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Reliability Analysis and Online Measuring Method of Fiber Optic Strain Sensors: Case Study on a Real Bridge

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Abstract. This paper presents a study on the reliability analysis and online measuring of sensors in Structural Health Monitoring (SHM) systems. As sensors are critical components in SHM, their reliability and accuracy are vital for the precise and effective operation of the monitoring system. By utilizing a strain testing platform and online measurement methods, this study analyzes the reliability and effectiveness of in-service sensors by comparing measurements on similar positions and applies the indoor experiment to an actual bridge structure. The results demonstrate that the proposed method can achieve precise reliability analysis and online measuring, ensuring the effectiveness and smooth operation of the SHM system and further enhancing the fundamental safety level of bridges while providing convenience to bridge management.

Keywords. Structural Health Monitoring, Fiber Optic Strain Sensor, Reliability Analysis, Data Matching Algorithm, Bridge Maintenance

1. Introduction

In recent years, a large number of bridge structures have approached their design life, and related research has gradually shifted from construction to management and maintenance [1]. To ensure the durability and safety of bridge structures, Structural Health Monitoring (SHM) systems have become increasingly important [2]. The reliability and accuracy of SHM systems are crucial for their precise and effective operation, and sensors play an important role in this system. Once the reliability of the sensors cannot be guaranteed, the data collected by the monitoring system becomes meaningless [3]. Therefore, global scholars have conducted various research on sensor measurement theory and reliability analysis. Surre et al. [4] conducted relevant research on the reliability of fiber Bragg grating strain sensors, and Jing et al. [5] found that sensor reliability analysis can be achieved by comparing the uncalibrated sensor and the standard sensor with similar positions in the sensor measurement traceability process, and sensor data can be matched using matching algorithms such as SAX. Mohammadzade et al. [6] conducted relevant research on sensor data using Dynamic Time Warping (DTW). With the popularization of big data and artificial intelligence

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technology, advanced techniques such as locality sensitive hashing (LSH) [7], neural networks [8], and Transformer based on self-attention mechanisms [9] have gradually been developed and applied to the sensor field, bringing great convenience to related research and work.

In terms of traceability of measurement values and online measurement technology, L. Peng et al. [10] studied the influence of temperature on sensors under different prestresses and verified the reliability and stability of strain sensors. Bai et al. [11] studied the calibration method of fiber optic grating strain sensors. Liu et al. [12] analyzed the reliability of fiber optic grating sensors in road applications, which enriched related research in the field of SHM and expanded their application prospects.

This paper builds a strain testing platform and analyzes the reliability and effectiveness of in-service sensors by using high-precision sensors on similar positions. The online measuring method is used to calculate and analyze the quantity values of sensors. The indoor experiment is successfully applied to an actual bridge structure, further verifying its feasibility, and achieving accurate reliability analysis and data calibrating, which guarantees the effectiveness and smooth operation of the structural health monitoring system, further enhancing the essential safety level of the bridge and bringing convenience to bridge maintenance.

2. Experimental Design

2.1. Verification of Indoor Sensors

To ensure the reliability and accuracy of strain sensors used for structural monitoring, a strain testing platform was designed and constructed. The platform consists of five parts: a control console, temperature control device, simulated beam, load device, and data acquisition equipment, as shown in Figure 1.

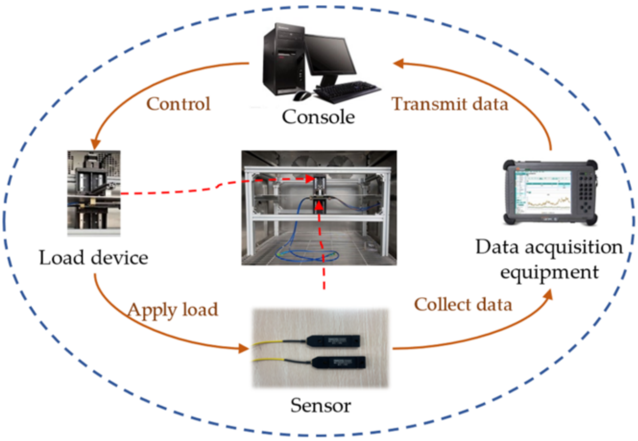


Figure 1. Strain Testing Platform

The control console is a desktop computer that can control load output and sensor response acquisition. The temperature control device is a temperature control box. The load device is a servo motor pressure rod which is calibrated according to national standards. The simulated beam is an S304 stainless steel which is calculated and manufactured by reverse engineering from an actual bridge, and its structure is shown in Figure 2.

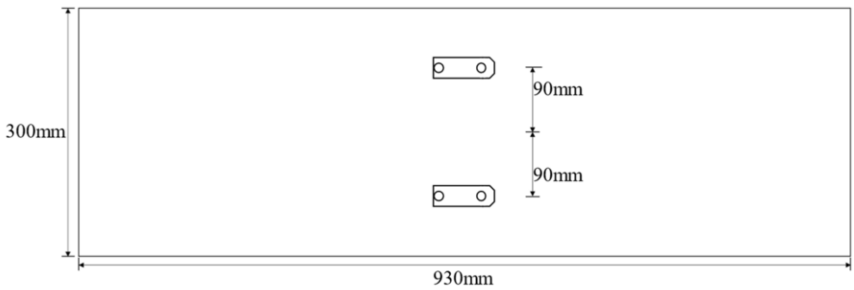


Figure 2. Structural Parameters of Simulated Beam

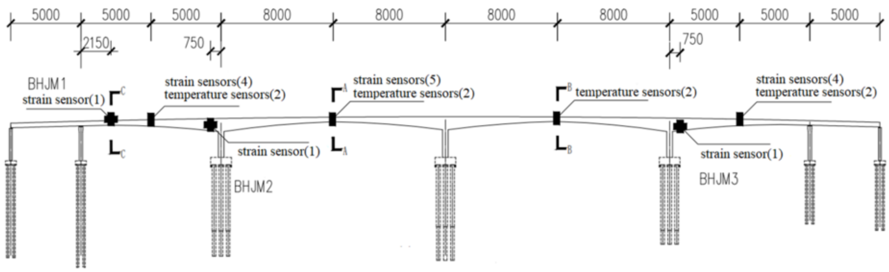
The experimental procedures comprised the following steps:

- Sensor installation: Two sensors were installed at symmetrical positions on the simulated beam, with one simulating the in-service sensor and the other simulating the sensor used for measurement traceability, as depicted in Figure 2.
- Loading: After installation, the simulate beam was placed into the temperature control device, and step forces were applied to the beam by controlling the load device through the console. The step forces were kept the same in seven periods while the working temperatures ranged from -10°C to 50°C.
- Data acquisition and processing: Sensor acquisition values were obtained through acquisition equipment. To enhance the accuracy of data, the median filtering method was applied before calculation. The Dynamic Time Warping (DTW) method was employed to match the time series of the data. The minimum path was found through dynamic programming by calculating the Manhattan distance matrix. And the similarity evaluation was conducted.

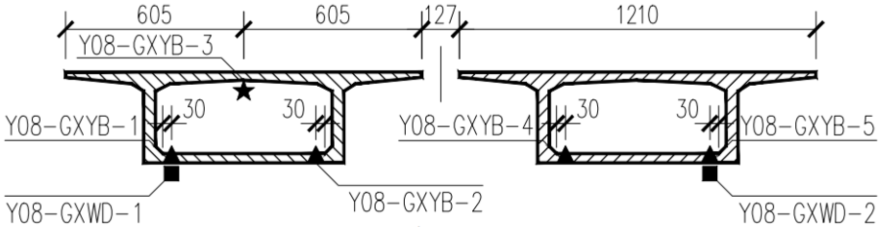
By comparing the sensor acquisition values on similar positions and using online measuring method, an accurate sensor accuracy evaluation method suitable for the field was obtained, ensuring the precise and reliable operation of sensors during structural monitoring.

2.2. Verification of In-Service Sensors on Actual Bridge

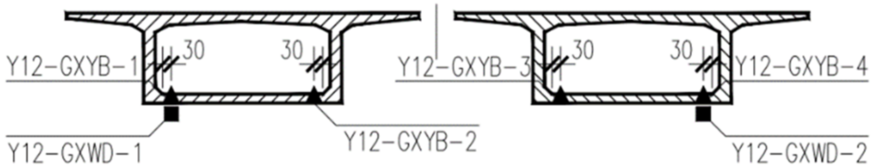
This article relies on a highway bridge built in 1996 in China to carry out theoretical verification of strain sensor reliability and value tracing. The bridge is 1,819.2m long, with a main span of 50+100+160+160+100+50m. Its upper structure uses prestressed variable cross-section continuous box girders, and its lower structure uses thin-walled bridge piers. According to inspections over the years, the overall condition of the bridge is rated as level 2, with cracking in most of the web plates and bottom plates of the girders, and cracking in some of the top plates. Various defects and fatigue problems were found in the joint seams. Although the maintenance institution has repaired and reinforced some of the defects, to avoid durability reduction and maintain structural safety level, it is still necessary to monitor the deteriorated components for a long time. The long-term reliability and value accuracy of the monitoring sensors are essential to ensure smooth and effective monitoring. Therefore, long-gauge-distance fiber optic strain sensors commonly used in structural health monitoring systems were selected, and real-time temperature compensation was carried out using fiber optic temperature sensors to ensure measurement accuracy. The overall layout plan of sensors is shown in Figure 3.



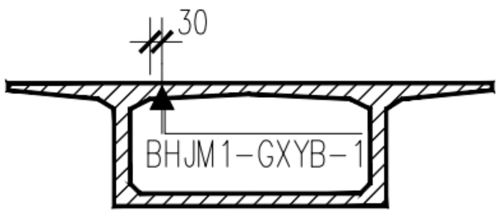
A. Bridge elevation and sensor layout plan (1:250, unit: cm)



B. Cross-section A-A profile and sensor layout plan (1:20, unit: cm)



C. Cross-section B-B profile and sensor layout plan (1:20, unit: cm)



D. Cross-section B-B profile and sensor layout plan (1:20, unit: cm)

Figure 3. Sensor Layout Plan

According to the layout plan in Figure 3, multiple sensors were installed at symmetrical positions on the box girder of the bridge to measure the strain-time curve of the bridge. The accurate evaluation method of the laboratory sensors and the online measuring method were applied to compare the strain curves of multiple sensors on different bridge members, in order to verify the feasibility of the method investigated in laboratory.

3. Results and Discussion

The indoor experiment showed that the online measuring method of installing uncalibrated sensors and calibrated sensors in similar positions for SHM sensor reliability evaluation has high accuracy, with small errors between the two sensors. The values of the sensors under seven temperature cycles ranging from -10°C to 50°C was measured. And the acquisition values increasing with the increase of step stress as shown in Figure 4.

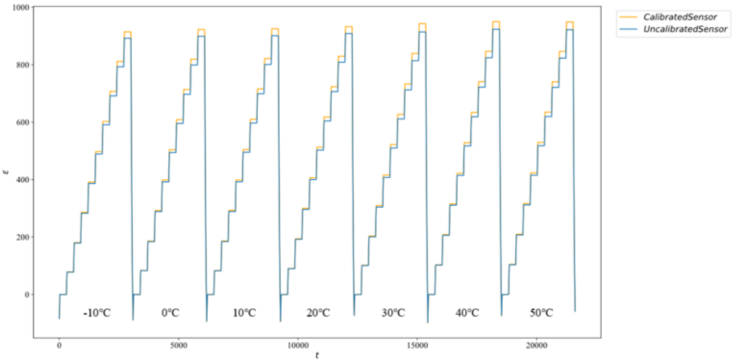


Figure 4. Collected value of the sensors at different temperature under stepped stress

Through computational analysis, it was found that the correlation coefficient between the two sensors was 0.99998, and the root mean square error (RMSE) was 13.2841, with small residuals. This indicates that the indoor testing method has high accuracy and can effectively achieve online calibration of sensors. The residual plot of the sensor acquisition values is shown in Figure 5.

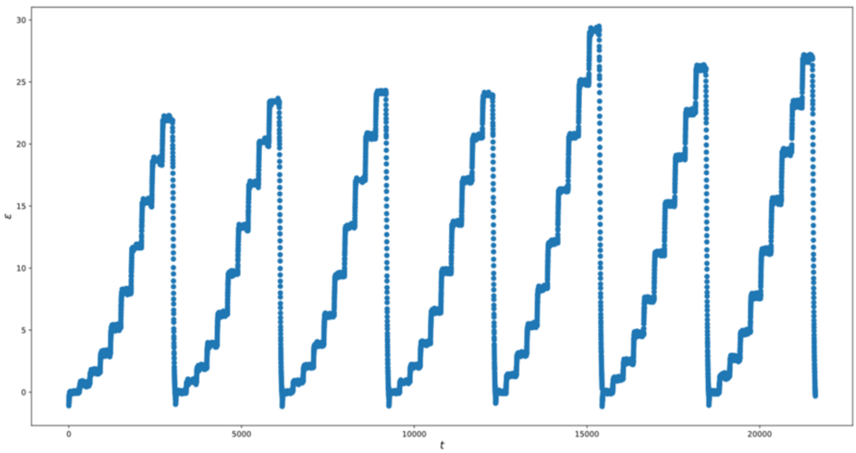


Figure 5. Residual plot of the collected values of the sensor

The results of this study were applied to actual in-service bridges. By observing the strain-time curves of key components and comparing the collected values of the calibrated sensors and the uncalibrated sensors, the reliability of the sensors was verified and value transfer was achieved. The strain-time curve of the sensors on the actual bridge is shown in Figure 6.

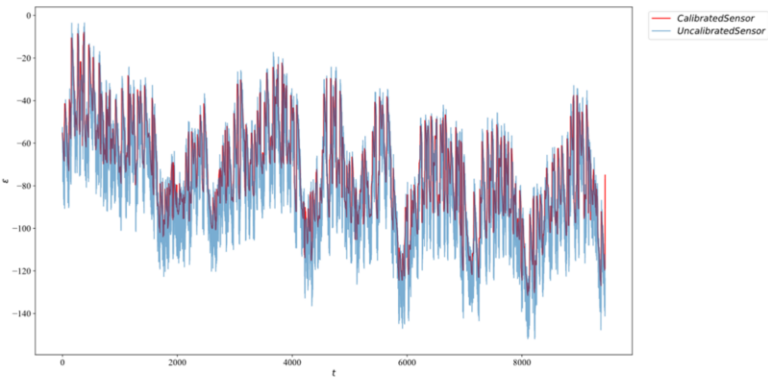


Figure 6. Strain-time curve of sensors on the actual bridge

By comparison, it can be known from Figure 6 that the data acquisition value of the uncalibrated in-service sensor deviated greatly after working for a long time. When the strain of the component was relatively large, the error was particularly significant. In addition, a certain amount of time delay was found. By using online measurement, the reliability and measurement performance of the in-service sensors can be effectively improved, thereby further ensuring the stable and effective operation of the SHM system.

4. Conclusion

This study aimed to evaluate the reliability of fiber optic strain sensors by conducting laboratory experiments on a simulated beam and verifying the feasibility of the method on an in-service bridge in China. The main findings of this study are as follows:

- The online measuring method of installing sensors on similar positions for reliability evaluation is highly accurate and feasible.
- The laboratory analysis showed that the correlation coefficient was 0.99998, the RMSE was 13.2841, and small residuals were observed.
- In-service sensors were found to deviate significantly after prolonged use, with significant strain errors and time delays, particularly when the bridge deformation was large. As a result, the application of the online measuring method is crucial to ensure accurate and reliable monitoring.

The implementation of this method is essential to ensure the accuracy of the SHM sensors, which guarantees the effectiveness and accuracy of the monitoring data for crucial components and cross-sections of the bridge. This method also provides greater convenience for bridge management and maintenance, enabling prompt responses to potential issues. The results of this study offer valuable insights for the application of similar methods in related fields, contributing to the advancement of SHM technology and promoting the safety and sustainability of infrastructure.

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