



A Review of Structural Damage Identification Research

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The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Conducting damage identification and detection of engineering structures can help to identify the location of structural damage and assess the extent of the damage, providing a basis for the reinforcement and repair of the structures. This ensures the normal operation of engineering structures and, in turn, protects people's lives and property. Therefore, the research on structural damage identification methods has always been an important research topic in the field of civil engineering. The existing damage identification methods can be roughly classified into the following categories: damage identification based on structural dynamic response, structural damage identification based on model updating techniques, and structural damage identification based on artificial intelligence methods. This paper reviews the development history of existing methods, expounds on several common damage identification methods and their advantages and disadvantages, and makes a prospect for the development of structural damage identification methods according to the current research status at home and abroad. It can provide a reference for the research and application of damage identification methods.

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1. INTRODUCTION

In the process of social development, the civil engineering industry holds a crucial position. Due to prolonged exposure, civil engineering structures are vulnerable to natural disasters, environmental erosion, and other detrimental effects. The materials in the structure are subject to deterioration, aging, and other chemical effects that can reduce structural stability and service life (Deng et al., 2024).

After entering the 21st century, structural health monitoring technology has developed rapidly.

This is mainly due to breakthroughs in technologies such as sensors, artificial intelligence, and information signals. Artificial intelligence technology can provide better solutions in the field of structural engineering. Therefore, intelligent health monitoring methods that combine with traditional monitoring methods such as static and dynamic monitoring have gradually become the mainstream (Tapeh & Naser 2022, Hou & Xia, 2021). Teng et al., (2023) utilized digital twin technology to provide massive amounts of data. They employed deep learning methods to accurately identify damage at different positions of the structure. According to Dong & Catbas, (2021) research on damage identification methods using computer vision, computer vision has many advantages. It has high identification efficiency, low cost, and minimal impact on the normal operation of structures. Structural damage identification methods based on static characteristics have been thoroughly investigated, and satisfactory identification outcomes have been obtained. Deng et al., (2023) explored the relationship between the distribution probability of quasi-static response data and local damage. They utilized the earth-mover's distance for damage location. By calculating the difference in the earth-mover's distance between two quasi-static responses, they could quantify the damage level. As a result, they were able to accurately identify the damage of steel box girders and stay cables. Over the past decades, with the rapid development of new sensing and data transmission technologies, Structural Health Monitoring (SHM) technology has become one of the commonly used solutions for maintaining structural safety (Azhar et al., 2024, Hassani et al., 2024). SDI, as a research topic in the field of SHM, has gained increasing attention (Wu et al., 2024). The current

mainstream method is the vibration-based SDI method, which can construct damage indicators using the measured vibration response of the structure¹⁰ (Bao et al., 2021). However, vibration-based methods alone cannot solve the key problems of SHM and need to be combined with computer techniques and mathematical methods (Chaupal & Rajendran, 2023).

2. DAMAGE IDENTIFICATION METHOD BASED ON MODEL UPDATING

At present, in the field of structural damage identification, finite element model updating technology is one of the most widely used methods (Alkayem et al., 2018). This technology has been highly regarded by researchers due to its effectiveness and versatility.

In practice, directly measuring forces exerted by the external environment is difficult to achieve (Zhang et al., 2023). Due to this, methods relying on finite element modeling, which offer the advantages of theoretical maturity and ease of use, are widely utilized (Pan et al., 2023). Real-life structures exhibit a wide variety of materials, shapes, and configurations, leading to significant discrepancies between the response of the initially designed finite element model and the response of the actual structure¹⁵¹⁶ (Park & Oh, 2024, Ereiz et al., 2024). To mitigate the effects of these uncertainties, finite element model updating is commonly used (Naranjo-Pérez et al., 2024). Currently, the finite element-based model modification method has been widely used in the field of civil engineering (Dinh-Cong & Nguyen-Thoi, 2023). In order to test the bridge under normal conditions, Guan et al., (2024) proposed a method for long-term monitoring of bridge data by combining the finite element model correction method, using random traffic force with certain characteristics as known static force and updating the model in real time. Zeng & Kim, (2022) developed a vibration-based Bayesian model update that addresses coupling effects and identifies mass and stiffness by incorporating known masses.

Selecting structural correction parameters is a prerequisite for ensuring the rapid convergence of the finite element model and achieving high - precision solutions. If too many correction parameters are selected, significant model errors will occur. Moreover, the solution response places high demands on hardware (Zhao et al.,

2023). In engineering practice, factors that cause changes in the mass of structural elements are explicit parameters. In contrast, factors that lead to a reduction in the stiffness of structural elements are implicit parameters. The latter are more in line with the actual situation and difficult to directly detect. As a result, modifying only the physical parameters related to stiffness has become the main approach in both engineering applications and academic research. Damage indicators quantify the differences in dynamic characteristics between the actual structure and the finite - element model. They are typically defined as the residuals between the experimental data of the actual structure and the calculated characteristics of the finite - element model. Measured data and theoretical data are used to construct damage indicators and solve them, thereby identifying the location and degree of structural damage. In the frequency - domain response, the frequency residual (Ding et al., 2022) and the Modal Assurance Criterion (Dinh-Cong & Nguyen-Thoi, 2023) are used as damage indicators. However, this kind of indicator is not sensitive to minor damage and is easily affected by environmental noise factors. As a result, it cannot accurately identify structural damage (Wang et al., 2022). Moreover, the frequency response function index constructed based on time domain data exhibits better performance. It can effectively enhance the accuracy of the finite element model and improve the solution efficiency (Zuo & Guo, 2023).

The damage identification method based on finite element model updating has an intuitive calculation process and clear physical meaning. It can simultaneously identify the location and degree of structural damage, making it a direct and effective damage identification approach. However, since the finite element model of a structure contains a large number of nodes, elements, and parameters to be updated, the efficiency of updating the finite element model of large - scale structures is extremely low, and in some cases, the updating process cannot even be completed. In addition, defects such as the large - scale ill - conditioning of the system matrix, errors in model simplification, and insufficient sensitivity of damage indicators limit the development and application of the model updating method in engineering.

3. DAMAGE IDENTIFICATION METHOD BASED ON DYNAMIC FINGERPRINTS

Within the field of SDI, the approach of damage identification based on the variation of structural

dynamic properties is one of the most popular methods, which is widely used in many studies nowadays (Huang et al., 2020). Various characteristics such as frequency (Ku et al., 2023, Mao & Lu, 2016), modal shapes (Katunin, 2021; Ren & Meng, 2024), curvature mode (Ma et al., 2022; Yang et al., 2016), modal strain energy (Li et al., 2022; Pooya & Massumi, 2022), power spectrum (Fang et al., 2023) and the frequency response function (Wen et al., 2023, Jalali & Rideout, 2022) are collected through vibrating the structure and subsequent signal processing.

According to the differences in analysis methods, the dynamic response method can be further divided into two types: the modal method and the statistical method. However, both methods have obvious drawbacks. They are extremely susceptible to environmental interference and have poor sensitivity to local minor damages of the structure. As a result, many scholars have been committed to improving them to enhance the accuracy of damage identification (Li et al., 2024). Quantitative indicators containing structural damage information can be constructed through modal parameters. Among the early quantitative indicators, the more typical ones are the frequency residual and the Modal Assurance Criterion (De et al., 2023; Minh et al., 2023). The natural frequency residual is insensitive to the location and degree of minor structural damages. At the same time, it is also highly vulnerable to environmental factors. This makes it difficult to effectively evaluate the health status of the structure. In contrast, the mode shape is more sensitive to local damages. However, it is prone to misjudgment in practical applications (Mazzeo et al., 2024).

After an extensive research period, Yang & Huang, (2020) proposed combining flexural curvature with a convolutional neural network to use the structure's flexibility as input for damage identification in bridges. However, the lower-order modes of structural dynamic properties are insensitive to minor degrees of damage, while the higher-order modes, although more sensitive, are challenging to obtain accurate results for (Zhang et al., 2024). Based on this problem, Kaveh & Zolghadr, (2017) introduced the cyclical parthenogenesis algorithm into the technique of structural damage identification based on guided modal strain energy. This approach offers a new method for capturing higher-order modal data and minimizing the impact of noise during measurements. Daneshvar et al., (2023) proposed a damage identification method that combines the iterative regularization technique

and the modal strain energy sensitivity index. This method can effectively reduce the interference of noise and efficiently and accurately identify structural damage. Jiang et al., (2023) first used the modal shape curvature subtraction index to locate the singular points and the damage positions. Subsequently, they combined the particle swarm optimization algorithm to evaluate the damage degree of the aluminum alloy plate.

After comprehensively analyzing the research results of the above scholars, it is found that the damage identification method based on vibration response parameters has a higher sensitivity to structural damage, requires fewer adjustable parameters, and does not affect the normal operation of the structure. Therefore, it has high engineering application value. However, the change in frequency is not sensitive enough to damage, especially in the areas near the supports, and it is difficult to eliminate the influence of the environment on the structural modal parameters. In addition, for symmetric structures, damage may lead to symmetric structural responses, and it is difficult to obtain the high - order modes of the structure. All these problems will affect the accuracy of damage identification.

4. DAMAGE IDENTIFICATION METHOD BASED ON INTELLIGENT ALGORITHMS

The structural damage identified by the swarm intelligence optimization algorithm is an approximate solution. However, compared with the analytical solution, its accuracy can meet the requirements of engineering. At the same time, it also has a high identification efficiency. The process of identifying structural damage by the swarm intelligence optimization algorithm is relatively concise, which is mainly manifested as a process of continuously approaching the analytical solution (Sang-To et al., 2022). The basic process of identifying structural damage by the swarm intelligence optimization algorithm is as follows: In the first step, generate sub-populations corresponding to the number of units within the optimization search space, and substitute them into the damage index respectively to select the initial global optimal fitness value and the corresponding sub-population. In the second step, generate a new population based on this sub-population and calculate the fitness value. Compare it with the global optimal value to select the optimal

population and its corresponding fitness. In the third step, repeat the above process until the iteration stop condition is met, and then output the fitness value and the sub-population. The magnitude of the elements in the vector and the column labels represent the degree of damage and the unit number respectively. By combining the two, the location and degree of the damaged unit can be determined.

In recent years, the civil engineering industry has been inspired by artificial intelligence. Increasingly, group intelligence algorithms have been applied in the field of SHM, and scholars have achieved promising results by integrating intelligent algorithms with SDI (Zhang et al., 2022; Minh et al., 2022). Gomes & De, (2020) first modeled the problem using the finite element method, then applied a modified sunflower optimization algorithm, and finally solved the inverse problem by optimizing in SDI. Ding et al., (2020) utilized the Jaya algorithm as the core. They employed a clustering strategy to substitute solutions with low-quality objective values. Additionally, they integrated the exploitation strategy from the tree seeds algorithm into each iteration to search for the optimal solution. This approach leads to improved identification of structural damage under incomplete and uncertain modal data. Chen et al., (2024) proposed a simulated annealing-artificial hummingbird algorithm for structural damage identification based on the artificial hummingbird algorithm. They combined the simulated annealing strategy and Sobol sequence initialization and verified the feasibility of the proposed method through experiments. Sang-To et al., (2022) utilized the Lévy flight strategy to enhance the exploitation process in the Gray Wolf Optimization algorithm and improve the exploration speed of the algorithm. The enhanced algorithm successfully passes 23 benchmark functions, a set of CEC 2019 functions, and three engineering problems, demonstrating a significant performance improvement. Although many swarm intelligence algorithms already exist in the field of SDI, the lack of stability and accuracy is a common issue with the existing algorithms.

Based on computer technology, artificial intelligence technology, and bionic principles, artificial intelligence methods such as neural networks (Yin et al., 2023), machine learning (Quqa et al., 2024), computer vision (Li et al., 2022), and swarm intelligence optimization algorithms (Li et al., 2024) have been derived.

The above-mentioned methods have high adaptability and solution accuracy when solving complex engineering problems. When conducting research related to structural health monitoring, a large amount of data needs to be processed (Bao et al., 2019). Among them, the swarm intelligence optimization algorithm is a bionic method derived by simulating the habits of organisms, natural phenomena, and scientific principles, such as the Human Memory Algorithm (Zhu et al., 2024), the Greylag Goose Optimization Algorithm (El-Kenawy et al., 2024), and the Walrus Optimization Algorithm (Han et al., 2024). Due to the advantages of good stability, strong applicability, and high precision of the swarm intelligence optimization algorithm, it has been widely applied in various practical engineering projects.

The structural damage identified by the swarm intelligence optimization algorithm is an approximate solution. However, compared with the analytical solution, its accuracy can meet the requirements of engineering projects. At the same time, it also has a high identification efficiency. The process of identifying structural damage by the swarm intelligence optimization algorithm is relatively simple, mainly manifested as a process of continuously approaching the analytical solution (Sang-To et al., 2022). The basic process of identifying structural damage by the swarm intelligence optimization algorithm is as follows: The first step is to generate sub-populations corresponding to the number of elements within the optimization search space, and substitute them into the damage index respectively to select the initial global optimal fitness value and the corresponding sub-population. The second step is to generate a new population based on this sub-population and calculate the fitness value. Then, compare it with the global optimal value to select the optimal population and its corresponding fitness value. The third step is to repeat the above process until the iteration stop condition is met, and then output the fitness value and the sub-population. The magnitude of the elements in the vector and the column labels represent the degree of damage and the element number respectively. By combining the two, the location and degree of the damaged element can be determined.

In conclusion, swarm intelligence optimization methods have strong applicability and high convergence efficiency when solving engineering optimization inverse problems. However, swarm

intelligence optimization algorithms have poor global and local search capabilities, and a weak ability to escape from local optimal traps, ultimately failing to effectively identify structural damage. In addition, in the current research on using these algorithms for structural damage identification, the main research direction is how to improve the local optimization accuracy of the algorithms and avoid getting trapped in local optima, which is also the key focus of the proposed methods. Therefore, the core of artificial intelligence methods lies in adopting a variety of improvement strategies to optimize the optimization mechanism of the algorithms, make up for their deficiencies, and apply them to the identification of structural damage.

5. CONCLUSION

Since the 1940s, the research and development of structural damage identification methods have a history of more than 70 years. By integrating the research achievements in structural damage identification both at home and abroad, it is believed that there are three aspects of structural damage identification methods that are worthy of in-depth research and exploration:

1. For civil engineering structures, they will enter the nonlinear stage when subjected to large-amplitude excitations such as earthquakes. Most of the current research methods focus on damage identification in the linear stage, and the methods and technologies for damage identification in the nonlinear stage are not yet mature. Even if they perform well in numerical simulations and experiments, they are rarely applied in practical engineering. Therefore, damage identification of structures in the nonlinear stage is one of the development directions of damage identification methods in the future.
2. So far, a variety of methods for structural damage identification based on unknown inputs have been developed. However, in practical engineering, not only the input responses and input positions are unknown, but also the output responses and structural parameters are incomplete. Therefore, developing structural damage identification methods under the conditions of unknown inputs and incomplete measurement data is of great significance for damage identification and health diagnosis in practical engineering.

3. The optimal layout of sensors is also a hot research topic in damage identification at present. If there are too many sensors, although the identification accuracy can be improved, the construction cost of the structural health monitoring system will also be increased. If the number of sensors is too small or the layout is unreasonable, it will lead to a shortage of measurement data and excessive identification errors. How to use the minimum number of sensors to implement the best layout scheme, and obtain accurate response data and identification results while saving costs is an important issue worthy of research.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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