Review Article

Research on Bridge Damage Identification Method Based on Dynamic Characteristics

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ABSTRACT

The identification of bridge structural damage can be divided into four processes: determining whether there is damage, determining the location of the damage, determining the degree of damage, and evaluating the load-bearing capacity of the bridge structure after the damage occurs. The dynamic response data takes modal parameters as characteristic parameters, and the modal parameters of the bridge structure are independent of external loads, reflecting the structural characteristics of the structure itself. This article introduces five methods for damage identification based on dynamic characteristics, analyzes the identification principles, characteristics, and applications of each method, and summarizes their application conditions.

Keywords:Damage identification; Frequency; Vibration mode; Modal strain energy

1. INTRODUCTION

1.1 Research background on damage identification of bridge structures

Bridges are key facilities related to national livelihood and national defense security, and their safety directly affects the safety of people's lives and property, the national economy, and social stability. After the completion of the bridge, during its long-term operation, with the increase of traffic flow, environmental factors erosion, and material aging, the bridge will inevitably experience a certain degree of damage, resulting in a decrease in its structural bearing capacity [1]. If these diseases cannot be detected and treated in a timely manner, it not only affects driving safety, but also endangers the property and life safety of the people. Therefore, it is very necessary to identify the damage status of bridges in a timely manner, which provides accurate scientific basis for the management, use, and maintenance of bridges, and is of great significance for fully understanding the health status of bridges and ensuring safe operation [2]. Therefore, comprehensive evaluation of bridge structures can not only ensure the safety of bridges, but also make significant contributions to China's economic development.

1.2 Research methods for bridge damage identification

Damage identification refers to the continuous decrease in load-bearing capacity during use. When the load-bearing capacity decreases to a certain extent, the structure will lose stability and even lead to accidents. Structural damage identification refers to the analysis and processing of feedback signals from structures to detect and repair damage in a timely manner, in order to avoid accidents that can have a significant impact on people's lives and property.

The identification of bridge structural damage can be divided into four processes: determining the presence of damage, determining the location of damage, determining the degree of damage, and evaluating the load-bearing capacity of the bridge structure after occurrence. At present, the main methods used for damage identification include: damage identification based on natural frequency, damage identification based on vibration mode, damage identification based on curvature mode, and damage identification based on modal strain energy [3].

2. INTRODUCTION TO FOUR DAMAGE IDENTIFICATION METHODS

2.1 Damage Identification Based on Natural Frequency

Natural frequency is an inherent property of the structure itself, and it is the most easily obtained modal parameter in structural dynamic testing [4]. Moreover, the measured frequency has high accuracy, which can better reflect the overall stiffness characteristics of the structure. Therefore, in structural damage identification, research on damage identification based on natural frequency is relatively early.

Liu Wenguang [5] simplified the breathing crack beam to two elastic beams connected by torsion springs, and derived the natural frequency equation of the breathing crack beam based on the assumption that the vibration response varies with amplitude; Considering the opening and closing of breathing cracks during vibration, assuming that the stiffness of the cracked beam is a nonlinear function of amplitude, a polynomial stiffness model of the breathing crack beam is established; A respiratory crack beam damage identification method based on natural frequency is proposed by combining the theory and method of contour crack identification. The feasibility and effectiveness of the method are verified by numerical examples. Du Siyi et al. [6] combined matrix perturbation theory, structural vibration theory, and finite element theory to derive a second-order perturbation formula for the natural frequency variation of structures. This formula can invert the damage location and degree of the structure. This method only requires the measurement of the natural frequency of the in-service structure to identify the location and degree of damage, and can also identify the degree of aging of the structure. The effectiveness and practicality of this method were demonstrated through numerical simulation examples. Lou Guobiao [7] conducted damage identification research based on the frequency change ratio index earlier in China, taking the four sided fixed support plate structure as the research object, setting different positions of structural damage, and establishing a localization fingerprint library based on the frequency change ratio localization index, which can effectively achieve structural damage localization. Yue Yanfang [8] analyzed and improved the sensitivity of this method to identify damage in a single position of a planar truss structure, in response to the situation where the natural frequency change ratio is no longer accurate when the damage degree exceeds 80%.

The theory based on natural frequency damage identification indicators is relatively mature, and natural frequencies are easy to obtain. There are many early studies on structural damage identification, but there are many limitations. Natural frequency, as an indicator of the overall stiffness parameter of the structure, reflects the current stiffness status of the structure. It is not sensitive to local damage with lower damage levels, and the weak sensitivity of natural frequency to damage is more prominent in large structures.

2.2 Damage identification based on vibration mode

The vibration mode is the inherent vibration form of the structure itself, reflecting the form maintained by the structure at the current order in the dynamic response, and the form of structural vibration is formed by the superposition of vibration modes [9]. The structural vibration mode shows the relative position distribution of various parts of the structure. Once the structure is damaged, the distribution of relative positions will inevitably change. Therefore, the structural vibration mode contains damage characteristics and can be used for structural damage identification. There are only two ways to use vibration modes to reflect damage: one is to directly compare the changes in structural vibration modes before and after damage. The second is the introduction of modal assurance criteria, coordinate modal assurance criteria, relative rate of change of vibration modes, modal proportion factors, commonly used modal confidence factors, and coordinate modal confidence factors.

Lu Weiwei et al. [10] used modal parameters of structural dynamic characteristics for diagnosis and positioning, significantly improving the efficiency of evaluating bridge structural performance and diagnosing bridge damage. Combining with the engineering example of prefabricated prestressed concrete T-beams, the bridge damage identification indicators that define displacement and curvature modes are used for analysis in bridge damage identification. The results show that using displacement and curvature modes for bridge damage identification can achieve good results and further improve the accuracy of bridge damage localization. When using neural networks for complex structural damage identification, Yu Fei et al. [11] encountered the problem of network size being too large to converge. A two-step method for structural damage identification based on modal difference curvature and neural network is proposed. The first step is to obtain the approximate area of damage using the difference curvature of the vibration mode. The second step is to use the BP neural network to determine the accurate location of the damaged component within the selected area in the first step. The numerical simulation and experimental results of a four layer offshore platform validate the effectiveness of this method. Chen Huan et al. [12] validated that when the first mode slope of a layer changes by more than 0, the layer may be a damaged unit and can be used to determine and calibrate damage; Damage is set on the structure and identified using the damage index; Change the stiffness and layer height conditions of the model, observe the law of the damage index changing accordingly, analyze the reasons for these changes, and propose auxiliary identification methods.

The mode shapes contain more structural information, and higher order modes have high sensitivity to small local structural damage. In addition, the most important point is that damage identification methods based on modal shapes can effectively locate damage. The damage identification method based on vibration mode can intuitively reflect the damage of the bridge and is more sensitive to damage compared to fixed frequency as the damage indicator.

2.3 Effect of ultrafine fly ash on durability of concrete

The establishment of dynamic fingerprints through dynamic characteristics, which qualitatively and quantitatively identify local damage through changes in structural dynamic fingerprints before and after damage, is the main means of damage identification methods based on dynamic testing parameters. A large number of dynamic fingerprints sensitive to changes in local damage characteristics have been proposed by scholars both domestically and internationally. Curvature mode is the most common type of damage fingerprint, which can better represent the local change characteristics of damage. The commonly used indicators for curvature mode methods include curvature mode difference, curvature mode change rate, average curvature mode damage factor, etc.

On the basis of the curvature mode damage identification method, Wu et al. [13] used polynomial fitting and BP neural network algorithm to locate damage in multiple parts of a simply supported beam bridge. The degree of structural damage was determined based on the mutation area of the curvature mode curve, verifying the effectiveness of the curvature mode damage identification method in practical engineering. Xu Feihong et al. [14] used finite element analysis to obtain displacement mode shapes and perform curvature mode analysis for simply supported beam structures under different damage conditions under noise conditions. The least squares fitting method was used to estimate the area of the curvature mode mutation region, in order to estimate the degree of structural damage, and it was verified that this method can effectively estimate the degree of structural damage under noise conditions. Li Jiankang et al. [15] conducted damage identification on a four sided fixed plate structure, utilizing the high approximation of the Chebyshev polynomial expansion form to obtain the vibration mode Chebyshev polynomial function of the plate structure, and then obtained the curvature modes in both horizontal and vertical directions by derivative. The difference analysis of the curvature modes before and after the structure was performed to achieve good identification results. Ding Ke et al. [16] used continuous wavelet transform to analyze the curvature modes of simply supported beams with different defects. The results indicate that the damage location of the structure can be determined based on the wavelet transform coefficients of the curvature mode. If the damage location is near the equilibrium position of the vibration mode, the wavelet transform results of multiple curvature modes can be stacked, and the location of the structural damage can still be determined based on the wavelet transform coefficients after stacking. Further research has shown that there is no necessary connection between the degree of structural damage and the peak size of wavelet transform coefficients. Its peak only indicates the location of structural damage, and other indicators are needed to determine the quantitative relationship between the degree of structural damage and the damage indicators.

The damage to the structure is more pronounced under higher-order vibration modes, although the dynamic parameters obtained in dynamic testing are often lower order. However, modal curvature is the second derivative of the displacement of the vibration mode, and the changes in the lower order vibration modes of the structure can be more clearly reflected in the modal curvature. The calculation of modal curvature adopts the central difference method, which requires that each measurement point is basically equidistant, and there is a high requirement for the number of measurement points. It is difficult to achieve for large and complex structures, making it difficult to carry out damage identification work for modal curvature indicators in the aforementioned structures.

2.4 Damage Identification Based on Flexibility Matrix

The main principle of the damage identification method based on flexibility changes is that the flexibility matrix is a function of the reciprocal of frequency and mode shape under the condition of modal normalization, that is, the mode and frequency information of lower order vibrations have a significant impact on the flexibility matrix . As the frequency increases, the reciprocal effect of high frequency in the flexibility matrix can be ignored , In this way, by measuring the first few low-order modal parameters and frequencies, a high-precision flexibility matrix can be obtained. Based on the difference matrix of the two flexibility matrices before and after obtaining damage, the maximum element in each column of the difference matrix can be determined. By comparing the maximum element in each column, the location of the damage can be identified.

Based on the characteristics of damage identification in engineering structures, Yi Xiaogang [17] used test modal parameters to determine the structural flexibility matrix and determine the location of structural damage through the changes in the flexibility matrix before and after damage. A calculation example of a bridge structure shows that this identification method is effective and has certain practical value in engineering applications. Xie Shaopeng et al. [18] studied the problem of structural damage identification using the least squares orthogonal triangular decomposition method. Firstly, a damage localization method was proposed, and then the damage identification problem based on the generalized modal flexibility matrix was transformed into a least squares problem. The effectiveness of the method was verified through numerical examples. Yang Hua et al. [19] studied a damage identification method based on modal analysis for engineering structural health monitoring and proposed a new method for damage localization using flexibility matrix. This method only requires low-order modal parameters of the engineering structure for damage localization. The effectiveness of this method was verified through numerical simulation of a cantilever beam under damage conditions. The flexibility matrix method can accurately locate damage and has certain practical value in engineering. Zhang Hua et al. [20] proposed a damage identification method based on flexibility matrix to address the difficulty in obtaining higher-order modes of structures in practical applications. Numerical simulation of a cantilever beam structure with multiple damage locations shows that damage localization can be achieved by identifying the first three modal parameters of the structure.

Early research on damage identification was mostly based on modal frequency and mode shapes, which are also the most common methods. However, the sensitivity of modal frequency and mode shapes to structural damage is not high. For minor damage, it is difficult to identify using only modal frequency and mode shapes. Therefore, a modal flexibility matrix was introduced. Research has shown that structural modal flexibility is more sensitive to damage response than modal frequency and mode shapes, and is more suitable for structural damage identification.

2.5 Damage Identification Based on Modal Strain Energy

Structural deformation can lead to changes in strain energy within the element, which can be used for damage identification. Based on the data measured by strain gauges, strain energy can be calculated. However, since the measurement of strain gauges is discrete, most modal strain energy is obtained by measuring modal parameters. When the structure is damaged, the stiffness of the corresponding element at the damaged location will decrease, and the corresponding vibration mode will change, resulting in a change in the modal strain energy of the element.

Guo Huiyong et al. [21] drew inspiration from the modal strain energy index and established a capacity equivalent equation, proposed the modal strain energy equivalent index, and conducted damage identification research on a five story three-dimensional truss structure using the equivalent index. It was verified that the modal strain energy equivalent index has good damage localization ability and a certain degree of damage identification ability. Ma Liyuan et al. [22] proposed the curvature difference index of modal strain energy and used the central difference method to calculate the curvature difference of the obtained unit modal strain energy. Based on the obtained measured vibration modes, using the modal strain energy curvature difference method can effectively locate and analyze damage levels. Wu [23] proposed a modal strain energy damage identification method for strain modes, derived the transformation relationship between strain modes and displacement modes of beam structures, and constructed a strain mode expression for modal strain energy. Wang Zijie et al. [24] established a simple supported beam model in the finite element software Abaqus, set different working conditions of single damage, double damage, and multiple damage, and extracted the first three modal parameters for damage identification and analysis. Afterwards, in order to simulate the noise interference in on-site measurement, noise was added to the obtained modal parameters and the noise resistance of the modal strain energy basis index was analyzed. The analysis results indicate that this damage indicator has good recognition effect on damage under different working conditions, and can still accurately identify the location of damage under noise interference.

Traditional modal strain energy calculation requires complete modal shape information, and there is a problem of difficult to accurately obtain rotational degrees of freedom in modal shape information. To solve this problem, research on modal strain energy damage identification based on strain modes has been carried out, achieving quantitative identification of structural damage. Firstly, based on the relationship between strain and displacement, the transformation matrix between strain mode and displacement mode is derived; Secondly, using strain mode instead of displacement mode to calculate the modal strain energy of the element, a damage identification equation system based on sensitivity analysis is established; Finally, the singular value truncation method is used to solve the equations to identify structural damage.

3. CONCLUSION

(1) Due to the fact that bridge structures are not sensitive to frequency, and noise can have a certain interference effect on frequency, and damage to symmetric structures is prone to misjudgment, there has been less research on using natural frequencies for damage identification in recent years.

(2) The bridge vibration mode can better reflect the actual situation of various parts of the structure, but in practical applications, due to the limited setting of vibration mode displacement measurement points, especially when the local damage of the structure is small, the final obtained vibration mode before and after the structural damage is not significantly different, leading to identification errors.

(3) The corresponding indicators of modal curvature have good structural damage identification ability. Due to the high requirements for the number and arrangement of measurement points,

the modal curvature is calculated using the difference method, and the node curvature cannot be obtained, making it difficult to identify damage to large and complex structures.

(4) The modal strain energy index can compensate for the disadvantage of modal curvature not being able to identify structural node damage, but the modal strain energy of the damaged area is relatively large compared to the actual value, and there are varying degrees of modal strain energy changes in adjacent areas of the damage, which may cause misjudgment.

(5) In summary, from the above damage identification methods, the modal strain energy index is widely used and more suitable for the field of bridge damage identification.

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