A Review of Structural Damage Identification Research

**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.

**Keywords:** Structural Health Monitoring; Structural Damage Identification; Structural Dynamic Response; Model Updating

0. Introduction

With the increase in the service life of structures, the accumulation of damage will lead to a reduction in the safety performance of structures, often failing to meet the normal service requirements. The health status of structures has become a key concern of society. Real-time monitoring of the health status of structures can effectively prevent the occurrence of similar safety accidents and reduce social and economic losses. The damage identification method is the core of structural health monitoring. Accurately identifying the location and extent of structural damage can provide technical support for the reinforcement and maintenance of structures. Therefore, accurately identifying structural damage is of great significance for ensuring the safe operation of structures.

Structural safety accidents occur from time to time abroad. For example, on August 14, 2018, the middle section of the Morandi Bridge in Italy collapsed, triggering a safety accident that attracted widespread social attention. The accident investigation report shows that the stay cables of the bridge were corroded by the environment, leading to the accumulation of damage, and there was no timely maintenance. Eventually, due to insufficient bearing capacity, some sections of the bridge collapsed. On October 3, 2022, a highway bridge in the province of Parma, Italy, collapsed, but there were no casualties. The cause of the accident was that the structural aging and the scouring of heavy rain led to a decrease in the bearing capacity of the bridge, resulting in its collapse. On October 30, 2022, a cable bridge in Morbi, Gujarat, India, collapsed, causing a total of 141 people to go missing. The cause of the accident was that the corrosion of the bridge cables led to a decline in their mechanical properties, ultimately causing the bridge to collapse. According to the data released by the Federal Highway Administration of the United States, there are currently 616,000 bridges in service in the United States, among which 283,000 are in good health, 286,000 are in average condition, and 47,000 bridges are in poor condition and pose potential safety hazards.

In China, building structures also face serious health problems. For instance, on July 15, 2011, a local collapse occurred on the right side of the deck of the Third Qiantang River Bridge in Hangzhou, Zhejiang Province, causing several trucks to fall. According to the official investigation report, the cause of the accident was that a large proportion of longitudinal cracks appeared in the bridge deck pavement along the hinge joint position of the hollow slab beams, resulting in the phenomenon of "single-slab stress" of the hollow slab beams. In addition, the failure to effectively monitor the health status of the bridge and the lack of timely maintenance were also among the contributing factors to the local collapse of the bridge. On July 10, 2019, the sidewalk on the west side of the southern end of the Third Wohe River Bridge in Bozhou, Anhui Province, collapsed. The collapsed area was about 20 meters long, and the maximum drop of the fracture was about 3 meters. On July 22, 2019, the deck of the Yinjiangjihan Bridge on National Highway 207 in Jingzhou, Hubei Province, China, collapsed, causing significant economic losses and attracting widespread social attention.

With the continuous progress of sensing technology, information processing technology, and numerical calculation technology, structural health monitoring is gradually penetrating into the field of engineering structures. Sensing technology involves installing sensors on the exterior or interior of a structure to obtain information such as strain signals, vibration signals, and the spatial environment inside or outside the structure. Information processing technology is used to transmit and process various types of collected data. It gathers massive amounts of data information and establishes divergent connections through the interrelationships among the data. Numerical calculation technology is a technique that uses mathematical methods and computers to calculate and analyze mathematical problems.The main research contents of a structural health monitoring system include the optimal arrangement of sensors, the collection and processing of data signals, and structural damage identification. Among them, structural damage identification is the core research content of the structural health monitoring system.

Structural damage identification can help people better understand the operation status of a structure, and conduct an objective safety evaluation and remaining life assessment based on the identification results, thus providing a reliable basis for the future maintenance and upkeep of the structure. Structural damage identification is a typical ill-posed inverse problem, and its basic principle is to invert the damage condition of the structure through the vibration response of the structure. In structural damage identification, the most commonly used method is to combine the finite element model updating technology with an optimization algorithm.The damage identification process based on finite element model updating is a repetitive iterative process. By continuously adjusting the characteristic matrices such as mass, stiffness, and damping of the benchmark finite element model, a better consistency between the damaged structure and the finite element model can be achieved, so as to evaluate the damage state of the structure using the updated parameters. When the measurement data of the finite element model and the actual structure are available, the characteristic equation of the structure can be used to construct a constrained objective function to detect the location and extent of structural damage.Bionic optimization algorithms search for the optimal value of a function by imitating the survival behavior of biological groups in nature. Therefore, when solving a nonlinear objective function, it is possible to search for the global optimal value without the need for gradient information.Due to objective factors such as incomplete data collection, deviations in the structural model, interference from environmental temperature, and uncertainties in actual damage, further research on structural damage identification methods is still needed. In the limited measurement information, how to extract effective data as much as possible and use appropriate and efficient optimization algorithms to solve the objective function is the core research direction in the field of structural damage identification.

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[1][2]. 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[3][4]. SDI, as a research topic in the field of SHM, has gained increasing attention[5]. The current mainstream method is the vibration-based SDI method, which can construct damage indicators using the measured vibration response of the structure[6]. However, vibration-based methods alone cannot solve the key problems of SHM and need to be combined with computer techniques and mathematical methods[7].

**1. Damage Identification Method Based on Model Updating**

After nearly three decades of rapid development, the structural finite element model updating technology has been widely used to monitor the health status of various structures. According to the differences in the objects to be updated, traditional finite element model updating methods can be generally divided into the matrix method and the design parameter method. The object of the matrix method for updating is the system matrix or element matrix in the structural dynamic equation. Although this method can reproduce the test results under specific conditions, it destroys the original banded and sparse characteristics of the mass and stiffness matrices. As a result, the physical meaning of the updating results becomes unclear, and problems such as virtual elements and negative stiffness may even occur. The design parameter method is a further exploration of the structural finite element model updating technology based on the matrix method. Its updating target is the structural design parameters, such as the geometric shape of components, material properties, and cross-sectional dimensions, etc. This method ensures the physical meaning of the updating results and simultaneously realizes the symmetry among the elements within the element matrix, so it has been more widely applied. Selecting the updating parameters, establishing the damage identification index, and determining the solution method are the key points in the finite element model updating technology.

In practice, directly measuring forces exerted by the external environment is difficult to achieve[8]. Due to this, methods relying on finite element modeling, which offer the advantages of theoretical maturity and ease of use, are widely utilized[9]. 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 structure[10][11]. To mitigate the effects of these uncertainties, finite element model updating is commonly used[12]. Currently, the finite element-based model modification method has been widely used in the field of civil engineering[13]. In order to test the bridge under normal conditions, Guan et al[14]. 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 et al[15]. developed a vibration-based Bayesian model update that addresses coupling effects and identifies mass and stiffness by incorporating known masses.

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.

**2. Damage identification method based on dynamic fingerprints**

Structural damage identification based on the structural vibration response is a method that analyzes and extracts the structural modal parameters according to the response parameters such as displacement or acceleration of the structure under dynamic loads, and then uses these parameters to identify the structural damage. According to the differences in the analysis methods, the dynamic response methods can be divided into two types: the modal method and the statistical method. However, these two methods are vulnerable to environmental interference and are not sensitive to local minor damages. Therefore, a large number of scholars have made improvements to them in order to enhance the accuracy of damage identification. Modal parameters can be used to construct quantitative indices that contain structural damage information. The earliest appeared indices are the frequency residual and the Modal Assurance Criterion (MAC). Among them, the natural frequency residual is not sensitive to the location and extent of minor structural damages. Moreover, it is easily interfered by environmental factors, so it is unable to effectively evaluate the structural health status. On the other hand, the modal shape is more sensitive to local damages but is prone to misjudgment.

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[16]. Various characteristics such as frequency[17][18], modal shapes[19][20], curvature mode[21][22], modal strain energy[23][24], power spectrum[25] and the frequency response function[26][27] are collected through vibrating the structure and subsequent signal processing. After an extensive research period, Yang et al[28]. 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[29]. Based on this problem, Kaveh et al[30]. 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.

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.

**3. Damage identification method based on intelligent algorithms**

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[31][32][33]. Guilherme et al[34]. 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[35]. 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[36]. 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. Thanh et al[37]. utilized the L$\acute{e}$vy 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[38], machine learning[39], computer vision[40], and swarm intelligence optimization algorithms[41] have been derived. The above-mentioned methods have high adaptability and solution accuracy when solving complex engineering problems. 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[42], the Greylag Goose Optimization Algorithm[43], and the Walrus Optimization Algorithm[44]. 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[45].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.

**4. 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.

5. References

1. Deng Y, Zhao Y, Ju H, et al. Abnormal data detection for structural health monitoring: State-of-the-art review[J]. Developments in the Built Environment, 2024, 17.
2. Ding Z, Hou R, Xia Y. Structural damage identification considering uncertainties based on a Jaya algorithm with a local pattern search strategy and L0.5 sparse regularization[J]. Engineering Structures, 2022, 261.
3. Azhar A S, Kudus S A, Jamadin A, et al. Recent vibration-based structural health monitoring on steel bridges: Systematic literature review[J]. Ain Shams Engineering Journal, 2024, 15(3).
4. Hassani S, Dackermann U, Mousavi M, et al. A systematic review of data fusion techniques for optimized structural health monitoring[J]. Information Fusion, 2024, 103.
5. Wu T, Tang L, Zhou F, et al. Damage detection based on accelerometers and computer vision measurements of moving load-induced structural responses[J]. Mechanical Systems and Signal Processing, 2024, 211.
6. Bao X, Fan T, Shi C, et al. Deep learning methods for damage detection of jacket-type offshore platforms[J]. Process Safety and Environmental Protection, 2021, 154: 249-261.
7. Chaupal P, Rajendran P. A review on recent developments in vibration-based damage identification methods for laminated composite structures: 2010–2022[J]. Composite Structures, 2023, 311.
8. Zhang X, He J, Hua X, et al. Simultaneous Identification of Time-Varying Parameters and External Loads Based on Extended Kalman Filter: Approach and Validation[J]. Structural Control and Health Monitoring, 2023, 2023: 1-18.
9. Pan C, Qiu Y, Jiang X, et al. Simultaneous identification of impact force and structural local damage under pre-segmentation of structural elements[J]. Structures, 2023, 57.
10. Park H S, Oh B K. CNN-based model updating for structures by direct use of dynamic structural response measurements[J]. Engineering Structures, 2024, 307.
11. Ereiz S, Fernando Jiménez-Alonso J, Gallegos-Calderón C, et al. Vibration based single-objective finite element model updating using cooperative game theory approach[J]. Mechanical Systems and Signal Processing, 2024, 212.
12. Naranjo-Pérez J, Rodríguez-Romero R, Pachón P, et al. Robust improvement of the finite-element-model updating of historical constructions via a new combinative computational algorithm[J]. Advances in Engineering Software, 2024, 190.
13. Dinh-Cong D, Nguyen-Thoi T. A chaos game Optimization-based model updating technique for structural damage identification under incomplete noisy measurements and temperature variations[J]. Structures, 2023, 48: 1271-1284.
14. Guan Z-X, Yang D-H, Yi T-H, et al. Bridge finite element model updating using stochastic vehicle-induced static response monitoring data[J]. Engineering Structures, 2024, 301.
15. Zeng J, Kim Y H. Probabilistic damage detection and identification of coupled structural parameters using Bayesian model updating with added mass[J]. Journal of Sound and Vibration, 2022, 539.
16. Huang M, Li X, Lei Y, et al. Structural damage identification based on modal frequency strain energy assurance criterion and flexibility using enhanced Moth-Flame optimization[J]. Structures, 2020, 28: 1119-1136.
17. Ku K, Silva K E S, Yoon G H. Statistical topology optimization scheme for structural damage identification[J]. Computers & Structures, 2023, 286.
18. Mao L, Lu Y. Selection of optimal artificial boundary condition (ABC) frequencies for structural damage identification[J]. Journal of Sound and Vibration, 2016, 374: 245-259.
19. Katunin A. Identification of structural damage using S-transform from 1D and 2D mode shapes[J]. Measurement, 2021, 173.
20. Ren X, Meng Z. Damage identification for timber structure using curvature mode and wavelet transform[J]. Structures, 2024, 60.
21. Ma Q, Solís M, Rodríguez-Mariscal J D, et al. Wavelet and Lipschitz exponent based damage identification method for beams using mode shapes[J]. Measurement, 2022, 205.
22. Yang Z-B, Radzienski M, Kudela P, et al. Two-dimensional modal curvature estimation via Fourier spectral method for damage detection[J]. Composite Structures, 2016, 148: 155-167.
23. Li M, Jia D, Wu Z, et al. Structural damage identification using strain mode differences by the iFEM based on the convolutional neural network (CNN)[J]. Mechanical Systems and Signal Processing, 2022, 165.
24. Pooya S M H, Massumi A. A novel damage detection method in beam-like structures based on the relation between modal kinetic energy and modal strain energy and using only damaged structure data[J]. Journal of Sound and Vibration, 2022, 530.
25. Fang Y, Liu X, Xing J, et al. Substructure damage identification based on sensitivity of Power Spectral Density[J]. Journal of Sound and Vibration, 2023, 545.
26. Wen T, Narita F, Kurita H, et al. Quantification of damage expansion influence on frequency response function of plate for structural health monitoring with integral differential method[J]. Composites Science and Technology, 2023, 244.
27. Jalali M H, Rideout D G. Substructural damage detection using frequency response function based inverse dynamic substructuring[J]. Mechanical Systems and Signal Processing, 2022, 163.
28. Yang S, Huang Y. Damage identification method of prestressed concrete beam bridge based on convolutional neural network[J]. Neural Computing and Applications, 2020, 33(2): 535-545.
29. Zhang G, Kang J, Wan C, et al. Output-only structural damage identification based on Q-learning hybrid evolutionary algorithm and response reconstruction technique[J]. Measurement, 2024, 224.
30. Kaveh A, Zolghadr A. Cyclical Parthenogenesis Algorithm for guided modal strain energy based structural damage detection[J]. Applied Soft Computing, 2017, 57: 250-264.
31. Zhang G, Wan C, Xiong X, et al. Output-only structural damage identification using hybrid Jaya and differential evolution algorithm with reference-free correlation functions[J]. Measurement, 2022, 199.
32. Minh H-L, Sang-To T, Abdel Wahab M, et al. Structural damage identification in thin-shell structures using a new technique combining finite element model updating and improved Cuckoo search algorithm[J]. Advances in Engineering Software, 2022, 173.
33. Hou R, Xia Y. Review on the new development of vibration-based damage identification for civil engineering structures: 2010–2019[J]. Journal of Sound and Vibration, 2021, 491.
34. Gomes G F, De Almeida F A. Tuning metaheuristic algorithms using mixture design: Application of sunflower optimization for structural damage identification[J]. Advances in Engineering Software, 2020, 149.
35. Ding Z, Li J, Hao H. Non-probabilistic method to consider uncertainties in structural damage identification based on Hybrid Jaya and Tree Seeds Algorithm[J]. Engineering Structures, 2020, 220.
36. Chen Z, Wang Y, Zhang K, et al. Damage detection and location using a simulated annealing-artificial hummingbird algorithm with an improved objective function[J]. Structural Health Monitoring, 2024.
37. Sang-To T, Le-Minh H, Mirjalili S, et al. A new movement strategy of grey wolf optimizer for optimization problems and structural damage identification[J]. Advances in Engineering Software, 2022, 173.
38. Yin X F, Huang Z, Liu Y. Bridge damage identification under the moving vehicle loads based on the method of physics-guided deep neural networks[J]. Mechanical Systems and Signal Processing, 2023, 190: 110123.
39. Quqa S, Li S J, Shu Y N, et al. Crack identification using smart paint and machine learning[J]. Structural Health Monitoring, 2024, 23(1): 248-264.
40. Li Y T, Bao T F, Huang X J, et al. An integrated underwater structural multi-defects automatic identification and quantification framework for hydraulic tunnel via machine vision and deep learning[J]. Structural Health Monitoring, 2022, 22(4): 2360-2383.
41. Li Y F, Minh H L, Cao M S, et al. An integrated surrogate model-driven and improved termite life cycle optimizer for damage identification in dams[J]. Mechanical Systems and Signal Processing, 2024, 208: 110986.
42. Zhu D L, Wang S W, Zhou C J, et al. Human memory optimization algorithm: a memory inspired optimizer for global optimization problems[J]. Expert Systems with Applications, 2024, 237: 121597.
43. El-Kenawy E S M, Khodadadi N, Mirjalili S, et al. Greylag goose optimization: nature inspired optimization algorithm[J]. Expert Systems with Applications, 2024, 238: 122147.
44. Han M X, Du Z X, Yuen K F, et al. Walrus optimizer: a novel nature-inspired metaheuristic algorithm[J]. Expert Systems with Applications, 2024, 239: 122413.
45. Sang-To T, Le-Minh H, Mirjalili S, et al. A new movement strategy of grey wolf optimizer for optimization problems and structural damage identification[J]. Advances in Engineering Software, 2022, 173: 103276.