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A CURVATURE BASED APPROACH IN DYNAMIC MONITORING USING LONG-GAGE FIBER OPTIC SENSORS

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Abstract

Drawing upon the numerous advantages of fiber Bragg grating (FBG) strain sensors, this research explores the ways to use a series of long-gage fiber optic sensors for structural analysis and damage detection through dynamic strain measurements and curvature analysis. Dynamic structural monitoring provides useful insight into the state of a structure because any changes or damage to the physical property of a structure will result in a change of the dynamic response of the structure. Typically dynamic structural monitoring relies upon detecting structural anomalies through frequency and acceleration based analysis. However, 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. Additionally, 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. 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 as well as subjecting the beam to several simulated damage conditions. From the dynamic strain measurements, the curvature of the aluminum beam can be determined. From these, a normalized parameter based on the strain and curvature from the dynamic strain measurements has been developed as potential means of damage detection. Both a theoretical analysis and experimental data were compared and carried out. The method provided both detection of damage and an indication of damage intensity. 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.

1 INTRODUCTION

There is a growing problem with aging infrastructure within the United States. Of the over 600,000 bridges in the US, the federal highway administration has deemed more than 25% of the bridges as structurally deficient or functionally obsolete [1]. Civil infrastructure is crucial to the economic well-being of a country and infrastructure failures lead to devastating social and financial impacts on the surrounding areas. With budget cuts in infrastructure expenditure, the need to extend the service life of bridges and minimize unnecessary maintenance has increased. In an effort to monitor the condition of bridges, the federal highway administration currently mandates that bridges are evaluated through visual inspection only every two years [2]. This process is both inefficient and prone to costly mistakes due to human errors. Structural health monitoring (SHM) provides a potential solution for addressing these issues in civil infrastructure. However, bridge engineers and owners are reluctant to use many of the currently available methods due to their limitations.

The aim of this research is to explore dynamic structural monitoring methods through the use of long-gage fiber Bragg grating (FBG) strain sensors by developing curvature based damage detection methods. The goal of this work to develop a simplistic and easily implemented SHM method for bridge monitoring that overcomes many of the limitations of currently available SHM methods. This research will focus on dynamic monitoring as any changes or damage to the physical properties of a structure will result in a change of the dynamic response of the structure. Typically, dynamic SHM methods rely upon frequency and acceleration based analysis to detect structural anomalies. 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]. Two different approaches for curvature based damage detection in beams have been explored. The initial method presented shows an approach for detecting changes in the behavior of the support conditions of a beam. Small scale experimental tests were performed and compared with an analytical model for the curvature of the beam. A quantitative analysis of the change in stiffness of the beam support is demonstrated. An additional method for curvature based damage detection was explored for detecting structural anomalies located anywhere along the span of the beam. This method is the normalized curvature ratio (NCR), a parameter that was developed as simplistic method that uses the curvature values at discrete locations from the FBG sensors and provides an indication of structural changes [5].

Due to their associated benefits, this research uses long-gage fiber Bragg grating strain sensors rather than other existing sensors available for structural monitoring. While accelerometers are among the most popular sensors for dynamic structural monitoring methods, due to their ease of instrumentation and their low cost, there are many limitations associated with accelerometers that may not make them the most optimal some monitoring methods. Some of these challenges include difficulty to multiplex the bulky sensors, they are limited to point sensors, the sensitivity to electromagnetic interference and their limited application in hostile environments [6]. FBG strain sensors overcome many of these limitations due to their numerous benefits such as they offer long gage sensor possibilities as well as static and dynamic monitoring abilities, they are durable and lightweight, immune to electro-magnetic interference and offer multiplexing capabilities [7]. The use of strain sensors allow the curvature of the structure to be directly computed from the response measurements, rather than requiring numerical differentiation which will increase the uncertainty in the results. 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 damage due to the larger coverage.

2 THEORETICAL BACKGROUND

An analytical model for the curvature of a beam was developed where the boundary condition of one beam support was varied by altering the stiffness of this support. The analytical model will be utilized to aid in the analysis and interpretation of the experimental test results. The beam utilized in the analytical model has the same physical properties as the beam used in the experimental testing performed. The beam is simply supported and the right support was changed with the rotational stiffness ranging from zero so it is behaving as a pin support to approaching the stiffness of a fixed support.

The deflection of a beam is equivalent to the double integral of the curvature of the beam. This research will focus on the dynamic beam and the deflection of a dynamically excited beam is related to the theoretical modal shape of a beam. The theoretical modal shape of a beam is shown in equation 1, where k_n is the eigenvalue parameter and is based on the natural frequency and material properties of the beam and $b_1, b_2, b_3, and\ b_4$ are coefficients that are determined based on either the boundary conditions of the structure or through a curve fitting procedure if curvature values at discrete locations in the beam are known. Utilizing the theoretical modal shape of a beam, the theoretical curvature shape of the beam can be determined, as shown in equation 2.

$$\phi(x) = b_1 \sin(k_n x) + b_2 \cos(k_n x) + b_3 \sinh(k_n x) + b_4 \cosh(k_n x) \tag{1}$$

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

Because the experimental tests will focus on the free vibration, only the first mode of vibration will be utilized in the development of the analytical model and no external loads are applied to the beam, it is only influenced by its self-weight. For the analytical model, the boundary conditions for the left support were kept constant with the support modeled as a pin support. For the right support, a rotational spring was placed at the location of the right support with a varying stiffness. The stiffness of this rotational stiffness was varied from 0 to approaching infinity. For each rotational stiffness value the curvature equation of the beam was determined. The results of the analytical model are shown in figure 1.

This analytical model shows that the curvature at the right support equal to zero when the rotational stiffness of the varying support is equal to zero. The curvature at the end of the beam increases as the rotational stiffness of the support increases and has some moment carrying capacity, approaching a fixed support. This figure also illustrates, as expected, that the inflection point shifts away from the right support, towards the left of the beam as the rotational stiffness of the support increases. By utilizing this behavior of the beam, an evaluation of the experimental testing results will be carried out.

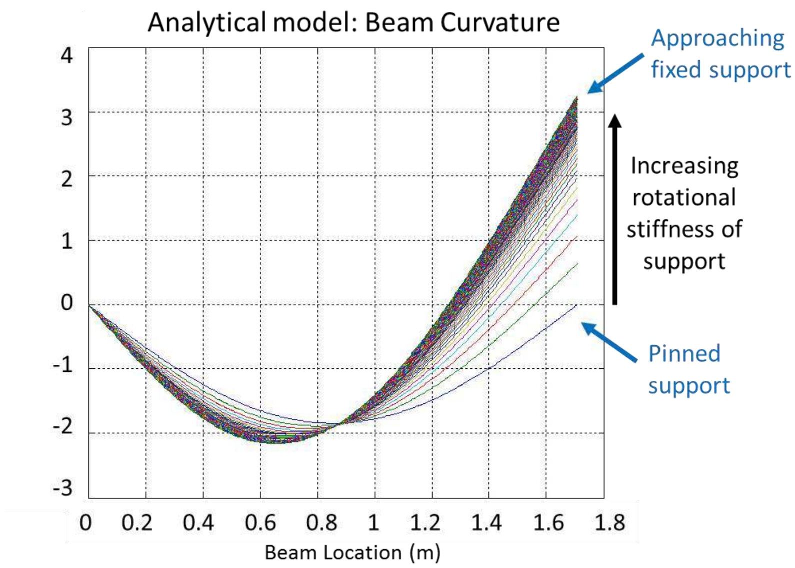

Figure 1: Analytical model for simply supported beam with increasing rotational stiffness of right beam support.

3 EXPERIMENTAL SETUP

Experimental tests were performed in the laboratory using an aluminum beam supported within a frame, as shown in figure 2. The beam is instrumented with a series of 5 FBG strain sensors with a gage length of 10 cm. The sensors are installed along the top surface of the beam. The sensors are placed 10 cm apart and are offset from the center line of the aluminum beam, as shown in figure 3. This gage length was selected to represent long gage FBG strain sensors on a full scale structure. Because the testing is performed within a controlled laboratory setting, temperature compensation is unnecessary and thus temperature sensors were not used. The aluminum beam has a clear span of approximately 1.7 m, a width of 25 cm and a height of 0.95 cm. The experimental setup with the supporting frame allows the beam to be tested under a variety of support conditions.

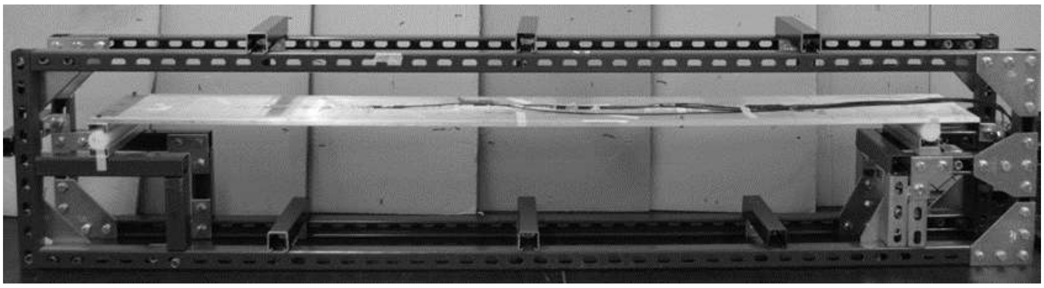

Figure 2. Simply supported aluminum beam used in experimental testing [8].

For the experimental tests performed, the aluminum beam was displaced at the mid-span location. Once the strain response stabilized, the displacement was released in order to induce a free vibration response in the beam. The beam was displaced distances between 0.5 cm and 1.5 cm. Experimental tests were also performed by simulating changes in the support conditions of the structure. This was done by altering the right support of the aluminum beam. The beam was first tested as a typical simply supported beam with normally functioning supports, no changes were made to the right support of the beam. The strain response of the beam was recorded for 10 free vibration tests with the unaltered support conditions. Next, the support conditions of the right support were altered to gradually increase the stiffness of the right beam support. The support of the beam was stiffened until it approached a fixed support. For each change in the roller support, 10 free vibration tests were performed on the aluminum beam. This change of the support 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.

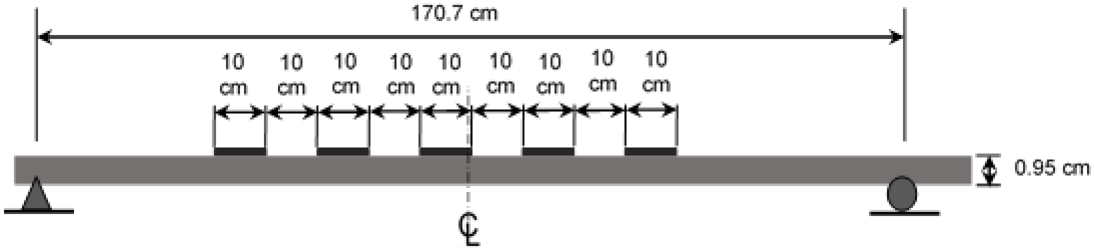

Figure 3. Simply supported aluminum beam dimensioning and FBG sensor positions [8].

4 RESULTS

Using the strain response for the period of free vibration for each of the experimental tests, the curvature of the beam can be determined. This can be done for each of the 5 sensor locations and for each time step. The FBG sensors are installed only along the top surface of the beam, it can be assumed that the strain along the bottom surface of the beam is equivalent to the strain measured by the sensors along the top surface of the beam. The curvature of the beam is directly proportional to the strain in the beam and can be calculated with the following equation where, where h, κ, r, ε_t and ε_b are the height of the aluminum beam, the curvature, the radius of curvature, the strain at the top of beam and the strain at the bottom of the beam:

$$\kappa = \frac{1}{r} = \frac{\varepsilon_t - \varepsilon_b}{h} = \frac{2\varepsilon_{top}}{h} \quad (1)$$

Using equation 2, the generic curvature mode shape was fit to the experimental data with 5 curvature values known at the sensor locations. Additionally, it was assumed that the left support was behaving as a normally functioning roller with a curvature value of zero. This curve was fit to the peaks of the free vibration response for all of the experimental tests performed. Using the fitted curves, the average inflection point of the curves for each experimental test can be determined by locating the average beam location where the fitted curves equal zero.

Examples of two of the experimental tests performed are shown below in figure 4. The left figure shows the curvature shapes for the undamaged case and right figure shows the results for a case where the roller support is stiffened. For the normal case, the inflection point is located at the location of the roller support as expected. For the altered support case, there is a shift of the inflection point away from the roller support location. This indicated that there is an increase in stiffness of the joint and is behaving different that the undamaged roller case. These results were consistent for all of the beam vibration tests performed, where the inflection point of the support was located farther from the support location the more the stiffness of the joint was increased.

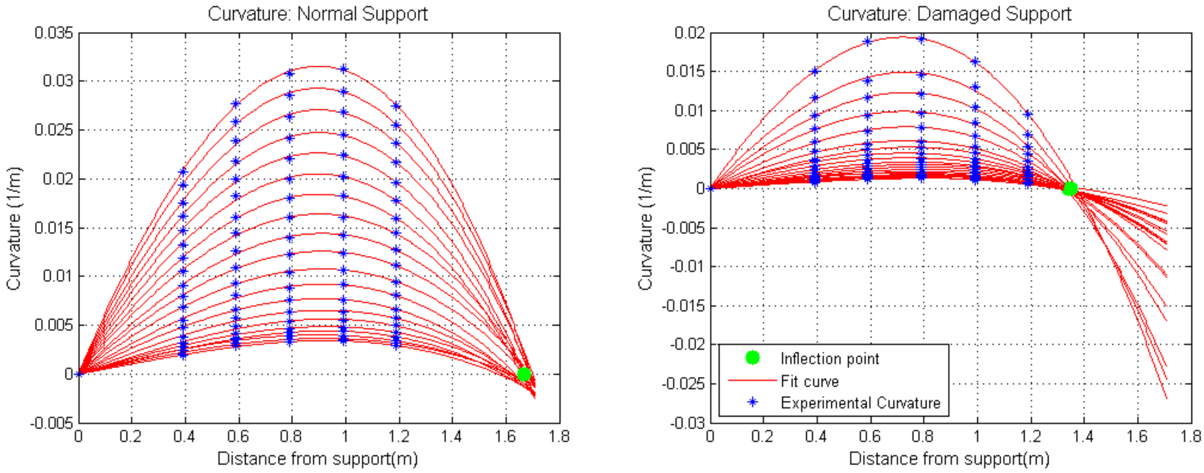

Figure 4: Curvature mode fitting for undamaged and damage laboratory tests.

Using the analytical model show in figure 1, a relationship between the location of the inflection point of the beam curvature and the stiffness of the beam support can be determined. This relationship is shown in figure 5. For all of the experimental tests performed, the average inflection points were determined with their associated uncertainties. From the analytical relationship determined between the inflection point of the beam and the rotational stiffness of the boundary condition, the rotational stiffness of the experimental beam tests can be determined. This is shown in figure 5, where the average inflection points for the normal case and the 3 altered support cases are placed on the curve showing the estimated rotational stiffness of the right support.

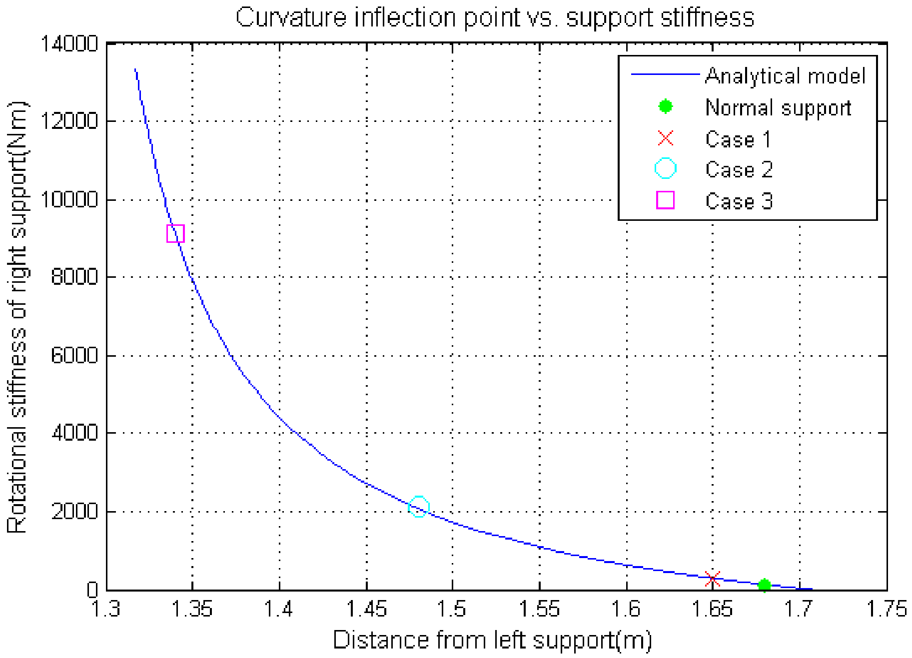

Figure 5: Experimental inflection points corresponding rotational stiffness of support based on analytical model.

As expected, for the normal support condition the rotational stiffness of the right support was found to be 125.6 Nm. When the uncertainty of the inflection point is taken into consideration, the support is behaving very close to a roller support with a rotational stiffness of close to 0 Nm. For each of the altered support cases tested, the stiffness of the support was arbitrarily increased. This is reflected in the experimental results observed with the inflection point shifting to the left along the beam. When compared to the analytical model, this results in an estimated increase of the right support as shown in Table 1.

Right Boundary Condition Case	**Inflection Point (m)**	**Stiffness of support**
Normal	1.68±0.16	125.6
Damage 1	1.65±0.14	288.1
Damage 2	1.48±0.13	2124.0
Damage 3	1.34±0.07	9111.8

Table 1: Experimental inflection point and uncertainties with estimated rotational stiffness from analytical model for each test case.

As an additional means to compare the different states of the support, parameter has been developed by taking a ratio of the curvature values at different sensor location. This parameter is called the Normalized Curvature Ratio (NCR) [5, 8]. This will allow a method to compare the state of a structure without requiring a known model of the structure. The 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.

5 CONCLUSIONS

This research showed the use of dynamic curvature under free vibration as a damage sensitive feature using fiber Bragg grating strain sensors. An analytical model of a beam with changing support conditions was developed, enabling a comparison and evaluation of experimental test results. Free vibration experimental tests were performed where one roller support was gradually stiffened and the other support was unaltered. A quantitative evaluation of the condition of the support for the experimental cases was demonstrated. These experimental results are encouraging and show the potential for utilizing curvature as a simplistic metric for evaluating the structural condition of a bridge using FBG strain sensors. By utilizing the free vibration of the structure, the method is independent of the load applied to the structure. This is optimal for real structures as it allows the bridge to remain in service during testing and avoids costly road closures some structural monitoring methods require.

Future research is currently in progress, applying this method to an existing in service structure, the US202/NJ23 overpass which is instrumented with a series of long-gage FBG strain sensors. Additional testing and research will be performed to further explore the capacity of curvature as a damage sensitive feature for bridge monitoring, focusing on the normalized curvature parameter. The aluminum beam will be subjected to incremental damage located in the span of the beam. Free vibration tests will be performed and the sensitivity of the NCR parameter for damage detection will be determined.

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