Research Article

Bridge Assessment and Health Monitoring with Distributed Long-Gauge FBG Sensors

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Received 3 July 2013; Accepted 18 November 2013

Academic Editor: Gangbing Song

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Most sensors for structural testing and health monitoring are “point” sensors which strongly limit the ability to correctly detect damage and structural assessment. In this paper, long-gauge FBG sensor which can sense the whole area within the gauge length is introduced. Bridge assessment and health monitoring with the microstrain distribution acquired by the distributed long-gauge FBG sensor are also studied. Experiments were conducted and application to a real prestressed box bridge was also implemented. Static and dynamic testing results show that distributed long-gauge FBG sensing technique can obtain not only the global information such as bridge deflection and natural frequency, but also the local parameters such as strain and modal macrostrain to detect damage of the bridge. It shows that structural assessment and health monitoring based on the proposed technique have great potential in maintenance of civil engineering infrastructures.

1. Introduction

Bridges are the most important facilities for many cities and countries. These infrastructures provide the necessary communication and transportation conditions for the residence. However, progressive deterioration of the civil infrastructure begins once they are built and subjected to normal continuous and occasional excessive loading, or adverse environmental conditions. For the purpose of protecting and maintaining these infrastructures, prompt and intensive monitoring of structural system becomes extremely important. Nowadays, most Structural Health Monitoring (SHM) research has focused either on global damage assessment techniques using structural dynamic responses or on limited local independent damage detection mechanisms. Vibration-based global SHM using typical acceleration measurements still faces some challenges for the reason that structural modal parameters seem too “global” to detect the damage that is an intrinsically local phenomenon in structures. On the other hand, although relatively reliable, local inspections are cost, labor-intensive, and too “local” to obtain the integrated information for the overall structure.

Under this background, the concept of distributed long-gauge FBG sensing techniques, which is dedicated to catching and utilizing the strain distribution throughout the full or some partial areas of structures to detect damage, has been proposed to develop an integrated SHM strategy [1]. As a typical local measurement, strain has been verified to be very sensitive to damage. However, for the health monitoring of large-scale civil structures, strain measurement always serves as an auxiliary role partly due to the fact that it is so “local” that the influence of damage on strain measurement cannot be reflected effectively unless the area where strain sensor is installed happens to cover the damaged region. Therefore, to detect arbitrary and unforeseen damage in a complicated structure, strain sensors have to be installed in a distributed way, which is difficult and even infeasible for conventional foil strain gauges. For such “point” sensing system, how to optimize the limited number of sensors [2–4] to achieve the best performance still needs to be developed. For more comprehensive information, fully distributed sensing, such as Brillouin optical sensing [5–9], actually is desirable, yet its resolution is not enough for bridge assessment and dynamic
2. Long-Gauge FBG Sensing Techniques

2.1. Long-Gage FBG Sensors. The long-gauge FBG sensor is designed and fabricated as shown in Figure 1. The gauge length can be lengthened as desired with a special tube and basalt fibers. The special tube ensures an even strain distribution among the gauge length. The package with basalt fiber reinforced polymer (BFRP) can provide the long-gauge FBG sensor with an exterior protection against harsh environment and improve its durability. The essential processes for the fabrication of long-gauge FBG sensors are the placement of the special tube and treatment of the fixation segments to prevent the possible slippage of optic fibers, inside which bare optic with FBG is fixed at two ends after a certain pretension. When the sensor is installed on the structure, the average strain within the gauge length can be measured.

Experimental results of the sensing property of the sensors are demonstrated in Figure 2, whereinasensingstability among different long-gauge FBG sensors is shown. From this figure, it is revealed that the package with BFRP has no influence on the sensitivity of FBG sensors.

2.2. Deflection Distribution from Distributed Macrostrain. In structural health monitoring, a useful physical quantity is the strain of the structure. Strain can directly indicate the stress and potential cracks of the structure in situ. In dynamic analysis, strain mode analysis was proved to be a very effective method for extracting structural dynamic characteristics and even for structural damage identification. As aforementioned, the macrostrain, that is, the average strain within the gage length can be obtained with the long-gauge FBG sensor. With the sensors being deployed distributedly, the strain distribution of the structure can be obtained, which can provide accurate and all-around strain status for the whole structure for the structural health evaluation.

In most cases, the deformation data are indices for damage accumulation and resistance reduction of engineering structures, such as bridges, tunnels, and pipeline systems until their final failure. The traditional methods for obtaining the structural deformation, such as Geodetic survey, Global Position System (GPS) survey, and direct survey using dial indicators, are characterized as "point" sensing. The main
disadvantage of the traditional methods lies in the incomplete deformation data collection, which may result in ignorance of some unforeseen damages. On the contrary, distributed sensing will be very helpful for acquiring continuous structural deformation for damage identification and structural control as well. Shen et al. proposed the conjugated beam method to obtain the deformation distribution from strain distribution [10]. Figure 3 shows the conjugated beam of a joint supported beam. With the averaged strain in a distance \( l_i \) regarded as the equivalent load distribution \( q_i \), and the moment distribution along the whole beam length \( L \) of the conjugated beam actually is equal to the displacement distribution, as the solid curve line shows.

In case the gauge length designed to be the same for all long-gauge FBG sensors, with the conjugated beam method, displacement at the boundary point between the \( p \)th element and the \( (p + 1) \)th element \( v_{p} \) and that at the middle point of the \( (p + 1) \)th element \( v_{(p+1)/2} \) can be expressed by (1) and (2) respectively [10]:

\[
v_p = -\frac{L^2}{n^2} \left( \sum_{i=1}^{n} \bar{\varepsilon}_i (n - i + \frac{1}{2}) - \sum_{i=1}^{n} \bar{\varepsilon}_i (p - i + \frac{1}{2}) \right),
\]

(1)

\[
v_{(p+1)/2} = -\frac{L^2}{n^2} \left( \sum_{i=1}^{n} \bar{\varepsilon}_i (n - i + \frac{1}{2}) - \sum_{i=1}^{n} \bar{\varepsilon}_i (p - i + 1) \right),
\]

(2)

where \( \bar{\varepsilon}_i \) is the averaged strain captured by the \( i \)th long-gauge FBG sensor, \( y_i \) is the distance from the sensor location to the inertial axis where the \( i \)th sensor deployed, \( n \) is the total number of sensors, and \( L \) is the length of the beam.

2.3. Damage Identification. Macrostrain is the average strain within the gauge length of the long-gauge FBG sensor and therefore is also a local quantity. However, with many sensors deployed throughout the structure as a sensor array, all-around examination of the structure can be fulfilled. Distributed long-gage FBG sensing techniques were developed by Li and Wu [11] and its effectiveness in structural health monitoring was also proved. In this paper, Modal Macrostrain-Vector (MMSV), a feature vector proposed by Wu and Li [12], will be briefly introduced.

For a beam structure with two local DOFs (one for vertical translation and another for rotation) at each node as Figure 4 shows, on a reasonable assumption that the distance from beam’s neutral axis to sensor of each element (denoted as \( h_m \)) is same, Macrostrain \( \varepsilon_m \) within gauge length \( L_m \) in frequency domain can be obtained as

\[
\varepsilon_m (\omega) = \frac{h_m}{L_m} \left[ v_i (\omega) - v_j (\omega) \right],
\]

(3)

where \( v_i \) and \( v_j \) are the rotation degree at the \( i \)th and \( j \)th node.
Therefore, the Macrostrain frequency response function between the measurement from the $m$th sensor and the excitation at the $p$th DOF can be achieved by

$$H_{mp}^{r}(\omega) = \frac{\varepsilon_{m}(\omega)}{f_{p}(\omega)}.$$  \hspace{1cm} (4)

The value at each peak for the $r$th mode can be written as

$$\left|H_{mp}^{r}(\omega = \omega_{r})\right| = \frac{\phi_{pr}}{2M_{r}\xi_{r}\omega_{r}^{2}} \cdot \delta_{mr},$$  \hspace{1cm} (5)

where $\delta_{mr} = (h_{mr}/L_{m})(\phi_{mr} - \phi_{pr})$.

For a given mode, $\phi_{pr}/2M_{r}\xi_{r}\omega_{r}^{2}$ is a constant. Ignoring the amplitude and only emphasizing the relative ratio of all components, the combination of Macrostrain magnitude FRFs from all FBG sensors can construct a vector, that is, MMSV, as

$$\{\delta_{1r}, \delta_{2r}, \ldots, \delta_{mr}, \ldots\}^T.$$  \hspace{1cm} (6)

The detailed theoretical modal analysis based on Macrostrain measurement can be referred to the study of Li and Wu [13].

For convenience, the MMSV can be further normalized by the MMS of a reference sensor as

$$\{\delta_{1r}, \delta_{2r}, \ldots, \delta_{(m-1)r}, \delta_{mr}\}$$

$$= \left\{\frac{\delta_{1r}}{\delta_{ref}}, \frac{\delta_{2r}}{\delta_{ref}}, \ldots, \frac{\delta_{(m-1)r}}{\delta_{ref}}, \frac{\delta_{mr}}{\delta_{ref}}\right\}.$$  \hspace{1cm} (7)

It should be noted that normalized MMS vectors are nondimensional quantities and reflect the structural status. If the structure status at the reference place remains unchanged, then the change of the MMSVs often indicates that damage happened in the structure. Of course, one measurement is not reliable due to noise; however, with multiple measurements, statistics can help provide a sound result.
3. Experiment Verification

In order to verify the structural health monitoring approach using the distributed long-gauge FBG sensors, related experiments were conducted. A steel cantilever beam is used as a simple structure. Five long-gauge sensors were deployed on the central line of the upper surface as a sensor array as shown in Figure 5.

The damage of the cantilevered beam was introduced by cutting a part of the beam to reduce the flexural rigidity of the beam, as shown in Figure 6. In this figure, (a) shows a single damage case with a damage located in element 1 and was covered within the gauge length of FBG sensor F1, while (b) shows a multidamage case with two damages which occur in elements 1 and 3 and were covered within the sensors F1 and F3.

An impulsive hammer was used to make an impulsive force to the beam before and after the beam was damaged. FBG interrogator SM-130 was used to collect the optical signal, change to the electrical signal, and save the data. Figure 7 shows the experiment and the strain history in a certain period at the FBG sensor F3 at the moment when the beam was subjected to an impulsive force. It shows...
that the beam vibrated suddenly just after the impulsive force at the beginning and then attenuated gradually. For simplicity, signals after the selected period were omitted and not appeared in the figure.

Also the modal Macrostrain vectors can be obtained, which can be used for damage detection. By deriving the MMSV from time to time, damage can be determined on the judgment whether the fitting curve has remarkable change.

Figure 8 shows some statistics of the MMS of each sensor with respect to that of a reference sensor. Reference sensor is usually selected by choosing the one which is deployed at the place where damage probably will not happen. In this experiment, sensor F5 was selected as the reference sensor. In the experiments, we made 4 tests with different damage scenarios which correspond to different damage extent, with no damage case S1 and increasing damage cases for S2, S3, and...
S4. From Figure 8, it can be found that the fitting line of the MMS of sensor F1 to MMS of sensor F5 shifted significantly, while the other fitting lines of MMS of other sensors to that of the reference sensor nearly have no change. This indicates that damage happens at element 1, while there is no damage at elements 2 to 4.

Figure 9 shows the MMS of the long-gauge sensors with respect to that of a reference sensor for multidamage case. It can be found that the fitting lines of the MMS of sensor F1 and F3 to MMS of sensor F5 shifted significantly, while the fitting lines of MMS of sensors F2 and F4 to MMS of reference sensor nearly have no change. This means that damage happens at elements 1 and 3, while no damage happens at elements 2 and 4. It shows that with this approach, damages can be accurately detected also for the multidamage case. At the same time, the damage location can also be determined.

4. Real Bridge Application

In this paper, real bridge assessment and health monitoring were also conducted at the Hongxing Bridge which is a three-span continuous prestressed beam bridge located at Wuxi city of China. The main span of the bridge is 110 m and its side span is 65 m as shown in Figure 10. It is a non-uniform prestressed concrete and consecutive box beam bridge. Before the operation of the bridge but after finishing its construction, load testing was firstly conducted on the bridge.

4.1. Sensors Deployment and Structural Testing Case. Before loading and testing, twenty long-gauge FBG sensors, with a gauge length of 1.0 m, were deployed on the bottom of the bridge as shown in Figure 11. Figure 11(b) shows the detail of the sensor positions. It can be found that sensors were deployed densely around the midspan where damages are easy to happen. While Figure 11(c) shows the sensors were deployed right on the center of the bottom of the box girder. A bridge inspection vehicle was used to carry people to the bottom of the bridge girder and make the sensor deployment just as shown in Figure 11(d). Among the deployed sensors one was kept in slack state and was used for temperature compensation. Other FBG sensors are numbered and labeled as 1 to 19 from the left to the right. Three accelerometers A1, A2 and A3 were installed in the midspan and quarter-span of the bridge as well.

Structural testing includes the static testing and dynamic testing. During the static testing, three load cases were applied. The bridge was loaded with ten 30-ton trucks at the middle of the main-span (load case 1), the quarter-span of the main-span (load case 2), and the middle of the side span (load case 3). Figure 12 shows the on-board load testing scene. Also, vehicle braking testing on the bridge was also conducted in order to study the impact resistance and dynamic coefficient. Dynamic testing was also implemented to study dynamic behavior and damage condition of the structure.

4.2. Static Testing. For load case 1, trucks were stopped at the middle of the main span of the bridge as shown in Figure 13. The corresponding measured strain distribution of the whole bridge (the one third part on the right was estimated via curve fitting) is shown in Figure 14. Maximum strain of the bridge is about 78 με, which is also at the middle of the main span.
A downward peak happens near the midspan which shows the abnormal result. It is probably due to the bad installation of the corresponding sensor, which makes the bad contact interface between the sensor and the structure. If the bad measurement is neglected, then the smoothed Macrostrain distribution can be shown by the dash red line.

Based on the strain distribution and (1) and (2), the deformation distribution can be calculated as shown in Figure 15. It shows that the maximum deflection happens also at the middle of the main span and is approximately 28 mm. However, it should be noted that if the deflection is calculated directly using the measured strain without ruling out bad measurement value, then the maximum deflection value will be about 1.5 mm smaller than that calculated by the smoothed strain distribution.

For load case 2, trucks were stopped at the quarter-span of the main span as shown in Figure 16. Figure 17 shows the corresponding strain distribution and Figure 18 shows the deformation distribution calculated based on strain distribution. The maximum strain is 38 με near the midspan and the maximum deflection is about 17 mm (downward) at the midspan. Also it can be found that sensor which is at the place about distance 47 m functions bad. This corresponds to what happens in Figure 14. Red dash line is the smoothed Macrostrain. The maximum deflection calculated by the smoothed Macrostrain distribution is about 0.85 mm larger than that obtained by the direct measured strain.

For load case 3, while Figures 20 and 21 demonstrate the corresponding strain distribution and deformation distribution, respectively. The minimum strain is about −18 με at the quarter-span with the maximum deformation of 6 mm (upward). It is noted that even some peaks for strain distribution happened due to the malfunction of the sensors, and their deflection curves still remain smooth as shown in Figures 15, 18, and 21. This also shows that deflection (displacement) is a global quantity and is not sensitive to the local change of the structure.

4.3. Braking Testing. In order to study the impact resistance and dynamic characteristics of the bridge, vehicle brake testing was conducted. A 30-ton truck with the speed of 20 km/h suddenly braked at the midspan, and the response of the sensor which was at the midspan shows that the maximum strain is 7.7 με during the whole process. The strain-time curve during the braking testing is shown in Figure 22, while the static strain after the truck completely stopped is 5.9 με. The dynamic coefficient can be calculated being about 1.30 due to the impact effect.

4.4. Health Monitoring Using Dynamic Testing. Structural health monitoring of the Hongxing Bridge using distributed long-gage FBG sensor has also been performed via the dynamic testing. Dozens of macrostrain time serial samples with each lasting for about several minutes were collected under ambient vibration. The sampling frequency was adopted to be 500 Hz. The signals were analyzed in frequency domain and their power spectral densities (PSDs) extracted from 3 randomly selected macrostrain signals and 3 acceleration signals from accelerometers are shown in Figures 23(a) and 23(b), respectively. It is evident that the first order natural frequency from FBG strain response is in accordance with the one from the accelerations, that is, about 2.37 Hz for all cases.

Figure 24 shows the statistical features of the MMS of the target sensor with respect to the reference sensors. Several tests were conducted within the period from June, 2010, to
November, 2012. The MMS of other FBG strain response have the analogous results. After testing several times, the ratios of MMS at the target sensor to that of the reference sensor should be stable around at a constant value if no damage occurs within gauge length of the target sensor. In this case, the slope of fitting line from a group of data should keep constant, even though the ratio for every single sample may differ slightly from each other due to noise pollution. However, when damage occurs within the gauge length of the target sensor, the MMS of the structure will change and hence the ratio to the reference MMS will also change. Thus the fitting line will deviate from the one in undamaged case. Figure 24 shows two randomly selected samples of the testing. Results show that fitting line does not have much deviation and therefore indicates the healthy status of the corresponding part of the structure.

5. Conclusions

In this paper, bridge assessment and structural health monitoring with distributed long-gage FBG sensors are introduced. Its application to the laboratory experiments and real bridge is also addressed. It shows the developed long-gage FBG sensors can provide a satisfactory measurement and monitoring for actual large-scale infrastructures. With distributed long-gage FBG sensing technique, the global information of the bridge such as deflection and natural frequency can be obtained effectively. At the same time, the local information, strain distribution, can be also acquired.
Using the normalized MMS together with the statistics analysis, structural damage identification can be realized, which may be a very useful method for civil engineering structures.

Acknowledgments

This work is supported by the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (Grant no. 2011BAK02B03), the Jiangsu NSF (no. BK2010015), the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), major project of Department of Communications of Jiangsu Province (2011Y03), and Graduate Research and Innovation Plan Project for the Regular Institution of Higher Learning in Jiangsu Province & Fundamental Research Funds for the Central Universities (no. CXZZ12_1208).

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