The maturing of optical sensing technology for commercial applications

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ABSTRACT: In this paper, we present a brief overview on the latest advances on optical fiber sensors and instrumentation for structural health monitoring (SHM) applications. Successful, field-proven, installations and reliability studies that validate the technology are also discussed. Emphasis is placed in reviewing actual commercially available solutions and equipment

1 INTRODUCTION

Over the last few years, optical fiber sensors have seen increased acceptance and widespread use for structural sensing and health monitoring applications in composites, civil engineering, aerospace, marine, oil & gas, and smart structures. One of the most common applications is for strain/stress sensing, but a variety of other parameters such as temperature, pressure, magnetic field, voltage, chemical species and others, can also be measured using them.

A variety of discrete fiber strain sensors based on Fabry-Perot (FP) cavities and fiber Bragg gratings (FBGs), as well as distributed techniques based on Raman or Brillouin scattering methods have been developed along with pertinent interrogation electronics and instruments, many of which are already commercially available.

The technical requirements imposed by many SHM applications combined with the increased demand for practical, reliable, field-portable and low cost equipment to perform on-line measurements, has led to a new wave of commercial product and a push for the development of new FOS solutions.

In this paper, we present a brief overview on the latest advances on optical fiber sensors and instrumentation for SHM applications. We will also present information of successful, field-proven, installations and reliability studies that validate the technology. Emphasis will be placed in discussing commercially available solutions and equipment.

2 FIBER OPTIC SENSORS & INSTRUMENTATION

Optical fibers, because their small size and lightweight, have the capability to be embedded within concrete structures—prior to curing—without affecting its properties and be used as sensitive, but rugged, transducers to measure the internal state of stress and act as an effective on-line SHM devices.

Fiber optic sensors (FOS) have attractive features that make them very suitable and, in some cases, the only viable sensing solution. Some of the key attributes of fiber sensors are summarized below:

Table 1. Benefits of Fiber Optic Sensors (FOS)

- Galvanic Isolation
- Intrinsically safe
- Passive: no need for electrical power at sensor end
- Possibility of remote, multiplexed operation
- Small size and lightweight
- Integrated telemetry: fiber itself is data link
- Wide bandwidth
- High sensitivity

The basic principle behind FOS for SHM applications is that light sent through the fiber has its intensity, phase, wavelength or polarization altered by changes in the mechanical and thermal states of the surrounding host. Fiber optic strain and temperature sensors can also be surface-mounted onto concrete or steel surfaces and determine parameters of interest such as stress, strain, elongation, crack onset and growth, delamination and several others.

Once installed, fiber sensors can provide high-resolution temperature and strain measurements, detect the onset and growth of cracks, as well as to monitor creep and thermal stresses. In addition, the actual location of a fault can be determined by optical time-domain reflectometry (OTDR) techniques or by distributed-sensing systems based on Raman or Brillouin scattering.

2.1 *Sensors & packaging*

Optical fiber sensor operation and instrumentation have become well understood and developed. However, two key areas in need of further development and commercial maturity are that of sensor packaging and sensor standardization.

With regard to sensor packaging, there is a need to develop appropriate protective coatings and housings for fiber sensors; investigate the fundamental transfer of strains, stresses, pressure and temperature from the host specimen or matrix to the sensing fiber and the associated materials interplay; as well as the development of field installation processes and deployment techniques suitable for different applications and environments.

With regard to sensor standardization, there is a need to build consensus across the industry about the most relevant parameters to be defined for sensors of a similar type. This in turn will open the gate for interoperability across different platforms and will greatly accelerate the rate of growth and benefit this emerging industry.

However, 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. Similarly, Synet Optics and Pi Optics—both of China—have also developed novel fiber sensors. Micron Optics recently released temperature and strain sensors passing strict reliability criteria.

2.2 *Instrumentation*

An area that has seen vast improvements and more commercialization over the last few years is that of electro-optic interrogators for FOS—mostly geared for fiber Bragg gratings (FBGs) and Extrinsic Fiber Fabry-Perot Interferometric sensors (EFFIs). Today, there are over a dozen or so vendors that offer a variety of sensor interrogation systems and associated signal processing modules for use with FBGs or EFFIs. Most systems offer anywhere from 1 to 16 input channels, addressable either by wavelength division multiplexing (WDM) or, alternatively, via time division multiplexing (TDM). Scanning and sampling frequencies range from 1 Hz all the way up to 1 Mhz. To expand the capability for multiple sensor interrogation, many systems can be used in conjunction with switch boxes and multiplexors to scale up the number of addressable sensors from few tens to several hundred.

Systems readily available today address the needs of Laboratory and those of heavy-duty rack-mount Industrial grade environments. New, over the last year, is the release of commercial grade interrogator systems of a much smaller footprint that are ideally suited for field applications that require limited power consumption, less space, and a “black-box OEM type configuration. These instrument models are also finding fast acceptance into smaller budget field applications where optical sensing did not compete due to historic higher system costs.

New instruments are addressing growing demand for FOS in civil structures. IDERS (Canada) for example, are being 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 Optics has released several new products in 2004 to address the civil engineering demand for more capable, smaller, and lower cost instruments.

2.3 *Installation*

A critical aspect of any SHM project—besides having good quality and reliable equipment—is the installation process. 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 (Baldwin, 2002) 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 (Mufti, 2004).

In places like China, the pool of knowledge and expertise is growing very fast and displaying broad diffusion and acceptance. Organizations such as the Harbin Institute of Technology (HIT) and the Chengdu Institute of Science and Technology (ES-TUC) are emerging as local knowledge bases for integrating optical sensing systems and SHM.

3 STRUCTURAL HEALTH MONITORING

Since the condition of civil engineering works and infrastructure around the world is in a state of deterioration—due to aging of its materials, excessive use, overloading, weathering, lack of maintenance and proper inspection—it has become increasingly important in the last few years to determine the safety of a structure by the non-destructive evaluation (NDE) of its strength and integrity. This assessment is essential for the repair, retrofit, rehabilitation, life extension or replacement of the structure in question. Furthermore, it would be very useful to develop means for the feedback and control of the state of health of a structure.

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.

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.

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 (Zhou, 2003). 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?

Nevertheless, the data provided by sensors can ultimately be used to provide "real-time" information on the state of a specific concrete element or structure by means of a built-in damage detection and evaluation system based on a grid of optical fiber sensors embedded within the structure during its construction. Having such capability renders the structure or building more "intelligent" and leads into the so-called smart structures, whereby a certain degree of self-inspection and control is provided thanks to the use of sensors and actuators in a closed-loop fashion.

4 FIELD INSTALLATIONS & APPLICATIONS

The fundamental applications envisioned for FOS within the field of civil engineering can be grouped into three main areas, namely:

- Structural monitoring and damage evaluation
- Experimental stress analysis
- Management and control of systems and service installations

The first group explores the incorporation of single- and multi-mode fiber sensors within structural concrete elements such as beams, columns, arches, slabs and others, so that stress, strain, flexure, bending, curing, cracks and creep in concrete can he measured individually, as well as the deflection and bending of structures as a whole. Table 1 below, summarizes specific applications in this area.

In the field of experimental stress analysis, fibers would make sensitive and versatile sensors for the measurement of mechanical characteristics of structural members in experimental studies. This might be particularly useful with structures and members having complex shapes for which analytical solutions can be difficult to obtain. An answer can be obtained by measuring experimentally the state of stress in a model.

Furthermore, embedded fiber optic strain sensors would enable structural engineers to compare between measured and designed values of stress, bending moments and deflection.

From this information more accurate design factors can be determined which would make structures safer and more economical to build.

The third set of applications considers that building services and installations (such as heating, air conditioning, lighting, electricity distribution and consumption, security, fire alarms, etc.) can be operated more efficiently and economically using fiber optic sensors that monitor and measure the state of affairs of pertinent parameters. For instance, reading of the pressure, flow and temperature of water pipes could be used to regulate the temperature and distribution of running water by controlling valves, pumps and boilers as required. Similarly, the temperature in rooms, hallways and offices could be monitored and controlled automatically. Electric currents could be controlled and regulated according to demand. Fibers coated with special heat-sensitive coatings could be used as distributed heat sensors for use in fire alarm systems. And the list goes on. In this fashion, integration of all the information supplied by a network of fiber and regular sensors into a single processing center within the same facility would result in a “smart building”

Table 2. Applications of fiber optic sensors for SHM

Bridges:
- Stress monitoring of long spans (>1km) with hundreds of sensors
- Tracking behavior in high stress conditions (earthquake, heavy traffic, high wind)
- Long-term stress& vibration monitoring
- Embedded sensors in concrete beams and pilings
- Embedded/surface sensors on cables for suspension structures
- Surface-mounted sensors on steel components in expansion joints
- Strain sensing on steel girders

Dams:
- Stress & vibration monitoring
- Footing settlement
- Temperature monitoring during curing

Tunnels:
- Monitoring of strains and stresses
- Crack detection and monitoring
- Settlements

Reservoirs:
- Precise reservoir water level monitoring for dam flow control
- River level and flow monitoring for improved flood control

Hillsides:
- Monitoring of gradual shift in soil and rock
- Detection and prediction of possible landslides

4.1 *Case examples & field installations*

One intent of this paper is to present several examples of the practice of SHM using fiber-optic sensors. Each example helps illustrate the motivations behind the project and the benefits of using fiber optic sensors.

4.2 *Monitoring of High Performance Bridges*

The East 12th Street Bridge crosses Interstate Highway I-235 in Des Moines, Iowa, USA (Figure 2). 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 use of HPS in the State of Iowa (Doorminck, 2004).

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.

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

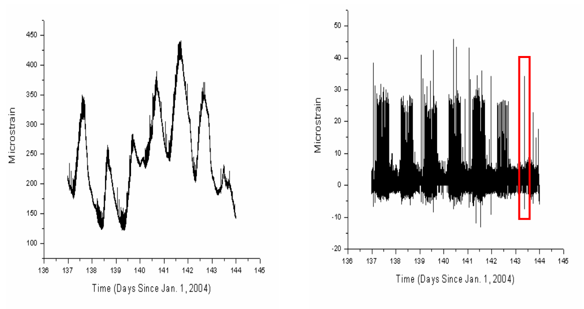
By using the SHM system to continuously monitor bridge behavior, at any point in time, the overall condition of the bridge can be evaluated.

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:

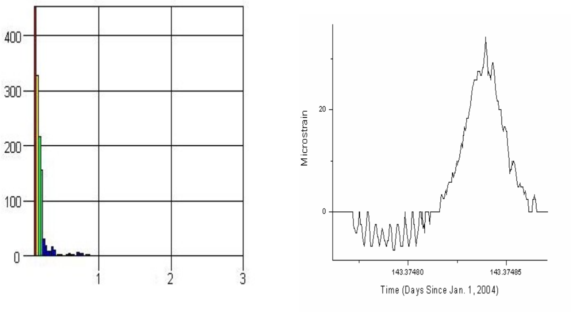
- Sensing equipment: Micron Optics si425-500 Interrogator
- Strain sensors: 30 FBG sensors
- Video equipment, networking components, and three computers for web service, data collection and data storage

Figure 1. East 12th Street Bridge as seen from the SHM site camera

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 2.



a. Raw b. Tempera-



c. Stress d. Traffic

Figure 2. Typical strain data – bottom flange of girder

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 were in need of replacement.

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.

4.3 *Soil Movement Monitoring*

Understanding of the soil characteristics and land movements under support columns, footings, pier anchors, structural foundations and several others is of importance to ensure the safety and longevity of the structures they help support.

An illustrative example of land movement monitoring applications is the research work being conducted by AVP-Optical Sensing Business Unit and Prime Optical Fiber Corp. in China. Jointly, they have developed a long-gauge bending deformation sensor that employs a discrete array of FBG sensors. Figure 3 is a photo of the basic sensing element. These bending sensor elements can form arrays by attaching them to support tubes and discrete distances as depicted in Fig. 4. In this fashion, it is possible to measure deformation in a quasi-distributed fashion over several 10s of meters.

Figure 3. Aspect of POFC's FBG bending sensor

Figure 4. 2m-long bending sensor array

One ideal application for such bending sensor is the monitoring of soil deformation and shifting under a bridge pillar. This project was conducted in China in 2004 and monitors de land movement at depth of 4mts. Tubular sensors were rammed into the soil at an appropriate depth. The sensor array is encased in a steel pipe provided with anchoring wings (Fig. 5a).

The FBG sensors inside the pipe were interrogated via a Micron Optics' si425-500 sensor scanner. Data was stored offline and processed to arrive at the quantitative values of deformation and a graphical representation of the soil deformation profile.

Figure 5. a) 4m-long FBG deformation sensor array inside pipe. b) Deformation sensor installed bridge footing.

5 CONCLUSIONS

A common aspect of many SHM applications is the reliance on fiber optic sensors to perform measurements in ways that were not possible with other technologies. In general, 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.

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