Growing Market Acceptance for Fiber-Optic Solutions in Civil Structures

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ABSTRACT

Owners must manage and ensure the safety of their civil structures even as use of many structures extends well beyond their design lifetime. Traditionally, most structures rely on strict maintenance procedures, visual inspections, and very few sensors. But maintenance is very expensive, visual inspections can miss critical problems, and conventional sensors can fail in harsh environments. Can fiber-optic sensing (FOS) address these issues? This is not a new question, but there are some new answers. This paper highlights several structures where FOS is used, and describes the associated successes and challenges for each application. Many successes are coupled to improved FOS tools: better sensor packages, simpler and less expensive instrumentation, improved installation techniques, and more efficient data analysis tools. Examples of each are provided. Particular attention is given to the economics of instrumenting civil structures – when and how it pays. Conclusions include recommendations for future developments that will further accelerate FOS acceptance and use.

Keywords: Fiber-optic sensors, civil structures, bridges, fiber Bragg grating, strain sensing

1. INTRODUCTION

When considering monitoring the health of civil structures, there are really two key issues in the context of this paper:

1) Is structural health monitoring (SHM) useful?
2) If so, when is it beneficial to use fiber-optic sensors?

Usefulness of SHM is typically more obvious for structures that have known problems. Selections of sensor type and placement are straightforward. Data analysis can be tailored to investigate a manageable set of hypotheses. But in a new structure, or in an older one that does not exhibit a particular problem, it is more difficult to justify the case for monitoring.

Cost of adding a relatively comprehensive monitoring system to a new structure can add ½ to 1% to the total construction cost. This cost would include the system hardware (instrumentation, sensors, cables, etc.) and installation into the structure. It does not include, however, the costs associated with data analysis.

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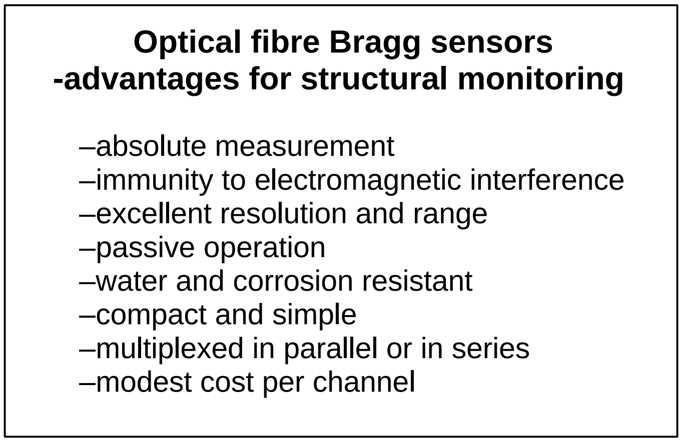
Sensing systems are very efficient in generating mountains of data. What to do with the data however is a tough challenge. Typically engineers start with a mathematical model of the structure. This provides a baseline of comparison for the measured data and forms the guide for sensor placement on the structure. To date most data analyses have been performed by universities and research centers. Few mainstream civil engineering organizations (e.g., local departments of transportation) are well equipped, trained or funded to perform this type of analysis.

What is it worth to have the model, the data, and the answers? It's difficult to assign a monetary value for these endeavors. Certainly, if one avoids a catastrophic failure, the payback is clear[1]. However other justifications are less tangible. For example, if more is learned about performance of a certain type of bridge over years or decades, then perhaps some design limits (i.e., costs) may be relaxed or useful-life standards increased. These have real value, but the payback is separated from the investment by generations. How does the local DOT (department of transportation) get the funding now? As a result most of today's monitoring projects do tend to have a specific, rather short-term objective and are justified on that basis. Examples that follow will illustrate this point. But first, why are so many choosing fiber-optic sensors for SHM projects?

2. FIBER-OPTIC SENSING

When promoting the use of fiber-optic sensors (FOS), both manufacturers and users of FOS list the same benefits almost universally. One version of "the list" comes from JRC, a research group in Italy, and is shown below (Figure. 1). The list is focuses one of the more prevalent types of sensors, the fiber Bragg grating (FBG).



Optical fibre Bragg sensors
-advantages for structural monitoring

–absolute measurement
–immunity to electromagnetic interference
–excellent resolution and range
–passive operation
–water and corrosion resistant
–compact and simple
–multiplexed in parallel or in series
–modest cost per channel

Figure 1: Advantages of Fiber-Optic Sensors[2].

For civil structures, two characteristics in particular make FOS attractive:

1) the ability to multiplex dozens or more sensors on a single optical fiber
2) the ability to operate for years in harsh environments

Multiplexing helps simplify routing, protection and management of cables running from sensors to the data collection instrumentation. Robustness of the sensors themselves provide for years of maintenance-free use. If fibers are protected from breakage, fiber-optic sensors can operate for decades without significant degradation.

2.1. Sensor packaging

Optical sensors have evolved considerably from their beginning as experimental devices. Packages are now more sophisticated and are analogous to conventional sensors. For example, LxSix in Canada produces FBG arrays with polyimide coatings that bond to surfaces with the same process as used for resistance foil strain gages. Systems Planning and Analysis, Inc. (SPA) in the USA has a similar packaging scheme. SMARTEC in Switzerland makes several types of fiber-optic sensors for embedding in concrete to measure strain. Prime Optical Fiber Corporation in Taiwan has an elegant package for FBGs used for temperature sensing.

2.2. Instrumentation

New instruments are addressing growing demand for FOS in civil structures. IDERS (Canada) for example, is sponsored by ISIS Canada to develop an instrument specifically for strain monitoring on bridges. Axsun (USA) made a splash this year by introducing a portable FOS interrogation device. Micron Optics, Inc (USA) a recognized leader in FOS has more interrogators in the field than all other manufacturers combined. Micron has released several new products in 2004 to address the civil engineering demand for more capable, smaller, and lower cost instruments.

2.3. Installation

Better instruments and sensor packages have helped make installation easier, but still about 50% of the cost of most FOS SHM systems is for installation. The knowledge base around installation is ever-improving. Engineering firms like SMARTEC and SPA offer complete solutions to their customers. Chris Baldwin, of SPA in the USA[3], says that, “One of the major issues to overcome in FOS installations is training the contractors who are building the structure. In a 2002 project while installing FBG sensors in composite bridge pilings, one of the workers tripped a yellow cable that led to an array of FBG sensors – ripping it from the structure. The worker asked, ‘Is that a bad thing?’.” It turned out SPA had a backup plan to connect to the embedded array, but it does point out how a lack of familiarity has been a factor affecting the rate of adoption of the FOS approach.

Organizations like ISIS Canada are in existence to develop and transfer expertise in this field. Their work is making it easier for contractors to learn the basics associated with FOS installation and overcome their potential discomfort with the new technologies. ISIS’ “Short Course on Fundamentals of Installation of SHM Systems” is one example of their steadfast efforts to teach practitioners how to use FOS tools[4].

3. APPLICATIONS

The main intent of this paper is to present several examples of the practice of structural health monitoring using fiber-optic sensors. Each example highlights the motivations behind the project and many results are shown.

3.1. An Historic Bridge in Moscow

The Bolshoi Moskvoretskiy Bridge was built in 1936-37, over the Moscow River. It is situated in the centre of Moscow, next to the Kremlin, and leads the one of the main traffic lines from city to the Red Square. This relatively long span was very advanced for its time. The bridge consists of three parallel 100m long reinforced concrete arches hidden behind stone walls. The cross-section of each arch contains three merged boxes. The superstructure of the bridge is supported by columns. Four traffic lanes cross the bridge in each direction.

Two types of degradation are apparent on the bridge (Figure 2).

1. Settlement in the center of the arch has provoked the cracking of the stone walls near abutments on both sides of the bridge
2. Chloride diffusion transverses the upper wall of the arch boxes in some sections, and penetrates inside the boxes.

The condition of the bridge after nearly 70 years of service and its functional and historical importance have led the authorities to decide to continuously monitor structural behavior of the bridge.

Figure 2. Cracking of the stone walls confirms the settlement in the middle of the arch; penetration of chlorides is visible in interior of the arch boxes

SMARTEC SA of Switzerland supplied the instrumentation and sensors, and SMARTEC's integrator partner in Russia, Triada Holding, designed and installed the solution. The aim of monitoring system is to:

a. Preserve this historic structure
b. Understand the structural behavior of the structure
c. Increase safety
d. Reduce maintenance costs.

A total of 16 optical sensors (SMARTEC's "SOFO®" sensors) are installed in order to continuously monitor average strain along the arch, curvature in both, horizontal and vertical direction and the deformed shape (Figure 3). In order to distinguish thermal influenced 6 thermocouples are also installed. The data is sent remotely to the control room using a telephone line.

The SOFO measuring system is based on the principle of low-coherence interferometry. Light is launched into a standard single mode fiber and directed, through a coupler, towards two fibers mounted on or embedded in the structure to be monitored. The measurement fiber is in mechanical contact with the structure itself and will therefore follow its deformations in both elongation and shortening. The second fiber, called reference fiber, is installed free in the same pipe. Mirrors at the end of both fibers reflect the light back to the coupler which recombines the two beams and directs them towards the analyzer where differences in the path length are converted to strain measurements.

Figure 3. SOFO sensor before and after protective cover was installed.

The installation of all the SOFO equipment was completed in June 2003, and the long-term monitoring began. The first year of data is now being used to establish a baseline to compare to future readings.

Optical sensors were chosen for several reasons. Optical sensors are insensitive to corrosion and vibration so they will last for decades on the structure without degradation. Once sufficient data is collected, the analyzing instrumentation can be disconnected and used for other applications – then returned to the Bolshoi Moskvoretskiy Bridge for periodic checks of the structure. The project also aimed to introducing innovative technologies in Russia.

Figure 4. A full view of the Bolshoi Moskvoretskiy Bridge

Visual inspections uncovered several worrisome conditions on the bridge (Figure 4). The fiber-optic structural health monitoring system will help the bridge's owners understand what, if any, corrective action is needed to repair the bridge. Perhaps the data will show that the structure remains sound and there is no need to invest huge sums for preemptive repairs.

3.2. High Performance Steel Girder Bridge in Iowa[5]

The East 12th Street Bridge crosses Interstate Highway I-235 in Des Moines, Iowa, USA (Figure 5). Although its appearance is similar to other highway bridges in North America, it is actually quite special. It is constructed using high-performance steel (HPS) girders and is the first application of HPS in the State of Iowa.

The Bridge Engineering Center at Iowa State University has been working with the Iowa DOT to improve methods of managing bridge infrastructures. Specifically, the Bridge Engineering Center is developing and utilizing short-term and long-term SHM systems to measure bridge behavior. Thus, quantitative information is being used to evaluate bridge performance, rather than just using more qualitative information typically provided from bridge inspections. Typical examples of short-term health monitoring include load tests performed to load rate an aging or deteriorated structure, or to study a complex phenomenon in a structure that requires advanced, atypical analyses. For this type of testing, the Bridge Engineering Center uses acquisition systems that utilize conventional electric strain gage technology, and the measured performance data is used to calibrate analytical models that are developed for each test. Cost of this type of test ranges from $2,000 to $10,000, depending on the bridge size, type, and location, as well as the degree of investigation and desired product. After each short-term test, the sensors are removed and employed for the next test. These sensors are not well-suited for outdoor environments, they drift over time, and electromagnetic interference can be a problem.

The East 12th Street project represents the dawn of a new approach. In early 2004, the Iowa DOT completed construction the bridge through the Federal Highway Administration's (FHWA)

Innovative Bridge Research and Construction (IBRC) program. When compared with conventional steels, HPS has improved weldability, weathering capabilities, and fracture toughness.

To better understand the behavior of HPS over an extended period of time, the IBRC also provided funding for long-term monitoring of the HPS bridge. As a result, in cooperation with the Office of Bridges and Structures at the Iowa DOT, the Bridge Engineering Center has developed a continuous SHM system to monitor and record the performance of the HPS bridge for a two-year period. With this system, the bridge performance can be evaluated at any point in time as well as with respect to time.

Figure 5. East 12th Street Bridge as seen from SHM network camera

The main objectives of the monitoring and evaluation portion of the HPS bridge include:

- Continuously evaluate local and global bridge structural performance
- Monitor the bridge over time to develop a baseline record for identifying structural performance changes
- Conduct a detailed fatigue evaluation

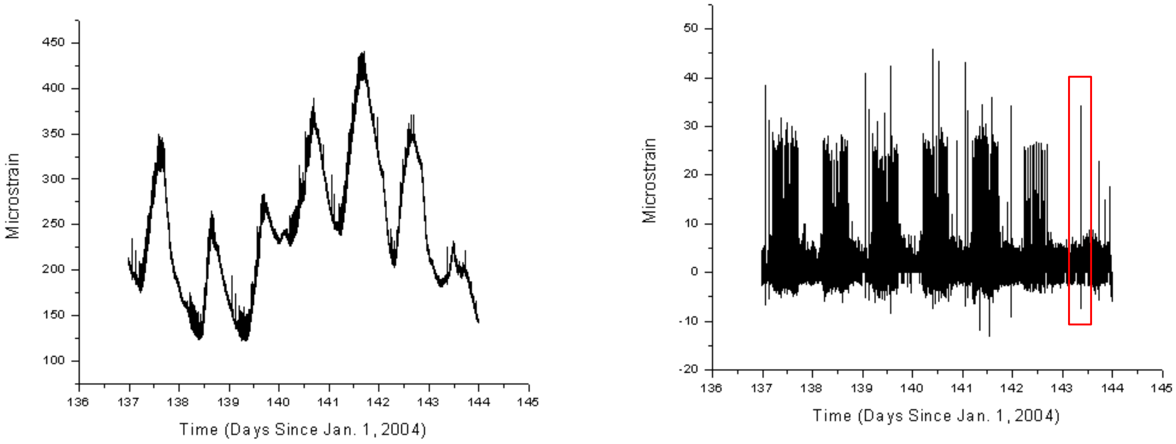
By using the SHM system to continuously monitor local and global bridge behavior, at any point in time, the overall condition of the bridge can be evaluated. Moreover, the technology configured in this project could provide the required information to predict bridge deterioration over time, and thus, provide an opportunity to predict the remaining life of a structure by knowing current characteristics of the bridge. Finally, the long-term performance of several typical and atypical fatigue sensitive details is being evaluated.

The HPS bridge SHM system consists of components developed from several different manufacturers. When possible, standard off-the-shelf components were utilized to maintain minimum cost for the system. The primary components of the SHM system are as follows:

- Strain sensing equipment: Micron Optics si425-500 Interrogator
- Strain sensors: 30 Fiber Bragg Grating (FBG) Sensors

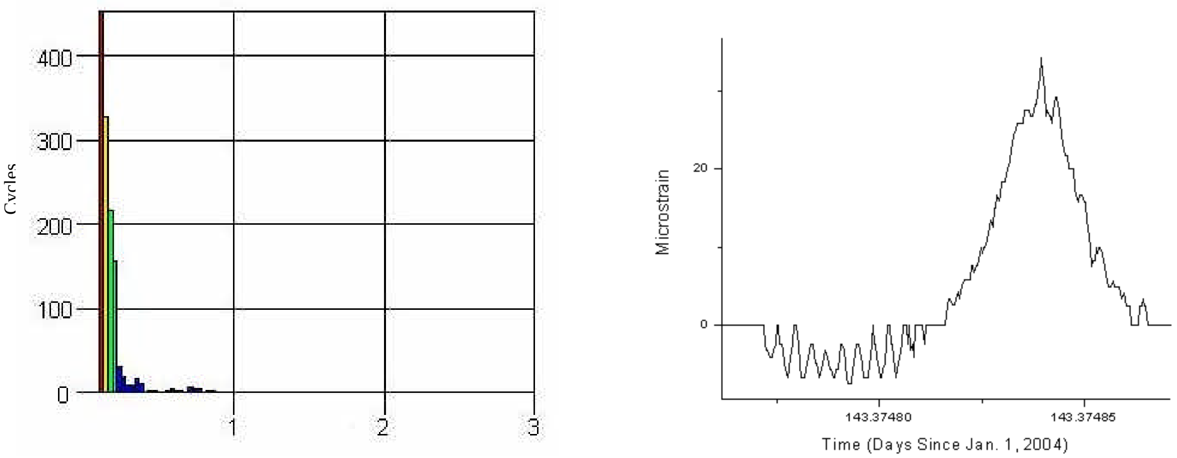
- Video equipment, networking components, and three computers for web service, data collection and data storage

The SHM system collects strain information at critical bridge locations, uploads the strain data to the internet where it can be viewed from anywhere in the world in real time, and automatically transfers the data to the Bridge Engineering Center at Iowa State University for analysis. Typical data is presented in Figure 6.



a. Raw Data for One Week

b. Temperature Corrected Data for One Week



c. Stress Cycles for One Week

Figure 6. Typical collected strain data – bottom flange of girder

A method for summarizing the daily, weekly, and monthly performance of the bridge is also being developed. These brief reports will be automatically generated to give the bridge owner an overview of the bridge condition and performance.

Due to some delays in getting materials, the bridge was open to traffic for about 45 days before the SHM system was installed. The team was able to install 28 of 30 of the first set of sensors without problems; the remaining two sensors were damaged during installation and needed to be replaced.

However, ten more sensors were later installed with no problems. To investigate the performance of the optical sensors, the Bridge Engineering Center team performed independent short-term tests to verify that the optical sensors were accurate relative to their conventional sensors. From experience with SHM, the Bridge Engineering Center team encourages sensor manufacturers to have supporting information available that not only provides proven sensor performance, but also information to make installation easier (e.g., recommended epoxy for attaching the sensor to various material types). In addition, instrumentation providers need to continue to reduce the cost of their sensor interrogation systems. The success of the project thus far clearly identifies applications for FOS and represents a significant advancement in the field of SHM.

Now the team is focused on data reduction, that is, how to summarize and present the data in a way that will illustrate clearly the status of the structure for DOT engineers. For real-time status, visit the SHM system online portal at http://www.ctre.iastate.edu/bec/structural_health/hps/index.htm. There clients can view live streaming video of traffic crossing the bridge and the resulting real-time girder strain measurements.

3.3. Characterizing Soils That Support Bridge Structures

Researchers at the University of California at Los Angeles (UCLA) are working with the California Department of Transportation (CALTRANS) to study how lateral loads are transferred from soils to reinforced concrete structures in a earthquake. Soils are traditionally modeled as a network of individual non-coupled springs. The aim of this project is to validate and/or improve upon widely-used soil mechanics data maintained by the American Petroleum Institute.

Figure 7. Bridge stack being prepared for destructive test

CALTRANS teamed with structural and geotechnical engineers from UCLA to build a testbed where bridge stacks are tested to failure. The basic premise is that as the concrete bends, engineers can deduce how the soils are acting upon the structure. In this case, strain is measured, curvature is calculated from the strain, and the non-linear spring behavior of the soils are indicated by this curvature.

UCLA decided to use fiber-optic sensors because they combine accuracy with a large strain range. They hoped to measure up to 6% strain. UCLA soon found FBG sensors that were strong enough to withstand the huge elongation, but were unable to devise a way to secure the sensors well enough to survive through the entire range. Later they switched to polyimide-coated FBGs (instead of the earlier acrylate coated sensors). Polyimide coatings work much better for firm attachment to anchors and provide a range of 2% strain.

The test shaft (Figure 7) behaves as a plastic hinge. That is, it breaks apart when the load reaches the critical point. Electrical strain gages are attached to the reinforcing steel bars (rebar) in the structure. But the rebar tends to slip relative to the concrete as failure begins. FBG sensors and linear variable displacement transducers (LVDTs) are embedded in the concrete (independent of the rebar) so that they accurately measure the strain in the concrete even after the rebar begins to slip. The FBG sensors are in a special package designed by SMARTEC SA are suspended in position while the concrete is poured around them.

Figure 8. View of the stack after failure.

Results of the first test (Figure 8) are still being developed as statistical analyses are performed on the test data[6]. Visual inspection of the FBG sensors and initial review of the data show that the optical sensors performed well.

Early results are encouraging enough that a second test is being prepared at the time of this writing. This will have more sensors:

- 54 FBG sensors (embedded in concrete)
- 50 LVDTs
- 11 Inclinometers
- 64 large-range strain gages (attached to rebar)

Eric Ahlberg of the UCLA team says that “The fiber-optic sensors are on their way to widespread use. However, to increase their attractiveness to testing programs, the total system cost probably needs to be at or below about US$500 per sensor, FBG strain gages need to have better more robust packaging, and the price of readout instrumentation needs to come down.” Even so with technology available right now, Ahlberg says “we were very pleased with the performance of the fiber-optic sensors as compared with traditional strain gages and displacement transducers.”

4. SUMMARY

A common theme of the four examples is reliance on fiber-optic sensors to measure structures in ways that were not possible with other technologies. Sensors, interrogation instruments, and installation methods are improving, but need to continue to improve for widespread, mainstream adoption. The numbers of both FOS gear manufacturers and FOS systems integrators are increasing as the SHM market emerges. Clearly, the degree of success with high visibility projects, like those in this paper, will continue to accelerate the pace of the growth of market acceptance for fiber-optic solutions in civil structures.

ACKNOWLEDGEMENTS

The authors wish to thank the many engineers and researchers around the world who shared their experiences with the authors for this paper: notably, Eric Ahlberg of the University of California at Los Angeles; and Chris Baldwin of Systems Planning and Analysis.

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