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16. Abstract

The goal of this study was to evaluate the performance of Fiber Bragg Grating (FBG) sensors able to detect impacts with different frequencies on a bridge pier. The FBG technology was evaluated under controlled conditions in a laboratory flume set-up to mimic the flow, sediment, and design characteristics of a pier structure. The system was calibrated using site-specific properties to relate strain to a known magnitude force for different bridge pier designs, different scour depths, and structural impacts. The FBGs proved a reliable measure of strain and displacement for key components of bridge structures, such as piers, during varying flow magnitudes. Additionally, the FBGs were used to assess the impacts of different flow-altering countermeasures on the displacement of a bridge structure. Sacrificial piers that were approximately three pier diameters from the bridge proved to minimize the strain at the top end of the pier significantly. Practical guidelines were developed on how the FBGs can be used to provide real-time state awareness information for making decisions on down time, repair cost, and functionality of bridges. The research will pave the way for inexpensive, bridge automated monitoring, while providing an open framework to expedite the development of similar systems for other critical infrastructure, such as roads, highways, dams, levees, and prevent catastrophic events such as the Minnesota bridge collapse in 2007.

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List of Abbreviations

Condition-Based Maintenance (CBM)
Fiber Bragg Grating (FBG)
Hungry Canyon Alliance (HCA)
Mid-America Transportation Center (MATC)
Piezoelectric Transducers (PZT)

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Abstract

The goal of this study was to evaluate the performance of a novel integrated condition-based maintenance framework utilizing state-of-the-art automated sensors for fully adaptive scour and structural damage monitoring to minimize the problems inherent in human inspections of bridges. The development and testing were conducted through detailed experiments using a fiber-optic pier impact detection system consisting of two-wave mixing, Fiber Bragg Grating (FBG) sensors that can detect impacts with different frequencies. The two-wave mixing FBGs sense deformations either in the pier structure and/or within the sediment river bed. The FBG technology was evaluated under controlled conditions in a laboratory flume set-up to mimic the flow, sediment, and design characteristics of a pier structure on the I-80 bridge crossing of Indian Creek, IA. The system was calibrated using site-specific properties to relate strain to a known magnitude force for different bridge pier designs, different scour depths, and structural impacts. The FBGs proved a reliable measure of strain and displacement for key components of bridge structures, such as piers, during varying flow magnitudes. Additionally, the FBGs were used to assess the impacts of different flow-altering countermeasures on the displacement of a bridge structure. Sacrificial piers that were approximately three pier diameters from the bridge proved to minimize the strain on the pier significantly. Practical guidelines were developed on how the FBGs can be used to provide real-time state awareness information for making decisions on the down time, repair cost, and functionality of bridges. This research will pave the way for inexpensive, bridge automated monitoring, while providing an open framework to expedite the development of similar systems for other critical infrastructure such as roads, highways, dams, and levees, and prevent catastrophic events such as the Minnesota bridge collapse of 2007.

Chapter 1 Introduction

The nation needs a comprehensive sensing and prognosis solution for its aging bridges. The reasons that no well-established technology exists today for total bridge monitoring are that available techniques are inadequate, either being too “crude” (e.g., based on broad dynamic parameters, hence, not sensitive to small defects) or too “local” (e.g., based on ultrasonic testing that can only cover a limited region around a sensor), and that the vast majority of sensor installations ignore bridge foundations. The challenges lie in developing cost-effective sensor systems that (a) cover multiple length scales, (b) work on different mediums (i.e., air, water, and soil), and (c) can be easily installed on the piers.

To address the above concerns, a comprehensive approach to state awareness and damage prognosis, with an emphasis on validation strategies, was conducted in this study for monitoring bridge structures. We tested a novel monitoring framework that combines information from fiber optic sensor arrays (known as FBGs for Fiber Bragg Grating sensors) supplemented with conventional sensors, such as Piezoelectric Transducers (PZTs), using multi-scale modeling (fig. 1.1).

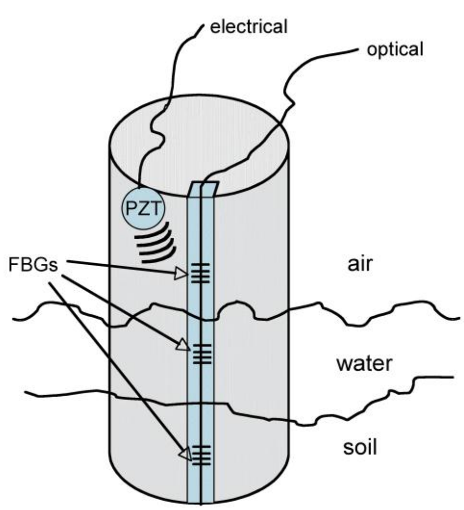

Figure 1.1 Sketch of a bridge pier with an FBG

This is a unique approach that can identify incipient damage well before it is detectable with conventional devices or visual inspection. This study utilized two-wave mixing FBGs that can sense deformations in both the bridge pier structure and the river bed sediments at the base of the pier. The concept behind a two-wave mixing FBG is shown, where a laser beam (with a moderate power density less than 100 mW/cm^2) is split into two beams with a 95/5 beam splitter. The two beams are forced to overlap within a photo-refractive crystal, creating an interference pattern, which in turn results in modulations of the refractive index. These modulations will then diffract the laser beams. It is this modulation of the phase difference that we exploit, through high-frequency FBG demodulation, to sense deformations in both the pier structure and/or within the sediment bed.

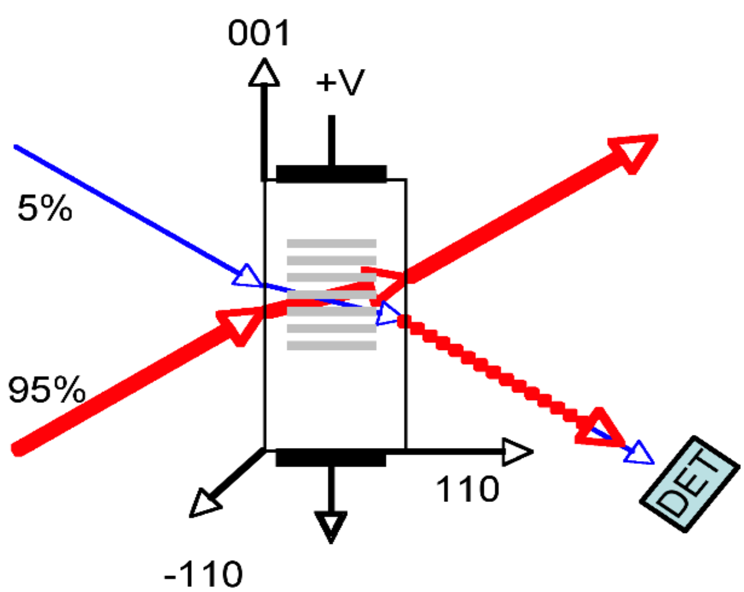

Figure 1.2 A two-wave mixing FBG sensor

The resulting information (i.e., strains from different loads and scour depths) were used to develop a robust prognostics framework, consisting of both online and offline modules that provide valuable residual useful life information to bridge inspectors and owners. A novel damage state awareness framework was also developed using state-of-the-art collective-computation data mining approaches combined with data-driven and physics-driven models. Uncertainties due to material properties, measurement noise and modeling errors, as well as uncertainties stemming from future anticipated loads and environmental conditions, were addressed in the prognosis algorithm development. Fundamental issues, such as evaluating extant prognostics metrics and designing a new metric for evaluation consistency, integrating and reducing data from multiple sources using complementary feature selection and compressive sensing, and developing a robust prognosis method via data mining were addressed in this study.

FBG sensors can be valuable tools for evaluating the potential of bridge infrastructure failure by providing continuous monitoring of localized erosion, especially in critical areas near bridge abutments, and at crucial times, such as during high flow events. Continuous monitoring will contribute missing, but key, data regarding the exact timing of erosion events and the conditions under which they occur. A field monitoring protocol, which utilizes FBGs, will assist engineers in evaluating bridge structures remotely during extreme conditions, when failure is most likely. This protocol can facilitate a condition-based maintenance (CBM) approach, which tends to be more cost-effective than the traditional approach of pre-scheduled maintenance. The FBGs can identify the true state of the bridge infrastructure well before visual inspection, so these areas can be targeted before the damage becomes too great. In summary, the FBGs will improve the overall infrastructure safety by offering new opportunities for monitoring high risk sites, keeping DOT personnel out of harm’s way.

The main goals of this project were to develop continuous monitoring techniques of scour and impact damage on bridge infrastructure, as well as improve estimates of scour depth, particularly under transient conditions with new modeling techniques. A recent survey conducted as part of a project performed for the HCA (Hungry Canyon Alliance) suggested that bridge scour results in an estimated $1.1 billion in damages to bridge infrastructure, jeopardizing public safety and the transport of goods (Baumel 1994). For example, Iowa has 5,152 bridges that are rated structurally deficient and 1,509 that are rated functionally obsolete. Of these bridges, a significant number were rated poorly due to bridge scour and caisson exposure. In Arizona, hundreds of bridges show structural deficiencies due to scour, but state resources can only allocate funds to repair and retrofit about four bridges per year. Furthermore, a robust technique that systematically quantifies bridge scour on a continuous basis is lacking. As a result of the insufficient funds and limitations of existing measurement methods, little knowledge has yet emerged regarding the dynamics of bed scour erosion and the effects that it may have on the stability of bridge structures.

Not only does this study provide an innovative means of monitoring a persistent threat to the surface transportation system (i.e., the FBGs), but this project also began the training of a future engineer (i.e., a graduate student) who will help to sustain a safe and reliable infrastructure for our growing society. This project encouraged the student to look beyond current practices for novel solutions, such as the FBGs, to address infrastructure risks.

Chapter 2 Tasks

During this project, the following sequence of tasks was conducted:

1. Soil samples were extracted that were representative of the region from a bridge site near the University of Iowa campus. A detailed geotechnical analysis using established U.S. Department of Agriculture procedures was conducted for site characterization. The samples were used for the FBG calibration and laboratory testing.
2. The FBGs were calibrated in a flume at the University of Iowa using the information collected in Task 1. In addition, flow design information from the Iowa Department of Transportation geotechnical and bridge design offices were obtained for Indian Creek, IA located near the University of Iowa campus to develop potential hydrologic/climatic scenarios for laboratory testing. FBGs are sensitive to minute changes in light intensity, and must be calibrated using site-specific characteristics. The section of the room containing the flume was enclosed to better control the light and climate conditions surrounding the FBGs.
3. A series of laboratory tests in the climate controlled room housing the flume was conducted to evaluate/calibrate the FBG response under different temperature and flow conditions. The optimal location of the FBGs relative to the local infrastructure was determined during these tests.
4. The testing of the FBG system in the University of Iowa flume was completed. The flume was established to mimic the dimensions and characteristics of the nearby sand-bed creek. The monitoring included cross-sectional depth and flow measurements around model bridge pier structures. Outcomes of the laboratory tests

were strain-scour depth and strain-structural deformation relationships for the different flow conditions.

5. A protocol was developed to mount the FBGs into structures and measure forces acting on particles. The location and number of FBGs required to capture pressure differences upstream and downstream of the structure was identified. Guidelines about the shape of the objects and the reduction of drag force were produced.

Chapter 3 Results

Figure 3.1 demonstrates an FBG system enclosed in a PVC pipe. The FBG is 1 cm long and measures strain at a high frequency of nearly 2000 Hz at a resolution of 10^{-6}.

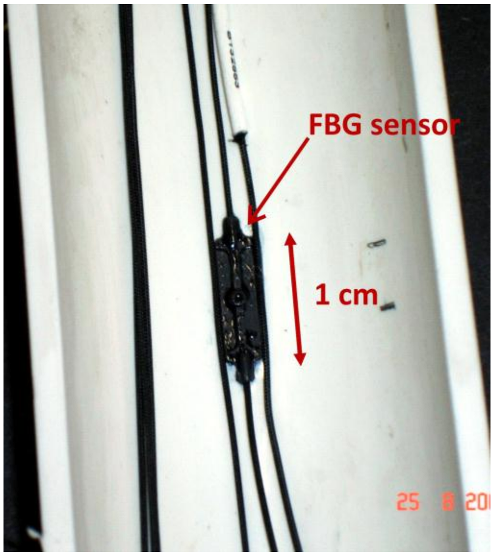

Figure 3.1 An FBG sensor enclosed in PVC pipe

Based on the strain information, we were able to measure the drag from a prototype bridge pier, shown in figure 3.2a. In this prototype bridge pier, we placed three FBG sensors, one each at the top, middle, and bottom of the useable length of the prototype bridge pier, which corresponded to the maximum flow depth possible in the flume (fig. 3.2a, c). The sensors were connected to a data acquisition system (fig. 3.2d). In the flume section shown in figure 3.2a, we fed material in the form of tennis balls to measure their impact as they impinged upon the pier. These tests were repeated several times for low, intermediate, and high (bankfull) flow conditions.

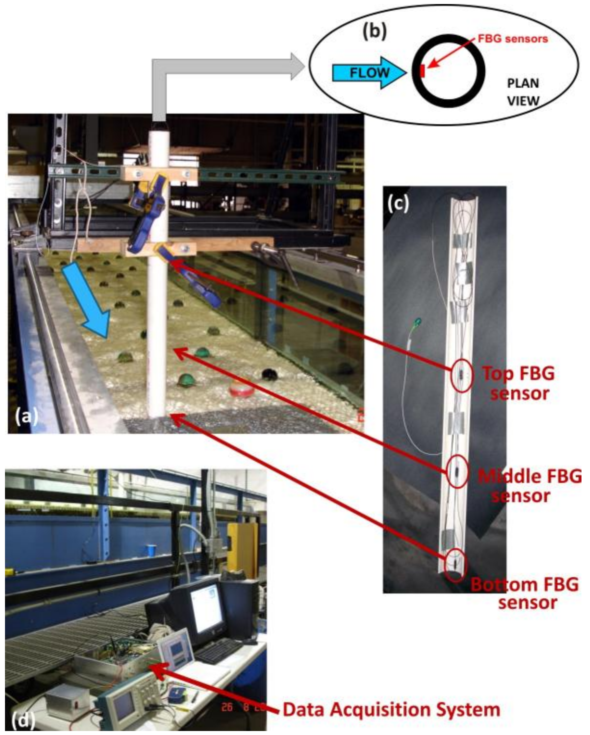

Figure 3.2 (a-c) Experimental setup and placement of the FBG sensors in the prototype bridge pier; (d) data acquisition system for the FBG sensors

Figure 3.3 shows the same test repeated for higher flow conditions to measure and test the response of the FBGs under these conditions:

Figure 3.3 Perspective view of the prototype bridge pier during the high flow (bankfull condition) experiment

Figure 3.4 illustrates detailed experiments performed for nearly bankfull flow conditions and a gradient corresponding to that of a steep channel. We clearly see three regimes in the strain versus time plot (fig 3.4). Regime A corresponded to conditions prior to the collision of the incoming material with the pier. Regime B was the period during which the collision occurred. Regime C corresponded to the condition following the collisional effects. We see that the bottom sensor basically demonstrated steady state behavior. On the contrary, the pier experienced some displacement near the middle and top FBG sections, as well as at the end of the pier where it connected with the bridge deck. It is not surprising that the top end of the bridge pier experienced the highest displacement. What is surprising, however, is the fact that this displacement was three times greater than the displacement near the mid-section. Therefore, this research and this specific experiment clearly highlighted the need for placing micro-sensors not only at the lower end of a bridge pier, but also along the whole length of the pier, resulting in a spatially distributed map of the strain.

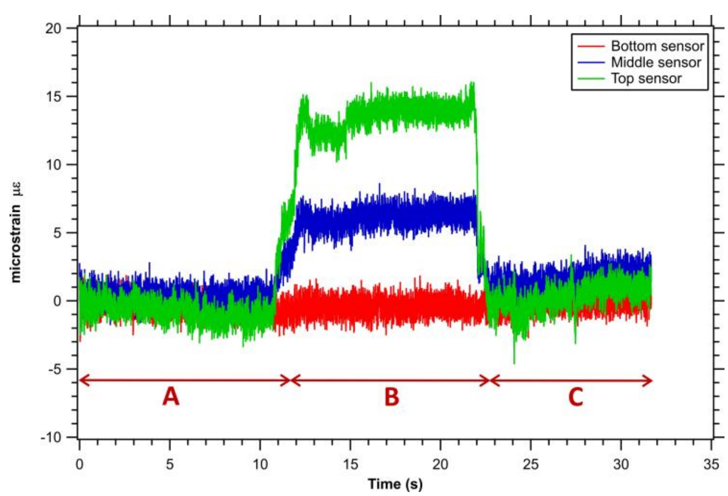

Figure 3.4 Response of the FBG sensors at the bottom, mid and top section of the prototype pier to the impingement of incoming material

Figure 3.5 is an additional experiment performed using the same setup with the three FBGs being present at the bottom, mid, and upper sections of the pier. This experiment was significant, because it incorporated the use of a sacrificial pile in front of the bridge pier. The sacrificial pile played the role of a flow-altering countermeasure. The sacrificial pile, in this case, was a bottle filled with lead beads of specific gravity 12.5, so the bottle could not be mobilized during the experiments. The sacrificial pile was introduced upstream of the pier at distances of 1D, 2D, and 3D, where D is the diameter of the bridge pier. Based on the experimental findings, it was concluded that for the 3D experiment the strain at the top FBG reduced significantly, whereas the strains for FBGs at the mid and bottom of the pier remained comparable to the strains experienced in regime A. A similar situation was pointed out by Haque et al. (2007). The same experiment should be performed in future studies using different flow-altering countermeasures, such as the ones shown in figure 3.6.

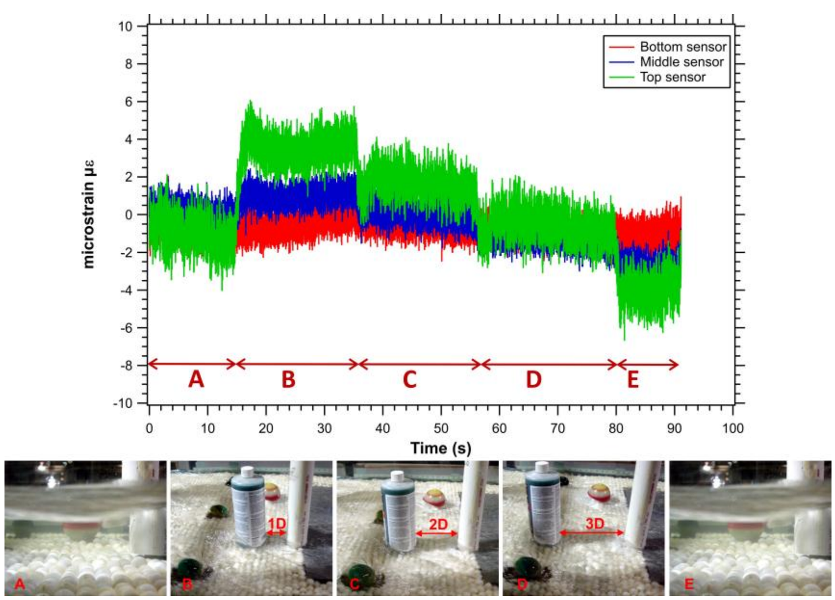

Figure 3.5 Response of the FBG sensors at the bottom, mid, and top section of the prototype pier to the placement of a sacrificial pile placed at 1D, 2D, and 3D upstream of the prototype bridge pier with diameter D

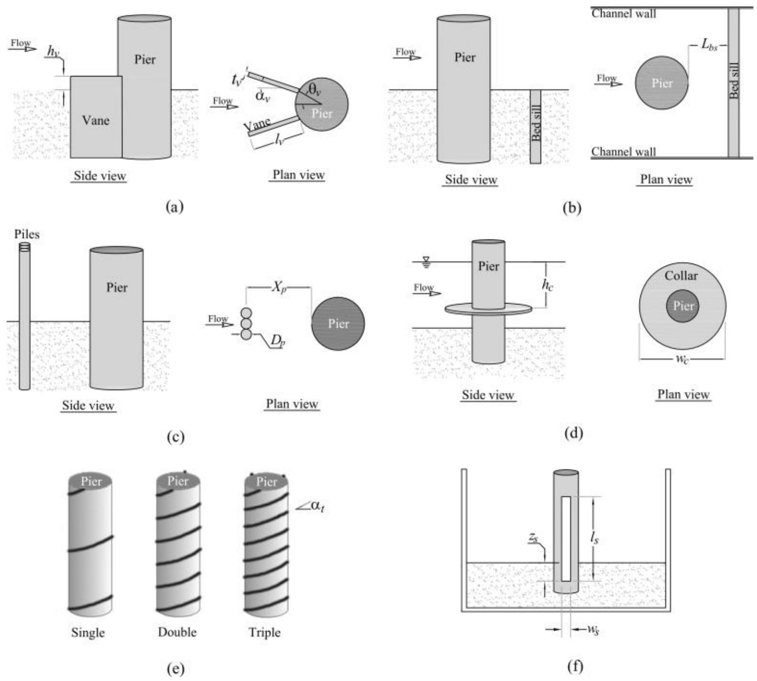

Figure 3.6 Flow-altering countermeasures: (a) submerged vanes; (b) bed sill; (c) sacrificial piles; (d) collar; (e) threading; (f) pier slot. From Tafarojnoruz et al. (2012)

Chapter 4 Conclusions

This study has led to the following outcomes:

1. FBGs can provide a reliable measure of strain and displacement for key components of bridge structures, such as piers and caissons.
2. FBGs can provide the displacement of multiple locations of a bridge simultaneously, which is of vital importance, especially for the submerged elements of the bridges on piers and caissons.
3. The FBGs can be used to assess the impacts of different flow-altering countermeasures on the displacement of a bridge structure.
4. FBGs can provide an accurate estimate of the hydrodynamic forces acting on a submerged structure.
5. FBGs require further testing in real-world setups to identify problems with installation and other problems related to prevailing environmental conditions.
6. FBGs have been verified in natural environments and can be used successfully to provide an autonomous system for bridge health monitoring.

Success in this study was measured by comparing scour modeling results to laboratory and field experiments, with an emphasis on producing estimates of equilibrium scour depth that had less than 10% error. Existing models do not consider vortex shedding and the role of turbulence on scour hole evolution and equilibrium scour depth prediction. Our analysis, reinforced through laboratory and field experiments, provided an improved tool for scour depth estimation and the volume of the scour hole. Knowledge of the geometric structure of horseshoe eddies and their associated frequency through measurements and statistical analysis of the turbulent flow quantities will lead to an improved estimate of the area that is affected by scour at a close proximity to the pier. Current state-of-the-art modeling methodologies tend to focus on other similitude issues, e.g., depth/pier diameter ratio; sediment size over depth ratio; however, the comprehensive methodology proposed here has not been explored, particularly in three types of sediments, namely gravel, sand and clay, under a wide range of flow conditions.

In summary, scour stability problems for bridges would be assisted greatly by the availability of an automated instrument such as FBGs, which allow unattended bank erosion measurements on a continuous basis. These instruments would serve as a practical and useful aid for existing monitoring procedures used by the DOT as well as consulting engineers engaged in the design and monitoring of bridge waterways. In addition, knowledge of the response of a bed around a pier under different weather conditions through sensor automation will allow the design of an early warning system for the public and remove the increased gephyrophobia (fear of crossing a bridge) that currently exists.

References

Baumel, C. 1994. “Impact of degrading western Iowa streams on private and public infrastructure costs.” In Hadish, G. (editor), “Stream stabilization in western Iowa.” Iowa Department of Transportation Report OT HR-352., Golden Hills Resource Conservation and Development: Oakland, IA, 4-1 - 4-39.

Haque, M.A., M. M. Rahman, G. M. T. Islam, and M. A. Hussain. 2007. “Scour mitigation at bridge piers using sacrificial piles.” *International Journal of Sediment Research*, 22, no. 1: 49-59.

Tafarojnoruz, A., R. Gaudio, and F. Calomiro. 2012. “Evaluation of flow-altering countermeasures against pier scour.” *Journal of Hydraulic Engineering*, 138, no. 3: 297-305.