Use of Sensors in Monitoring Civil Structures

By

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Submitted to the Department of Civil and Environmental Engineering
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ABSTRACT

This thesis surveys the use of sensors and sensor networks in monitoring civil structures, with particular emphasis on the monitoring of bridges and highways using fiber optic sensors. Following a brief review of the most widespread form of civil infrastructure inspection -- visual inspection -- the thesis describes the anatomy, mechanisms, and types of fiber optic sensors and characterizes the tradeoffs involved in choosing between fiber-optic and conventional sensor technologies. The thesis then presents a survey of contributions to this field, followed by a discussion of deployed applications of fiber-optic sensors, many of them in North America.

The latter portion of the thesis first briefly discusses the emerging technology of wireless sensor networks and then presents an abbreviated case study comparing the costs and time required to deploy a fiber optic system to traditional visual inspection on the same structure. The case study suggests that the fiber optic sensors are a cost-effective technology, particularly when indirect savings are considered.

The thesis concludes with some comments on the prospects and challenges for sensor technologies in civil infrastructure monitoring.

Thesis Supervisor: Nathaniel D. Osgood
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Dedication

To my parents Amal and William for all their seen, unseen and unforeseen heroic sacrifices. May God protect you and bless you forever.

To my Grandmother Teta Nabiha Daou Haddad, being your first grandson to enter Graduate School. Your love and prayers are always with me and accompany me.

Do to others as you would have them do to you.

For if you love those who love you, what credit is that to you? Even sinners love those who love them.

And if you do good to those who do good to you, what credit is that to you? Even sinners do the same.

If you lend money to those from whom you expect repayment, what credit (is) that to you? Even sinners lend to sinners, and get back the same amount.

But rather, love your enemies and do good to them, and lend expecting nothing back; then your reward will be great and you will be children of the Most High, for he himself is kind to the ungrateful and the wicked.

Be merciful, just as (also) your Father is merciful.

Luke 6: 31-36

Acknowledgements

First and foremost my gratitude is to the LORD my GOD for all the uncountable blessings that he continues to overwhelm me with from the first day I saw light.

His greatest blessing will always be my parents Amal & William to whom I express my deepest gratitude, and whose continuous sacrifice, love, care, moral and financial support made my MIT dream a reality.

I am also most grateful to my wonderful sister Salam and to my precious uncle Nabil, whose continuous advice and moral support have always strengthened my will.

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I can never forget the continuous support and faith of Dr. Gebran Karam, my professor, advisor, mentor and friend forever.

I would like also to thank all the people who helped provide me additional information in this thesis and particularly: Dr. Aftab Mufti and his assistant Mr. Chad Klowak from ISIS Canada, Dr. Dryver Huston from University of Vermont, Dr. Brent Phares from Iowa

State University, Mr. Ahmad Abu-Hawash from Iowa DOT, Mr. Tom Graver from Micron Optics Inc. , Mr. Dave Fletcher from IDERS, and Ms. Marina Colotti from SMARTEC.

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1. INTRODUCTION

The advent of miniaturized sensors enabled by the advances of information technology and fiber optics have revolutionized the way the world measures the physical environment. These advances allow scientists and engineers to monitor and analyze realms that were previously inaccessible remained till very recently virgin or hardly accessible. Monitoring of the health of civil structures is one area where these new technologies show exceptional promise.

This thesis reviews the use of sensors in advancing the performance of civil infrastructure. The first part of the thesis (chapters 2 to 6) discusses Fiber Optic Sensors (FOS) through. The second part of the thesis (chapters 7 and 8) is a brief description of wireless sensors and concludes with an examination of advanced sensor technology in one case study.

The thesis is organized as follows:

Chapter 1 is an introduction to structural health monitoring, as well as a brief description of strain gauges and an overview of the shortcomings of visual inspection of bridges.

Chapter 2 presents a background on fiber optic sensors (FOS), their anatomy, mechanism of use and a description of the different types and classifications.

Chapter 3 discusses the characteristics of FOS: desirable advantages as well as reliability and limitations.

Chapter 4 describes research efforts undertaken in the application of FOS to monitoring civil infrastructure.

Chapter 5 presents different examples cases in which FOS have been deployed in USA, Canada and Europe.

Chapter 6 provides a brief introduction to wireless sensing.

Chapter 7 includes a short case study where the cost of visual inspection and of FOS based monitoring are being compared for a real life application.

Chapter 8 contains the conclusions and recommendations.

Chapter 9 is a glossary.

1.1 INTRODUCTION TO STRUCTURAL HEALTH MONITORING (SHM)

As defined by Pines & Aktan infrastructure health monitoring is the ability "*to proactively manage (structural) health by diagnosing deterioration and damage at their onset, and to deliver an effective response to operational incidents, accidents, natural hazards and other emergencies" (Pines & Aktan, 2002).*

1.1.1 Purpose for Monitoring

Monitoring is a management tool intended to deliver information on the state of the given structure. A common misconception exists about monitoring: that monitoring is primarily a security tool. While monitoring can play an important security role for structures where failure may be of disastrous consequence (e.g. nuclear-waste-containment vessels, bridge decks, dams, and structures under construction, etc.) (Huston et al., 1994), in most cases monitoring serves a more prosaic purpose: gathering information in order to anticipate maintenance needs and to identify safety concerns (Inaudi, 2000).

1.1.2 Economic Importance

Infrastructure maintenance costs impose an increasingly heavy burden on developed countries. In Europe, construction and maintenance of the civil infrastructure is estimated to cost somewhere between 10% and 20% of the public expenditure. A report from the Collaborative Research Centre estimates the overall value of all buildings in Germany to be nearly $25 trillion. In the over-optimistic assumption that a building's average lifetime is one century (100 years), $250 billion will be required annually to be able to maintain the existing structures (Mufti et al., 2003).

In USA, the estimate for infrastructure remediation is around $ 1.4 Trillion over the next 5 years (ASCE).

1.1.3 Safety and Failure of Bridges

In the USA, more than 600,000 bridges are subject to at least one inspection on a biennial basis. According to a Sufficiency Rating by AASHTO, more than 40% of US bridges (200,000 bridges) are either structurally deficient or functionally obsolete and it is estimated that 150 to 200 spans collapse yearly (Mufti, 2003). The cost to correct all the deficient bridges is estimated to be over $90 billion (Measures, 2001). In Canada there exists about 30,000 deficient bridges (Mufti, 2003).

Long Span Bridges

Long-span bridges (bridges of 100 m or longer span) constitute a category of their own as they fall outside the Standard Specifications issued by AASHTO and as there is limited experience when it comes to maintaining their performance (Pines & Aktan,2002). In the USA, there exists around US 1,100 major long span bridges that are more than half a century old, and some of these are even more than a century old (Pines & Aktan,2002).

1.1.4 Steel Corrosion

Corrosion of the ferrous component of steel has been the main factor in significantly shortening the useful lives of structures (Mufti et al., 2003). Most of civil structures contain steel, either as the main structural component (bridges, skyscrapers…) or as reinforcement for concrete (dams, buildings, marine platforms, etc.). The presence of water, pH variations, exposition to chlorine (either deicing salts or coastal wind) are the usual suspects for degradation of concrete or corrosion of steel (Inaudi, 2000). Therefore, monitoring the presence and concentration of these factors becomes a necessity, in order to signal threshold levels above which corrosion is more likely to occur (Inaudi, 2000). Structural health monitoring of pipelines using sensor technology can minimize risks resulting from gas and oil pipeline failure due to corrosion. Corrosion of steel leads to wall thinning of the pipes and their subsequent failure. In addition to risking the interruption of production, weakened pipelines constitute a major threat to the environment and to neighboring communities (Mufti et al.2003).

1.1.5 Smart Structures and Fiber Optic Sensors (FOS)

Engineers have always sought ways to enable them to obtain further information about the behavior of a structure. Some of the most promising techniques being developed are based on the use of fiber optic sensors (FOS). Therefore they resort to incorporate sensing devices (e.g. structurally integrated FOS) either during or following the construction process. Such sensing devices provide engineers with information about parameters such as strain, temperature, and humidity. From the concept of smart structures arose the development of structurally integrated FOS (Mufti et al., 2003). In 1993, the National Science Foundation initiated a program aiming at developing new technologies intended to prolong the life and to enhance the capacity of the existing and future civil infrastructure systems (Merzbacher et al. 1996).

1.2 CURRENT PRACTICE

1.2.1 Visual Inspection

Currently, visual inspection is the most widespread used to detect deterioration and possible damage. The disadvantage of this practice lies in the fact that visual inspection of structures is performed by observing the signs exhibited by these structures. Unfortunately this can only be of advantage when system distress is visible and perhaps only after damage propagates and begins affecting, even threatening, system reliability. In the case of long-span bridges, the effectiveness of visual inspection becomes particularly questionable when considering the ability to reach every critical location and identify every potential defect. As an example of a major bridge, consider the Brooklyn Bridge in New York, visual inspection is performed on a biennial basis. The inspection lasts at least three months and costs no less than \$ 1 million (Pines & Aktan, 2002). According to a study undertaken by the FHWA (Federal Highway Administration) in 2001, at least 56% of the average condition ratings of bridges assigned by visual inspection were incorrect with a 95% probability from the visual inspection (Pines & Aktan, 2002).

1.2.2 Visual Inspection and Shortcomings

The predominant Non Destructive Evaluation (NDE) technique used in bridge inspection is the visual inspection (VI). In 1971, the National Bridge Inspection Standards were implemented, but comprehensive reliability studies of (VI) were not performed. The Federal Highway Administration (FHWA) undertook to investigate the reliability of VI through an investigation by the Nondestructive Evaluation Validation Center (NDEVC), a body of the FHWA. The detailed findings were compiled in two reports (FHWA-RD-01-020 & FHWA-RD-01-021). Among the objectives of the study were to provide overall measures of the reliability and accuracy associated with routine inspections as well as in-depth inspections (FHWA, 2001).

1.2.3 FHWA-NDEVC Study 2001

After conducting a literature review, the NDEVC performed a survey of bridge inspection agencies and then held a series of performance trials utilizing bridge inspectors from 49 state DOTs. The inspectors had to complete a total of 10 inspections: 6 routine inspections, 2 in-depth inspections and 2 inspections according to the procedures in use in their respective states. Information about the inspectors and the environments in which they work were collected. The NDEVC used the latter information to try to establish possible correlation with the inspection results (FHWA, 2001).

1.2.4 Results of The Study

The detailed tests, procedures, and results of the study filled in two volumes and over 800 pages, and is larger than the scope of this limited thesis. However, the findings of the report can be summarized as follows (FHWA, 2001):

- Professional engineers are typically not present on site during the bridge inspections. About 60% of state respondents stated that a PE was present on site for less than 40% of the time.
- In most states (47 out of 49 states) inspectors were never subjected to vision testing.
- Many inspectors did not notice the presence of important structural aspects (support conditions, fracture critical members, fatigue-sensitive details) in the bridge structures they were assigned to inspect.
- A significant discrepancy was noticed between the time an inspector anticipated he needs to inspect a structure and the actual time it really required.
- For the same structural member, four or five (on average) different ratings were assigned. It was found also that there was no systematic approach according to which condition ratings were assigned.
- In-depth inspections were also found to be unlikely to correctly identify defects. For instance, inspectors were able to identify indications of the presence of cracks in just 3.9% of weld inspections.

- A significant proportion of in-depth inspections were found to be incapable of revealing deficiencies beyond those detected in routine inspections.
- Inspectors were found to have a "pattern" in detecting or missing a specific type of defects, and this occurs independently of the bridge. For example inspectors who found small detailed defects in a given bridge were more likely to note small defects in other bridges. Conversely inspectors finding gross dimensional defects in one bridge were more likely to find defects of the same nature in other bridges.
- Finally the report found that few inspection teams do perform in-depth level inspections of decks as part of the routine inspection. Significant inaccuracies were found when the inspection teams were asked to perform in-depth inspections. An example is when 22 teams were asked to determine the delamination percentage only 6 teams were within 5% of the delamination percentage determined by the NDEVC for the deck.

1.3 Conventional Sensor Technology

1.3.1 Background

Past practice of SHM for long span bridges relied on the use of conventional sensors such as resistance strain gauges, three-axis accelerometers, weigh-in-motion systems, and tiltmeters. The performance of these conventional sensors is considered reasonable for in-service applications. Nevertheless they are sensitive to environmental effects (temperature, moisture, alkalinity, etc.). This sensitivity gave rise to the need to develop new sensors characterized by robustness and reliability and which are capable of properly providing all the information that is needed to assess the structure's health (Pines & Aktan, 2002).

Many problems for a sensor system arise from the overall size of most civil structures. Wiring/cabling is among the major problems with conventional electronic sensor systems. More than 100 data channels may be needed by a sensing system on a major structure. Heavy weight, and high material and installation cost are the major disadvantages of the conventional electronic sensor cable (Huston et al., 1994). Typically a sensor channel requires at least two high quality wires for signal transmission, another two wires for power supply and one wire for shielding. All the five wires should be high quality wires configured in parallel; all the wires are put inside a weatherproofed jacket, with strain relief for each transducer (Huston et al., 1994). Strain gauges cost $20 per unit and they need to be mounted on a flat surface prepared with sanding, cleaning, and acid washing. The installation of one gauge will take a skilled technician one hour of labor at a cost up to $30 per unit. The electrical strain gauges require attachment to electronic demodulators (e.g. Wheatstone bridge) that cost between $300 and $2,000 per channel. (Udd et al., 1998b)

1.3.2 Conventional Strain Sensors

Many applications in health monitoring of civil structures involve strain monitoring. The design of conventional strain gauges is based on the fact that the electric resistance of a conductor changes when the conductor is subjected to strain (tensile or compressive). Since resistance is directly proportional to the length of the conductor, any change in the length of the conductor resulting from strains will lead to a change in resistance.

Strain gages can be divided to: wire gages, foil gages and semi-conductor gages. There are two kinds of wire gauges: *flat wound* and *wrap around.* In flat wound gauges, the filament wire is zigzagged between two pieces of paper. With wrap around gauges, the wire is wrapped around a paper support. Wire gages are still largely manufactured by hand (Scott, 2003).

A foil gage (Figure 1) consists of a pattern of resistive foil which is mounted on a backing material; such gauges constitute the majority of extant strain gauges. Foil gauges are made from very thin metal strips (2-10 micrometers thick), and have very fine grids. They are essentially a printed circuit. Foil gauges can be mass produced and are available in different sizes and shapes (Scott, 2003).

In order to measure strain with a bonded resistance strain gage, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain. Strain gage transducers usually employ four strain gage elements electrically connected to form a Wheatstone bridge circuit (source: www.omega.com).

The strain gauge is connected into a Wheatstone Bridge circuit (Figure 2) with a combination of four active gauges (full bridge), two gauges (half bridge), or, less commonly, a single gauge (quarter bridge). In the half and quarter circuits, the bridge is completed with precision resistors. The complete Wheatstone Bridge is excited with a stabilized DC supply and with additional conditioning electronics, can be calibrated. As stress is applied to the bonded strain gauge, a resistive change takes place and unbalances the Wheatstone Bridge. This results in a signal output that can be used to determine the stress value (Source: Sensorland).

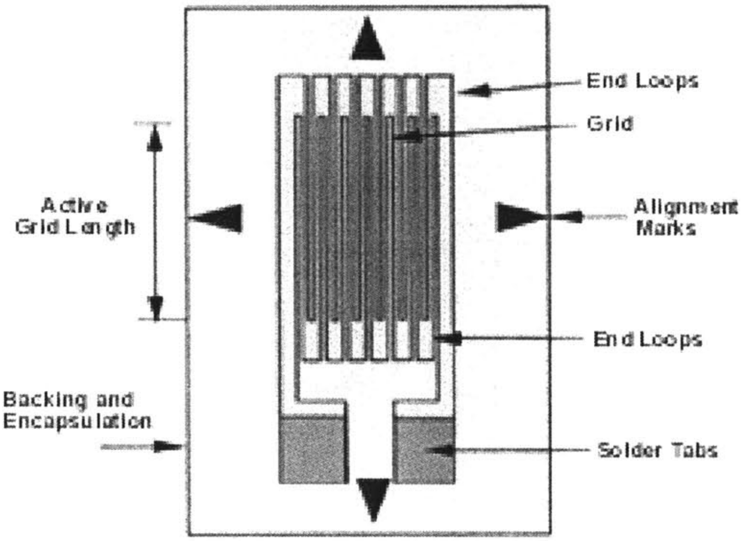


Figure 1: Schematic diagram of a foil strain gage (www.sensorland.com)

Advantages	**Disadvantages**
Determine accurately the normal strain in a given direction	Measure the strain only at the point where they are attached
Suitable for monitoring strains over a wide range of values, from about 1 $\mu\varepsilon$ to well over 10,000 $\mu\varepsilon$, in either tension or compression	Measure the strain in only one direction
Provide an electrical signal that can be measured with a wide variety of circuits	Must be used in groups of 3 at a point to determine principal strain directions and values
Available in a wide variety of gage lengths and configurations	Determine only the average strain in the region of the gage element
Can be bonded to most stiff materials with suitable adhesives	Require relatively expensive equipment for recording the strains
Operate over a wide range of temperatures	Require temperature compensation of one or more types if the temperature changes
Can be used remotely	Tedious to install, particularly if they are very small or are installed in awkward locations
Relatively inexpensive individually	Provides false signals in noisy electromagnetic environments
Suitable for dynamic applications	Require shielded leadwires even in ordinary electromagnetic environments
	cannot be used easily with soft materials

Table 1: Comparison of advantages and disadvantages of strain gages (Source: Phillips, 2000)

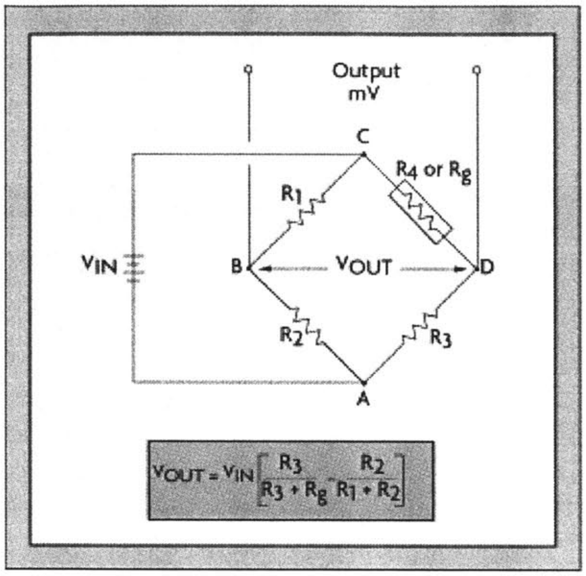


Figure 2: Schematic diagram of a Wheatstone Bridge (www.omega.com)

1.4 STRUCTURAL HEALTH MONTORING USING FOS

Distributed sensors –sensors capable of moving beyond point measurements and instead making measurements throughout or at many points on a curve or surface – offer an attractive means for condition monitoring of civil structures. The geometric versatility of FOS (short-gauge length, long-gauge length, multiplexed, and distributed configurations), as well as their readiness to be integrated within different types of structures and materials (refer to 3.2 and 3.3.3) make FOS attractive for distributed sensing (Chen et al., 1998). *"Instead of detecting a discrete event, the fiber optic monitoring can be used to sense a change in the mechanical properties that implies deterioration of the materials such as the aging of asphalt or the micro-cracking of concrete, or in the effective length of members caused by cracking or by the freezing of bearings due to corrosion"* (Livingston, 1998).

When available and feasible, wireless sensors can offer an alternative to wired monitoring. Wireless sensors eliminate the need for cables and wiring, and consequently reduces significantly installation time and cost (refer to 6.4). However the main issue with wireless sensors will always remains ensuring a renewable/rechargeable source of power (refer to 6.1).

2 FIBER OPTIC SENSORS: BACKGROUND

2.1 INTRODUCTION

Fiber optic sensors are made of a thin optical fiber. The fiber diameter ranges typically between 75 microns (3 mils) and 125 microns (5 mils) (Udd et al., 1998) (Refer to the glossary in 9). A set of characteristic parameters/properties fully define a beam of light traveling through the fiber. These parameters include among others: wavelength, phase, intensity, polarization state, etc. Changes in one or more of these properties of light are induced by external perturbations incident on the optical fiber such as variation of strain, salinity, pressure, alkalinity, temperature, etc. The change in the properties of light can then be related to the parameter (perturbation) being measured (Farahi, 1993).

2.2 ANATOMY OF AN OPTICAL FIBER

As shown in Figure 3, an optical fiber is composed of several layers. The interior region is termed core, a glass cladding surrounds the core of the fiber. The refraction index of the cladding is lower than that of the core in order to allow for total internal reflectance of the light. During the fiber drawing process, the glass fiber is further coated with one of several polymers designed to protect the glass fiber surface from potential abrasion flaws, which can be aggravated by the presence of moisture. Abrasion can cause weakening of the fibers and accelerated crack growth. In concrete, high alkalinity (pH 12) induced corrosion is an additional concern for the durability of the glass fiber (refer to section 1.1.4). A carefully chosen polymer can again provide the necessary protection layer.

Finally, the polymer undertakes a stress absorption role in order to minimize fiber bending. In the telecom industry micro-bending leads to transmission losses, therefore the stress absorption characteristic of the polymer is particularly important (Merzbacher et al., 1995).

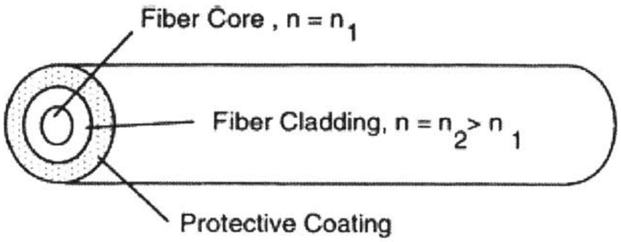


Figure 3: schematic diagram of an optical fiber (Leung, 2000)

2.3 MECHANISM

Snell's law and the concept of total internal reflection govern the transmission of light through the optical fibers. Simply put, when light travels from a fiber core that has a high refractive index into a cladding with a lower index, the light wave is totally reflected back into the core (Figure 4). Whether the optical fibers will carry either one or many modes of the light wave will depend on the diameter and the refractive indices of the core and cladding. Fibers are termed "single-mode" or "multi-mode" based on whether the fiber transmits single or multiple modes of light (Ansari, 1997).

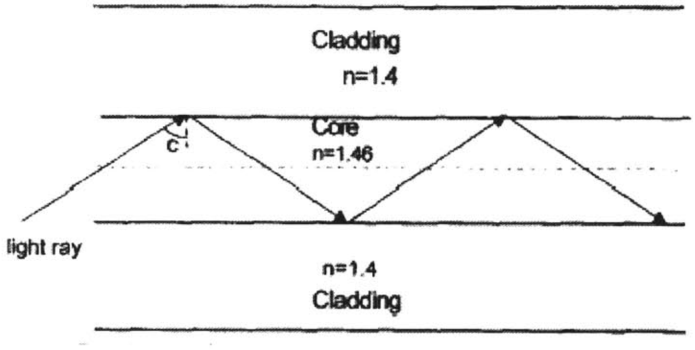


Figure 4: Basis for light transmission in optical fibers (Ansari, 1997)

The respective diameters of the core, cladding, and protective coating are 5, 125, and 250 μm in a typical single mode fiber. In order to allow for the propagation of various modes through the length, multi-mode fibers require a larger core diameter. In the latter case the core, cladding, and coating diameters are typically 50, 125, 250 μm, respectively. It is much easier to work with multi-mode fibers are easier to work with due to the fact that their large core diameters permit simpler interfacing of the terminal hardware that transmits or receives the light (Ansari, 1997). Usually, quartz (SiO_2) is the component of the core and the cladding. It is the doping with germanium dioxide (GeO_2) that differentiates the core from the cladding. This process creates a higher refractive index for the core. A plastic coating surrounds the cladding and provides mechanical protection (against brittleness) by giving flexibility to the fiber (Ansari, 1997).

2.4 STRUCTURAL MONITORING MEASURANDS

Typically, a health monitoring system is composed of a network of sensors. The task of these sensors is to measure one or many relevant parameters. In the case of civil structures (skyscrapers, nuclear plants, tunnels, hydroelectric dams, etc.), the most relevant parameters are (Source: Inaudi, 2000):

- Physical quantities:
    - position
    - deformations
    - inclinations
    - strains
    - forces
    - pressures
    - accelerations
    - vibrations
- Temperature
- Chemical quantities:
    - Humidity
    - Alkalinity
    - Chlorine concentration
- Environmental parameters:
    - air temperature
    - wind speed and direction
    - irradiation
    - precipitation
    - snow accumulation
    - water levels and flow
    - pollutant concentration.

2.5 CLASSIFICATION of FOS

Having described the basic anatomy and mechanisms underlying fiber optic cables and electric strain gages, this section turns to a discussion of fiber optic sensors (FOS).

As depicted in Figure 5, Ansari (1997) distinguishes between two categories of FOS: 1) According to the transduction mechanism (Intensity, Phase, Spectrometric) and 2) According to the application (Localized, Multiplexed, Distributed). In addition to these two divisions, FOS may be categorized according to other schemes. In one taxonomy FOS can be also categorized based on the purpose of use (Udd et al, 1998). In another scheme, sensors are classified as *intrinsic* and *extrinsic*. Finally, fiber optic strain sensors may be divided into two broad categories, intensiometric and interferometric (Ansari, 1997). The next several sections of this document describe each of these classifications in greater detail.

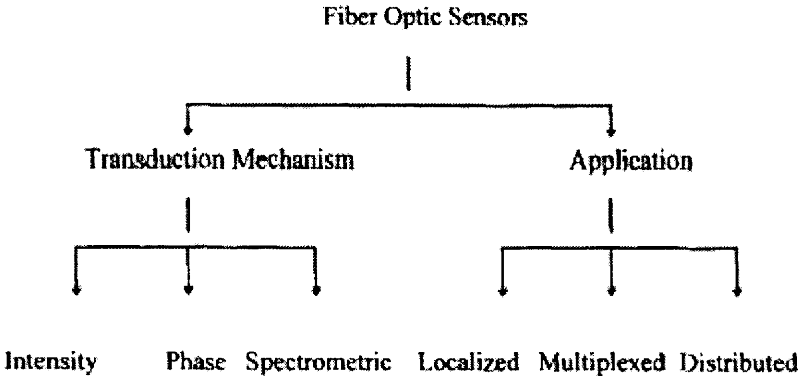


Figure 5: Classification Diagram (Ansari, 1997)

2.5.1 Transduction Mechanism

2.5.1.1 Intensity- or Amplitude-Type Sensors

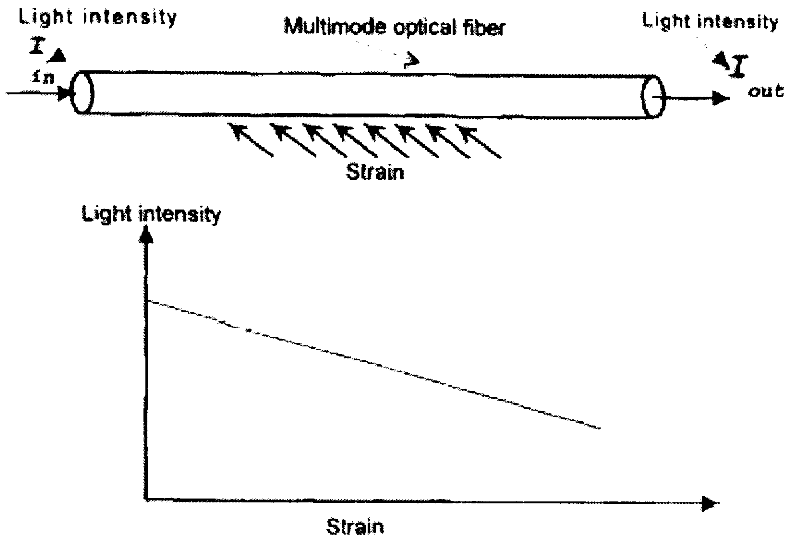


Figure 6: Optical fiber intensity sensor (Ansari, 1995)

Intensity based sensors, called also Intensiometric sensors, measure properties based on the intensity of light transmitted through the length of the fiber. When a fiber breaks and transmission is interrupted damage can be detected. The location of fiber breaking can be determined using OTDR. Although researchers have produced strain sensors that attempt to relate the loss in intensity arising through microbending losses, they suffer from sensitivity, inaccuracy and have a limited range of detection (Merzbacher et al. , 1996).

In the example of an intensiometric strain sensor (Figure 6), straining along any portion of the length of optical fibers will induce losses in light intensity. Intensity type sensors are based on the latter losses. Their simplicity of construction and compatibility with multi-mode fiber technology are the main advantages offered by intensity-type sensors (Ansari, 1997).

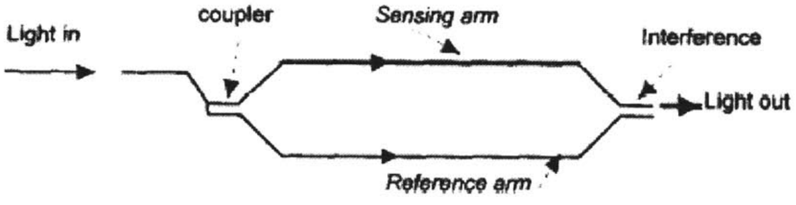
2.5.1.2 Spectrometric Sensors

Spectrometric sensors are characterized by a transduction mechanism based on relating the changes in the wavelength of light to the changes in the parameter of interest. Sensing of chemical reactions, and remote monitoring of contaminants in ground water are the areas where spectrometric sensors are most widely employed (Ansari, 1997).

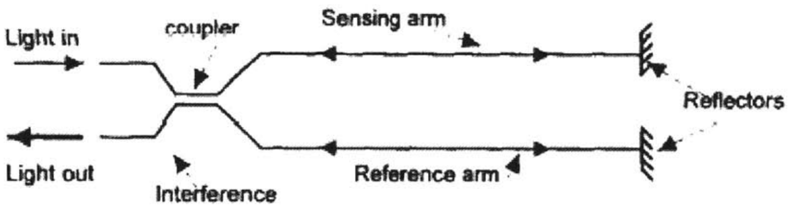
2.5.1.3 Phase Sensors

Different configurations of phase sensors use interferometric sensors to measure the phase change of the light. Interferometric sensors are characterized by their strain measurement sensitivity. Phase sensors depend on a mechanism that establishes the interference of light emitted by two identical single-mode fibers. One of these fibers serves as a reference arm while the other operates as the actual sensor. Polarimetric sensors are a subclass of phase sensors *"that take advantage of the polarization characteristics of light for transduction"* (Ansari, 1997).

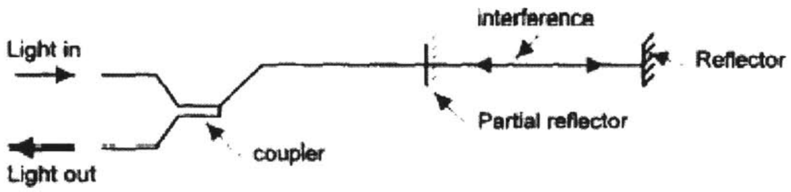
The Mach Zender, Michelson and Fabry-Perot are considered the most promising configurations among the FO variants of the classical optical interferometers (Figure 7). Whenever used as sensors, all three of them share a common transduction mechanism. In this mechanism a change in the optical phase is induced by the parameter being measured; this change in optical phase will be detected as an intensity change in output signal of the interferometer (Jackson, 1993). Many applications for FO interfeometric sensors include high sensitivity sensors that are based on single mode fiber such as magnetic field sensors and acoustic sensors (Merzbacher et al., 1995).



(a) Mach Zender



(b) Michelson



(c) Fabry Perot

Figure 7: Fiber optic interferometric sensors (Ansari, 1995)

2.5.2 Application

The previous section taxonomized sensors by mechanism; this section characterizes sensors according to the region being measured (single localized regions, a discrete set of regions, or a continuous set of regions lying along the fiber optic cable).

2.5.2.1 Localized Fiber-Optic Sensors

Localized fiber-optic sensors can be seen as similar to conventional strain or temperature gage sensors in the sense that localized FOS determine the parameter of interest (temperature, strain, etc.) over a specific segment of the optical fiber. Localized FOS detect the variation in the parameter of interest only in the vicinity of the sensor a characteristic which may assist in determining in what region the measured parameter is changing. However, in the case when many individual sensors would be required, complication will arise as the numbers of connections and fiber leads augment (Ansari, 1997).

2.5.2.2 Multiplexed Sensors

Multiplexing, called also quasi-distributed sensing, is performed whenever multiple localized sensors are placed at intervals along the length of the fiber length. The purpose of multiplexing will be to measure one or different types of perturbations over a given large structure. Within a multiplexed sensor, one can distinguish (and isolate) the outputs of each sensor according to the frequency or time characteristics of its signal and this allows for the real-time profiling of parameters throughout a structure (Merzbacher et al., 1995).

An interesting multiplexing technique is based on multiplexing multiple Bragg gratings via wavelength division multiplexing (Ansari, 1997). For this technique a number of FBG are scanned by the use of a broad-band light source. Each Bragg grating has a slightly different reflectance wavelength from the others. Thus it is possible to recognize and detect the shift in wavelength for each sensor; this shift will be related to the magnitude of the perturbation at specific locations (Ansari, 1997).

2.5.2.3 Distributed Sensors

Within a distributed sensor, each element of the optical fiber is used for the double purpose of measurement and data transmission. Measurement of parameters all along the fiber length requires the use of multiplexed or distributed optical fibers, which allow a given measurand to be quantified as a function of length along the fiber, this is only permitted by distributed sensor configuration. The measurand induces change in the transmission of light. As a result of this ability to perform multi-point measurements, distributed sensors are particularly well adapted to deployment in large structures.

In the most widely employed distributed technique, delays in the light propagation time are measured using an optical time domain reflectometer (OTDR). Within this technique, one of the fiber receives a pulsed light signal. Partial reflectors placed along the length of the fiber reflect the light signals. The reflected signals are recovered from the same end of the cable from which the transmission occurred (Ansari, 1997). This concept makes it possible to determine the distance to the strain field, (1) through the round trip delay in propagation time, (2) by the kinematics relations of distance, time and velocity (Ansari, 1997).

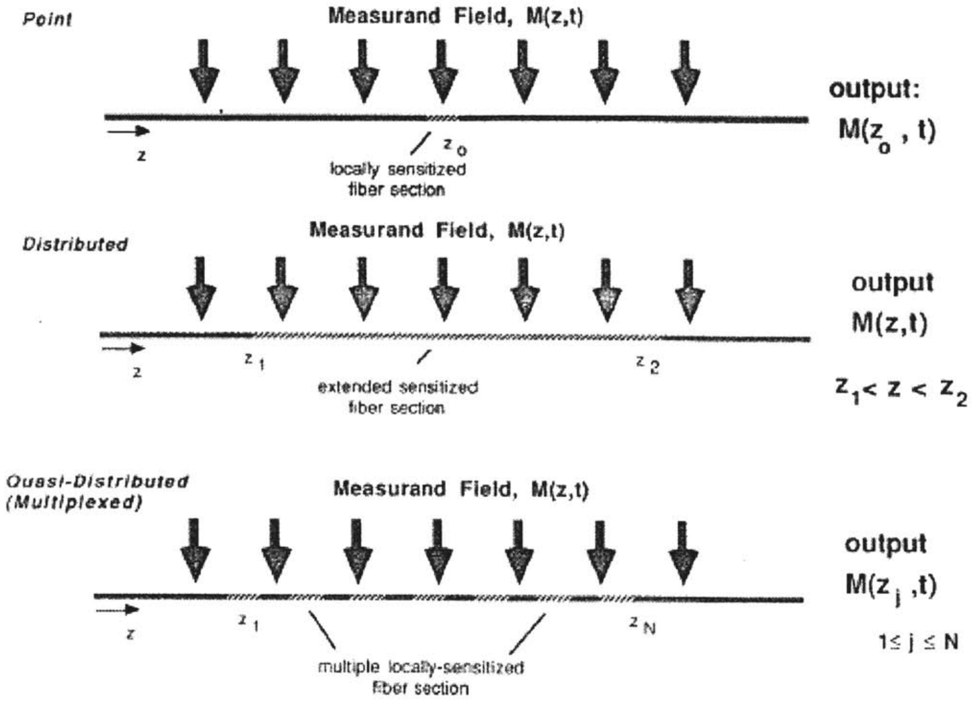


Figure 8 : Schematic depiction of localized (top),distributed (middle), and multiplexed (bottom) FOS (Merzbacher et al,1996)

2.5.3 Purpose of Use

In their report to the Oregon DOT entitled "Fiber Optic Sensors for Infrastructure Applications SPR 374", Udd and coworkers divided FOS into 4 categories according to the purpose of their use as follows (Udd et al, 1998):

2.5.3.1 Attached or Embedded Sensors

When monitoring the manufacturing processes in large sections (e.g. curing of concrete) FOS can be either attached or embedded in the structure (Udd et al, 1998).

2.5.3.2 Nondestructive Testing of Parts Prior to Installation

FOS can be used in evaluating properties of a manufactured part prior to its installation. An example of this process can include embedding FOS or FO acoustic detectors to measure strain fields variations (Udd et al., 1998).

2.5.3.3 Structural Health Monitoring Systems

In SHM systems, the condition of a structure (e.g. a bridge) is assessed by the deployment of arrays of FOS (e.g. strain sensors) (Udd et al., 1998).This use of sensors is the primary focus of this thesis and is further discussed in 1.1.

2.5.3.4 Control Systems

An FOS system can be "interactive" in the sense that it can be used for the purpose of collecting environmental data as well as performing control functions based on this same data. For example an ITS (intelligent transportation system) may enable the activation of a warning sign whenever an accident or a traffic jam is sensed) (Udd et al., 1998).

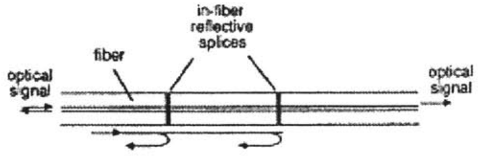
2.5.4 Intrinsic vs. Extrinsic

An FOS is called *intrinsic* if the effect of the measurand on the light being transmitted takes place in the fiber (Figure 9). The sensor is considered to be *extrinsic* if the fiber carries the light from the source and to the detector, but the modulation occurs outside the fiber (Merzbacher et al., 1996). In extrinsic FO sensors, after a light with known parameters enters the modulation region it emerges having one of its features changed resulting from an external perturbation or environmental signal (Fuhr, 2002). Intrinsic sensors are also said to be "all-fiber sensors". In this type of FOS, an external perturbation causes the "local changing of the optical fiber's waveguide", the subsequent light modulation is measured by the intrinsic FOS (Fuhr, 2002). Table 2 briefly compares Extrinsic and Intrinsic FOS.

Extrinsic FOS	**Intrinsic FOS**
Less sensitive	More sensitive
Easier to use	More difficult to shield from unwanted external perturbations
Easily multiplexed	"all fiber" which reduces the sensing region connector problems
Subject to ingress/egress connectorization problems (into and out of the light modulator)	Usually dependent on more elaborate signal demodulation system
Cheaper than intrinsic	Significantly more expensive than extrinsic
Lower robustness and adaptability to unusual installation requirements	Higher robustness and adaptability

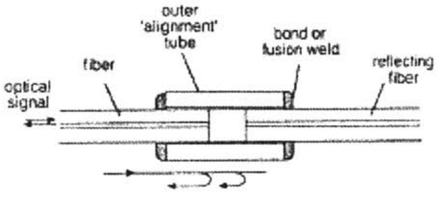
Table 2: Intrinsic vs Extrinsic FOS (Source: Fuhr, 2002)

(a)



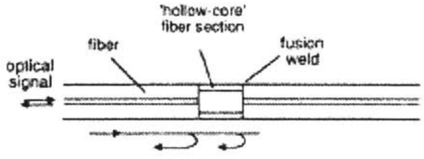
Intrinsic Fabry-Perot Interferometer (IFPI)

(b)



Extrinsic Fabry-Perot Interferometer (EFPI)

(c)



In-Line Fiber Etalon (ILFE)

Figure 9 : Schematic diagrams of (a) IFPI, (b) EFPI, (c) ILFE (Merzbacher et al., 1996)

2.5.5 Intensiometric vs. Interferometric

2.5.5.1 Intensiometric Sensors

(Refer to section 2.5.1.1)

2.5.5.2 Interferometric Sensors

(Refer to section 2.5.1.3)

2.5.5.3 Fiber Bragg Gratings

A third category may be added to the intensiometric and inferometric sensors: the fiber Bragg grating (FBG). FBG is seen as particularly attractive whenever embedded sensing is to be performed (Mezerbacher et al. 1995). (FBG is discussed in more details in 2.6.3)

2.6 MAJOR FOS TYPES

2.6.1 SOFO Displacement Sensors

The SOFO system (French acronym for Surveillance d'Ouvrage par Fibres Optiques – Structural Monitoring Using Optical Fibers) is a fiber optic displacement sensor that was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL). SOFO system is characterized by a high resolution of 2μm, a precision of 0.2%, as well as an excellent long-term stability (Inaudi, 2000). A SOFO strain sensor is shown in Figure 10, where black dots refer to couplers.

Two optical fibers are installed in a same pipe on the structure be monitored, the difference in length between the two fibers is measured by the using low-coherence interferometry. The measurement basis ranges between 200 mm and 10 m. In more than 50 structures, the SOFO system has proved to be successful in SHM (Inaudi, 2000). Structures being monitored included nuclear power plants, historical monuments, piles, dams, anchored walls, bridge and, tunnels (Inaudi, 2000).

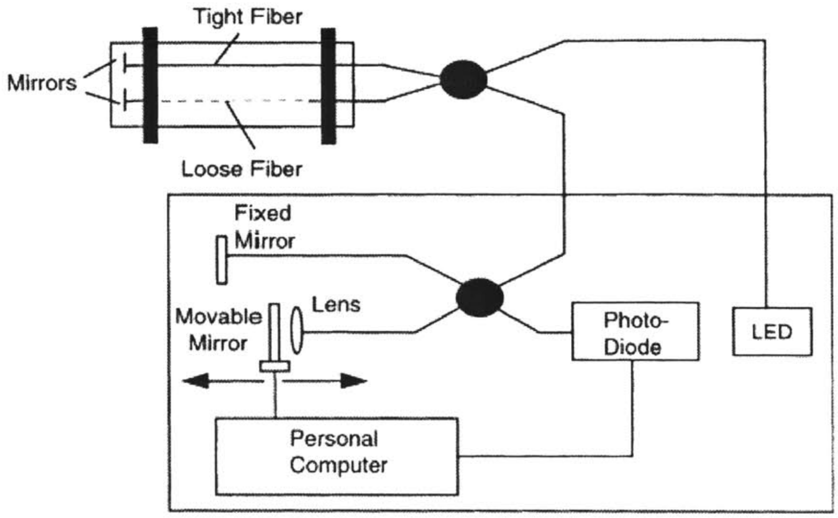


Figure 10: SOFO strain sensor (Leung, 2001)

2.6.2 Microbend Displacement Sensors

A micro-bend displacement sensor is formed by twisting, along the sensing length, an optical fiber with one or more optical fibers or even with metallic wires (Inaudi, 2000). Fibers will induce bending in one-another whenever this FO twisted pair is elongated. As a consequence to bending, light loss occurs as a fraction of the light escapes the fiber. The reconstruction of the deformation undergone by the structure will be made possible by the measurement of the intensity of the transmitted light. For periods shorter than one day resolutions of 30 μm can be achieved, for longer periods resolution deteriorates to 100 μm. Being among the earliest commercial applications of FOS for the SHM of civil structures, this system was installed in different bridges, tunnels and high-rise structures (Inaudi, 2000).

In spite of being conceptually simple, microbending sensors are still challenged by a set of factors such as temperature compensation, intensity drifts, system calibration and the inherently non-linear relationship between intensity and elongation. The microbend displacement sensor can be especially suitable for short-term and dynamic monitoring and for issuing alarms (Inaudi, 2000).

2.6.3 Bragg Grating Strain and Temperature Sensors

Bragg gratings are periodic alterations in refractive index of the fiber core. These alterations are produced by having the fiber exposed to intense UV light. The length of these gratings is usually on the order of 10 mm. Only the wavelength that corresponds to the grating pitch gets reflected when white light is injected in the fiber; all the remaining other wavelengths will pass undisturbed through the grating. Because the grating period depends on both strain and temperature these parameters may be measured via Bragg grating sensors. The measurement takes place through the analysis of the spectrum of the reflected light using a tunable filter or a spectrometer (Figure 11). The best demodulators are capable of achieving high resolutions of the order of 1 $\mu\varepsilon$ and 0.13°C. The use of a free reference grating will be needed whenever we expect simultaneous variation in strain and temperature. In this case, the free reference grating performs an isolated measurement of the temperature, allowing measured strain values to be corrected using this temperature reading (Inaudi, 2000).

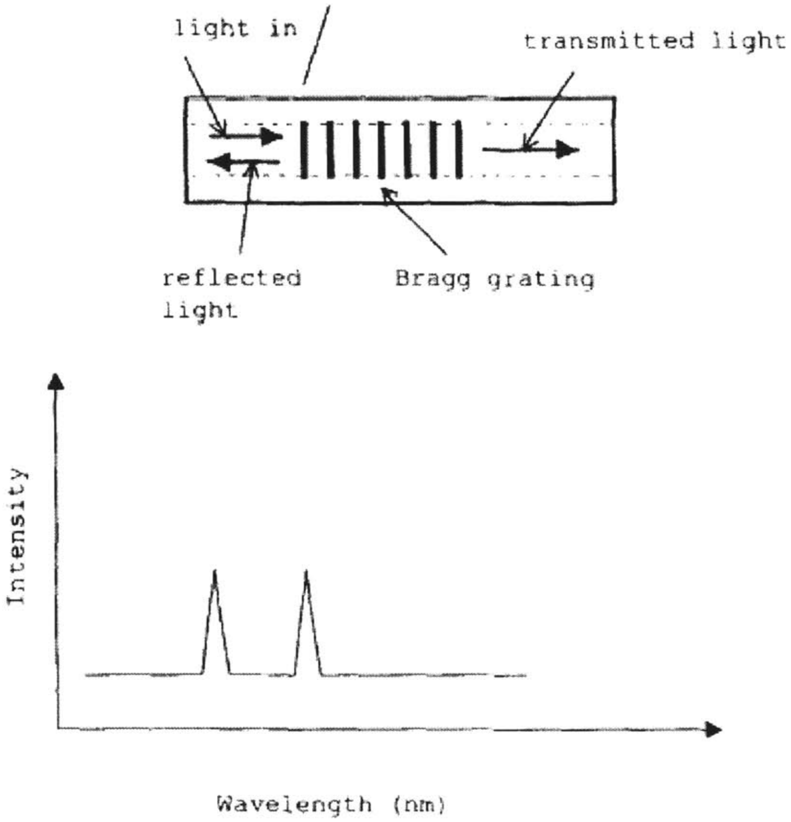


Figure 11 : Strain induced shift in wavelength for an FBG (Ansari, 1997)

The measurement capabilities of FBG as well as its automated fabrication make the Bragg grating unrivaled FO structural sensor (Measures, 1997). The popularity of FBG sensors for SHM is due to two particular properties of theirs: multiplexing and self-referencing. As noted in section 2.5.2.2, multiplexing makes it possible to interrogate several grating sensors by the use and sharing of the processing optics and electronics. Advantages of multiplexing include a reduction in the unit cost of sensor, a lighter overall weight, and an improved system robustness (Sirkis, 1998). Self-referencing is a property of a system where measurements made with reference to the time the sensor is manufactured therefore they do not suffer from interruption whenever the electronic instrumentation is turned off. This feature can be contrasted to the "bridge balancing" in the case of a resistance strain gage (Sirkis, 1998).

Typically, up to 16 (but usually no less than 4) gratings can be measured on the same fiber line. One limitation of multiplexing that results from the fact that multiple gratings must share the spectrum of the illuminating source is a trade-off between the count of sensors and the width of the frequency window (and thus the dynamic range) allocated to each such sensor. The length of FBG allows them to replace conventional sensors; installation is typically done by gluing them on smooth surfaces (Inaudi, 2000).

One special advantages that gives an edge to FBG and sets it apart from competing sensing schemes, is that the particular property of encoding the sensed information directly into wavelength. Consequently the output will not be directly dependent on *"the total light levels, losses in the connecting fibers and couplers, or recalibration or re-initialization of the system"* since wavelength is an absolute parameter (Merzbacher et al., 1995). In addition, *"wavelength division multiplexing is readily achieved by fabricating each grating at a slightly different frequency within the broad-band source spectrum." (Mezerbacher et al,. 1995)* Finally gauge lengths offered by FBG are similar to widely used foil gauges. All the above mentioned features of FBG allow the designer of FOS systems for infrastructure to have a range of options that will be otherwise unavailable (Udd et al., 1998).

In some cases, it is possible to use FBG sensors as acoustic sensors to monitor irregular sounds caused by potholes or by excessive vibration , thereby it becomes possible to track anomalies in roads, bridges, railways, etc. (Udd et al., 1998).

2.6.4 Fabry-Perot Strain Sensors

The main components of an EFPI (Extrinsic Fabry-Perot interferometer) are two cleaved optical fibers placed in front of each other and contained by a capillary silica tube. An air gap is left between the two fibers (on the order of microns or tens of microns). Light is emitted into one of the two fibers. This incoming light is reflected on the glass-to-air and on air-to-glass interfaces resulting in a back-reflected interference signal. In the capillary tube where the two fibers are attached each to one extremity (of the tube), a gap of 10 mm exists between the two fibers (Figure 12). The subsequent change in the gap corresponds to the variation in average strain between the two points of attachment (Inaudi, 2000).

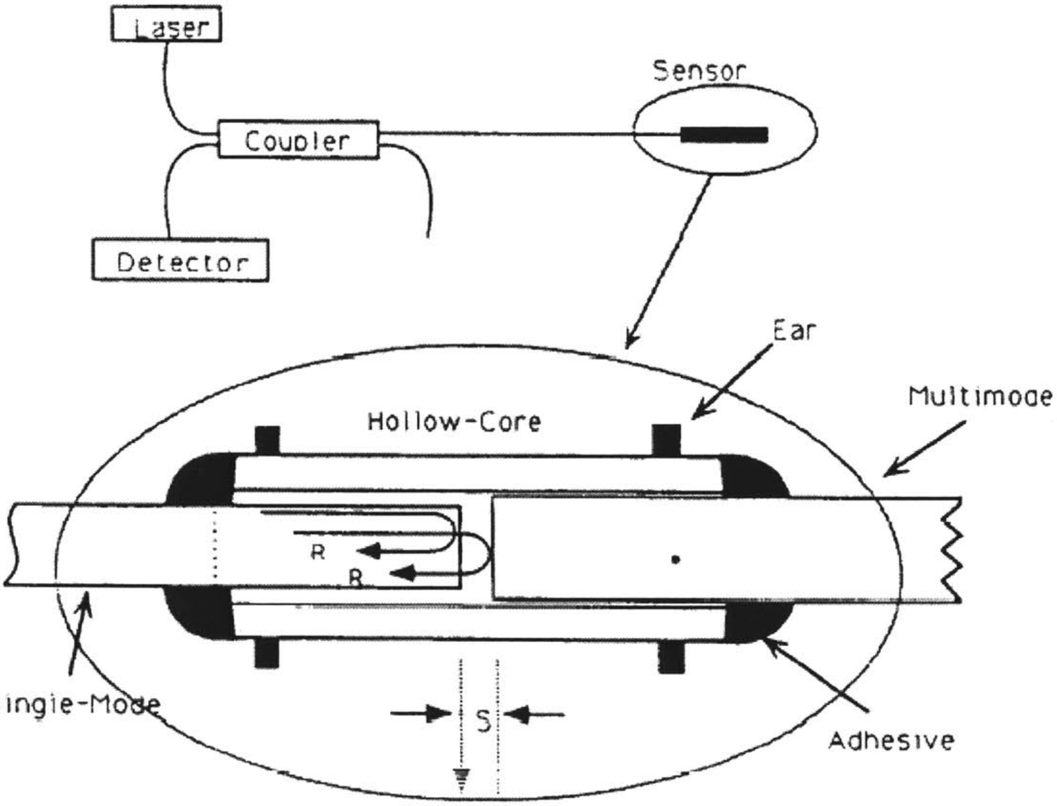


Figure 12 : Fabry-Perot sensor system and geometry (Claus et al. ,1993)

2.6.5 Raman-Distributed Temperature Sensors

Raman scattering is the phenomenon arising from the scattering of light from molecular vibrations (Jackson, 1993). The Raman Stokes and Raman anti-Stokes are two frequency-shifted components that appear in the back-scattered spectrum after an intense light signal is shone into the fiber. The local temperature of the fiber affects the relative intensity of the Raman Stokes and anti-Stokes. Obtaining the temperature profile along the fiber is made possible as whenever a light signal is pulsed and backscattered, this backscattered intensity will be recorded as a function the time taken by the light go forth and back (round trip). In a multi-mode fiber, resolutions of the order of 1°C in the measurement of temperature were attained. In the case of spatial measurement, high resolutions of less than 1 m corresponding to a 10 km measurement range were achieved as well. A new single-mode-fiber based system can extend the measurement range to 30 km, thus trading off the spatial resolution to 8m and the thermal resolution of 2°C (Inaudi, 2000).

2.6.6 Brillouin Distributed Temperature Sensors

Brillouin distributed sensors have shown a considerable promise for distributed temperature and strain monitoring. Field trials have demonstrated new systems capable of measuring variations in temperature or in strain with a spatial resolution in the meter range for fiber length up to 50 km. The Brillouin sensor is unrivaled in strain measurement while it fiercely competes with Raman scattering based systems in the realm of temperature measurement. In optical fibers, interacting optical and sound waves result in Brillouin scattering. As acoustic waves (phonons) are thermally excited, they produce a periodic modulation of the index of refraction. Backward diffraction (by the moving grating) of the light propagating in the fiber gives rise to a frequency shifted component thus giving birth to the (spontaneous) Brillouin scattering (Inaudi, 2000).

2.6.7 Hydrogel-Distributed Humidity Sensors

The hydrogel humidity sensor is based on a hydrogel that swells when exposed to water. This sensor was developed for the first time at Strathclyde University by Mitchie and coworkers (Figure 13, where GFRP stands for Glass Fiber Reinforced Plastic). It can detect the presence or absence of water, indicate regions of high humidity and it is capable of distinguishing between water and humidity (Culshaw, 1998). Swelling of the hydrogel leads to microbending losses in the optical fiber. Losses can be detected with an OTDR. Measurement of water ingress and humidity using the hydrogel sensor becomes particularly advantageous when dealing with large structures or with areas difficult to inspect. Researchers expect that this hydrogel sensor can be improved to detect other chemicals by the simple use of a different type of gel. A particular interest is given to the measurement of pH changes resulting from the carbonation in concrete (Inaudi, 2000)

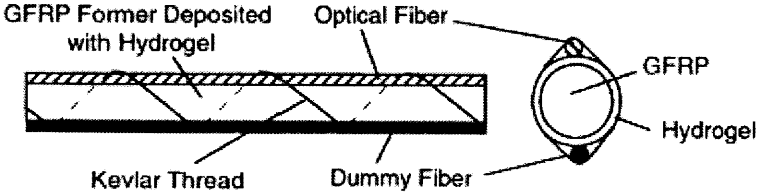


Figure 13: A distributed water/moisture sensor (Leung, 2001)

2.6.8 Mach-Zender Interferometer

The Mach–Zender is one of the most common configurations of interferometric sensors. With the Mach-Zender interferometer, and by the attachment of the signal arm to the structure we can monitor strain directly, while the reference arm (having a length equal to the original length of the signal arm) is kept isolated from the environment (Merzbacher et al., 1995). In a Mach-Zender setup, a coherent light is first injected into a fiber, then an optical coupler splits the injected light into two optical paths. The light retains its coherence due to the coupler. The two optical paths are recombined at a second optical coupler which results in interference fringes (Rempt, 1993). The fringes shift according to the unequal change in length in the fibers. The change in the difference in optical path between the two fibers is measured by the shift of fringes across the interferometer (Rempt, 1993). *"The output of the interferometer appears as a voltage from the PIN diode detector at the end of each of the optical fibers in the output coupler" (Rempt, 1993).*

2.6.9 Michelson Interferometer

The Michelson interferometer depends on the same physical principles as Mach-Zender and makes use of an experimental setup not far different from that used in Mach-Zender with one exception. The exception is that in the Michelson setting, the two beams do not recombine at the end they are instead both reflected back through the fibers by mirroring the fiber ends. The two reflected beams are combined and made to interfere. It is possible to relate the applied axial strain to the light intensity output from the sensor in a similar fashion to the Mach-Zender sensor. The sole difference in these calculations arises from the fact that the effective gage length of the Mach-Zender sensor is optically half that of the Michelson since in the latter's case the sensing beam of light must traverse the sensing zone twice (Shukla et al., 1993). Successful applications of the Michelson interferometer include European bridges and tunnels (examples from Switzerland in the application section) boosts the interest for further research and applications (Udd et al, 1998). The Michelson has been deployed in a series of bridges in Switzerland. One example of a deployed application is in a bridge near Lausanne in Switzerland. "The sensor has a resolution of about 10 microns for a range of gauge lengths that can be many meters long with compensating fiber lengths. Each measurement takes about 10 seconds. The bridge was instrumented with 30 fiber optic deformation sensors, as well as foil strain gauges and thermocouples to test the system." (Udd et al., 1998 citing Vurpillot, 1996).

Type of Sensor	Application	Advantages	Disadvantages
Microbend Sensors	Measure qualitative information through the loss of light : fire detection in large buildings, excess stress locations for pipelines	Low cost; possible coverage of wide area	Low accuracy
Extrinsic Fabry Perot Fiber Etalon Sensors	Measure longitudinal component of strain, pressure or temperature through two mirrored surfaces: single point static strain measurements in experiments and manufacturing processes for structures and bridges, pressure measurements	Gauge lengths similar to conventional strain gauges; immunity to EMI; high temperature, shock & vibration resistant	Difficulties in measuring temperature and strain simultaneously, which may be important for internal measurements in hard to access areas
Intrinsic Fabry Perot Fiber Etalon Sensors	Measure longitudinal component of strain, pressure or temperature through two mirrored surfaces: time varying strain measurement applications, including strain on cylinder heads operating at elevated temperatures, vibrating machinery and dynamic loads on railway bridges	Gauge lengths similar to conventional strain gauges; immunity to electromagnetic interference; high temperature, shock & vibration resistant	Difficulties in measuring temperature and strain simultaneously, which may be important for internal measurements in inaccessible areas
Fiber Grating Sensors	Measure an index of refraction modulation of the fiber core produced by an interference pattern formed through the fiber: strain on bridges, aircraft parts naval vessel parts and utility poles,compared to the same measurements from conventional electric strain gauges	Possible future low cost; multiparameter sensing of transverse & longitudinal strain, strain gradients, temperature, pressure and corrosion	Expensive, due to limited production and use
Mach Zender and Michelson Interferometric Sensors	Measure acoustic waves and vibration, both the time varying and static quantities, since strain, temperature and pressure all affect their response: Undersea surveillance and geophysical seismic exploration.	Extremely flexible geometry and high sensitivity, wide area distribution	High cost; the long coherence length light sources required cannot handle high temperatures.

Table 3: Summary of Types of FOSs (Source: Udd et al., 1998)

2.7 COMPONENT COST AND AVAILABILITY

(Source: Udd et al., 1998)

2.7.1 Microbend Sensitive Optical Fiber

The microbend sensitive optical fiber is commercially available. In very small quantities, it can be a few dollars per meter as opposed to a few cents per meter for telecommunication grade optical fiber (Udd et al., 1998).

2.7.2 Fiber Etalons

In 1998 each demodulator unit costs somewhere between $12,000 to $15,000 while the price of an individual sensor is around $300. A basic demodulator unit costs $9000 and its sensors are about $150 to $200 per unit. A 14-channel unit sells for a price of less than $20,000.The cost of Individual sensors ranges between $300 and $500 depending on type and packaging (Source: Udd et al., 1998).

2.7.3 FBG

In 1998, the price of a single element fiber gratings ranged between $150 to $500 (prices vary with manufacturers). A reasonable price for a 1000 unit buy may reach 50,000 (i.e $50 per fiber grating). In 1998, the cost is expected to drop to the range of $25 to $40 by year 2000. Manufacturers argue that the intrinsic costs of the fiber gratings are quite low and it they expect their cost to compete with conventional foil gauges (Udd et al., 1998).

2.7.4 Michelson Interferometer

“Each sensor in a plastic tube for mounting costs between $500 and $1000 dependent on the exact configuration used. The demodulation system is about $35,000.”(Udd et al., 1998)

3 FIBER OPTIC SENSORS CHARACTERISTICS

3.1 DESIRABLE CHARACTERISTICS

Merzbacher and coworkers (1995) listed the desirable characteristics in the ideal FOS for Structural health monitoring purpose in civil structures as follows:

> *"(i)stable; (ii) localized; (iii) adequate sensitivity and dynamic range; (iv) linear response; (v) sensitive to direction of measurand field change; (vi) single ended, to minimize the number of leads; (vii) insensitive to thermal fluctuations; (viii) capable of absolute measurement; (ix) non-perturbative to the structure; (x) immune to power interruption; (xi) able to multiplex; (xii) easy to mass produce; (xiii) durable for the lifetime of the structure" (Merzbacher et al., 1995).*

The measurand of interest, the sensitivity and dynamic range required are among the most important factors that determine the type to be employed, since there exists no individual sensor capable of meeting simultaneously all the criteria mentioned above (Mezerbacher et al. 1995).

The harshness of the structural environment should be taken into serious consideration whenever a sensor is to be selected. Chemical and mechanical durability of the FOS are an absolute pre-requisite for the embedding of optical fibers in concrete. The main challenges to FOS reliability are the high alkalinity of concrete (pH 12) and the physical abuse associated with placing fiber into concrete or pouring the concrete mix over the fiber. In general, the polymer coating is the only protection between the glass fiber and the surrounding environment. Therefore the coating must be strong and chemically impervious, ideally with an elastic modulus that closely matches that of the glass fiber (Merzbacher et al. 1995).

3.2 ADVANTAGES

FOS exhibit a set of advantages that make them attractive to users; some of these features are unique to FOS and are not offered in other types of sensors.

- **Light Weight.** FOS cables are lightweight. This economy of weight and size reflects the fact that a single FOS cable can carry both the excitation and signal light over the same line. Further savings also arise from the fact that such cables can be multiplexed, thereby reducing many of the cabling problems (Huston et al, 1994).

- **Allowing for Distributed Sensing.** Some configurations allow FOS to sense spatially distributed quantities. Distributed sensing (refer to the previous chapter's explanation of distributed sensing in section 2.5.2.3) can be particularly useful in several applications especially in those with large structural members (Huston et al, 1994).

- **Immunity to Electromagnetic Interference.** In conventional sensors, the long metallic cable lengths can act as large antennae, thus making them vulnerable to risks such as electro magnetic interference (EMI), creating ground loops, attracting lightning strikes. In FOS and since cables are non-metallic, all these risks are eliminated (Huston et al., 1994).

- **Very Small Size.** Due to their small size FOS are non-intrusive and therefore do not affect the properties of the concrete where they are embedded. An additional advantage to the small size is that the FOS become a less obvious target for vandalism and theft (Merzbacher et al, 1996).

- **Environmental Ruggedness.** FOS can be embedded in composite materials with no major concern, if not at all. They can successfully operate and withstand both high and low temperatures as well. The initial quasi-liquid state of freshly poured concrete facilitates the task of placing sensors into the mix (More details about reliability of FOS are presented in 3.3.3) When cured concrete begins to solidify, FOS will be able to sense its internal state. Material compatibility is a major advantage of embedding fibers in composite materials mainly because fibers are not subject to degradation during curing along with their strong bond to the matrix (Ansari, 1997). FOS' resistance to corrosion may be the most salient feature of their environmental ruggedness mainly because corrosion is the main culprit for the degradations inflicted on structural materials (concrete and steel). Corrosion risks must be particularly accounted for in the case of long-term installations that are exposed to the elements (Huston et al, 1994). (For more details on corrosion risks, refer to 1.1.4)

- **Geometric Compatibility.** During construction, the embedment process of FOS is greatly facilitated due to the geometric adaptability of FO, thus providing an exceptionally powerful tool for crack detection (Ansari, 1997). The possibility of embedding FOS in tight areas is especially valuable when used in concrete or earthen structures where accessibility is sometimes a major issue (Huston et al, 1994).

- **Multiplexing.** Multiplexing is the technique where a series of parameters (temperature, corrosion, strain...etc) can be sensed simultaneously along the same fiber line (Ansari, 1997). Multiplexing of sensing and communication signals on the same fiber is made possible owing to the high bandwidth of the cabling (Huston et al, 1994). *"The ability to interrogate numerous sensors multiplexed along a single fiber permits an entire structure to be outfitted with sensors with a manageable number of leads routed to central access points" (Merzbacher et al. 1996).* (Refer to section 2.5.2.2).

- **Future Cost and Performance.** As a high degree of synergy with the telecommunication and optoelectronic markets exists, the promise of reducing costs of the sensing applications components is expected to materialize soon, especially that the FO telecommunication enjoy all the advantages associated with a larger market (research & development, mass production, economies of scale, etc.). Experts expect that in the near future FOS will gain further ground in the structural sensing industry (Inaudi, 2000).

- **Feasibility of Remote Monitoring.** FOS enjoy the inherent ability to serve at the same time as both the sensing element and the signal transmission medium, thus allowing the remote placement of the electronic instrumentation. This property may be especially useful in the particular case of bridge remote monitoring (Ansari, 1997).

- **Diversity of Sensor Lengths.** FOS have a wide range of gauge lengths the values of which can range between fractions of millimeter and many kilometers. Moreover they can use FO demodulators located as far as many kilometers from the sensors themselves. The signal to noise ratio is not substantially affected by the distances involved (Udd et al. 1998).

3.3 LIMITATIONS

The path toward large scale implementation and commercialization of fiber optic sensors for structural health monitoring is still impeded by many factors. Some of the most salient are described in the following sections.

3.3.1 Codes and Standards

Engineers are still reluctant to apply FOS even in the instances where it outperforms conventional methods. The idea is still relatively new and the use is not widespread. However reluctance from the part of engineers to use FOS in structures can be fully understandable in the absence of approved design codes that regulate standard practices. In Canada, ISIS (Intelligent Sensing for Intelligent Structures) published four manuals for design engineers. These manuals deal with new technologies such as FOS as well as FRP (fiber reinforced polymers). For the Canadian civil engineering practice, this can be seen as an important step toward the widespread use of FOS (Mufti, 2003). Two of the four manuals are related to FOS, as manual No.1 discusses the installation, use and repair of fiber optic sensors , while manual No.2 contains guidelines for structural health monitoring *(Mufti, 2003).*Once the industry is standardized economies of scale can be realized.

3.3.2 Difficulties With Large Structures

Difficulties confronting the deployment of FOS in large civil structures include the following (Fuhr and Huston, 1993):

- Many sensors are to be installed in spatially diverse areas
- The freedom in embedding a desired number of fibers will be seriously limited by one or a combination of considerations of structural, mechanical (power, heating, ventilation, etc.) and architectural/aesthetic nature (interior walls, flooring and ceiling materials, etc). The number of sensors, the placement of the sensor and the access to fiber ends will be limited as well.

- The transition and transfer of technology between lab and field is not as easy as some may imagine. The harsh construction environment, building space preferences of the owner and even acts of vandalism are some of the factors that impact proper use and functioning of FOS.

A real life example of difficulty is presented by (Huston et al., 1994): in the field application in the Winooski dam in Vermont, where they deployed more than 70 sensors all over the structure (sensors having different lengths ad spacing). In this case it was not possible to associate one access point per sensor. Consequently it was particularly important to use multiplexed sensors in order to reduce to a minimum the number of access points (Huston et al, 1994).

3.3.3 Reliability Issues for FOS

In the view of some authors, for a sensor system to be employed on a construction site, the system must be made sufficiently robust that it need not factor into the consideration of pedestrians, construction personnel, or maintenance crews (Sirkis, 1998). While this is a valuable opinion, I think there can legitimately be some disagreement on this issue.

Mechanical and optical reliability will be presented next, for the general case of a FOS and for the particular case of FBG

3.3.3.1 Mechanical Reliability

The main material component used in manufacturing of FO is amorphous quartz, which is characterized by a low fracture toughness (Sirkis, 1998). Usually low fracture toughness is associated with low mechanical strength. Surprisingly, the case of optical fibers is an exception as optical fibers benefit from very high mechanical strength that is almost 3 times as large as the strengths of the strongest steels. This seemingly contradiction is explained by the fact that the initial surface flaws in optical fibers are on the atomic scale due to the very well controlled manufacturing conditions. In a properly coated fiber, these atomic scale flaws rarely exceed the minimal threshold length needed to initiate a crack growth (Sirkis, 1998). Finally, properly selected high strength optical fiber can substantially mitigate the risk of a stress induced failure of the FO (Sirkis, 1998).

Despite its high strength, the proper selection of high strength FO, cannot ensure protection against failure scenarios such as crushing, stress corrosion, and surface oxidation. Small diameter FO cable structures intended to protect against crushing were successfully developed by the telecom industry (one of the examples of the synergistic benefits due to the Telecom industry). Sirkis (1998) defines stress corrosion as *"the breakdown of covalent bonds in the amorphous silica dioxide fibers"* that primarily arises from exposure to moisture. Dams are an example of civil structure that experience a constant state of 90% relative humidity. Once again the solution was provided by the fiber optic community: this time the solution was based on coatings made of materials, like carbon and gold, known for their hermetic properties (Sirkis, 1998).

Embedding the FOS in concrete complicates the issue of coating design. Every concrete mix involves cement and water whose mixing results in a hydration reaction. Calcium hydroxide is the product of the hydration reaction and it is responsible for the high concrete alkalinity. Protective coatings offering 100% protection against such alkalinity are not yet available; available coatings made of acrylate, polyimide, fluorine thermoplastic, and Tefzel experienced some degradation when embedded in concrete (Sirkis, 1998). Finally, in the case of strain sensors, it should be considered that coatings must be able to provide sufficient strain transfer to the fiber (Sirkis, 1998).

3.3.3.2 Optical Reliability

Whenever an optical fiber is exposed to elevated temperatures properties such as reflectivity and bandwidth in general and Bragg wavelength in the particular case of FBG, will experience an initial rapid change then the decay becomes slower (asymptotically returning to steady state). Annealing the gratings at temperature levels higher than the temperature level intended for operation guarantees the thermal stability at high temperatures. Annealing leaves only the very stable portion of the grating properties as it relaxes the portions that are susceptible of changing over the lifetime. As an example, gratings that are annealed at 650°C gratings are designed for an actual use at 427°C (Sirkis, 1998).

The absorption characteristics of the fiber can be seriously altered and damaged by humidity. Sirkis (1998) states the following example: *"Tests on fiber optics were conducted in order to determine how temperature and humidity affect the optical properties of the fibers. After exposure to 1000 hours at a 85°C temperature and 85% humidity, no change was observed. Also after 1000 thermal cycles from 40 °C to 85 °C or 512 cycles from 21 °C to 427 °C no change in gratings properties was observed. Mechanical testing was also applied to gratings, 1.4 million strain cycles from 0 to 2500 $\mu\varepsilon$, and no change in properties was observed"* (Sirkis, 1998).

3.3.4 Practical Considerations

A group of researchers (Huston, Fuhr and coworkers) from the University of Vermont conducted extensive research on fiber optic sensors and had the opportunity to deploy sensors in a good number of structures (refer to section 5). Their experience included, among others, bridges, a five-storey building, and a medium-sized hydroelectric dam. Out of this experience they brought a number of issues to be considered during installation and repair. These issues as quoted from Huston & Fuhr (1998) are:

- ***"Construction Environment Site:** The typical construction site is a very harsh environment with lots of vigorous activities and the use of heavy equipment. The FOS must be designed to be rugged enough so as to withstand routine mishaps. It will also be useful to have sensor personnel on site during all phases of the operation when sensors are exposed and vulnerable".*
- ***"Ingress and Egress from Concrete Formwork:** When sensors are to be embedded in concrete, cables connecting to the embedded sensors must be placed so that they are easily accessed once forms are removed. This requires careful coordination with the engineers and the construction crews".*
- ***"Construction Site Timing:** The installation techniques for the fiber sensors should be rapid and produce minimal disruption to the construction crew.*
- ***"Avoidance of Cable Runs:** The difficulty of placing sensors into the internal workings of a complicated bridge structure, particularly if it is a mesh of reinforcing bars , seems to go up exponentially with the length of the cable that is directly attached to the sensor. These difficulties can be avoided either by creating multiple points for the attachment of optical instruments, splicing, or a distributed spliced fiber optic network".*
- ***"Sensor Access:** It is very desirable to have embedded fiber optic sensors placed in a way that they can be accessed and repaired, otherwise sensors should be either very robust or expendable".*

4 PREVIOUS and RECENT WORK

Fiber optical sensors (FOS) were built for the first time in Germany in 1978 by Butter and Hocker (Measures, 2001 citing Butter and Hocker, 1978); these were primary gauges characterized by their inability to provide any additional information beyond the change in total length of the instrumented component, as well as their very limited strain resolution (Mufti, 2003).

Hill et al. (1978) discovered how to produce Bragg gratings by exposing the optical fiber core to light (Measures, 2001 citing Hill et al. (1978)).

Varham et al. (1983) developed a polarimetric FO strain gauge, and Corke et al (1984) developed a localized FO temperature sensor (Measures, 2001 citing Varham (1983) and Corke (1984)).

Civil engineering research and experimenting with FOS did not start earlier than the late 1980s, most of this work was motivated by the desire to use FOS in conjunction with construction materials (Ansari, 1997).

The use of embedded fiber-optic sensors to measure physical quantities in concrete was first suggested by Mendez and coworkers in 1989 (Merzbacher et al. 1995).

In 1988, an FOS capable of determining the content of air in fresh concrete mixes was developed by Ansari (Figure 14 & Figure 15). The sensor measures the reflected intensity of light through the tip of an optical fiber in contact with fresh concrete (Ansari, 1997).

The research of Rossi and LeMaou (1989) involved crack detection on the basis of light intensity loss in the embedded optical fiber" by embedding FOS in concrete beams (Ansari, 1997).

Meltz et al. (1989) succeeded in turning the FBG discovered by Hill et al. (1978) to a practical device (Measures, 2001 citing Metz et al. (1989)).

Morey et al. (1989) showed that FBG make excellent strain sensors (Measures, 2001 citing Morey et al. (1989)).

Lee and Taylor (1989) produced the first intrinsic Fabry-Perot interferometric sensor (Measures, 2001 citing Lee and Taylor, 1989).

Murphy et al. (1991) developed the first extrinsic Fabry Perot interferometric sensor (Measures, 2001 citing Murphy et al., 1991).

Nanni et al. (1991) embedded polarimetric optical fibers in cylindrical specimens of concrete. They analyzed the characteristics of the fiber-interface bond with respect to the surrounding concrete matrix (Ansari, 1997 citing Nanni et al.).

In 1992, Measures et al. developed a passive method to read FBG, this led to the first commercial sensing systems based on Bragg gratings (Measures, 2001).

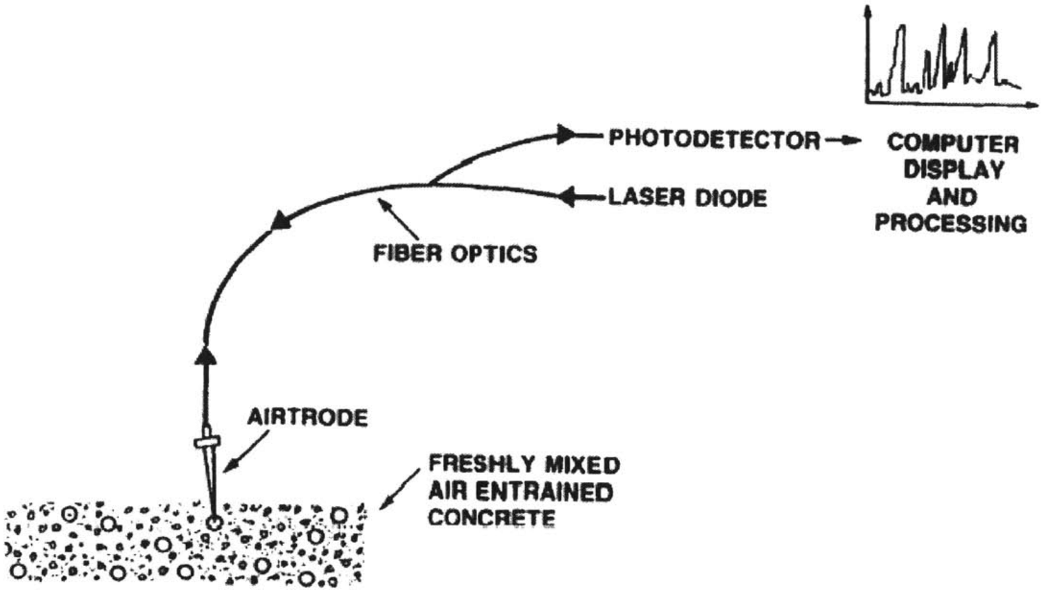


Figure 14 : Detection of air bubbles in fresh concrete by an optical fiber (Ansari, 1997)

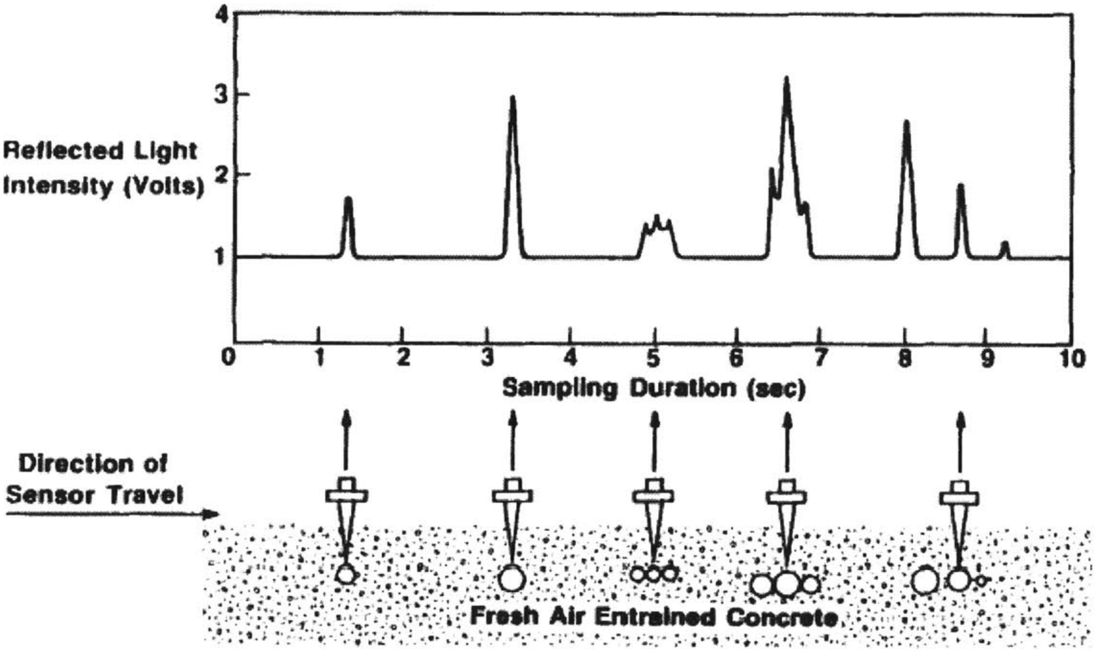


Figure 15: Effect of bubble size and spacing on the amplitude of the reflected signal (Ansari, 1997)

Ansari and Navalurkar (1993) developed an intensity-based FOS capable of direct measurement of the crack-tip opening displacements (CTODs) in cementitious materials (Figure 16) (Ansari & Navalurkar, 1993).

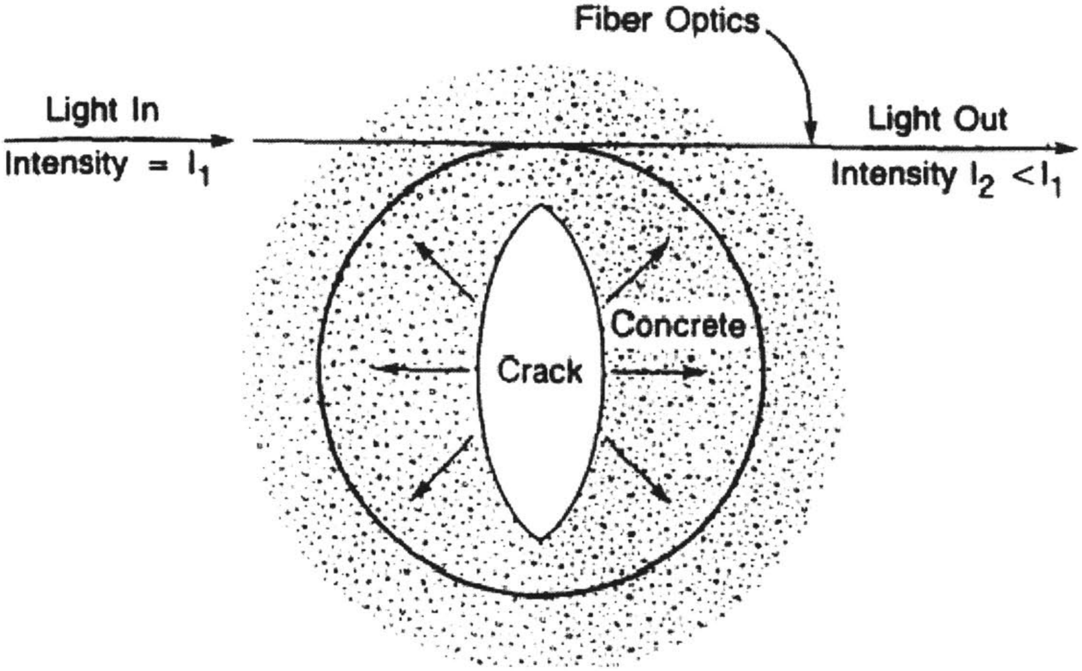


Figure 16 : Fiber Optic CTOD sensor for Concrete (Ansari & Navalurkar, 1993)

Wolff and Miesseler (1992) employed FOS to monitor the prestressing force, and crack formations in the Schiessbergstrasse bridge in Germany (Ansari, 1997 citing Wolff & Miessler, 1992).

Maher and Nawy employed FBGs for measurement of strains in steel rebars in high-strength concrete beams. Measured strains showed good agreement between FBG and conventional strain gages (Maher & Nawy, 1993).

Hendrick et al. (1992) simulated typical soils by epoxying polarimetric FOS in polyurethane samples. The elastic modulus ranged between 2,000 and 50,000 psi (Mezerbacher et al. 1995 citing Hendrick et al, 1992).

Escobar et al (1992) have done lab experimental studies where they used bonded FO strain gages on concrete beams (Huston et al., 1994).

Huston et al. (1992) and Fuhr et al. (1992) were among the first groups to report laboratory studies of the use of FOSs in reinforced concrete. They embedded various types of optical fibers inside small 0.1 x 0.1 x 1.0 m^3 reinforced concrete beams. Their first test determined the optical fiber survivability during the embedding and curing processes (Huston et al., 1992).

If optical fiber can be wrapped into metal rope, this will permit for embedded strain detection along the length of the metal rope. May et a1 (1992) used extrinsic Fabry-Fizou interferometric strain sensors to monitor steel ropes. Harrison and Funnel (1991) reported the use FOS in monitoring the overheating of power transmission lines (Huston et al., 1994 citing May et al and Harrisson &Funnel).

Holst and Lessing (1992) monitored shifting between segments in dams by installing FO displacement gages (Huston et al., 1994 citing Holst & Lessing (1992)) .

In some field installations, FOSs are used to measure the weight of trucks as they drive over sensitive strips at highway speeds. Caussignac (1996) has reported field stress measurement of the internal stresses in neoprene bridge bearings (Udd et al., 1998 citing Caussignac, 1996).

"Askins et al (1994) have demonstrated the ability to write large numbers of gratings, each with slightly different resonant frequency, along a single fiber on a draw tower during the fiber drawing process, making processing costs comparable to those for telecommunication fiber" (Merzbacher et al. 1995 citing Askins et al).

Fuhr et al. (1994) conducted a series of studies on FOS. They embedded sensors in reinforced concrete (RC) beams that were subjected to four-point bending stress tests. At the end of the experiments, they compared the results of FOS detection with those of more traditional inspection techniques The tests revealed that the embedded fiber-optic sensors regularly recognized cracking in the reinforced concrete beam at load levels about 80% of the loads detected by the conventional methods for determination of cracks in RC beams. Structural engineers showed a strong interest in these findings since SHM is performed through an automated method and most importantly because the new technology offers an earlier crack detection that was never available through the use of conventional methods and particularly via the external visual inspection (Huston et al, 1994).

Habel and Hofmann (1994), a German research group at BAM in Berlin, used Fabry Perot sensors *"to monitor the early-age deformations of mortars and has applied them to the monitoring of a concrete bridge in Charlottenbourg"* (Inaudi, 2000). They deployed interferometric sensors on the bridge that had visible cracks. While the bridge was subjected to a test load and to a normal traffic load , they measured the deformation and vibration in the exposed steel rebars by means of extrinsic Fabry-Perot Interferometer (EFPI) sensors attached to the rebars. The strains detected were on the order of 10 microstrains with 1 microstrain uncertainty (Merzbacher et al., 1995).

Wolff and Miesseler (1992) monitored crack formation and corrosion in a bridge in Keverkusen, Germany. FOSs were embedded in the upper and lower surfaces of the bridge during the construction process (Mezerbacher et al. 1995 citing Wolff and Miesseler, 1992).

Teral and coworkers (1992) used polarimeteric interferometric fiber sensors as "weigh in motion" sensors for vehicles (Udd et al., citing Teral, 1992). FOS were embedded in a road surface. They remarked that as the weight and speed of a vehicle increased the number of fringes and their frequency in the output of the polarimetric sensor increased accordingly (Mezerbacher et al. 1995 citing Teral 1992).

Inaudi and co-workers carried out many applications of FOS to underground civil projects. Part of their work aimed to instrument of the anchoring cables that are used to stabilize a rock slide area. They also installed a double-interferometer system in a precast concrete tunnel lining in Fribourg, Switzerland (Mezerbacher et al., 1995).

Claus et al. (1993) developed an extrinsic Fabry-Perot interferometric sensor (Figure 17) element that has been demonstrated at temperatures between -200 and 900 °C. As a strain sensor the EFPI was capable to detect and measure structural deformations as small as 0.1 nm (Claus et al., 1993).

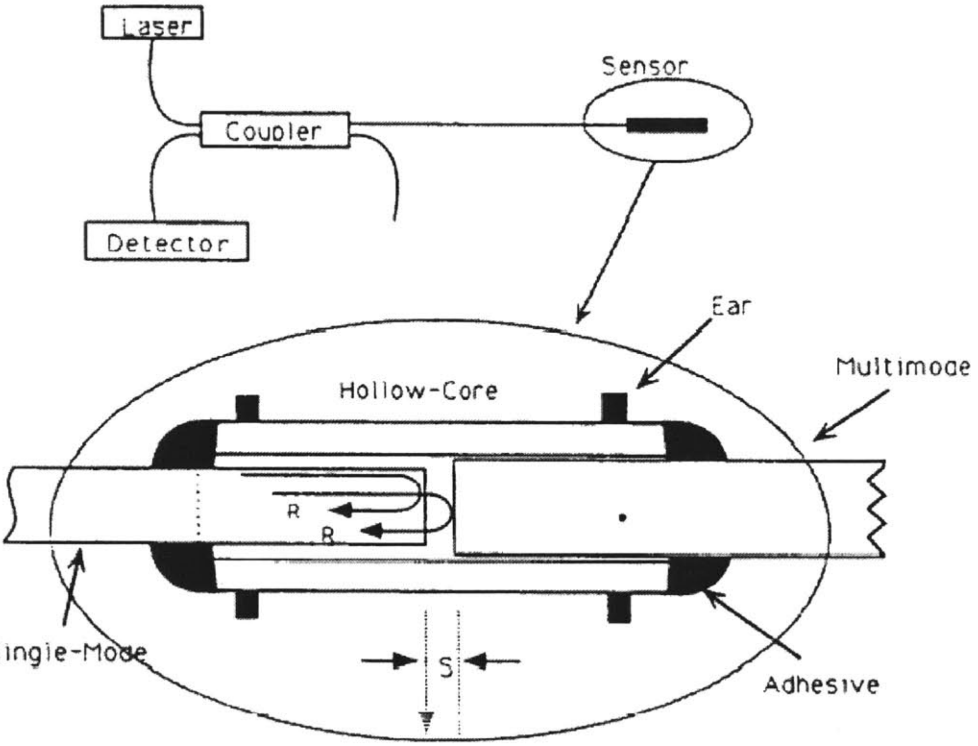


Figure 17: Fabry Perot sensor system and geometry (Claus et al., 1993)

Zimmerman and Claus demonstrated the feasibility of an optical fiber time domain time domain reflectometer (OFTD) strain sensor (Figure 18). This OFTD is designed for the distributed measurement of strains at various segments along the length of anchoring tendons (Zimmermann & Claus, 1993).

Michie et al. (1994) developed a distributed FOS system for grout detection in ducts containing prestressing steel tendons. In voided areas, prestressing steel becomes exposed and unprotected which makes it an easy prey to corrosion, consequently it becomes very important to be able to detect voids in grouted ducts (Ansari, 1997). The system mechanism is described previously in the section on hydrogel sensors.

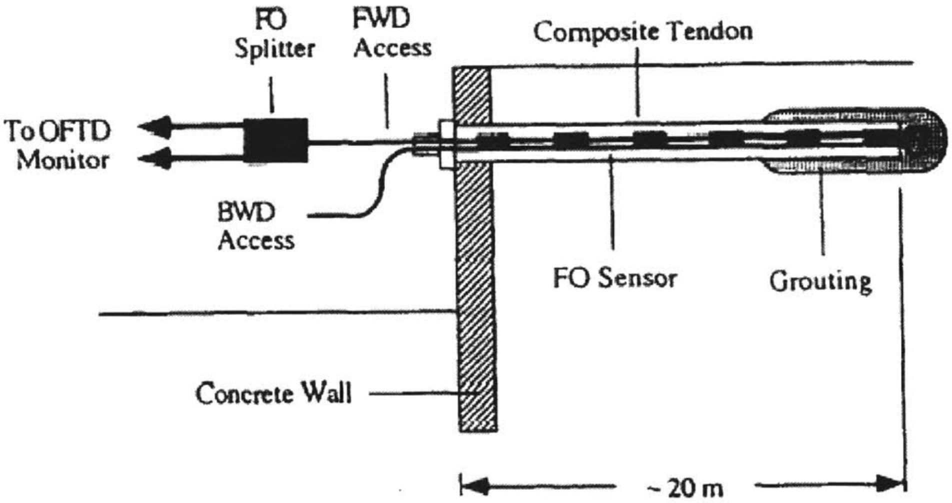


Figure 18 : Distributed sensor for concrete wall anchoring system (Zimmermann & Claus, 1993)

Habel and co-workers (1994) used a Fabry-Perot sensor to monitor the condition of a cracked box girder in the Charlottenburg Bridge in Berlin (Huston et al., 1994). The system measured the natural frequency of the bridge and the load-carrying capacity of the cracked girder. They also measured the hydration associated strains of concrete in a wall by using the same Fabry Perot sensor. Habel and coworkers' most important work was the development of a set of experiments intended to determine the durability of optical fibers in the highly alkaline (pH 12) concrete environment. Their effort culminated in finding that the most durable coatings were the ones based on fluorine-containing polymers (Huston et al., 1994).

FOS to detect chloride were also developed; these sensors' greatest promise lies in their applications to roadways and bridges, where salinity is a major cause of corrosion (Udd, 1998 citing Fuhr, 1996). This chloride detection sensor is to be embedded into the rebar-concrete highway. The chloride sensor uses a fiber sensor that consists of a reagent at the end of an optical fiber. When Light propagates down the fiber it will cause the fluorescence of the reagent. Spectroscopic analysis will be used in order to measure the chlorine content (Udd et al., 1998).

Another approach to chloride sensing is based on the change of color of a silver chromate strip whenever exposed to chloride, that changes the overall transmission efficiency of an FOS system (Udd et al. 1998 citing Cosentino, 1995).

A new FOS for that detects and monitors cracks in concrete structures (Figure 19) was developed by Leung et al. (2000). The main advantages inherent to this new technique, as compared to the conventional detection and monitoring methods, are: (1) there will be no need to know in advance the location of the crack, (2) a large number of cracks can be detected and monitored by the use of a small number of fibers (Leung et al., 2000).

Ansari, Libo and Lee (1997) developed a high resolution optical fiber sensor for measurement of strains and deformations in structural elements. This allowed for direct measurement of crack tip opening displacements (CTOD). Fiber optic results suggest the detection of crack tip opening displacements much smaller than the ones the traditional methods are able to detect (Ansari, Libo & Lee, 1997).

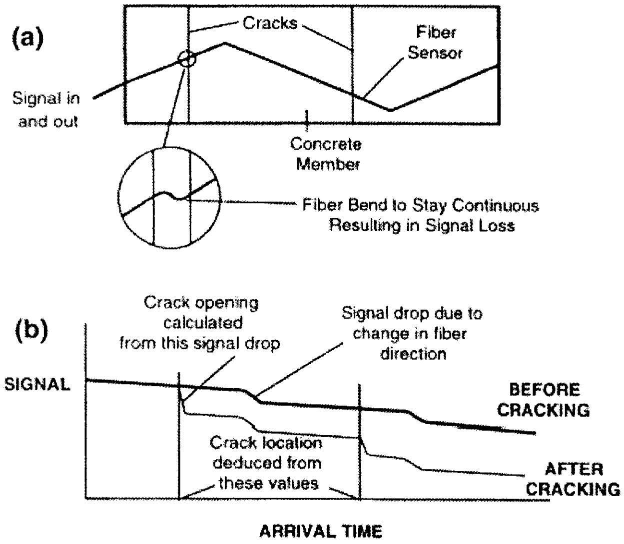


Figure 19: The crack sensing concept (Leung , 1997)

Libo and coworkers (1997) developed a theoretical expression describing the constant of proportionality used to compute the actual strain induced in the material given the strain sensed by the optical fiber (Libo et al., 1997). The researchers argued that the relationship found would eliminate the need for calibration tests usually performed prior to the employment of the sensor (Libo et al., 1997).

Carolyn Dry at the University of Illinois-Urbana developed "*an adhesive liquid core optical fiber to detect the cracks and their locations and volume in opaque and semi-*

opaque brittle materials. The liquid filled hollow fibers can carry light in the liquid. The cracked fiber releases liquid and projects diffraction patterns from the meniscuses at the end of the liquid. The size relationship of these patterns allows to determine the location of the cracks and the volume of the cracks given the volume of liquid lost." The released repair chemicals or adhesives act to bond and seal the cracks and rebond fibers making the cement stronger in bending (Dry, 1998).

Bock and Eftimov developed an optical fiber sensor capable of directly measuring internal stress in concrete structures. The technique offers important advantages over the use of strain gauges method (Bock & Eftimov, 1993).

RECENT WORK

Inaudi (1996) and Vurpillot (1996) developed a multiplexed Michelson interferometer for the multiple locations strain measurement in bridges and tunnels (Udd et al., 1998 citing Inaudi, 1996 & Vurpillot, 1996).

Udd (1996) proposed the combination of interferometric sensors and FBG to be used on bridges and other large civil structures. They will be using static and dynamic sensing and their task will be a multifunction distributed sensing for damage location detection (Udd et al., 1998).

FBGs were deployed in the Mont Teri tunnel in Switzerland as part of STABILOS and COSMUS which are two European research initiatives on the applications of FBGs to the measurement of movements in geostructure (tunnels, mines, etc.) (Inaudi, 2000)

The French group LETI used FBG to monitor lock gates. They are also attempting to introduce the system in the nuclear power industry (Inaudi, 2000).

Measures and coworkers developed a “universal” demodulation capable of accommodating the full range of FBG sensing (short-gauge length, long-gauge length, multiplexed, and distributed) (Measures, 2001).

ISIS Canada is conducting research using four sensors (Fiber Bragg Grating, Fabry-Perot, Long Gauge and Brillouin Scattering). Researchers in ISIS Canada developed a new type of fiber optic sensor: the Long Gauge, similar efforts are spent in developing the Brillouin Scattering technology (Mufti, 2003).

5 DEPLOYED APPLICATIONS

This chapter examines several real applications of sensor technology for infrastructure monitoring. Each example provides insights to the realities. We discuss briefly the approach and and success of each system. Much of the information discussed is from Mufti et al. who have catalogued one of the most extensive set of references for monitoring of bridges and structures in North America. Examples also include the research pursued at the University of Vermont (Huston, Fuhr & coworkers).

5.1 THE BEDDINGTON TRAIL BRIDGE, CALGARY

"The Beddington Bridge is a two-span, continuous skew bridge of 22.83-m (75-ft) and 19.23-m (63-ft) spans, each consisting of 13 bulb-T-section, precast, prestressed concrete girders"(Mufti et al., 2003). This is the first bridge in Canada to be instrumented with fiber optic sensors, and the first bridge known to contain pre-stressed carbon fiber composite cables with FBG sensors embedded in the concrete girders supporting the bridge (Measures et al., 1995). A total number of 20 FBG temperature and strain sensors were installed in 1993. The system monitors structural behavior first during the construction phase and later on when the bridge becomes operational (Mufti et al., 2003). The interrogation system developed was a portable four channel demodulation system that can interrogate at any time a minimum of four FBG. The prestressing tendons were of three types: two different types of fiber reinforced polymers (FRP) were used in 6 girders (4 of one type and 2 of another), while steel tendons were used in the remaining

20 girders. The measurement system recorded the strain relief for each of the three types of tendon. The time interval for the measurement spanned several months since the time of construction of the bridge. The system measured also "*the change in the internal strain within one of the concrete girders resulting from both static and dynamic loading of the bridge by a large truck" (Measures et al., 1995).*

In 1999, following 6 years of operation the durability of the FOS was assessed by testing the bridge statically and dynamically. All FOS were functioning, which suggests the long term durability and reliability of FOS used for SHM purposes (Mufti et al., 2003).

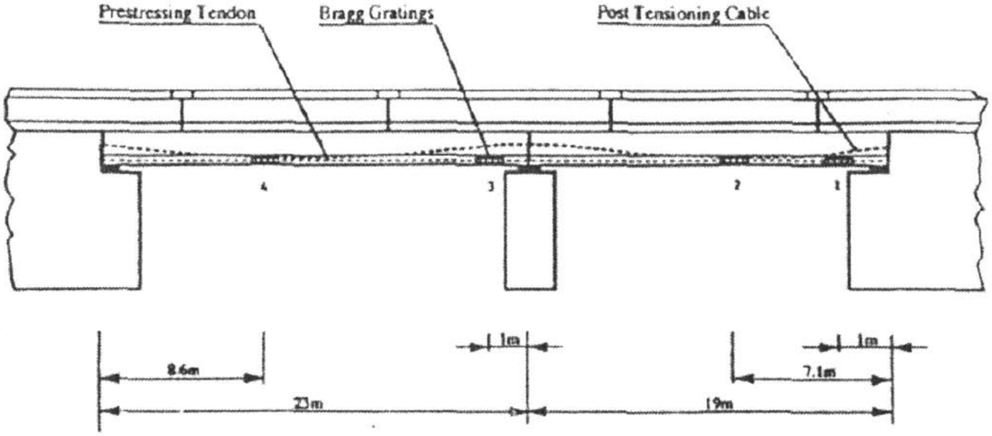


Figure 20: Bragg grating laser sensor locations in the Beddington Trail Bridge (Measures et al. ,1995)

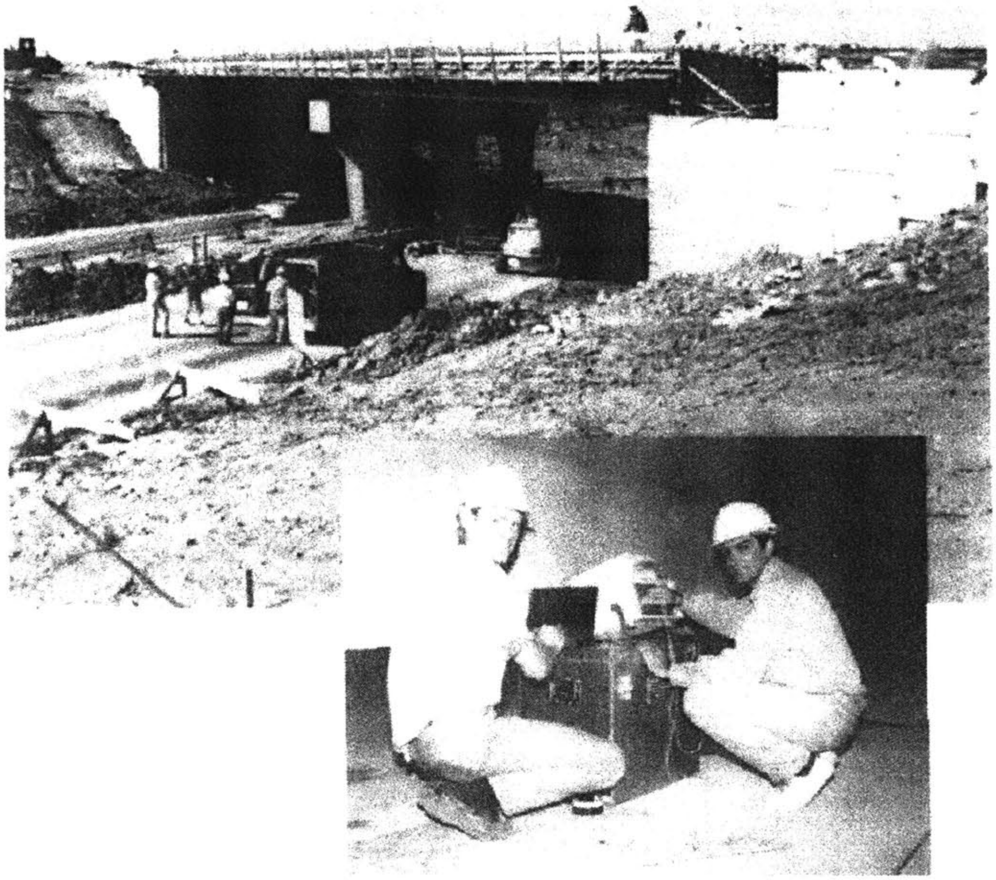


Figure 21: Beddington Trail Bridge (Top), a four channel Bragg grating demodulation system used (Bottom) (Measures et al. ,1995)

5.2 THE TAYLOR BRIDGE, WINNIPEG MANITOBA

This is a two lane, 5 spans, 165.1 m long and 9.6 m wide bridge spanning the Assinboine River (Maaskant et al., 1998). The structure consists also of 40 prestressed concrete AASHTO-type girders (Mufti et al., 2003). When it was designed, the Taylor Bridge was considered to be the world's largest highway bridge reinforced by fiber reinforced polymers (FRP) and monitored using FOS (Mufti, 2003). A network of 64 FBG sensors were distributed over the structure to monitor the strains and temperature in the FRP reinforcement of the girders. Sensors were glued to the structure using a rigid epoxy. As they were mounted on both steel reinforced girders, FRP reinforced girders and in the FRP reinforced deck and wall barrier (Maaskant et al., 1998).

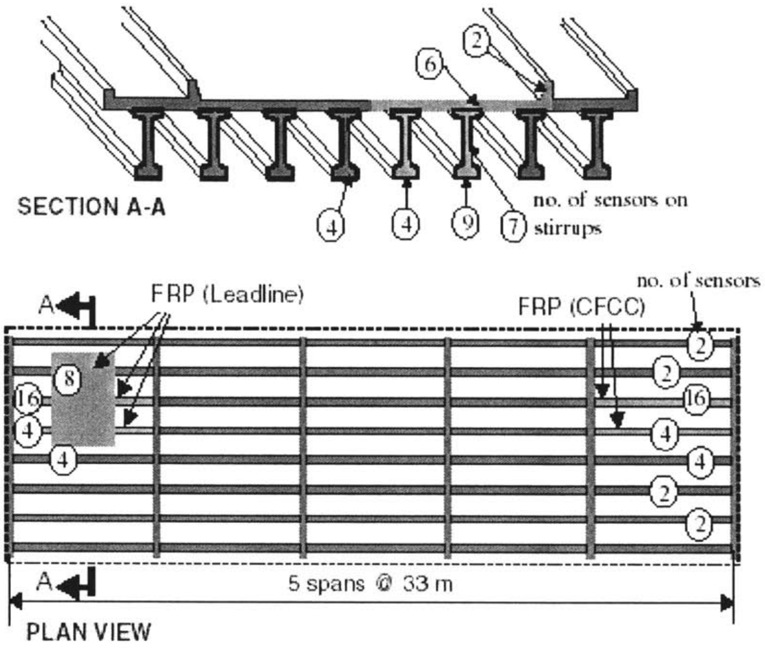


Figure 22 : Sensors locations in the Taylor Bridge (Mufti et al.,2003)

*"The FBG sensors were installed at different locations along the girders (*Figure 22*). FBG sensors located at the midspan were designed to monitor the maximum strain in the reinforcement due to applied loads, while FBG sensors located at the girder ends were designed to evaluate the transfer length of pre-stressing tendons" (Mufti, 2003).*The FBG sensing system described above, is based on a parallel sensor architecture which means that one fiber lead will be required for each of the 64 sensors installed. This parallel configuration offers an advantage over the serially structured sensing system, for in the case of failure of a fiber or of any of the sensors the remaining sensors will remain functional. This is especially important in the case where sensors are embedded or physically inaccessible (Maaskant et al., 1998).

Strain measurements were performed using a 32-channel fiber optic grating indicator, FLS 3500R, that was connected to a PC to be able to download the strain readings by telephone line (Mufti et al., 2003). In order to check the validity of the values obtained from the FOS, an additional 26 conventional electrical strain gauges were mounted on the reinforcement to monitor the bridge deformations (Mufti et al., 2003).

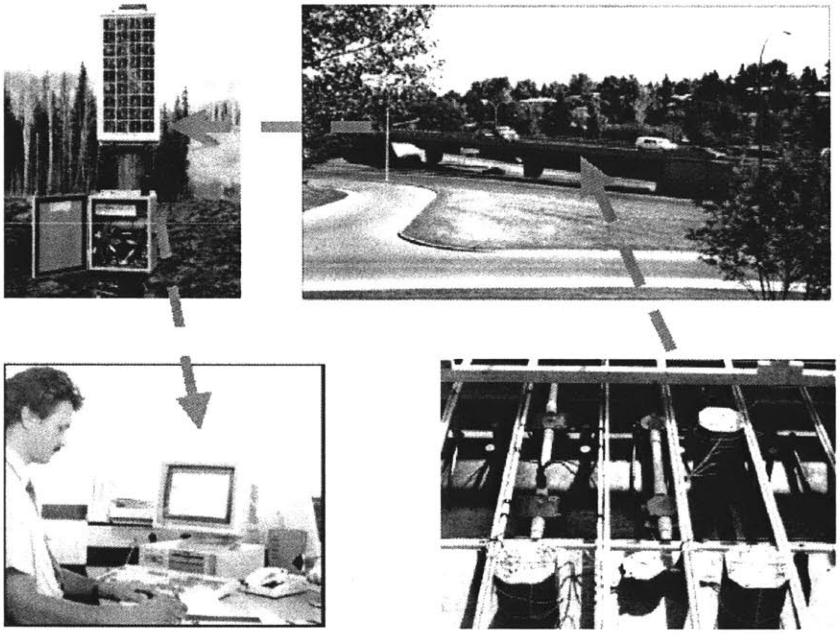


Figure 23: FRP reinforcement, FOS and remote monitoring system of Crowchild Trail bridge (Mufti et al. 2003)

5.3 THE CROWCHILD TRAIL BRIDGE, CALGARY

The Crowchild Trail Bridge (Figure 23) is one example of many Canadian bridges that were initially designed for traffic loads much below that which they are subjected to today. Therefore the superstructure was replaced in June 1997 after an inspection/analysis indicated that the bridge was under strength and that upgrading was needed. The innovation in the new superstructure is its being the first continuous span steel-free bridge deck in the world. The new structure is a two lanes, three continuous spans bridge, 295-ft long, 36-ft wide (Mufti, 2003). A remote monitoring sytem was implemented on the bridge. The system consists of 81 strain gauges, 19 embedded gauges, 5 thermistors, 3 smart glass rebars and 2 fibre optic (Mufti et al., 2003).

5.4 HALL'S HARBOUR WHARF, NOVA SCOTIA

"Hall's Harbour Wharf in Nova Scotia is a 96-year-old combination wharf/breakwater. It is the world's first marine structure with fiber optic sensors embedded in a steel-free concrete deck for remote monitoring. It is designed to last 80 years, three times longer than traditional construction methods. This design received the 'Award of Excellence' from the Canadian Consulting Engineer Association" (Mufti et al., 2003).

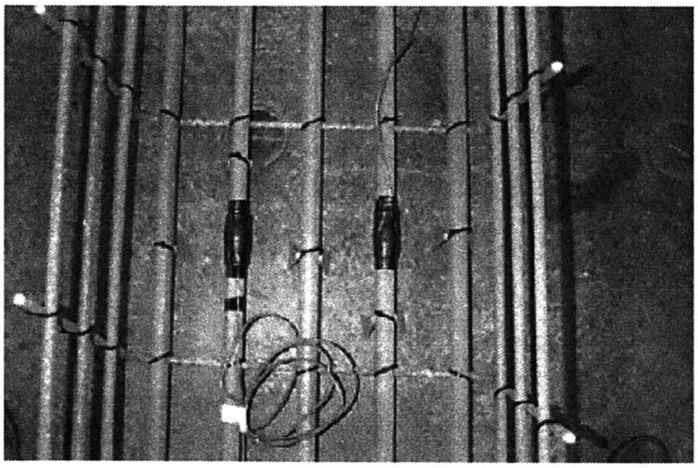


Figure 24: Installed sensors in Hall's Harbor Wharf (Mufti et al., 2003)

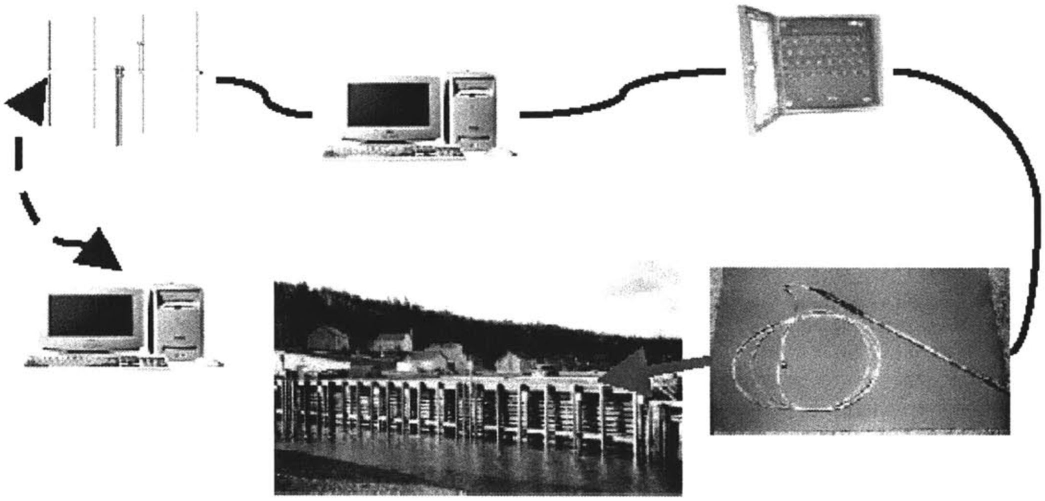


Figure 25 : Remote monitoring system for Hall's Wharf (Mufti et al., 2003)

5.5 JOFFRE BRIDGE, QUEBEC

The bridge was constructed in 1997 and FRP were used in a portion of its concrete deck slab. The Joffre bridge "*is outfitted extensively with different kinds of monitoring instruments, including fibre optic sensors embedded in the FRP reinforcement (smart reinforcements). Over 180 instruments (fibre optic sensors, vibrating wire strain sensors and electrical strain gauges) were used" (Mufti et al., 2003).* Remote monitoring of the structure is performed through data transmission from sensors to a telephone line. Remote monitoring makes it easier to obtain information on long term performance of the innovative FRP reinforced concrete deck (Mufti et al., 2003).

5.6 PIPELINE, FT MCMURRAY, ALBERTA

In this example the degradation of pipeline materials is considered. This becomes of critical importance for oil and gas transmission potential. Corrosion of steel leads to wall

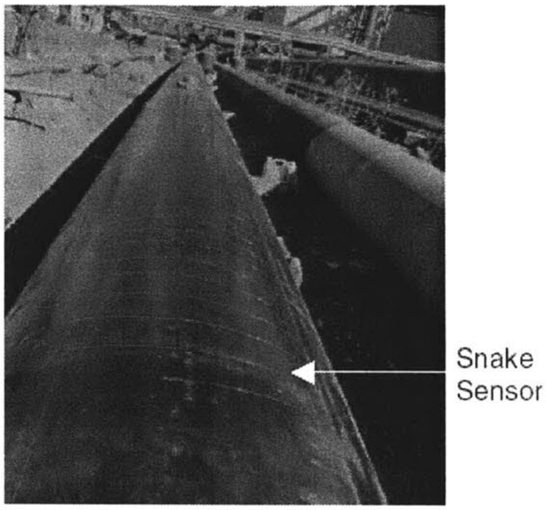


Figure 26 : FOS snake configuration, pipe in Ft McMurray, Alberta (Mufti et al. 2003)

thinning of the pipelines and their subsequent failure. This poses a major threat to the environment, to neighboring communities, in addition to the practical interruption of supply. SHM of pipelines using sensor technology provides a preventive measure that can mitigate the economic and environmental risks resulting from gas and oil pipeline failure due to corrosion (Mufti et al.2003).

FOX-TEK Inc. and a Canadian pipeline consortium (ISPIR) initiated the effort of installing long-gauge fiber optic sensors on a tailings pipe that was suffering from rapid and combined erosion/corrosion (Mufti et al., 2003). Six sensors used to detect wall thinning, were installed (adhesively bonded to the surface) in different configurations (Figure 26). To provide protection for the FOS from the environment, the FOS were overcoated with a caulking compound (Mufti et al., 2003).

"The pipe was run at about 60 °C at a pressure that varied from 200 to 700 kPa (29–102 psi). The sensors were connected to an on-site FOX-TEK FTI3300 8-channel long-gauge instrument, linked to a PC containing a Sierra 700 Aircard to provide wireless

transmission of the data via the internet to the monitoring site in Toronto."(Mufti et al., 2003).

Continuous monitoring and measurement of wall thinning were conducted over several months. Thinning of the pipe wall and subsequent increase in the hoop strain resulted from erosion and corrosion processes. After a certain time of monitoring, it was possible to estimate the numerical value of an average daily wall-thinning rate and the subsequent knowledge of residual thickness (Mufti et al., 2003).

5.7 COMMODORE BARRY BRIDGE, PA-NJ

The Commodore Barry bridge connects Pennsylvania to New Jersey. The bridge structure is a cantilever truss, the middle span length between towers is of 1644 ft (501 m) (Pines & Aktan, 2002). Monitoring this bridge was performed using many types of sensors: vibrating-wire accelerometers, strain sensors, weigh-in motion systems and tiltmeters (Figure 27) (Pines & Aktan,2002).

5.8 BENICIA-MARTINEZ BRIDGE, CALIFORNIA

Benicia-Martinez bridge crosses the San Francisco Bay. Caltrans (California DOT) has developed a plan for the SHM to instrument this bridge starting with construction and continuing during post-completion operation. It is hoped that the data collected from this structure will be of help to *"bridge designers, owners, and engineers in future bridge designs for seismic loading" (Pines & Aktan, 2002).*

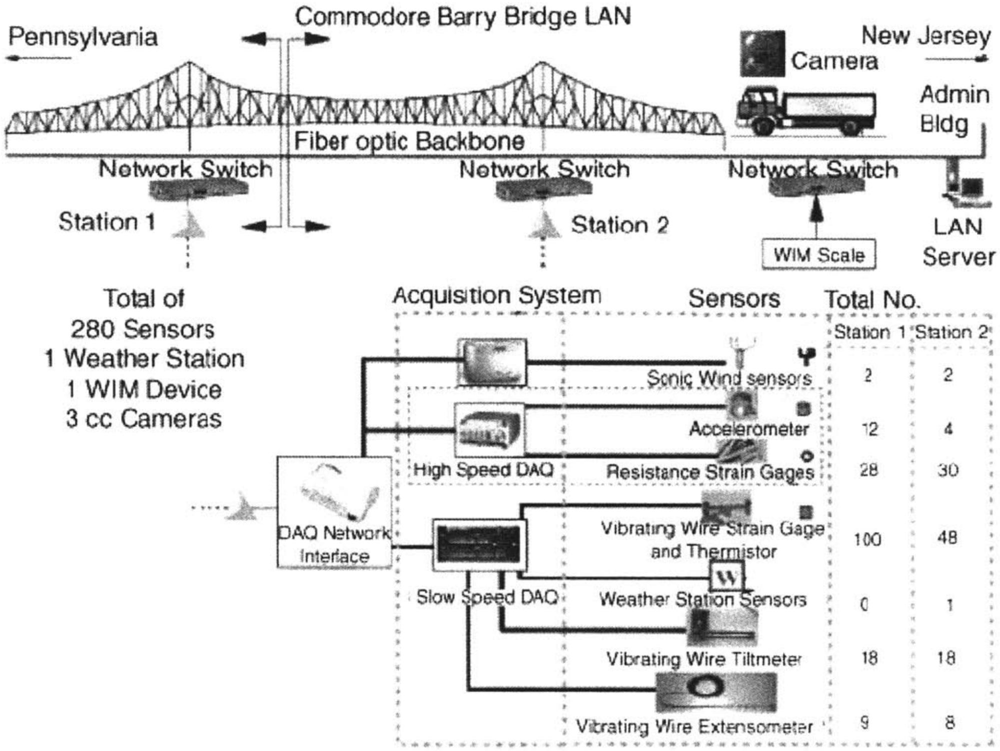


Figure 27 : Architecture for health monitoring system for the Commodore Barry Bridge (Pines & Atkan , 2002)

5.9 LUZZONE DAM-SWITZERLAND

The Luzzone dam in Switzerland was built in 1963, it is a 1,330,000 m³ volume and it retains a 108,000,000 m ³ of water (Structurae, 2004). Between 1996 and 1997 the capacity was increased by 25%. Increasing the capacity required a 17m raising of the dam that was achieved by the successive concreting of 3m thick blocks (Inaudi, 2000). Tests to monitor the temperature of the concrete were performed with emphasis on the block that rests against the rock foundation, this block also happens to be the largest one to pour. The sensor used was a distributed Brillouin sensor (section 2.6.6), it has a serpentine layout and it is made of an armored telecom cable. Immidiately after concrete was poured, temperature measurements started, they extended for over half a year (Inaudi, 2000). The harsh environment present at the construction site did not impact the reliability of the measurement system. Good agreement in results was shown when the measurements of the FOS Brillouin based system were compared to results from conventional thermocouples. In similar cases and where large structures are involved, the distributed nature of Brillouin sensing gives it an absolute edge while the requirement of extensive cabling will be the main hurdle in using conventional sensors (Inaudi, 2000).

5.10 STORK BRIDGE-SWITZERLAND

The Stork Bridge is located in Winterthur Switzerland. In 1996,the bridge was already old and it was replaced by a stay cable bridge. The main innovation in the new Stork bridge was that in one pair of the twelve cable pairs, CFRP wires replaced the usual steel wires (Sennhauser et al., 1998). The Swiss Federal Laboratories for Materials Testing and Research (EMPA) instrumented the two 35 m long CFRP cables with seven fiber Bragg grating sensors. Results showed good agreement when compared to strain gauge measurements (Inaudi, 2000).

5.11 THE VERSOIX BRIDGE, SWITZERLAND

Each one of the parallel North and South Versoix twin bridges is a two lane highway segment of the A9 Swiss national highway linking Geneva to Lausanne. In both bridges consist of a 30 cm concrete deck and two overhangs are supported by two parallel pre-stressed concrete beams (Inaudi, 2000). To accommodate the addition of a third traffic lane and a new emergency lane, it was necessary to widen the exterior beams as well as to extend the overhangs. During the construction phase the bridge underwent horizontal and vertical bending as well as twisting due to several factors such as the added weight, the prestressing and the differential shrinkage between new and old concrete. More than 100 SOFO sensors were deployed for the monitoring the long-term deformations of the bridge as well as for the measurement of fresh concrete displacements associated with the the setting phase. The 6 meter long fiber optic cables with attached sensors were placed in the same direction of the bridge length. *The sensors were first used separately to quantify the concrete shrinkage and study the performance of different concrete mix designs. Once the construction completed, the sensors were used combined to calculate the horizontal and vertical curvature of each cell. By double-integration of these curvature measurements it is possible to calculate the horizontal and vertical displacement of the whole bridge "(Inaudi, 2000).*

5.12 INTERSTATE 89-WINOOSKI RIVER BRIDGE, VERMONT

Huston and coworkers (1994) from the University of Vermont developed a multimode fiber-optic vibration sensor in the lab. They wanted to have a field validation of their sensor and decided to take measurements on the multi-lane multi-span I-89 highway bridge which spans the Winooski River in Vermont. "*During the summer of 1989 the University of Vermont Civil and Mechanical Engineering faculty obtained accelerometer-based measurements of the span's segments to determine resonant and harmonic frequencies. Hammer impacts were imparted into the structure by a massive pneumatic jackhammer which was being used to break up the existing roadway surface* *(which was then removed). A 100m multimode 100/140 (core/cladding diameter) optical fiber was surface attached to the protective medium separating the temporary traffic-flowing lane from the two lanes being redecked" (Huston et al., 1994.)* Although, no formal result comparisons between the FOS and conventional sensors were made, the performance of the proposed FOS showed promise and potential (Huston et al., 1994).

Houston and coworkers monitored vibrations in a wooden pedestrian bridge located on Route 127 north of Burlington, Vermont (Huston et al., 1994). FOS were used to obtain vibration measurements that were subsequently compared to conventional sensing counterparts. Comparison showed good agreement (Huston et al., 1994).

5.13 STAFFORD BUILDING, UNIVERSITY OF VERMONT

In 1992, Huston, Fuhr, Ambrose and coworkers at the University of Vermont (UVM) have instrumented a new multistory building (65 000 ft^2) on the UVM campus (Figure 28): the Stafford Biotechnology Research Complex (Merzbacher et al., 1995).

It took them 8 months as they embedded fiber-optic and conventional sensors into the concrete superstructure of the Stafford Building. *"The process resulted in a spider's web of over 2.5 miles of multimode and single-mode fiber-optic sensors capable of measuring vibration, wind pressures, wind conditions, in-service loading, creep, and building health (cracks, etc.) complemented by point measurements of temperature and stress /strain" (Huston et al., 1994).* By instrumenting the Stafford Building, Huston and coworkers' main goals were *"to develop and examine the methods, practices, and needs of building* *construction and to field evaluation of FOS developed in UVM labs in real world settings to understand further the technology transfer issues" (Huston et al., 1994).*

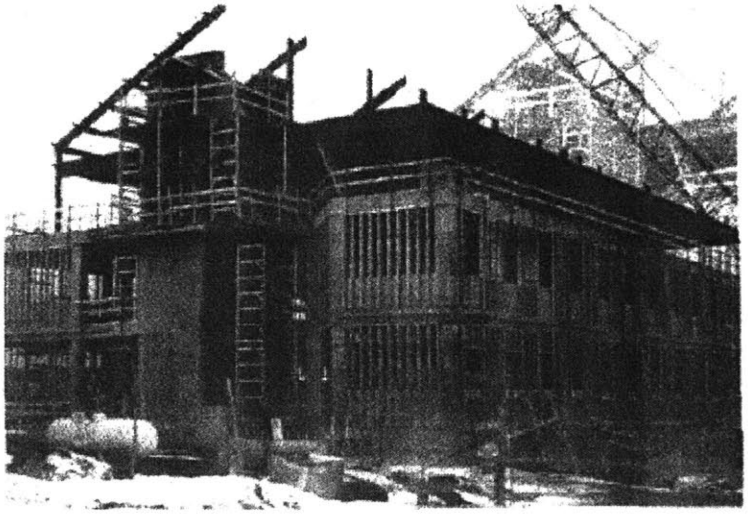


Figure 28 : Stafford Building at the University of Vermont (Huston et al.,1994)

They used embedded FOS for the measurement of concrete curing. Prior to concrete pouring, an FO vibration sensor was embedded into the rebar steel body and was able to provide the necessary information about the concrete curing. The mechanism of the vibration FOS is simple: elastic waves were imparted into the concrete using a hammer. As the concrete curing progresses the wave speed increases, consequently the impact-generated elastic wave will interact sooner with the embedded fiber (Huston et al., 1994). This method can determine the level of concrete curing with sufficient accuracy by correlating the time-of-flight measurement with conventional droop tests (Huston et al., 1994).

"The basement of the Stafford Building will house a large vibration, or shaker, table capable of vibrating approximately 2200 pounds at frequencies ranging from effectively

DC to over 100Hz. (This table will be used in motion-induced muscular/skeletal resonant frequency research). While this shaker rests on its own (supposedly) isolated foundation, it is surrounded by the rest of the building and as such will undoubtedly influence the building's motion. Researchers placed thermistors and fiber optic vibration sensors in the ground underneath this area, and in the floor, walls, and support columns for this section of the building to be able to perform dynamic studies of this structure to determine vibration isolation/coupling throughout the building" (Fuhr et al., 1992).

Protection of the FOS, in the harsh construction site environment, remains an important issue of concern. In this case, and in order to provide the fiber access to the interior of the forms "*a standard 4"x 4" electrical conduit box was chosen to house the fiber due to low cost, availability, versatility, rugged design*" (Figure 29, Figure 30, and Figure 31). Since the installation of these boxes was to cause a change in the original design of the structure approval of the engineers was sought (Fuhr et al., 1992).

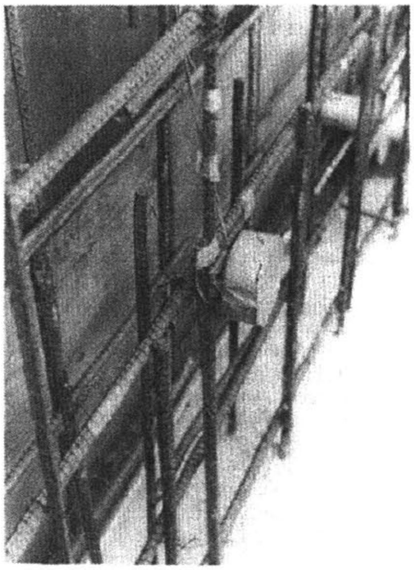


Figure 29 : Electrical conduit box for gracefully exiting the forms (Fuhr et al., 1992)

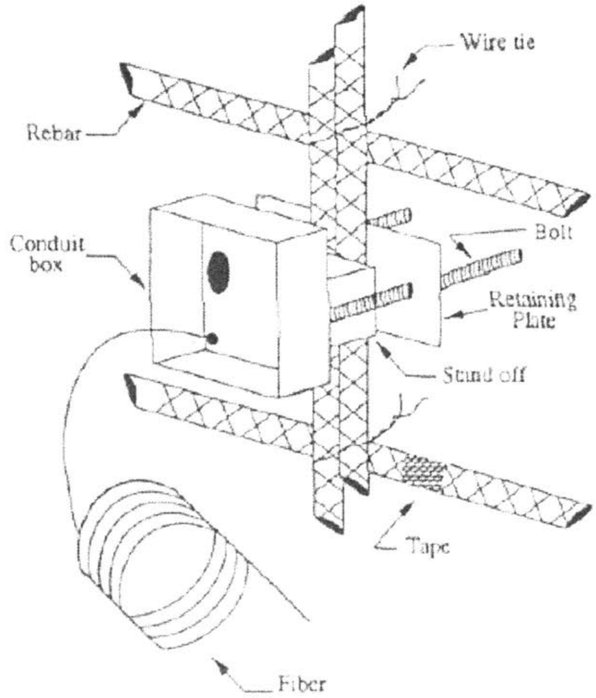


Figure 30: Vertical rebar attachment of optical fibers and conduit box (Fuhr et al., 1992).

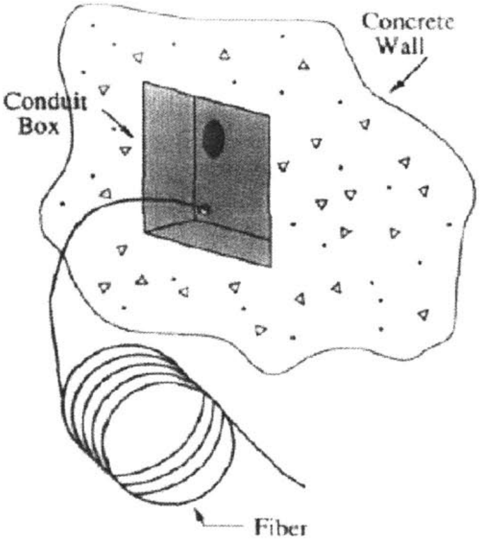


Figure 31 : Configuration after the concrete pouring (Fuhr et al., 1992)

5.14 WINOOSKI ONE HYDROELECTRIC DAM, VERMONT

The Winooski One is a hydroelectric project, a 7.5+ MW modest-sized dam on the Winooski River in Vermont. As the construction began in 1992, Huston and coworkers agreed with owners to instrument the project. Power plants typically suffer from large amounts of electromagnetic interference (EMI), and EMI is capable of seriously disrupting electrical sensors. Reflecting this, FOS were determined to be the best devices to use, given their immunity to EMI. Moreover FOS offer other attractive characteristics such as geometric versatility and the ease of multiplexing that makes them further attractive particularly when the installation site, a hydroelectric dam in this case, has limited accessibility. The vibration signatures at some critical locations in the dam as well as the externally applied water pressure were of special interest to the dam owners. Different types and lengths of FOS installed amounted to more than 4 miles of fiber length. *"In this hydroelectric application, 8 intensity modulating pressure sensors were to be equally spaced along an 85m length of 100/140 multimode fiber. In addition to simple sensor multiplexing along a single transmit/receive fiber, multifunction fiber sensors were used. In such a configuration a single fiber is used to simultaneously measure more than one parameter"(Huston et al., 1994).* Over 90% of the embedded sensors have withstood the hardships associated with the construction process (placement, casting, pouring, concrete curing and formwork removal) (Huston et al., 1994). The interrogation was done through optical frequency domain reflectometry (OFDR) and the outcome of the FOS instrumentation for measurements of pressure and vibration confirmed the robustness of fibers as sensing was performed with minimal admissible levels of error (Fuhr and Huston, 1993).

It was not long (few weeks) after the full scale measurement began in Spring 1993 before the importance of the embedded FOS was irrevocably shown to the owners. In March 1993, while the power-generation utility of this facility was still within its 'shakedown' phase one FOS vibration sensor (embedded in a turbine) detected a spike occurring at 168 Hz while the original design specified its occurrence at 174 Hz. The discrepancy was accompanied by a drop in the electrical output of the turbo generator from the design value of 92% to an actual value of 81%. The defect gear was replaced and the unit's efficiency restored to the original design value (Huston et al., 1994).

5.15 MIDDLEBURY RAILWAY BRIDGE

Figure 32: The Middlebury railway bridge (Huston et al. ,1994).

In 1992, the Middlebury railway bridge was being replaced. During the construction of the new bridge deck, Huston et al embedded about 400 m of fiber-optic sensors. The fiber included single-and multi-mode fiber (cables and multi-strands). The task of FOSs was to monitor the performance of the bridge by sensing vibration and structural-integrity (Huston et al., 1994).

5.16 I-10 BRIDGE IN LA CRUCES , NEW MEXICO

Vohra et al. (1998) performed strain measurements on the I-10 highway bridge in La Cruces, New Mexico using a 32 channel FBG system. *"The 32 channels showed a wide range of peak strains being induced at various locations on the girders of bridge structure. These measurements showed that it is possible to distinguish not only between heavy (e.g trucks) and light (e.g cars) transient loading events occurring on the bridge, but it is also possible to determine the induced bridge vibrations" (Vohra et al., 1998).*

By developing a statistical pattern of the strain response for the bridge, a baseline can be established and any subsequent deviation can be tracked *"as possible defect or change in the structure, thus giving the bridge engineer a warning signal if abnormal conditions should occur" (Idriss et al., 1998).*

Table 4 : Ongoing Bridge SHM Demonstration Projects (Source : Pines & Aktan, 2002)

Researchers	Organization	Bridge	Project Objective	Year
Farrar; Doebling et al.	Los Alamos National Laboratory	I-40 Highway Bridge New Mexico	Evaluate modal vibration health monitoring algorithms	1996
Aktan et al.	Drexel University	Commodore Barry Bridges , Pennsylvania -New Jersey	Evaluate real-time SCADA system	1998
Sikorsky & Stubbs	CalTrans , Texas A&M	California Highway Bridges	Vibration monitoring	2001
Feng	University of California at Irvine	Jamboree Road I-5 Highway Bridge Overpass	Vibration monitoring	2001
Wang	University of Illinois at Chicago	Korea Long Span Bridges	Vibration monitoring	2001
Nigbor	University of Southern California	Bangkok	Vibration monitoring	2000
Muouresh	CalTrans	Benicia-Martinez	Vibration monitoring, corrosion and bearing monitoring	2002
Seible	UC San Diego	Gilman Road I-5 Crossing, CA	Proposed health monitoring system	2002

Table 5 : Fiber Optic Sensors for Civil Structural Monitoring in Europe (Source : Inaudi, 2000)

	Measured Parameters	Maturity	Active Groups in Europe	Estimated Units Installed
SOFO	Displacement	Commercial	SMARTEC, IMAC-EPFL	1000 +
Microbend	Displacement	Commercial	DehaCom	Hundreds
Bragg Gratings	Strain, Temperature	Field trials	EMPA	Tens
Fabry-Perot	Strain	Field trials	BAM	Tens
Raman	Distributed temperature	Commercial	York Sensors	Tens
Brillouin	Distributed temperature and Strain	Field trials	MET-EPFL, AESA Cortaillod	Units
Hydrogel	Humidity, water ingress	Field trials	Un. of Strathclyde	Units

6 WIRELESS SENSORS

This chapter introduces concepts of Wireless Sensor Networks (WSN), then focuses on a particular implementation/study performed by Lynch and coworkers from Stanford University. WSN consist of autonomous sensing devices incorporating a microcontroller sensor array, power unit, and a communication module, typically using Radio Frequency (RF). These devices have become known as "motes" in the current research literature. The first mote was developed in a collaboration effort by Intel Research and CITRIS (Center for Information Technology Research in the Interest of Society) at University of California at Berkeley. An ad-hoc wireless network is a configuration where motes self-organize to relay data from one mote to the neighboring one, the sequence ends when a given processing destination is reached (Intel, 2004).

Motes can organize in many different ways. One technique was developed by Cerpa & Estrin (2004) from CENS at UCLA, it was called ASCENT (Adaptive Self-Configuring sEnsor Networks Topologies). *"In ASCENT, each node assesses its connectivity and adapts its participation in the multihop network topology based on the measured operating region (Cerpa & Estrin, 2004):*

- Whenever a node detects a high packet loss, it requests additional nodes in the region to join the network so as to improve the relaying of message.
- When a packet loss due to collision is detected, a node reduces its duty cycle (i.e. spends more time sleeping), so as to lower the chance of a future collision.
- A node joins the multi-hop routing infrastructure only after it probes the local communication environment and finds that joining the multi-hop will be helpful

Wireless sensor networks are expected to facilitate a new computing concept termed "proactive computing" which is "*a paradigm where computers anticipate human needs and, if necessary, act on our behalf" (Intel, 2004).* Potential benefits are expected to result from the application of sensor networks and proactive computing. These benefits include among others: enhanced monitoring, better operations, increased safety and more economical deployment of sensors (due to the absence of wires).

The road to ad-hoc wireless sensors and proactive computing is expected to be long as several technological hurdles still need to be removed. Innovation in hardware, software, and network design is required to overcome the fact that individual motes are constrained by a set of limitations, most particularly in their power consumption, computational performance, capacity for data storage, and rate of communication. The conservation of power is probably the most important single issue for a wireless sensor. The operational lifetime of wireless sensors depends on power availability: the less power is consumed the longer a mote's lifetime can extend. Much research into efficient communications, processor duty cycling, and use of low power sensors is hoped to reduce these limitations. Finally it is noted that any technological breakthrough to solve the above mentioned issues must be, first and foremost, economical to implement and capable of effective communication in the market.

6.1 ANATOMY

The intended application for a network of motes determines the details of the network: its connectivity, size and algorithms (Intel, 2004). Nevertheless the tightest constraint is likely to remain the ability to conserve power that is the real index for the effectiveness of any given mote. Ideally, a mote is powered by a compact set of commodity batteries that must be sufficient to let it survive a minimum of one year of service. Of course, a mote's lifetime is shortened every time an activity is performed (data reading, transmission, etc.). Therefore power consumption must be always strictly rationed by running at extremely low duty cycles. In a 1 % cycle, a mote is in a sleeping mode for 99% of the time, then the mote awaking only to perform sensing or communication tasks (Intel, 2004). Hardware and software parts of a mote are engineered to cope with low duty cycles, for example in the **μAMPS** (Micro AMPS: Micro Adaptive Multi-domain Power aware Sensors) research effort in MIT , research efforts *"focus on innovative energy-optimized solutions at all levels of the system hierarchy including: physical layer (e.g., tranceiver design), data link layer (packetization and encapsulation), medium access layer (multi-user communication with emphasis on scalability), network/transport layer (routing and aggregation schemes), session/presentation layer (real-time distributed OS), and application layer (innovative applications)"(Micro Amps, 2004).*

Typically, small sized semi-conducting circuits are more power efficient than their large sized counterparts. *"Simple microcontrollers like those that function as a mote's brain can operate with just a milliwatt of power when active, or 1-10 microwatts in standby mode"(Intel, 2004).* For conservation of power consideration a mote's memory must be limited. For example, for the Intel iMotes, motes are associated with less than 100 KB of software storage, 10 KB of RAM and less than 1 MB of data storage (Intel, 2004).

The sensing system in a mote cannot be exempt from the low power consumption "doctrine". Both the sensor array itself and the associated analog-to-digital converter must be kept as efficient as possible[1]. For example, the high levels of power consumption associated with fiber optic sensors (often measured in dozens of watts) lie outside the range acceptable for a long lived mote.

Wireless networking using radio is the predominant mode of communication using motes. Radios are used to communicate information such as sensor readings or data processed from such readings to other nodes in the network, or through "gateway" nodes leading out of the network. Production of low cost, low power radios are now possible using conventional techniques for the processing of silicon. "*This new class of RF (radio frequency) devices is one of the key enabling technologies behind 802.11 (WiFi) networks, Internet-enabled PDAs, ever-smaller mobile phones, and sensor networks"(Intel, 2004).*

While RF forms the most common medium for wireless communication, wireless networking can also use optical communications. Warneke et al. (2001) at UC Berkeley, have explored two approaches to optical communications in the development of Smart Dust project[2]: passive reflective systems and active-steered laser systems. In the passive reflective systems the mote does not require a light source on board and the device consists of three mutually orthogonal mirrors. On the other hand, in active-steered laser systems motes have onboard their light source that sends to a receiver via a tightly

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[1] ADCs (Analog to digital converters) are devices that translate changes in an analog signal such as voltage into a digital format that a microprocessor can decipher.

[2] The Smart Dust project explores the possibility of packing autonomous sensing, computing and communication system into a cubic millimeter mote (Warneke et al., 2001)

collimated light beam (Warneke et al., 2001). Figure 33 shows a schematic diagram of a Smart Dust mote, in particular the passive and active transmitters are shown.

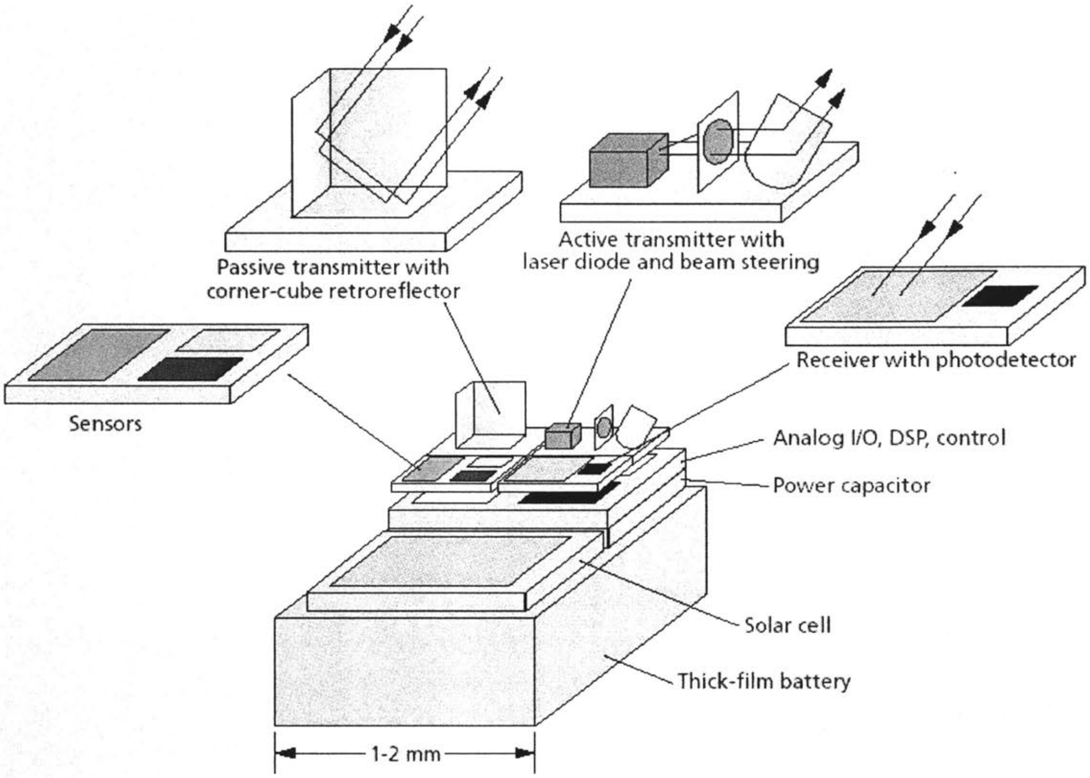
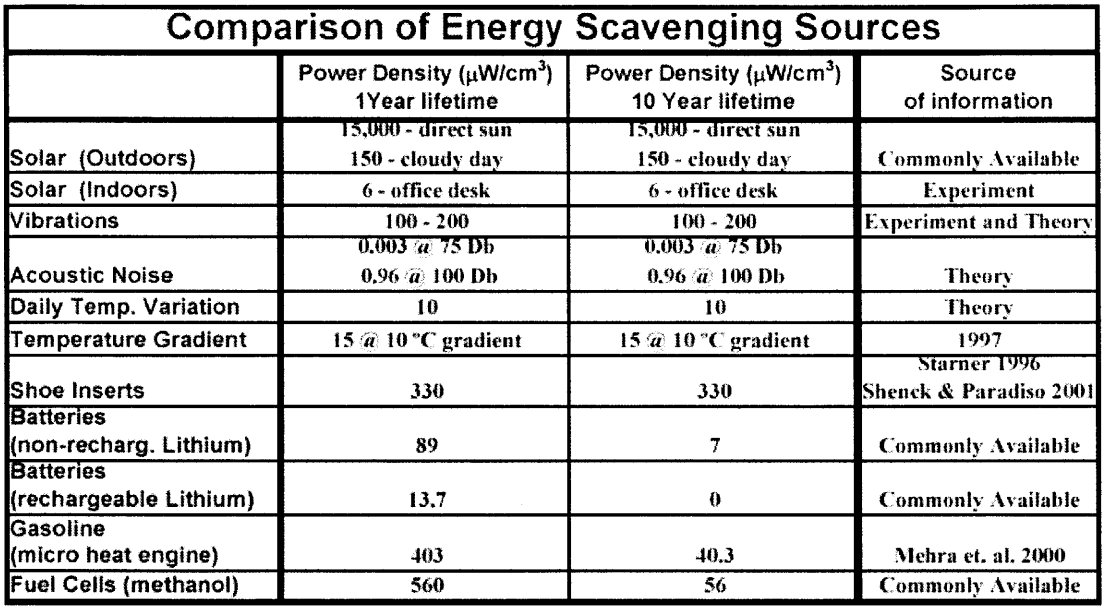


Figure 33: Smart Dust mote major components: power system, sensors, and integrated circuits (Warneke et al., 2001)

Networks are usually designed to run on batteries. It takes typically between many months to deplete a commercial AA battery powering a mote. However as motes increase in number and the devices decrease in size, replacing depleted batteries becomes increasingly impractical. Other sources of power alternatives are actively sought and developed by researchers. One alternative is solar power for application where motes are deployed outdoors and can subsequently recharge their batteries. Some of the research has centered on the development energy scavenging systems. These are systems used to harvest ambient strain energy and they can be piezoelectric, capacitive or inductive (refer to Figure 35) (Roundy, 2003). Roundy (2003) from UC Berkeley, pursued converters based on both piezoelectric and electrostatic (capacitive) coupling. He designed built and tested meso- and micro- scale prototypes. Current prototypes have demonstrated power densities of about 200 $\mu W/cm^3$ from input vibrations of 2.25 m/s^2 at 120 Hz (Roundy, 2003).



Comparison of Energy Scavenging Sources

	Power Density ($\mu W/cm^3$) 1Year lifetime	Power Density ($\mu W/cm^3$) 10 Year lifetime	Source of information
Solar (Outdoors)	15,000 - direct sun 150 - cloudy day	15,000 - direct sun 150 - cloudy day	Commonly Available
Solar (Indoors)	6 - office desk	6 - office desk	Experiment
Vibrations	100 - 200	100 - 200	Experiment and Theory
Acoustic Noise	0.003 @ 75 Db 0.96 @ 100 Db	0.003 @ 75 Db 0.96 @ 100 Db	Theory
Daily Temp. Variation	10	10	Theory
Temperature Gradient	15 @ 10 °C gradient	15 @ 10 °C gradient	1997
Shoe Inserts	330	330	Starner 1996 Shenck & Paradiso 2001
Batteries (non-recharg. Lithium)	89	7	Commonly Available
Batteries (rechargeable Lithium)	13.7	0	Commonly Available
Gasoline (micro heat engine)	403	40.3	Mehra et. al. 2000
Fuel Cells (methanol)	560	56	Commonly Available

Figure 34: Comparison of energy scavenging sources (Roundy, 2003)

In Figure 34 Roundy compared different energy scavenging sources (first seven rows denotes sources with a constant power output, remaining rows denote sources with a fixed amount of energy).

Batteries based on thin film chemistry also promise to have infinite recharge cycles. Successful combination of these batteries with energy saving electronics can give birth to wireless strain monitoring systems characterized by their operational longevity as well as their no need for maintenance (Arms & Townsend, 2003).

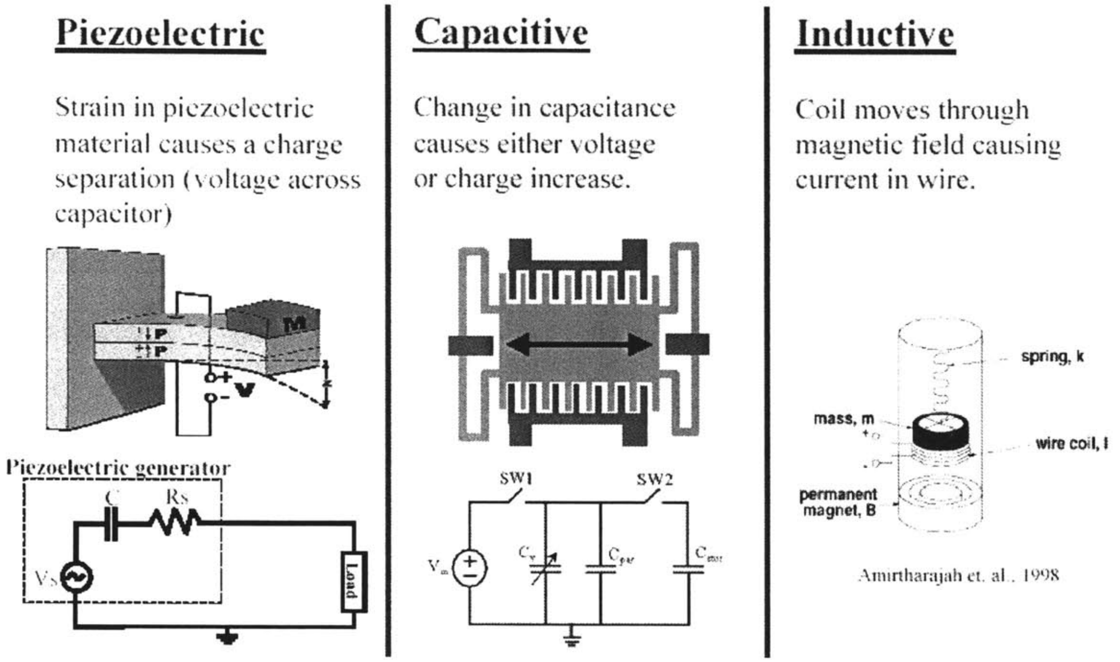


Figure 35: Three ways to convert vibrations (Source: Roundy, 2003)

6.2 THE PATH TOWARD PROACTIVE COMPUTING

As noted above a mote is made up of four components: microprocessors, sensors, low-power radios and power supply. Year after year, both the size and cost of microprocessors of a given capacity are shrinking. According to the statistical observation known as Moore's Law, the transistor density for integrated circuits microprocessors increases log-linearly, doubling roughly every few years. Semi-conductor manufacturing processes originally focused on electronic components are now being utilized to build interactive MEMS (Micro Electro Mechanical Systems). MEMS technology enables the production of very low cost and small size "*velocity sensors, thermometers, and even low-power radio components that fit on the head of a pin" (Intel, 2004).* In conclusion, the cost of wireless sensors is expected to keep dropping. Cost along with power conservation will be the main drivers for the commercial success of this technology.

The low cost and small size of the motes can be described as necessary but not sufficient conditions to realize a broad set of sensor based applications (Intel, 2004). It was due to the ad-hoc, multi-hop networking capabilities that wireless sensor technology gave scientists/engineers the unprecedented ability to deploy huge numbers of sensors for the purpose of their work, thus adding credibility to analysis through a large representative sample of data. The work in the general area of WSN was initiated by Pottie and Kaiser who established that scalable WSN require multi-hop operation in order to avoid the transmission of large amounts of data over long ranges (Cerpa & Estrin, 2004). The techniques they developed enable wireless nodes to discover their neighbors and acquire synchronism (Cerpa & Estrin, 2004). Because communication costs are relatively high, it is desirable to try as much as possible to process data inside the network in order to reduce the number of bits transmitted, particularly when transmission takes place over long distances (Estrin et al., 2001).

6.3 EXAMPLE OF A WIRELESS STRAIN SENSING NODE

Figure 36 and Figure 36 provide, respectively, a schematic anatomy and a photograph of a packaged wireless strain sensing node. Information from Microstrain Inc. summarizes the typical performance specifications for the wireless strain sensing node shown in Figure 36 (Arms & Townsend, 2003):

- *"Temperature coefficient offset 0.007% / deg C (tested from +20 to +50 deg C)*
- *Temperature coefficient span 0.004% / deg C (tested from +20 to +50 deg C)*
- *Operating temperatures -20 to +85 deg C*
- *Programmable full scale range: 1000 to 5000 microstrain*
- *Resolution + / -2.5 microstrain".*

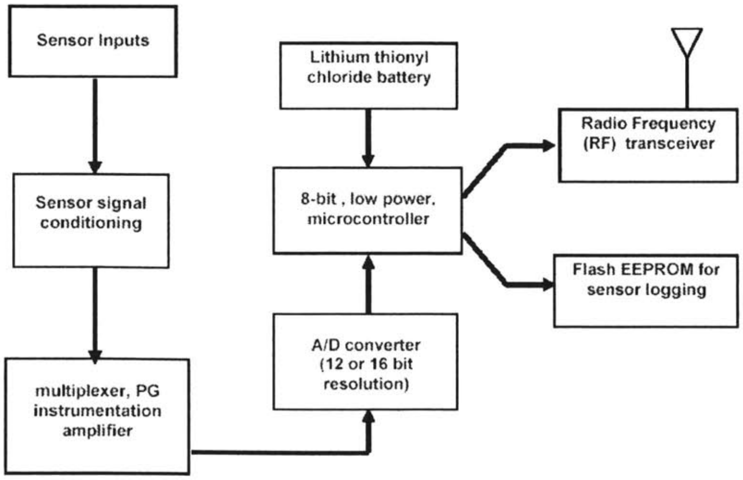


Figure 36 : Wireless Sensor block diagram (Arms & Townsend, 2003)

Figure 37 : Compact Wireless Strain sensing node with integral rechargeable Lithium ion battery (Arms & Townsend, 2003)

6.3.1 Batteries and Alternative Power Sources

The shelf lifetime of batteries with no load ranges between 5 and 10 years. In many instances, placement of the sensors renders replacement of the batteries infeasible and therefore the monitoring application requires the use of an alternative (renewable/rechargeable) source of power to substitute for batteries.

Arms & Townsend (2003) state: *"One strategy to achieve this is by inductive coupling of magnetic field energy from an external coil into an embedded coil within or on the structure under test. Power is delivered at a low frequency to facilitate transmission of magnetic energy through metallic materials. Digital RF data is communicated through an antenna feed-through at higher frequencies. Microstrain Inc. have reported on the validation of their* *magnetically powered sensing nodes for composite cure monitoring during autoclave cure with excellent correlation between hard wired vs. wireless test results" (Arms & Townsend, 2003).*

6.4 THE PROMISE OF WIRELESS SENSORS IN SHM

Three characteristics define existing conventional structural monitoring systems (Lynch et al., 2003):

1) The use of hub-spoke architectures having connection between sensors and centralized data collection at data logger connected to a PC (data server).

2) The data server performs the processing of raw sensor data.

3) Extensive wired electronic communication, through shielded cables, is mainly used to ensure the reliable transfer of measurements between sensors and the data server.

Moreover the adoption of commercial structural monitoring systems is hindered by a set of limitations proper to these systems. For example, a typical commercial SHM system cannot support a large number of sensing channels, it is said to become "saturated" by reaching a value of 10 or 15 channels (Lynch et al., 2003). When wired systems are installed within buildings, the mechanical and communicational reliability of wires will be affected by wear and tear as well as by signal noise (Lynch et al., 2000).

Furthermore, the installation of cables in a structure is a time consuming and expensive activity. In the case of buildings or bridges, installation time of a complete measurement system takes up to 75% of the total testing time. Labor costs for installation and operation may exceed 25% of the total system cost. According to Caltrans (California DOT), the cost of equipping a toll bridge with a system of 60 to 90 accelerometers exceeds $300,000 (Lynch et al., 2000).

Another indication of the cost of wired sensor systems is provided by the United States Geological Survey (USGS) who installed monitoring systems that have a cost of $5,000 on a per channel basis (Lynch et al., 2003 citing Celebi 2002). If we account for at least 60 sensors per system, we retrieve the $300,000 minimum value reported by Caltrans.

Wireless communications technology is one of the numerous by-products of the IT revolution the world has witnessed in the past 2-3 decades. Wireless modems have the potential to advance SHM systems. The ability to eliminate the need for wired installation, and thus gain in substantial savings of time and money, is what makes the wireless SHM a desired alternative (Figure 38) (Lynch et al., 2003).

It was in 1998, that the first time a wireless sensing unit for SHM applications was proposed by Straser and Kiremidjian at Stanford University (1998). Their work was extended by other researchers who included sophisticated computational core. The latter are capable to perform key tasks such as sensor data processing for damage detection and establishing ad-hoc network topologies within a given sensor node (Lynch et al., 2003 citing Straser & Kiremidjian, 1998).

6.5 Case Study: Wireless Modular Health Monitoring System (WiMMS)

Lynch and coworkers proposed a cost effective, easily operated and maintained wireless system as a replacement for wired systems. *"The system will provide rapid and global damage diagnosis" (Lynch et al., 2003).* It will consequently facilitate the tasks of visual inspectors by telling them where to look first for critical states or damages (Lynch et al., 2000).

6.5.1 System Description

A wireless communication system eliminates the need for wires and provides direct communication between sensing units. The system is flexible so as to permit ad-hoc multi-hop wireless network in which nodes are capable of engaging in peer-to-peer communication if this is judged desirable. The computational power was thus transferred from the centralized data acquisition to the sensors themselves (Lynch et al., 2000). Gateway nodes may ferry data arriving from the network out of the network for archiving or further processing.

Lynch and coworkers presented the design of a low cost yet advanced wireless sensing unit that is capable of being deployed in Wireless Modular Monitoring Systems (WiMMS). To perform peer-to-peer transfer of measurements a RangeLAN2 wireless modem was employed. Design was based on two microcontrollers: a low-power 8-bit microcontroller responsible for the general operation of the sensing unit and a second 32-bit microcontroller used to execute embedded engineering analysis algorithms (Lynch et al., 2003).

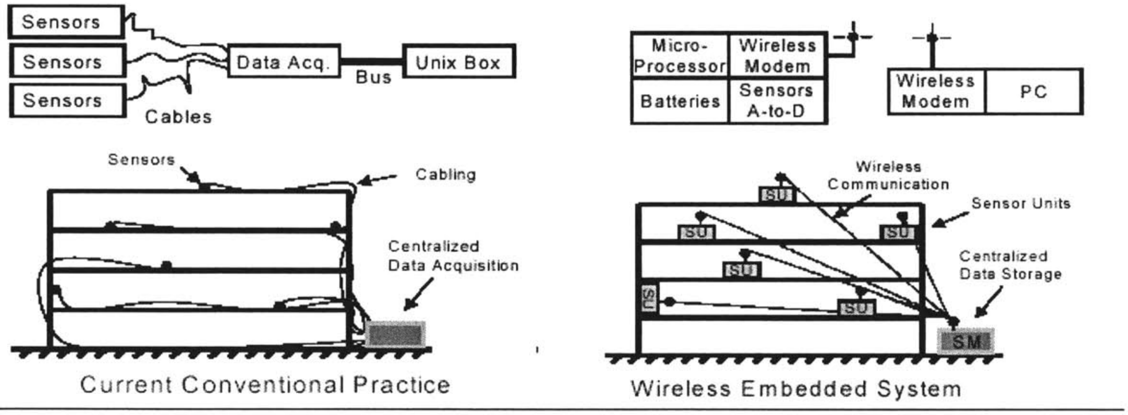


Figure 38 : Wire-based versus wireless structural monitoring systems (Lynch et al, 2002)

6.5.2 Hardware Design of a WiMMS sensing Unit

As noted above, the major requirement in the design of the wireless sensing unit for SHM purpose is a low power consumption, which consequently means low operational cost. By using off-the-shelf electrical components Lynch and coworkers managed to design a low cost unit (below $500 per unit) and to provide upgradeable hardware (Lynch et al., 2003).

The design of the wireless sensing unit, as presented in Figure 39, includes the three major functional components discussed earlier: sensors, processing components and a wireless communications component (Lynch et al., 2003).

The first stage in the journey of data flowing in the WiMMS sensing unit starts at the sensor interface as the unit is connected to several sensing transducers (accelerometers, strain gages, and anemometers, etc.). The data having been collected, the second stage is the computational core that stores collected data in memory. Here the processor can either pack the data for communication or else use the raw data with embedded algorithms for analysis. The course of action to be chosen is then determined by the end user (i.e. engineer/scientist) or using some automated inferencing system such as a neural net (Lynch et al., 2003).

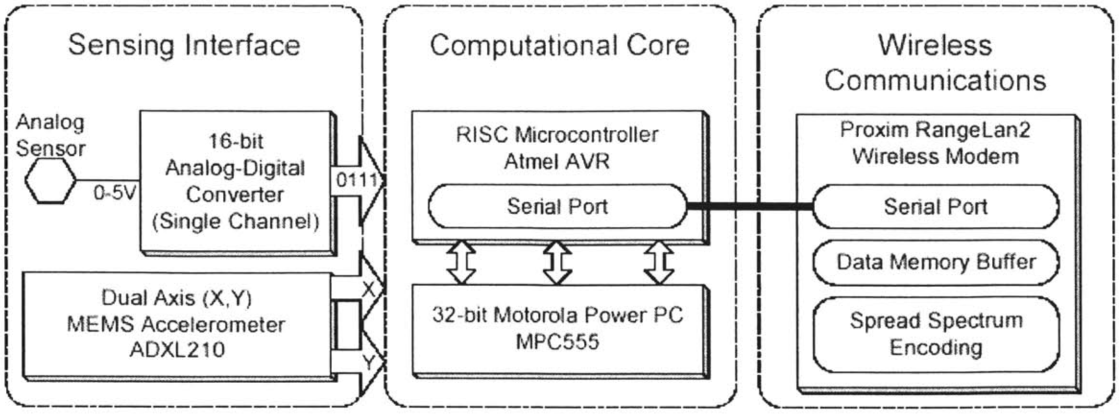


Figure 39 : Architectural schematic design of the wireless sensing unit proposed and implemented (Lynch et al. , 2002)

6.5.3 Power Consumption of a WiMMS Sensing Unit

Lynch and coworkers achieved a low power consumption computation core by using two microcontrollers. One microcontroller, an 8-bit Atmel AVR (AT90S8515), was chosen for the overall operation of the wireless unit because it can do so at a low power consumption (8 mA at 5V, i.e. 40mW power consumption). The second microcontroller, a 32-bit Motorola MPC555, is chosen to execute embedded engineering analyses, because of its high performance (110 mA at 3.3V, i.e. 330 mW power consumption). Being a high power consumer, it is preferred not to turn the MPC555 ON unless it has to execute an embedded algorithm (Lynch et al., 2003).

6.5.4 Wireless Communication Channel

Wireless SHM advocates hope to replace the cables commonly used in conventional SHM systems with inexpensive integrated wireless radios. To be realistic in civil structures, it is estimated that a minimum of 150 m node-to-node range will have to be ensured by radios. They must also ensure reliability in communication and the capacity to overcome the electromagnetic shielding associated with reinforced concrete or other civil engineering construction, so that they can penetrate the material (Lynch et al., 2003 citing Davidson & Hill 1997).

The wireless modem used by Lynch, RangeLAN2, is a high power consumer (190 mA at 5 V, i.e. 950mW) when it is in active communication with wireless network. When placed in a sleep mode the modem consumes far less power (60 mA at 5V, i.e. 300mW). Obviously, the largest portion of the total consumed power in the sensor unit is from the modem, therefore it becomes desirable to perform data processing using the computational core instead of using the modem to transmit raw data (Lynch et al., 2003).

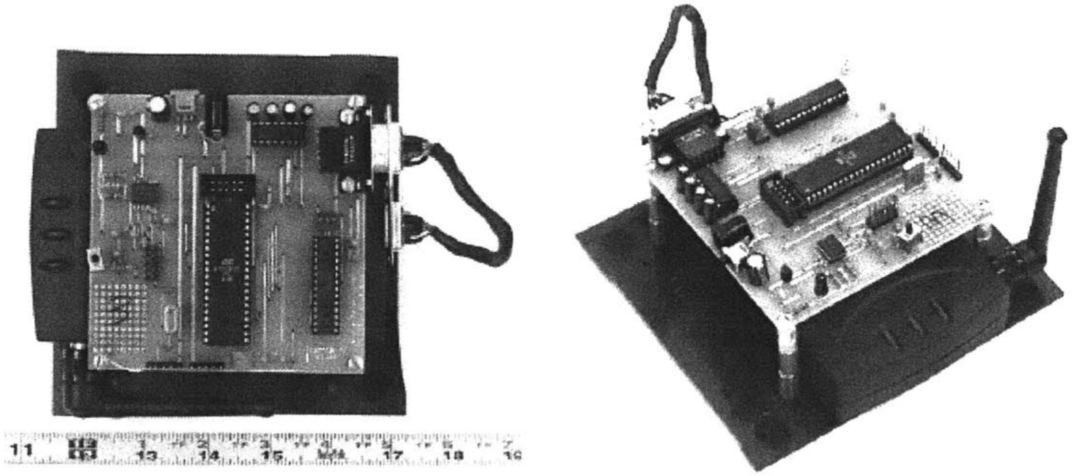


Figure 40 : Top and perspective view of prototype wireless sensing unit (Lynch et al. , 2002)

Operational State	Current (mA)	Internal Voltage (V)	Power Consumption (mW)	Energizer L91 7.5 V Li/FeS$_2$	Energizer E91 7.5 V Zn/MnO$_2$
AVR Sleep/MPC Sleep	8	5	40	500	300
AVR On/MPC Sleep	54	5	270	50	30
AVR On/MPC On	160	5	800	15	5
RangeLAN Active	190	5	950	13	4
RangeLAN Sleep	60	5	300	40	25

Table 6 : Operational life expectancies of battery sources (Lynch et al., 2003)

Table 6 compares two different 7.5 V battery packs for the wireless sensing unit: a standard alkaline (Zn/MnO$_2$) battery and a long duration lithium (Li/FeS$_2$) battery. Estimates of operational life expectancy are based on the engineering design charts provided by the battery manufacturer. The tabulated values assume the batteries will be used continuously till depletion and do not account for occasional use (Lynch et al., 2003).

The final design requirement is the footprint or size of the sensor unit to be deployed. After assembly, Lynch's wireless sensing unit volume is 350 cm^3 (10 x 10 x 3.5 cm) (Figure 40).

6.5.5 Lab and Field Validation

After successful lab validations, Lynch and coworkers proceeded to field validation of the wireless sensing unit in the Alamosa Canyon Bridge, New Mexico (Figure 41).

The Alamosa Canyon Bridge, that was constructed in 1937, has seven simply supported spans. Each span (15.24 m long, 7.32 m wide) is constructed from a 17 cm concrete deck supported on six W30x116 steel girders (Figure 41). A network of wireless sensing units was deployed on a single section of the bridge. In parallel to the wireless network instrumentation, they used a commercial wired SHM, for the sake of comparison and validation of results (Lynch et al., 2003).

The absolute acceleration response to forced vibrations (induced using a modal hammer) of the bridge were recorded and the frequency response of the structure were obtained. When results from both systems were compared no significant difference was revealed. It is worthwhile to mention that the wireless system performance cost a fraction of the wired system cost and required an installation time that never exceeded one third of the installation time needed for its wired counterpart (Lynch et al., 2002).

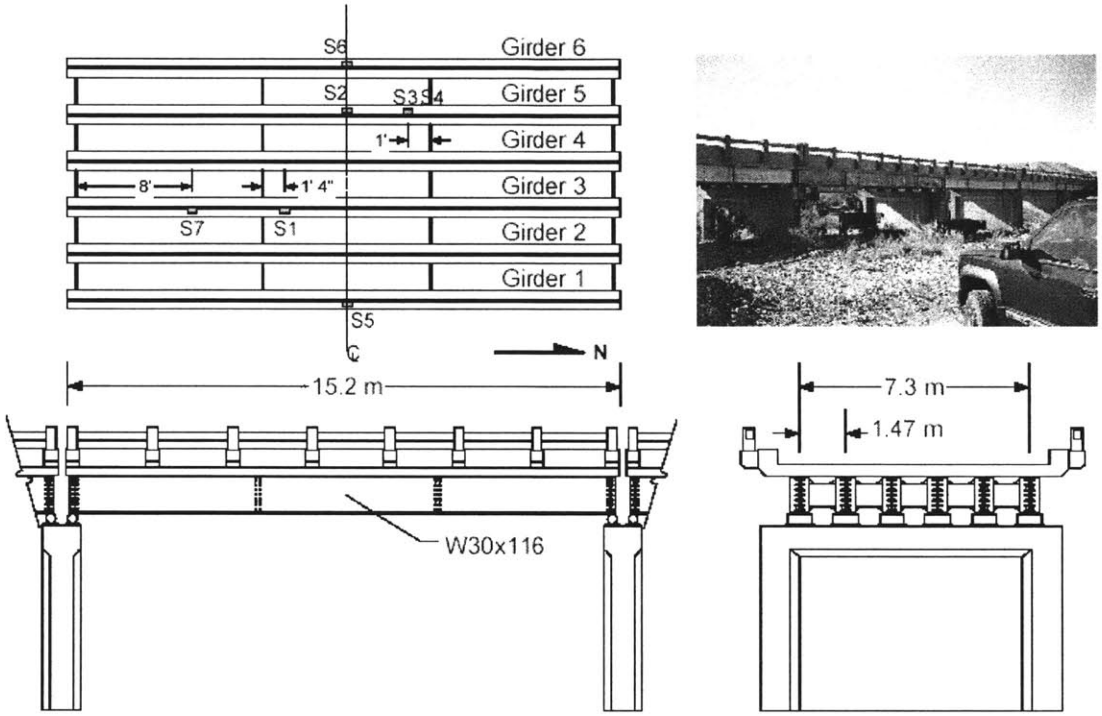


Figure 41 : Field validation structure – Alamosa Canyon Bridge, New Mexico (Lynch et al., 2002)

6.5.6 Power Efficiency with Embedded Algorithms

As is typical for wireless systems, Lynch's wireless modem is used only when needed because of its high power consumption. Consequently transmissions of raw data that make use of the modem must be avoided and the computational core of the sensing unit will assume the task of interrogating the time history records and then transmitting the results of the analysis. Due to the use of two microcontrollers and because the computation was performed locally at the sensor level, significant energy savings were achieved. Saving in energy resulting from the sensor processing data locally rather than simply communicating it to a central processing location were estimated at 53% (Lynch et al., 2003).

7 CASE STUDY

In this chapter we present a real application of a remote health monitoring of a bridge in Des Moines, Iowa. The system is described then its cost compared to the cost of visual inspection over the lifetime of the structure.

7.1 EAST 12TH STREET BRIDGE OVER I-235, DES MOINES, IA

In early 2004 the construction of the East 12th Street Bridge over I-235 in Des Moines, Iowa was completed by the Iowa DOT. The bridge was the first HPS (High Performance Steel) bridge in the state of Iowa. A system for continuous SHM was developed by the joint efforts of the Office of Bridges and Structures at the Iowa DOT and the Bridge Engineering Center at the Iowa State University. The system developed is intended to monitor, record and subsequently evaluate the performance of the bridge in real time.

7.2 BRIDGE DESCRIPTION

The aforementioned bridge is a continuous two span HPS girder bridge having a cast-in-place concrete deck and integral abutments. The structure is 298 ft-6 in. long and is supported by 6 transverse girders equally spaced along its 50 ft- 3 width. The bridge also includes walkways for pedestrians (Doornink et al., 2004).

7.3 OBJECTIVES

Structural health monitoring of this bridge structure has three main objectives (Doornink et al., 2004):

1- To perform an overall evaluation of the bridge structural performance through the continuous monitoring of local and global bridge behavior.

2- To identify structural performance changes by developing a baseline record. This can be achieved with monitoring over time.

3-To conduct a detailed fatigue evaluation for the bridge structure

One of the advantages of the system deployed is that it enables the engineer/researcher to predict the remaining life of a structure given its current characteristics. Finally the system can evaluate long term performance of several typical and atypical fatigue sensitive details (Doornink et al., 2004).

7.4 DESCRIPTION OF THE FOS MONITORING SYSTEM

The components of the HPS bridge SHM system were made by several different manufacturers. In order to maintain a minimal cost, system designers tried to use, whenever possible, standard off-the-shelf components. The main components of the FOS monitoring system are listed below (Source: Doornink et al., 2004).

Strain Sensing Equipment

- o Si-425-500 Interrogator, developed by Micron Optics, Inc.

- 30 FBG sensors

Video Equipment

- Network video camera

Networking Components

- DSL Modem with internet service (transfer rates = 1.5 MBps for download and 1.0 MBps for upload)
- 2.4 GHz Wireless 802.11g Router
- 2.4 GHz Wireless-802.11g Access points

Data Management Equipment

- Data Collection Server (desktop computer- 450 MHz Processor, 8.0 GB Hard Drive, 256 MB RAM
- Web Server (desktop computer – 700 MHz processor, 20.0 GB hard drive, 256 MB RAM)
- Data Storage Server (Server- 3.0 GHz processor, 1.2 TB hard drive, 4.0 GB RAM)

The components of the described above structural health monitoring system can be classified into three sub-systems (Figure 42). Data is collected by a data acquisition sub-system, located at the bridge pier, then it is transferred via wireless communication to the gateway sub-system which is located near the bridge, in a secure facility. The strain data is uploaded via DSL line to the internet through the gateway sub-system, thus it will become accessible in real-time from anywhere in the globe. The gateway also compresses and temporarily stores the strain data (Doornink et al., 2004).

After the data storage sub-system at the Bridge Engineering Center at Iowa State University automatically retrieves the data packets, many steps are taken to ensure the proper operation of the entire system. Efforts are made in developing a method to summarize the performance of the bridge on a daily, weekly and monthly basis. Automatically generated brief reports enable the bridge owner to obtain an overview of the bridge condition and performance (Doornink et al., 2004).

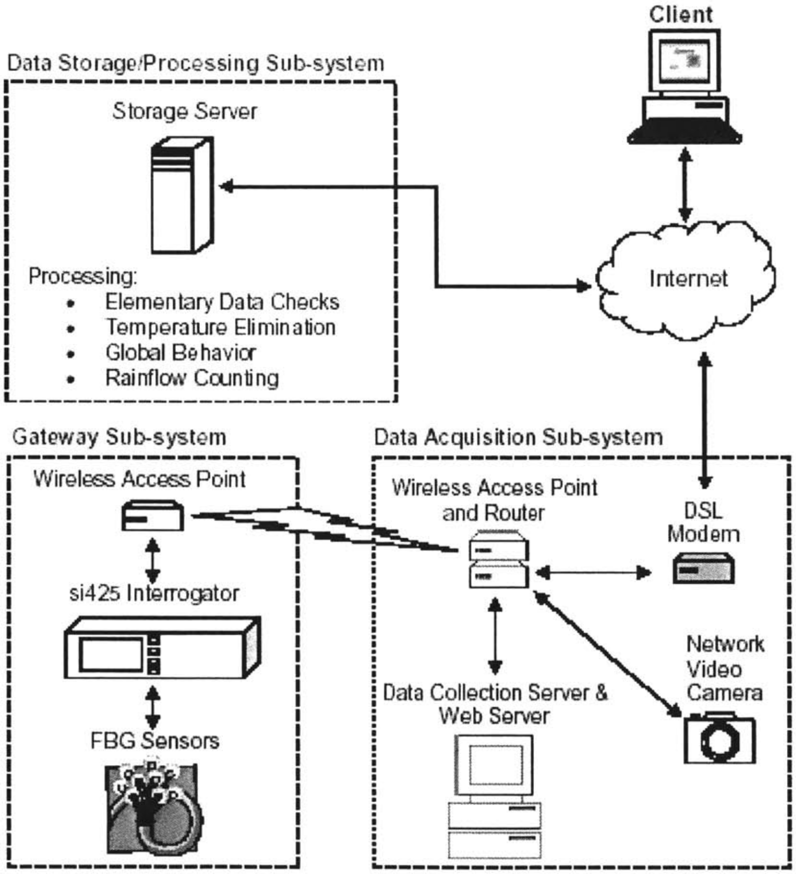


Figure 42: Flow diagram of East 12th St. bridge SHM (Doornink et al., 2004)

7.5 COST OF THE FOS SYSTEM

The total cost of the SHM system was $ 36,000 detailed as follows (Phares, 2004 & Micron optics 2004):

- $6,000 cost of 30 FBG at $200 each, and
- $6,000 installation cost of 30 FBG[3], with $200 installation cost per unit (5 x $40 labor hour)[4],
- $20,000 cost of the interrogation unit
- $4,000 cost of computer hardware in the system

7.6 COST OF THE ROUTINE INSPECTION

According to the chief structural engineer at the Iowa DOT, Ahmad Abu-Hawash:

The cost of visual inspection of East 12th Street bridge is minimal due to the condition and type. A visual inspection of a typical steel girder bridge with integral abutments of this size will need an inspection crew of three bridge inspectors, it will take about four hours to perform. The cost of a labor hour is $30 per inspector. Adding high reach equipment with operators costs around $1000. Also, traffic control for four hours of lane closure need to be added and this costs $ 625 (Abu Hawash, 2004).It is worthwhile to mention that other indirect cost (time delay, pollution, etc.) should be seriously considered (as discussed in 7.77.7)

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[3] According to Chad Klowak, Engineer in Training in ISIS Canada, It takes up to 4 hours to install an FBG sensor and 1 additional hour to hook it up to the system.

[4] In Canada, the cost of labor is $56 (Canadian$), $1US=$1.37 Can.

The direct cost of the visual inspection can thus be summarized as follows:

Labor cost = 3 persons crew x 4 hours per crew x $30/person/hour = $ 360

High reach equipment and operation = $ 1,000

Traffic Control for four hours = $ 625

The total cost of one visual inspection is thus roughly $ 1,985 ≈ $2,000

7.7 COMPARISON & CONCLUSION

Professor Brent Phares from the Bridge Engineering Center in Iowa, expects the SHM system to have a lifetime of at least 30 years (Phares, 2004).

Assuming a lifetime of 30 years of the FOS system and a biennial routine visual inspection. Visual Inspection will be performed 15 times during the 30 years. The net present value of the (VI) cost will be $ 30,000, assuming zero discount rate. On the other hand the NPV of the cost of the FOS SHM is $36,000.

The difference in cost is $ 6,000 is an equivalent of an annual $ 200, assuming zero discount rate.

The cost of visual inspection is not strictly limited to the direct monetary cost that we calculated. Important qualitative issues that cannot be readily quantified and cost accounted for should also be considered. At least from a qualitative point of view: these issues include issues such as traffic delay during 4 hours of inspection for thousands of drivers and cars (also consider the risk of disruption of high-priority vehicles such as police, ambulances, emergency cases, etc.), an increase in fuel consumption and thus in air pollution, and potential for accidents involving traffic by itself or in conjunction with the inspectors.

Given the shortcomings of the visual inspection on one hand, and the frequency, accuracy, and reliability of the FOS based SHM on the other hand, the negligible difference in prices (favoring visual inspection) will not overcome the advantages of the accurate and reliable FOS system. Early detection of trouble can save money time and lives, which is not available with the (VI) practice that happens once in two years and suffers from considerable deficiencies (section 1.2.2). Given these deficiencies, it seems reasonable to absent cost and resource constraints that authorities may want to improve the performance by imposing a higher frequency of inspections in the intent of reducing the possibilities of failures. In this case the cost will be further increased: simply put, the cost will be multiplied by the ratio of new frequency/old frequency. This will simply multiply all the costs mentioned above without offering a frequency or accuracy in monitoring that can effectively compete with the FOS system.

Finally, it is worth noting that the prices of FOS are expected to drop further as a result of the growing interest in the technology, the commercialization efforts, standardization attempts and the synergistic relation with the telecom industry. All these factors and others contribute to having an improved mass produced technology with lower prices. This is expected to happen in the medium if not the short term, and it will not be surprising to obtain the same FOS system (or even a better performing system) for a cost that is cheaper than the cost we calculated for the visual inspection for the lifetime of the bridge (not accounting for the qualitative costs mentioned above).

8 CONCLUSIONS

8.1 SUMMARY

The use of sensors in civil engineering structures is relatively new. Structural Health Monitoring (SHM) is a concept for the management of structures that provides engineers an unprecedented opportunity to closely track changes in important parameters (strain, cracks, temperature, corrosion) relevant to the overall well being of the structure. SHM is realized by instrumenting structures with different types of sensors that measure the one or multiple parameters of interest. SHM is particularly important in the case of remote structures (e.g. bridges, dams), critical structures (nuclear plants, skyscrapers) or structural elements that are difficult to manually inspect and access once the construction is complete.

In this thesis our main focus has been on fiber optic sensors (FOS) as it is a relatively new and promising technology that offers many features unavailable in other approaches. The main advantages of FOS include its environmental ruggedness, high mechanical and optical reliabilities, support for high resolution measurements, insensitivity to electro-magnetic interference, the small size and weight of optical fibers, the ability of multiplexing and the option for distributed sensing, and a remarkably long lifetime. The fact that the FOS relies upon the same technologies as the telecom industry also benefits FOS technologies as a side-effect by boosting prospects for technological advances and cost effectiveness.

However, FOS are not yet a widely deployed technology, reflecting obstacles still hindering its widespread use. The lack in standardization is one obstacle, the relatively high prices is another. These two obstacles are related, in that a standardized industry will be more competitive in improving performance and driving the costs down.

Wireless sensors are an innovative technology briefly discussed in this thesis. While very promising, wireless sensors remain very much constrained by the power conservation issues. Many power scavenging techniques are being developed but an ideal system has not yet been found, and sensor node robustness is considerably less than for other sensor systems. Section 8.3.1 and 8.3.2 discusses tradeoffs between wireless and FOS sensors in greater detail.

A case study briefly compared the costs of an FOS SHM system deployed in Des Moines, Iowa versus a traditional visual inspection. The cost of the FOS monitoring system was mildly higher (20%), however given the high performance of FOS, and some qualitative indirect costs of visual inspection, FOS appear to be a better choice in this case. Costs are expected to decrease further and it will not be long time before this FOS system will have both cost and performance advantages.

The next several sections of this chapter discuss implications of the survey in particular areas.

8.2 FUTURE DEVELOPMENTS

Microbend sensors, will be likely used when low cost is of essence and low accuracy is not an issue (Udd et al., 1998). FBG will see their greatest application in measurements in civil structures and for related research. Sometimes FBG are used as acoustic sensors that monitor irregular sounds caused by potholes or excessive vibration in roads and bridges (Udd et al., 1998). FBG have an advantage over Fabry-Perot by having a versatility in gauge length (FBG can be short-gauge length, long-gauge length, multiplexed, and distributed while Fabry-Perot are constrained to a given gauge length), by being easily multiplexed and because the method of production of FBG can be automated during the manufacturing of the optical fibers (Measures, 2001). However vibration and acoustic sensing are among the fields where Fiber etalons have an important potential to show (Udd et al., 1998).

Successful applications of the Michelson interferometer include European bridges and tunnels, applications which have boosted the interest in further research and applications (Udd et al., 1998).

8.3 WIRELESS vs. FOS SENSORS

Wireless sensor nodes and fiber-optic-based sensor infrastructures are both relatively new technologies, each showing considerable promise and having achieved much acclaim. This section notes some tradeoffs between these techniques, comments on areas in which each technique shows the most promise and prospects for their joint use.

8.3.1 Wireless vs. FOS Tradeoffs

Some significant tradeoffs exist between fiber-optic-based and wireless systems. Some of these tradeoffs are listed below.

- Wireless sensors are localized units while one of the distinguishing characteristics of FOS is its ability for distributed sensing due to geometric versatility, a property best exhibited in the FBG. While a FOS can measure parameters at discrete and sometimes continuous points throughout a one dimensional curve, each wireless sensor node can only make a single point measurement of these parameters. This advantage reflects the fact that FOS uses the fiber both as a sensing instrument and a communication medium, while in wireless sensors sensing and communication rely upon distinct mechanisms. Because fiber optic cables used for sensing can reach up to kilometers in length, such distributed sensing capabilities give a strong cost advantage to fiber-optic sensors for many types of measurements.

- Wireless sensor networks offer an attractive transport architecture for communicating sensed data (in raw or processed form), but it must be kept in mind that in order to be useful they must be paired with compatible domain-specific sensors. It is difficult to evaluate the prospects for wireless sensors in infrastructure monitoring without knowledge of the particular sensors with which they will be used. This concern is made more notable because of the fact that wireless sensors operate within tightly constraints, and because the needs of a given sensor may be in tension with the constraints associated with wireless systems. For example, a high accuracy or robust sensor may require power levels that exceed what is feasible to deploy in a wireless context. A rigorous evaluation of the prospects for wireless sensor networks in infrastructure monitoring requires careful attention to sensor choice and characteristics.
- Motivations for the use of wireless sensors include the elimination of time-intensive and error-prone wiring, the ability to place sensors in less accessible

locations, independence from the local power grid and weight reductions by the elimination of heavy cabling. While these are serious problems with conventional sensors, such considerations only impose modest or small burdens for FOS. The long and light weight of fiber-optic cables make them easier to install than traditional cables, and they can be run through regions of a structure where it would be difficult to place traditional sensors (e.g. strain gages). While the fiber-optic transceivers are traditionally bound to the electrical grid, roads and bridges are some of the most important civil infrastructure where FOS are deployed for SHM purposes and where the infrastructure for power availability is present for the transceivers. By virtue of the long cable length of FOS and their distributed sensing, power need not be present throughout a structure instrumented with FOS: Long sensor cables allow such sensors to be stretched into and over regions of a structure that may lack power.

- Wireless sensor nodes have very limited track record for reliability, and some early experiments (Szewczyk et al., 2004) suggest that some commercially available motes they have a long distance to go before they can offer robust operation in external environments. By contrast, FOS have been extensively tested for environmental reliability and have seen considerable amounts of deployment in challenging environments (See Chapter 5). It appears that many years will be required before wireless sensor networks achieve the level of reliability needed to operate cost-effectively in civil infrastructure monitoring.

8.3.2 Domains of Application

Given the tradeoffs above, FOS remain the most attractive technology for many types of civil infrastructure monitoring. Nonetheless, wireless technology is a very valuable tool for many particular domains of application. These include temporary instrumentation (e.g. in a facility under construction or temporary testing of a structure), cases where power is non-existing or prohibitively expensive to provide (e.g. in remote regions), instances where accessibility limits hinder the use of wires (e.g. placing sensors inside a highly pressurized chamber). The rapid advance of wireless sensor network technology and expected progress in making motes more robust and devising low-power sensing techniques for such nodes is expected to make wireless sensors an increasingly attractive option for infrastructure monitoring in increasing number of domains.

8.3.3 Prospects for a hybrid System

Hybrid systems combining FOS and wireless sensors are an attractive prospect, but important challenges remain to be overcome. Power requirements are foremost among these challenges. While current wireless sensor node power consumption varies between dozens of microwatts (for sleep mode) and dozens of milliwatts (or more), fiber optic sensors differ widely in power requirements. Some of the light sources for FOS are in the order of Watts or even 10s of Watts; for example, the system presented in the Iowa case study (See Section **Error! Reference source not found.**) requires 80W transceivers. In other cases, low power light sources (as low as 55 dBm for an LED) exist and are widely used. Frugality in power use does not come without its costs, however: A fundamental tradeoff exists in FOS between power consumption and the number of sensors and sensor accuracy that can be supported. Some of the most compelling advantages of FOS (such as the large linear range that can be surveyed by a given transceiver) depend on the use of higher-power transceivers. Low-power sensors suffer from a limitation in the dynamic range available for sensing sensor. The dynamic range must be such that it can at least overcome the total of multiple losses resulting from different factors (reflectivity losses, connector losses, bend losses, fiber distance losses) (Micron Optics, 2004).

8.4 Conclusions and Recommendations

From the topics and issues discussed in this thesis, I suggest the following recommendations and observations:

- Standardization of the FOS industry in general and of SHM using FOS in particular are two important steps that will confirm the maturity of the field in civil engineering. As is common a chicken-and-egg problem exists between deployment and standardization as to which one to start with. It will be important to start somewhere. Engineers will be more motivated to apply technologies according to a well defined code instead of trying an "unheard of" technology at their "own risk", also project owners will rarely be motivated to incur extra costs unless they ensure the value of the money they have spent will not be wasted. A first effort in this direction was initiated by ISIS Canada by publishing a set of design manuals to help engineers with FOS technology. Further efforts can be spent by technical authorities (e.g. ASCE) who may impose codes to standardize the practice. Publishing some guidelines may be a useful important transitional step to move from an unregulated to regulated industry.

- The synergy existing with the telecom industry will bring to the FOS industry the technological advances in research and development. Another synergy, though it is still of lesser extent, exists between FOS and FRP (fiber reinforced polymers). The use of innovative materials such as FRP in new structures is intended to reduce construction, repair, and maintenance costs. This innovation may induce a desire of owners to monitor the new material. FOS have been deployed and proved their merit which encourages their future deployments as well. This creates another kind of "synergy" between FOS and FRP.

- In the 21st century and given the global terror threats there will be no scenario that can be deemed impossible. The monitoring of structures can gain an additional dimension in the sense that SHM in buildings being monitored can provide a real-time diagnosis of a structure that was under attack but is still standing, thus reducing the uncertainty of whether or not the building is still safe to users. For example the World Trade Center explosion in 1993, required an evacuation of 50,000 employees and visitors for a certain time in order for experts to be able to make sure the building could be safely used again. Unfortunately this caused $ 0.5 billion of losses, most of which resulted from insurance claims due to the closure of the building (Measures, 2001). It is needless to say that such deployment of FOS should take into account redundancy issues, to provide backup systems, and to make sure that the system will be functioning (correctly) after an unfortunate incident. Moreover imagination may lead some to think about sabotage targeting the SHM themselves so failures will happen while all readings seem to be in shape. Although such case may seem a science fiction scenario, considering it will be worthwhile. All of types of computer network compromises familiar to system administrators of wireless networks (unauthorized access to data, data tampering, analog or digitally based denial-of-service attacks, etc.) must be considered. Wireless sensor networks pose particular security concerns and risks due to the fact that the signals propagate through free space. Clearly encryption, careful authorization mechanisms and other network security mechanisms require especially careful concerns for such networks.

- With the reduction in costs of FOS expected in the short to medium term, SHM can gain an additional dimension in a globalized world economy where privatization is gaining ground even in developing countries. Being able to monitor structures and provide preventive low cost maintenance (rather than late remedial measures) will be an attractive prospect to both public and private sectors, as public tries to reduces expenses and debt and as private is always driven by further profits.

- The ability to monitor remote buildings and infrastructure is an attractive option in many cases. A step was taken in this direction by the effort from ISIS Canada in the monitoring of a pipeline in Alberta from a PC in Toronto (Mufti et al., 2003). The case of monitoring oil pipelines to prevent interruptions resulting from pipe failures becomes especially important at a time when world prices of oil are at a record high. The case of a country like Iraq that has an old oil infrastructure would form a particularly valuable target for monitoring.

- Hybrid systems combining FOS and wireless sensors may be an interesting new domain, however given the large discrepancy in the power requirements of the two systems and the tradeoffs between power and performance in FOS, some research challenges must be overcome before feasible systems can be assembled.

- With the reduction in costs of FOS expected in the short to medium term, SHM can gain an additional dimension in a globalized world economy where privatization is gaining ground even in developing countries. Being able to monitor structures and provide preventive low cost maintenance (rather than late remedial measures) will be an attractive prospect to both public and private sectors, as both the public sector focus increasingly on life-cycle costs.

9 GLOSSARY

(Source : Udd et al., 1998)

absorption – The loss of some or all of the energy contained in an electromagnetic wave to the medium in which it is propagating. The lost energy is usually converted to heat.

attenuation – The decrease in power of a signal, or light wave, from interaction with the propagation medium. The decrease usually occurs as a result of absorption, reflection, diffusion, scattering, deflection, dispersion or resistance.

bandwidth – The range of frequencies that a device is capable of handling.

cladding – An optical transparent material over the core of the fiber optic cable, with a refractive index lower than that of the core, to provide total internal reflectance.

core – The primary light-conducting region of an optical fiber. The refractive index of the core is higher than its cladding, the condition necessary for total internal reflection.

coupler – A connector that is used interconnect two or more optical fibers.

coupling – The connection between elements,whether physical or across a gap, where energy from one element is transferred to one or more other elements.

demodulation – The extraction of the original signal from the carrier.

detector – A device that responds to a signal and reproduces the signal in a new form, usually in a form that is easier to process.

diffraction – The bending of radio, sound, or light waves around an edge; typically aperture edges.

electromagnetic interference (EMI) – Interference caused in a circuit by radiation through coupling.

electro-optic device – A devices that converts electronic signals to optic signals or optic signals to electronic signals.

Fabry Perot interferometer – A high resolution multiple beam interferometer especially sensitive to linear motion of the mirrors.

fiber optic sensor – A sensor in which light is modulated by a specified environmental variable.

heterodyne detection – Signal detection based on the mixing of two frequencies.

homodyne detection – Signal detection based on the use of only one frequency.

intensity sensor – In fiber optics, a fiber optic sensor in which the optical intensity of a light beam varies with an environmental signal. (e.g. micro-bend sensor).

interferometer – An instrument in which the interference effects of light waves are used for purposes of measurement.

interferometric sensor – A sensor that employs the principles of interferometry to perform a sensing function.

interferometry – The study of electromagnetic wave interference for precise measurements of things such as wavelength determination and index of refraction.

light-emitting diode (LED) – A diode without lasing action. The output is about 10 times the spectral width of a laser.

Mach-Zehnder interferometer – An interferometer in which the light wave is split,
and then recombined at a photo-detector.

microbend sensor – A sensor that converts mechanical movement to fiber bending so that the output light wave intensity is proportional to the mechanical movement.

mode – The characteristic state of a specific light beam traveling in a fiber. The mode is a function of the core diameter, the index of refraction of the core and cladding, and the wavelength of the light.

multimode fiber – An optical fiber waveguide that will support more than one mode.

multiplexing – A method of transmitting several signals on the same channel.

polarimetric sensor – A sensor in which the environmental signal alters the polarization of a light wave in an optical fiber.

Rayleigh scattering – The scattering of light waves due to small particles in the medium.

sensor – Any device that responds to an environmental signal and outputs a signal that
can be used as a measure of the environmental signal.

time-division multiplexing (TDM) – Multiplexing in which separate channels are established by connecting one circuit to many signal sources sequentially in time.

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