary, the damage position can be predicted if the relative R values are calculated after testing.
4. Conclusion
Dynamic relative method was presented to predict the falling risk of the stone panels in building. With the increase of the structural damage, the first three natural frequencies of the curtain wall stone are decreasing. So the natural frequencies is used to evaluate the safety performance of stone curtain walls.

The damage position affects the mode shapes of the stone panels. The damage position behind the stone panel can be determined by comparing the amplitude at the fixed points of the stone panel.

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