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Technical Analysis of Safety Monitoring and Evaluation of Existing Bridge Structures

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Abstract: Bridge structure safety monitoring and assessment has been a great concern for the government and the public, and bridge structure safety monitoring and assessment technology has also developed rapidly over the years. Its goal is to equip relevant organizations and professionals with a deep understanding of the principles and practical applications of these technologies. By doing so, it seeks to facilitate the effective implementation of safety monitoring and assessment practices in bridge management. Ultimately, the aim is to foster the constructive development of road and bridge construction and operational management at a broader level.

Keywords: Bridge structure; Safety monitoring; Defect diagnosis; Theoretical modeling method

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1. Introduction

Since the 1950s, countries around the world have begun to apply bridge structural safety monitoring and assessment technologies to bridge projects of different scales [1]. In China, as the number of long-span bridges grows and projects get larger, there's been a steady improvement in safety monitoring and evaluation technology. Many new monitoring technologies are now being used on real bridges. These technologies play a vital role in extending the lifespan of bridges and ensuring their safe operation [2]. Therefore, for the existing bridge structure safety monitoring, and assessment technology research, is to promote the sustainable development of China's road and bridge engineering and to protect the public travel safety of high-value research behavior.

2. Importance of structural safety monitoring and assessment of bridges

Monitoring and assessing the safety of bridges is crucial for public safety, prolonging the lifespan of structures, and wisely allocating maintenance funds. Bridges, as integral parts of transportation networks, face diverse loads and environmental wear, which can lead to damage and decreased functionality over time [3]. By employing systematic monitoring and assessment processes, we can keep track of the health of bridge structures in real-time, identifying potential risks and preventing them promptly.

Firstly, the use of structural safety monitoring technology enables the continuous recording of data regarding bridge structural safety. This data empowers engineers to develop safety strategies grounded in precise structural behavior analysis. By analyzing this data, engineers can swiftly identify any abnormal behavior in bridge structures, such as crack expansion, local instability, or material aging, facilitating prompt intervention and maintenance actions [4].

Additionally, leveraging advanced safety assessment technology allows for precise evaluation of bridge bearing capacity, stability, and seismic resilience. This enables the anticipation of necessary enhancement measures or tailored maintenance plans. Such proactive measures aid engineering units in judiciously allocating maintenance resources, preventing excessive maintenance, and optimizing cost investments [5].

Lastly, the adoption of bridge safety monitoring and assessment technology serves to advance the implementation of new maintenance techniques and materials for bridge structures. Simultaneously, it facilitates the testing of various maintenance strategies to gauge their effectiveness. Furthermore, this technology offers valuable scientific data and experiential insights to bridge management departments, aiding them in making well-informed decisions regarding maintenance practices.

3. Research on safety monitoring technology of existing bridge structures

3.1. Bridge structure condition monitoring technology

The primary monitoring targets of condition monitoring technology for bridge structure safety include vibration, acoustics, temperature, performance direction, strength, and surface morphology [6].

(1) Vibration monitoring

Vibration monitoring for bridge structures involves capturing the dynamic response of the bridge to external loads, such as dynamic frequency, amplitude, and modal shape, using sensors like accelerometers and strain gauges placed at strategic points on the bridge. The principle behind this monitoring technique is to indirectly assess the health of a bridge by analyzing changes in its vibration characteristics [7]. For instance, a reduction in frequency might signal a decrease in the stiffness of the bridge structure. Key to conducting vibration monitoring is ensuring the continuity and stability of data collection, and analyzing the data with precise spectral analysis to effectively evaluate the structural integrity of the bridge.

(2) Acoustic monitoring

Acoustic monitoring of bridge structures involves harnessing the propagation properties of acoustic waves within materials. It aims to assess the presence of defects in the bridge structure by analyzing changes in received signals. The principle of this monitoring technology revolves around employing acoustic emission technology to track the formation and expansion of microcracks within bridge materials. The critical aspect of this technology lies in accurately locating and analyzing acoustic emission signals throughout the monitoring period. This enables technicians to conduct early diagnosis of microcracks and corrosion within the structure [8].

(3) Temperature monitoring

Temperature monitoring of bridge structures involves the use of precision equipment such as thermocouples, infrared thermography, or fiber optic sensors to record temperature variations in different environmental conditions. These temperature changes can affect the material properties of the bridge structure, potentially impacting its stability. The key technical aspect of temperature monitoring is accurately determining the correlation between ambient temperature and structural response.

Additionally, continuous testing data obtained through long-term monitoring enables the evaluation of material durability and the identification of potential issues.

(4) Performance trend monitoring

Performance trend monitoring involves the continuous tracking of various parameters of bridge structures over time, such as displacement, strain, and inclination trends. Its purpose is to accurately depict the performance of the bridge structure and identify potential deterioration. The principle underlying performance trend monitoring relies on the utilization of multiple sensors for ongoing data collection, complemented by statistical analysis methods to forecast structural performance trends. The critical technical aspect of performance trend monitoring lies in the rational selection of key indicators that reflect structural performance and ensuring long-term, stable data collection [9].

(5) Strength monitoring

Strength monitoring of bridge structures aims to evaluate the load-carrying capacity by measuring the stress and strain data of the bridge under actual loading conditions. Typically, this involves the use of strain gauges, fiber optic sensors, and other precision measuring equipment. Key technical elements for monitoring the strength of bridge structures include real-time monitoring of loads and precise measurement of strain distribution.

(6) Surface morphology monitoring

Surface topography monitoring involves assessing the health of bridge structures by observing and analyzing external features such as crack width, corrosion degree, and spalling area on the bridge surface. Typically, this monitoring relies on high-definition cameras and three-dimensional laser scanning. The key focus of surface morphology monitoring is enabling observers to quantitatively analyze and periodically track these features. During the observation period, it’s essential to judiciously apply non-destructive detection methods and image processing technology to ensure accurate assessments.

3.2. Defect diagnosis technology

Defect diagnosis technology for bridge structures commonly employs methods such as threshold logic, contrast diagnosis, artificial neural networks, and fuzzy mathematics.

(1) Threshold logic valve technology

Threshold logic valve technology is designed to facilitate the monitoring of bridge structure health by utilizing pre-established thresholds. The principle behind this technology involves setting safety thresholds for different performance indicators based on historical data and engineers’ expertise in disease monitoring [10]. When monitored data surpasses these predefined thresholds, the information system automatically alerts to potential issues within the bridge structure. This method of technology is straightforward to operate, responsive, and well-suited for real-time monitoring and swift diagnosis.

(2) Comparative diagnosis method

Comparative diagnostics is geared towards detecting structural issues by comparing the differences between the current state and the normal state of the structure. Typically, statistical analysis methods are employed to standardize monitoring data, which is then compared with baseline data during comparative diagnosis. This method allows for an intuitive reflection of the structural health status and change trends, offering high efficiency in identifying structures that deviate from the normal range.

(3) Artificial neural network method

The artificial neural network method emulates the processing mechanism of the human brain, achieving pattern recognition and classification by establishing numerous nonlinear relationships within data. Through training, the neural network can process complex bridge structure data, identifying potential relationships and patterns within it. Compared to other methods, artificial neural networks excel in handling fuzzy, nonlinear, and complex problems, offering higher efficiency and demonstrating strong adaptability and flexibility in disease monitoring tasks.

(4) Fuzzy mathematical method

The fuzzy mathematical method integrates uncertainty and imprecision into the analysis process using fuzzy set theory. This approach can handle incomplete information and unclear boundaries. In diagnosing bridge structural issues, the fuzzy mathematical method enables technicians to consider multiple indicators, even if these indicators are influenced by external factors and exhibit some degree of ambiguity. Despite these challenges, the fuzzy mathematical method can still produce reasonable diagnostic results.

3.3. Bridge dynamic response monitoring technology

Bridge dynamic response detection technology encompasses the vibration modal method and the strain modal method, both leveraging the structural response characteristics under dynamic action to monitor and assess the integrity and safety of bridge structures in real time through precise measurement and data analysis.

The vibration modal method evaluates the structural performance of bridge structures based on their natural vibration characteristics under dynamic loads, including natural frequencies, shapes, and damping ratios of vibration modes. Accelerometers and displacement sensors are typically deployed at key locations of the structure for data collection. Following data collection, dynamic parameters of the bridge structure are extracted through spectral analysis and system identification and then compared and analyzed with standard and historical data. This method effectively reflects changes in the bridge structure's stiffness, mass, and damping properties. As the performance of the bridge structure changes, so do the vibration modes. By monitoring these parameters, the health status of the structure can be effectively assessed.

On the other hand, the strain modal method employs strain measurement to monitor the health status of bridges. Strain gauges and other sensing equipment are arranged at key locations of the bridge structure to record strain data under static and dynamic loading conditions. These data effectively reflect the inherent stress state and deformation capacity of bridge structural materials under loading, enabling the determination of structural stress and deformation modes from a strain perspective.

3.4. Existing safety assessment methods for bridge structures

The current safety assessment methods for bridge structures can be categorized into safety assessment and service life assessment. Safety assessment primarily relies on well-established technical processes, ensuring the safety of the bridge structure. On the other hand, service life assessment is based on theoretical modeling, cumulative stress tracking, and monitoring characteristic parameters over time to estimate the remaining service life of the bridge structure.

(1) Safety assessment method

The goal of bridge structural safety assessment is to achieve an objective evaluation of the bridge's safety performance, thereby providing a foundation for decision-making in subsequent maintenance, reinforcement, and repair efforts. **Figure 1** illustrates the technical process of bridge structural safety assessment.

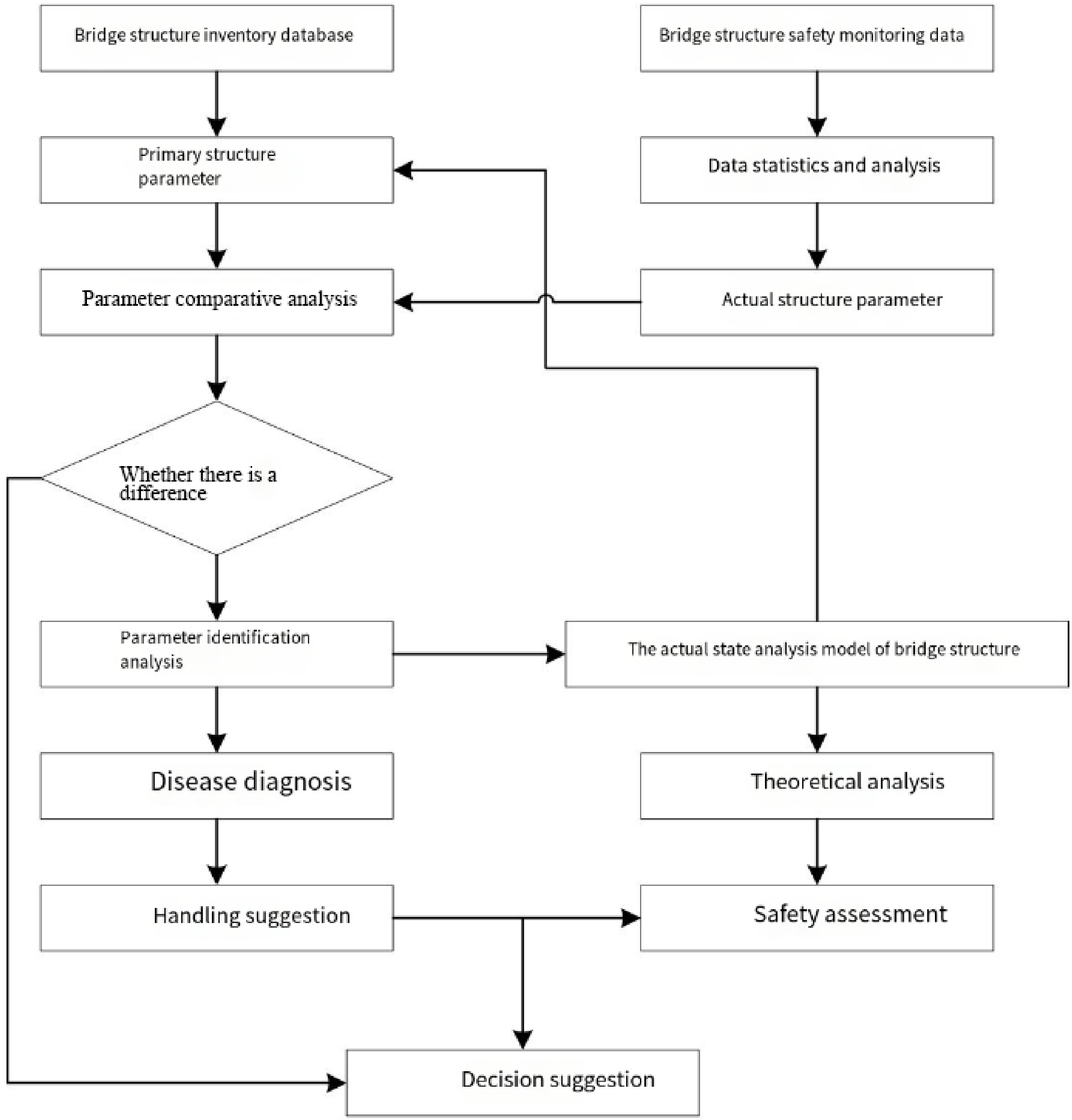

Figure 1. Bridge structure safety assessment technology

As depicted in **Figure 1**, the core of bridge structural safety assessment lies in acquiring bridge safety parameters through continuous inspection. By analyzing historical data, the assessment infers the trend in bridge structural safety development. Simultaneously, it determines the remaining service life of the bridge structure. The progression from a normal state to abnormal conditions causing defects is termed the damage or deterioration process. This deterioration process can be further categorized into proportional deterioration, accelerated deterioration, rapid acceleration of deterioration, and sudden deterioration.

(2) Service life assessment methods

(i) Theoretical modeling method

The theoretical modeling method aims to simulate and predict the long-term behavior and performance of bridge structures under various factors such as material aging, corrosion damage, and usage load. This is achieved by establishing a mathematical model based on deterministic and probabilistic principles, along with theories of material mechanics, structural mechanics, and fatigue crack extension of the bridge structure. The model utilizes initial data including bridge design parameters, material properties, environmental conditions, and historical usage records during the assessment period to analyze the degradation trend and estimate the remaining service life of the bridge structure. However, despite its low cost, this method often relies on simplified assumptions to construct a model, which may not accurately capture the complex behavior of real bridge operations. Moreover, uncertainties in the initial data can also impact the prediction results. As a result, this method is less commonly used in practice.

(ii) Cumulative stress tracking method

The cumulative stress tracking method operates on the principle of material fatigue theory and employs damage tolerance for cumulative stress analysis. According to this theory, bridge structural materials accumulate microscopic damage under repeated loading. As damage accumulates, the performance of structural materials gradually deteriorates, potentially leading to structural failure over time. By monitoring and analyzing the stress response of the bridge structure under various operating conditions, this method assesses the degree of material damage and fatigue accumulation. Consequently, it allows for the evaluation of the remaining life of the structure.

During the application of the cumulative stress tracking method, the first step involves deploying measuring instruments such as strain transducers to key locations on the bridge to collect stress-strain data in real time. In the second step, this stress response data is used along with the material S-N curve (stress-cycle number curve) to assess the fatigue life of the material. Following this, in the third step, the accumulated stress data is statistically analyzed to cumulatively calculate the damage to the structure under actual loading conditions. Finally, in the fourth step, the remaining service life of the structure is predicted by damage accumulation modeling.

(iii) Characteristic parameter tracking method

The characteristic parameter tracking method for bridge structures aims to establish the next diagnostic time, predict the value of the characteristic parameter at that time, determine the remaining life of the bridge structure, and assess the probability of disease occurrence based on historical data of characteristic parameters obtained from bridge structure monitoring.

During the application of this method, the first step involves confirming the initial values of the characteristic parameters of the bridge structure (X_0), the limit values of the characteristic parameters (X_c), and the standard service life of the bridge structure (X_i). Simultaneously, recent historical data, i.e., the results of the last n bridge and structure-oriented monitoring (X_1, X_2, X_3……X_n), are obtained. Subsequently, the relative deterioration is calculated using Equation 1.

$$\xi_i = \frac{X_i - X_0}{X_C - X_0} \quad i = 1,2,3\ldots\ldots, n \qquad (1)$$

If the settlement of ξ_i is 0, then $X_i = X_0$. If ξ_i=1, then $X_i = X_c$, indicating that the bridge structure has reached the deterioration limit. During the life prediction of the bridge structure based on the relative deterioration, it is necessary to perform curve fitting and smoothing on the data $\xi_1,\xi_2\ldots,\xi_n$ in advance. This can be achieved by using the least squares method for quadratic curve fitting, introducing the time parameter t during the fitting period, as shown in Equation 2.

$$t_i = T_i - T_1;$$

$$\xi_i = at_1^2 + bt_i + c;$$

$$Q = \sum_1^n [\beta_i \xi_i - (at_1^2 + bt_i + c)]^2$$

$$\beta_i = \frac{t_i m}{\sum_i^n t_i m} t_i = T_i - T_1;$$

$$\xi_i = at_1^2 + bt_i + c;$$

$$Q = \sum_1^n [\beta_i \xi_i - (at_1^2 + bt_i + c)]^2$$

$$\beta_i = \frac{t_i m}{\sum_i^n t_i m} \quad (2)$$

In Equation 2, a, b, and c are constants, Q represents the weighted sum of squares, β_i represents the weighting factor, and m is the index used in calculating the weighting factor. When $m = 1$, it signifies the average of equal weights, with each data point having equal weight. If $m > 1$, it enhances the importance of the most recent data, as depicted in Equation 3.

$m = \lambda \xi_n$ (3)

In Equation 3, λ is a constant > 0, i.e., representing the weighting constant. In this expression, the larger the degree of current relative deterioration, the more importance is placed on recent data. In $\xi_i = at_1^2 + bt_i + c$, the constants can be determined by minimizing Q, i.e., by using the condition $\frac{\partial Q}{\partial a} = 0, \frac{\partial Q}{\partial b} = 0, \frac{\partial Q}{\partial c} = 0$. Equation 4 can be derived as follows:

$$\left(\sum_1^n \beta_i t_i^2\right) a + \left(\sum_1^n \beta_i t_i\right) b + \left(\sum_1^n \beta_i\right) c = \sum_1^n \beta_i \xi_i;$$

$$\left(\sum_1^n \beta_i t_i^3\right) a + \left(\sum_1^n \beta_i t_i^2\right) b + \left(\sum_1^n \beta_i t_i\right) c = \sum_1^n \beta_i \xi_i t_i;$$

$$(\textstyle\sum_1^n \beta_i t_i^4) a + (\sum_1^n \beta_i t_i^3) b + (\sum_1^n \beta_i t_i^2) c = \sum_1^n \beta_i \xi_i t_i^2; \quad (4)$$

From this, the constants can be obtained. When the relative deterioration degree reaches 1, it indicates that the bridge structure has reached the deterioration limit. At this point, by substituting ξ_i=1 into $\xi_i = at_1^2 + bt_i + c$, the relative service life of the bridge structure can be obtained, as shown in Equation 5.

$$t_r = \frac{-b + \sqrt{b^2 - 4a(c-1)}}{2a} \quad (5)$$

Therefore, from the current time to the degradation limit, the residual life (T) of the bridge structure can be calculated by Equation 6.

$$T_r = \frac{-b + \sqrt{b^2 - 4a(c-1)}}{2a} - t_n \quad (6)$$

4. Conclusion

Currently, structural reliability stands as the primary core theory in bridge structure design. Throughout the operational phase, ensuring the reliability of the bridge is vital for the safety of public travel and the surrounding environment. Bridge structure design units, operational entities, and related management departments can utilize the methods proposed in this paper to evaluate the safety of bridge structures according to their specific requirements. By leveraging various technologies, they can establish a solid technical foundation for the stable and safe operation of bridges.

Disclosure statement

The authors declare no conflict of interest.

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