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A curvature based approach in dynamic monitoring using long-gage fiber optic sensors

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ABSTRACT

Fiber Bragg grating (FBG) sensors offer a significant advantage for structural health monitoring due to their ability to simultaneously monitor both static and dynamic strain while being durable, lightweight, capable of multiplexing, and immune to electro-magnetic interference. Drawing upon the benefits of FBG sensors, this research explores the use of a series of long-gage fiber optic sensors for damage detection of a structure through dynamic strain measurements and curvature analysis. Curvature and strain based analysis may be a more reliable means for structural monitoring as they show more sensitivity to damage compared to modal parameters such as displacement mode shapes and natural frequency. Small scale experimental testing was performed using an aluminum beam instrumented with a series of FBG optical fiber sensors. Dynamic strain measurements were obtained as the beam was subjected to various support and loading conditions and damage was simulated by creating imperfect support constraints. From this, a normalized parameter based on the strain and curvature from the dynamic strain measurements has been developed as a potential means of damage detection. The results demonstrated the potential of FBG long-gage sensors to facilitate dynamic monitoring at both the local and global scale, thus allowing assessment of the structures health.

KEYWORDS: *Structural health monitoring, long-gage fiber optic sensors, dynamic strain measurements, FBG sensors*

1. INTRODUCTION

American infrastructure is currently rated as a D+ by the American Society of Civil Engineers [1]. According to the US federal highway administration, there are over 600,000 bridges in the United States and over 25% of those bridges are structurally deficient or functionally obsolete [2]. In an effort to monitor the state of bridges, the federal highway administration currently mandates periodic inspection of all bridges every two years which typically done through visual inspection [3,4]. However, this is both inefficient and unreliable and can lead to costly mistakes due to human errors [5]. Civil infrastructural systems such as bridges, roads, dams and buildings play a crucial role in the socio-economic life and development of a country. Structural health monitoring provides an approach for addressing this growing problem of aging infrastructure and the increasing cost of replacement.

This research explores dynamic structural monitoring through the use of long-gage fiber Bragg grating (FBG) strain sensors by developing a curvature based damage detection parameter. Dynamic structural monitoring is central to this research because any changes or damage to the physical property of a structure will result in a change of the dynamic response of the structure [6]. A common approach for dynamic monitoring methods is to rely upon detecting structural changes through frequency and acceleration based analysis. However, it has been found in the literature that curvature and strain based analysis may be a more reliable means for structural monitoring as they show more sensitivity to damage [3,4]. Due to the associated benefits, this research utilizes long-gage fiber optic sensors. Long gage FBG strain sensors offer a promising alternative to traditional dynamic measurement methods as the curvature can be computed directly from the FBG strain measurements without the need for numerical differentiation. Additionally, they offer static and dynamic monitoring capabilities, they are durable and lightweight, immune to electro-magnetic interference and offer multiplexing capabilities [7,8]. They provide a more relevant response parameter, strain, allow simultaneous measurement of static and dynamic parameters and they allow for both local and global analysis of the structure. Additionally this research will focus on the use of long-gage sensors as opposed to point sensors as they are not influenced by local inhomogeneity of monitored material and increase the chance of detecting the damage by their larger spatial coverage [9].

2. EXPERIMENTAL SETUP

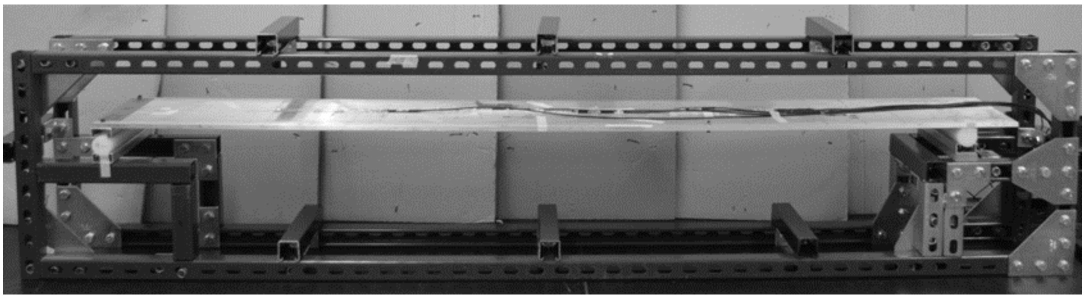

Figure 2.1 Simply supported aluminum beam used in experimental testing

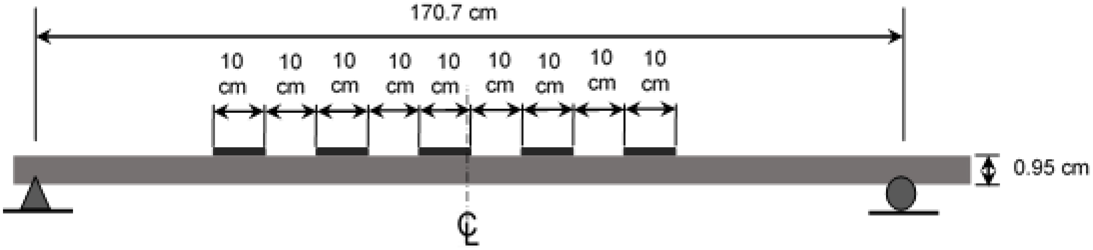

Figure 2.2 Simply supported aluminum beam dimensioning and FBG sensor positions

Preliminary experimental tests were performed using a simply supported aluminum beam installed with 5 FBG strain sensors as shown in Figure 2.1. The FBG sensors are 10 cm long in order to simulate long-gage optical fiber sensors on a full scale structure. Additionally, the sensors are spaced 10 cm apart for ease of analysis. The beam has a clear span of 170.7 cm and the position of the FBG strain sensors are shifted from the center line as seen in Figure 2.2. A series of tests were performed by intentionally displacing the beam at three different locations, the mid-span and the quarter-spans, and released to induce free vibrations. Additionally, a change in the boundary conditions was simulated at the roller support. This was done by placing a clamp on the beam at three different locations: on the roller, to the right of the roller, and to the left of the roller. In real life, this would be similar to an improperly functioning roller such as one that has corroded or in some other way is no longer functioning at its designed capacity. Figure 2.3 shows a typical strain response for a mid-span displacement with no changes to the roller support, where the loading period occurs when the beam is displaced and held until the strain response stabilizes. The displacement is then released and the period of free vibration starts.

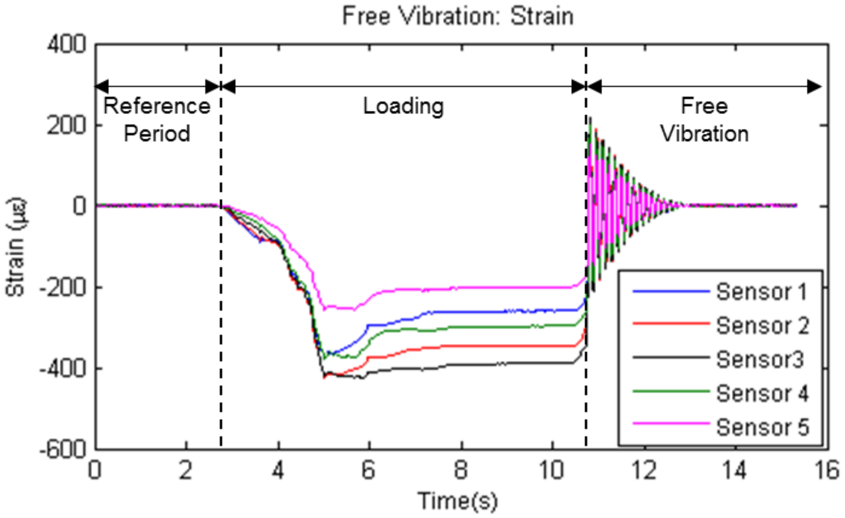

Figure 2.3 Simply supported aluminum beam free vibration strain response

3. RESULTS

The curvature values were determined from the strain measurements at each sensor location during the period of free vibration. It is assumed that the strain along the top surface of the beam is equivalent to the strain observed on the bottom surface of the beam. The FBG sensors are installed along the top surface of the aluminum beam, so the strain at the top surface of the beam is known and thus the calculation of the curvature of the beam at the location of each sensor is found with the following equation, where κ, r, ε_t and ε_b are the curvature, radius of curvature, strain at the top of beam and the strain at the bottom of the beam.

$$\kappa = \frac{1}{r} = \frac{\varepsilon_t - \varepsilon_b}{h} = \frac{2\varepsilon_{top}}{h} \tag{3.1}$$

Once the curvature values have been determined, the peak curvature values are found. A curve is then fit to these peak curvature values at each sensor location. Because the beam deflection is equal to the double integral of the curvature, the curve fit to these points, $\kappa(x)$, is based on the theoretical general modal shape for a beam, $\phi(x)$. If the boundary conditions are assumed to be that of a simply supported beam, a more precise theoretical equation can be determined for a simply supported beam. However, because the true behavior of our roller is known, the equation is kept more general. The equation for the displacement mode shape, $\phi(x)$, and the derived general equation for curvature, $\kappa(x)$, are shown below where the *b* values are coefficients determined thorough boundary conditions or curve fitting and k_n is the eigenvalue parameter for the associated mode.

$$\phi(x) = b_1 \sin k_n x + b_2 \cos k_n x + b_3 \sinh k_n x + b_4 \cosh k_n x \tag{3.2}$$

$$\kappa(x) = -b_1 k_n^2 \sin k_n x - b_2\, k_n^2 \cos k_n x + b_3 k_n^2 \sinh k_n x + b_4 k_n^2 \cosh k_n x \tag{3.3}$$

As seen in Figure 3.2, in the case where the right support is behaving as a typical roller, we see the curvature values at the right support are very close to the theoretical value as the point of inflection is at approximately the same location as the support. However, this procedure is repeated for a case where the condition of the roller is altered in order to simulate damage at the roller, there is a non-zero curvature values at the location of the roller and we see the inflection point has shifted to the left of the roller. As a means to compare the different states of the support, a ratio of the curvature values at different sensor locations will be utilized. This will allow a method to compare the state of a structure without requiring a known model of the structure. Curvature ratio for a set loading condition will be constant, if there is a change in the structure it will be reflected in the curvature response and the ratio will change for the same loading condition.

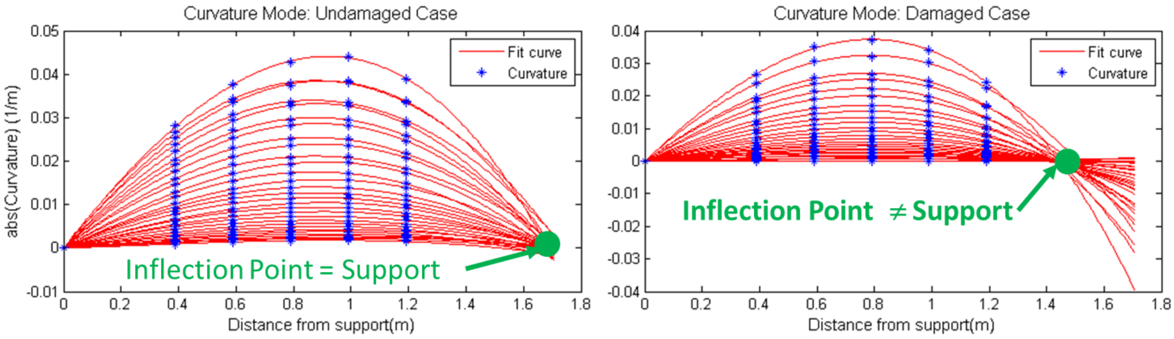

Figure 3.2 Curvature mode fitting for undamaged and simulated damage cases

Histograms were created for each of the curvature ratios and roller states and it was found that a normal distribution can be fit to the curvature ratio values. Figure 3.3 shows the probability density functions for each of the normal distributions fit to the data when the beam is displaced in the center. The sensors are numbered sequentially from left to right. A shift in the mean values and a change in the standard deviation of the curvature ratios is apparent when the different roller states are compared to the normal roller state. Additionally, the p-values using Welch's t-test were found for the altered roller states compared to the normal roller state, and values significantly lower than 0.001 were found for all of the distributions aside from the Sensor3/Sensor4 curvature ratio for the 1st damaged case, where the p value is 0.0054. This indicates that for all damaged states and curvature ratio combinations, the two distributions are statistically different from one another. This process was repeated for the both quarter span displacement tests, and similar results were observed with a distinct shift in the mean and standard distributions of the damaged cases compared to the undamaged case. Additionally, the p-values for all of the damaged cases compared with the undamaged case are less than 0.001, indicating that the damaged distributions are statistically different than that of the normal case.

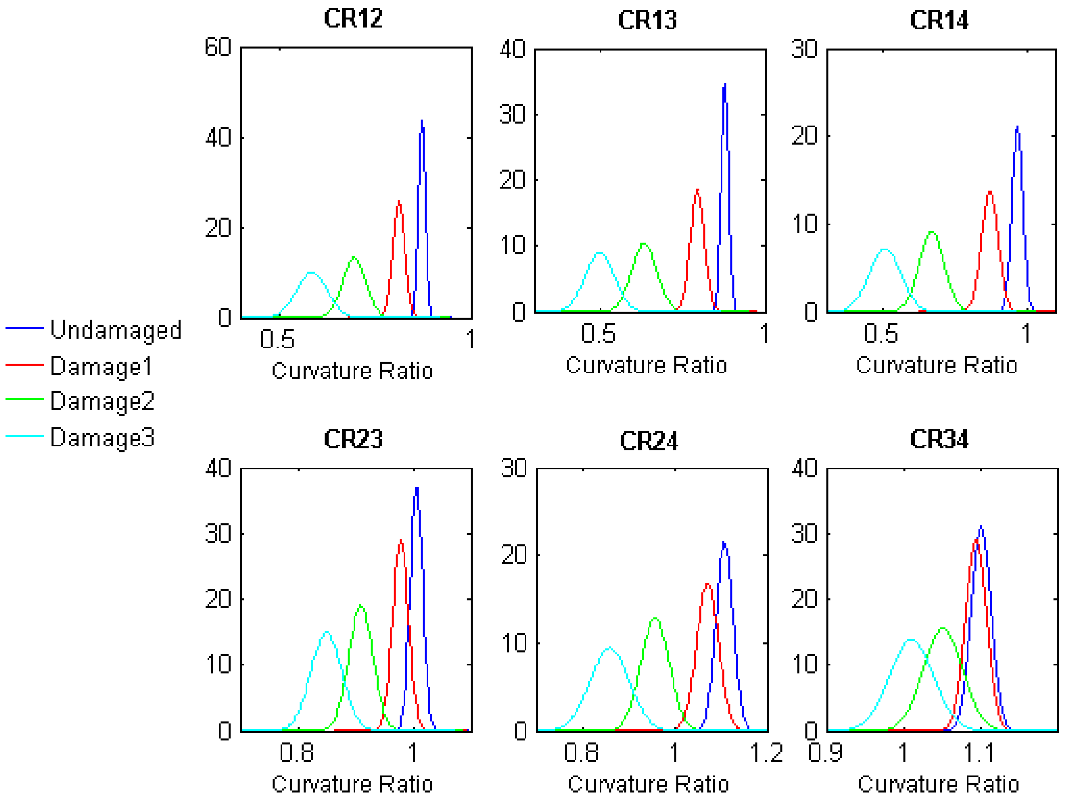

Figure 3.3 Probability density function plots for curvature ratios for beam with center displacement.

As an additional means of comparison, the receiver operating characteristic (ROC) curves were generated for each of the three damage cases for the center displacement condition. These curves are shown in figure 3.4 and plot the rates of true positives against the false positive rates at different possible points for a diagnostic test to distinguishing between the damaged and undamaged case. The closer these curves follow the left border, the more accurate the parameter is and the closer the curve comes to a 45 degree diagonal, the less accurate the parameter is. The results shown in the ROC curves agree with what was observed in the probability density function plots for the curvature ratios. For damage cases 2 and 3, all ROC curves fall very close to the left border so the curvature ratio parameters perform well in distinguishing between the damaged and undamaged cases. For damage case 1, all curvature ratios perform well except the curvature ratio between sensors 3 and 4 which was also observed in the probability density functions.

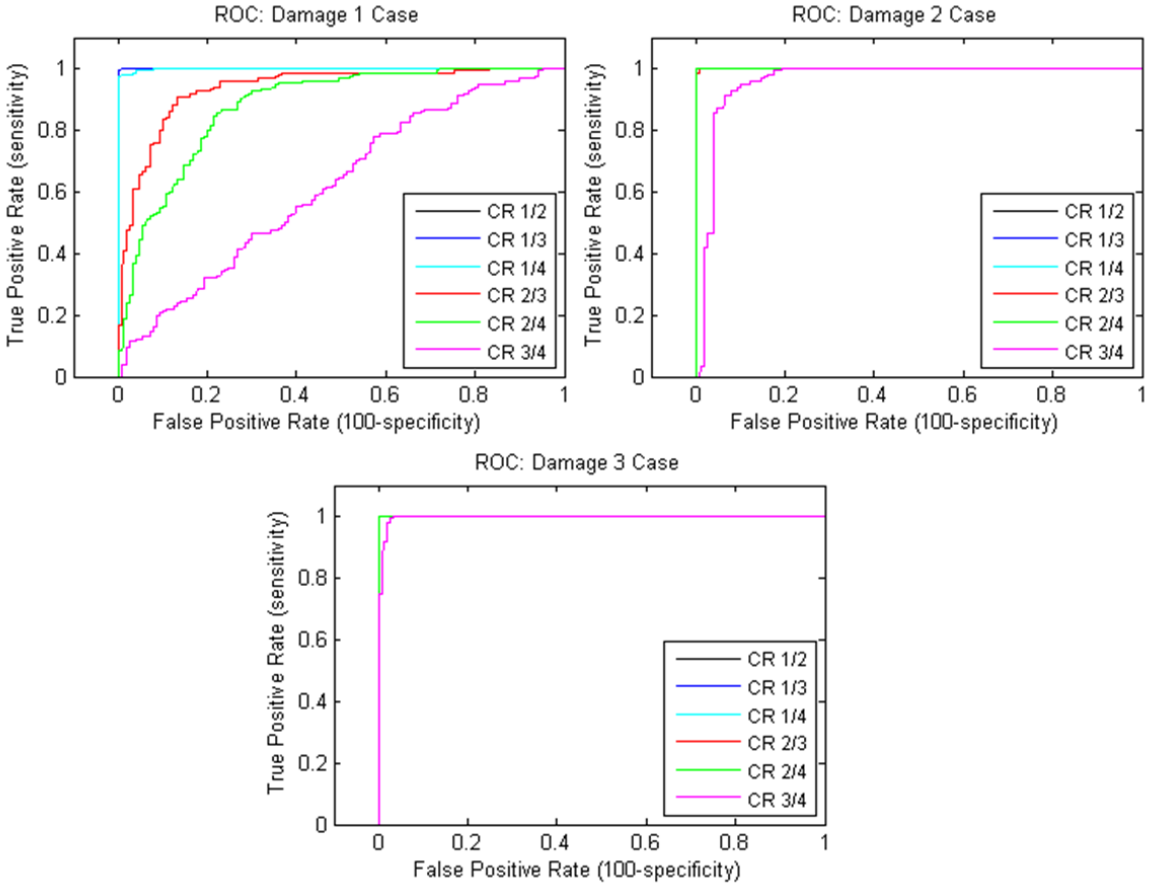

Figure 3.4 ROC curves for the three damaged cases compared to the no damage case

4. CONCLUSIONS

This preliminary research has shown encouraging results indicating the potential for curvature to be used as a simplistic metric for damage detection using FBG strain sensors. Additionally, this method is independent of the load applied as it is based on free vibration and thus allows for real bridge applications as the bridge may remain in service during the testing. A promising alternative for dynamic structural health monitoring has been presented that provided detection and a qualitative indication of damage intensity. However, additional testing and research is needed for the curvature ratio, including numerical analysis and laboratory tests. These will help to provide a physical interpretation of the meaning of the dispersion spread and the mean shifts of curvature distributions. Lastly, determination of the uncertainties and quantification of the damage is needed, and will be a topic of the future work.

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