ISIS and SAMCO Educational Module 5:

An Introduction to Structural Health Monitoring

Prepared by ISIS Canada and SAMCO Network of the European Commission
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Objectives of This Module

The objective of this module is to provide engineering students with basic introductory knowledge of the field of Structural health monitoring (SHM). It is one in a series of modules on innovative SHM and fibre reinforced polymer (FRP) technologies available from ISIS Canada. While research into the field of Structural health monitoring is ongoing, an overall awareness of currently available monitoring devices and systems is essential for the new generation of structural engineers. The primary objectives of this module can be summarized as follows:

1. to provide engineering students with a general awareness of Structural health monitoring and some of its potential applications in civil engineering;
2. to introduce students to the general apparatus and testing used for monitoring typical engineering structures;
3. to facilitate and encourage the use of SHM in the construction and structural rehabilitation industries; and
4. to provide guidance to students seeking additional information on this topic.

The material presented herein is not currently part of a national or international design code, but is based mainly on the results of numerous detailed research studies and field projects conducted in Canada and around the world. Information presented in this document is based primarily on the recommendations of ISIS Canada Design Manual No. 2: Guidelines for Structural Health Monitoring. As such, this module should not be used as a design document, and it is intended for educational use only. Further information on Structural health monitoring can be found on the internet at www.isiscanada.com.

Additional ISIS Educational Modules

Available from ISIS Canada (www.isiscanada.com)

Module 1 – Mechanics Examples Incorporating FRP Materials

Nineteen worked mechanics of materials problems are presented which incorporate FRP materials. These examples could be used in lectures to demonstrate various mechanics concepts, or could be assigned for coursework or exam problems. This module seeks to expose first and second year undergraduates to FRP materials at the introductory level. Mechanics topics covered at the elementary level include: equilibrium, stress, strain and deformation, elasticity, plasticity, determinacy, thermal stress and strain, flexure and shear in beams, torsion, composite beams, and deflections.

Module 2 – An Introduction to FRP Composites for Construction

FRP materials are discussed in detail at the introductory level. This module seeks to expose undergraduate students to FRP materials such that they have a basic understanding of the components, manufacture, properties, mechanics, durability, and application of FRP materials in civil infrastructure applications. A suggested laboratory is included which outlines an experimental procedure for comparing the stress-strain responses of steel versus FRPs in tension, and a sample assignment is provided.

Module 3 – An Introduction to FRP-Reinforced Concrete

The use of FRP bars, rods, and tendons as internal tensile reinforcement for new concrete structures is presented and discussed in detail. Included are discussions of FRP materials relevant to these applications, flexural design guidelines, serviceability criteria, deformability, bar spacing, and various additional considerations. A number of case studies are also discussed. A series of worked example problems, a suggested assignment with solutions, and a suggested laboratory incorporating FRP-reinforced concrete beams are all included.

Module 4 – An Introduction to FRP-Strengthening of Concrete Structures

The use of externally-bonded FRP reinforcement for strengthening concrete structures is discussed in detail. FRP materials relevant to these applications are first presented, followed by detailed discussions of FRP-strengthening of concrete structures in flexure, shear, and axial compression. A series of worked examples are presented, case studies are outlined, and additional, more specialized, applications are introduced. A suggested assignment is provided with worked solutions, and a potential laboratory for strengthening concrete beams in flexure with externally-bonded FRP sheets is outlined.

Section 1

Introduction and Overview

THE GLOBAL INFRASTRUCTURE CRISIS

The population of the modern developed world depends on a complex and extensive system of infrastructure to maintain economic prosperity and quality of life. The existing public infrastructure of Canada, the United States, Europe, and other developed countries has suffered from decades of neglect and overuse, leading to the accelerated deterioration of bridges, buildings, municipal and transportation systems, and resulting in a situation that is approaching a global infrastructure crisis. For example, in Canada more than 40% of the bridges currently in use were built over 50 years ago, and a significant number of these structures need strengthening, rehabilitation, or replacement. Much of our infrastructure is unsatisfactory in some respect, and public funds are not generally available for the required replacement of existing structures or construction of new ones.

Many factors have led to the unsatisfactory condition of our infrastructure. One of the primary factors is the unsatisfactory inspection and monitoring of existing infrastructure, with problems becoming apparent only once structures are in such dire need of attention that the cost of repair often approaches that of replacement. Other factors include the widespread corrosion of steel reinforcing bars in concrete structures, corrosion of steel structures and components, increases in loads and/or design requirements over time, or simply overall deterioration and aging.

Because infrastructure owners can no longer afford to upgrade and replace existing structures using the same materials and methodologies as have been used in the past, they are looking to newer technologies and rehabilitation schemes, such as *structural health monitoring (SHM)*[1] in combination with *fibre reinforced polymers (FRPs)*, that will provide materials and monitoring tools which will prolong the useful service lives of structures while reducing ongoing maintenance costs.

STRUCTURAL HEALTH MONITORING

In the last ten to fifteen years, SHM technologies have emerged creating an exciting new field within civil engineering. These technologies are currently becoming more and more commonplace. SHM refers to the broad concept of assessing the ongoing, in-service performance of structures using a variety of measurement techniques (many of which are discussed in this document). Smart structures – those structures which incorporate numerous SHM sensors of various types – have emerged as a potential solution in diagnosing infrastructure deterioration before it becomes critical, and thus represent powerful tools in the ongoing struggle for sustainable infrastructure. Furthermore, the relatively recent introduction of advanced, high-performance materials, such as FRPs, in civil engineering structures necessitates ongoing monitoring to ensure that these new materials are performing as planned, and that the safety and integrity of structures is not compromised.

Fig. 1-1. Taylor Bridge, in Headingly, Manitoba, incorporates numerous sensors into its design. In this way, the bridge is capable of sensing loads and deformations and conveying that information to engineers at a remote location. The Taylor Bridge thus exemplifies structural health monitoring, and is an example of one of the world's first "smart" structures

It is clear that SHM is an important tool in the current and future design, analysis, and maintenance of modern civil engineering structures and systems. This module outlines some of the primary considerations to keep in mind when designing and utilizing SHM technologies.

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[1] Italicized terms are defined in Section 13.

Section 2

What is Structural Health Monitoring?

Structural health monitoring is not a new idea. For thousands of years engineers have been examining the ongoing performance of their structures in an effort to prolong structures' service lives and ensure public safety (see Figure 2-1). However, only recently has SHM become a more essential component of a civil engineer's education. Infrastructure sustainability is an issue that the developed (and developing) world can no longer afford to ignore, and a general awareness of the need for, and implementation of, detailed SHM programs is critical to the success of the next generation of engineers.

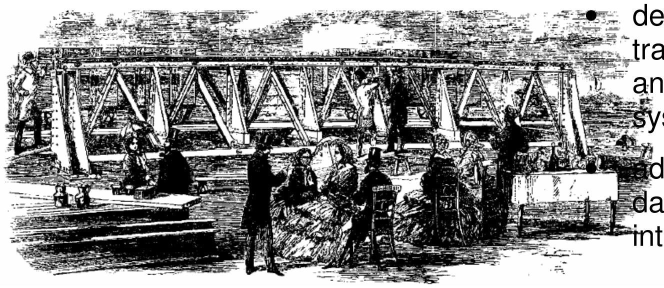

Fig. 2-1. Testing of a steel truss in England for a railway bridge in India in the 19th century
(print courtesy of R.A. Dorton)

The current rapid evolution and advancement of SHM technologies can be attributed to several compounding factors, many of which are due, in part, to the efforts of organisations such as ISIS Canada. The current trend toward increased use of SHM in civil engineering and be attributed to:

- the need for long-term monitoring of innovative designs using new materials (i.e. to monitor and ensure the safety of as yet unproven materials and systems);
- the need for long-term monitoring for better management of existing structures;
- the recent advancements in the development of new, functional, and economical sensors (e.g. *fibre optic sensors (FOSs)* and *smart materials*);
- ongoing developments in the field of digital *data acquisition systems (DASs)*;
- ongoing developments in communication technologies, including internet-based and wireless technologies;
- developments of powerful data transmission and collection systems, and data archiving and retrieval systems; and
- advances in data processing, including damage detection models and artificial intelligence algorithms.

Definition of SHM

In this document, structural health monitoring can be defined as a non-destructive *in-situ* structural evaluation method that uses any of several types of sensors which are attached to, or embedded in, a structure. These sensors obtain various types of data (either continuously or periodically), which are then collected, analyzed and stored for future analysis and reference. The data can be used to assess the safety, integrity, strength, or performance of the structure, and to identify damage at its onset.

The definition of SHM given above does not encompass all technologies used in the evaluation and assessment of structures. The broader field would also include the use of many devices, techniques and systems that are traditionally designated as Non-Destructive Testing (NDT) and Non-Destructive Evaluation (NDE) tools. Common to all is the objective of learning about the in-service condition of the structure. There is no formal delineation between each approach, so the following distinction is adopted by ISIS. NDT/NDE normally refers to a one-time assessment of the condition of materials in the structure using equipment external to the structure. SHM normally refers to activities focussed on assessing the condition of the structure or its key components based on response to various types of loads. It generally involves on-going or repeated assessment of this response. Some parts of the sensory system are usually embedded in or attached to the structure for the complete monitoring period.

BODY ANALOGY

One way of gaining an appreciation of Structural health monitoring is to draw an analogy with the human body. Just as a doctor is required to monitor the health of her patient, today's engineers are able to monitor the prevailing condition of structures (as in Figure 2-2). A medical doctor uses specialized equipment to check a patient's vital signs and thereby monitors the patient's overall health. In the same way, the engineer utilizes specialized sensors to collect information on the structure's overall health. If a patient's blood pressure is too high, the doctor prescribes corrective medicine. Similarly, in SHM applications, if the data flowing from the sensors indicate excessive stresses or deformations on the structure, the engineer can take the appropriate measures to correct the situation. In both cases, immediate preventative action can avert catastrophic consequences.

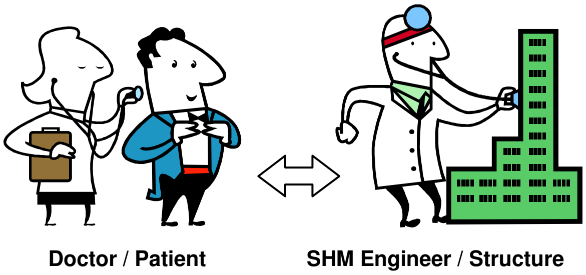

Fig. 2-2. The SHM / body analogy

Annual check-ups by doctors are now a routine form of preventative maintenance for human beings, and few people would argue that this has not improved the general health of the global population. In the future, SHM of infrastructure will similarly be commonplace, and it will provide early warning of structural damage or decay, thus improving the health of our infrastructure systems. This rapidly emerging technology is destined to be of great value to those responsible for the safety and well-being of civil engineering structures.

SHM SYSTEM COMPONENTS

As mentioned previously, structural health monitoring refers to the continuous or periodic monitoring of a structure using sensors that are either embedded in it or attached to its exterior. SHM systems are applicable to all types of civil engineering structures, including bridges, buildings, tunnels, pipes, highways and railways.
While the specific details of SHM systems can vary substantially, a modern SHM system will typically consist of six common components, namely:

1. acquisition of data (a sensory system);
2. communication of information;
3. intelligent processing and analyzing of data;
4. storage of processed data;
5. *diagnostics* (i.e. damage detection and modelling algorithms); and
6. retrieval of information as required.

A typical flow pattern between the six components of an SHM system is shown in Figure 2-3; however, other flow patterns are also possible, and the flow of information between system components can certainly take more than one path. Each of the various system components is discussed in more detail in Section 3.

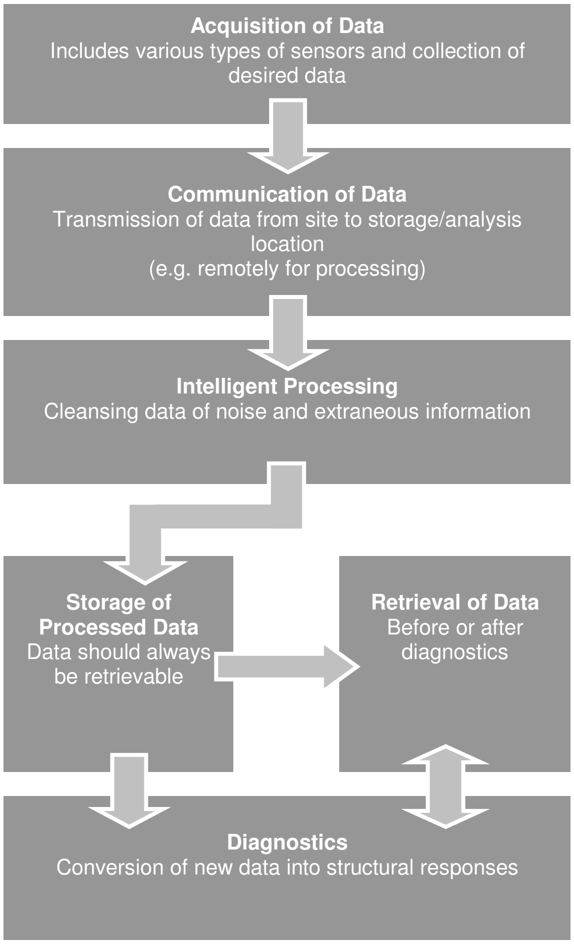

Fig. 2-3. Components of a typical SHM system

SHM CATEGORIES

In addition to the various components of SHM systems, structural health monitoring can be classified into one of at least four overall types or categories, each consisting of several smaller sub-categories as shown in Figure 2-4. These categories are distinguished by the type of testing undertaken, both in terms of how data are physically collected, and with respect to the timescales over which data are obtained. The main categories are:

1. static field testing;
2. dynamic field testing;
3. periodic monitoring; and
4. continuous monitoring.

These various categories are outlined in Figure 2-4, along with the associated sub-categories, and are discussed in more detail in Section 5.

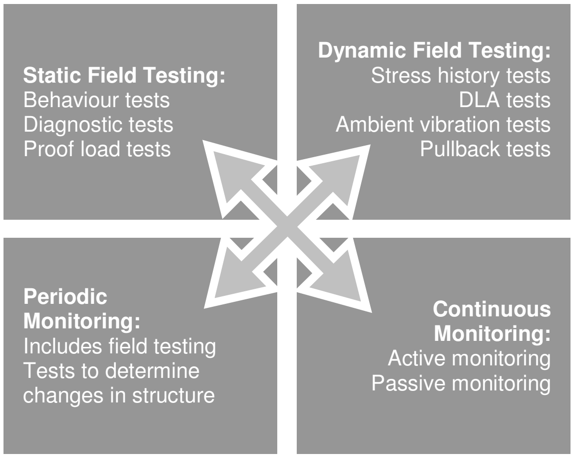

Fig. 2-4. Categories and sub-categories of SHM systems

CLASSIFICATION OF SHM SYSTEMS

According to Sikorsky (1999), SHM systems can be classified both in terms of their level of sophistication and by the types of information (and decision making algorithms) which they are capable of providing. These classifications are particularly instructive in understanding the goals of SHM and some of the concepts that are discussed later in this module. The classifications of SHM systems can be summarized as follows:

- **LEVEL I:** This basic level SHM system is capable of detecting damage in a structure, but cannot provide any information on the nature, location, or severity of the damage. It cannot assess the safety of the structure.

- **LEVEL II:** Slightly more sophisticated than Level I SHM systems, Level II systems can detect the presence of damage and can also provide information on its location.
- **LEVEL III:** A Level III SHM system can detect and pinpoint damage, and can provide some indication of its severity.
- **LEVEL IV:** This most sophisticated level of SHM systems is capable of providing detailed information on the presence, location, and severity of damage, and it is able to use this information to evaluate the safety of the structural system. Obviously, Level IV SHM systems are the most complex and costly class.

A visual comparison of the various classifications of SHM systems is shown in Figure 2-5.

ADVANTAGES/BENEFITS OF SHM

Structural health monitoring presents a number of key benefits for civil engineering structures, including decreased ongoing inspection and maintenance costs, increased structural safety, and an improved understanding of the behaviour and durability of the monitored structure. Some of the most commonly cited benefits of SHM include:

Improved understanding of in-situ structural behaviour

The bulk of information which is currently used in structural design codes has been obtained from research programs conducted in structural engineering laboratories around the world, where it is often difficult, if not impossible, to completely model (physically or numerically) the behaviour of full-scale structures in-situ. As a result, testing and analysis is more commonly performed on small-scale specimens, which represent only small portions of the actual structures, subjected to idealized loads. In-service monitoring of civil engineering structures provides a wealth of information on how real structures actually behave when subjected to actual structural and environmental loads. This information is critical to advance the future practice of structural engineering. The information obtained through detailed SHM programs can thus be used to improve design equations and practices.

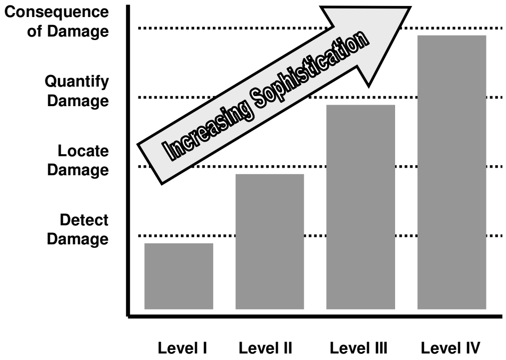

Fig. 2-5: Classification of SHM systems based on sensing and decision-making capabilities

Early damage detection

Detection of structural damage at its onset permits early action which may prevent the structure from having to sustain loads for an extended period of time while in a damaged state. As a result, it becomes less necessary for structures to be *overdesigned*, which significantly lowers construction costs (Lau, 2003) and increases the overall efficiency of infrastructure projects. Early damage detection also allows repairs to be made at the onset of damage, which can drastically decrease the resulting repair costs and prevent further deterioration (Pines and Aktan, 2002). Additional cost savings are due to decreased site visits and manual investigations by maintenance workers, since in some cases pertinent data can be transferred remotely from the structure to an offsite location for analysis.

Assurances of a structure's strength and serviceability

This can be particularly important for long-span bridges, where visual inspections are, in many cases, impossible or inadequate for determining a bridge's safety (Pines and Aktan, 2002). In addition, SHM can be used where data is needed to provide confidence in a new building material or an innovative construction technique. In the case of a structure nearing the end of its service life, SHM may permit its continued use for a time by providing confidence of its satisfactory performance.

Reduction in down time

Down time during structural repair or upgrade works is one of the major costs that must be considered in assessing the whole-life cost-effectiveness of our infrastructure systems. While costs due to down time can be extremely difficult to quantify, since they include costs to society due to loss of productivity and economic growth, inconvenience costs, and energy costs, it is now widely accepted that these costs must be considered when examining various rehabilitation and upgrading schemes, particularly for highway bridges. Early damage detection and an improved understanding of structural behaviour result in a reduction in down time for structures which may require repair or strengthening.

Improved maintenance and management strategies for better allocation of resources

SHM systems reduce the requirement for field inspection and enable the development of large-scale infrastructure condition databases which can be automatically updated. Decision makers can formulate better strategies to effectively deal with infrastructure deterioration and allocate shrinking budgets and scarce resources more efficiently.

Enables and encourages use of innovative materials

In an effort to address the looming infrastructure crisis, the engineering community is actively investigating the use of various innovative materials and structural systems which can increase the durability of civil engineering structures. Some of these innovative materials (e.g. FRPs) and methodologies (e.g. *steel-free bridge decks*) are currently being investigated by researchers within the ISIS Canada Research Network, and information on these technologies is available from www.isiscanada.com. However, the use of new and innovative technology requires the implementation of monitoring and inspection to ensure that these materials are performing as planned. Thus, SHM and FRP technologies are rightfully evolving together.

Section 3

Methodology

SYSTEM COMPONENTS

An ideal SHM system should be capable of providing information on demand about the health of a structure as well as warnings regarding any significant damage that has been detected. Clearly, the development of such a system involves the use of expertise in many disciplines, such as structures, materials, damage detection, sensors, data management and intelligent processing, computers, and communication. The six overall components of a typical SHM system were presented previously in Section 2 and are shown below in Figure 3-1. In this section, more detailed information is provided on each specific SHM system component.

The components are discussed in the general order of data flow presented in Figure 2-3. The design of an SHM system for a particular application would follow a different methodology, as will be discussed in Section 6. It is important, however, to understand each component and its purpose prior to discussing SHM system design.

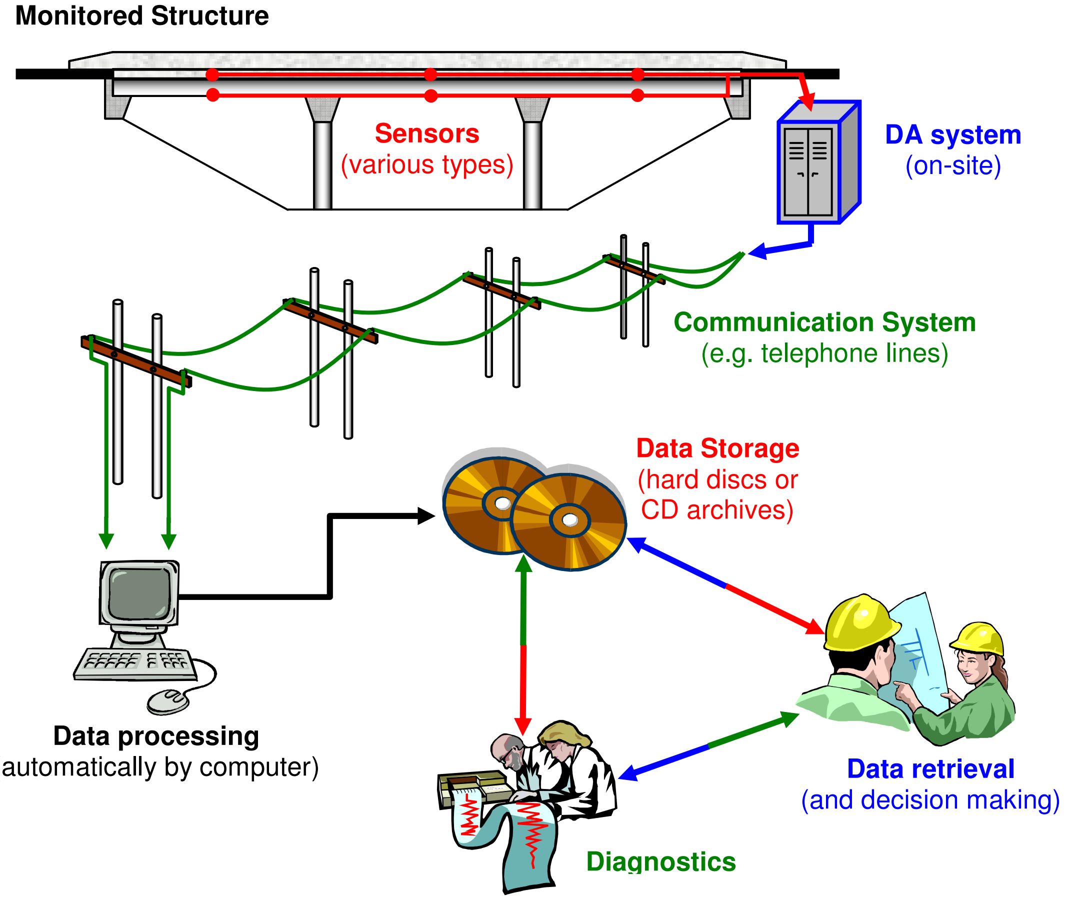

Fig. 3-1. Visual schematic of a typical SHM system

ACQUISITION AND COLLECTION OF DATA

This component involves the collection of raw data such as strains, deformations, accelerations, temperatures, moisture levels, acoustic emissions, and loads. Included in this component are the actual sensors and systems used to physically monitor the structure. Various conventional sensors may be used to record data and may include: *load cells, electrical resistance strain gauges, vibrating wire strain gauges, displacement transducers, accelerometers, anemometers*, *thermocouples* and *fibre optic sensors* (which will be discussed in greater in Section 4 of this module).

Selection of Sensors

Essential to the effectiveness of an SHM system is the selection of appropriate and robust sensors which will provide the information required for monitoring and analysis. The specific types of sensors selected for a project depend on several considerations. Obviously the sensor must be able to measure the desired response parameter such as strain or vibration. In addition, the selection criteria should include accuracy, reliability, sensor installation limitations, power requirements, signal transmission limitations, durability and cost. For cost, consideration must be given to the cost of the whole sensory system including the sensor, associated cables or wiring and the signal conditioning/data acquisition system. Provided that the project requirements can be met, there is no limitation of the types of sensors which can be used in a specific SHM system.

It is critically important to have some idea at the outset as to the long term performance of the various types of sensors available on the market. For instance, certain sensors are not appropriate for long term monitoring due to deterioration in sensor performance with time. Extreme care should be taken in the selection of the number of sensors and their location within the structure to ensure satisfactory performance.

Sensor Installation and Placement

Recent field applications of SHM systems in real structures have demonstrated that care should be taken during the design of the SHM system to ensure that sensors can be easily installed within a structure without substantially changing the behaviour of the structure. The presence of sensor wiring, conduit, junction boxes, and other accessories needed to house the SHM system on site must be considered and accounted for during the design process. Experience has shown that while the embedded sensors themselves can be quite durable, poor durability or installation of the cable network and poor design of the data acquisition equipment for field environments can significantly reduce the functionality of the SHM system. While not discussed any further in this module, various installation issues are addressed in detail in the recently published Civionics Specifications, available from ISIS Canada.

Transfer to Data Acquisition System (DAS)

The data acquisition system refers to the onsite system where signal demodulation, conditioning and storage of measured data are conducted prior to being transferred to an offsite location for analysis (the data-logger). For most sensors an input signal is required, and then interpretation of the sensor output signal must be conducted to convert the analog sensor response into engineering terms. For example, for fibre optic sensors, an input light source must be supplied and the reflected light from the sensor must be measured and converted into strain. The system then stores the response information in a temporary buffer or in long-term memory. Therefore, all sensors must communicate with the DAS. This is normally conducted via one of two means. The most common (and inexpensive) method to transfer data is via a physical link called a *lead cable or wire*. This cable transfers the sensor signal directly to the DAS. In some cases, very long lead wires can lead to errors resulting from electromagnetic interference (EMI), particularly in the presence of high-voltage power lines or radio transmitters. The use of differential signalling techniques and properly shielded cables can sometimes mitigate the effects of EMI. Note that FOS technologies are not normally affected by EMI. In any case, extreme care must be taken during the construction process to ensure that sensor cables are not accidentally sheared off or otherwise damaged.

Lead cable connections are appropriate in most situations and in cases where structures are not so large as to make physical connections problematic. However, for very large structures in which lead cable transmitted sensor signals might be corrupted by excessive noise, or where long lead cables are otherwise impractical, emerging wireless communications technologies can be used to transfer sensor signals to the DAS. Wireless data transfer is currently more expensive than direct connections, data is typically transferred much more slowly, and the signals are not completely secure. However, it is expected that wireless communications will be increasingly used for SHM of very large structures in the future. For some sensory systems, a combination of the two transmission techniques may be employed. For example, many sensors will require that the sensor be connected to the signal source/demodulation system by a physical link. The communication from demodulation equipment nodes to the main data logging system for the structure can be wireless. Another solution which has been used successfully, on the Golden Boy SHM project in Manitoba (discussed in Section 11), is to convert voltage signal (the standard output of sensors) to current. The reason is that the current signal can be transmitted much further without corruption. Many types of DAS can read current directly, or current can be converted back to voltage at the DAS. This has proven to be a reliable and inexpensive solution.

Data Sampling and Collection

As sensor signals arrive at the DAS, the data must be sorted for onsite storage. A well thought out *data acquisition algorithm*, which captures an adequate (but not excessive) amount of data, is a very important component of a successful SHM system.

As one might expect, structures which are extensively instrumented with a variety of sensors in a variety of locations can, particularly in the case of *continuous monitoring* (discussed later), rapidly generate large quantities of data which can easily become unmanageable if the system is not set up efficiently. A general rule is that the amount of data should not be so scanty as to jeopardize its usefulness, nor should it be so voluminous as to overwhelm interpretation. A low sampling rate leads to the former, and an unnecessarily high rate to the latter. Of course, in some cases, as in the case of *dynamic testing* (discussed later), high sampling rates are required to accurately measure the structure’s response to transient loads. It is important to sample data at the appropriate rate for the type of testing which is being conducted. Decisions regarding appropriate sampling rates should thus be based on experience.

What is monitored, how, and why?

It is probably useful at this stage to briefly describe the types of information in which engineers/owners are interested when assessing the health of a structure. The following is a list of some of the data types that are typically monitored by SHM systems, along with a very brief explanation of how the data might be used.

- **Load:** SHM systems can, by using one of a variety of techniques, collect information about the magnitude and configuration of loads applied to a structure. Using this data, engineers can determine if the loads on a structure are as expected, or if it is subjected to greater (perhaps damaging or dangerous) loads. SHM can also be used to learn how the various loads are distributed within and supported by the structure. Loads can be measured directly using load cells installed within a structure, or it can be inferred through strains or other parameters measured on selected structural components.
- **Deformation:** All structures deform or deflect to some degree. Engineers approximate these deformations in design based on simplifying assumptions; but SHM can monitor actual deformations caused by all physical and environmental loading. Excessive deformation, or deformation in unexpected places, might signal deterioration or changes in structural condition and can be used to assess the need for rehabilitation or upgrade. Deformations and deflections can be measured with a variety of types of *displacement transducers* and *tiltmeters*. In many structures, the direct measure of displacement is difficult due to the need for an appropriate reference point or grounding point for the transducers.
- **Strain:** Strain is a measure of the intensity of deformation of a structural component. Strains can be used to gain a wealth of information about the behaviour and ongoing performance of a structure; these are probably the most commonly used measurements in SHM systems. For instance, if the strains continuously recorded in a tension member of a steel truss bridge suddenly change, engineers know that something significant is happening to the structure – perhaps a particularly heavy freight train is going over the bridge or deteriorated member. The magnitude of the measured strains, and the variation of the magnitudes recorded over the life of the structure, can be examined to evaluate the safety and integrity of the structure. Strains in structural components can be directly measured at the desired locations using standard electrical resistance strain gauges, *vibrating wire strain gauges*, or more recently developed fibre optic sensors.
- **Temperature:** Changes in temperature cause materials to expand or contract due to the effects of thermal expansion. Repeated cycles of heating and cooling can cause damage to structures through repeated cycles of deformation or thermally-induced loads. By incorporating temperature measurements, an SHM system can provide information on how temperature changes affect a structure, and whether the temperature-induced loads and strains are as expected. Temperature may also affect the readings of certain sensors or sensing equipment used in SHM systems. Thus, when collecting data from temperature sensitive gauges, temperature effects must be measured and accounted for. Temperatures can be measured using thermocouples, *integrated temperature circuits*, *thermistors*, or certain types of FOSs.
- **Acceleration:** Loads experienced by structures cause accelerations of structural components (recall $F=Ma$). Conversely, ground accelerations, caused by seismic loads for instance, result in the dynamic loading of structural components. The

combination of the frequency of the response as well as the amplitude of the response to these dynamic excitations is called the modal response. Although structures are designed to withstand these accelerations, SHM can be used to determine exactly how a structure is responding to these accelerations and the resulting loads via determination of the modal response parameters. This type of monitoring is now widespread in seismic regions, where many structures are extensively instrumented in an attempt to gain insight into the effects of real seismic events on structures and their components. Even in non-seismic situations the modal response parameters of a structure can be monitored. Due to changes in support conditions or material properties, there can be a shift in these modal parameters. Hence, in certain situations, an SHM system may be able use these changes in the measured modal response to identify damage or deterioration. Accelerations are typically measured using a class of sensors called *accelerometers*.

- **Wind Speeds and Pressures:** Wind speeds are not normally primary considerations for most civil engineering structures. However, for tall buildings and long-span bridges, wind can be a governing design criterion and should be recorded at various locations in an SHM system. Wind speed can be measured using *anemometers*.
- **Acoustic Emission:** An emerging suite of SHM technologies by sound waves, or *acoustic emission* (AE) waves, can be used to determine the location and characteristics of damage in a structure. AE monitoring is based on the principle that the arrival times of sound waves at different sensors (microphones in this case) will be different depending on the distance between the sensors and the origin of the sound. The most common example of AE SHM is in its use for monitoring unbonded post-tensioned concrete structures or cable-stayed bridge ducts. Unbonded post-tensioned concrete structures are reinforced internally with highly-tensioned steel strands which are not bonded to the concrete. Many of these structures are susceptible to corrosion of the steel strands, which can lead to explosive (and noisy) failures of the strands within the concrete. AE SHM is used both to determine the occurrence of a strand break and its location. If a steel strand breaks at some location, microphones distributed throughout the structure record the sound and the time at which the sound was recorded at each microphone. Using special algorithms this information can be used to find the location of the strand break, and immediate action can be taken to repair the structure.
- **Video Monitoring:** The relatively recent introduction of low cost video surveillance and webcam systems has enabled the use of video monitoring in SHM systems. As an example of the use of video surveillance in SHM, consider a typical highway bridge which is subjected to an overloaded truck. Sensors within the bridge (load cells, strain gauges, displacement transducers) detect the presence of the overloaded truck and send a signal to the DAS to save the video which was recorded as the truck passed over the bridge. This allows the bridge owner to determine the identity of the overloaded truck (by examining the licence plate for instance) and to seek compensation for any damage incurred by the excessive load. It is worth noting that periodic overloads can cause significant distress to civil engineering structures, and periodic overloading of bridges has been an important

motivating factor which has accelerated the development of advanced SHM systems incorporating video surveillance.

COMMUNICATION OF DATA

This component of an SHM system refers to the mechanism of transfer of data from the location where they are collected (the DAS) to the location where they will be processed and analysed (normally some remote location). The communication of data is an important aspect of an effective SHM system, since it allows monitoring to occur remotely, and eliminates the need for site visits and inspections by engineers. In this way, engineers/owners can monitor the performance of their structures from the comfort of their own offices. Modern SHM systems transmit field data remotely, either through telephone lines or the internet, or using wireless technologies such as radio or cellular transmission. Examples of communication systems used in ISIS projects can be found in Han et al. (2004). Further details of the various types of transmission systems are beyond the scope of this document.

INTELLIGENT PROCESSING AND MANAGEMENT OF DATA

The data obtained by the various sensors in a structure are likely to contain extraneous information and *noise* that are of little or no use for the purposes of structural health monitoring. Hence, intelligent processing of data is required before it can be stored for later interpretation and analysis. The goal of intelligent processing is to remove this unwanted information and to make data interpretation easier, faster, and more accurate. In many cases, intelligent processing is also required to remove the influence of thermal or other unwanted effects in the data.

In addition, to deal with the sometimes overwhelming amounts of data generated by SHM systems, various data management strategies have been developed to eliminate unnecessary data without sacrificing the integrity of the overall system. One simple technique is to record only changes in readings, along with the times that these changes occurred. In this way, long periods in which nothing changes are omitted from the data. Alternatively, an SHM system may record readings only above a certain threshold value, or perhaps only the peak readings measured over a designated length of time.

In more sophisticated systems, neural computing and artificial neural network techniques may be employed (McNeill 2004). Algorithms are designed to learn the characteristic patterns of the signals and identify only those patterns which can be classified as ‘novel’. For example, on bridges with low to medium traffic volumes, particularly with respect to heavy trucks, the majority of signals produced by a continuous monitoring program will be small compared to the signals generated by heavy trucks. The latter is of more interest. Neural computing can be used to isolate the truck response as novel compared to all other responses and only this section of the data will be tagged for storage or further analysis. This can be conducted in an unsupervised mode by the monitoring computer such that no human input is required and the data management becomes automatic and efficient.

Sometimes a combination of data acquisition algorithms may be required so that only peak values are recorded as a general operating mode, and continuous data is recorded for discrete periods of time if a threshold value is exceeded. Selection of the most appropriate data acquisition algorithm is a critically important component of SHM as it will affect both the volume of stored data and the type of diagnostic information that can be obtained.

STORAGE OF PROCESSED DATA

Once the data have been intelligently processed, they can be stored for later use in structural health diagnostics. In some cases, the data could be stored for long periods of time, and it is important that, once retrieved, the data are easy to understand. Thus, the medium for storage of the data should be such that the data will be available for a period of many years without susceptibility to corruption. Obviously, the amount of memory required for storage can be very large in SHM applications with numerous sensors or higher data sampling rates, and care must be taken to ensure that sufficient memory is available to store all of the data which will be generated. It is also important to ensure that the data files contain enough information about the data so that anyone could interpret them. It is possible that the data collected could be used by an engineer many years in the future, so the data files should be logical and well-documented.

It is common to disregard raw data and store only processed or analyzed data, thereby decreasing the amount of space necessary for storage. Unfortunately, discarding the raw data does not allow for reinterpretation at a later time.

DIAGNOSTICS

Arguably the most important component of an effective SHM system, diagnostics involves further interpretation of the collected, cleansed, and intelligently processed data. Diagnostics is concerned with analysing the more abstract data signals to produce useful information about the response and health of the structure. This activity requires expert structural knowledge about the behaviour of structures as well as an understanding of how that behaviour may be affected by damage, deterioraton or other changes in condition. The level of complexity of the analysis will change based on the needs of the monitoring program and the SHM system components. In a simple application, it may be sufficient to convert strain readings into stresses for assessment against critical limits such as yielding. The degree of sophistication can increase up to a point where artificial neural networks are required to determine the probability that a measured change in response readings indicates a specific damage type and location by a statistical comparison against a wide range of possible damage situations generated by parametric analysis using numerical models. Whatever the level of sophistication of diagnostic activity, an appropriate numerical model of the structure calibrated against baseline field measurements is normally required.

RETRIEVAL OF DATA

When selecting data to store for retrieval, both the significance of the data and the confidence in its analysis should be considered. For example, for a *static field test* (discussed later), the volume of data generated is relatively small; therefore, both the raw data and the diagnostic information can be easily stored for retrieval. Conversely, for a *dynamic field test*, the volume of data generated is quite large, and therefore only the diagnostic information is stored.

Of course, the overarching goal of structural health monitoring is to provide detailed physical data which can be used to enable rational, knowledge-based engineering decisions.

Section 4

Sensor Technology

As mentioned previously, engineers involved in SHM of civil engineering structures may be interested in various types of data about a structure's response, and hence many different types of sensors might be used in any specific SHM application. Through the activities of ISIS Canada and other organizations a new class of fibre optic sensors (FOSs) is emerging for use in SHM applications. In this section, various types of FOSs used in SHM applications are discussed at the introductory level, with a view to providing students with a general awareness of the suite of options currently available in practice.

FIBRE OPTIC SENSORS

One of the driving forces behind recent rapid advancements in SHM technology has been the development of new types of robust sensors that can be installed in or on a structure and which can provide reliable data over extended periods of time without *drifting*. A class of sensors in which recent developments are particularly important to modern SHM applications are fibre optic sensors, which are used primarily to measure variations in strain and/or temperature. Since the early 1990s, researchers within the ISIS Canada Research Network have been developing new types of FOSs which can be used in specific SHM applications. Many of these recently developed FOSs have now been used in SHM field applications and continue to perform well. For example, FOS strain gauges were installed in the Beddington Trail Bridge in Calgary, Alberta in 1993 (shown below in Figure 4-1), and in both 1999 and 2004 the sensors were found to be performing as expected. Detailed information on the installation, use, and repair of FOSs is available from ISIS Canada at www.isiscanada.com.

Advantages of Fibre Optic Sensors

The development of FOS technologies has been driven both by the tremendous advancements in fibre optic communications technologies, and by the numerous advantages that they offer as compared with more conventional types of sensors. Some of the specific advantages of FOSs include:

- **Non-conductive:** Unlike conventional sensors such as electrical resistance strain gauges, which read changes in electrical voltages and convert these voltages to strains, FOSs are immune to electromagnetic and radio frequency interference.
- **Stability:** FOSs are generally not subject to noise or signal loss due to connector and lead wire resistance. The light signals can be transmitted along very long lengths such that the DAS need not be located close to the sensor. In addition, FOSs exhibit long-term stability and are capable of intermittent readings with no reconnection errors.
- **Convenience:** FOSs are very light, they have small diameters, they are non-corrosive, and they are embeddable, particularly in FRP materials and components. Furthermore, FOSs can be easily bonded to most materials.
- **Flexibility:** These sensors can be applied to virtually any structural shape. A variety of different lengths of sensors are available and *multiplexing* and *distributed sensing* are also possible (discussed later).

Fig. 4-1. Beddington Trail Bridge is prestressed with carbon FRP prestressing tendons. FOSs were shown to be performing 11 years after installation

How do FOSs Work?

In lay terms, FOSs are based on the fact that light waves transmitted down a thin optical cable will reflect specific light patterns and signals based on the condition of the cable. Special equipment measures microscopic differences in the reflected light from the original baseline (installation) measurements. A change in the signal properties of the light waves is correlated to a change in size (elongation or contraction), measured in *microstrain*. The measured strain can be caused by external mechanical loads, internal effects within the structure such as shrinkage, and/or environmental loads such as temperature changes.

A light beam is sent down the fibre optic cable to the sensor and is *modulated* according to the amount of the expansion or contraction (change in length of the sensor). The sensor reflects back an optical signal to a measuring device which translates the reflected light into numerical measurements of the change in sensor length. These measurements indicate precise amounts of strain on the structure at the sensor location (calculations are made to eliminate the effect of temperature change on the strain measurements). A special *demodulation unit* senses the light signal and processes it to yield an electronic signal (a voltage). Converting these voltage signals to strains or temperatures is then performed by the data acquisition system.

Types of Fibre Optic Sensors

Fibre optic strain gauges are commercially available in various different forms. In the simplest form, a fibre optic strain gauge consists of an optical fibre lead with a bare fibre optic sensor at one end and a special connector to the readout unit at the other end. In this form, the fibre optic sensor is small in diameter and can be used for embedment in fibre-composite sheets and bars. It can also be used for bonding directly to the surface of a component. In such a case, it might be necessary to put a layer of insulation over the fibre optic gauge to protect it against environmental and mechanical damage.

Other forms of fibre optic strain gauges include *weldable* and *embeddable* (Refer to Figures 4-2 and 4-3). These gauges are used for attachment to steel and embedment in concrete, respectively, and are pre-manufactured such that minimal effort is required for installation and protection. They contain an ordinary optical sensor bonded and encapsulated inside a stainless steel container. Although these gauges are more expensive than ordinary bare FOS gauges, the higher cost is compensated for by their ease and speed of installation.

Fig. 4-2. A close-up view of an embeddable FOS strain gauge

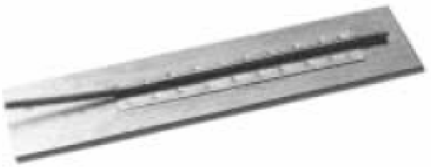

Fig. 4-3. A close-up view of a weldable FOS strain gauge

Weldable gauges are installed, as their name implies, by welding them in place. These gauges do not require protection against humidity, although if the installation is in a harsh environment they may require a coating for protection against mechanical damage. Embeddable gauges can be placed directly in concrete without any extra precautions against humidity or the chemical environment of the concrete. However, care should be taken to avoid damage to the gauge and its cable when placing and vibrating concrete.

A number of different fibre optic sensors have been developed in recent years based on various different optical measurement techniques, from simple sensors that only measure an on/off state, to *multiplexed* sensors (see discussion below) that measure a range of wavelengths to provide more detailed information. While research into the development of FOSs is ongoing, currently four general types are available or are being developed for use in SHM applications, each of which has its specific advantages and disadvantages.

1. Fibre Bragg Grating (FBG)

In a FBG sensor, an optical *grating* (essentially a series of tiny reflectors) is placed on the fibre and the grating spacing is proportional to the wavelength of light reflected when a light pulse is sent down the fibre. When strain is induced at the location of the grating, it causes this grating spacing to change, and this causes a shift in the wavelength of the reflected light. Through the use of a specialized optical technique, along with analysis and calibration of the FBG, the data obtained from the grating spacing can be converted to a measured strain value.

FBG sensors measure local “point” strains only. They can be used for both static and dynamic monitoring, and can be serially multiplexed. These sensors have successfully been embedded within construction materials, and they are bondable and weldable. However, it should be noted that FBG sensors are sensitive to temperature and require *thermal compensation* during data collection.

2. Long Gauge Sensors

Long Gauge FOSs directly measure the displacement, elongation, or contraction of an object. The method involves using a conventional telecom optical fibre of arbitrary length bonded to a structure. The Long Gauge sensing system is highly versatile, and can be configured to gauge lengths from as small as 5 cm to 100 m. This type of sensor measures the change in path distance between the optical fibre’s mirrors while bonded to the structure or host material using the optical principle of *low coherence interferometry*. The deformation obtained represents the average value measured over the gauge length. The distance between the two mirrors along the cable defines the *gauge length*.

Since the Long Gauge sensor is a flexible optical fibre, it can be used in many different configurations. For example, it can be wrapped around a column to measure circumferential contraction or expansion, or strung across a crack to monitor crack growth. These sensors are well suited to monitor permanent long-term deformation from thermal or mechanical loading. Current long-gauge sensors must also be temperature compensated and currently they are available for static monitoring only.

3. Fabry-Perot

Fabry-Perot FOSs consist of fibre optic cables in which the optical fibre is cut and a gap is inserted between the two ends of the severed fibre. The sensor uses a sophisticated optical technique to determine the change in length of the gap, and hence a measurement of strain can be obtained if the original gap width is known.

Like a FBG sensor, the Fabry-Perot FOS measures the local point strain of an object. This type of sensor cannot be *serially multiplexed*, but Fabry-Perot sensors do have dynamic and static capabilities. Fabry-Perot sensors are bondable, weldable, and are easily embedded in most construction materials, including concrete.

4. Brillouin Scattering

Brillouin scattering sensors are still in the developmental stage. These sensors measure *static strain profiles* using a single optical fibre. This means that these sensors can be used to measure the distribution of strains along their length, a somewhat unique capability. The gauge length of these sensors can vary from 15 cm to more than 1000 m. Unlike FBG sensors, Brillouin Scattering FOSs provide data from which temperature and mechanical strains can be separated. Use of this type of sensor requires extensive analysis of optical signals and data, and at present Brillouin Scattering FOS systems are very expensive.

Typical optical fibres are manufactured with several protective layers of material, as shown in Figure 4-4. The **optical fibre** core, at the centre of the fibre, typically about 0.007 mm thick, carries the optical signal. An *amorphous* solid fused silica glass cladding, about 0.125 mm thick, surrounds the core to act as the **fibre buffer**. The optical cladding is contained in a 0.75 mm thick coating of material such as *acrylate* or *polyimide* buffer. An **inner jacket**, either tightly bound to the fibre or in the form of a loose tube, is surrounded by ***aramid* reinforcing fibres** embedded in an **outer jacket** consisting of a polymer such as polyvinyl chloride (PVC). The various coatings surrounding the fibre optic core protect the glass fibre surface from abrasion during handling and installation, from moisture, which weakens the fibre and can contribute to the growth of microcracks, and in concrete from the alkaline environment which is corrosive to conventional glass fibres.

A more detailed discussion of the theory and technology of FOSs is avoided here, since a detailed discussion is available to the interested reader in ISIS Canada Design Manual No.1: Installation, Use and Repair of Fibre Optic Sensors.

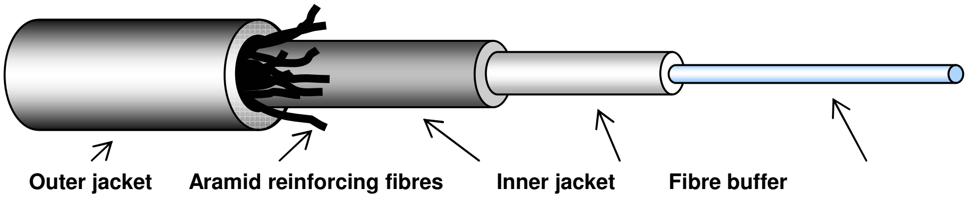

Fig. 4-4. Schematic showing the typical components of a bondable fibre optic sensor

Distributed Sensing

Distributed sensing refers to a sophisticated type of measurement that is possible with the fibre Bragg gratings and Brillouin Scattering FOSs. In FBG sensors, the technique permits continuous strain-versus position measurement over the length of the Bragg grating (typically between 5 mm and 200 mm). These measurements are valuable in estimating such phenomena as the width of cracks, strain transfer in bonded joints, and stress concentrations due to holes in members.

In this type of FOS application, a grating that is bonded in the presence of a strain distribution can be thought of as a series of smaller gratings. Each of these smaller gratings can be measured individually using a specialized optical procedure, and a spatial distribution of strains can hence be obtained. A series of these gratings, called *subgratings*, can be conceptualized one after the other along the optical fibre.

Multiplexed Sensing

In practical SHM applications, a single sensor is rarely sufficient to provide the required health information. This is particularly true within the context of smart structures, where large numbers of sensors are required to properly monitor various aspects of a structure. When a large network of sensors is interrogated by a single sensor reading device (demodulation unit) the sensors must be multiplexed.

Sensor multiplexing schemes are classified according to their physical geometry. When several sensors are distributed along a single optical fibre, they are called *serial multiplexed*, while sensors on separate fibres are called *parallel multiplexed*. A sensor network may include a combination of serial and parallel multiplexing with multiple fibres, each serving as host to more than one sensor. A detailed discussion of multiplexing is not included here, and the reader is referred to ISIS Canada Design Manual No. 1: Installation, Use and Repair of Fibre Optic Sensors for more complete discussion of this topic.

OTHER TYPES OF SENSORS

A variety of other types of sensors are of course available for use in SHM applications. These have been discussed previously and include load cells, electrical resistance and vibrating wire strain gauges, accelerometers, displacement transducers, thermocouples and other thermal sensors, etc. A complete discussion of pertinent sensor types is presented in Appendix A of ISIS Canada Design Manual No. 2.

Section 5

SHM Testing Categories

In Section 2, the four overall categories and sub-categories of SHM systems were introduced (refer to Figure 2-4). It is evident that these overall categories are distinguished based on the timescale of the monitoring (continuous or periodic) and the manner in which a response is invoked in the structure (static load, dynamic load, or ambient vibrations). In this section, each category and sub-category is described in detail.

STATIC FIELD TESTING

Static field testing is the most commonly used method to determine the load carrying capacity of a structure, and provides data about a structure's behaviour and ability to sustain live loads. This type of testing is not new; indeed static field testing of bridges was widespread in Europe at the beginning of the twentieth century. These early tests typically measured only deflection, and as a result the data could only be used to determine a bridge's stiffness in flexure and safety in the short term. Little information was obtained on the long term health of the structure. More recently, various departments of transportation, most notably in Ontario, have instituted programs of static load testing of highway bridges to examine structural behaviour and health. These programs have provided a wealth of information on the in-situ behaviour of real structures.

Types of Static Load Tests

During static tests, loads are slowly placed and sustained on the structure (i.e. trucks or calibrated test vehicles travelling at crawl speed across the bridge) and the structural response is measured and recorded by a network of sensors. These types of loads do not cause any dynamic effects such as impact, vibrations or resonance and hence the interpretation of data is less complex and more easily calibrated against theoretical models and calculations. However, the tests do not capture the full load response actually experienced by most structures, particularly for the case of bridges. Dynamic tests may also be required in which moving loads excite the dynamic response of the structure. There are three basic types of static load tests: *behaviour*, *diagnostic*, and *proof*.

Behaviour Tests

The aim of a behaviour test is to study the mechanics of a structure's behaviour and/or to verify the methods of analysis that should be used on similar types of structures. The test is carried out using loads that are less than or equal to the maximum allowed service load on the structure. Results of a behaviour test show how a load is distributed throughout a structure, but no information is provided about the load capacity of the individual structural components.

Diagnostic Tests

The method used to carry out a diagnostic test is the same as that used for behaviour tests; however, the goal of diagnostic testing is to determine if the response of a particular component of a structure is hindered or helped by another structural component. By understanding the interactions between structural components (the effects of the interaction may be either detrimental or beneficial to the behaviour of the component concerned), the engineer can take appropriate action to fix a detriment or utilize a benefit. A diagnostic test is the surest way to establish a source of distress or enhancement of the load-carrying capacity of a component. In the case of bridges, a large number of tests have confirmed that diagnostic testing can be used with advantage to locate the sources of distress that might exist in a bridge due to inadvertent component interaction, and to determine the positive effects of this interaction. The source of distress in many cases can be eliminated by simple remedial measures. Beneficial interaction, on the other hand, can be used to advantage in establishing an enhanced load carrying capacity of the bridge.

Proof Load Tests

Proof tests are used to study the load-carrying capacity of a structure by inducing *proof loads* on the structure. Proof loads are usually static loads which are greater than the maximum service loads and are defined as the maximum load of a given configuration that a structure has withstood without suffering any damage. During the course of a proof test, loads are gradually increased until the limit of linear elastic behaviour is reached – extreme care must be taken to ensure that a proof loaded structure is not permanently damaged by excessive loading. Care should be taken to ensure that all calculations are correct, all safety precautions are taken, and that the structure is continuously monitored during testing. It should also be noted that subjecting a structure to a sufficiently high proof load is not always a confirmation of its load carrying capacity. Supporting analysis based on sound engineering reasoning is essential for determining if there is reason to believe that a structure can be relied upon to carry the required loads for the foreseeable future.

DYNAMIC FIELD TESTING

Dynamic field tests are used to assess the behaviour of structures subject to moving loads. These types of tests are most applicable to bridges, since vehicle loads are generally moving (unless a traffic jam occurs on the bridge). Thus, this section focuses on dynamic testing of bridges – although the principles are equally applicable to other types of structures.

In a typical dynamic field test, a *test vehicle* moves across a “bump” of a pre-determined size on the bridge being tested. The test is usually carried out several times with the test vehicle travelling at a range of velocities. The vehicle hitting the bump introduces an impulsive dynamic load into the structure, which excites the bridge’s dynamic response. There are four types of dynamic field tests: *stress history* tests, dynamic load allowance (DLA) tests, ambient vibration tests, and pull-back tests.

Stress History Tests

Stress history tests are used to determine the range of stresses experienced by parts of a bridge which are prone to failure by *fatigue loading* – a potentially disastrous type of failure which is caused by repeated cycles of loading and unloading. This type of testing requires a modern DAS with large storage capacity, rapid sampling rate, and the capability to provide a continuous record of strain profiles in various instrumented structural components. The strain profiles are analysed to determine the strain ranges experienced by the components, and hence to arrive at an estimate of the *fatigue life* of the structure – the time remaining before the component or structure could be expected to fail by fatigue.

Dynamic Load Allowance (DLA) Tests

Structures are typically designed based on factored best estimates of the maximum loads which can be expected to act during a structure’s lifetime. For the purposes of design, these loads are normally treated as *static*. For example, the weight of a transport truck passing over a bridge is treated as a static load for which the bridge's members are designed. However, in reality many of these loads (the weight of the transport truck for instance) are dynamic, and so the effects of the static truck load (its weight) are amplified by some factor. This factor is referred to as the *Dynamic Amplification Factor*, and it is determined through DLA testing. There are several different methods used to determine the dynamic amplification factor and many parameters that will affect it, such as the type and weight of the test vehicle. No single standard for DLA testing currently exists.

Ambient Vibration Tests

The purpose of an ambient vibration test is to identify the vibration characteristics of a bridge by measuring its response to ambient dynamic forces caused by wind, human activity and traffic. This information is of interest to engineers for a variety of reasons, but in the context of SHM, changes in the vibration characteristics of a structure can in some cases provide an indication of structural damage or deterioration. The use of vibration characteristics to identify damage is sometimes referred to as vibration-based damage detection (VBDD). In these types of tests, strategically placed sensors (generally accelerometers) are used to measure the vibration response of the structure and these data are used to determine its natural frequencies and characteristic shapes of vibration (i.e. the mode shapes). Once these vibration characteristics have been determined, sophisticated analysis techniques are required for damage identification since changes to vibration characteristics resulting from damage are relatively small unless damage is severe.

Vibration testing for damage identification is still relatively new when applied to civil engineering structures, and appropriate techniques are actively being improved and refined. A number of challenges still exist. Many of these relate to the fact that the *global properties* of a large structure (which include its vibration characteristics) are only very slightly affected by local damage. Because of this, very precise knowledge of the vibration characteristics is essential, and this requires not only precise measurements but generally numerous repeated measurements to reduce the influence of variability caused by random errors (including *noise*). It also requires a sufficient number of sensors and knowledge of where a limited number of sensors should be placed. Deciding on the placement of sensors is a task which requires experience and an in-depth understanding of the structure's behaviour. Moreover, the variability of measurements is relatively large when ambient sources of dynamic excitation are used, which means that greater effort is required to obtain vibration characteristics with the necessary precision. Other methods of excitation that produce less variability (e.g. controlled shaking by a hydraulic actuator) may be more appropriate in the context of damage identification.

In addition to the challenge of precisely identifying vibration characteristics, the characteristics themselves vary as a result of normally occurring events such as daily and seasonal temperature variations, normal changes to support conditions as the structure ages, and snow accumulations. In fact, these types of events generally produce changes that are much larger than those caused by small-scale local damage. Methods to isolate the effects of damage from the effects of normal events have yet to be developed.

Despite the challenges, researchers believe that vibration-based damage detection will soon become a viable tool for SHM.

Pull-Back Tests

These types of tests are usually conducted on bridges, although pull-back testing can be performed on certain other types of structures to determine their response to lateral (sideways) dynamic excitation. In the case of bridges, since normal traffic loads do not significantly excite a bridge in the lateral direction, it is usually difficult to determine their lateral vibration characteristics from the results of ambient vibration tests. The lateral vibration characteristics of a bridge can be obtained from a pull-back test. This type of test is conducted by pulling the structure laterally by means of cables anchored in the ground (or to some other fixed object) and releasing the cables suddenly. The response of the structure is monitored with the help of accelerometers, and the process of analyzing the data is much the same as for an ambient vibration test.

PERIODIC MONITORING

Structural health monitoring of civil engineering structures can be either periodic or continuous. Periodic SHM is conducted to investigate any detrimental change that might occur in a structure (or in a repair that has been made to the structure). By monitoring the behaviour of a structure at specified time intervals (weeks, months, or years apart), changes in the behaviour can be detected and these changes may be used as an indication of damage or deterioration. There are several different techniques for periodic monitoring, some of which fall into the SHM categories discussed previously. A few examples include:

- **Monitoring through ambient vibrations:** As previously discussed, this type of monitoring uses ambient vibrations caused by live or wind loads to examine the dynamic response of the structure and identify changes in the vibration characteristics which might signal damage. In an ambient vibration monitoring system, sensors may be permanently installed on the structure at previously determined ideal locations or they may be temporarily installed at the time of testing.
- **Bridge monitoring through testing under moving traffic:** Periodic records of a structure’s response, such as records of strains in various components, can be used to track changes in the behaviour of a structure. By measuring the progression of strains observed in various bridge components over time, observed changes can be used to provide an indication of damage or deterioration.
- **Monitoring through static field testing:** This type of testing, discussed previously, is seldom used for periodic monitoring due to the high costs associated with its use. However, in certain situations, particularly when innovative structural systems are used and engineers are interested in validating their designs, static field testing can be used to periodically check for changes in the behaviour of a structure. Indeed, this approach has recently been successfully used in Ontario to monitor the performance of highway bridges which incorporate innovative steel-free bridge deck systems.
- **Monitoring crack growth:** Most concrete structures will, over time, develop cracks in regions which are exposed to tensile forces. When a concrete structure has been in service for some time, the formation of cracks will stabilize and the structure becomes elastic. However, if cracks continue to form and grow, the health of the structure may be called into question. Thus, in certain applications, particularly when the consequences of cracking could be more severe, it is

important to periodically monitor crack formation and growth. Currently, this type of periodic monitoring typically involves mostly manual work, with bridge inspections being conducted visually. However, instrumentation can also be used to measure crack openings once they initially form. Research is on-going to use acoustic emission systems and long-gauge FOSs to detect the occurrence of cracks as well as monitor subsequent crack growth.

- **Periodic monitoring of repairs:** Static field tests done before and after structural repairs can be useful in quantifying the effectiveness of repairs, particularly when a repair was performed to enhance the stiffness of the structure. For example, static proof testing before and after a structural repair can give engineers confidence that the repair will perform its intended function. This type of testing has successfully been used in a variety of applications, where externally-bonded fibre reinforced polymer materials have been used to strengthen existing reinforced concrete structures in flexure and/or shear.

CONTINUOUS MONITORING

Continuous monitoring, as the name implies, refers to monitoring of a structure for an extended period of time (weeks, months, or years). This type of monitoring has only recently been used in full scale field applications, due in part to the higher costs and complexity involved. In continuous monitoring, data acquired at the structure are either collected or stored on site (logged) for transfer, analysis, and interpretation at a later time, or they are continuously communicated to an offsite (remote) location. In the most sophisticated of these types of SHM applications, field data are transmitted remotely to the engineer's office for *real-time monitoring* and interpretation.

Customarily, continuous monitoring is only applied to those structures that are either extremely important or if there is a doubt about their structural integrity. The latter might be the case if the structure is likely to be exposed to extreme events, such as severe earthquakes and hurricanes, or if its design includes an innovative concept that does not have a history of performance to prove its long-term safety.

Section 6

Structural Health Monitoring System Design

Structural health monitoring is a relatively new and constantly evolving science, and as such there is no commonly accepted methodology specified for designing an SHM system for a particular project. As with traditional structural design, the engineers involved ultimately make decisions based on objective technical considerations coupled with personal experience and preferences, jurisdictional requirements, economics and project partners. Below is a brief list of some of the common technical issues of which the engineer must remain cognizant when designing, installing, and using SHM systems. Also presented is a brief general methodology recommended for the design of an SHM system. The reader should note that it is important to consult an SHM specialist to ensure the successful application of these technologies in practice.

SHM SYSTEM ISSUES

Design Issues

- Definition of SHM objectives
- Sensor placement
- Types of monitoring
- Durability and lifespan of SHM system

Installation Issues

- Sensor identification
- Contractor education
- Sensor damage during construction
- Structural changes induced by presence of SHM system (embedded conduits and junction boxes in particular)
- Protection against deterioration and vandalism

Use Issues

- Data collection and management
- Continuity of knowledge
- Dissemination of performance results / public awareness

SHM System Design Methodology

Once the structure to be monitored has been identified, the recommended steps in the evolution of the SHM system from the structural engineer's perspective are as follows:

1. Identify the damage or deterioration mechanisms that are of concern for the structure.
2. Categorize the influence of this deterioration on the mechanical response of the structure or its key components under service loads; this includes the development of appropriate theoretical and numerical models of the structure.
3. Establish the characteristic response of key parameters, experimentally and/or theoretically, such as strain, vibration, or tilt and establish the sensitivity of each to an appropriate level of deterioration.
4. Select the most sensitive parameters and define a damage or performance index which relates the change in response under services loads to the level of deterioration.
5. Design the monitoring system, including the selection of sensors, data acquisition and management and data interpretation; this will include a determination of which type of monitoring should be conducted such as static or dynamic, continuous or periodic, controlled loading or ambient loading.

6. Install the system and calibrate with baseline readings.
7. Assess field data and adapt the system as necessary.

This is a general methodology based on the assumption that the SHM system is being developed to assess health via detection of damage. As discussed in previous sections, SHM covers a wide variety of activities and damage itself is not the only reason for monitoring. If damage detection is not the objective for a particular project, the design process outlined above still provides a useful framework for developing an SHM system if the idea of a 'monitoring objective' is substituted for the 'damage mechanism' concept. In addition, the level of sophistication adopted at each stage will be driven by the nature of the project. The most important elements are to first ensure that one has a full understanding of why the structure is to be monitored, and then to design an appropriate SHM system that provides the desired information.

Section 7

Case Studies

Field applications of structural health monitoring have become increasingly common in the last decade, due in large part to the efforts of Canadian engineers working under the auspices of the ISIS Canada Research Network. In this section, four representative case studies are presented to give examples of the type of monitoring that is possible with technologies currently available to the Canadian engineering community. A number of additional case studies are presented in ISIS Canada Design Manual No. 2, and the most up to date information is available from the ISIS Canada website at www.isiscanada.com.

BEDDINGTON TRAIL BRIDGE (1993)

Background

The Beddington Trail Bridge, shown in Figure 4-1 above, was the first bridge in Canada to be outfitted with fibre reinforced polymer prestressing tendons and a system of structurally integrated fibre optic sensors for structural health monitoring. The bridge is a two-span, continuous bridge with spans of about 20 m, each consisting of 13 pre-cast, pre-stressed concrete T-shaped girders. Two different types of carbon fibre reinforced polymer (CFRP) tendons were used to pretension six pre-cast concrete girders.The SHM system was incorporated to monitor the long-term performance of the unique and innovative design incorporating FRP materials which were not yet considered proven technology in 1993.

SHM System

A total of 20 fibre Bragg grating sensors were installed to monitor the bridge's behaviour during construction and under service conditions. A four-channel fibre Bragg grating laser sensor system was used as a data acquisition system at different locations along the bridge girders. The sensors were connected, through a modular system, to a laptop computer used on site to record the measurements at different stages of construction and after completion of the bridge. The network of FBG sensors was connected to a junction box that was incorporated into the structure for periodic on-site monitoring.

System Performance and Results

To verify the integrity of the carbon fibre cables and the FBGs after approximately six years of service, measurements were taken in November 1999 and again in November 2004 after eleven years in service (a periodic SHM testing procedure). Readings of strain taken under traffic loads were consistent with those taken initially in 1993, with no observed changes in structural behaviour.

Since this project represents the first civil engineering application to use FOS gauges in Canada, it is important for assessing the durability and functional life of FOSs. During the periodic monitoring performed in 2004, 13 of the original 20 FOSs were still functional. The dynamic response of the structure, as recorded by a FBG sensor on a fibre reinforced polymer prestressing tendon during one specific truck pass, was assessed and the shape of the strain variation with time curve was found to be consistent with that predicted for the truck. Based on the performance of this simple SHM system, both the structure and the sensors have been shown to perform satisfactorily during the first 11 years of service. Periodic tests are planned to continue to assess the long-term durability of the sensors.

References

1. Rizkalla and Tadros (1994).
2. Tennyson and Mufti (2000).

CONFEDERATION BRIDGE (1997)

Background

The Confederation Bridge (Figure 7-1), perhaps Canada's most famous bridge, is located in the Northumberland Strait joining Borden, Prince Edward Island to Cape Tormentine, New Brunswick. The 13.1 km long prestressed concrete box-girder bridge opened to traffic in June 1997. It is currently the world's largest pre-stressed concrete box girder bridge built over salt water. Each of its 44 main spans is 250 m long and consists of four pre-cast segments which are linked in the final structure through the use of post-tensioning. Each main span consists of main girders consisting of pre-cast concrete boxes ranging in depth from 4.5 m to 14 m, and 190 m in length, completed with drop-in pre-cast concrete box girders 60 m in length (refer to Figure 7-2). The bridge deck is 11 m wide and includes one lane and one emergency shoulder in each direction. The elevation of the navigation span above water level is 60 m.

Confederation Bridge is one of the largest infrastructure projects ever undertaken in Canada, and its construction involved the development and use of several innovative technologies to create a finished bridge with a 100 year design life (twice as long as a typical highway bridge). Because of its unique size and extremely high cost, the Confederation Bridge is one of the most extensively instrumented bridges in the world, incorporating many different types of sensors, including FOSs, thermocouples, *tiltmeters*, accelerometers, electrical resistance and vibrating wire strain gauges, displacement transducers, *anemometers*, *corrosion probes*, and video cameras. The SHM activities on the Confederation Bridge represent a partnership of many organizations and researchers. The primary organizations are the bridge owners/operators (Strait Crossing Bridge Limited), the federal government (Public Works and Government Services Canada), and researchers at the Carleton University and the University of Calgary. ISIS Canada has a primary role in the fibre optic sensor technology used in the structure.

The Confederation Bridge was an excellent candidate for SHM for a variety of reasons (Cheung, 1997), including:

1. the bridge is exposed to extremely harsh environmental conditions;
2. this bridge was designed to have a design life that is twice as long as a typical similar bridge;
3. SHM can be used to verify some of the design and performance assumptions made concerning safety and serviceability;
4. SHM may lead to the development of new strategies for the ongoing maintenance and repair of the structure; and
5. information obtained through SHM may be useful for the design and construction of other long-span bridges in the future, and could also be used to develop industry standards for similar long-span bridges.

Fig. 7-1. The Confederation Bridge, linking the provinces of New Brunswick and Prince Edward Island, was completed in 1997 and is extensively monitored

SHM System

The structural health monitoring system of the Confederation Bridge was designed to monitor both its short term and long term behaviours. Numerous sensors of various types were placed throughout the structure during its construction. A total of 22 sensors were installed on several sections of the reinforcing steel and eventually embedded within a main girder component. Six FBG sensors were installed in one of the main girders, and 16 were installed in the adjacent drop-in span, four as temperature sensors and 12 as strain sensors. FBG sensors were installed by bonding them to 2.0 m long sections of steel reinforcing bar, and the instrumented bar sections were tied to the structural rebar and embedded in the concrete during construction.

Three fibre optic gauges were installed in each of the two webs which made up one of the main girders. In addition, eight fibre optic gauges—two temperature sensors and six strain sensors—were installed in each web of a drop-in span (Figure 7-2). Vibrating wire strain gauges were also installed within 50 cm of each of the fibre optic sensors, such that results from the two types of gauges could be compared.

The FOSs and vibrating wire strain gauges, along with a number of more conventional sensors installed on and in the structure, allow engineers to asses the short and long term performance of the bridge with respect to the following factors (Cheung, 1997):

- **Ice Loads:** Inside the shafts of the bridge piers tiltmeters were installed. These sensors indirectly determine the global ice force acting on the bridge by measuring the responses of the piers to ice loading. Accelerometers were also installed to measure the lateral accelerations of the bridge under impact from ice, while ice load panels (now removed) equipped with strain gauges measured the local ice pressures on various bridge sections and determined the overall ice load distributions. Video cameras are used to assist in taking visual observations. Sonar is used to measure the size (depth) of ice as it impacts the bridge. Lasers are used to measure the *free board* of ice on the bridge piers.
- **Short and long-term bridge deformations:** Displacements and strains are measured at various locations in the structure by mechanical, FOS, and vibrating wire strain gauges. These measured deformations result from a combination

of thermal, traffic, ice, wind, snow, wave, and dead loads.

- **Thermal Effects:** Understanding the effects of thermal expansion of the various components of the Confederation Bridge is important because of the way in which the bridge is constructed, allowing some of the expected thermal deformations to be restrained by the bridge piers. One goal of the SHM system on the Confederation Bridge was to predict thermal stresses and potential thermal cracking. This is done through the use of various sensors, including:
    - thermocouples to measure temperature;
    - vibrating wire strain gauges to measure intensity of deformation;
    - *pyranometers* to record the amount and intensity of solar radiation impacting the structure; and
    - *cable-tension linear transducers* which measure movement in two expansion joints.
- **Traffic Loads:** Strain gauges are used to indirectly infer vehicle loads on the structure as well as any longitudinal and transverse stresses in the bridge spans due to stationary and/or moving vehicles. Video cameras are also used to approximate vehicle positions for comparison with strain sensors.
- **Vibration/Dynamics:** A total of 76 accelerometers are used to monitor the vibration characteristics of the bridge and to detect any earthquake loads. Dynamic displacement transducers measure any sliding which might occur at the bridge piers. Responses at the piers are also measured by additional acceleration sensors, and anemometers are used to measure wind forces.
- **Corrosion Monitoring**: Since the Confederation Bridge spans a large distance over salt water, and because it is expected to perform well for more than 100 years, it is essential that any corrosion of the bridge's steel components and reinforcement be detected and addressed as quickly and efficiently as possible. Thus, during construction, corrosion probes (which detect corrosion of steel) were cast inside the concrete in the *splash zones* on the piers (the regions which are most susceptible to corrosion).

The DAS used in the Confederation Bridge SHM system comprises a central computer and various data loggers. Two types of data loggers (high speed and low speed) have been used. Each type of logger is responsible for monitoring different aspects of the bridge response. High speed data loggers are used to monitor dynamic response due to factors such as ice floe impacts and traffic loads, while low speed data loggers record data relating to deformations and thermal stresses.

The data loggers collect raw data from sensors on the bridge and subsequently convert those data into standard engineering units before transferring them to the central computer system on shore. From the on-shore system, the data are transferred to a permanent retrieval site at Carleton University, Ottawa.

An interesting aspect of the data loggers used in the Confederation Bridge is that they operate in two different modes: time-averaged mode and event-triggered burst mode. *Time-averaged* mode logs data over a fixed period of time, and the data are converted into means, variances, minima and maxima. *Event-triggered* burst mode begins when a data value greater than some predetermined threshold value is observed at the sensor. This indicates the presence of a major event, and the data collection rate subsequently increases. Examples of such an event may include a severe storm, the passing of a particularly heavy vehicle, or impact from an ice floe.

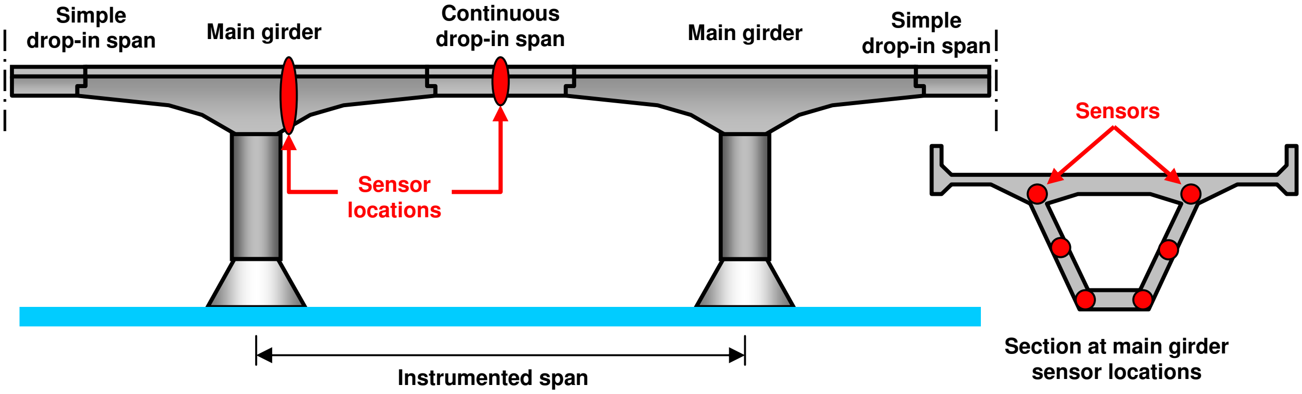

Fig. 7-2. FBG sensor locations on the Confederation Bridge box girder

System Performance and Results

For ISIS Canada, researchers were specifically involved in the use of fibre optic sensors and only the performance that system will be discussed here. An important aspect of this SHM project was to study the robustness of FOSs under actual construction conditions on a large scale civil engineering project. The FOSs in the two extensively instrumented bridge sections were checked once in August 1996, while the sections were still in the construction yard (the bridge was built in sections on land and then placed in the strait using a massive ship-mounted crane), and a second time in March 1997, after the components had been assembled over the Northumberland Strait but before the bridge had been opened to traffic. All six sensors in the main girder section were functioning properly. It was determined that three of the 12 strain sensors installed in the drop-in span had been damaged during construction; one of the leads had been broken off at the concrete, and two of the connectors had been jammed with concrete and were giving unusually low signal values. All four temperature FOS gauges were functioning properly. In 1998, the sensors were again evaluated and it was found that three of the 19 sensors from 1997 were no longer functioning (three of the original 22 were damaged during construction).

A return visit was conducted in September 2004 (Rivera et al. 2004). The objective was again to assess sensor functioning and durability. All temperature sensors continue to function but four of the strain sensors were not functioning compared to three non-functional sensors in 1998. In addition to assessing sensor functionality, continuous monitoring was conducted for a short period to gain representative information about the sensor response characteristics due to vehicle loads. Figure 7-3 shows a typical response of four of the FOSs in the main girder section recorded during this monitoring period. Peaks in the recorded strain readings represent the effects caused by passing vehicles on the bridge, and it is clear from the data that the sensors responded consistently to the applied loads (depending on their depth in the bridge cross-section). Work is underway to install a permanent fibre optic monitoring system to continue to monitor these FOSs remotely.

References

1. Tadros (1997)
2. Mufti et al. (1997).
3. Cheung et al. (1997).
4. Rivera, Card and Newhook (2004)
5. Web site: www.isiscanada.com

TAYLOR BRIDGE (1997)

Background

The Taylor Bridge spans the Assiniboine River in the Parish of Headingley, Manitoba. It is the world's largest span bridge that uses FRP bars for shear reinforcement of concrete, pre-stressing of the main concrete girders, and an FOS system for remote structural health monitoring. The 165 m long bridge, shown in Figure 7-4, consists of 40 pre-stressed concrete I-girders. The bridge is divided into five equal simple spans of 33 m each. Each span consists of eight, 1.8 m deep, I-shaped pre-cast, pre-stressed concrete girders. Four girders of the Taylor Bridge were pre-stressed using two different types of carbon FRP prestressing cables. Two girders were reinforced for shear using carbon FRP stirrups.

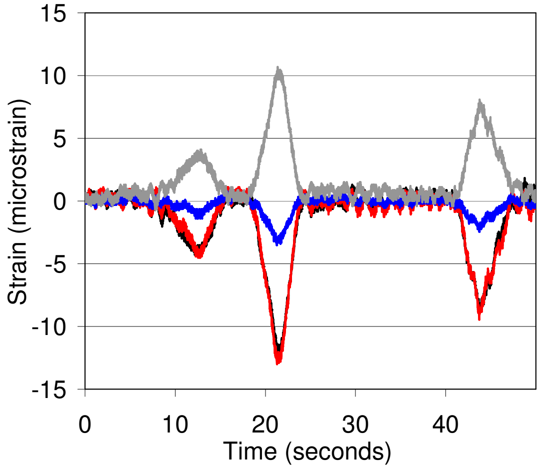

Fig. 7-3. Typical response of the FOSs in the main girder section of the Confederation Bridge recorded during testing in 2004

Fig. 7-4. Taylor Bridge in Headingly, Manitoba. Built 1997

A 16×18 m portion of the concrete deck slab was reinforced with carbon FRP reinforcing bars, instead of using conventional steel reinforcement. The rest of the deck slab was reinforced with steel. In addition, glass FRP bars were used to reinforce a 14.2 m long portion of the barrier wall. Manitoba Highways and Transportation conservatively estimates the design service life of this bridge built with innovative materials as 75 years, compared to 50 years for conventional steel-reinforced structures. The Taylor Bridge is an extremely innovative and unique structure, and so it was desired that the structure be extensively monitored to provide much needed information on the short and long-term performance of the FRP-reinforced concrete structure.

SHM System

The SHM system used in the Taylor Bridge is shown schematically in Figure 7-5. Fibre Bragg grating FOSs were used to monitor the strains in the carbon FRP reinforcement of the girders and the deck slab, and in the glass FRP reinforcement of the barrier wall. A total of 65 FOSs were installed on the reinforcement. Out of the 65 sensors, 63 were single FBG sensors and the remaining were *multiplexed* FBG sensors. As shown in part in Figure 7-5, these 65 sensors were installed on the following bridge components: the girders reinforced by CFRP; selected girders reinforced by steel; the deck slab reinforced by CFRP; and the barrier wall reinforced by GFRP. In addition, 20 thermocouples were used at different locations on the bridge to allow for compensation of temperature effects. The DAS system was connected to a computer to download the strain readings remotely using a telephone line. The bridge is also being monitored by 26 conventional electrical resistance strain gauges mounted on the reinforcement (to verify the FOS readings). Both the fibre optic multiplexing units and the data logging system were installed in a heated enclosure located under the bridge deck slab near one of the supports.

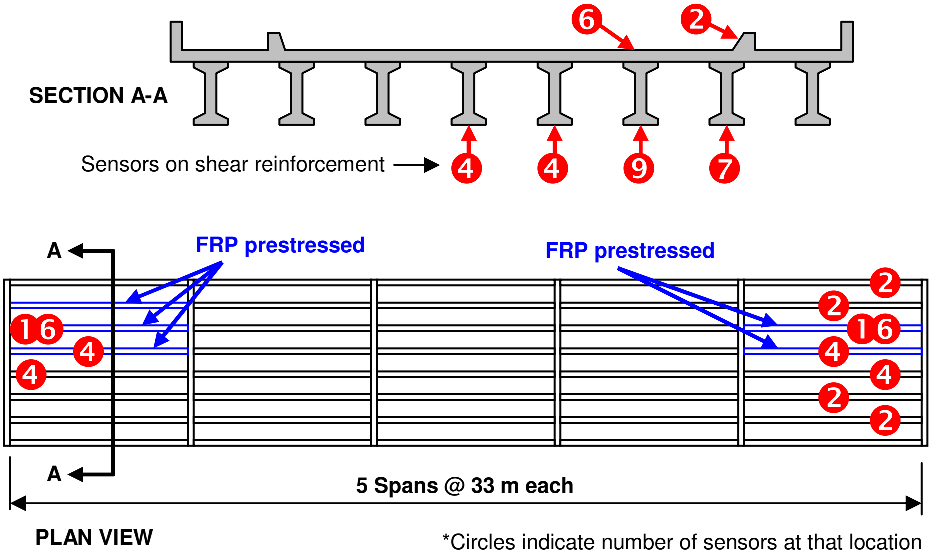

Fig. 7-5. Sensor locations on the Taylor Bridge

In 2002, 16 concrete strain gauges were installed externally on each of the girders at mid-span and the abutment. Four temperature gauges were also installed at various locations on the girders. Since 2002, the DAS has been programmed to read 16 strain sensors and four temperature sensors, and transmit the signals of 12 selected strain sensors and four temperature sensors to the resident data logging computer. A high speed cable modem was installed and is activated in the resident computer to allow for remote monitoring. Data from the resident data logging computer are sent to a database every five seconds. The bridge is also continuously monitored with an internet camera. The real time data from this bridge can be viewed at www.isiscanada.com.

System Performance and Results

FBG sensors were installed on the carbon FRP prestressing tendons at the end of the bridge girders to measure the effective stress level in the tendons during fabrication. The strain in the carbon FRP pre-stressing tendons was also monitored during transportation of the girders to the bridge site. There was no significant change in the strain of the CFRP prestressing tendons. Various diagnostic tests have been performed on the bridge since it opened to traffic in 1997. The response of the bridge to a slow moving truck and trailer was monitored soon after the bridge was completed. Frequent load tests will be conducted in the future to evaluate the performance of the bridge girders, deck, and barrier wall which are reinforced by FRP materials.

References

1. Rizkalla et al. (1998).
2. Shehata and Rizkalla (1999).
3. Wardrop Engineering Inc. (1999).
4. Korany and Rizkalla (2000).
5. Web site: www.isiscanada.com

JOFFRE BRIDGE (reconstructed 1997)

Background

The Joffre Bridge, shown in Figure 7-6, crosses the Saint-François River in Sherbrooke, Québec, and was originally built in 1950. The bridge was reconstructed in 1997 following severe deterioration of the concrete deck slab and girders resulting from corrosion of the original bridge's steel reinforcement and girders. Joffre Bridge is a two-lane, steel-concrete composite structure, consisting of five spans of different lengths varying between 26 and 37 m. Each span consists of five girders at a spacing of 3.7 m. During the reconstruction process it was decided that a portion of the deck slab would be reinforced with fibre reinforced polymer reinforcement in lieu of conventional reinforcing steel. As such, a 7.3 m ×11.5 m section of the deck slab was reinforced with carbon FRP grid reinforcement as shown in Figure 7-7.

Fig. 7-6. The Joffre Bridge in Sherbrooke, Québec. During reconstruction in 1997

Fig. 7-7. Installation of the instrumented sections of bridge deck reinforcement in the Joffre Bridge

SHM System

The Joffre Bridge is extensively instrumented with three types of gauges: FOSs, vibrating wire strain gauges, and electrical resistance strain gauges, at a total of 180 critical locations in the concrete deck slab and on the steel girders. A total of 44 FOSs were installed for strain and temperature monitoring, including 26 Fabry-Perot strain FOSs bonded on the FRP grid reinforcement installed in the bridge deck, six Fabry-Perot sensors integrated into the FRP grid, two Fabry-Perot temperature fibre optic sensors and two Fabry-Perot sensors embedded in the concrete, three Fabry-Perot strain fibre optic weldable sensors welded on the steel girder, three FBG sensors bonded on the FRP grid, and one Fabry-Perot and one FBG sensor bonded on an FRP bar for thermal strain monitoring. The following table summarizes sensor placement in the Joffre Bridge.

System Performance and Results

After the successful installation of the sensors in the bridge, it was re-opened to traffic in 1997. Since then, static and dynamic responses of different components of the bridge have been recorded regularly (refer to Figure 7-8) using computer-aided data logging systems. The sensors in this structure have provided a wealth of information on the thermal and mechanical stresses occurring in the reconstructed bridge. The variation of recorded strain with time and temperature clearly indicates that it is possible to obtain meaningful and consistent results from FOSs used in SHM applications, and that temperature is the dominant factor influencing the strain variation in the bridge deck.

Fig. 7-8. Load testing of the Joffre Bridge with three loaded trucks

References

1. Benmokrane et al. (2000).
2. Web site: www.isiscanada.com

SALMON RIVER BRIDGE (1995)

Background

The Salmon River Bridge, in Nova Scotia, is a composite steel/concrete highway bridge that consists of a slab on girder design with two simple spans of about 32m each. One of the two spans was constructed using an innovative steel-free deck technology that is thought to provide significant benefits over the life cycle of the structure. These benefits arise primarily due to the elimination of all internal steel reinforcement from the concrete deck, significantly decreasing its susceptibility to electrochemical corrosion. This project represented the first time such a bridge deck system had been implemented in a field-scale application, and as such it presented an ideal opportunity to use SHM technologies to support the application of an innovative structural system. The structure has been monitored since completion of construction in 1995.

Sensor Type	Method of instrumentation and location in bridge	# of gauges	Data output
Fabry-Perot	Integrated in carbon FRP reinforcing grid of bridge deck slab	6	Strain
Fabry-Perot	Bonded to carbon FRP reinforcing rod	1	Thermal Strain
Fabry-Perot	Bonded on carbon FRP reinforcing grid of bridge deck slab	26	Strain
Fabry-Perot	Embedded in concrete bridge deck	2	Strain
Fabry-Perot	Welded on web of middle steel girder	3	Strain
Fabry-Perot	Embedded in concrete deck slab	2	Temperature
Bragg grating	Bonded on carbon FRP reinforcement grid of bridge deck slab	3	Strain
Bragg grating	Bonded on carbon FRP reinforcing rod	1	Thermal Strain

Table 7-1: Summary of SHM Sensor Placement in the Joffre Bridge

Omitting details of the bridge construction, it essentially consists of a steel-free, polypropylene fibre-reinforced concrete slab resting on six steel girders that are restrained laterally using steel straps that are fastened to the compression flanges of the girders. Where internal reinforcement was deemed necessary in the slab, FRP reinforcement consisting of glass FRP grid was used. A view of the unique steel-free design from the underside of the deck slab is given in Figure 7-9.

Fig. 7-9. View of the Salmon River Bridge's steel-free deck construction (from below)

SHM System

Due to uncertainties associated with the behaviour of the innovative steel-free construction system, it was desired to study the response of the bridge over time. To accomplish this goal, conventional foil strain sensors were installed on the steel girders at various locations and on several of the lateral steel straps. In addition, fibre optic sensors (Bragg gratings in this case) were installed inside the FRP reinforcement grids during their fabrication. Changes in crack patterns and widths have also been monitored on an ongoing basis.

System Performance and Results

Data obtained from the strain gauges installed on (and in) the bridge have successfully been used to demonstrate the satisfactory performance of this innovative structure over the past 10 years, and to increase the engineers' confidence in this structural system. In particular, the SHM system has been used to demonstrate that:

- service load strains are within acceptable limits and that load sharing between the girders is adequate;
- the girders behave as composite sections under live load;
- cracking that was observed on the underside of the concrete deck slab did not affect the load sharing between the girders;

- the straps and their welded connections were in no danger of failure due to fatigue under service load conditions; and
- strains in the GFRP grid reinforcement remained sufficiently low under service conditions that failure of the glass FRP due to creep rupture is not a concern.

Thanks, in part, to the success of the SHM system on the Salmon River Bridge, steel free bridge deck systems have now been implemented in numerous applications in Canada and the United States.

1. Mufti et al. (1999).
2. Web site: www.isiscanada.com

LIVE DATA

Several structures which have been instrumented for structural health monitoring by ISIS Canada, some of which were discussed above can be viewed in real-time through live-monitoring websites. These websites are available to the general public and can be accessed through the ISIS Canada webpage. To view live data from one of these sites, go to www.isiscanada.com, and select the "Remote Monitoring" link.

References

Section 8

Civionics Specifications

SHM technologies represent a critical shift in philosophy within the field of structural engineering. An important step towards achieving the goal of widespread application of SHM systems in infrastructure applications is the cooperation between engineers from various specific disciplines within a single new discipline called *Civionics*. Civionics will create engineers with the broad knowledge base required to design and build smart structures, and with further efforts to realize the full benefits of SHM of civil engineering structures.

Civionics is a new term derived from Civil-Electronics, and refers to the application of electronic systems in civil engineering applications. ISIS Canada, with detailed experience in integration of FOS and FRP in innovative structures, has been promoting Civionics applications for over 10 years. As a result, and for the purposes of promoting this emerging discipline, ISIS Canada has recently published its Civionics Specifications, a manual providing best-practice guidelines and advice for engineers interested in applying SHM in the field.

The ISIS Canada Civionics Specifications are not discussed in detail here. The following is a list of the various topics for which specifications are provided:

- Fibre optic sensors
  - Fibre Bragg grating sensors and readout units
  - Long gauge FOSs and readout units
  - Fabry-Perot FOSs and readout units
- Wiring procedures and connections
  - Sensor cables
  - Conduits
  - Junction boxes
  - Cable termination
  - On-site control rooms
- FOS installation procedures
- SHM system and FOS suppliers

Section 9

The Future of Structural Health Monitoring

As has been demonstrated through the information presented in this module, SHM offers an enormous range of options to engineers who are interested in characterising the short and long-term behaviour of their structures. SHM is increasingly seen as an important tool in the maintenance of sustainable infrastructure systems, and it is reasonable to assume that ongoing advancements will continue well into the foreseeable future (under the auspices of International Society for Health Monitoring of Intelligent Infrastructures (ISHMII) and other organizations). In particular, two interesting emerging technologies are worthy of note: *smart composites* and *live structures*.

SMART COMPOSITES

Smart composites are materials (such as FRP) which have sensors (typically fibre optic sensors) embedded inside the material. In this way, the materials that make up a structure actually become sensors which can provide information about the structure's health. To draw an analogy, the use of smart composites in a structure can be likened to the presence of the nervous system in the human body. Our muscles have nerve cells embedded within them which provide information to our brain about the performance of the muscles (e.g. pain or fatigue). Smart composites are similarly able to send information to an engineer for analysis and to determine if damage is present or if failure is imminent. At present, smart composites are widely used in the aerospace industry and it is expected that their use will soon be widespread in the civil engineering industry.

One example of a smart composite which can be used in the civil engineering industry is the use of smart FRP bars. In this application, an FOS is placed inside an FRP reinforcing bar during the bar's fabrication. The FRP bar is subsequently installed as tensile reinforcement inside concrete (as replacement for conventional steel reinforcement), and the FOS is connected to a data acquisition system. These types of smart FRP bars have recently been successfully used in field applications of SHM.

LIVE STRUCTURES

Live structures represent the cutting edge of civil engineering design and analysis. These are, at present, largely theoretical types of structure that will be possible one day in the not-so-distant future. Live structures are not only able to sense loads, deformations, and/or damage (through sophisticated SHM and analysis systems), but they are also able to respond to the sensory input and take action to counter or correct the effects of loading. Recent developments in the area of *self-actuating* materials – materials which can change in shape and mechanical properties on command – are allowing civil engineers to consider the day when intelligent structures will both sense and respond to external loads and environmental influences.

Section 10

Summary and Conclusion

Structural health monitoring, as described in this educational module, provides the civil engineering community with a suite of options for monitoring, analysing, and understanding the health of our infrastructure systems. The range of applications is virtually endless, as are the potential combinations of sensors and systems which can be used. These systems will provide essential tools to the next generation of engineers, who must take steps to improve the sustainability of infrastructure systems in the face of rising costs, shrinking budgets, and rapidly deteriorating existing systems.

While the technology and application of SHM systems continues to evolve, it is essential that the next generation of engineers understand this new field of civil engineering, and that they have an awareness of its motivations, applications, and benefits. This module has presented a very broad overview of the current practice of SHM. The interested reader should consult ISIS Canada (www.isiscanada.com) or the International Society for Health Monitoring of Intelligent Infrastructures (ISHMII) (www.ishmii.org) for additional information and guidance.

Section 11

Detailed Example: The Golden Boy

As outlined in this document, SHM systems can be used to provide engineers and infrastructure owners with a tremendous amount of information on the performance and health of various types of structures. SHM systems used in monitoring bridge structures are often quite complex and appear somewhat daunting to the inexperienced engineer. Thus, undergraduates (and even graduate students and professors) sometimes shy away from looking into the details of specific SHM applications. The Golden Boy SHM project, implemented beginning in 2002 in Winnipeg, Manitoba, provides a relatively straightforward and illustrative example of how SHM can be used to monitor an unusual type of structure: a historic statue mounted on the dome of the Manitoba Legislature. The Golden Boy SHM project is described in complete detail by Mufti (2003).

BACKGROUND AND MOTIVATION

The Golden Boy, shown in Figure 11-1, is one of the Province of Manitoba's best known symbols, stands on top of the main dome of the Manitoba Legislative Building. The sculpture was designed by Artist Georges Gardet and was cast in 1918 in Paris, France. After being shipped to Canada it was mounted on the Legislative Building in 1919. The statue is highly symbolic for Manitobans and carries a sheaf of grain, symbolizing the fruits of labour, in one hand, while the other hand holds a torch, symbolizing a call upon the youth of Manitoba to join in the pursuit of building a more prosperous future.

The original design of the Golden Boy called for the statue's support shaft, a solid steel rod running up inside the Golden Boy's left leg, to be cast integrally with the statue. However, because the First World War was just ending at the time of the statue's casting, there was a shortage of steel in Europe, and the support shaft had to be purchased in the United States and added to the statue once it had arrived in Canada. The shaft was inserted in the leg of the statue, and the heel was plugged to prevent the ingress of moisture.

In 1966, an electric light fixture was added to the statue to illuminate the torch held in the Golden Boy's right hand. This had a detrimental effect on the statue's structural health. During the installation of the electrical torch, a number of holes were drilled in the statue's bronze outer sheathing to accommodate electrical wiring. These holes were not properly sealed, and eventually allowed the intrusion of precipitation and moisture.

In 2000, at an age of about eighty years, a careful examination of the statue revealed that the central support structure (the steel support shaft) of the statue was severely corroded, resulting largely from moisture intrusion. The statue's inspectors noted that corrosion of the steel support shaft had reduced the shaft's diameter by about 10%. The magnitude of the corrosion of the steel support shaft observed in the Golden Boy's left foot is shown schematically in Figure 11-2. Furthermore, wind tunnel testing of a scaled down version of the Manitoba Legislative Building, conducted at the University of Western Ontario, and complex finite element numerical modelling of the statue indicated that the shaft would be stressed to 93% of its ultimate strength under expected wind velocities, thus causing a serious safety risk. Indeed, engineers felt that there was a chance that, if not repaired, the Golden Boy could fall from the roof of the Legislature under a 1/100 year wind. A need for major repairs and replacement of the central support structure was thus identified, and the Manitoba Government embarked on the Golden Boy's restoration and repair.

Fig. 11-1. The Golden Boy, perched on top of the Manitoba Legislative Building

Safety and cost concerns led to the decision to completely remove the statue from the roof of the building during the restoration process, and in February, 2002, the 1,520-kilogram Golden Boy was removed from the dome and taken to an offsite location. Restoration was completed during the summer of 2002 and Golden Boy was reinstalled in September 2002.

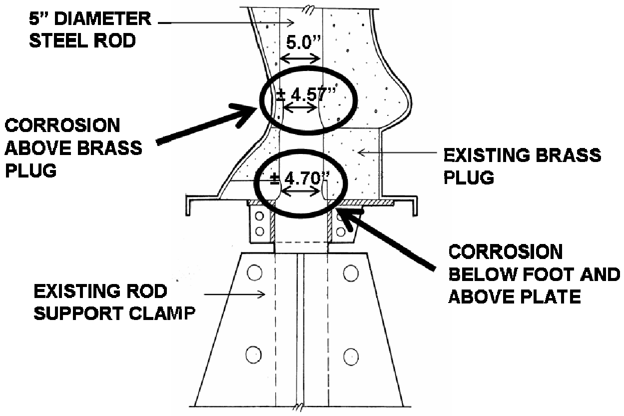

Fig. 11-2. Schematic showing the magnitude of corrosion of the Golden Boy's steel support shaft within his left foot

DECISION TO REPLACE SUPPORT SHAFT

The decision to replace the Golden Boy's steel support shaft was based on an analysis of the combined stress condition in the shaft under wind loads as predicted from a detailed wind tunnel testing program.

The structure was treated as a simple cantilever, fixed at the base and subjected to combined axial, flexural, and torsional loads. During a 100-year storm the calculations, which are based on results of wind tunnel testing, indicated that the structure could actually fail. The details of the calculations follow below. The wind tunnel testing indicated the following:

Wind-induced moment at base = $16.9\,\mathrm{kN \cdot m}$

Wind-induced shear at base = $6.2\,\mathrm{kN}$

Wind-load moment arm = $\frac{16.9}{6.2} = 2.726\,\mathrm{m}$

The dead-load of the statue is taken as:

$$DL = 3.0\ \mathrm{tons} = 27.0\,\mathrm{kN}$$

Table 11-1 gives details of the shear and flexural loading on the steel support shaft, along with appropriate load factors.

Table 11-1: Details of the loading on the steel support shaft

Load Type	Unfactored Load (kN)	Load Factor	Factored Load (kN)	Moment Arm (m)	Factored Moment at Base (kN·m)
Wind Load	6.2	1.99	12.34	2.400	29.62
Dead Load	27.0	1.25	33.75	0.15	5.06
				Totals	34.68

The torque on the shaft can be calculated as the product of the shear due to wind and the lever arm about the vertical axis, hence:

Torque due to wind = $12.34 \times 0.15 = 1.85\,\mathrm{kN \cdot m}$

Thus, the design loads on the shaft at its base can be approximated as:

Moment, $M_f =$ 34.68 kN.m

Axial, $P_f =$ 33.75 kN

Shear, $V_f =$ 12.34 kN

Torque, $T_f =$ 1.85 kN.m

The stresses in the shaft can now be calculated using simple mechanics of materials, Figure 11-3 shows the idealized shaft and the loads that act on it due to wind and dead load. The mechanical properties of the shaft, in the deteriorated (corroded) condition were as follows:

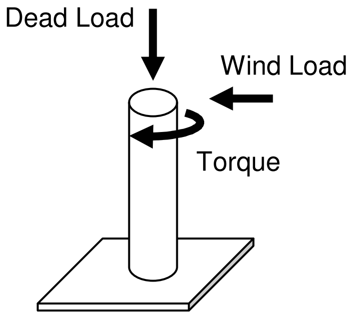

Fig. 11-3. Forces acting on the Golden Boy

Yield strength of steel, $f_y =$ 275 MPa

Diameter at base, $d =$ 116.1 mm

Moment of inertia, $I = \frac{\pi d^4}{64} =$ 8.91 × 10^6 mm^4

Polar moment of inertia, $J = \frac{\pi d^4}{32} =$ 17.82 × 10^6 mm^4

Cross-sectional area, $A = \frac{\pi d^2}{4} =$ 10.6 × 10^3 mm^2

Thus, the stresses in the shaft at its base can be calculated as follows:

Bending Stress

$$\sigma_b = \frac{Mc}{\phi_s I} = \frac{34.68 \times 10^6 \times 58.04}{0.9 \times 8.91 \times 10^6} = 251.01\,\text{MPa}$$

Axial Stress

$$\sigma_a = \frac{P_f}{\phi_s A} = \frac{33.75 \times 10^3}{0.9 \times 10600} = 3.53\,\text{MPa}$$

Shear Stress

$$\tau_v = \frac{4V_f}{3\phi_s A} = \frac{4 \times 12.34 \times 10^3}{3 \times 0.9 \times 10600} = 1.72\,\text{MPa}$$

Torsional Shear Stress

$$\tau_t = \frac{Tc}{\phi_s J} = \frac{1.85 \times 10^6 \times 58.04}{0.9 \times 17.82 \times 10^6} = 6.69\,\text{MPa}$$

Mohr's circle can then be used to determine the maximum principal stress due to the combined loading condition in the shaft. This has been left as an exercise for the reader. Performing the appropriate calculations, it can be shown that the maximum principal stress is:

$$\sigma_{\max} = 254.72\,\text{MPa}$$

The yield stress of the steel in the shaft is approximately 275 MPa. It is evident that the factored maximum principal stress in the shaft under a 100-year wind load is about 93% of the yield load: an indication that upgrading of the shaft was required.

SHM SYSTEM

At the request of the Government of Manitoba, ISIS Canada and Dillon Consulting designed and installed a structural health monitoring system for Golden Boy, consisting of three types of gauges: accelerometers, strain gauges (both electrical resistance and fibre optic), and temperature sensors. This system was designed to monitor the statue's performance on an ongoing basis, and to provide information to engineers and government representatives about the long-term effectiveness of the statue's restoration. Figure 11-4 shows the locations of the various SHM sensors within the statue.

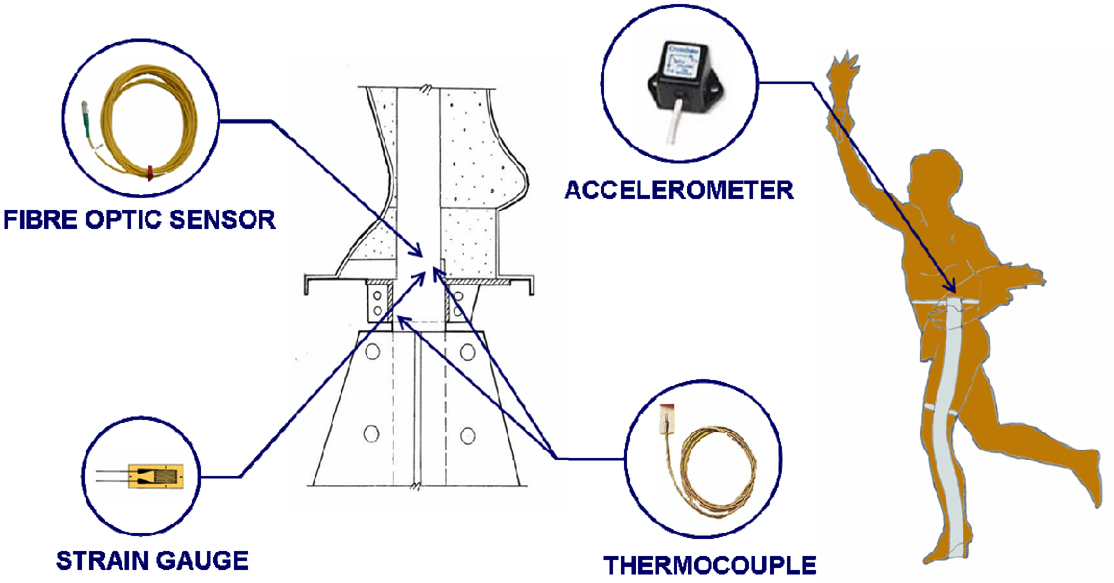

Fig. 11-4. Schematic showing the SHM sensor locations within the restored Golden Boy

Two accelerometers were placed at the top of the statue's new steel support shaft. These sensors measure the frequencies of vibration of the Golden Boy, which are due primarily to wind-induced oscillations. The accelerometers measure movement in three directions as wind and weather systems cause the Golden Boy and his steel support shaft to move or vibrate. If the accelerometers give a frequency reading outside the normal range, further examination into the health of the structure may be required.

Two types of strain gauges have also been installed on the Golden Boy's steel support shaft. Strains in the shaft are caused by the action of wind on the statue. The strain gauges are placed in several locations around the base of the support shaft, near the Golden Boy's left foot. Electrical resistance strain gauges and Bragg grating fibre optic strain sensors monitor strains in the support column on an ongoing basis. If the strain readings fall outside the normal range, an alert is provided to potential structural health issues well before a major problem develops.

Finally, a number of thermocouples have been installed within the Golden boy in close proximity to the strain gauges. These sensors measure temperature, which has a direct effect on the material properties of the column and the strains measured by both types of strain sensors. With access to these three diagnostic tools, the Golden Boy's health will be well monitored—an important step for moving the care of the statue away from a high cost, acute care method of maintenance towards a more cost efficient, preventative maintenance model.

The various sensors are wired to a data acquisition system (a data logger and personal computer), located within the Legislative Building. The data can be accessed on an ongoing basis through the ISIS Canada Active Structural Health Monitoring Website (go to www.isiscanada.com and click on "Remote Monitoring"). The web access allows for instantaneous examination of accelerations, strains, temperatures, and wind speeds. A web camera can also be accessed through this website, allowing for real time viewing of weather conditions.

PRINCIPLES OF MONITORING

SHM of the golden boy, as mentioned previously, is accomplished primarily through the use of accelerometers. These sensors are used to record the natural frequencies of vibration of the statue. If the frequencies remain unchanged, the statue is deemed to be performing well. However, if the frequencies change significantly, it is a signal to engineers that all is not well and that inspection may be required.

It is beyond the scope of this document to present a detailed discussion of structural dynamics, natural frequencies, and resonance. It is useful, however, to examine the vibration characteristics of the Golden Boy at a simplified level, as it relates to the statue's SHM system.

The Golden Boy's steel support shaft is a simple structural element that can be approximated as a single vertical cantilever. Cantilevers can be modelled as single degree of freedom systems using straightforward structural dynamics principles (not covered herein) as follows (refer also to Figure 11-5):

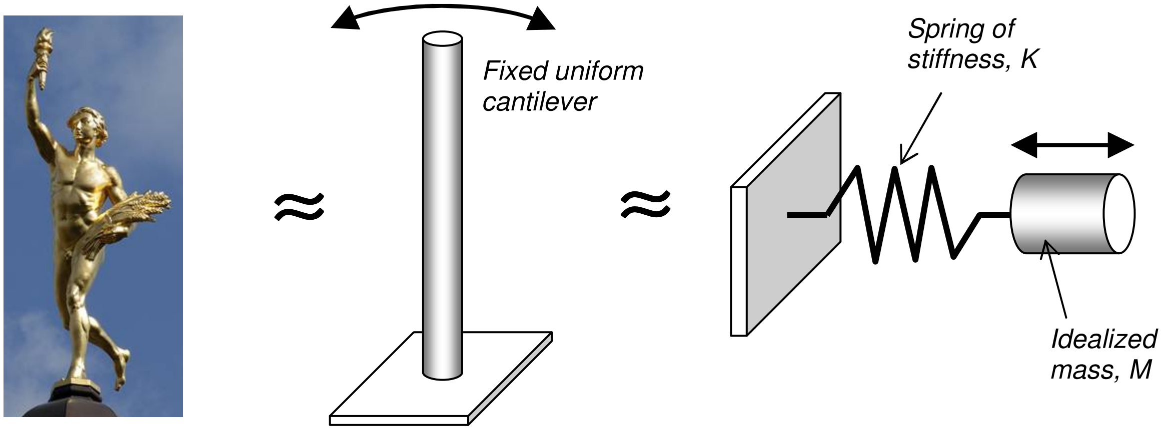

Fig. 11-5. Schematic showing the SHM sensor locations within the restored Golden Boy

1. The moment of inertia, *I*, of a cylindrical solid rod of diameter, *d*, is:

$$I = \frac{\pi d^4}{64} = \frac{\pi(127)^4}{64} = 12769820\,\text{mm}^4$$

2. The cantilever is treated as a 2750 mm long steel (elastic modulus, *E* = 200 GPa) spring of stiffness, *K*, where *K* is calculated using the following :

$$K = \frac{3EI}{L^3} = \frac{3(200000)(12769820)}{2750^3}$$
$$= 368.4\ \text{N/mm} = 368400\ \text{kg/s}^2$$

3. The mass, *M*, of the idealized single degree of freedom system can be roughly approximated as the mass of the statue:

$$M = 1.52\ \text{Tons} = 1520\ \text{kg}$$

4. The theoretical first *natural frequency* of the idealized system is given by the following:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} = \frac{1}{2\pi}\sqrt{\frac{368400}{1520}} = 2.48\ \text{Hz}$$

The normal *natural frequency* of the Golden Boy, determined by performing a dynamic analysis of data obtained from the accelerometers mounted on the steel support shaft, was found to be about 3 Hz (or three cycles per second). This compares quite closely with the approximate theoretical value of 2.48 Hz calculated above. The difference between the theoretical and observed (measured) natural frequencies is likely due to the inaccuracies involved in approximating the true system as a fixed uniform cantilever.

Figure 11-6 shows a screen capture taken from the live data website of the Golden Boy SHM project, where the first and second natural frequencies of the statue are shown as peaks in the recorded vibration amplitude. A peak is visible at about 3 Hz, indicating that this is the observed first natural frequency of the statue. Interested readers are encouraged to visit the ISIS Canada website to view live data in real time, which is available 24 hours a day.

The reader will note that the difference between the theoretical and calculated natural frequencies of the statue is not a serious concern, since what engineers are really interested in are any changes in the natural frequency that occur over time.

SUMMARY

The Golden Boy's SHM system provides continuous readings from diagnostic tools which monitor the statue's ongoing performance. SHM of the statue represents and important first step in the long-term preventative care program for the statue, and will hopefully result in more cost-effective maintenance and a higher level of safety in the future.

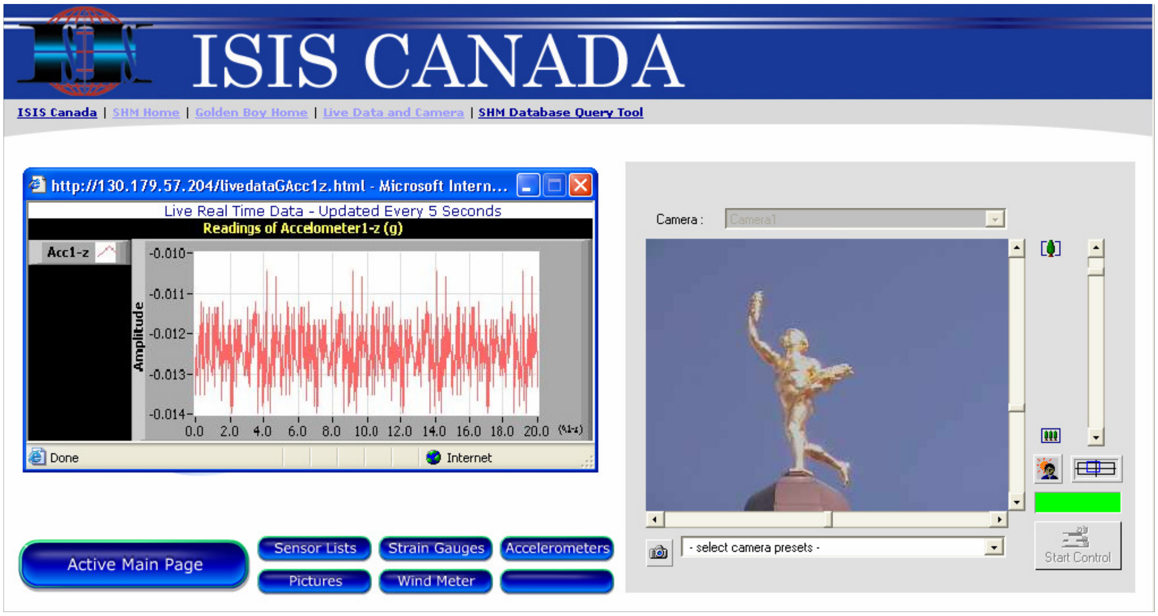

Fig. 11-6. Screen capture from the ISIS Canada website (www.isiscanada.com) showing vibration data for the Golden Boy. The first natural frequency is visible as a clear peak in the vibration amplitude at about 3 Hz

Section 12

References and Additional Guidance

Additional information on the following topics is available from ISIS Canada in the form of Educational Modules:

- ISIS Educational Module 1: Mechanics Examples Incorporating FRP Materials.
- ISIS Educational Module 2: An Introduction to FRP Composites for Construction.
- ISIS Educational Module 3: An Introduction to FRP-Reinforced Concrete Structures.
- ISIS Educational Module 4: An Introduction to FRP Strengthening of Concrete Structures.

The following publications have been used in the preparation of this module and can be consulted for a more complete discussion of the various topics presented herein:

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- ISIS Canada 2004. ISIS Design Manual No. 6: Civionics Specifications. Intelligent Sensing for Innovative Structures Canada, Winnipeg, MB.
- ISIS Canada 2001. ISIS Design Manual No. 1: Installation, Use and Repair of Fibre Optic Sensors. Intelligent Sensing for Innovative Structures Canada, Winnipeg, MB.
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- Rizkalla, S.H., Shehata, E., Abdelrahman, A., and Tadros, G. 1998. Design and Construction of a Highway Bridge with CFRP. Concrete International, Vol. 20, No. 6, pp. 35-38.
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- Tadros, G. 1997. The Confederation Bridge: An Overview. Canadian Journal of Civil Engineering. Vol. 24, pp. 850-856.
- Tennyson, R.C., and Mufti, A.A. 2000. Monitoring Bridge Structures Using Fibre Optic Sensors. Proceedings of European COST F3 Conference on System Identification of Structural Health Monitoring. June 6-9. 2000. Universidad Politéenica de Madrid. Madrid, Spain, pp. 511-520.
- Wardrop Engineering Inc. 1999. Remote Monitoring of Taylor Bridge. Progress Report.

Section 13

Glossary of Uncommon Terms

The following are definitions of some of the technical terms that appear in this document:

WORD	EXPLANATION
Accelerometer	A sensor which measures accelerations.
Acoustic emission	Sounds created by significant events in structures (e.g. a vehicle collision with a bridge or fracture of a prestressing strand).
Acrylate	A type of polymer used for sheathing of FOSs.
Amorphous	A substance which is lacking in distinct crystal structure
Anemometer	A sensor which measures wind speed.
Behaviour test	A test carried out to study the mechanics of a structure's behaviour and/or to verify the methods of analysis that may be used on similar types of structures.
Cable-tension linear transducer	A sensor which uses a cable in tension to measure displacements or deflections.
Civionics	An emerging discipline that involves cooperation between engineers from various specific disciplines to design and build smart structures and engage in further efforts to realize the full benefits of SHM of civil engineering structures. The term is coined from Civil-Electronics.
Continuous monitoring	SHM of a structure which is ongoing for an extended period of time (weeks, months, or years).
Corrosion probe	A special type of sensor used to measure corrosion currents within a structural component.
Data acquisition algorithm	An algorithm used to sort the acquired data prior to their onsite storage or transfer to an offsite location for analysis.
Data acquisition system (DAS)	The onsite system (data logger) in which measured data are stored prior to being transferred to an offsite location for analysis.
Demodulation unit	A piece of electronic equipment used to convert optical signals from FOSs into voltages which can be recorded for analysis by computer. These units use a variety of sophisticated optical techniques to make these conversions.

Diagnostic test	A test carried out to determine if the response of a particular component of a structure is hindered or helped by another structural component.
Diagnostics	A damage detection and modelling system or algorithm which uses data obtained by SHM systems to make knowledge-based engineering decisions.
Displacement transducer	A sensor which measures displacement.
Down time	The time during which a structure is unavailable for use due to construction or repair work being conducted.
Drift	The tendency of some types of sensors to give different readings (in the absence of true changes of the measured property) when the sensor is interrogated over extended periods of time.
Dynamic amplification factor	A factor (>1) which is used to increase static loads to account for the increased severity of an equivalent dynamic load.
Dynamic testing	Testing in which the dynamic (vibration) response of a structure is monitored.
Electrical resistance strain gauge	A sensor whose electrical resistance changes when stretched and can therefore be used to measure strain.
Embeddable	Refers to sensors that are capable of being embedded within construction materials to form “smart” materials.
Event triggered burst mode	A mode of data collection which begins when a data value greater than some predetermined threshold value is observed at the sensor. This indicates the presence of a major event and the data collection rate increases.
Fatigue life	The time remaining before the structure could be expected to fail by fatigue loading.
Fatigue loading	A loading condition consisting of repeated cycles of loading and unloading.
Fibre optic sensor (FOS)	A sensor used to monitor strain or temperature of the material upon which it is installed. These sensors use optical fibres and specialized optic techniques to measure microscopic variations in strain and temperature.
Fibre reinforced polymer (FRP)	Composite materials composed of high-strength fibres embedded in a polymer matrix.
Gauge length	The total length of gauge over which changes in length are measured in order to obtain strain data.
Global properties	The properties of the structure as a whole, as opposed to the properties of individual structural components.

Grating	A series of tiny reflectors which are placed within an optical fibre to allow for measurement of strain or temperature using the fibre Bragg grating technique.
Integrated temperature circuit	A sensor which measures temperature using a specialized electrical circuit.
Lead wire	The physical link (wire) which transfers data signals from the sensors directly to the DAS.
Live structure	A structure that is not only able to sense loads, deformations, and/or damage, but also to respond to the sensory input and take action to counter or correct the effects of loading.
Load cell	A sensor used to measure load. These sensors convert measured load into an electrical signal.
Low coherence interferometry	An optical technique that uses interference phenomena between a reference wave and an experimental wave or between two parts of an experimental wave to determine wavelength and wave velocity, measure very small distances and thicknesses, and/or calculate indices of refraction.
Microstrain	Strain multiplied by 10^6
Modulated	A process in which optical signals are altered by changes in the length of an FOS gauge.
Multiplexing	An arrangement used in SHM with FOSs where multiple sensors must be interrogated.
Natural Frequency	A frequency at which a structure will vibrate freely when disturbed, in the absence of sustained external excitation.
Noise	Electronic or electromagnetic errors in data which are due to very long lead wires, particularly in the presence of high-voltage power lines or radio transmitters.
Parallel multiplexing	An arrangement where multiple FOSs are located on separate individual fibres.
Periodic monitoring	Monitoring the behaviour of a structure at specified time intervals (typically months or years apart).
Polyimide	A type of polymer used for sheathing of FOSs.
Proof load	The maximum load of a given configuration that a structure has withstood without suffering any damage.
Proof test	A test carried out to study the load-carrying capacity of a structure by inducing a proof load on the structure.
Pyranometer	A sensor used to measure the magnitude and intensity of solar radiation to which a member or structure is subjected.

Real time monitoring	Monitoring in which the data are viewed at the instant they are sensed.
Self-actuating material	A material which can change in shape and mechanical properties on command.
Serial multiplexing	An arrangement where multiple FOSs are distributed along a single optical fibre.
Smart material or composite	Material in which sensors (typically FOSs) are incorporated internally.
Smart structure	Structure incorporating numerous SHM sensors of various types.
Splash zone	The region of a marine structure which is subjected to repeated wet-dry cycles. These regions are those which are typically most susceptible to electrochemical corrosion of steel reinforcement.
Static strain profiles	Profiles providing information on the variation of strain over some gauge length.
Static testing	A testing technique in which the response of a structure to static (stationary) loads is monitored.
Steel-free bridge deck	An innovative type of concrete bridge deck which is free of internal reinforcing steel. FRP reinforcement may be provided in the concrete deck. This type of deck is presumed to have superior durability characteristics since it is not susceptible to corrosion of the reinforcement.
Stress history	The range of stresses experience by a component of a structure.
Structural health monitoring	The broad concept of assessing the ongoing, in-service performance of structures using a variety of measurement techniques.
Subgratings	Divisions of fibre Bragg gratings into smaller gratings which allow for distributed sensing capabilities and the ability to measure strain profiles.
Sustained loads	Loads which act on a structure for a prolonged duration.
Test vehicle	A vehicle used to apply static or dynamic loads to a bridge structure for the purposes of field testing.
Thermal compensation	Removal of thermal effects from sensor data.
Thermistor	A resistor made of semiconductors having resistance that varies rapidly and predictably with temperature.
Thermocouple	A sensor which measures temperature by reading the tiny temperature-dependent voltage created by the contact of two electrochemically dissimilar metals.

Tiltmeter	A sensor used to measure change in the orientation of a structural component with respect to the vertical axis.
Time-averaged mode	A mode of data collection in which data are logged over a fixed period of time, and the data are converted into means, variances, minima and maxima.
Vibrating wire strain gauge	A type of sensor which measures strain by measuring the tension in a vibrating wire by examining its resonant frequency.
Weldable	Refers to sensors that are capable of being welded onto metallic construction materials.