Research on the Structural Response Over-Limit Early Warning Technology for Bridge Structures based on Structural Health Monitoring System

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Abstract

This research focuses on the development of a structural response over-limit early warning technology for bridge structures based on The structural health monitoring system (SHMS). We first present a thorough overview of existing SHMS technologies and their applications in bridge engineering. We then propose a novel approach for real-time monitoring, analysis, and prediction of structural responses in highway bridges. The proposed method integrates advanced sensor technologies, data acquisition systems, and algorithms for accurate and efficient data processing and analysis. To demonstrate the effectiveness of the proposed approach, a case study is conducted on a typical bridge structure using a combination of field tests and simulations. The results show that the SHMS can effectively monitor various types of structural responses, such as displacement, strain, and vibration, and provide reliable early warning signals before reaching the limit state. The proposed technology has several significant implications for the safety management of bridges. It enables timely detection of potential hazards, reduces the need for costly repairs or replacements, and ultimately contributes to enhancing public trust in transportation infrastructure. Additionally, the developed SHMS can be easily adapted to other types of civil engineering structures, providing a versatile tool for structural health monitoring in various fields.

Keywords

Bridge Structures; Structural Health Monitoring System; Over-Limit Early Warning.

1. Introduction

As an important part of transportation infrastructure, bridges have a vital role in ensuring traffic safety and smoothness. The application of structural health monitoring system (SHMS) makes real -time monitoring of the bridge structure possible. Through the monitoring of response, strain, and vibration of the bridge structure, it can timely grasp the bridge in time in natural loads, temperature changes, vehicle loads, and external environments[1]. The state changes under the action of factors, and take corresponding maintenance measures accordingly.

In recent years, with the advancement of technology and the accumulation of application experience, the application of SHMS in bridge engineering has become increasingly wide. Since the 1980s, structural health monitoring technology has developed rapidly, and many countries have formulated relevant standards and guidelines. The "Guide to Highway Bridge Health Monitoring Systems" released by DOT organization pointed out that SHMS is a monitoring method of integration,

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continuity, real -time, and reliability. It ensures the accuracy, timely and real -time collection of data through the coordination of multiple subsystems and sensor networks. In the bridge structure health monitoring system, the deployment of sensors is essential for collecting structural response data and implementing structural state prediction. Nevertheless, the existing research is mostly focused on static measurement, and the complex response caused by factors such as dynamic loads such as vehicle loads, temperature changes, and foundation settlement due to dynamic loads such as vehicle loads, temperature changes, windloads, and foundations during the operation. Therefore, the research on over -limit warning technology for highway bridge structure response is particularly urgent[2].

1.1 Highway Bridge Structure Response Monitoring Technology

Highway bridge structure response monitoring technology (SHMS) is a key technical means to monitor real -time response to the bridge structure through the advanced sensor network deployed on the bridge. These sensors can capture dynamic responses such as displacement, strain, and vibration of the bridge when they are affected by external loads, and then provide an important basis for assessing the health status of the bridge. Once an abnormal response is detected, the SHMS can issue alert to the bridge operation management team through the warning system, prompting it to take timely and effective intervention measures to reduce potential risks[3].

The core components of SHMS include three links: sensor network, data collection system, and data analysis and processing system. The sensor network is like the tentacles of the bridge, responsible for collecting the data captured by various sensors, and converting it into a meaningful signal; the data collection system plays the role of the information center to summarize the data transmitted by the sensor network. , Organize and preliminary analysis; finally, the data analysis and processing system uses professional algorithms and models to in -depth data processing data, thereby extract key information of structural response and forms early warning. As shown in Fig. 1.

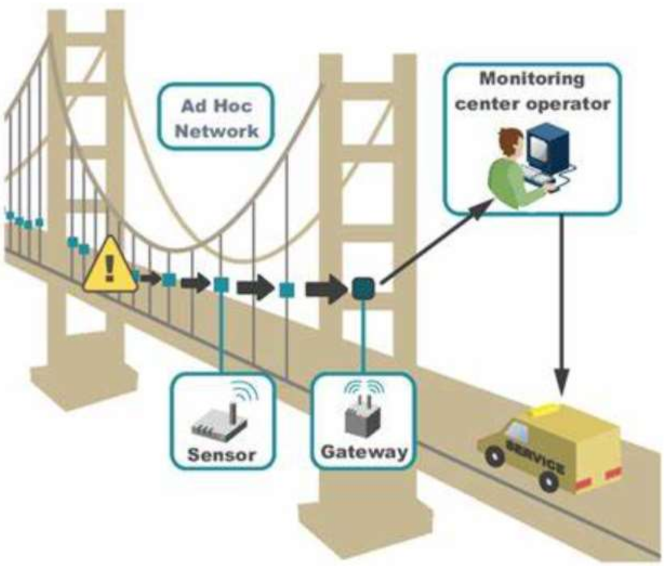

Fig. 1 Highway bridge structural response monitoring technology

1.2 Excellence Early Warning Method

During the operation of highway bridges, changes in structural response are often affected by various factors, such as natural loads, temperature fluctuations, vehicle loads and external environmental conditions. These factors may cause the response value of the bridge structure to exceed the preset security limit, which trigger potential safety hazards. In view of this, it is particularly important to conduct over -limit warnings for bridge structures under different scale[4].

Excellent warning methods can be roughly divided into three types: hierarchical warning, segmented early warning and combined warning. The hierarchical warning focuses on dividing different early

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warning levels according to the severity of the bridge structure response, and sets the corresponding warning line or warning point according to this; Set a specific early warning threshold for each stage; the combination warning uses the advantages of the above two methods to improve the accuracy and timeliness of early warning by constructing a more complex early warning model[5].

1.3 Engineering Example

In order to verify the effectiveness of the SHMS method proposed in this article in practical applications, this article selects typical highway bridges as engineering instance for research. These bridges are located on the highway and the urban lanes, and are all consecutive box beam structures. In order to better understand the response characteristics of these bridges under different loads and environmental conditions, this article has arranged multiple sensors in the key positions of the bridge for on -site tests.

By comparing the on -site test data and simulation results, this article can find that the SHMS method shows higher sensitivity and accuracy in capturing changes in the bridge structure response. At the same time, the early warning system can also issue alarm in a timely manner before the bridge structure response exceeds the safety limit, providing valuable decision -making time for the bridge operation management team[6].

However, this article also noticed that the SHMS model may not fully reflect the actual structural response in some cases. This is mainly caused by the complexity and uncertainty of the road bridge structure itself. In addition, factors such as the quality, installation location, and interference in the data transmission process may also have a certain impact on the predictive accuracy of the SHMS model. Therefore, in the future research and development work, this article needs to further optimize the design and algorithm selection of the SHMS model to improve its prediction ability and robustness of the actual structural response. At the same time, strengthening the quality control and maintenance of sensor equipment is also one of the important guarantee measures to ensure the long -term stable operation of the SHMS system[7].

2. The Development of SHMS Technology

As an important achievement of modern engineering technology, the structural health monitoring system (SHMS) has gradually become a key tool for bridge safety assessment. The core of the SHMS is to capture the structural response of the bridge through a series of precision sensors, and combined with high -level data collection and processing technology to conduct comprehensive monitoring and early warning of the health status of the bridge. This system is mainly composed of four parts: sensors, data collection, data processing and early warning mechanisms.

In the historical process of bridge structure monitoring, various sensors such as temperature sensors, vibration sensors, and acceleration sensors have been widely used. However, these sensors are often difficult to accurately measure the full picture of structural response, and when facing the complexity of the road and bridge structure, cross -interference problems often occur between different types of sensors, which seriously affects the accuracy of measurement data. In view of this, it is particularly urgent to develop a set of SHMS that can comprehensively use the advantages of multiple sensors.

2.1 Instrument -based SHMS

The instrument -based SHMS relies on a series of high -precision sensors, such as the optical fiber Prague grille (FBG) sensor, the fiber grating acceleration sensor, and the voltage ceramic acceleration sensor. These sensors are specially used to measure the strain and displacement of the structure. The supporting data acquisition system contains data collection cards, professional software and hardware facilities, which is responsible for collecting data from sensors. Data processing software further analyzes data and identification of data to evaluate the performance and health of the bridge. The entire system is built on the computer, network communication equipment and user interfaces, forming a complete bridge health monitoring solution. Nevertheless, the instrument -based SHMS also exposes some limitations during the application process, such as high costs, equipment maintenance needs, etc.

2.2 Model -based SHMS

Unlike the instrument -based SHMS, model -based SHMS focuses on using mathematical models to analyze and predict the bridge structure. The basic concept of this method is to establish a model on the basis of actual bridges, and predict the actual response of the bridge through the model. The advantage of this method is that it can quickly and accurately predict the dynamic response of the bridge, which has an irreplaceable effect on evaluating the performance of the bridge. In practical operations, model -based SHMS is widely used in non -linear problems that solve the bridge structure, such as bending, turning, and vibration response of beams. Through the assistance of the model, engineers can not only predict the structure response more accurately, but also simulate the damage mode where the structure may occur. However, due to the complexity of the highway bridge itself, the model -based SHMS still faces challenges in processing the cross interference of different types of sensor data and complex data processing. In practice, in order to overcome these problems, simplified models or linear systems are often used to analyze and predict.

3. Monitoring Results Analysis

In the typical bridge structure, as shown in Figure 2, multiple structural health monitoring systems (SHMS) are carefully arranged in this article. Each SHMS is equipped with a precise temperature sensor and two sensitive strain sensors. These sensors can be controlled independently and are coordinated by a series of highly integrated controllers. The communication between sensors depends on a stable fiber connection to ensure the stability and accuracy of data transmission.

Combining the results of on -site trials and simulation analysis shows that SHMS performed well in capturing various response of the bridge structure. For example, in Fig. 2, the process of changing the main beam strain with time is clearly displayed. Whether it is a small displacement or significant vibration of the bridge structure, SHMS can capture and record it in real time. Once the bridge structure is deformed or vibrated, the sensor in the SHMS will immediately capture this change and transmit the data to the data processing center in real time, so as to achieve real -time monitoring, in -depth analysis and future trends of the bridge structure response predict.

Fig. 2 Sensors mounted on the outside and middle of the main beam

In order to further verify the effectiveness of the SHMS method, a representative highway bridge was selected in this article for example research. This bridge is 545 meters long and 10 meters wide. It is an important traffic hub on a two -way four -lane highway. The design of its main cross -continuous suspension makes it a leader in similar bridges. Since its opening in 2011, the bridge has always attracted the attention of the world with its magnificent structure and excellent performance. Through

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SHMS, the main beam of the bridge is comprehensive and in -depth monitoring of the displacement, strain and vibration response of the bridge, and uses advanced data analysis technology to analyze the collected data to evaluate the structural health of the bridge.

Prior to the experiment, this article uses the finite element method to build a detailed simulation model of this bridge. The model covers key structural elements such as the main beam, pulling cable, bridge paving layer, and main tower. In the process of model construction, this article fully considers various factors that may affect structural response to ensure the accuracy and practicality of the model. This article has designed a series of loading conditions for different load conditions to comprehensively examine the performance of the bridge in various extreme conditions. At the same time, the corresponding sensor array is deployed in each operating condition to capture the displacement, strain and vibration response data of the main beam in real time.

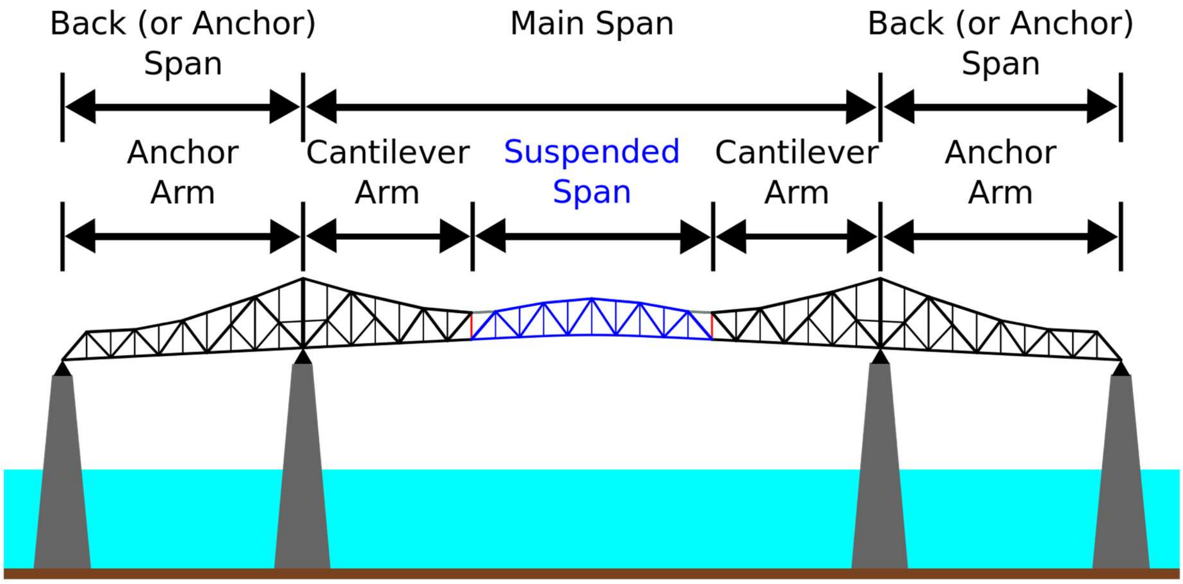

Fig. 3 Six main load conditions are designed for 7 sections of highway bridge to simulate different degrees of load

Fig. 3 is the deflection six main load conditions are designed for 7 sections of highway bridge to simulate different degrees of load response data table measured by the main beams measured in each of this article. These data not only provide valuable experimental basis for this article, but also further verify the accuracy and reliability of the structural response model of this article through comparison analysis with the simulation data. In terms of the displacement of the main beam, the main beam displacement curve obtained through the SHMS monitoring is very good with the on -site test data, which fully illustrates the effectiveness of the model correction and prediction method of this article. Similarly, in terms of main beams, the forecast value after model correction is also very close to the results of the on -site test, which once again proves the superiority and practicality of the SHMS method in the health monitoring of the bridge structure.

In order to further study the performance of the bridge under the action of mobile loads, this article also specially carried out the bridge structure response prediction test under different mobile load conditions. Specifically, this paper uses SHMS to install multiple sensors in the key positions of the bridge to monitor the displacement, strain and vibration response data of the main beam in real time. The experimental results show that under the conditions of various mobile loads, the structural response of the bridge meets the expected design requirements, and there is no problem with any excessive damage or excessive deformation. This fully illustrates that the SHMS method has high accuracy and reliability in practical applications, and provides strong technical support for the safe operation of the bridge. At the same time, this article also noticed that under certain specific operating conditions, the structural response of the bridge will fluctuate and change to a certain extent, which may be caused by factors such as uneven distribution of loads and local defects in the structure. In response to these issues, this article will continue to carry out in -depth research work to continuously improve and optimize the SHMS methods and technical systems of this article.

4. Prediction and Verification

In the field testing session, the strain data of the structure installed on the main beam installed on the bridge is used to evaluate the performance of the bridge in the actual working state. In terms of numerical simulation, for the physical characteristics of the bridge, a variety of structural parameters have been considered, including but not limited to geometric attributes (such as beam high, main beam cross section area), material properties (such as elastic modulus, Patson ratio, and steel steel The yield strength of the material) and the specific situation of the load (such as constant load and change load). In order to ensure the accuracy of the simulation results, multiple rounds of tests were implemented and the data obtained was performed detailed. Limited to the technical constraints of the test environment and finite element modeling, this article selects a representative model as the research object. As shown in Fig. 4.

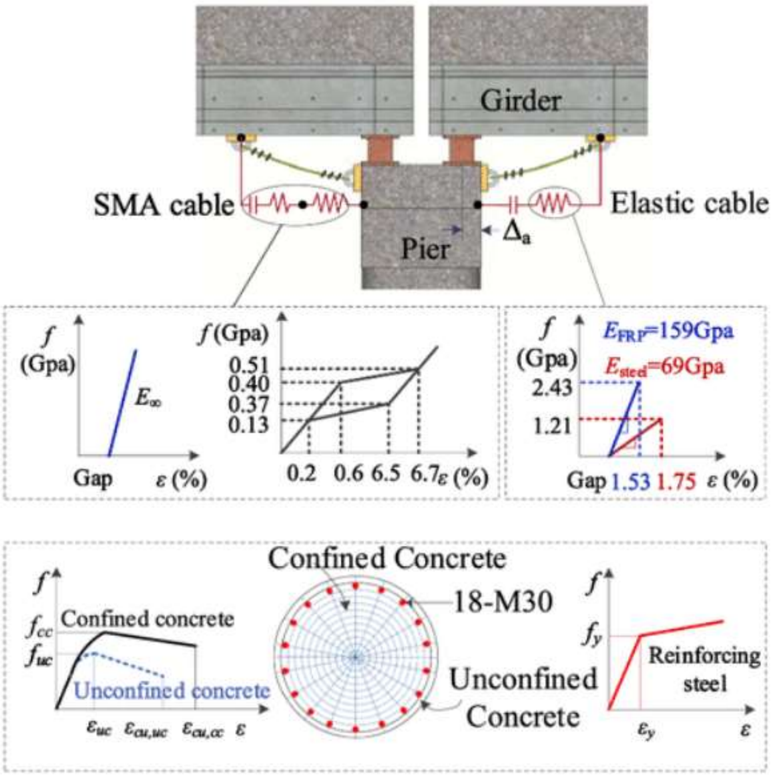

Fig. 4 Highway bridge finite element model is used to simulate geometric parameters

4.1 Structure Response Analysis

The response characteristics of bridges under different load levels. Analysis shows that with the improvement of the load level, the variability and stress level of the bridge have increased significantly, and the changes in strain are particularly prominent. The increase or decrease of the load level causes the deformation and stress under the level of the structure to produce corresponding changes. The comparison analysis results show that under the load level of 300 kN, the shape of the bridge is maximized, mainly because the load effect of the load level is the most significant. Specifically, when the load level increases to 300 kN, the strain on the main beam has risen sharply, especially under the action of the load level, the growth of the strain is particularly severe. When the

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beam existence reaches its peak, the growth rate of the strain is the fastest, which further confirms the direct impact of the load level on the bridge deformation and stress. Therefore, at the 300 kN load level, the variability and stress of the bridge reached the maximum value.

4.2 Bridge Response Overdue Warning Mechanism

When constructing a bridge response over -limit early warning model, this article adopts a set of dynamic early warning algorithms. The algorithm describes the structural response overrun situation based on the four -parameter index function to achieve real -time monitoring and early warning of the bridge status. In order to evaluate the accuracy of the early warning model, this article has selected a typical bridge case for prediction analysis. First of all, through in -depth analysis of the measured data, this article identifies three key influencing factors (constant loads, liveloads and maximum speeds), and builds the corresponding index function relationship according to this. Then, through the analysis of the characteristics of the transformer signal, the warning result of the bridge response overrun was obtained in this article. Finally, the reliability and effectiveness of the early warning algorithm were verified by comparing the warning results with the actual measurement data.

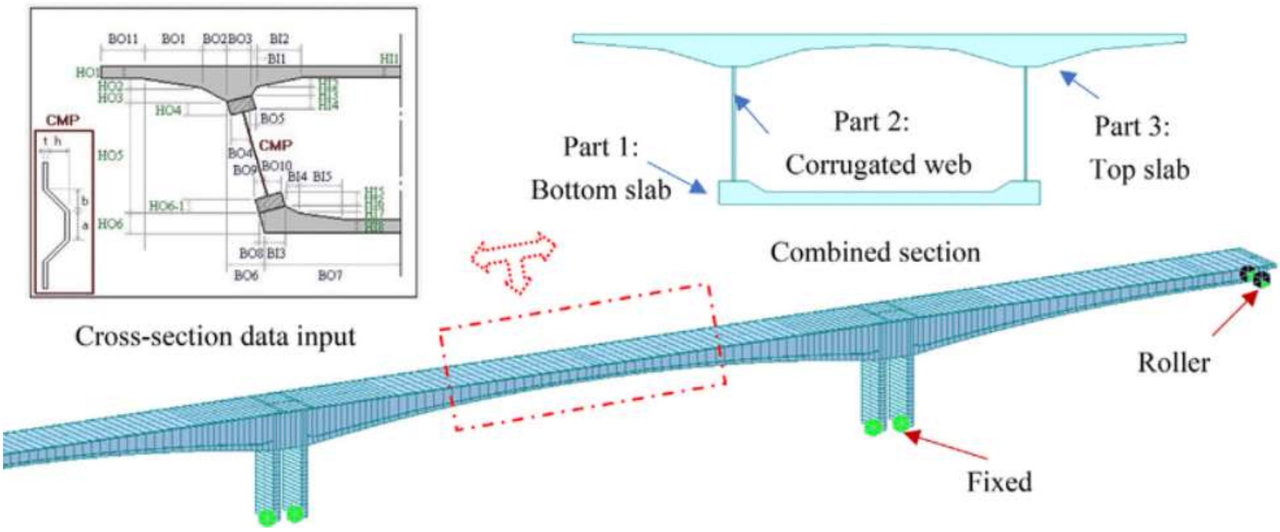

Fig. 5 Three parts of highway bridge finite element model are selected for testing

Fig. 5 shows the effects of load level changes on the bridge response over -limit warning index. Data show that with the improvement of the load level, the bridge response overrun warning index shows a significant reduction trend. After analysis, it can be concluded that when the constant load level is 100 kn, the early warning index decreases by about 60%; when the liveload level is 200 KN, the early warning index declines by about 40%; and the livingload level reaches 300 at 300. At KN, the decrease of the early warning indicators was about 70%.

5. Conclusion

This research innovatively proposes a bridge -based bridge response over -limit warning method based on structural health monitoring system, and has verified its effectiveness through experimental research and numerical simulation experiments of actual bridges. This method uses multi - dimensional structural response data such as the displacement, strain and vibration of the bridge in real time, accurately capture the working status of the bridge, and issue a warning signal in time before it reaches the extreme state, thereby achieving a advanced warning of the bridge structure. In addition, research results are not only applicable to bridge engineering fields, but also can expand the application of civil engineering structures in other types of civil engineering, providing strong

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technical support and decision -making basis for the safety management and risk prevention and control of the engineering structure.

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