The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

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).

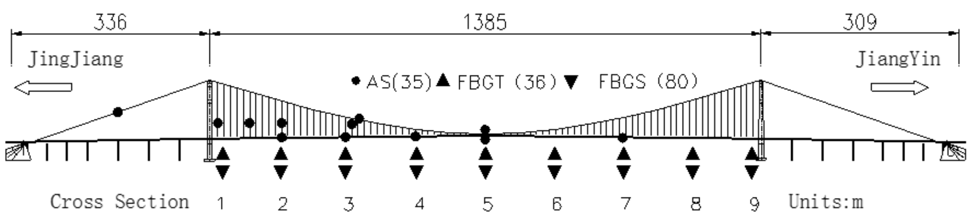


Fig. 1 Jiangyin Bridge SHM system

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:

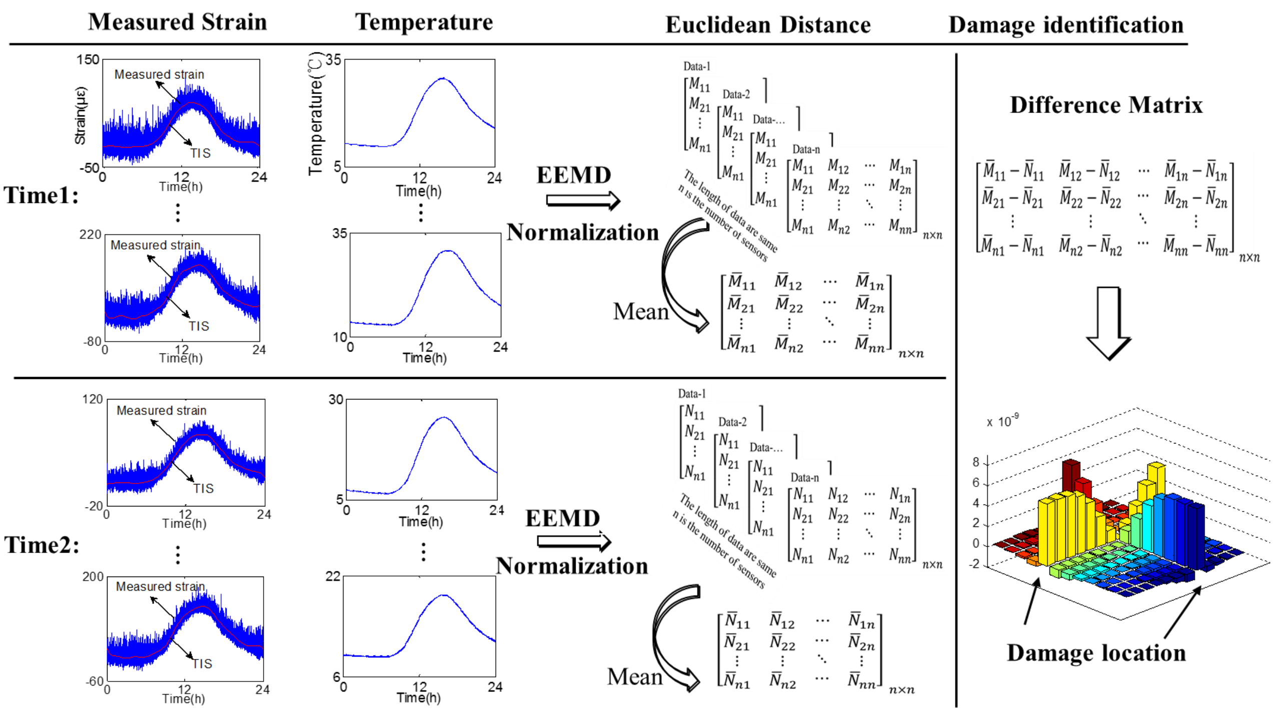


Fig. 2 Overview of the proposed methodology

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.

4. THEORETICAL BASIS OF THE PROPOSED METHOD

The measured temperature is decomposed into uniform temperature, ΔT, and gradient temperature, T_y. The temperature-induced strain, ε_T, for a simply supported beam structure under a uniform temperature change and the nonlinear temperature gradient is expressed as follows:

$$\varepsilon_T = \varepsilon_U + \varepsilon_y^N + \varepsilon_y^M \tag{1}$$

where, $\varepsilon_U = \alpha \Delta T$ and $\varepsilon_y^N = [\int_0^{\mathrm{h}} \alpha T_y b(y) dy]/A$ are axial strains caused by uniform temperature and nonlinear temperature gradient, respectively. α is the thermal expansion coefficient. $b(y)$ is the cross-sectional width, which changes with y. h is the cross-section height. A is the cross-sectional area. $\varepsilon_y^M = [\int_0^{\mathrm{h}} \alpha T_y b(y) y dy] y_o / I$ is the temperature induced bending strain at depth *h* caused by the nonlinear temperature gradient. I is the moment of inertia of the cross-section. y_o is the distance to the neutral axis. ε_U is related to the uniform temperature and the expansion coefficients, $\varepsilon_y^N, \varepsilon_y^M$, by including the stiffness and cross-sectional information of structure. The temperature induced bending strain ε_y^M is separated from Eq. (1).

$$\varepsilon_y^M = \varepsilon_T - \varepsilon_U - \varepsilon_y^N = \frac{\int_0^h \alpha T_y b(y) \mathrm{y} dy}{I} y_o \tag{2}$$

It should be noted that the temperature-induced bending strain, ε_y^M, is time varying due to the temperature gradient, T_y, is time varying. Thus it is not reasonable to make damage assessment by comparing ε_y^M at different time. As described in Eq. (2), $\varepsilon_y^M = [\int_0^{\mathrm{h}} \alpha T_y b(y) y dy] y_o / I$, and $\int_0^{\mathrm{h}} \alpha T_y b(y) y dy$ in fact is the temperature induced moment. Thus, the bending strain can be normalized to be the output/input format as follows:

$$\bar{\varepsilon}'^M_y = \frac{\varepsilon_y^M}{\int_0^h \alpha T_y b(y) \mathrm{y} dy} = \frac{y_o}{I} \tag{3}$$

It is seen that $\bar{\varepsilon}'^M_y$ is time in-varying and it has direct relation with structural stiffness. Thus it is able to be used for structural damage detection.

The Euclidean distance of the normalized bending strains ($\bar{\varepsilon}'^M_n$) at each cross-section is expressed as:

$$d_{ij} = \sqrt{\left(\bar{\varepsilon}'^M_i - \bar{\varepsilon}'^M_j\right)^2}, i, j = 1 \ldots 9 \tag{4}$$

$$\bar{d}_{ij} = \frac{1}{1 + d_{ij}} \tag{5}$$

where, d_{ij} is Euclidean distance between $\bar{\varepsilon}'^M_i$ with $\bar{\varepsilon}'^M_j$. $\bar{\varepsilon}'^M_i$ ($\bar{\varepsilon}'^M_j$) is normalized bending strain of the i^{th}(j^{th}) cross-section.

When the strains measured at all sections are used, the Euclidean distance matrix, EDM^{t_0}, at the time t_0 is assembled as

$$\mathrm{EDM}^{t_0}=\begin{bmatrix} \bar{d}_{11}^{t_0} & \bar{d}_{12}^{t_0} & \cdots & \bar{d}_{1j}^{t_0} & \cdots & \bar{d}_{1n}^{t_0} \\ \bar{d}_{21}^{t_0} & \bar{d}_{22}^{t_0} & \cdots & \bar{d}_{2j}^{t_0} & \cdots & \bar{d}_{2n}^{t_0} \\ \vdots & \vdots & \ddots & \vdots & \cdots & \vdots \\ \bar{d}_{i1}^{t_0} & \bar{d}_{i2}^{t_0} & \cdots & \bar{d}_{ij}^{t_0} & \cdots & \bar{d}_{in}^{t_0} \\ \vdots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \bar{d}_{n1}^{t_0} & \bar{d}_{n2}^{t_0} & \cdots & \bar{d}_{nj}^{t_0} & \cdots & \bar{d}_{nn}^{t_0} \end{bmatrix}_{n\times n} \tag{6}$$

where, $d_{ij}^{t_0}$ is the Euclidean distance between sensor *i* and sensor *j*. *n* is the section number. Similarly, the Euclidean distance matrix, EDM^{t_1}, at another time t_1 can also be calculated by using the measured strain at that time.

A damage index is defined as the difference of the Euclidean distance matrices at different times as shown in Eq. (7):

$$\mathrm{EDMD}=\mathrm{EDM}^{t_0}-\mathrm{EDM}^{t_1} \tag{7}$$

The physical meaning of this damage index is that damage occurs when the Euclidean distance between the normalized temperature induced bending strains at each section at different times changes.

5. NUMERICAL EXAMPLE OF THE JIANGYIN SUSPENSION BRIDGE

Thermal analysis of the Jiangyin suspension bridge was performed in ANSYS 14.5 to validate the proposed damage detection method. The FE model is shown in Fig. 3. The girder adopted the elastic shell element 63. The vertical bending moment of inertia and lateral bending moment of inertia are $1.844m^4$ and $93.318m^4$ respectively. The mass density is $16351.15\mathrm{kg}/m^4$ which include dead load and secondary dead load. The nonlinear element of link 10 is used in the main cable and hangers. The atmospheric temperature at any hour t of the day can be expressed by the function:

$$T(t)=0.5(T_{max}+T_{min})+0.5(T_{max}-T_{min})\times\sin[(t-9)\times\pi/12] \tag{8}$$

where, T_{max} and T_{min} are the highest and lowest temperatures in a day respectively. t is the time of day. The main girder was divided into 18 areas, which were given different temperature loadings. The orthotropic bridge deck consists of steel deck plates, asphalt concrete cover, and deck troughs. The element length of the main girder is 1 meter and 18 target elements were abstracted as shown in Fig. 3. The entity rectangle and hollow rectangular section represent the damage area and intact elements respectively. The FE model exported the temperature and strain for target elements.

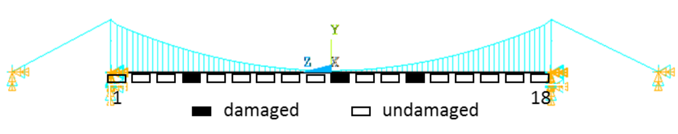
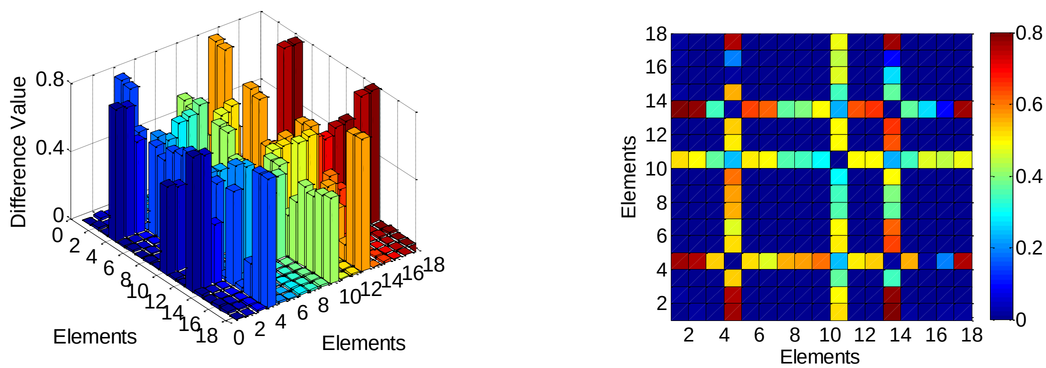


Fig. 3 Finite element model and case

Two damage cases were simulated in the FE analysis. The case was the multiple damage case in which the stiffness of the 4th, 10th, and 13th elements were reduced by 10%, as shown in Fig. 3. First, the temperature-induced strain and temperature gradient were extracted. Second, the temperature-induced strain data were normalized by using Eq. (3). Third, the Euclidean distance matrix was calculated and compared before and after the damage. When calculating the Euclidean distance matrices, 10% white noise was added into the simulated data as observed noise, in which 10% represents the standard deviation of the standardized bending strain. For the multiple damage case, the calculated damage index for the proposed method is plotted in Fig. 4. The damage locations can be clearly identified in both single and multiple damage cases.



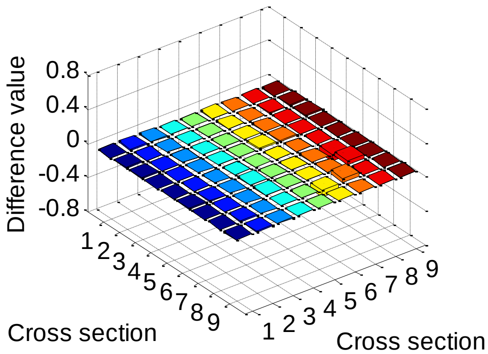
(a) difference histogram

(b) difference matrix figure

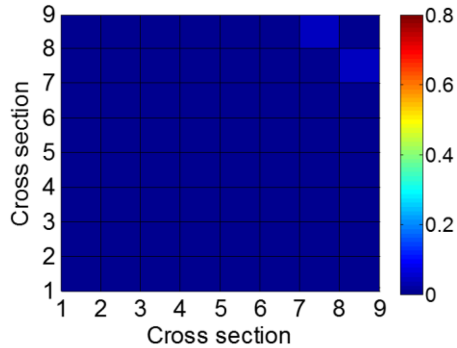
Fig. 4 Multiple damage identification results (10% stiffness loss and 10% noise)

6. VERIICATION USING MONITORING DATA OF THE JIANGYIN BRIDGE

On the night of June 2, 2005, a piling ship collided with the second cross-section of the girder of the Jiangyin bridge. The sensors including accelerometers and fiber optic strain sensors in the SHM system of the bridge monitored girder vibrations during the ship collision. The collision-induced vibration response lasted about 3 minutes. The strain amplitude was 53 $\mu\varepsilon$ at the second cross-section, and was within 30 $\mu\varepsilon$ at other cross-sections. The strain was very sensitive to the deformation of the bridge. Thus, the real-time strain can be used as an early warning indicator for an emergency event.



(a) index difference histogram



(b) index difference matrix

Fig. 5 Damage detection results before and after the ship collision

After the incident, engineering staff were most concerned with the severity of bridge damage and whether the bridge could continue to be used safely. The authors have identified the damage to the bridge by using the monitoring data from 6/1/2005 and 6/3/2005. If girder damage had occurred, then the Euclidean distance matrix would have changed as a result of the incident. First, the third and fifth sensor strain data were abstracted at each section by using the EEMD technology and then the bending strain was calculated. Second, the change of temperature gradient was calculated at each section and the bending strain was normalized by using Eq. (3). Third, the Euclidean distance matrices were calculated and compared. The damage identification results are shown in Fig. 5. Figure 5(a) shows that there was no sudden change of row or column, and no deep color changes within the histogram. The maximum Euclidean distance is 0.04 in Fig. 5(a). It is seen that there is no bright color in Fig. 5(b) which indicate there is no significant structural stiffness reduction on the girder due to the ship collision. Visual inspection of the bridge has also been performed, and there are no obvious damages found.

7. CONCLUSIONS

Structural health monitoring using temperature-induced responses has received increasing attention from researchers. In this article, a structural damage identification method was proposed by using measured temperature and temperature-induced strain data as input-output data, unlike traditional vibration based methods using output-only data. With the application of the proposed approach to the Jiangyin suspension bridge, the following conclusions and discussions have been made: The input-output relationship between temperature load and temperature induced response is derived, and the normalized bending strain defined as the bending strain divided by the input term ($\int_0^h \alpha T_y b(y) y dy$, *a function of measured temperature*) is derived as an indicator for structural damage detection. The novelty of the propose method is that it uses both the input (the measured temperature) and the output (temperature-induced strain) for structural damage assessment. Numerical studies of a long span suspension bridge successfully verified the effectiveness of the proposed to detect stiffness reduction in a single or multiple locations. The proposed method has been performed to evaluate structural safety conditions of the Jiangyin suspension bridge before and after a ship collision, which illustrates that no significant stiffness reduction induced by the ship collision. Long term monitoring data has also been studied to evaluate structural safety conditions under normal operation conditions.

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