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Damage Identification of a Long-Span Suspension Bridge Using Temperature-Induced Strain Data

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ABSTRACT

Long-term monitoring data of large-scale civil structures include load-induced and temperature-induced structure responses. Traditional damage detection methods use vibration based structure responses by eliminating temperature effects from the measured data. In this article, a structural damage identification method using temperature-induced responses is proposed and applied to a long-span suspension bridge. A structure transfer function is constructed by taking temperature variation and temperature-induced strain as input-output data; thus, it has the potential to accurately reveal inherent structural characteristics, unlike traditional methods, which mainly use structural vibration responses from ambient testing. In the proposed method, the temperature-induced strain is first separated from measured strain responses by using ensemble empirical mode decomposition technology; the Euclidean distance matrix is then defined by using temperature variations and temperature-induced strains for structural damage detection. Numerical simulation and long-term monitoring data of the Jiangyin suspension bridge under normal operating conditions have been used to verify the proposed method's effectiveness and robustness. Damage identification of the Jiangyin suspension bridge before and after a ship collision has also been studied with the proposed method by using the data from the structural health monitoring system. The research results show that the proposed method accomplishes successful condition and damage assessment.

Keywords: Temperature strain; Damage detection; Long-term monitoring; Suspension bridge.

1. INTRODUCTION

Civil structures inevitably suffer material deterioration, environmental corrosion, traffic

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loads, and even natural disasters such as earthquakes and typhoons. How to guarantee their safety and structural health has become an important research area in civil engineering (Aktan et al. 2000; Catbas et al. 2008). Damage detection is an important tool for structural health monitoring and condition assessment. Advanced signal processing technologies, including wavelet, ensemble empirical mode decomposition (EEMD), neural networks, and support vector machines, have been used to develop various kinds of damage detection methods. Vibration-based damage detection methods have been well developed; these use the changes in structure vibration characteristics before and after damage. A variety of damage indices have been proposed, including mode shape curvature, strain mode shape, flexibility matrix, and modal strain energy; these mainly use structural acceleration and strain dynamic responses (Brownjohn et al. 2011; Lei 2012; Zhang et al. 2015). The limitation of these vibration-based methods is that structure vibration characteristics are generally unavoidably affected by environmental factors, particularly temperature load, during long-term structural monitoring. Accordingly, a number of methods have been developed to eliminate the temperature effect from structural response, including singular value decomposition, principal component analysis, auto-associative neural network, and support vector machine. However, even if the temperature influence has been completely eliminated, the damage identification results are still not satisfactory because they only use output data and cannot extract the structural transfer function.

The number of studies of temperature-based structural health monitoring has been gradually increasing. Ni et al. (2012) studied the correlation between measured temperatures and thermal movements of expansion joints for structural cumulative displacement prediction. Kim and Lamam (2010) investigated the relationship between thermal load and structure responses, including girder axial force, girder bending moment, pile lateral force, pile bending moment, and pile head/abutment displacement. Laory et al. (2013) used thermal variations as load cases to evaluate structural candidate models. Yarnold and Moon (2015) proposed a transfer function to calculate structural displacements and restrained member forces from recorded temperature-induced strains. A number of interesting methods are being developed for temperature-based structural health monitoring, and it has the potential to update a structural finite element model by using measured temperature load and temperature induced reactions.

In this article, a damage detection method is proposed using measured temperatures and temperature-induced strains that were separated from measured strains using the EEMD technology, and it is applied to a long-span suspension bridge by using long-term monitoring data including ship collision data. This paper is organized as follows: First, the Jiangyin suspension bridge and its structural health monitoring (SHM) system are briefly described. Second, the methodology of using measured temperatures and temperature-induced strains is presented for structural damage detection; this includes theory derivation for the proposed method, separating temperature-induced strain by using the EEMD technology, a Euclidean distance calculation using measured temperatures and temperature-induced strains, and the damage index defined by the difference between the Euclidean distance matrices at different times. In the third and fourth sections, numerical simulation and long-term monitoring data of the Jiangyin suspension bridge under normal operating conditions are used to verify the respective effectiveness and robustness of the proposed method. Damage identification of the Jiangyin Bridge before and after a ship collision is also studied with the proposed method by using the monitoring data from the SHM system.

2. THE JIANGYIN BRIDGE AND ITS SHM SYSTEM

The Jiangyin Yagntze River Bridge is a suspension bridge with a main span of 1,385 meters over the Yangtze River in Jiangsu, China (Fig. 1). The main girder is a welded streamlined flat steel box girder, with a height of 3 m and a width of 36.9 m, and the navigation clearance is 50 m. It has two 190-m tall reinforced concrete towers. The suspension cables are anchored directly in rock using gravity anchorages. In recent years, the average traffic flow over the bridge has increased to 70,000 daily units—much higher than the 15,000 daily units of the first year of its operation (1999).

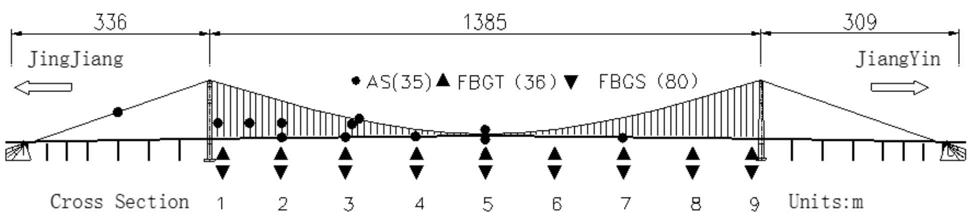

Fig. 1 Jiangyin Bridge SHM system

A SHM system was installed on the Jiangyin bridge and was upgraded in 2005. One hundred and sixteen fiber Bragg grating sensors were used for strain(FBGS) and temperature(FBGT) measurement of the main span, including 72 fiber optic sensors on nine equidistant cross-sections of the main span for longitudinal strain measurement, eight on the mid cross-section for transverse strain measurement, and 36 on nine equidistant cross-sections for temperature measurement as shown in Fig. 1. Thirty-five uni-axial accelerometers (AS) represented by solid circles in Fig. 1 were used in the SHM system, in which 15 were mounted in positions 1/8, 1/4, 3/8, 1/2, and 3/4 of the main span, eight on main cables, and 12 on hangers. Other types of sensors such as GPS and displacement transducers were also used, but these are not studied in this article.

3. THE PROPOSED DAMAGE DETECTION METHODOLOGY

Thermal analysis using temperature as the input has been well studied, and temperature distribution on the bridge is easy to measure. Thus, one can use the measured temperature and temperature-induced response as input and output data for structural identification based on well-developed thermal analysis theory. The framework of the proposed methodology is shown in Fig. 2. The procedure is described as follows:

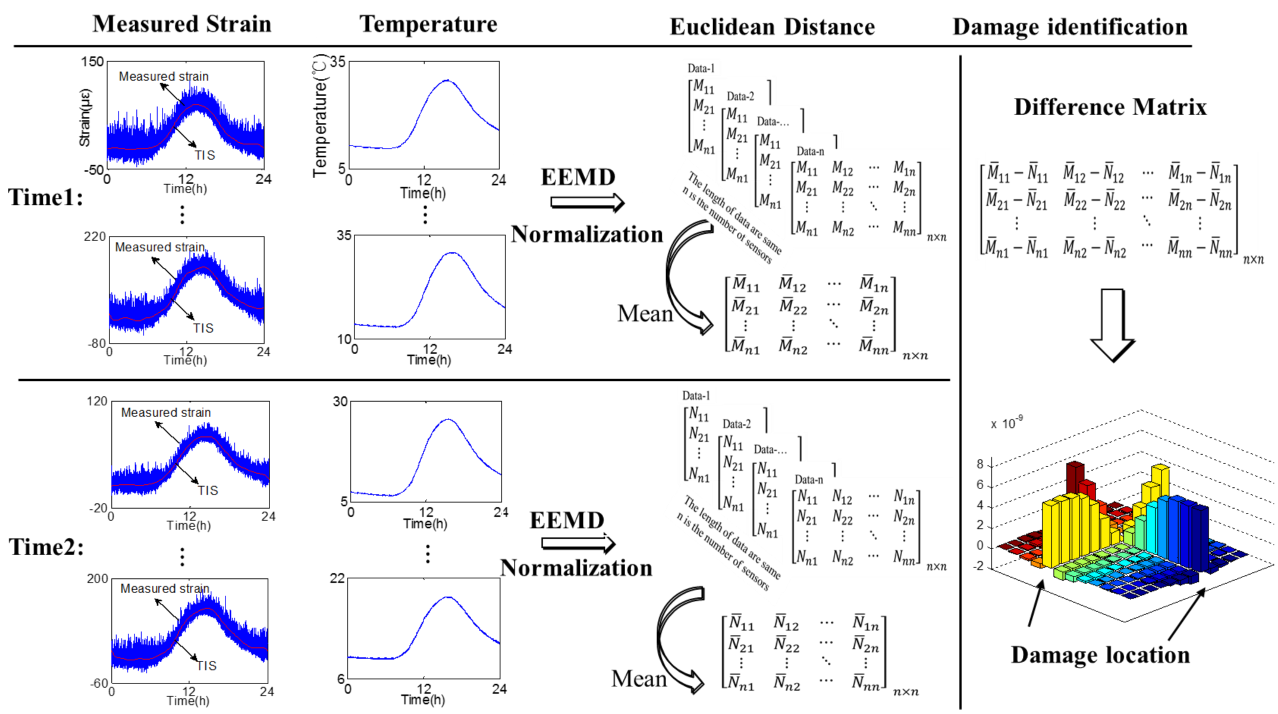

Fig. 2 Overview of the proposed methodology

Step 1: Temperature and structural dynamic strain responses in ambient vibration tests are measured by using the SHM system. Typical temperature and strain time histories of the Jiangyin Bridge are shown in Fig. 2. They have a similar trend, and the temperature-induced strains are greater than the traffic-induced strains;

Step 2: Temperature-induced strains are separated from measured strains using the EEMD technology. Each location of the temperature-induced strain was used for normalization processing with temperature. Structural intrinsic characteristics can be represented by the measured temperature and the temperature-induced strain, thus they have the potential for use in structural damage detection;

Step 3: The Euclidean distance of each sensor is calculated to form the distance matrix by using the monitoring data. Two Euclidean distance matrices at different times are calculated to detect the structure changes between those times.

Step 4: The damage index matrix, defined as the difference between the Euclidean distance matrices at different times, is calculated. This difference matrix will clearly show whether there is a change in each element of the structure; thus structural damages can be easily located by observing the changes of the damage index matrix as shown in Fig. 2.