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Bridges Structural Health Monitoring and Deterioration Detection - Synthesis of Knowledge and Technology

Final Report

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By

Yongtao Dong
Ruiqiang Song

Department of Civil & Environmental Engineering
University of Alaska Fairbanks

Helen (He) Liu

School of Engineering
University of Alaska Fairbanks

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ABSTRACT

The objectives of this report are to synthesis the current knowledge and technologies available for health monitoring of civil infrastructures, and to simplify the process of selecting structural health monitoring (SHM) systems for applications to bridge structures. This report focuses on (a) the state-of-the-art of SHM systems and their capabilities and (b) companies that offer particular systems and services, special attention is paid on the potentials of these systems being implemented to bridges in cold, remote regions of Alaska.

Many of American's bridge were aging and experiencing deterioration. It's very difficult to properly evaluate the structural condition and performance of these bridges under today's traffic and to decide which bridges or structural components need to be retrofitted or replaced by new structural members to optimize the available budget. As more and more state DOTs realize the importance of monitoring the performance of their bridges and are developing appropriate structural health monitoring (SHM) programs for their bridges, the Alaska Department of Transportation & Public Facilities (AKDOT&PF) also shows great interest in the potential implementation of SHM and damage detection technologies to Alaska's bridges.

Bridges in Alaska are routinely subjected to harsh weather conditions, earthquakes, and usually located in remote areas. Maintenance, rehabilitation and replacement of Alaska's bridges in a cost effective manner depend critically on reliable inspection and condition assessment. These inspections are both costly and time consuming. Compared with other states in the nation, monitoring bridges in Alaska is more challenging because of the harsh weather conditions and the remoteness.

As the first step toward the establishment of a bridge SHM program for the State of Alaska, this report focuses on synthesis of current SHM knowledge by summarizing literature, available technologies and ongoing research, including

- a literature review, telephone interview and survey of the current advancement in SHM technologies and their applications;
- synthesis and evaluation of current knowledge in SHM methodology and design of SHM systems to meet special monitoring needs;
- synthesis of current available products (sensors, hardware and software, etc.) needed to establish a SHM system, especially advanced fiber optic sensing (FOS) technology;
- synthesis of complete monitoring systems offered by different companies; products available for monitoring cracks, corrosion, scour and integration of bridges, etc.,
- special attention is paid to the potentials of the available systems in applications to bridges in cold and remote regions of Alaska, and
- application examples of SHM systems worldwide.

Due to the variety of products offered by a variety of companies, this report tries to categorize their products in terms of their functions. Many companies specialize in a particular type of system, while others claim to offer customized complete systems that can be tailored to a specific bridge. Here a

complete system was defined as one that comprises sensors, data acquisition units, communication tools, and software.

Based on the results of this study, majority of SHM products and systems can be used to cold regions with special care taken to tailor the system, e.g., to house the field equipment in NEMA enclosure with air-conditioning. Due to the advancement in computing, data communication and network technologies, a number of sensors and systems are able to perform wireless/remote monitoring. This means they can be used to bridges in remote regions. A number of companies offer an alarming feature. Normally, the alarm is triggered by breaching a predetermined threshold and a message is sent to the bridge owner by email or cellular.

In summary, the report explains the basic knowledge of structural health monitoring, and summarizes the commercially available SHM products and systems. Many companies claim to offer ‘turn-key’ systems that can be easily used to the bridge SHM. A quite number of bridges have been instrumented with SHM systems and are under monitoring, but literature of the system performance, monitoring results, and how they helped the bridge owners are often not available. It’s still challenging to not only see data stream in real-time and to archive them for future use, but also to interpret, analyze, characterize the response, detect damage and deterioration and assess the condition of the bridges.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Bridges are continuously subjected to destructive effects of material aging, widespread corrosion of steel reinforcing bars in concrete structures, corrosion of steel structures and components, increasing traffic volume and overloading, or simply overall deterioration and aging. These factors, combined with defects of design and construction and accidental damage, prompt the deterioration of bridges and result in the loss of load carrying capacity of bridges.

For example, of the country's nearly 600,000 bridges, 26% were found structurally deficient or "functionally obsolete" in a report from U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics (Accessed on January 07, 2011 at https://2bts.rita.dot.gov/current_topics/2009_03_18_bridge_data/html/bridges_by_state.html). The condition of heavily used urban bridges is even worse: one in three are classified as aging or unable to accommodate modern vehicle weights and traffic volume. Therefore, a significant number of these structures need strengthening, rehabilitation, or replacement, but public funds are not generally available for the required replacement of existing structures or construction of new ones.

Bridges can suffer structural deterioration due to aging, misuse or lack of proper maintenance. Among the many factors which have led to the unsatisfactory condition of bridge structures, one factor that has been neglected is the unsatisfactory inspection and monitoring of existing structures. It is crucial to inspect the bridge periodically and to assess its condition and evaluate its "soundness". Visual inspection, complemented with Non-destructive Testing and Evaluation (NDT/NDE) has long been used to examine the structural health of bridges. But this still does not resolve the problems of subjectivity and periodic nature of inspection. Therefore, continuous monitoring is the best way to resolve the aforementioned problem.

The most common objectives for monitoring a bridge are to obtain quantitative data about the structural behavior in order to confirm design assumptions and to provide real-time feed-back during construction (especially true for new bridges), and to evaluate the real current condition of the bridge and allows the engineers to take informed decisions about their future and to plan maintenance or repair actions (especially for existing bridges). In the later, the monitoring system is used to increase the safety of the structure and provide early warning of an acceleration of the known degradations that are being monitored. And the application of SHM to existing bridges to perform a controlled lifetime extension of the bridges with known problems has greatly increased in recent years.

With the recent advances in SHM and computing technology, developing and deploying intelligent bridge monitoring systems becomes possible. After AASHTO's workshop, several states had started working on the bridge monitoring system (Alampalli and Ettouney 2007). SHM technologies are promising for a wide range of infrastructures (Carden and Fanning 2004, Fanning and Carden 2004, Catbas and Aktan 2002, Farrar and Doebling 1999, Halling et al. 2001, Lee and Shin 2002, Samman and Biswas 1994, Shi and Zhang 2000 and 2002, and Wahab and De Roeck 1999), but there are many challenges in cold-region application.

Currently, in the State of Alaska, except for a scour monitoring system established by the USGS, there is no initiation of a monitoring system for the bridge stock yet (although a few bridges were instrumented, there was no SHM program created and the data were not used for the assessment of bridge condition or damage detection).

Bridges in Alaska are routinely subjected to harsh weather conditions, earthquakes, and often located in remote areas, and usually the only pathways for the traffic in the area. Maintenance, rehabilitation and replacement of Alaska's bridges in a cost effective manner is critically dependent on reliable inspection and condition assessment. Compared with other states in the nation, monitoring bridges in Alaska is more challenging because of the harsh weather and the remoteness.

Focusing on synthesis of available knowledge and technologies, this study will perform a comprehensive literature review to obtain a state-of-the-art advancement in SHM; evaluate the potential technologies; identify challenging issues related to cold region applications of the SHM program; and provide recommendations for implementation of SHM program to bridges in State of Alaska and other remote, cold regions.

1.2 Research Objectives

The objective of this study is to synthesize the state-of-the-art knowledge and technology in bridge SHM and deterioration/damage detection/diagnosis. Special attention will be paid to application of the available technologies in cold and remote regions.

It was indicated in AASHTO workshop (AASHTO 2005) that the "Important Activities/Areas for Research" on bridge monitoring include

- identification of most useful data and information to be collected,
- identification of the types of structures/parts of structures where enhanced monitoring is needed and most promising,
- deployment of the most promising technologies as demonstrations,
- development of recommended revisions to the AASHTO condition evaluation manuals,
- evaluation of current visual methods and recommendation of improvements,
- development of automated data collection and reporting,
- development of interpreting protocols and damage models using the data collected by the systems,
- evaluation of cost/benefit of monitoring/assessment systems, and
- study the implications of security and traffic management systems.

According to the AASHTO workshop, the benchmark objectives for monitoring bridge condition can be organized as follows:

- in the short term (2-3 years): the identification of promising cost-effective technologies (including what data and how and where it should be collected) and enhanced monitoring strategies (including how the data should be used);
- in the mid-term (4-5 years): implementation and evaluation of prototype strategies, and recommendation of actions; and
- in the long term (beyond 5 years): deployment of multiple integrated health assessment systems.

These suggestions are considered as the guidelines for most states to develop their bridge monitoring programs. As the first step toward to evaluation and development of a SHM system for the bridges in Alaska, the primary objective of this study is to review current advancements in knowledge and technologies of SHM, to identify the promising technologies for bridge SHM, and to explore the solution to reliable measurements and operations of SHM technologies in cold, remote regions.

1.3 Methodology

Since the proposed study is to synthesize current knowledge and technology on bridge SHM and detection/diagnosis of possible deterioration/damages, the major work will focus on

- Current sensing technologies in bridge monitoring
- Current data communication tools
- Select equipment for non-destructive vibration testing
- Software needed for SHM
- Security control systems
- Challenges for remote, cold region applications

The research consists of the following tasks:

Task 1: Literature review: A comprehensive literature review to identify the state-of-the-art technologies in bridge health monitoring and condition assessment will allow us to find the best suitable knowledge, technology, hardware and software for potential application the bridge SHM in the State of Alaska.

Task 2: Telephone interview and survey: Based on literature review, survey to manufacturers and state DOTs about the current status of their bridge monitoring and condition assessment program will provide us a good knowledge of the up-to-date advancement of bridge SHM system.

Task 3: Field observation: If necessary, field observation will focus on whether the sensor and technology are appropriate for use in Alaska.

Task 4: Synthesis of knowledge and technology: The knowledge and technology reviewed, collected and studied will be synthesized and documented. The reported knowledge and technology will emphasize on the newly developed and most promising technologies to Alaska. For example, low-temperature effects on the accuracy of sensor applications, reliability of wireless data transmissions, power supply and communication obstacles in remote areas of Alaska.

1.4 Significance and Benefits

It was well agreed (AASHTO 2005) that effective bridge structural health monitoring (SHM) systems (not necessarily continuous monitoring) can

- improve the credibility of inspections and subsequent ratings through less subjective data,
- improve data consistence enabling the development of better decision-making tools,
- evaluate existing inspection techniques,
- improve and augment visual assessment, and provide early detection and warning,
- assess long-term performance,
- result in modified specifications and inspection standards, and optimization of inspection schedules,
- allow more rational maintenance scheduling resulting in the optimization of maintenance dollars, and
- increase the reliability of the structures.

1.5 Report Contents

This report consists of three parts. Part I is the synthesis of current knowledge and recent advancement in structural health monitoring, including components of a SHM system, advanced sensing technologies, different types of SHM methods. More attentions are paid on the fiber optic sensing technology and vibration-based testing in bridge structural health monitoring.

Part II is the synthesis of current available and newly developed SHM technologies. The information of manufacturers/providers of these technologies and their products is discussed. If possible, some example projects of using the corresponding technologies are briefly discussed.

Part III presents a few selected application examples worldwide to show that it is possible to establish and implement SHM systems using the current knowledge and technologies for monitoring purposes.

Part I Synthesis of Current Knowledge of Structural Health Monitoring

The objective of the first part of this report is to review the up-to-date knowledge about Structural health monitoring (SHM) of civil infrastructures, with a special interest in SHM application on bridges. It begins with the definition of SHM, levels of SHM and general categories of SHM are introduced for ease of description in SHM discussions. Chapter 2 focuses on the basics of SHM and Chapter 3 is devoted to mythology of structural health monitoring. State-of-the-art sensing technologies, specifically, the fiber optic sensors (FOSs), are discussed in Chapter 4. Chapter 5 and Chapter 6 are about static and dynamic testing in SHM, with more details in dynamic testing because this testing is complicated and also often used in SHM. Chapter 7 discusses the issues and steps to design a successful SHM system to meet monitoring needs. In the end, the future of SHM and a summary of the current knowledge of SHM are presented in Chapter 8 and Chapter 9.

The material presented here is based mainly on the results of numerous available literatures and field projects conducted worldwide, especially the recommendations of ISIS Canada Design Manual No. 2: Guidelines for Structural Health Monitoring (Mufti 2001) and ISIS Canada Educational Module 5: an Introduction to Structural Health Monitoring (Bisby 2006).

2 BASICS OF STRUCTURAL HEALTH MONITORIGN

2.1 Definition of SHM

Structural health monitoring is a non-destructive *in-situ* structural sensing and evaluation method that uses a variety of sensors attached to, or embedded in, a structure to monitor the structural response, analyze the structural characteristics for the purpose of estimating the severity of damage/deterioration and evaluating the consequences thereof on the structure in terms of response, capacity, and service-life (Housner *et al.* 1997, Karbhari 2005, Mufti 2001). The 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 identify damage at its onset, to assess the safety, integrity, strength, or performance of the structure.

SHM may 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. There is no formal delineation between each approach, but there is a difference between NDT/NDE and SHM. NDT/NDE normally refers to a one-time assessment of the condition of materials at a single point and the effect or extent of the deterioration in the structure using equipment external to the structure. SHM normally refers to activities focused 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 sensor systems may need to embedded in or attached to the structure for the complete monitoring period.

Structural health monitoring is common considered only as acquisition of data from a structure about its response to external and internal excitations. More importantly, structural health monitoring also includes the interrogation of this data to quantify the change in state of the structure and thence the prognosis of aspects such as capacity and remaining service-life. The former is hence a necessary, but not sufficient, part of the latter. Also, the concept of monitoring prescribes that it be on ongoing, preferably autonomous, process rather than one that is used at preset intervals of time through human intervention. Thus SHM is essentially the basis for condition-based, rather than time-based, monitoring and the system should be integrated into the use of real time data on aging and degradation into the assessment of structural integrity and reliability.

In addition to the need for current condition assessment and long-term monitoring for better management of existing structures, the following factors also contribute to the recent rapid development and advancement of SHM technologies in civil engineering (Bisby 2006):

- the recent advancements in sensing technologies with high speed and low-cost electronic circuits, and development of highly efficient signal validation and processing methods (e.g. *fiber optic sensors (FOSs)* and *smart materials*);
- ongoing developments in communication technologies, widely use of internet 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.

In the future, SHM of infrastructure is expected to provide early warning of structural damage or decay, thus improving the health of our infrastructure systems.

2.2 Classification of SHM

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 report. The classifications of SHM systems can be summarized as follows (Bisby 2006):

- **Level I:** At this 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. 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 quantify the damage to indicate the extent of its severity.

- **Level IV:** This is the most sophisticated SHM systems. At this level, the system is capable of providing detailed information on the presence, location, and severity of damage. It is able to use this information to evaluate the safety of the structural system.

Obviously, as the level goes higher, more information could be obtained from the SHM system although the system is becoming more complicated and costly.

2.3 Types of SHM

In addition to the sophistication and objective, SHM can also be classified into at least four types or categories in terms of the type of field testing undertaken and the timescale how data is physically collected, as shown in Fig. 2.1 (Bisby 2006): static field testing, dynamic field testing, periodic monitoring and continuous monitoring.

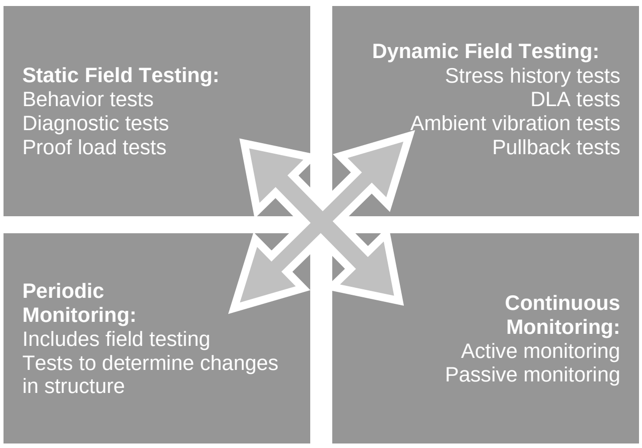


Fig. 2.1 Categories and sub-categories of SHM systems

These various types are not independent to each other. More than one type of testing or monitoring may be necessary in a complete SHM program. More details, along with the associated content in static and dynamic field testing will be discussed in more details in Chapter 5 and Chapter 6.

Periodic Monitoring
Structural health monitoring of civil engineering structures can be either periodic or continuous. Periodic monitoring is conducted to investigate the structural response or any detrimental change that might occur in a structure at specified time or time intervals (e.g. weeks, months, or years apart). Analysis of the monitoring data may indicate damage or deterioration. For example, monitoring through static field testing or moving traffic, monitoring crack growth, monitoring before and after a repair, can all be done periodically. In periodic monitoring, sensors may be permanently installed on the structure or temporarily installed at the time of testing (Bisby 2006).

Continuous Monitoring
Continuous monitoring, as the name implies, refers to monitoring of a structure for an extended period of time (weeks, months, or years) without interruption. This type of monitoring has only recently been used in full scale field applications, due in part to the higher costs and complexity of SHM system (Bisby 2006). 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.

2.4 Components of SHM Systems

As mentioned previously, structural health monitoring refers to subjecting the structure to static or dynamic excitations, continuous or periodic monitoring of the structure's response using sensors that are either embedded in or attached to the structure.

New advances in sensor and information technologies and the widely use of Internet is making SHM a promising technology for better management of civil infrastructures. There have been many case studies worldwide in the past decade. While the specific details of each SHM system can vary substantially, SHM basically involves sensor and data acquisition, data transfer and communication, data analysis and interpretation, and data management. Thus a SHM system will typically consist of six common components, namely:

- sensors and data acquisition networks;
- communication of data;
- data processing;
- storage of processed data;
- diagnostic and prognostic analysis (i.e. damage detection and modeling algorithms, event identification and interpretation); and
- retrieval of information as required.

A typical flow pattern between the six components of a SHM system is shown in Fig. 2.2 (Bisby 2006); 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 details in Chapter 3.

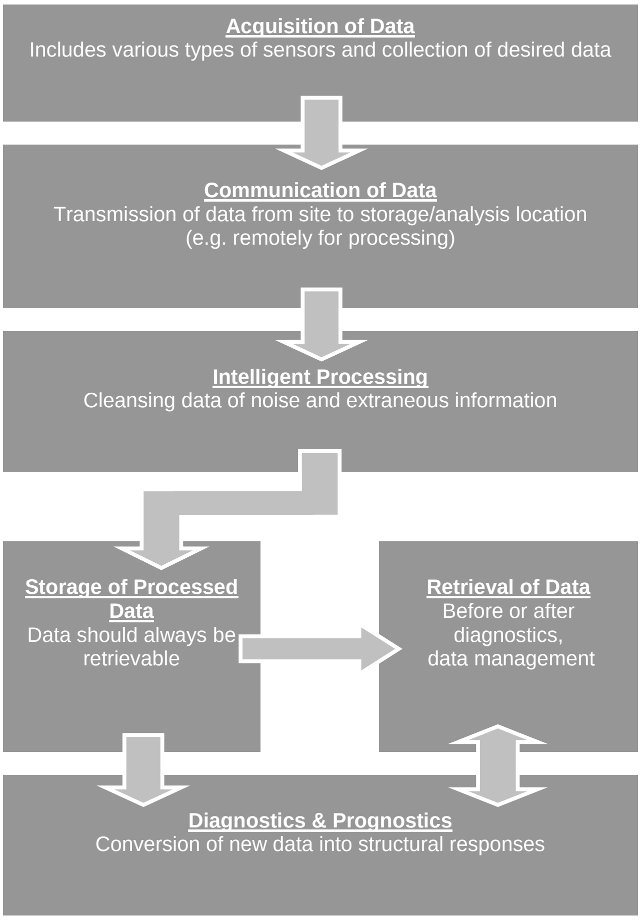


Fig. 2.2 Components of a typical SHM system

2.5 Advantages and Benefits of SHM

Structural health monitoring presents a number of key benefits for civil engineering structures. Some of the most commonly cited benefits of SHM include (Bisby 2006):

Improved understanding of in-situ structural behavior

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 behavior 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.

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 behavior 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.

3 METHODOLOGY OF STRUCTURAL HEALTH MONITORING

An ideal SHM system should be capable of providing information on demand about the condition 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 (Bisby 2006). The six overall components of a typical SHM system were presented previously in Chapter 2 and are shown schematically below in Fig. 3.1. In this chapter, more detailed information is provided on each specific SHM system component.

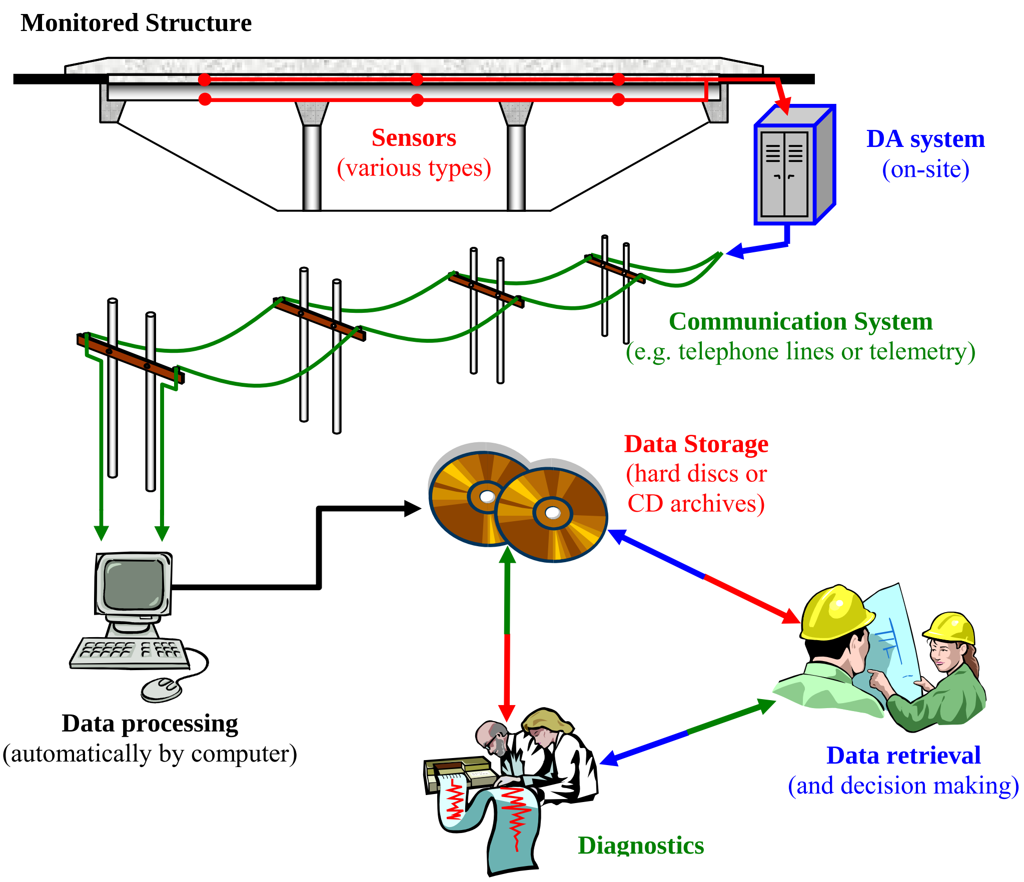


Fig. 3.1 Visual schematic of a typical SHM system (Bisby 2006)

3.1 Sensors

3.1.1 Selection of sensors

Once the structure and measurement metrics are identified, the first step for an effective SHM system is the selection or development of appropriate and robust sensors. Although 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 which will provide the information required for monitoring and analysis. For example, the measurement needs can be one or a combination of any of the following: strains, deformations, accelerations, environment (temperatures, moisture, pressure, etc), load, and other attributes of a structure.

Literature surveying had disclosed significant development in sensing technologies from conventional sensors of electrical resistance strain gauges, vibrating wire strain gauges, deflection transducers, accelerometers, anemometers, etc. to novel sensors of fiber optic gauges, etc. These sensors are commercially available, but many of them are not always suitable for SHM. For example, 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.

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 (Bisby 2006).

Since sensors are essential to a successful SHM system, current knowledge of novel fiber optic sensors will be discussed with more details in this chapter. The commercially available sensors and their providers will be discussed in more details in the chapters of Part II of this report.

3.1.2 Installation and placement of sensors

In addition to follow the instructions of sensor providers, great 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 behavior 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.

A detailed set of installation specifications should also be prepared for each type of sensor and data acquisition component that will be used. These specifications should detail the methods and techniques to be used for installing and configuring the sensors and data acquisition components, and a methodology for verifying that they are working correctly (i.e. testing and calibration of the sensors). If the installation work is done by a general contractor, installation of all systems must adhere to the supplier's specifications, with appropriate instruction and supervision.

3.2 Data Acquisition (DAQ) from Sensors

This component is data acquisition (DAQ) networks used to physically collect raw data from sensors such as strain gauges, displacement transducers, accelerometers, anemometers, fiber optic sensors, load cells, etc. The DAQ system, often called data-logger, is the onsite system where signal demodulation, conditioning and storage of measured data are conducted prior to being transferred to an offsite location for analysis (Fig. 3.2). This is also the procedure where the analog output signals from sensors are converted into engineering term. Therefore, all sensors must communicate with the DAQ system by either wired or wireless connection.

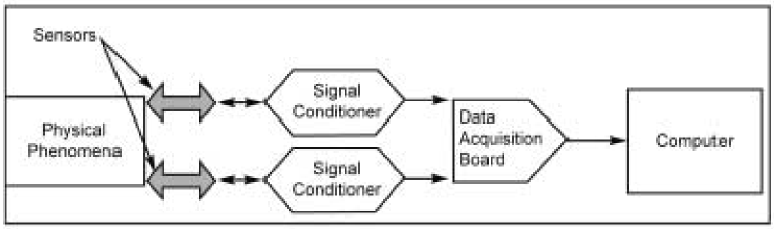


Fig. 3.2 Components of a computer-based data acquisition system (Mufti 2001)

Wired connection by a lead cable or wire is sometimes subjected to electromagnetic interference (EMI) which can lead to errors in the measurement. The use of differential signaling 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.

Wireless connection is needed for some large structures where lead cable transmitted sensor signals might be corrupted by excessive noise, or where long lead cables are otherwise impractical. 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.

Most sensor manufacturers offer data loggers (wired or wireless) with their sensor products. There are also manufacturers who only provide data loggers which are compatible with most commercially available sensors. This will be discussed in more details in Part 2 (current technologies).

Data Sampling and Recording

Experiences have shown that SHM data can easily become very large in quantity especially when the structure are extensively instrumented with a variety of sensors in a variety of locations, particularly in the case of continuous monitoring (Ni 2010). Therefore a well designed data acquisition algorithm-data sampling and recording, which captures an adequate (but not excessive) amount of data, is a very important component of a successful SHM system and will affect both the volume of stored data and the type of diagnostic information that can be obtained.

In setup the data sampling rate, 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 (Mufti 2001). 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. For example, the data collected during continuous monitoring activities may be substantially compressed by recording only changes in readings or only data exceeding a specified threshold value. Another option is to only keep peak values of readings for each event, such as a heavy truck passing over a bridge.

3.3 Data Communication

Data communication refers to the mechanism of transfer of data from DAQ system to the location where they will be processed and analyzed (normally not on the bridge site). 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. Sometimes it is also possible to remotely control the DAQ system through proper monitoring software. Currently SHM systems transmit field data remotely, either through telephone lines or the internet, or using wireless technologies such as radio or cellular transmission (Han et al. 2004).

3.4 Data Processing and Analysis

This is the operational part of the process. The data is processed before it is stored in a database.
Due to the many possible sources of error and uncertainty in the field, 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.

One method for data quality assurance is to implement quality control at multiple levels of the signal path. At the level of the sensors and data acquisition hardware, a thorough initial calibration of the sensors and data acquisition hardware followed by periodic re-calibration of these components, verifying and ensuring the quality of the initial installations, are needed.

Elementary data checks can also be programmed in the data acquisition software to automatically validate and process the data before it can be stored for later interpretation and analysis. The goal of intelligent processing is to remove this unwanted or redundant information. The various data management strategies should be able to eliminate unnecessary data without sacrificing the integrity of the overall system.

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.

In more sophisticated systems, neural computing and artificial neural network techniques may be employed (McNeill 2004, McNeil and Card 2005). Artificial neural networks (ANNs) are basically statistical signal processing techniques that are inspired by the learning capabilities of biological systems. Similarly to their biological counterpart, ANNs have the capability to learn through experiences, rather than through explicit rules or procedures. This learning could be carried out in a supervised or unsupervised manner. Either case results in the system able to develop an internal model of the characteristic properties of a collection of the data. The internal data modeled stand for the physical response of a bridge due to its environment. This response is it in the form of strain, temperature, and acceleration measurements under normal operating conditions.

The specific nature of the learned model is dependent on the algorithm that is used to train the network and the quality of data that is made available. An algorithm is a set of rules or computational procedure for solving a problem. Should the network training data have sample inputs; the model will be capable of differentiating between similar varieties of such inputs in the future. In the absence of pre-labeled inputs, identifiable classes can still be incorporated into the learned model in cases where markedly distinguishable types of phenomena exist within the input data. In both case, the learned model will provide a reference against which to compare future inputs. Therefore, it can be used to determine a measure of novelty for a given new input relative to the learned model. Measurements that are consistent with the model will display low levels of novelty, while those which differ substantially from the model will produce high novelty value (McNeil and Card 2005).

In neural network, 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.

3.5 Storage of Processed Data

The processed data can then 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.

Developing appropriate algorithms for data quality assurance, processing and archival represents the major IT (information technology) related challenges in a SHM system. 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. The result of this step is a database of measurements and a log of events.

3.6 Diagnostics and Prognostics

This is the most difficult step and also the most important component of an effective SHM system. Diagnostics involves further interpretation of the collected and processed data, analysis of the responses of the structure, and identifying if any of the foreseen damage or deterioration have occurred. Diagnostics is concerned with converting the data from monitoring to useful information about the response and health of the structure. This activity requires expert structural knowledge about the behavior of structures as well as an understanding of how that behavior may be affected by damage, deterioration 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.

In a long-term structural health monitoring application, the system should be able to interpret the measurement data, compare the result with some predetermined set of criteria, and execute a decision in an automated manner. The simplest example is to program a health monitoring system to issue an alert when the measurement data indicates that some behavior has exceeded a particular threshold value. The decision criteria should be thoroughly tested before it is implemented and must be rigorous enough to prevent the occurrence of false positives.

3.7 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.

4 SENSING TECHNOLOGIES

Based on the monitoring interests, a various types of data about a structure's response may be needed in a SHM program and therefore different types of sensors might be used. Conventional used sensors available commercially for a long time include: *load cells, electrical resistance strain gauges, vibrating wire strain gauges, displacement transducers, accelerometers, anemometers*, and *thermocouples*, etc. Instructions of how to apply these sensors are usually available with the sensor datasheets. Guidelines on how some of the sensors are used in SHM are provided in Appendix A of ISIS Canada Design Manual No. 2 (Mufti 2001) for the selection of sensors, protection against mechanical and chemical damage, reduction of noise, and the collection of more representative data.

The spur for development of novel sensors is driven by the limitations of the conventional electric sensing technologies to capture linear or planar continuous information (Fujihashi 2005). In instances where numerous points are measured over a huge area, a staggering amount of sensors require separate, individual cables for supplying power and transmitting measurement signals. Therefore, this increases the intricacies of the system and presents a challenge in terms of construction costs, maintenance costs and operating costs.

In this chapter, knowledge of conventional measurements of train, displacement, acceleration and temperature will be discussed first followed by a detailed discussion about fiber optic sensing technology which have experienced a huge advancement in the most recent in bridge SHM. Manufacturers of these sensors and relative DAQ systems are reviewed in Part 2 of this report.

4.1 Strain Measurement

4.1.1 Foil strain gage

Foil strain gauges (Fig. 4.1) have been widely used for strain measurement in experimental stress analysis. However, they are less attractive for field SHM of bridges especially when the distance between the gauge and the readout unit increases. This is due to the fact that the low-level voltage signal produced by the foil strain gauge is susceptible to electromagnetic and electrostatic interference from external sources. When unconditioned signals from foil gauges are transmitted a relatively long distance, the electrical noise superimposed by the electromagnetic and electrostatic fields becomes significant and can lead to inaccurate results and incorrect interpretation of the strain signals. The problem is more severe for dynamic measurements, since filtering the noise can change the characteristic of the original signal.

Foil strain gauges are generally attached to the surface of structural components and wired to readout units. As the component experiences strain, the change in length at the surface of the component is transmitted to the strain gauge through the connecting substances. From there, the corresponding signal is transmitted to the readout unit through the lead wires. To ensure the output of the readout unit represents the true strain change in the material, it is important to understand the various factors that affect the quality of the measurements (Mufti 2001).

Weldable strain gauges are also available in the market (Fig. 4.2). This kind of gauge consists of a specially manufactured foil strain gauge pre-bonded to a metal carrier for spot welding to steel components. Adhesively bonded strain gauges are preferred over weldable strain gauges when the highest accuracy is desired. However, where bonding conditions are not ideal, the weldable type is the preferred choice. Weldable gauges are more costly than bondable gauges, but the overall installation cost is reduced significantly because of the shorter installation time, and elimination of the strict requirements for surface preparation and adhesive curing required for bondable strain gauges. It should be noted that the bonding component should be free from drift.

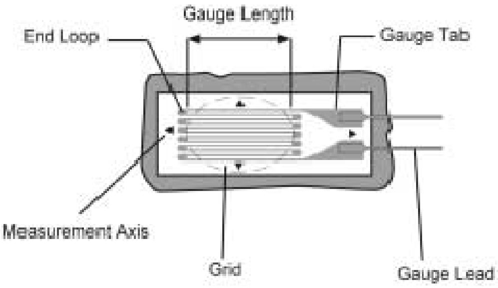


Fig. 4.1 Foil strain gauge

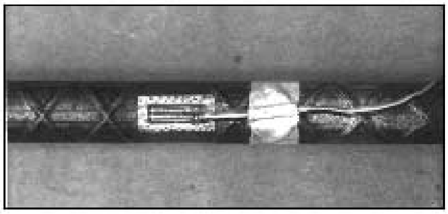


Fig. 4.2 A weldable strain gauge attached to a reinforcing bar

Another type of foil strain gauge on the market is the embedment strain gauge. This type of strain gauge is used for measuring strains inside concrete structures. An embedment gauge consists of a long foil gauge (about 100 mm) embedded in a polymer concrete block. The long length of the embedded strain gauge is necessary to ensure that the measured strain is the average strain in aggregate materials, and not the localized strain due to discontinuities in concrete. The concrete cover protects the embedment strain gauge against mechanical damage during construction, as well as moisture and corrosive attacks afterwards. It also provides a means for the proper transfer of strain from the structure to the strain gauge.

Sensitivity of strain gauges to moisture and humidity is another concern, especially when long-term measurement is planned, particularly in a harsh environment, and when it is important to maintain a stable reference (zero-stability) for the gauges. Special provisions are often needed to protect the gauges in order to obtain acceptable measurements.

4.1.2 Vibrating wire strain gauges

Vibrating wire (VW) strain gauges are relatively bulky (usually larger than 100 mm in length) and are produced for embedment in concrete or attaching to the surface of components. Surface strain gauges can be welded, bolted or bonded to the material. Embeddable strain gauges can be directly placed in concrete or cast into a concrete briquette before being placed in their final position. In either case, the placement of large diameter aggregates in the proximity of the gauge must be avoided. This is essential for preventing stress discontinuity in the gauge area. Theoretically, the maximum aggregate size, within an envelope of 1.5 gauge lengths around the gauge, should not exceed 1/5 of the gauge length.

Vibrating wire strain gauges are encased in sealed steel tubes. The gauges are equipped with a magnet/coil assembly for exciting the wire inside the tube, and sensing its frequency. In some of the models available on the market, the magnet/coil assembly is attached to the outside of the tube, and in others it is built inside the tube. In general, VW gauges are not susceptible to humidity, however the surface gauges should be protected against direct contact with weather.

A temperature sensor is a standard feature on every VW strain gauge. The same readout unit used to read the strain, reads the temperature sensor. The temperature reading lets the user apply the necessary correction for the temperature effect. To do this, calculate the temperature-induced strain from Equation A.6 and deduct it from the strain reading. Since the temperature-induced strain is the result of the difference in thermal expansion coefficients of the gauge and the instrumented component, no temperature correction is considered when the gauge is attached to a steel component.

4.2 Linear Variable Differential Transducers (LVDT)

The linear variable differential transducers (LVDT) are used for displacement measurements, and consist of a hollow metallic casing in which a shaft, called the core, moves freely back and forth along the axis of measurement. The core is made of a magnetically conductive material, and a coil assembly surrounds the metallic shaft.

As shown schematically in Fig. 4.3, the coil assembly consists of three transformer windings. A central primary winding is flanked by two secondary windings, one on either side. The outputs of the secondary windings are wired together to form a series opposing circuit. When an AC excitation is applied to the primary winding, it generates an inductance current in the secondary windings, due to the mediation of the magnetically conductive core. When the core is equidistant between both secondary windings, no voltage appears at the secondary outputs. However, when the core moves, a differential voltage is induced at the secondary output. The magnitude of the output voltage changes linearly with the magnitude of the core's excursion from the centre.

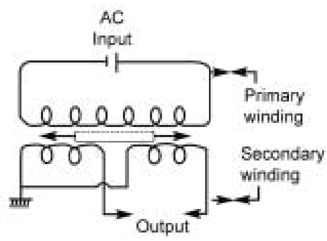


Fig. 4.3 Schematic diagram of a typical LVDT sensor

4.3 Accelerometer

Accelerometers used for civil engineering applications are either piezoelectric accelerometers or spring-mass accelerometers. Piezoelectric accelerometers are light and small, and operate over wide acceleration and frequency ranges. On the other hand, spring-mass accelerometers are relatively bulky and operate over a limited range of accelerations and frequencies. However, they are very sensitive to small accelerations and provide better resolution than the piezoelectric accelerometers.

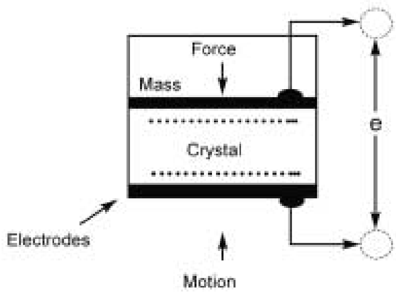


Fig. 4.4 Schematic diagram of a piezoelectric accelerometer

The piezoelectric accelerometer is made of a piezoelectric crystal element and an attached mass that is coupled to a supporting base. When the supporting base undergoes movement, the mass exerts an inertia force on the piezoelectric crystal element. The exerted force produces a proportional electric charge on the crystal (Fig. 4.4). Since the force is equal to mass times acceleration, the charge is proportional to acceleration.

The spring-mass accelerometer is essentially a damped oscillator.

4.4 Temperature Sensors

Temperature can be measured by a diverse array of sensors. Three types commonly used for civil engineering applications are: resistive; vibrating wire; and fiber optic temperature sensors.

4.4.1 Resistive temperature sensors

Resistive temperature sensors are based on the fact that the electrical resistance of a material changes as its temperature changes. There are two types of resistive temperature sensors: metallic sensors and thermistors. A typical metallic sensor comprises a fine platinum wire wrapped around a mandrel and covered with a protective coating, or encased in a protective housing. The variation of the platinum resistance with temperature is linear. This variation can easily and accurately be measured by installing the sensor in one arm of the Wheatstone bridge circuit.

Thermistors are based on resistance change in a ceramic semiconductor. The resistance temperature relationship of a thermistor is negative and highly nonlinear. However, this difficulty is resolved by using thermistors in matched pairs in such a way that the nonlinearities of the two semiconductors offset each other. The operation range of thermistors is smaller than that of metallic temperature sensors, but thermistors usually provide higher accuracy.

Resistive sensors all have a very important limitation. The current for the operation of these sensors, even though very small, creates a certain amount of heat, leading to an erroneous temperature reading.

4.4.2 Vibrating wire temperature sensors

Vibrating wire temperature sensors operate similarly to VW strain gauges. A change in temperature causes a change in the frequency signal output from the VW temperature sensor. The readout device processes the signal and converts it to a voltage proportional to the temperature, or displays a reading in temperature units. The VW temperature sensor is encased in a cylinder to prevent physical contact between the sensor and the material. Therefore, no special precaution is needed for the effect of the strains on the reading of the sensor.

4.5 Fiber Optic Sensing Technology

In recent years, the demand of monitoring large civil infrastructures and the harsh conditions of monitoring environments prompts the development of new sensor technologies, including fiber optics sensors, di-electric measurement sensors, and piezo-electric sensors, for applications in civil infrastructures. In this section, fiber optic sensing technology which has experienced a huge advancement in the most recent in bridge SHM will be reviewed.

4.5.1 Advantages of fiber optic sensors (FOSs)

Fiber optic sensors are used primarily to measure variations in strain and/or temperature in SHM applications. Compared to conventional strain gages, FOSs offer the following advantages (Grivas and Garlock 2003, Pinet, et al. 2007):

- **Stability:** light signals can be transmitted along very long lengths with a very low signal transmission loss, allowing remote monitoring. FOSs are free from corrosion, having long-term stability, and allowing continuous monitoring;

- **Non-conductive:** FOSs are free from electromagnetic and radio frequency interferences, avoiding undesirable noise;

- **Convenience:** FOSs and cabling are very small and light, making it possible to permanently incorporate them into the structures. Long gage sensors are available for distributed sensing and the sensors can be virtually applied to any structural shape.

4.5.2 Basic principles

Typical optical fibers are made of silica glass with a core, cladding to guide the lightwave, and plastic coating to prevent fracturing of the silica glass due to high modulus, and allow flexibility and bending for the fiber. Transmission of light through optical fibers can be explained by Snell's law and the concept of total internal reflection According to Fig. 4.5, as indicated by the refractive index, *n*, when light travels from the fiber core that has a high refractive index into the cladding with a lower index, the light–wave totally reflects back to the core. The various coatings surrounding the fiber optic core protect the glass fiber surface from abrasion during handling and installation, from moisture, which weakens the fiber and can contribute to the growth of microcracks, and in concrete from the alkaline environment which is corrosive to conventional glass fibers.

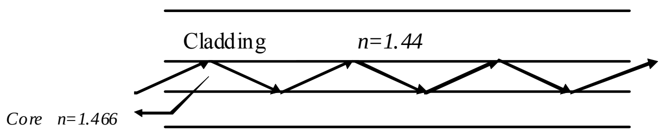


Fig. 4.5 A typical single mode optical fiber (Ansari, 1997)

Fiber optic sensing technology is based on the fact that light waves transmitted down an optical cable will change the light patterns and signals based on the condition of the cable. A light beam is sent down the fiber 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.

4.5.3 Types of fiber optic sensors

Since FOSs work by measuring changes in the physical properties of the guided light, a number of different fiber optic sensors have been developed in recent years based on different modulation of properties of the light sensing techniques. Intensity, interferometric and spectrometric sensors are categorized by their transduction mechanisms while localized, multiplexed and distributed sensors by their applications.

Sensors based on intensity modulation pertain to light intensity losses that are associated with straining of optical fibers along any portion of their length (see Fig. 4.6). The advantages of intensity or amplitude type sensors are the simplicity of construction, and compatibility with multi–mode fiber technology. The drawbacks are measurements are only relative and variations in the intensity of the light source may lead to false readings unless a referencing system is used.

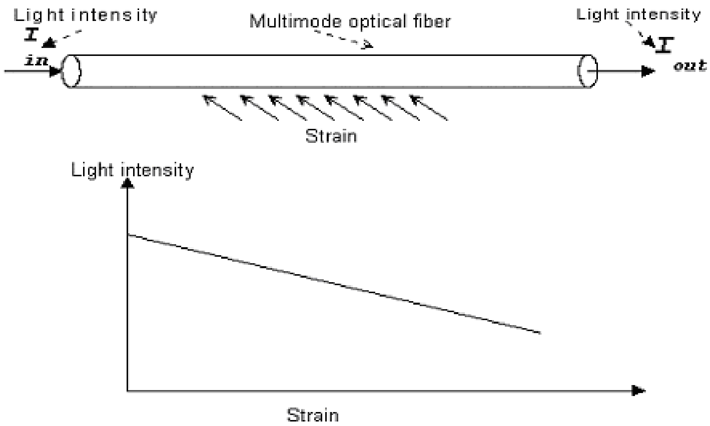


Fig. 4.6 Optical fiber intensity sensor (Ansari, 1997)

Spectrometric sensors are based on relating the changes in the wavelength of light to the measurement of interest, i.e. strain. An example of such sensors for measuring strains is Bragg grating sensor (Morey et al. 1989) (see Fig. 4.7). In a FBG sensor, an optical *grating* (essentially a series of tiny reflectors) is placed on the fiber and the grating spacing is proportional to the wavelength of light reflected when a light pulse is sent down the fiber. 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.

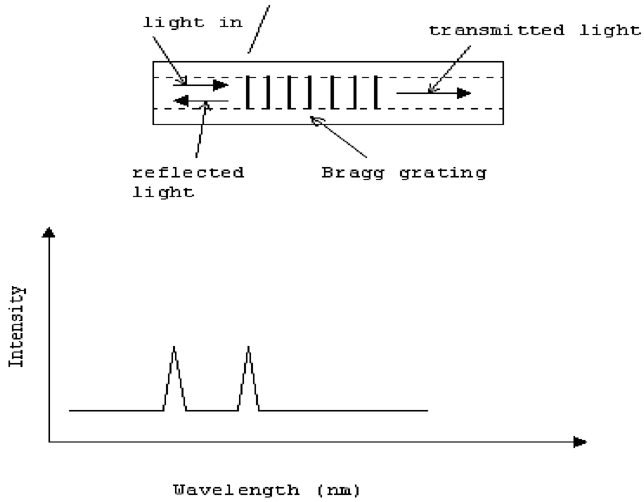


Fig. 4.7 Strain–induced shift in wavelength for a fiber Bragg grating (Ansari, 1997)

FBG sensors are commercially available and are intended to 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. FBG sensors are sensitive to extremely small strains. Fiber optic sensors based on FBG technology are suitable for direct strain and temperature sensing (as well as indirect measurement) and have a number of advantages compared to conventional strain gauges.

Interferometric sensors can be configured in a number of different ways for sensing purposes (see Fig. 4.8). Interferometric sensors require the interference of light from two identical single–mode fibers, one of which is used as reference arm and the other is the actual sensor. An exception to a two–arm interferometric sensor is a single–fiber Fabry–Perot type sensor (Claus et al., 1993). In a Fabry–Perot type sensor, the fiber is manipulated with two parallel reflectors (mirrors) perpendicular to the axis of the fiber. The interference of the reflected signals between the two mirrors creates the interference pattern. The interference pattern generated at the output end of the phase sensors is directly related to the intensity of the applied strain field between the two reflectors.

Like a FBG sensor, a Fabry–Perot sensor is only capable of providing localized measurements at the gap formed between the two mirrors. 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.

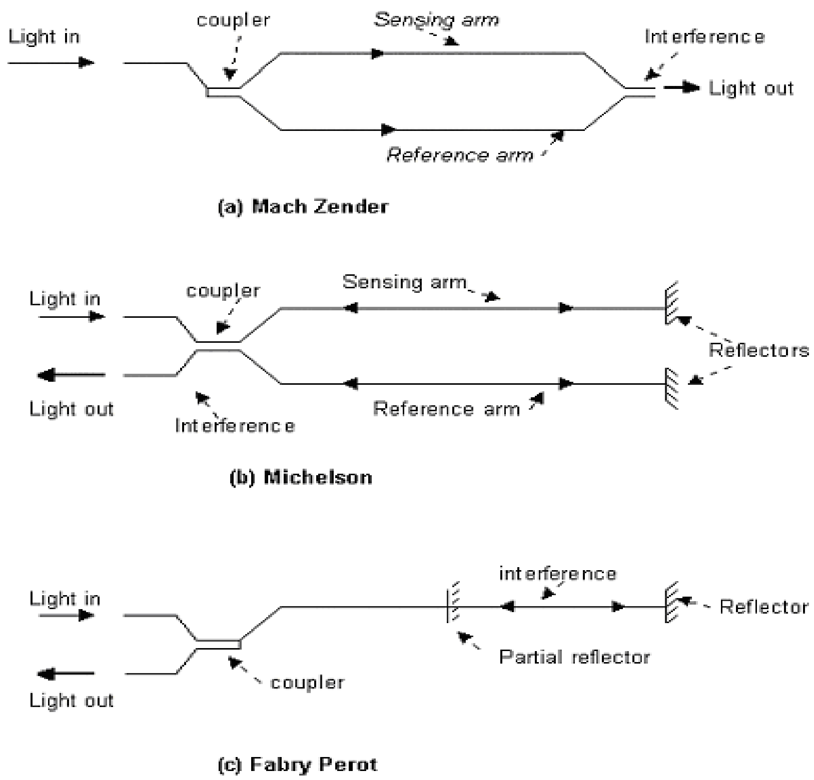


Fig. 4.8 Fiber optic interferometric sensors (Ansari, 1997)

<u>Brillouin scattering</u> based sensing systems are still in the developmental stage. When light travels through a transparent media, the most part of it travels straight forward, as a small fraction is back scattered. Different components of the back scattered light can be identified. A Brillouin scattering sensor exploits the sensitivity of the Brillouin frequency shift for temperature and strain sensing applications. The technique uses standard low-loss single-mode optical fiber offering the longest distance range with unrivalled performances and a compatibility with standard telecommunication components. In this technology, Brillouin scattering is usually optically stimulated leading to the greatest intensity of the scattering mechanism and consequently an improved signal-to-noise ratio. Brillouin frequency-based technique is opposed to intensity based techniques such as Raman and is inherently more accurate and more stable in the long term, since intensity-based techniques suffer from a high sensitivity to drifts.

Brillouin scattering sensor measure *static strain profiles* using a single optical fiber. 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. The Brillouin scattering wavelength shift is dependent upon temperature and strain. To function as a strain sensor it must be configured to discriminate between strain and temperature in a manner similar to the approach taken for Bragg grating sensors. Use of this type of sensor requires extensive analysis of optical signals and data, and at present Brillouin Scattering FOS systems are very expensive.

Of the sensor types discussed above, intensity type sensors are simple to construct but their sensitivity is rather low. Interferometric sensors offer highest sensitivity but the required components are quite complicated. Most commercially available FOSs are FBG sensors and Fabry-Perot sensors.

4.5.4 Examples of fiber optic sensors

Fiber optic strain gauges are commercially available in various different forms. In the simplest form, a fiber optic strain gauge consists of an optical fiber lead with a bare fiber optic sensor (See Fig. 4.9 from FOX-TEK) at one end and a special connector to the readout unit at the other end. In this form, the fiber optic sensor is small in diameter and can be used for embedment in fiber-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 fiber optic gauge to protect it against environmental and mechanical damage.

Other forms of fiber optic strain gauges include *weldable* and *embeddable* (Fig. 4.10 and Fig. 4.11). 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. 4.9 A close-up view of a bare FOS strain gauge (photo courtesy of FOX-TEK)

Fig. 4.10 A close-up view of an embeddable FOS strain gauge

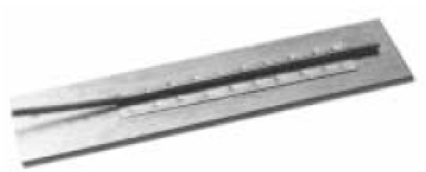


Fig. 4.11 A close-up view of a weldable FOS strain gauge

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.

4.5.5 Distributed and long gauge sensing

In distributed sensing, the whole optical fiber is the sensor itself. The purpose of making measurands by distributed or long gauge fibers is to determine locations and values of measurands along the entire length of the fiber.

FBG sensors are considered the most promising state-of-the-art technology platform for distributed sensing. 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 fiber.

Distributed sensors make full use of the optical fiber, in that each element of the optical fiber is used for both measurement and data transmission purposes. These sensors are most appropriate for application to large structure owing to their multi–point measurement capabilities. Another most widely used distributed sensing technique is based on measurement of propagation time delays of light traveling in the fiber based on the measurand–induced change in the transmission light. An optical time domain reflectometer (OTDR) is used for this purpose (Tateda and Horiguchi, 1989; Dakin, 1990). A pulsed light signal is transmitted into one end of the fiber, and light signals reflected from a number of partial reflectors along the fiber length are recovered from the same fiber end. By using this concept, it is possible to determine the location of the strain fields by the two–way propagation time delay and measurement of the reflected time signals (see Fig. 4.12).

More recent developments in distributed sensing involve interferometric system (Zhao and Farhad, 2001), which was developed for specific applications in civil structural monitoring. A typical schematic diagram of a white light distributed sensing system is shown in Fig. 18.10. The system consists of two parts: the sensing interferometer module, and the receiving unit. The sensing module is comprised of a number of individual single mode fibers of desired gauge lengths. The individual fibers are mechanically connected through ferrules and a portion of beam is reflected when the light wave passes through them. The receiving unit consists of a Michaelson white light interferometer with a scanning translation stage, signal processing and the system control unit.

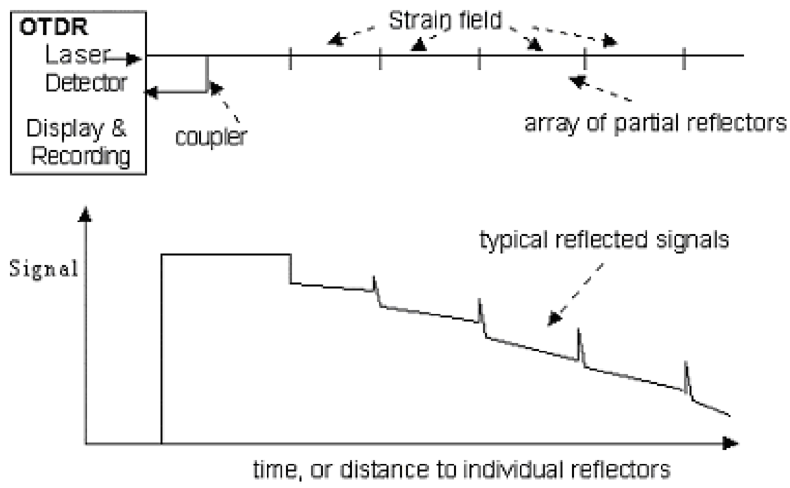


Fig. 4.12 Distributed sensing through an optical–fiber time–domain reflectometer (Ansari, 1997)

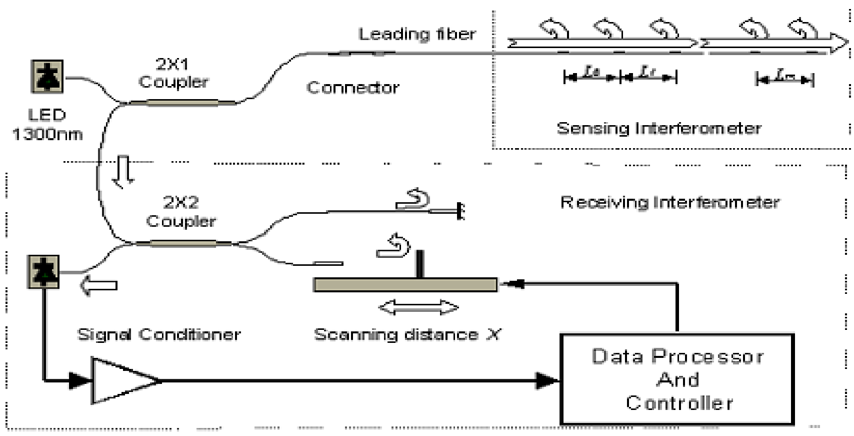


Fig. 4.13 Schematics of the interferometric distributed sensor (Zhao and Ansari, 2001)

Distributed or long gauge FOSs directly measure the displacement, elongation, or contraction of an object. Long gauge structural sensors can provide integrated strain measurements that are not susceptible to the high local strains associated with crack forming in concrete. The long gauge sensing system is highly versatile, and can be configured to gauge lengths from as small as 5 cm to 100 m.

Since the Long gauge sensor is a flexible optical fiber, 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.

There are several systems available on the market, e.g. fiber bragg gratings or brillouin technology. A review of these systems by different manufacturers is in Part 2 of this report.

4.5.6 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.

Multiplexed sensors are usually constructed by combining a number of individual sensors for measurement of perturbations over a large structure. The technique of wavelength division multiplexing by using Bragg grating makes this possible (Kersey and Morey, 1993). In this technique, a broad–band light containing a number of wavelengths within a certain region of the spectrum is employed for scanning a series of Bragg grating type sensors. The reflectance wavelength of each Bragg grating is slightly different from the others. The wavelength shifts of individual sensors are recognized, detected, and then related to the magnitude of strain at specific sensor locations (see Fig. 4.14).

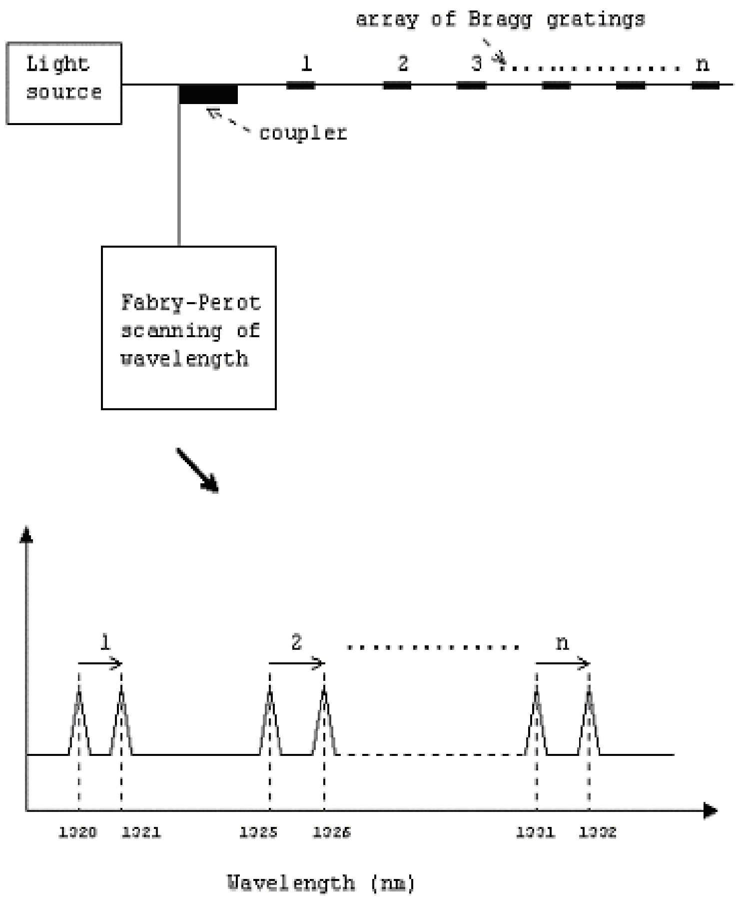


Fig. 4.14 Multiplexed Bragg grating sensor array (Ansari, 1997)

Sensor multiplexing schemes are classified according to their physical geometry. When several sensors are distributed along a single optical fiber, they are called *serial multiplexed*, while sensors on separate fibers are called *parallel multiplexed*. A sensor network may include a combination of serial and parallel multiplexing with multiple fibers, each serving as host to more than one sensor (Tennyson 2001).

5 STATIC FIELD TESTING

Since field testing of bridges is an critical part of a complete SHM program, this and the following sections devote to bridge field-testing. In a broad sense, bridge tests are either static or dynamic which indicates how the structure is excited (static load, dynamic load, or ambient vibrations) to obtain its response.

Static field testing is commonly used to determine the load carrying capacity of a structure, and to provide data about a structure's behavior and ability to sustain live loads. 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. Static testing is easy to perform and able to examine structural behavior and health, although the tests do not capture the full load response actually experienced by most structures, particularly for the case of bridges where moving loads excite the dynamic response of the structure.

Based on ISIS Canada Design Manual (Mufti, 2001), there are three basic types of static load tests: *behavior*, *diagnostic*, and *proof*.

Behavior Tests
The aim of a behavior test is to study the mechanics of a structure's behavior 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 behavior 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 behavior 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 behavior 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 behavior 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.

6 DYNAMIC FIELD TESTING

6.1 Introduction

Every structure has its own typical dynamic behavior, known as the 'vibration signature'. Vibration, i.e. the periodic to-and-fro motion of a structure of its members is characterized by three basic parameters : how quickly the motion is repeated (frequency), the magnitude of the motion is (amplitude), and how soon it dies out without new supply of excitation energy (damping). Changes in a structure, such as damage and deterioration leading to decrease in the load-carrying capacity, affect the dynamic response of it. Subsequently, the measurement and monitoring of dynamic response characteristics can be used to evaluate structural integrity.

Dynamic field testing is most applicable to bridges since bridge structures are generally subjected to moving traffic loads. To perform a dynamic testing, the bridge needs first to be excited by operational conditions or artificial vibrations. One of the following methods are usually used: 1) moving traffic (ambient vibration); 2) controlled moving truck loads; or 3) forced vibration using impact hammer or shakers. Dynamic response (acceleration or velocity versus time) of the bridge can be acquired by instrumentation of the structure with various sensors. Data and information from the monitoring sensors are accumulated and integrated for analysis, interpretation and decision-making (Patjawit, 2005). In general, tests with forced vibration are conducted on smaller bridges. For larger truss, suspension and cable-stayed bridges, ambient tests become the only practical means of exciting the structure. In a typical dynamic field testing using a moving controlled vehicle, a *test truck* 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. (Jinka) Many studies in the past have shown that vibration measurement can be effectively used to study the structural integrity of the structures (Burgueno et al., 2001; Salawu and Williams, 1995).

This chapter provides a general review of the current knowledge of bridge dynamic testing for SHM, including the different types of dynamic field testing, data acquisition and data analysis. The current technologies used to perform a dynamic testing will be reviewed in Section xx of Part II in this report.

6.2 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 data acquisition system 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 analyzed 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. (Tennyson 2006)

6.3 Vibration-Based Testing (Modal Testing and Modal Analysis)

The purpose of a vibration test is to identify the dynamic characteristics of a bridge by measuring its response to dynamic forces caused by operational conditions or, man-made vibrations. 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 this information 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 (Tennyson 2006).

6.3.1 Ambient vibration

Bridges vibrate continuously under traffic, wind, wave motion and also under seismic excitations. All these excitation sources are commonly referred to as ambient. Bridge response can be acquired due to ambient excitation and processed to obtain frequencies and mode shapes. Typically, the input is not, or cannot be, measured during dynamic tests that utilize ambient excitation. For larger bridges ambient excitation is the only practical means of exciting the structure as the ability to input significant energy into the structure, particularly at higher frequencies. Ambient excitation is also used with smaller bridges when other constraints prevent the bridge from being taken out of service during the tests. The use of ambient vibration often provides a means of evaluating the response of the structure to the actual vibration environment of interest. A drawback of using ambient excitation is that this type of input is often non-stationary. Also, because the input is not measured it is not known if this excitation source provides input at the frequencies of interest or how uniform the input is over a particular frequency range.

In practice, either controlled test vehicles or moving traffic loadings can be used to excite the structure. The general procedure consists of measuring vibration data (for example using accelerometer to measure the acceleration) and study the dynamic response of the structure.

Depending on the coupling between torsional and lateral modes, traffic excitation has the limitation that it may not sufficiently excite the lateral modes of a bridge and these modes are often of interest, particularly in seismic studies.

6.3.2 Forced vibration test

Impact excitation
The excitation in a forced vibration test can be induced by using an instrumented sledge hammer or an instrumented drop weight hammer. This is especially appropriate for tests of smaller bridge structures. This type of excitation offers the advantage of quick setup time, mobility, and the ability to excite a broad range of frequencies. Precautions must be taken to avoid multiple impacts. In general, impact excitation is not practical for excitation of a bridge’s lateral modes. Many variations of impact testing have been applied to bridge structures (Farrar, etc 1999).

Shaker excitation
Eccentric mass shaker, electro-dynamic shaker, servo-hydraulic linear inertia shaker are also used as excitation sources in forced vibration testing of bridges. Shakers offer the advantage of being able to vary the input waveform. Typically, harmonic, random or swept-sine signals are generated with a shaker. Electrodynamic shakers have difficulty producing lower frequency excitations and are limited in the force

levels that can be generated. Servo-hydraulic shakers can provide higher force levels, but have difficulties producing excitations at frequencies above 100 Hz. In practice, eccentric mass shakers have rarely been used to apply loads in the vertical direction. All types of shakers have a considerable amount of infrastructure that is needed for their operation such as power supplies, control hardware and cooling systems. The disadvantage of this excitation approach is (a) high cost of excitation equipment, (b) inconvenience of moving this equipment from structure to structure, and (c) interference of the structure with normal function of the structure.

6.3.3 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.

6.4 Experimental Modal Analysis

The current condition assessment of an existing structure by vibration testing is actually a modal testing in terms of not only the natural frequencies, damping and mode shapes, but also the flexibility directly derived from the unit-normal modal vectors. In modal analysis, the dynamic characteristics (modal parameters) of a structure are estimated through vibration measurements. Although having being well used in advanced mechanical and aerospace engineering disciplines where modal parameter identification was based on both input and output measurements, vibration measurement of civil engineering structures is only being developed recently since these structures usually have a completely different scale, logistics and rationale, and are often complex, large in size and low in frequency. Doebling et al (1998) and Carden and Fanning (2004) presented an extensive survey of damage detection methods that use changes in modal properties (i.e. natural frequencies, modal damping factors and mode shapes).

Most of the literature focused on laboratory structures or controlled damage to field structures. The different damage identification techniques were categorized and listed in (Table 6.1 (Karbhari 2009))

Table 6.3 Summary of damage detection categories and methods

Features		Methodology
Modal parameters	Natural frequencies	• Frequency changes • Residual force optimization
	Mode shapes	• Mode shape changes • Modal strain energy • Mode shape derivatives
Matrix methods	Stiffness-based	• Optimization techniques • Model updating
	Flexibility-based	• Dynamically measured flexibility

Machine learning	Genetic algorithm	• Stiffness parameter optimization • Minimization of the object function
	Artificial neural network	• Back propagation network training • Time delay neural network • Neural network systems identification

In this report, only the methods which are recently used in global bridge monitoring of in-service bridge are discussed, with particular emphasis on modal parameters and stiffness changes. Readers interested in the state-of-the-art of these methods are referred to Doebling et al (1998) and Carden and Fanning (2004).

If an ambient vibration is carried out under operational conditions, the input forces or excitations are extremely difficult to quantify, and only the output data can be measured. A modal parameter identification procedure will therefore need to base itself on output-only measurements. The operational modal analysis, or output-only modal analysis, has several advantages. It is inexpensive since no equipment is needed to excite the structures. The service state of the structure does not have to be interrupted in order to use this technique. A knowledge of the loading is not necessary, and more realistic boundary and loading conditions prevail (Yu and Ren 2005).

Based on Yu and Ren (2005), among the several modal parameter identification techniques, the stochastic subspace identification (SSI) algorithm is probably the most advanced method known to date for extracting structural vibration characteristics from operational vibration measurements. The procedure identifies the state space matrices based on the measurements, and by using robust numerical techniques such as QR-factorization, singular value decomposition (SVD) and least squares. QR-factorization results in a significant data reduction, whereas SVD is used to reject the noise. SSI has been successfully applied by the authors to a half-through concrete-filled steel tubular arch bridge of 90m in span to effectively identify the dynamic characteristics of the full-size bridge under operational conditions.

The stochastic subspace identification (SSI) algorithm is an advanced technique for performing such an operational modal analysis. Yu and Ren (2005) developed empirical mode decomposition (EMD), a newly signal processing technique, to deal with non-stationary signals. The output-only measurements are first decomposed into modal response functions by means of the EMD techniques, on the basis of specified intermittency frequencies. The stochastic subspace identification method is then applied to the decomposed signals to yield the modal parameters. The applicability of this technique was illustrated by a case study of the operational measurements from a real bridge. It is demonstrated that the stable pole in the stabilization diagrams becomes unique and the vibration characteristics are easily identified for the decomposed signals, bypassing the influence of other modal components and fake frequencies due to unwanted noise.

Yan and Golinval (2005) presented a damage diagnosis technique based on changes in dynamically measured flexibility and stiffness of structures. The objective is not only to detect the existence of damage, but also to locate it. The covariance-driven subspace identification technique is applied to identify structural modal parameters, and these are then used to assemble the flexibility matrix of dimensions corresponding to the measured degrees of freedom. The corresponding stiffness matrix is obtained by a pseudo-inversion of the flexibility matrix. Damage localization is achieved by a combined assessment of changes in these two measured matrices in moving from the reference state to the damaged state. Since the location of damage is given directly by the position of sensors, no geometrical measurements and finite element models are needed. When using output-only measurement data, an approximate mass-normalization of the mode shapes is adopted and an appropriate correction procedure is proposed.

Numerical and experimental applications to a simple three-span bridge are considered, in order to examine the efficiency and limitations of the presented method.

An evaluation of the mode shapes should indicate any discernable changes due to damage, but not all the time. Since the information obtained from the modal tests, i.e., frequencies, damping and mode shapes, could nor reliably identify the location and level of damage in the structure, additional derivative indices were needed. The modal flexibility and deflected shapes of the bridge obtained by loading the modal flexibility by various load patterns was discovered as damage-sensitive indices.

Toksoy and Aktan (1993) proposed a global health-evaluation/condition-assessment method to evaluate the global state of health by modal flexibility directly obtained by processing modal test data, complemented by structural identification. The flexibility matrix is a signature of the structure in a form that conveniently lends itself to visual and quantitative analysis. The mass-normalized modal vectors that are obtained from a modal test can be directly transformed into respective contributions to flexibility. A nominal finite-element model of the bridge was calibrated in the modal space using the results of the first modal test (of the undamaged structure) to provide a suitable analytical baseline for damage detection. The method is proven and implemented to a three-span reinforced concrete highway bridge with impact tests.

Patjawit and Nukulchai (2005) proposed to the global flexibility index (GFI) for inferring the health deterioration of highway bridges. This index is the spectral norm of the modal flexibility matrix obtained in association with selected reference points sensitive to the deformation of the bridge structure. The modal flexibility matrix can be evaluated from the dynamic responses at these reference points under forced vibration. A sharp increase in the index calls for further detailed investigation for appropriate actions. The sensitivity of the proposed index against different levels of controlled damages was first tested in laboratory on the tested structure, and then demonstrated by a field test on an existing highway bridge.

In spite of the widespread interests and efforts in condition assessment and NDE of bridges, a quantitative technique for evaluating the global health of a structure has not been available. Most methods require specialized research personnel (Mufti 2001). Unless a bridge structure is completely and accurately characterized, it is questioned whether it would be possible to accomplish effective and reliable NDE or health monitoring.

Research is needed to explore practical intermittent tests that will permit monitoring changes in some selected critical flexibility parameters as well as derivative indices following an initial implementation of the NDE method. Once problems related to long-term sensor and adapt-acquisition reliability under field conditions are resolved, it would also be possible to explore continuous health-monitoring schemes.

6.5 Emerging Technology

Literature surveying shows vibration-based testing can provide some information as to the testing techniques required for a full scale multi-degree of freedom structure. However, much of the system identification research has taken place on models (Lin 1985, Kobayashi, et al. 1997). For damage assessment and structural integrity analysis through system identification to be accepted by practicing engineers, there must be more studies performed on the feasibility, practicality and validity of applying these principles to full scale structures.

Ultimately it is anticipated that system identification might be implemented as a routine damage detection method. Bridges within the state would be tested and their dynamic characteristics logged in a database with subsequent tests performed every few years or immediately after a catastrophic event so that the condition of these bridges might be assessed based on the changes in their dynamic characteristics.

In a bridge maintenance program, the GFI of a bridge can be monitored to see the trend of its structural health deterioration. In Patjawit and Nukulchai (2005)'s study, the change in the GFI has been shown to be sufficiently sensitive to the global weakening of the structure, caused by deteriorations. It is recommended that the present impact test be implemented as a routine maintenance for major highway bridges in Thailand under the Department of Highway. This regular monitoring of any bridge will provide an advanced warning for any sharp decay in its GFI, which is directly related to the global weakening of the bridge.

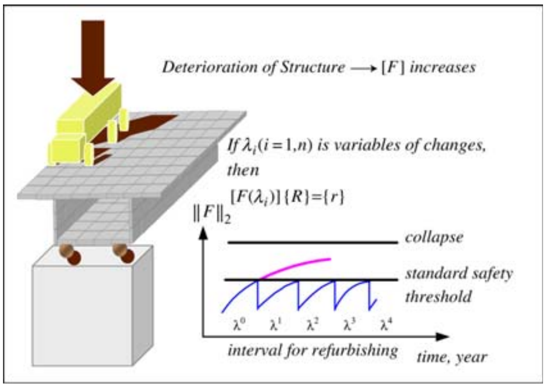


Fig. 6.1 Schematic bridge maintenance

In practice, a monitoring program can be set in such a way that when the GFI increases beyond a standard safety threshold, a major investigation will be conducted to strengthen the bridge, and thus restore the safety margin of the bridge. The maintenance program is demonstrated in Fig. xx. This program will ensure that the bridge will never fall into a state beyond repair and become unsafe to the public.

6.6 Summary

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, including

- Better use of the nonlinear response characteristics of the damaged system,
- Development of methods to optimally define the number and location of the sensors,
- Identification of the features sensitive to small damage levels,
- The ability to discriminate changes in features cause by damage from those caused by changing environmental and/or test conditions,
- The development of statistical methods to discriminate features from undamaged and damaged structures,
- Performance of comparative studies of different damage-detection methods applied to common datasets (or benchmark problems), and
- many others

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 (Bisby 2006). 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 behavior. 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.

7 DESIGN OF SHM SYSTEM

In order to design and establish a SHM system, it is imperative to identify the needs, requirements, expectations and constraints of the project at first. The expected outcomes of monitoring may include (Catbas 2010):

- providing answers to specific questions such as load rating;
- addressing uncertainties related to construction processes, structural behavior or performance;
- evaluating the effectiveness of maintenance or modification activities;
- providing an objective assessment of present or future conditions;
- detecting damage or deterioration for optimal maintenance planning;
- evaluating the effects of hazardous events or accidents;
- tracking operational parameters and providing statistics; or
- addressing security concerns.

Once the overall objectives and expectations are established, the following critical issues need to be considered.

Structural characterization
This is about the information of the current status of the structure (e.g. past inspections, details regarding any significant maintenance activities or modifications to the structure, and the findings of any intermediate studies or investigations that may have been conducted); and numerical modeling and analysis of the structure to simulate the loading effects and the structural response.

Measurement needs
This may include the loading effects and the associated structural responses, serviceability criteria, fabrication/construction activities, environmental parameters and operational characteristics that need to be monitored to meet the project objectives. The parameters to be measured can be forces, stresses, strain, displacements (linear and rotations) and movements, acceleration, environmental parameters (such as temperature, humidity, precipitation), wind speed and direction, traffic quantities, images, etc. Some parameters are static in nature while others dynamic.

Types of testing and monitoring
Based on the identified measurement parameters, static or dynamic, or both may be necessary in a complete SHM system to obtain data for structural health assessment. The monitoring application also involves estimating the type, level, and duration of monitoring that is necessary to meet the identified objectives – periodic monitoring or continuous monitoring.

Selection and installation of sensors and systems
Identification and/or development of sensors and other instruments and software; installation and placement, power supply, wired or wireless data communication tools, durability and reliability of the system; the testing and calibration of the system

Data collection and management
Data quality assurance and data validity, data processing and analysis, data storage and retrieval;

Dissemination of performance results / public awareness
Periodic reports, alerts and warning

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 (Tennyson 2006):

- Identify the damage or deterioration mechanisms that are of concern for the structure.
- 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.
- 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.
- 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.
- 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.
- Install the system and calibrate with baseline readings.
- 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.

8 The FUTURE OF STRUCTURAL HEALTH MONITORING

As has been demonstrated through the information presented in the previous sections, SHM offers an enormous range of options to engineers who are interested in characterizing the short and long-term behavior 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. In particular, two interesting emerging technologies are worthy of note: *smart structures* and *live structures*.

SMART Structures
(Choo 2009 thesis) The term "*smart structure*" has been increasingly used in the bridge SHM communication. Literature review has yielded various definitions of "*smart structures"*. Simply "*smart structures"* was defined as structures incorporated with sensors in some of the most advanced building materials (Tennyson 2000) or structures integrated sensing system (Measures 2001). A detailed definition by Phares et al. (2005) is given as:

A "Smart" technology is one in which the system systematically reports on the condition of the structure by automatically making engineering-based judgments, records a history of past patterns and intensities, and provides early warning for excessive conditions or for impending failure without requiring human intervention. These features make the system capable of providing and facilitating self-diagnostic, real-time continuous sensing, advanced remote sensing, self-organizing, self-identification, or self-adaptation (decision making and alarm triggering) functions. Further, the user is not burdened with demanding operational and maintenance tasks.

Phares *et al. (*2005) further elaborated that these features make the system capable of providing and facilitating self-diagnostic, real-time continuous sensing, advanced remote sensing, self-organizing, self-identification, or self adaption (decision making and alarm triggering) functions. The user is also not burdened with demanding operational and maintenance tasks.

"Smart structures" can thus be simply summarized as structures that are instrumented with SHM system that proactively report the structural condition and warn the users upon the detected damage and deterioration within the structures.

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.

9 SUMMARY AND CONCLUSION

Some basic definitions about SHM, components of SHM, application scenarios, critical considerations in integrating and leveraging experimental, analytical and information technologies for SHM data analysis and interpretation are discussed in the first part of this report. It is possible to see more and routine SHM applications in civil infrastructure due to the new advances in sensing, communication and information technologies, and the efforts of researchers and industry to develop new products and systems for specific monitoring needs.

It is seen that sensing and data acquisition technologies have advanced and are advancing significantly such that the limits of sensing are fast disappearing. A critical issue is to effectively use Internet architectural standards and associated networking protocols and technologies that offer data integration, communication, real-time visualization and archival over large distances and very long time durations such as decades. The principal challenges that remain mainly related to data analysis, timely and effectively interpretation, and information management.

10 STRAIN SENSORS

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 behavior 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 foil strain gauges, *vibrating wire strain gauges*, or more recently developed fiber optic sensors. Please refer to Chapter 4 for the basic knowledge of these strain gages.

Strain gauge is usually attached to the object by a suitable adhesive. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain. The installation of a strain gage to a specimen by adhesive mounting is probably the most critical step in the strain measurement. An improper installation may seriously degrade or even completely mess up the validity of a test. Since mounting installation is often cumbersome, certain types of strain gages can be welded on the surface of the structure.

For example, Hitec Products, Inc. (HPI) manufactures and supplies weldable and bondable strain gages which are precision foil strain gages bonded to stainless steel shim, pre-wired and waterproofed. All gages can be built to custom specifications using a variety of configurations and materials. They can be simply installed in the field by using standard epoxies (where welding is not suggested or permitted) or spot welding. For example, the HPI weldable gages have been installed at mid span on each of eight girders of a single span highway bridge on a major truck route to compile data on the frequency and magnitude of truck overloads. Lead wires were brought out through conduit to an instrumentation van parked at the end of the bridge. Typical data taken on a x-y plotter is shown in diagram at right (Fig. 10.1). Similar projects have been performed by other state DOT.

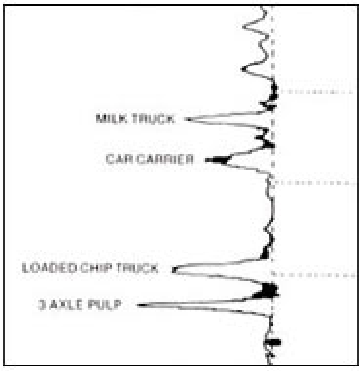


Fig. 10.1 Strain history showing truck load
(http://www.hitecprod.com/Html%20Pages/bridges.html)

There are many strain gage manufacturers and providers in the market. Some of them and their products will be discussed in the following sections of this report along with other products they offer which can be used in a structural health monitoring system.

11 DISPLACEMENT SENSORS

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*. Displacement sensors measure the distance an object moves and they can also be used to measure dimension and deformation, as well as profile and position of an object. There usually are two types of displacement sensors: contact type, utilizing a dial gage, differential transformer, etc., and non-contact types, utilizing a magnetic field, laser beam, ultra-sonic wave, etc. This section focuses mainly on non-contact sensors capable of fast response measurement.

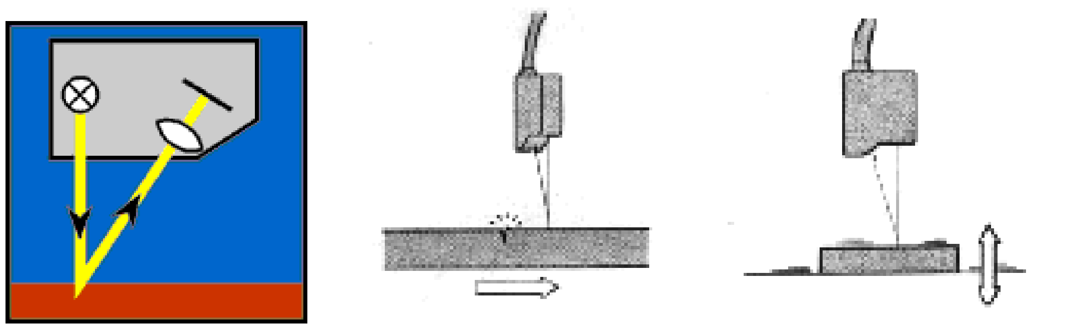
The most commonly used contact-type displacement instrument is LVDT (linear variable differential transformer). LVDT is a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal. LVDT linear position sensors are readily available that can measure movements as small as a few millionths of an inch up to several inches, but are also capable of measuring positions up to ±20 inches (±0.5 m).

Non contact measurements are rapidly replacing the traditional contact methods for two very important reasons, first they make objective measurements since they are not operator dependent and secondly, they do not mar the surface to be measured and can measure objects which are uneasy to access.

11.1 Laser based displacement sensors

Laser theory

Laser distance sensors use high speed non-contact laser gages to measure products in terms of diameter, thickness, width/length, geometric profile, and movement, etc. Laser shines onto surface of material which reflects to receiver. Location of reflected beam allows calculation of reflection angle and consequently distance can be calculated (Fig. 11.1).



(a) Laser operation (b) Flaw Detection (c) Displacement/Vibration Amplitude

Fig. 11.1 Laser-based displacement transducers

For example, Acuity Research Inc. provides laser displacement sensors and laser rangefinder for long-distance sensing. Its AR200 displacement sensor is capable of measuring from 0.24 inches (6mm) to 1.97 inches (50mm) with up to 12 micron accuracy. The laser distance sensors vary in measuring range from 30 meters to 300 meters. Using a reflective target board, the sensors will measure 5 to 10 times longer distances. The sensors can hold up to very tough environments and have been used by worldwide customers in forest products, metal working, medical and heavy industrial applications (bridge related monitoring project not available).

11.2 Vibrating Wire (VW) Based Displacement Sensors

The resonant frequency of vibration of a tensioned steel wire is dependent on the strain or tension in the wire. This fundamental dependency is utilized in a variety of configurations to make sensors for the measurement of strain, load, force, pressure, temperature, and tilt.

The advantage of vibrating wire sensors over more conventional types lies mainly in the sensor output, which is a frequency rather than a voltage. Frequencies can be transmitted over long (>2000 m) cables without appreciable degradation of the signal caused by variations in cable resistance, which can arise from water penetration, temperature fluctuations, contact resistance or leakage to ground. This factor, coupled with the elegance and ruggedness designs results in sensors which exhibit excellent long-term stability and which are ideally suited for long-term measurements in adverse environments of structural, hydrological, and geotechnical applications.

11.2.1 VW sensors by Geo-Instruments

Geo-Instruments manufactures and supplies vibrating wire sensors and systems in assisting geotechnical and civil engineers to monitor movement, pressure, vibration and other environmental changes in structures and in the earth. Their sensor product line includes VW strain gage, extensometer, inclinometer, jointmeter/crackmeter, load cell and pressure cell, settlement cell, thermometer, tiltmeter, vibration recorder, and others (Fig. 11.2). Special angle brackets may be provided to allow configuration of three crackmeters in an X Y and Z orientation.

Fig. 11.2 Crackmeter unit shown with standard rebar anchors

Geo-Instruments produces a variety of unique data acquisition systems designed to collect data from remote and hard to access locations. The systems are available for short and long term use, and even permanent installations. The data can be collected and uploaded to many data processing applications. Its ARGUS program uploads data to a website for clients to access instantly and conveniently from anywhere with an Internet connection. ARGUS Monitoring Software is also highly customizable in that it can create graphs, generate reports, and issue email alerts if a sensor's value exceeds a client's defined alarm threshold.

The applications of Geo-Instruments system to a variety of geotechnical and civil engineering projects are available at its website. The application temperature range is -25 to 50°C.

11.2.2 VW sensors by Geokon, Inc.

Geokon's complete line of geotechnical instruments include vibrating wire extensometers, piezometers, strain gages, crackmeters, jointmeters, load cells, settlement sensors, pressure cells, inclinometers and dataloggers suitable for monitoring the safety and stability of a variety of civil and mining structures including earth dams, concrete dams, tunnels, excavations, foundations, piles, mine openings, etc.

Geokon's single or multi-channel data loggers housed in a rugged, weather-resistant NEMA 4x aluminum enclosure are available for easy use with all types of vibrating wire sensors. Channels can be expanded with multiplexers. Windows based software allows the task of configuration, communication, monitoring, data collection, plus a real-time text-based monitor, graphical monitor and terminal emulator. Data is retrieved by telephone modem, via Internet/Ethernet, solid state storage module, radios, or satellite transmission. Internet-accessible data acquisition systems ensure that any significant change in the condition or behavior of the structure is logged, reported and efficiently monitored. Real-time, continuous monitoring with alarm triggering capability is available.

Geokon sensors have been used on bridge structures in many countries around the world for measuring key parameters such as strain, displacement, force, temperature, inclination, alignment and settlement. Sensors are installed permanently for long-term health monitoring, temporarily for load testing and/or to ensure safe working conditions during repair or strengthening. The following is one example of the many projects using Geokon sensors and monitoring system.

11.2.3 Point Marion Bridge, Pennsylvania, USA

A new bridge is being built 20 m south of the historic Point Marion Bridge (Fig. 11.3), which will be replaced due to its structural deficiencies.

Fig. 11.3 Point Marion Bridge

Fig. 11.4 data acquisition system

The soft nature of the surrounding foundation soils prompted a geotechnical / structural instrumentation program to monitor the impact of new bridge construction on the aging structure. Automated measurements were taken of 19 vibrating wire piezometers to monitor water pressures in the foundation soils on both sides of the river. In addition, a vibrating wire piezometer was used to record river water levels, and two vibrating wire strain gages were used to monitor the old bridge. Manual measurements were taken of tilt plates, settlement pins (placed in the fill) and inclinometers installed in the foundation soils.

Data were automatically collected and imported into a MultiLoggerDB database on an hourly basis (Fig. 11.4). MLWeb software was then used to provide the construction contractor and owner with access to data via the Internet (Fig. 11.5). Most of the Geokon sensors and dataloggers can be used at a temperature of at least -20°C to 80°C.

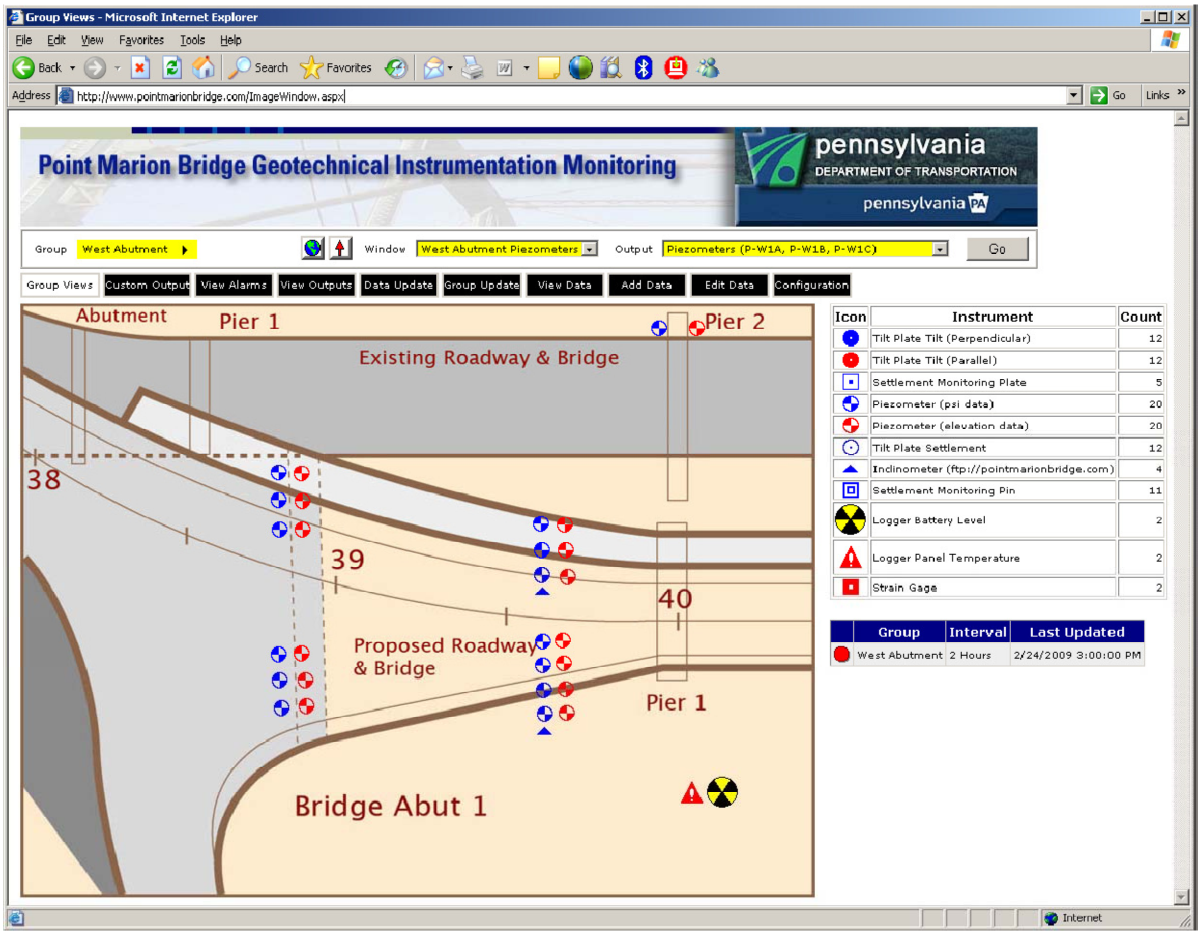


Fig. 11.5 Data access through internet

11.3 Fiber Optic Based Displacement Sensors

Please see the Chapter 13 fiber optic sensing technology.

11.4 Sensors Based on Other Technologies

11.4.1 Bridge Diagnostics, Inc. (BDI)

BDI Structural Monitoring System (BDI-SMS) is designed for tracking structural movement or degradation for short or over long periods of time. BDI sensors include

- strain sensors (BDI strain transducers, vibrating wire (VW) sensors and rugged and reusable Wheatstone bridge completion units) for live load testing or long-term monitoring, including embedded gages for new concrete;
- a range of displacement sensors (BDI LVDTs and potentiometer displacement sensors) for measuring live-load (dynamic) responses or VW crackmeters for long-term monitoring;
- ruggedized accelerometers designed for field use in tough environmental conditions;
- various tiltmeters for measuring live load or long term rotations. Several ranges available;
- wireless position indicator for tracking truck, locomotive, lift gate height, and other moving loads;
- thermistor temperature sensors can be used for ambient or internal temperatures when embedded in concrete; and
- all types of dynamic or long-term load cells in all ranges.
- transducers for measuring water and hydraulic pressures.

BDI sensors can be attached with adhesive for short-term or permanently mounted with anchor bolts or welding for long-term monitoring (Fig. 11.6).

(a) Monitor rotation in piers (b) Monitor displacement in critical locations

Fig. 11.6 BDI sensors

BDI offers the following data acquisition systems:

- The BDI offers Wireless Structural Testing System (STS-WiFi), an efficient field evaluation system which can be implemented with a wide range of Intelliducer™ sensors including strain transducers, accelerometers, foil strain gages, LVDT's, and rotation monitors.
- BDI Dynamic Monitoring Systems are designed to capture and record high-speed structural responses due to moving loads such as large trucks or wind loads. They can automatically trigger system to record when load is detected, record strain & acceleration response histories, and store stress cycle counts using ASTM Rainflow algorithm.
- BDI also supplies various cable force measurement systems for determining tension loads in multiple cables simultaneously, allowing for very efficient force adjustment procedures.

BDI WinGRF software makes evaluating structural response data much faster and easier than using spreadsheets.

- Plot response histories as function of time & load position
- Calculate and display neutral axis locations
- Extract maximum and minimum values for each sensor
- Digitally filter data to reduce noise or unwanted frequencies
- Average multiple data files with common load application
- Analyze stress cycle data (rainflow histograms) for fatigue analyses

Most BDI monitoring systems can be configured with wireless communication capabilities. When coupled with its Live Monitoring Service, the customer can log in on-line with their username and password and review data from any PC. The stored data and photographs can be remotely downloaded and viewed online from any PC using our Live Monitoring Service

All hardware is rugged and has been field-proven to be reliable, even in harsh conditions.

11.4.2 Penny & Giles

Penny & Giles uses potentiometric and inductive technologies (Eddy current and Hall effect) and manufactures sensors packaged in rugged housings for linear and rotation displacement measurement. A wide range of linear position sensors, linear displacement transducers and linear potentiometers offer stroke length measurements from 0.2" (5mm) to 196" (5000mm). The rotation displacement sensors offer angle measurements from 10° to 360°.

A variety of mounting options are available that give the user the flexibility for installation: self-aligning bearings, body clamp kits and flange mounting kits; additional protective kits can be used for harsh environment.

11.4.3 3DeMoN by SMARTEC

The 3DeMoN (3-Dimentional Deformation Monitoring Network) monitoring system integrates conventional measurement techniques and sensors (e.g. GPS receivers, Laser distance meters, Thermal Imaging Infrared Camera, etc.) with lowest power semiconductors. Combined with solar power supply, wireless communication, advanced database systems and Internet, 3DeMoN is a remote monitoring platform with the aim of providing a unified management and view of remote monitoring data (Manetti & Steinmann 2007).

The 3DeMoN system is an autonomous and automatic monitoring system consisting of a number of Monitoring Stations and a Central Server Station (CSS). The Monitoring Stations are distributed on the object to be monitored (e.g. a bridge) and connected to one or more digital (e.g. GPS receivers or laser distance meters) or analogue sensors (e.g. inclinometers, load cells, etc.) A monitoring Station consists of a weatherproof box containing the electronic components for the management of the sensors, the data transmission and the power supply modules. The Monitoring Stations communicate with the Central Server Station through a wired connection (RS-232/485, fiber optic) or though a wireless connection (GSM/GPRS/EDGE, radio modem). The Central Server Station provides for data collection, data storage, management of the configuration of the Monitoring Stations, automatic data processing (e.g. automating batch postprocessing of GPS data) and monitoring of the correct operation of the network.

3DeMoN Robotic Laser ROBOVEC is a measuring system based on a laser distance meter and a bi-axial modular robotization for horizontal and vertical movements (Fig. 11.7). The ROBOVEC unit has been designed for (semi-)permanent installation in structural or geotechnical monitoring projects requiring a continuous monitoring of the 3-dimensional displacements of significant points under harsh environmental conditions. The ROBOVEC allows measuring distance, horizontal and vertical angles, temperature and reflected signal strength for an unidentified number of points. This information can be used to determine the variation of the positions of the monitored points on a bridge structure.

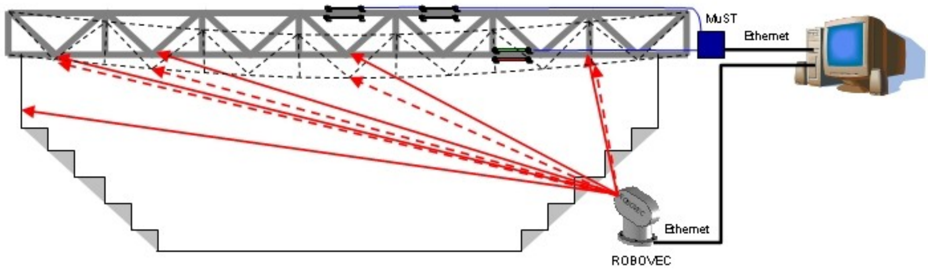


Fig. 11.7 Schematic view of the s ROBOVEC system components

The 3DeMoN system has been implemented to a number of bridge monitoring projects (http://www.roctest-group.com/references/byproduct). It could be used to environment with a temperature range of -30°C to 70°C.

11.4.4 Omega Engineering Inc.:

Omega Engineering offers a variety of sensors and data acquisition system (various sensors and electronics, instruments supplier), including displacement measuring and monitoring system. Please see Chapter 16 for more details for Omega displacement meters/sensors.

11.4.5 Inclinometers by Rieker Inc.:

Rieker provides a complete line of inclinometer and accelerometer sensors for tilt monitoring and slope measurement. Its inclinometer sensors are typically liquid capacity gravity based and used for vehicle tilt monitoring, slope measurement, process motion control, wheel alignment, vibration indication, and pitch & roll measurement for equipment, aircraft, and ships. Rieker also manufactures a versatile series of digital inclinometers with LCD display, analog, and RS232 outputs making it the most customizable angle monitoring and early warning tilt indication system. For example, its **SB2i** and **SB2G** are inclinometer packages providing dual axis inclination or acceleration measurement in an environmentally protected housing (-40°C to 85°C. IP65 Environmental Protection.). The sensing package incorporates a modular design allowing users to select the measurement range and sensor for each axis that suits the individual application.

11.5 Sensors for Geotechnical Monitoring

Monitoring the substructures of a bridge is often an important part of the bridge SHM program. This requires a wide range of important information coming from the sensors, which are of vital importance for evaluation of movement, pressure, vibration and other environmental changes in structures and in the earth.

11.5.1 Geo Instruments

Geo-Instruments include sensors and systems in assisting geotechnical and civil engineers for monitoring purpose. See Section 2.2 (VW based displacement sensors) for information about their sensors and products.

11.5.2 Applied Geomechanics Inc.

Applied Geomechanics provides automated tiltmeter monitoring of bridge and bridge components with electrolytic tiltmeters, clinometers and inclinometers. These meters include full signal conditioning electronics that produce stable output signals over a wide range of input voltages. The high-level voltage, current and serial outputs from data acquisition system are reliably delivered over long cables and wireless data links. Applied Geomechanics can continuously record relative movements of bridge components and can compare such movements to predetermined thresholds for warning (Fig. 11.8).

Case Study - Load Testing on Parrotts Ferry Bridge, Vallecito, California
Tiltmeters installed on this scenic, but sagging, concrete bridge in California's historic 49er Gold Country measured structural response to a series of load tests (Fig. 11.9). Project engineers rated the tiltmeter results "more accurate" than theodolite measurements that were also performed. The tiltmeters can record continuously, revealing the complete history of flexure during the loading/unloading cycle. The overall investigation, which also involved laboratory testing and computer modeling, established that the bridge superstructure's unusual profile is mainly due to creep of the lightweight concrete.

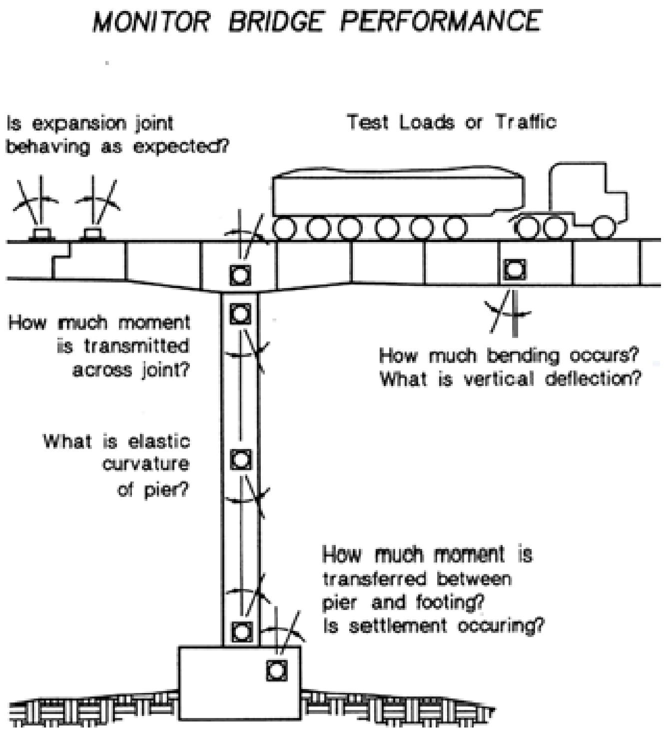
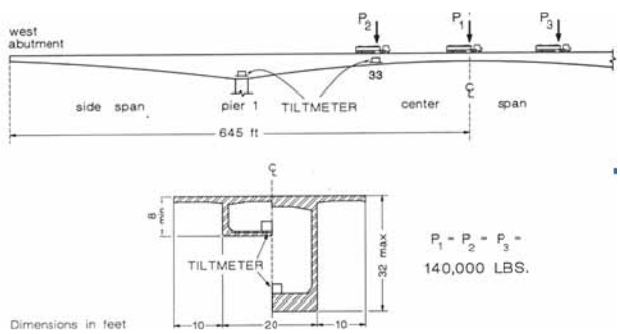
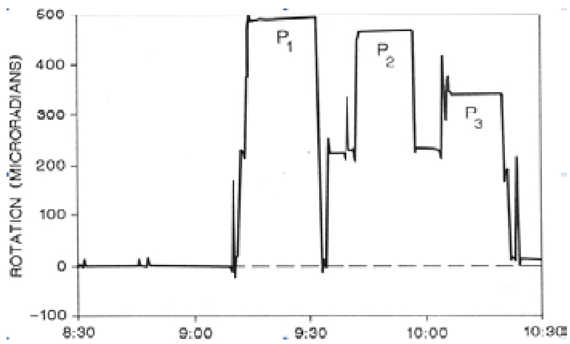


Fig. 11.8 Tiltmeters monitor bridge performance



(a) load testing



(b) Tiltmeter on joint 33

Fig. 11.9 Load testing (Parrott's Ferry Bridge)

11.5.3 Slope Indicator

Slope Indicator manufactures a full range of geotechnical and structural sensors for monitoring tilt, displacement, pressure, and strain. The company also supplies data acquisition systems and web-based monitoring software for automated processing and distribution of data. The sensors could be used for bridge monitoring include:

- Extensometers for monitoring settlement foundations and embankments, movements in rock slides, walls, and abutments;
- inclinometers for providing settlement profiles of embankments, foundations, and other structures;
- EL beam sensors for monitoring differential movement and rotation in structures (Fig. 11.10);
- Crack and jointmeters for monitoring movement at joints and cracks in concrete and rock;
- Weldable strain gauges for measuring strain in steel; Embedment strain gauges for strain in concrete;
- The tape extensometer for detecting and monitoring changes in the distance between two reference points;
- Tiltmeters for monitoring changes in the tilt of a structure.

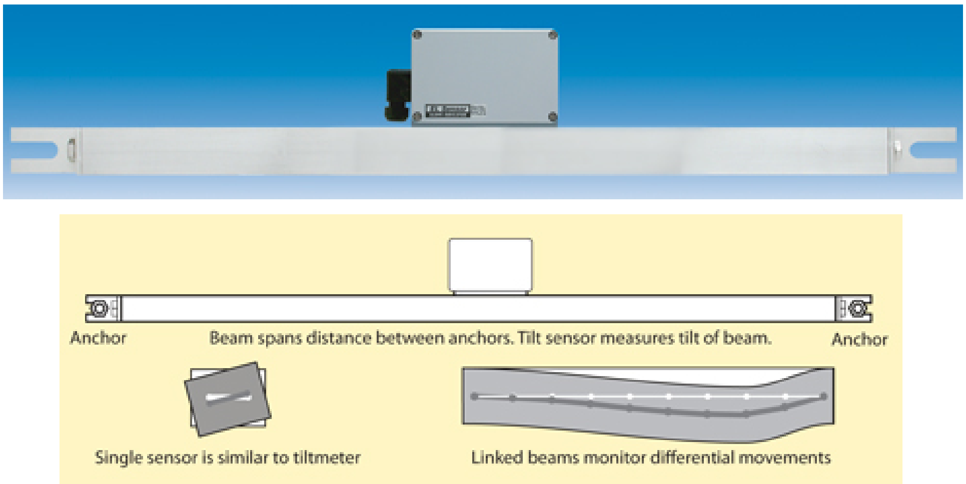


Fig. 11.10 Beam sensors to monitor differential movement and rotation

12 FORCE SENSORS

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 to convert measured load into an electrical signal or it can be inferred through strains or other parameters measured on selected structural components (Bisby 2006).

12.1 Load Applied Measurements, Ltd.

Applied Measurements offer a comprehensive range of load cell and force sensors with capacities ranging from 0-25 grams to 0-3000 tons to suit a huge range of applications, and also a select range of sensors for the measurement of displacement and position including LVDT, draw wire and strain gauge displacement. To support its load transducers, Applied Measurements provides a complete range of analogue and digital instrumentation offering the facility to indicate, display, amplify, condition, transmit, acquire, log and record data. Application temperature range is -30 to 85°C (-30 to 150°C optional upon request).

12.2 Load/Pressure Cells by Geo Instruments

Geoindicator load cells include:

GEO bonded strain gage load cell comprises a set of up to eight strain gage rosettes mounted parallel and perpendicular to the cell axis and equally spaced in a ring around the steel alloy cylindrical housing. This method of construction results in a very robust instrument suitable for use where high performance, longevity and mechanical strength are important. All load cells are manufactured with a center hole to accommodate rock-bolts, tendons or anchor cables. For use as a solid center cell the instrument can be supplied with top and bottom bearing and a heavy gauge multicore. PVC sheathed cable connects the load cell to the read-out unit. Bonded SG load cells are used on support of excavation applications, and provide an excellent choice when an intrinsically temperature corrected, robust waterproof load measurement in harsh environments is needed.

Vibrating Wire Load Cells are ideally suited for measuring loads in rock bolts, cable anchors and tendons, structural beams, piles, loads between tunnel supports and loads in pull-out tests on trial anchors. Vibrating Wire Load Cell consists of a high strength steel alloy cylindrical housing with three to six vibrating wire gauges for measuring the compression of the cylinder under load. The readings of all gauges are averaged thus minimizing the detrimental effects of eccentric or uneven loading. Furthermore the cells are fitted with thermistors for correcting the effects of temperature variations on load readings.

Strain Gauge Load Cells are ideally suited for measuring loads in rock bolts, cable anchors and tendons, structural beams, piles, loads between tunnel supports and loads in pull-out tests on trial anchors. The Strain Gauge Load Cell consists of a stainless steel cylindrical housing with up to sixteen resistance strain gauges to minimize the sensitivity to eccentric loading. When the cell is subjected to load the strain gauges will change their resistance value. The load cell output signal is directly proportional to the applied load.

The Vibrating Wire Push-In Pressure Cell is normally installed in vertical boreholes and measures total horizontal stresses. They are often installed in stiff clay behind and in front of retaining walls, in soft puddle clay cores of old embankment dams and in glacial till adjacent to sea cliffs. The cells can also be installed in horizontally drilled boreholes for example from tunnels and cliff faces. In these situations both horizontal and vertical stresses can be measured by the appropriate orientation of a number of cells. The cells may be used as a site investigation tool to measure the in situ stresses in the ground prior to any disturbance.

The Vibrating Wire Concrete Stress Cell is used for measuring total stresses in tunneling process, mass concreting and rock walls in underground works. The cell is installed either prior to shortcreting, concrete pour or within a slotted hole in the rock and incorporates a re-pressurization tube to enable the cell face to be placed into intimate contact with the concrete should shrinkage occur during hydration, or with the rock face to take account of the slight overslotting needed to fit the cell in rock (Fig. 12.1).

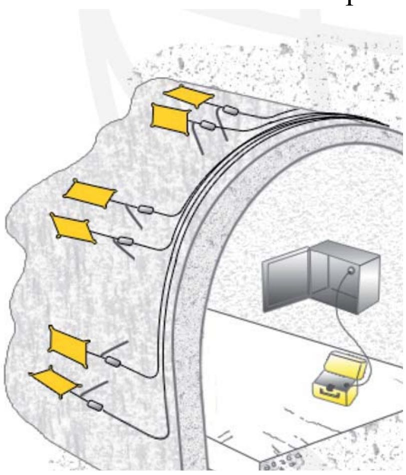


Fig. 12.1 Schematic Concrete Stress Cell

12.3 EM sensors for cable/strand force measurement

The magnetic properties are high sensitive to stress change in ferromagnetic materials. The magnetoelastic effect of ferromagnetic materials can be used to measure the force or stress without contact to the steel. Elasto-Magnetic (EM) stress sensors are thus developed to monitor stress and corrosion in steel during bridge health evaluations. EM sensor measures magnetic properties by subjecting the steel to pulsed or periodic magnetic field, which can be accomplished without any contact through two solenoids consisting a primary coil and a secondary coil. Changes in flux through circuits surrounding the steel allow the EM sensor to sense these magnetic properties.

Division Projstar Monitoring Group International offers products and technologies for determination of forces and tension in prestressed concrete components by using elastomagnetic (EM) sensors. Projstar, using its single coil, double coil, multistrand, or integrated multistrand sensors, offers a contact-free measurement method for force distribution in the pre- or post-stressed steel core both during their construction and throughout the entire lifetime. Projstar monitoring system can make temporary or continuous, manual/automatic stress or force measurement and time-dependant changes in stressed steel, wire, and cable after anchoring by direct connection or remote control via Internet. It has been used to a number of cable-stayed bridges worldwide. Application temperature range is -10 to 60°C.

12.4 Load cells by Strainstall Ltd.

Strainstall designs and manufactures a wide variety of load sells including tension load cells, compression load cells and a well-proven range of load shackles. Its products and systems are particular for harsh environments and hazardous areas.

12.5 Load cells by Transducer Techniques, Inc.

Transducer Techniques designs and manufactures a complete line of load cells, torque sensors, special purpose transducers and related signal conditioning instrumentation.

Transducer Techniques load cells are electro-mechanical transducers that translate force or weight into voltage. All transducer sensing elements utilize bonded foil strain gages wired in a full Wheatstone bridge configuration. Data acquisition systems and data logging software are available with load cell transducers.

12.6 Weigh-In-Motion System (WIMS) by OSMOS USA

OSMOS' WIMS uses optical extensometer and fiber optic strain sensors (up to 95% measurement accuracy at highway speeds). The high resolution extensometers can be placed vertically nearby the bearings to measure the dynamic deformations caused by the impact of crossing traffic (Fig. 12.2). This dynamic impact is typical according to the weight of the traffic. Therefore, this measurement is then used to weigh the traffic.

OSMOS monitoring station connected to the optical sensors collects and processes the signal to computerize the monitoring through its patented 'dashboard' displays. The entire system can be configured online to monitor real-time load data. Easy-to-read, color-coded load information is displayed graphically with the OSMOS Dashboard application. Automatic alerts and proactive notification that overload has occurred can be setup.

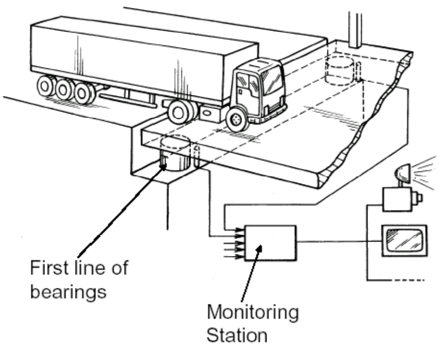


Fig. 12.2 Schematic view of OSMOS WIMS sensor adaptable to neoprene or steel bearings

Fig. 12.3 Optical extensometer as a WIMS

Rugged sensors (made of inert materials) can be permanently attached to the exterior of the bridge. OSMOS WIMS can record a moving load as it passes over a bridge automatically without the need to stop or slow down. No modification is necessary to the bridge structures, and the sensors can be installed without interrupting traffic (Fig. 12.3). A surveillance camera can be connected to the monitoring station to capture the images of each overweight vehicle. The on-site monitoring station can synchronize the sensors and video information and upload it to an offsite server for real-time data processing.

12.7 Osterberg-Cell (O-Cell) by LOADTEST, Inc.

Osterberg-Cell (O-Cell) method by LOADTEST is used for bi-directional deep foundation load testing which can be performed even in difficult locations. The O-Cell method improves safety at the job site since there are no loads, load beams, jacks or spherical seating overhead or above ground.

The O-cell is a hydraulically driven, high capacity, sacrificial loading device installed within the foundation unit. As the load is applied to the O-cell, it begins working in two directions; upward against upper side shear and downward against base resistance and lower side shear (if applicable). Single or multiple O-cells® can be arranged on multiple levels to isolate strata of interest. A zone of interest can be isolated within the 2 levels of O-cells and zone specific data can be retrieved from mobilizing this section. With horizontal Osterberg Cell assemblies cast into a shaft or pile, lateral testing of specific soil and rock formations can be performed.

Each Osterberg Cell is specially instrumented to allow for direct measurement of the expansion. Controller and data logger, site monitor and PC allow data processing and display by automatic data acquisition and real time plotting.

Fig. 12.4 O-Cell and reinforcing cage of an ACIP pile

LOADTEST has tested a variety of foundation elements (Fig. 12.4). Project profiles are available at its website.

12.8 Load rating by Bridge Diagnostics, Inc. (BDI)

The basic approach of BDI load rating and structural testing is very similar to that used in both standard highway and railroad bridge design codes, with only exception being that instead of relying on estimated distribution factors and assumed member behaviors, actual field data is used to develop an accurate analytical model of the structure for developing the rating factors. Since the model has been actively "calibrated" with field data, it represents the live load distribution behavior such as end-restraints that simply cannot be accurately assumed. This approach is suitable for structures that have a low load rating based on the standard methods and on structures that appear damaged. BDI uses the following general procedures to develop accurate load ratings for highway bridges (from http://dev.bridgetest.com/services/posted_bridges_services.html):

Obtain strain responses due to a known load

Continuous response histories are obtained by recording strains at many locations (minimum of 32) as a loaded truck is driven slowly across the bridge. A key aspect of this test is that the position of the vehicle is tracked and recorded as well.

Preliminary investigation of data

Information concerning the structural behavior can be determined directly from raw strain data such as the verification of linear behavior, the neutral axis locations for flexural members, and indications of possible moment resistance at beam supports.

Develop representative model

A realistic simulation of a bridge can be developed with simple finite element techniques. The actual geometry of the structure is represented, including span lengths, girder spacing, skew, transverse members, and deck characteristics.

Simulate load test on computer model

Use a two-dimensional model of the test vehicle and apply it to structure model at the same locations as those recorded during the field tests. Perform analysis and compute strains at each gage location for each truck position.

Compare measured and computed strain values

Systematically compare the results at all gage locations and truck positions. Various local and global error values are computed directly from the analysis program and visual comparisons are also made.

Improve the model based on data comparisons

Engineering judgment and experience is required to determine which variables are to be modified. General rules have been defined to simplify this operation. An automated process built into the analysis program is used to evaluate the adjustable parameters so as to obtain the best correlation.

Perform load rating on calibrated model

Use standard design, rating and permit loads. Rating factors are determined by an elastic structural analysis and the same rating equation specified by the AASHTO - Manual for the Condition Evaluation of Bridges is applied:

$$RF = \frac{C - A_1 D}{A_2 L(1 + I)}$$

Stress envelopes are generated for several truck paths, and envelopes for paths separated by normal lane widths are combined to determine multiple lane loading effects. The only difference between this rating technique and standard beam rating programs is that a more realistic model is used to determine the dead- and live-load effects. Two-dimensional loading is applied because wheel load distribution factors are not applicable to a planar model. The detection and evaluation of "unreliable stiffening effects" during the model identification process does not require that these factors be implemented in the rating process. This means that the final rating factors are still a function of the engineer’s judgment.

13 FIBER OPTIC SENSORS

Optical sensors provide an alternative to traditional electrical sensors for many applications, with high accuracy, long term stability, streamlined installation, and premium performance under harsh environmental conditions. Please refer Section xxx for the technology behind fiber optic sensing and the types of fiber optic sensors. This chapter reviews the current fiber optic sensor and SHM systems using these sensors on the current market.

13.1 Advanced Optics Solutions (AOS) GmbH:

Advanced Optics Solutions (AOS) offers both bare and assembled FBG sensors: strain gauges, FBG vibration sensors for dynamic strain, embeddable strain sensors, temperature sensors and displacement sensors. AOS's sensors can be integrated directly into structures; once implemented, there is no need for calibration or maintenance during its lifetime. Sensors also can be fixed to existing structures (Fig. 13.1).

AOS sensing/data logging units consist of several modules that can easily be combined with each other for interrogating Bragg grating sensor. Single or multiple channel units are available for long term strain or temperature monitoring of structures and for measuring of vibrations. AOS has fully developed software which is capable of displaying strain/temperature, storing data, and supporting time shift and/or trigger mode.

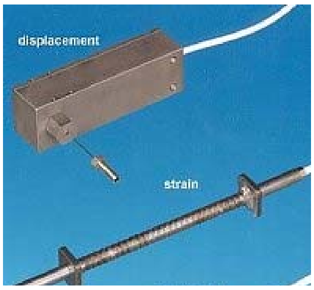


Fig. 13.1 Assembled FBG sensor

The sensors can work in a temperature range of -60 to 120°C but the interrogators 5 to 50°C without air-conditioning.

13.2 Blue Road Research:

Blue Road Research offers single and multi-axis long gauge FBG sensors for both static and dynamic measurements. Blue Road sensors can avoid problems arising from local stress concentrations while maintaining durability and resistance to electromagnetic interference. These sensors can be used alone or combined with temperature, humidity, or corrosion sensors to monitor structural health.

Blue Road readout systems including light sources, filters, and detectors in integrated or modular configurations are spliced in a single enclosure, using FC/APC optical connections and patch cables. Blue Road DAQ software with user friendly graphical interfaces performs data logging and initial processing.

Blue Road systems may be permanently installed or removable, and set up for continuous or periodical monitoring. The system has been used for real-time monitoring of structural dynamic and quantified loading data for use in performance analyses of bridges. Optical strain sensors have proven themselves in a project conducted in cooperation with the Oregon Department of Transportation to monitor the health of the Horsetail Falls Bridge in the Columbia River Gorge. Twenty-six sensors, including both embedded and surface mounts, were successfully used to monitor the effectiveness of strengthening the concrete beams with composite wrap and even showed an ability to monitor and classify traffic (Fig. 13.2 and Fig.13.3).

Fig. 13.2 Sensors mounted onto glass epoxy

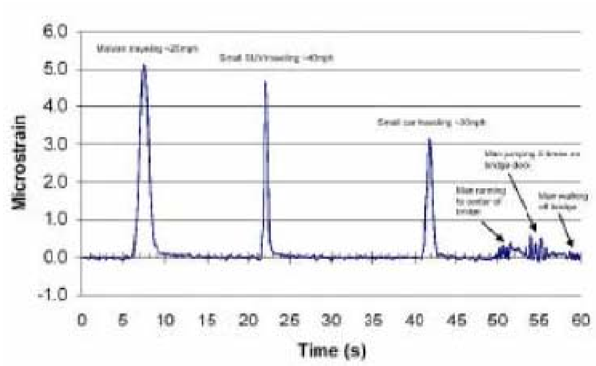


Fig. 13.3 Dynamic data from a sensor Traffic Across Bridge: Minivan, SUV, Car, Pedestrian (Left to Right)

13.3 FIBERPRO

FIBERPRO optic sensor systems are based on FBG sensing technology. Its fiber optic strain gage sensor (Fig. 13.4) is very easy to attach and remove with FIBERPRO strain gage installation kit. It provides accurate test result in harsh environmental conditions and several sensors can be connected in series. IBERPRO's FBG interrogation system was developed for the purpose of providing fast and accurate multi-wavelength analysis for FBG sensors; it has a modular structure with a main-frame, a laser module, and sensor modules; the laser module is based on a patented wavelength swept fiber laser; compatible with various types of sensor heads. The system can be expanded by adding optional modules for monitoring needs.

FBERPRO FBG system can be used for real-time data monitoring. The maximum sampling rate can be fast up to 100KHz with high resolution and accuracy. It can detect dynamic loading, acoustic emission, impact location, shock wave experiments and transient response. In particular it is a good solution for high speed temperature sensing in turbulent airflow, refractive change measurement in water, accelerometer for seismic application, etc

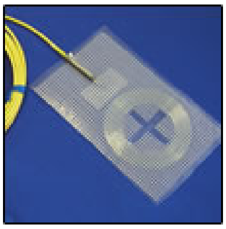
13.4 Fiber Optic System Technology, Inc

Fiber Optic Systems Technology, Inc. (FOX-TEK) designs, develops and supplies SHM systems using fiber optic sensors, related monitoring instruments, and software.

Fig. 13.4 FIBERPRO optic sensor

FOX-TEK FT fiber optic sensors, depending on the application involved, are available as bare fiber, coil with integrated rugged fiberglass mesh backing, and ruggedized (Fig. 13.5). Bare sensors can be applied to any part of a structure (e.g. around a pile or pipe, along a girder) to measure total displacement along gage length. Coil sensors are provided in differing sizes in oblong or circular shapes to measure crack opening, localized deformations and temperature. Both of these sensor families are available in normal or high temperature ranges. Ruggedized sensors are designed to be embedded into concrete foundations or bolted into support structures for measurement of total displacement along gage length. All these sensors are available in long gages with an operating temperature range of -25° to +55°C.

(a) Bare Fiber FT Sensors



(b) FT Coil Sensors

(c) Ruggedized FT Sensors

Fig. 13.5 FOX-TEK sensors

The FOX-TEK FT Sensor Monitors precisely and accurately measures the length of FT Sensors. Once the sensors are installed, the lead cables are routed to the monitor, the monitor is activated. Automatic or manual operation commences for either continuous measurement or periodic measurement. The units can be controlled locally through an easy to use touch screen or remotely through a secure connection established over a local network or the internet. Collected data is uploaded from the monitor to FOX-TEK database management and analysis tool DMAT for analysis. Data from all channels of FT Monitors is collected and processed into easily understood tabular or graphical formats. FT Sensor Monitors are designed for outdoor use with an operating temperature range of -10° to +45°C (14 to 113°F).

FOX-TEK Continuous Systems have a dedicated monitor that can access the sensors at any time, usually on a pre-programmed schedule. This is ideal for those situations requiring continuous updates to support operations, or those involving critical equipment or asset care. These systems are composed of sensors on the structure, monitors and analytical processing software in a control center. Sensor placement is optimized and the sensors are permanently installed. An FT Monitor is installed at the site in an enclosure suitable for the operating environment. Often, the sensors are some distance from the monitoring point, so cabling is installed to carry signal to and from the sensors. Cabling from the sensors and solar, battery, or line power is connected. After commissioning, the monitor works on a programmable schedule, interrogating the sensors, storing the raw data, and sending data files to a central analysis point using telemetry.

For sites that do not require continuous reporting, a scheduled or on-demand visit by field staff to the monitoring location is all that is required to collect data which indicates rate of change, or shows that the asset is healthy. Data is collected using a battery-powered portable monitor. In most instances, the data is later sent to the analysis office and processed.

For remote sites that don’t supply AC power and access to wired communication, FOX-TEK offers its Site Support Services including mounting FT Monitors in proven self-powered enclosures meeting the environmental conditions at hand. Low bandwidth telemetry via radio or satellite link enables scheduled measurement, measurement on request, or continuous data streaming from an operations center.

13.5 Intelligent Fiber Optic Systems (IFOS) Inc.

Intelligent Fiber Optic Systems (IFOS) designs and manufactures fiber optic sensors and sensing systems, photonic modules, and environment monitoring subsystems.

IFOS fiber optic sensors include off-the-shelf FBG sensor packages for rugged industrial usage (strain meter, thermometer, accelerometer, pressure meter, inclinometer and displacement meter) and bare FBG sensors that can be adhered to various structures for strain and temperature measurements.

IFOS I*Sense interrogation systems provide simultaneous data display and storage for each of its sensing elements with high precision, automatic calibration, remote monitoring, long life, large dynamic range, and high measurement bandwidth. Different sensing elements can be deployed on a single optical fiber enabling a mix of strain, vibration, acceleration, displacement, tilt, pressure, temperature, and other variables (multiplexed sensing). These sensors can be deployed at a single location or at multiple locations. All IFOS systems equipped with data acquisition software and hardware run with any computer with a MS Windows operating system.

Other features of IFOS's products include: high sensor sampling speed, intelligent data management to monitor, detect, and assist in decision making; multiplex sensing; and customizable end-user displays; real-time, automated continuous monitoring.

13.6 Light Structures AS

Using fiber Bragg gratings (FBG), Light Structures AS offers fiber optic short-based and long-based strain sensors, fiber optic accelerometers and fiber optic displacement sensors. Strain sensors are surface mountable with epoxy adhesive, and are normally covered with a glass fiber reinforced polymer laminate for mechanical protection.

Light Structures' FBG Analyzer or scanning filter interrogator is designed for long-term monitoring of FBG-based sensors under field and laboratory conditions. It is used together with an industrial PC that handles data analysis and storage. The FBG Analyzer features a high sensor capacity at relatively high sampling rates, determines the Bragg wavelength of each grating with high precision.

13.7 Luna Innovations

Luna Innovations' Distributed Sensing System™ (DSS) 4300 is a fiber optic sensing tool for making distributed measurements of temperature and strain. The DSS uses swept-wavelength interferometry to simultaneously interrogate thousands of sensors integrated in a single fiber (multiplexed sensing). These sensors consist of discrete FBG point sensors which can each reflect the same nominal wavelength. The DSS combined with Luna's sensing fiber provides a tool for distributed sensing for strain and temperature with up to 1 cm spatial resolution along the length of the fiber.

Luna is developing a dynamic distributed sensing system that uses optical fiber consisting of continuous FBG sensors. With measurement rates of up to 1 kHz, cost effective fiber sensors, and significantly reduced installation time compared to equivalent foil strain gauges, Luna dynamic distributed sensing system is ideal for obtaining dynamic strain data over a continuous object – something no other technology can achieve. This enabling technology has applications in bridge structural health monitoring for:

- dynamic structural health monitoring
- model & simulation validation for mechanical structures & prototypes

- mechanical vibration

13.8 LxDATA Inc.

LxDATA developed a revolutionary process for manufacturing FBG-based components in long spliceless array of fiber. LxDATA is able to create km long arrays of FBG based sensors which can accurately measure a multitude of parameters from the same fiber array and hence be read from the same instrumentation (multiplexed sensing). LxIQ™ is a state of the art and very powerful optical distributed temperature monitoring system by LxDATA for extremely harsh down hole environments. No application in SHM yet.

13.9 Micron Optics Inc.

The Micron Optics sensing products include a complete line of optical sensors, laser-based measurement instruments, and a suite of system software for data acquisition and analysis.

Micron Optics fiber-Bragg grating (FBG) optical sensors include: single or serialized FBGs in polyimide coated fiber, FBG strain and displacement sensors (regular and rugged), FBG accelerometers, and FBG temperature sensors. These sensors can be used in an environment of -20°C to 50°C with instrumentation in controlled enclosure. Optical information from the sensors is gathered and processed by the Micron Optics instruments. Data is transferred to a central system for further processing and analysis.

Micron Optics interrogators offer both static or dynamic real time acquisition or periodic monitoring. The interrogators provide fast and accurate readings of as many as hundreds of fiber-Bragg gratings or extrinsic Fabry-Perot sensors. The interrogators are also compatible with most commercially available optic sensors. The Micron Optics "Sensing Module" platform responds directly to the user commands of the optical interrogator core and outputs sensor wavelength data via Ethernet port and custom protocol. All module settings, sensor calculations, data visualization, storage, and alarming tasks are run on external PC or sensor processor module. The Sensing Module platform is ideal for custom, client developed system management tools, but is equally compatible with local or remote installations of Micron Optics ENLIGHT software.

Micron Optics ENLIGHT sensing analysis software is included with Micron Optics sensing interrogator systems and provides a single suite of tools for data acquisition, computation, and analysis of optical sensor networks. ENLIGHT combines the useful features of traditional sensor software with the specific tools needed to optimize optical properties during the design, implementation, and operations phases of an optical sensor system. Tables, graphs, and additional data visualization features make ENLIGHT easy to use.

Micron Optics' products are used by many companies, agencies, institutes, and universities throughout the world in various applications: for example, monitoring of the integrity and behavior of the bridge structure and effects due to high traffic and heavy truck loads that could cause possible damage and fatigue; real-time quantitative information on a bridge's response to live loading and environmental changes, and fast prediction of the structure's integrity; monitoring of strain, displacement and temperature on a post-tensioned concrete bridge following remedial work; continuous long-term data on the strain, deformation and temperatures of the main cable and anchorage of the bridge. The data generated by the monitoring system is used to provide baseline data and to evaluate the possibility of detecting wire brakes through deformation monitoring. A number of case studies of bridge monitoring projects are available on http://www.micronoptics.com/civil_structures.php. One project is presented in Chapter 21.

13.10 OMNISENS SA:

OMNISENS uses fiber optics Brillouin distributed sensing technology and developed the DITEST SHM for large and complex civil engineering projects, tunnels, bridges, dams, nuclear plants, etc.

DITEST Fiber Optics Brillouin Analyzer is a fiber optics and laser-based monitoring system using an optical interaction measurement principle (stimulated Brillouin scattering) for distributed measurement of strain and temperature(Fig. 13.6). It's capable of measuring thousands of locations (points) by means of a single optical fiber end. DITEST system is compatible with standard database and can be integrated with measurements from other sensors (e.g., SOFO, ADAM from SMARTEC).

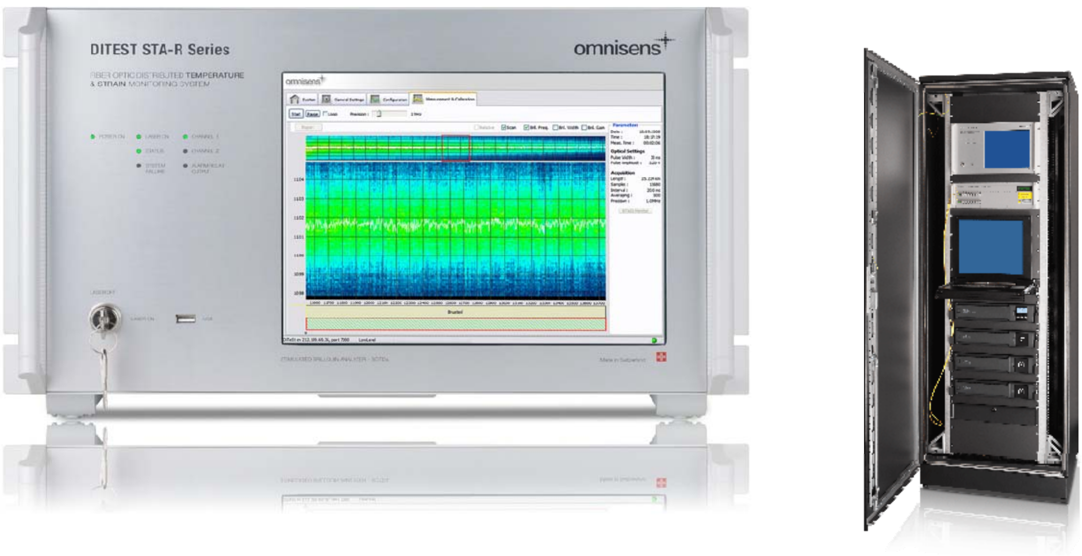


Fig. 13.6 DITEST-SHM system

DITEST-SHM solution offers long-term uninterrupted monitoring for complete mapping of the structure and high resolution strain monitoring. A few other features of the system include:

- detection of cracks occurrence with resolution better than 1 mm
- continuous analysis of very small variations in, strain and temperature along the entire fiber optic sensor and early detection and classification of alerts along the infrastructure.
- configuration of zones with associated alarms and relays activation
- data management, system interfacing and communication interface with third party' systems

the database is accessible from remote computers through a LAN network. Other options are possible.

13.11 OSMOS USA

OSMOS (Optical Strand Monitoring System) offers long-term monitoring of global changes in structural characteristics through intensity-based fiber optic sensing technology. OSMOS sensors include optical extensometer (fiber-optic displacement sensor), optical strand (measuring changes in shape or position), EX-Large (similar to extensometer but for longer measurement), X-Trigger (for monitoring joint movements), etc.

In OSMOS, a monitoring station is used for measuring, evaluating and displaying signals from sensors. The monitoring station consists of a master unit and a slave unit. The slave registers measurement values from the sensors, while the master processes and displays signals and performs communications with peripheral devices. Database server establishes a modem connection with measurement points and archives all raw data and accumulated data. The raw data are converted into measurement data and visualized. All the required information concerning the state of the monitored structure can be displayed on computer monitor. The entire system can be configured online.

OSMOS allows real time, continuous monitoring and alarm triggering. Alarms can be generated via e-mail, fax, or any other user specified means when exceeding predetermined thresholds.

OSMOS system has been used in a number of bridge SHM projects to monitor the condition of prestressed concrete girders (Fig. 13.7) and to establish a database for normal strains on damaged bridge girders, the aging cracks of a prestressed concrete bridge deck (Fig. 13.8), the movement of a bridge during strengthening, and the strain to verify load assumptions and the maximum strain in critical construction parts of bridges. Detailed information is available at http://www.osmosusa.com/bridges.html

Fig. 13.7 Orthogonal Optical Strands to measure shear stress (Champlain Bridge, Montreal, Canada)

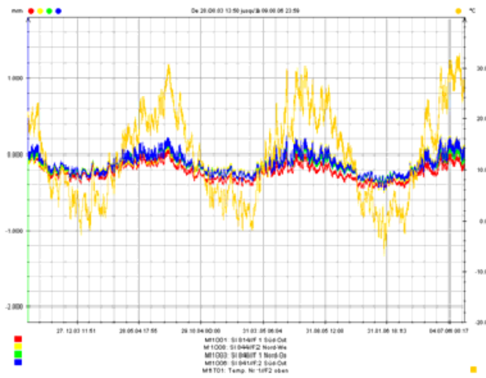


Fig. 13.8 Static deformations over 3 years (Kohlbrand Bridge, Hamburg, Germany)

13.12 Smart Fibers Ltd.

Smart Fibers' "Smart" FBG sensors include SmartFBG, SmartPatch, SmartWeld, SmartCell, SmartBridge, SmartBar, SmartTape, SmartRod, SmartTemp and Smart Accel, etc. These are all packaged sensors developed for measuring strain, temperature and pressure in harsh environments and for embedment or surface mounting to all manner of substrates.

Smart Fibers SmartScan is an ultra compact and robust interrogator for dynamic measurement or ultra high-resolution quasi-static measurements of FBG sensors. It provides deterministic data interrogation and data processing with a laptop PC. SmartSoft (LabView based) is the software to provide up-to-date information in a variety of formats and allows for simple on-line calibration, data display and logging of the FBGs. Hundreds of FBG sensors can be recorded onto a single optical fiber and interrogated simultaneously with a single instrument. Real-time, continuous monitoring with optional alarm triggering system is available through direct wire connection, modem, Internet or satellite.

Case studies using Smart Fibers SHM products are available at http://www.smartfibers.com/civil-engineering-and-infrastructure?page=references. One project is monitoring of strain, displacement and temperature on a post-tensioned concrete bridge constructed in the late 1960s. The bridge forms part of the UK's motorway network and carries slip road traffic at a busy intersection. The sensor system is being used to monitor the behavior of the bridge following recent remedial works (Fig. 13.9).

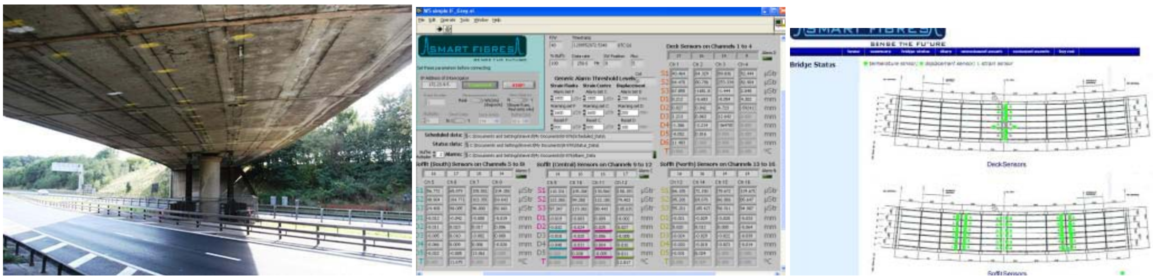


Fig. 13.9 Soffit sensors installed, data available from site computer,
typical web utility screen showing bridge health

FOS systems are becoming mature and have been used in a variety of bridge monitoring projects worldwide. Most systems require direct wire connection. Ethernet or Internet are available upon requests.

13.13 Summary

Most FOS sensors can operate in a temperature range of about -20 to +80°C, but the interrogators need an operating temperature range of above 0°C without air-conditioning. DAQ instruments will need to use NEMA enclosure for operating in the field. In very cold regions, air-conditioning is needed to keep the required temperature and humidity for normal operations.

Most systems require direct wire connection. Wireless data communication is available upon request.

14 DATA ACQUISITION (DAQ) AND DATA PROCESSING

In evaluating structural behavior of bridges, field measurements on structures are the oldest and most effective means. This past decades had seen the evolution of field measurements from intensive manual reading of instruments to automated systems with response activated alarms and posting of real-time data to web sites. Data had been traditionally manually collected, recording values by hand to be converted to engineering units later. The post-processing of the measurements was labor intensive and time consuming.

Modern on-site system usually called data logger is quite different. These instrument not only physically demodulate the signal from various sensors, collect the raw data, but also condition the data and storage the data before it is transferred to a computer for processing. Most manufacturers offers DAQ systems and software with their sensor products. Here are a few manufacturers whose major products are DAQ.

14.1 Analog Devices Inc. (ADI):

Analog Devices develops and supplies high performance signal conditioning devices, and analog, mixed-signal and digital signal processing (DSP) integrated circuits (ICs). Various products and systems are available (e.g., data converters, display electronics, integrated systems, etc). Data acquisition system is, in most cases, custom designed for specific application. Radio frequency (RF), cellular handset ICs, optical networking, RS-232/422/485 transceivers, and wireless are a few options for data communication.

14.2 Daytronic Corporation:

Daytronic offers high-speed data acquisition and control systems, and transducer signal conditioners/indicators for automated testing, remote safety monitoring, prototype evaluation, and statistical analysis of both "real time" and "historical" data.

Daytronic systems incorporate a unique array of selected Signal Conditioner Cards, as dictated by the specific collection of sensors to which it is connected (LVDTs, Strain gage load cells, displacement transducers, and others). The systems are capable of a wide range of configurations, from small bench-top data loggers to local area networks that can handle thousands of data points, while monitoring and controlling multiple complex processes simultaneously (data collection, display, archiving, communication and processing).

Data communications are through RS-232/485, GPIB, Modbus, Profibus, and Ethernet. Other wired or wireless communication options (e.g., satellite communication) are available upon request.

Environmental limitations: System 10, -20 to 70°C; 5D modules: -10 to 70°C, 5 to 95% relative humidity, non-condensing.

14.3 Digitexx Data System, Inc

Digitexx Data System offers solutions for real-time data acquisition and processing in structural health monitoring. Digitexx system is compatible with most commercially available sensors (accelerometers, strain gauges, temperature sensors, displacement sensors, etc.). The systems are capable of broadcasting streaming data (Internet TCP), data retrieval (TCP, FTP) and remote tele-control, manual/event driven triggering (E-mail, web), etc. (Fig. 14.1).

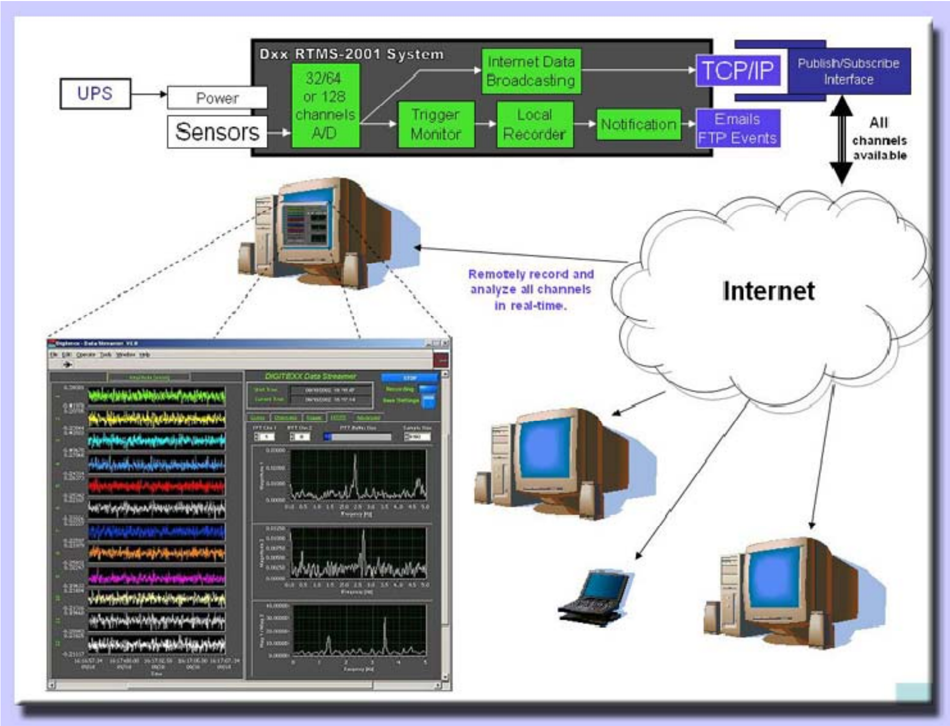


Fig. 14.1 The real-time monitoring system flow diagram

Digitexx provides portable, semi-permanent to permanent bridge monitoring systems which can:

- provide continuous, simultaneous *real-time* sensor data both locally and remotely
- accept just about any third-party sensor input and be designed to accept multiple sensor types--all managed through a single Digitexx system
- manage 100's to 1,000s of channels
- provide multi-point distribution. The Digitexx Client Software provides remote *real-time* bridge monitoring management from any location with Internet access.
- supply alert management...something happens, the users are informed immediately

Fig. 14.2 Digitexx server software

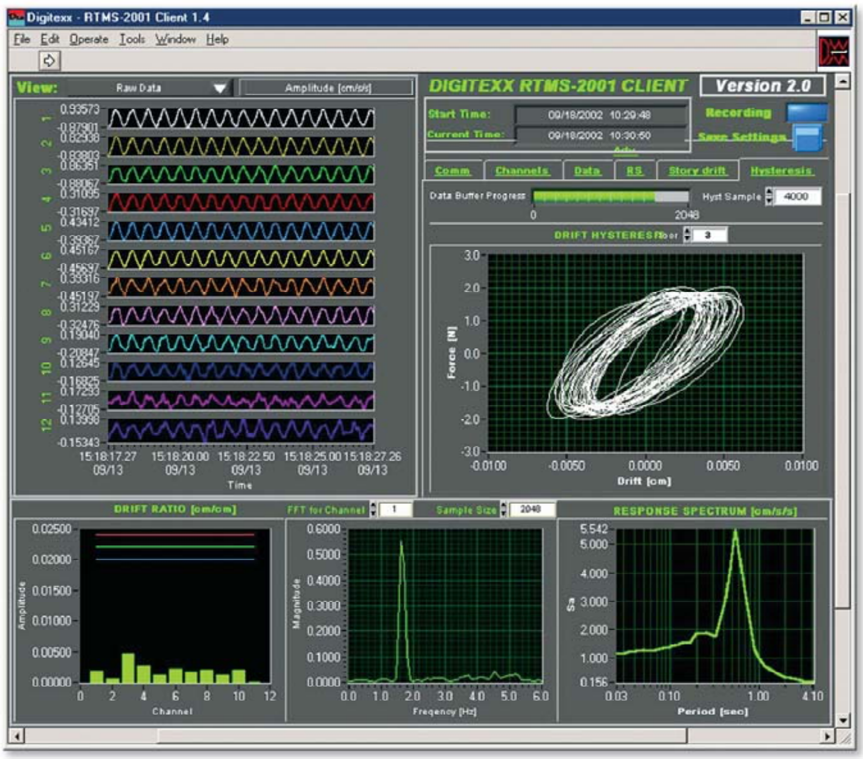


Fig. 14.3 Digitexx client software

14.4 Frequency Devices, Inc

Frequency Devices provides analog and digital products for signal conditioning, signal processing and data acquisition. Its products include a wide variety of complex hardware and software; analog and digital (FIR and IIR) fixed frequency and programmable low-pass (anti-alias), high-pass, band-pass and band-reject (notch) electronic filters, along with differential input amplifiers and oscillators.

Frequency Devices can provide noise and distortion performance to 20+ bits with precision amplitude, phase and quadrature match. A growing selection of single and multi-channel signal processing platforms and instruments that perform FFT, signal analysis and signal correlation are also available. Architectures include VME, VXI, compactPCI and PCI form factors as well as IEEE-488, RS-232, Ethernet and USB I/O’s with MatLab, Labview and LabWindowsCVI compatible GUI interfaces.

14.5 IMC Dataworks, LLC.

IMC DataWorks’ instrumentation and software are specialized in multi-parameter, mixed-signal mechanical data acquisition, measurement, and control. IMC data acquisition hardware can record many different physical parameters, such as temperature, pressure, acceleration, vibration, or other transducers providing a voltage, current, bridge, IEPE/ICP, encoder, or discrete digital information. IMC data processing and signal analysis software is capable of automation of any real-time analysis and system response functions as well as display, storage and documentation of results. Direct wire connection or other communication protocols (modem, cell phone, telephone, Fax, PDA, Ethernet, GSM, etc.) are available.

IMC systems can be used in civil engineering for test and measurements of static load, dynamic structural forces, railway track irregularities/resonances, long term stability and fatigue analysis, and pressure measurements (tunnels).

14.6 IOtech, Inc.:

IOtech offers a variety of Ethernet-based data acquisition system for strain, temperature or vibration and mixed signal measurement solutions. Its DaqBook/2000 Series and WaveBook/516E products (Fig. 14.4) are ideal for mixed signal systems with their extensive line of signal conditioning and channel expansion options to measure strain, accelerometers, temperature, frequency, encoders and more.

Fig. 14.4 DaqBook/2000 Series and WaveBook/516E

IOtech PCI-based DaqBoards offer unmatched channel expansion options, the ability to measure various sensor types. All DaqBoards are supported by a range of software options to match users' preference. Software support includes Visual Studio® and Visual Studio® .NET, DASYLab®, NI LabVIEW™, MATLAB®, and DaqView *Out-of-the-Box* software.

IOtech also offers a large selection of USB-based data acquisition modules and boards. Personal Daqs offer multifunction data acquisition in a low-cost, portable package for voltage or thermocouple inputs.

14.7 Omega Engineering, Inc.

OMEGA offers more than 100,000 state-of-the-art products for measurement and control of temperature, humidity, pressure, strain, force, flow, level, pH and conductivity; and a complete line of data acquisition and custom engineered products. Please see Chapter 16 for data acquisition system from OMEGA.

14.8 Omni Instruments

Omni Instruments provides various sensors and instruments for measurement, control and data acquisition. Please see Chapter 16 for data acquisition system from Omni Instruments.

Fig. 14.5 SoMat eDAQ system

14.9 Somat Ltd.

Somat manufactures portable, rugged data acquisition and analysis system (Fig. 14.5) for strain gages, accelerometers, pressure gages, load cells, tiltmeter, and temperature gages. Somat systems are able to perform signal conditioning and a broad range of on-board data processing. This includes; custom computed channels, triggers, gates, boolean expressions, and the SoMat DataModes™. Utilizing the SoMat DataModes™ allows users to save data in multiple, easy to manage and analyze formats including; Burst History, Time-at-Level, Event Slice, Peak/Valley and Rainflow Histograms. Hundreds of synchronous channels are possible in a single system with superior signal conditioning for Analog, Digital I/O's, Vehicle Bus, GPS and more. Infinite channel counts are available when networking this Ethernet-based system. SoMat systems are designed for lab and field testing as well as unattended monitoring in harsh environments.

14.10 Superlogics, Inc.

Superlogics supplies data acquisition solutions to a variety of sensors (accelerometers, strain sensor, temperature gage, impulse hammers, load cells and others). Superlogics DAQ hardware connects any PC to voltage inputs, thermocouples, strain gauges, rtds or virtually any analog or digital sensors. Easy-to-use data acquisition solutions are available in USB, PCI, RS-232, RS-485, Ethernet, and wireless systems. The hardware is compatible with its own WINview Series Software, or third party packages like DASYLab, TestPoint and LabVIEW. The system is compatible with Windows-based PCs and laptops through USB, LAN and wireless devices.

14.11 Texas Measurements, Inc.

Texas Measurements offers civil engineering transducers and data loggers for measuring various physical quantities. Its DAQ includes static strainmeters, dynamic strainmeters and histogram recorder indicators, etc. The dynamic strainmeter is intended for on-line measurement with a computer; self diagnostic function for sensitivity, input and insulation. The histogram recording system uses preset programs to analyze phenomenon such as strain that changes over time, and it stores that analytical data as a histogram. The histogram recording systems yield histograms immediately after measurements are taken because they analyze and record a phenomenon count while they measure. They can also measure continuously for periods exceeding one full year because they do not store waveform data or use magnetic tape.

14.12 Summary

Most DAQ instruments will need to use NEMA enclosure for operating in the field. In very cold regions, air-conditioning is needed to keep the required temperature and humidity for normal operations.

15 WIRELESS/REMOTE MONITORING

Monitoring systems are traditionally composed of data logger units on-site and various sensors over the structure connected by long cable to the logging units. These systems are time consuming to install and thereby cost-intensive. The drawbacks also included recurring cabling problem. With the advancement in wireless and cellular technologies, attempts are being made to address this issue by introducing wireless data communication techniques, i.e. the data transfer is performed by a wireless sensor network, to the monitoring system.

As shown in Chapter3 2 and 3, wireless technology can be used in different stages of data communication in a SHM system. Wireless sensor network will make acquisition of data from sensors to on-site DAQ instruments. Using wireless technology is especially beneficial in this stage when the monitored points are not easy to access and running wires/cables are difficult to connect the sensors to data acquisition instruments.

When configured with telemetry, data can be transmitted in real-time from the bridge site to a project computer, eliminating the need for periodic site visits to upload data. Two factors help determine the best telemetry method - site conditions and distance to the project computer. When the project computer can be located within a few miles (line-of-site) or few hundred feet (non-line-of-site), license free spread spectrum radio telemetry is the best choice. If the project site is remotely located relative to the project computer, cellular or satellite telemetry becomes the best option. Options are also available for landline phone or Ethernet telemetry if the site has access to a landline or Ethernet hub.

15.1 Acellent Technologies, Inc.: (also a SHM system)

The SMART Suitcase by Acellent Technologies. Please say Chapter 16 (SHM system) for the attributes of wireless/remote monitoring of Acellent Technologies.

15.2 Advanced Telemetrics International (ATi)

ATi Point to Point Telemetry Systems are used in an assortment of wireless roles including bridge health monitoring. ATi telemetry transmitters can modulate sensor signals from many different sensors and inputs, e.g. most ICP (integrated circuit piezoelectric) type accelerometers, most AC type LVDTs, strain gages or other Wheatstone bridge type sensors with millivolt outputs, Type J or Type K thermocouples, any current output type sensor or current source, voltage transmitters in AC, DC or RMS types for use with any type sensor or voltage source. ATi transmitters, housed in a weatherproof NEMA 4x enclosure, use radio frequency (RF) telemetry technology to supply excitation to sensors and transmit signals to a conveniently located stationary receiver up to 4 miles from the sensors (Fig. 15.1). Operating temperature range of -40°C to 85°C.

Fig. 15.1 ATi's wireless bridge health monitoring telemetry systems

ATi manufactures single channel, multi-channel and multiplexing telemetry receivers with analog outputs which can be integrated with other data logger or acquisition system. ATi systems bridge the gap between bridge mounted sensors and data recording equipment; eliminate cabling/wiring effort.

15.3 The WiSe system by Geo Instruments.

Geoindicator’s WiSe data logging system is a low cost Wireless Mesh Network datalogging solution capable of reading all sensors (vibrating wire, 4-20mA, voltage output, electrolevel and resistance) of Geoindicator’s product range (see Chapter 12 Force Sensors). Applications include the wireless monitoring of bridges, tunnels, excavations, earth structures, railways, buildings and dams. It is also ideal for the rapid deployment of flexible, robust monitoring systems within difficult environments where a cabled solution is not possible.

Containing a full suite of signal processors, ADCs, flash memory, ancillary device drivers and self diagnostic facilities. The WiSe system can be easily and rapidly adapted to measure almost any sensor type required.

15.4 RMS Lite by GEODEV Earth Technologies

GEODEV Remote Monitoring System (RMS Lite) allows collecting data from analog, digital or serial RS-232 devices, instruments or sensors in order to perform wireless remote monitoring. The system can be applied in **structural monitoring for** alarm generation, remote diagnostic, event notification, etc.

RMS Lite allows a two-way data communication between the measuring device and the user through the cellular network (SMS messages or data transmission). For the data distribution and the alarm notification, the system allows to define up to 10 phone numbers for each measuring channel. The user can ask at any time for the last measurement data of any channel with an SMS message from his cellular phone. The system can also run automatically with a scheduled automatic data download from the user's PC running the GEODEV *RMS Control Center* software.

An unlimited number of registered users can be enabled to receive the acquired data or the alarm notifications from the *RMS Mobile Service.* This message re-distribution service is offered by GEODEV through the *RMS Mobile Gateway* for the dispatch of SMS or email messages.

More information at http://www.geodev.ch/pdf/RMS%20lite%20eng.pdf.

15.5 Global Navigation Satellite Systems (GNSS) by Leica Geosystems AG:

Leica Geosystem offers real-time kinematic (RTK) Global Navigation Satellite Systems (**GNSS)/**Global Positioning System (GPS) for continuous, comprehensive monitoring of displacement/deformation of long span bridges with three-dimensional (3D) point sets.

Leica Geosystem's GPS receiver utilizes RTK techniques to provide independent position solutions with high accuracy. It provides high quality signal reception, satellite tracking, jamming resistance and multipath integration. It is packaged in a rugged aluminum housing with shock mount isolators and designed for high vibration environments and for unattended or remotely controlled operation. Leica's GPS Network software provides full Internet connectivity, for controlling and operating GPS reference stations and networks. It can control single reference stations providing GPS services for local areas as well as networks of stations supplying GPS data, RTK and DGPS (differential GPS) services over entire regions, states or countries.

Once started, Leica Geosystems' GPS monitoring system runs continuously and automatically supplying the full range of GPS data, RTK and DGPS services that are needed for monitoring, surveying, engineering, construction, geodesy, GIS, etc.

Leica Geosystems' monitoring systems have been implemented in various industries in more than 120 countries around the world, including a number of bridge projects which are available at Leica Geosystems' website. For example, they have been used to monitoring of girder geometric form, the displacement of bridge towers, 3D scan surveying of bridges, etc.

15.6 Invocon, Inc:

Invocon's Micro-Miniature Wireless Instrumentation System (MicroWIS) implements Invocon's wireless network communication system with a MEMS sensor (Micro-Electro-Mechanical Systems) for wireless structural health monitoring. Its systems which can be used for bridge structural health monitoring include:

EWB MicroTAU™ (Enhanced Wide-Band Micro-Miniature Tri-Axial Accelerometer Unit): Wireless, high-speed, synchronized data acquisition network for dynamic acceleration sensing, processing, and recording. Post acquisition download is either USB or wireless.

MicroWIS™-XG (Micro-miniature Wireless Instrumentation System): A real-time asynchronous wireless transmission system. Immediate graphical representation and storage on a PC. The units can support any resistive sensor type.

MITE WIS™ (Multiple-Input Tiny Enhanced Wireless Instrumentation System): A real-time and/or store-and-forward system capable of recording data from up to four channels on 2Mbytes non-volatile memory (enough for 2 years at 1 sample per 5 minutes with 4 channels). Post-acquisition download is wireless to a receiver and GUI. Designed for 2-year usage without battery exchange. The units can support any resistive sensor type.

WEBDAS™ (Wireless Ethernet-Based Data Acquisition System): This system enables the use of existing Ethernet hardware and Web-based IT resources for the configuration, acquisition, transmission, and display of sensor data from extremely low-power radio frequency (RF) sensors.

WSGIS™ **(**Wireless Strain Gauge Instrumentation System**):** Programmable initiation triggers over a 10 minute acquisition and non-volatile storage. Post acquisition download is either USB or wireless. The units can support a wide range of resistive and voltage output transducers.

Typical operating temperature range is -35°C to 85°C. According to Invocon, their products can operate in most terrestrial environments and temperatures.

In 2002, Invocon's Micro-miniature Wireless Instrumentation (MicroWIS) System was used on a box girder overpass in Huston, Texas to study stresses on a local bridge during the construction and testing (Fig. 15.2). The units measured the strains induced on the beams by both mechanical loads and diurnal temperature effects. The temperature-induced stresses were used to interpret results of load testing that was performed using weighted trucks after the bridge was completed. During this testing, the MicroWIS units were wirelessly instructed to sample at once per 16 seconds. Wireless download capability was essential in this application. The box girders being tested were located 70 feet above the ground making direct access to the units very difficult. The wireless nature of this system greatly simplified the installation process and eliminated the risk of broken data and power cables during construction.

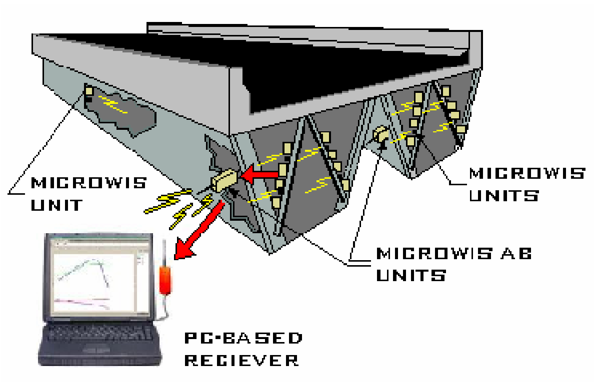


Fig. 15.2 MicroWIS System Configuration

Fig. 15.3 MicroWIS units mounted on K-frame

15.7 mXRS Wireless Sensing Systems by Microstrain Inc.

Microstrain offers a variety of wireless data acquisition systems for high-speed data acquisition and condition based monitoring. Microstrain's wireless systems feature complete signal (from from strain gages, accelerometers, and displacement sensors) conditioning, embedded processing, wireless communications, and precision timekeeping. MicroStrain's extended range synchronized (mXRS™) wireless systems operate within a fast, synchronized, scalable network of wireless sensor nodes located up to 1 km from its WSDA® -Base. WSDA® -Base is the core of the mXRS systems. WSDA® -Base (Fig. 15.4) uses Microstrain's exclusive beaconing protocols to synch precision timekeepers embedded within each sensor node in the network. The WSDA® -Base also coordinates data collection from all sensor nodes. Users can easily program each node on the scalable network for simultaneous, periodic, or burst mode sampling with Microstrain's Node Commander® software, which then automatically configures network radio communications to maximize the aggregate sample rate.

Microstrain's wireless systems can operate in a temperature range of -20˚C to +60˚C with standard internal battery and enclosure, extended temperature range optional with custom battery and enclosure. -40˚C to +85˚C for electronics only.

Fig. 15.4 WSDA® Wireless Sensor Data Aggregator

15.8 Summary

A variety of wireless technologies are not available for line-of-site or non-line-of-site data communication in SHM. This is very important for bridges in remote regions. Power supply and harsh environment (especially low temperature) should be the major concerns when using this technologies.

16 SHM SYSTEMS

A few commonly used SHM systems are presented in this Chapter. Only companies who provide a complete product line of sensors, data loggers, software, etc. which can be used to develop a SHM system are reviewed.

16.1 Acellent Technologies, Inc.

Acellent Technologies, Inc. develops and manufactures sensor network products that leverage its proprietary SMART Systems technologies to obtain solutions for real-time structural health monitoring.

Acellent's SMART Layer (Fig. 16.1) is a thin dielectric film with an embedded network of distributed piezoelectric actuators/sensors for area sensing. It can be manufactured in a variety of sizes, shapes, and complexity conforming to any geometric shape, and also customized to incorporation with other types of sensors, such as piezoelectric sensors, fiber optics, temperature, strain gauges, and more. Single sensors can be placed exactly where they are needed for maximum sensing, or SMART Layer strips with predetermined sensor spacing can be used for active or passive monitoring. Sensors can either be surface-mounted on existing structures or integrated into new structures during fabrication or construction.

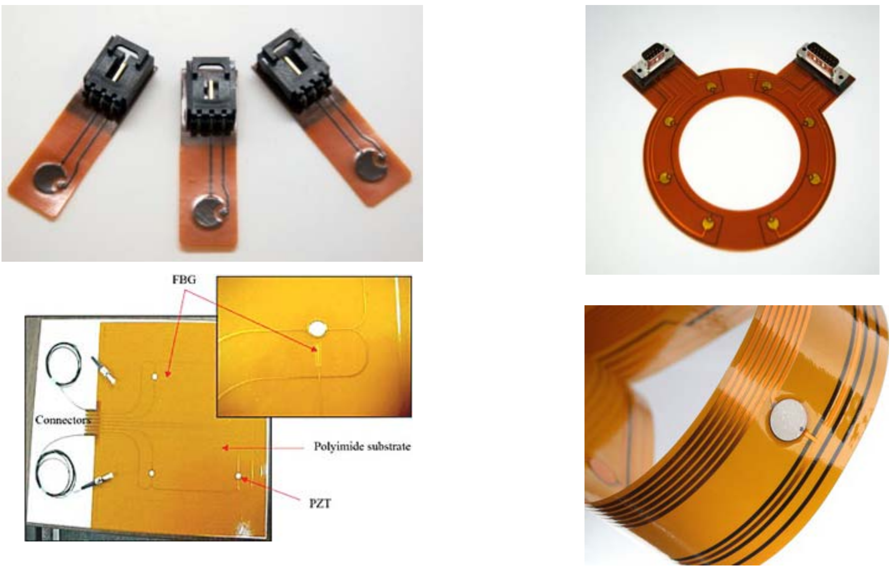


Fig. 16.1 Acellent's SMART Layer

Acellent's SMART Suitcase is a portable signal generation and data acquisition instrument with high-speed data acquisition board. ScanSentry is an energy-efficient, battery-operated controller for actively examining the integrity of local structural areas or components where low power and portability are needed. ScanGenie® controls the active interrogation of both metal and composite structures through sensor activation and response for damage detection, particularly for large area monitoring. The IMGenie® is a lightweight, battery-powered device that detects impact events in real time. Using a "passive mode" for energy savings, the unit reports where the impact occurred, when it occurred, and with what force. SCS-4300 High-Speed Suitcase, the arbitrary waveform generator unit generates very-high-frequency signals for use in structural health monitoring damage detection processes.

Acellent's software integrates seamlessly with the SMART Layer® sensor network and the corresponding data acquisition hardware to detect and characterize structural anomalies in metals and composites due to the presence of cracks, debonds, corrosion, or any combination thereof. All software is Windows-based. With the push of a button, the software will instruct the hardware to interrogate the structure and collect data. The software analyzes the data and presents the results in a clear, easy-to-understand manner. Software can not only detects damages, but also quantifies damages in composite and metal structures.

Direct wire connection is needed. System can also be remotely controlled through Ethernet or internet (remote control software is needed for this function).

SMART Layer Technology can be used to monitor the health and condition of diverse structures ranging from damage detection of composite structures, impact events in real time, specific locations of critical components and intense interest, cracks and their propagation in metal structures, corrosion growth in metal structures, and structural properties such as temperature and strain, etc. For example, Acellent's *in situ* damage detection system for fatigue crack monitoring allows fatigue crack damage quantification, which is key in determining the severity of the fatigue crack, providing insight into the status of the structure's expected performance and helping to determine if an immediate repair is required or if a repair can be scheduled when it will have the least impact on users of the bridge (Fig. 16.2).

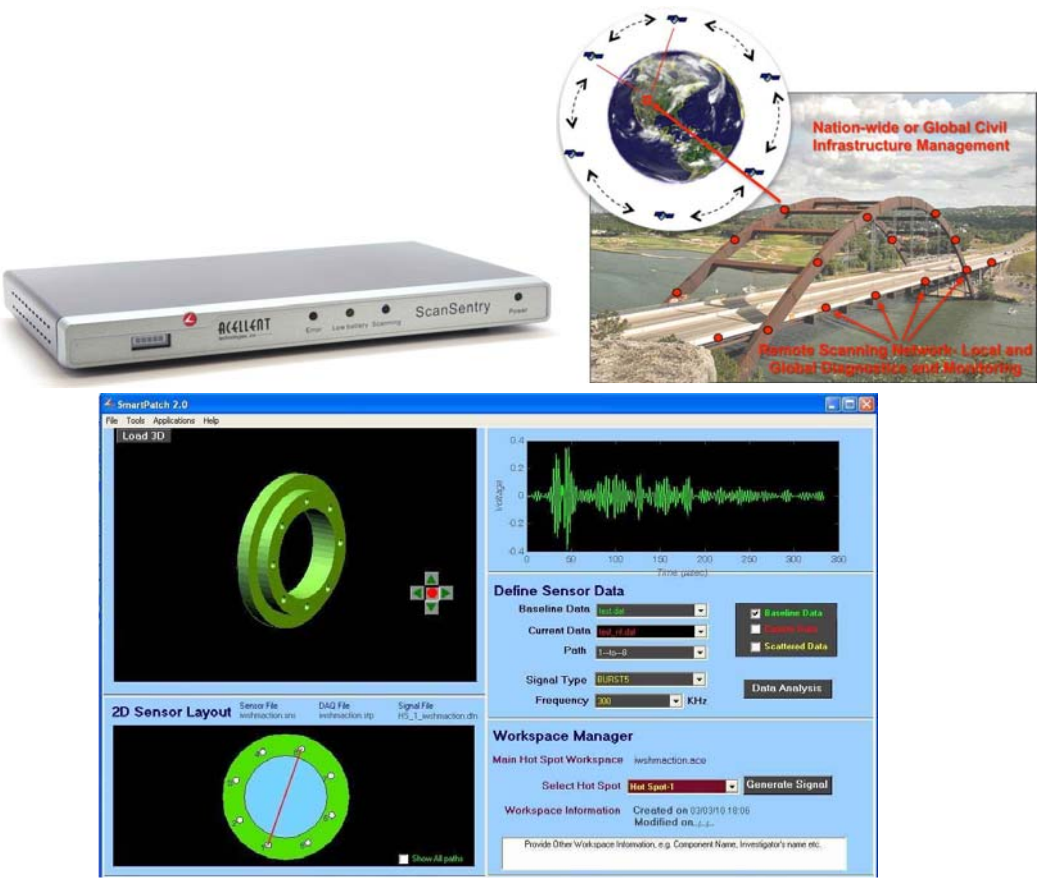


Fig. 16.2 Acellent SHM system

Acellent has an ongoing program with the National Institute of Standards and Technology (NIST) for the Development of Scalable Cognitive Autonomous Nondestructive Sensing network (SCANSn) for Advanced Health Management of Civil Infrastructures. The goal of this program is to develop an extensible and self-powered sensor network for nondestructive evaluation of bridges, buildings, pipelines, and other major infrastructure components, with a key focus on the health monitoring of bridges.

Moreover, Acellent's SMART Layers have high tolerance to withstand long term exposure to marine, underground, and other harsh environments, when protected by commercially available coatings. SMART Layer: -40°C to 90°C. SMART Suitcase: 0 to 45°C.

16.2 Campbell Scientific, Inc.

Campbell Scientific Inc. (CSI) manufactures dataloggers, data acquisition systems, and measurement and control products used worldwide in research and industry.

CSI offers a variety of sensors of which the following may be used for SHM:

- Carlson strain meters
- vibrating wire strain gauges
- foil strain gauges (set up in quarter, half, or full bridge strain configurations)
- inclinometers
- crack and joint sensors
- tilt sensors
- piezoresistive accelerometers
- piezoelectric accelerometers
- capacitive accelerometers
- borehole accelerometers
- servo force balance accelerometers

All CSI data acquisition systems are based on the same measurement concepts: on-board real-time clocks data acquisition systems (accurate to 30 seconds per month). CSI dataloggers feature variable scan rates from a few hours to 100,000 times per second; up to large 100+ channels; on-board processing system (no post processing required); and server-based archiving system. Measurement types, recording intervals, and processing algorithms are also programmable. CSI dataloggers are compatible with nearly every commercially available sensor.

CSI’s Windows-based software simplifies datalogger programming, data retrieval, and report generation. The datalogger program can be modified at any time to accommodate different sensor configurations or new data processing requirements. CSI supports a full range of telecommunication options that allow interrogation of a datalogger from a remote computer (Fig. 16.3). CSI’s data storage and retrieval peripherals allows clients to collect data during a site visit, to contact the datalogger via telemetry, or both. Its data storage and retrieval peripherals have wide operating temperature ranges allowing their use in extreme, remote environments.

Fig. 16.3 This station for the National Estuarine Research Reserve (NERR) in Virginia transmits data via CSI GOES satellite transmitter

Additional features and possible benefits of CSI's products include:

- Systems provide triggered output with pre-trigger data capture capability.
- Systems operate reliably in harsh environments.
- Systems can report conditions by calling out to pagers, radios, or phones.
- Systems support long-term, unattended data storage and transfer.
- Pick-and-click software facilitates programming.

CSI's bridge SHM is used for a variety of structural and seismic applications. For example, the monitoring possibilities on an overpass are shown in Fig. 16.4. A list of bridge projects and case studies using Campbell's instruments are on its website (http://www.campbellsci.com/bridge-monitoring).

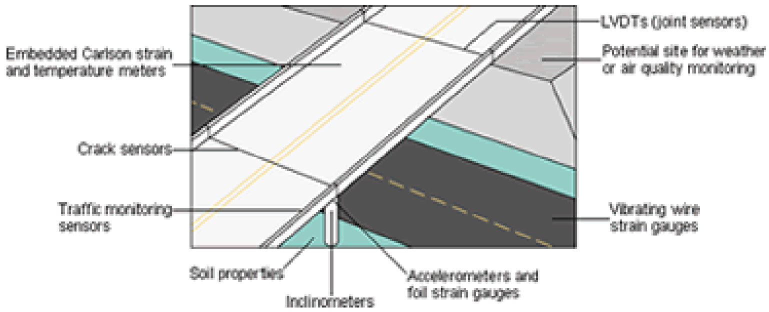


Fig. 16.4 Schematic bridge monitoring possibilities

16.3 Canary Measuring System

Canary measuring system consists of four functional blocks (Fig. 16.5). Depending on the application, each of these blocks may consist of one or more components.

Sensors (Input) are installed to provide electronic feedback of the project environment. This may consist of a single instrument or thousands, depending on the application.

Dataloggers (Measure) read the outputs of the attached sensors and store the results for later retrieval. Specialized sensor interface components and/or multiplexers may also be used to enhance and/or expand the number of inputs.

Communications (Transfer) gets the stored values from the dataloggers to the monitoring computers. The communications devices may be simple or complex depending on the application.

Software and Web Delivery (Output) provides a way to collect, store and provide access to the measurement data. Configuration of the data acquisition hardware is also managed by the software (Fig. 16.6).

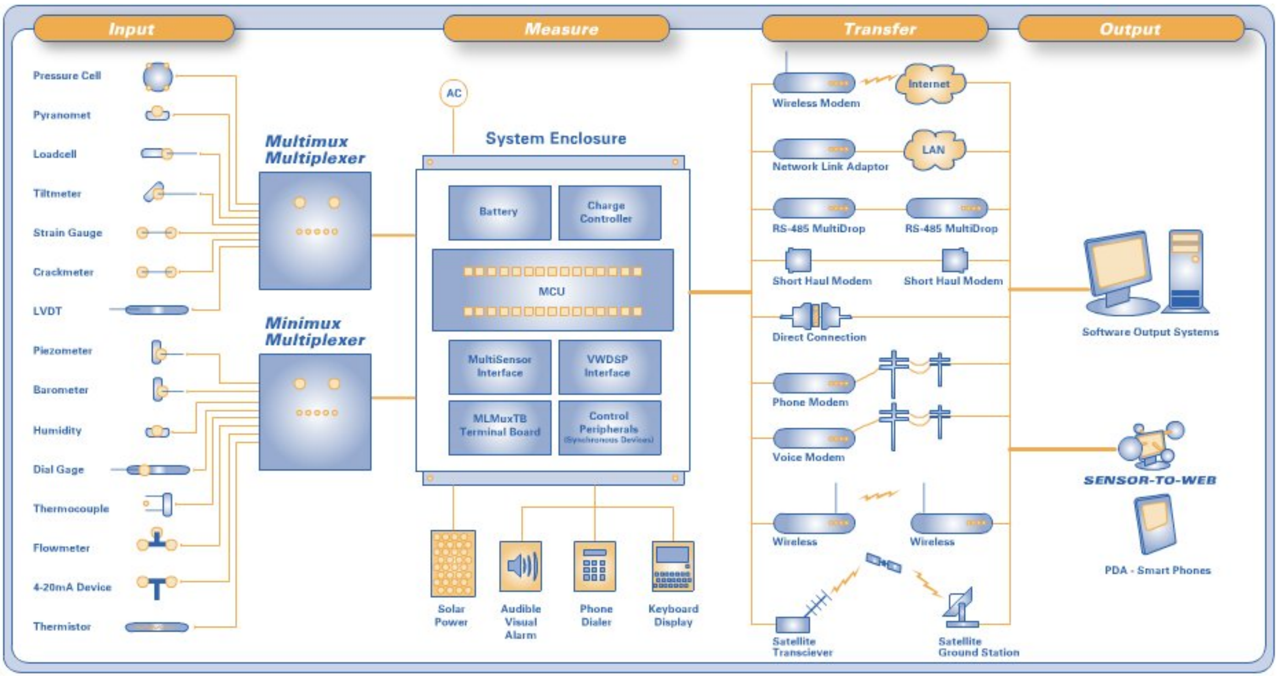


Fig. 16.5 Canary measuring system

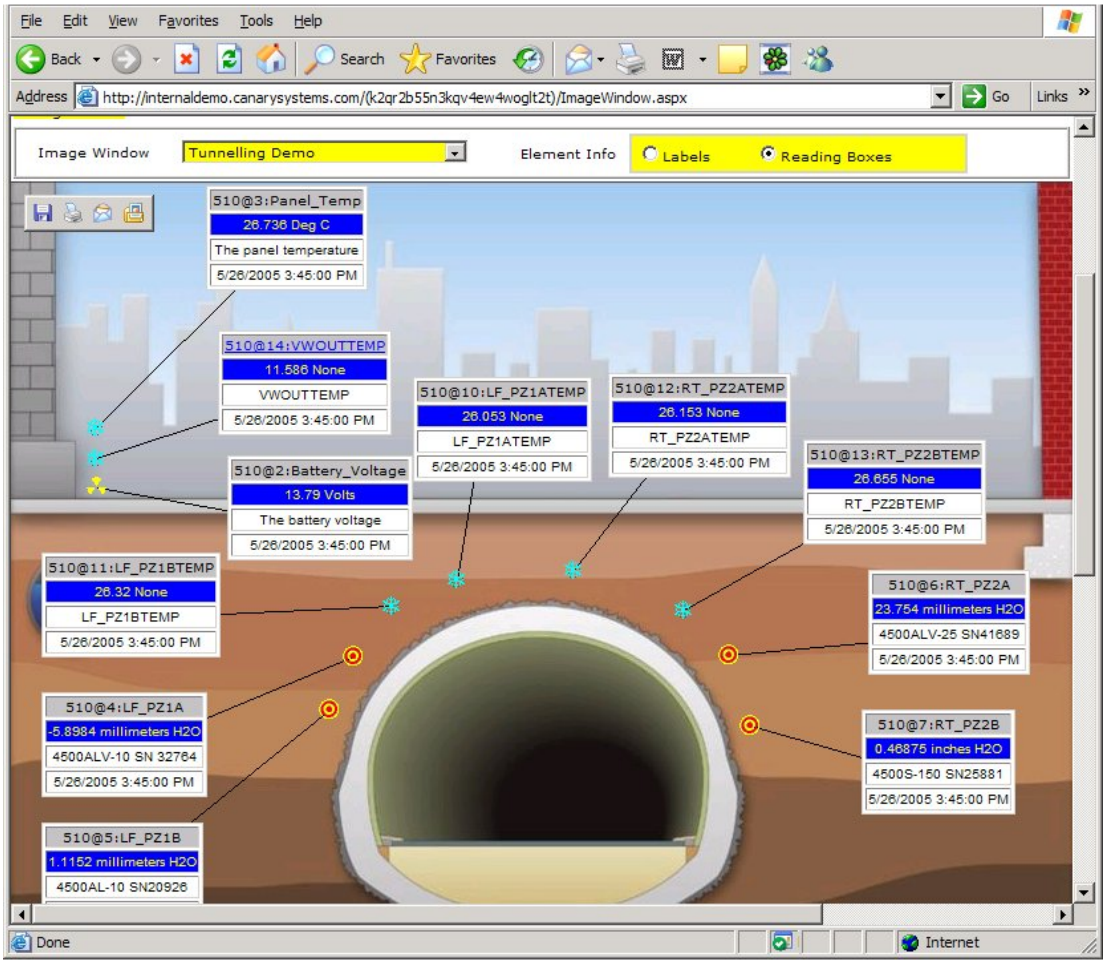


Fig. 16.6 Canary's Web data access

Canary's Measurement and Control Units (MCU's) are manufactured by Campbell Scientific, Inc. Canary's MultiLogger software also supports data acquisition hardware from other manufacturers, contact us for additional details. It is an effective measurement system requires other peripherals in addition to the MCU, including instrument multiplexers for expanding the number of channels, sensor interface products, power supply, charging system, field worthy enclosures and alarm devices such as audio/visual alarms and/or voice dialers.

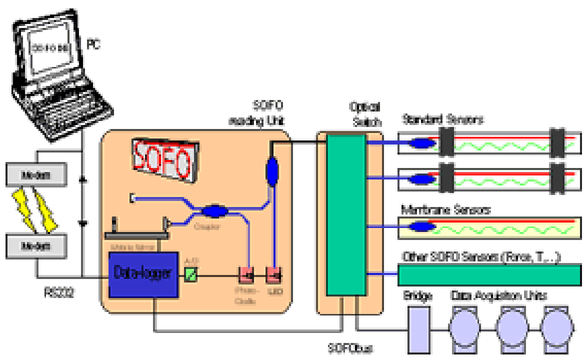
16.4 Roctest Group

The Roctest Group provides Integrated Structural Health Monitoring Solutions for bridges, based on advanced fiber optic technologies and conventional sensors. Of a number of expertise areas, Roctest has developed automated, customized structural health monitoring system for bridges. Different Roctest packages are used to meet the specific monitoring requirements and needs of each project:

SOFO advanced fiber optic system for global monitoring of structures,MuST multiplexed strain and temperature monitoring system based on fiber Bragg gratings (FBG) FISO point sensing sensors based on Fabry-Perot Interferometers DiTeST/DiTemp Distributed temperature and strain monitoring (Brillouin/Raman scattering) Vibrating Wire for long-term monitoring and geotechnical applications 3DeMoN 3-dimensional movement monitoring network based on Laser technology SensCore corrosion monitoring systems
Each system is composed of appropriate sensors for measurement needs; hardware for field data acquisition, transmission and management; and software for data acquisition, management, publishing and analysis. In addition to fiber optic sensors, the Roctest Group also integrates local corrosion sensors and other third party transducers for additional information. All sensing technologies are seamlessly integrated into a single database and user interface.

For example, the SOFO Monitoring System is shown in Fig. 16.7. Besides being a real-time, continuous and autonomous monitoring system capable of measuring deformations over a long measurement basis, it provides quantitative data on structural behavior with a micrometer resolution and long term stability. The SOFO software enabled automatic and scheduled measurement and real-time, simultaneous display of several different views within the same window. This software can trigger an alarm based on a user-defined action such as sound, phone call, e-mail and etc. when specific threshold had been crossed.

The Roctest Group offers a comprehensive solution for bridge monitoring. This includes the design of the system, its delivery and installation, maintenance and operation, web access to the data and data analysis by experienced engineering partners, all for a fixed monthly fee through its SHMLive service.



(a) SOFO configuration

(b) Embedded in concrete (c) Deformation measurement of a concrete bridge deck

Fig. 16.7 SOFO Monitoring System

The Roctest Group has been instrumenting a number of bridges worldwide with their SHM systems (http://www.roctest-group.com/references/byapplication). Pont Adolphe Luxembourg Bridge in Luxembourg, Manhattan Bridge in United States of America, Bolshoi Moskvoretskiy Bridge in Moscow and etc. are among the bridges that had been installed with this SOFO System.

16.5 Omega Engineering Inc.

OMEGA offers a variety of sensors and data acquisition systems (various sensors and electronics, instruments supplier). Some of the Omega products can be used to establish a bridge SHM system to meet special monitoring needs although OMEGA itself doesn't offer complete SHM systems.

For example, Omega offers linear displacement potentiometer, thermocouple/temperature sensor, strain gage, load cell, etc., and portable, battery powered data logging system of analog and/or digital channels, and analog to digital converters.

Some of Omega data logging systems are designed for long-term remote data collection applications. Software configuration with plug-in interface modules. PCMCIA data memory modules available. Icon-based Windows software (graphically plot up to seven data channels vs. time). Software provides a real time, scrolling display of data collected on a serially connected PC screen. Other various data acquisition systems available.

16.6 Omni Instruments:

Omni Instruments supplies various sensors and instruments for measurement, control and data acquisition. The products which can be potentially used to develop a bridge SHM system include

- Sensors for most measurement applications: displacement, accelerometer, humidity and temperature sensors, vibration, load cells, etc

Single or multi channel data logger or data acquisition systems with power supplies and weatherproof housings etc.

- Radio/GSM/GPRS Telemetry: a full range of remote monitoring and communication solutions using modern technologies such as GPRS and SMS text messaging. The systems can be accessed via a simple web browser and daily readings sent via email to multiple engineers.

- Control and Display Products: LED and LCD displays, trip amplifiers, signal conditioning units to complement Omni sensors and loggers for current, voltage, temperature, resistance, frequency and strain gauge devices, power supplies, analogue to serial and MODBUS converters.

Depending on products used and the system configuration, direct wire connection or other communication options (e.g., radio, modem, telephone line, Internet, etc.) are possible for real-time, continuous monitoring with alarming capacity in a SHM system with Omni Instruments' products.

Limitation:

- Remote data logging system: -40°C to 60°C operating temperature, 0 to 90% relative humidity.

- DataWeb 4000 logger: -5°C to 45°C (23 to 113°F) operating temperature, 0 to 90% relative humidity.
- Radio data logging system: -10 to 55°C operating temperature, 0 to 90% relative humidity (non-condensing).

16.7 Smart Structures LLC:.

Smart Structures has developed and manufactured standard products and customized systems capable of monitoring all aspects of the structural health. Its structure health monitoring system uses elasto-magnetic (EM) stress sensors, a wireless smart sensor network, and fiber optic sensor (FOS) system.

Smart Structures product for bridge SHM include:

Smart Scanner: a line sensor scanner uses photonics to measure surface displacement strain, interpreting pre-event and post-event images through the use of digitalized image correlation analysis. Its software can perform a correlation analysis between the two test events to document the directions and magnitudes of strain on the bridge.

EM sensors for monitoring stress and corrosion in steel cables/tendons/strands.

A wireless smart sensor network for strain gages and accelerometers. Remote controller is housed in an enclosure that collects and controls data using the serial port of a PC and customized software Coverage has a range of 300 feet with 33.6k baud. – over large areas (several miles) are available.

Smart FBG Sensor Array for fiber optic monitoring applications such as sensing strain and temperature at concrete and steel structure for a long-time monitoring purpose. The complete FOS system include the FBG sensor, a control unit and optional internet server (Fig. 16.8). Here a single sensor is shown hooked up to the Control Unit by a fiber optic cable. The Large Motion Sensor tracks displacements up to 10 cm (4”) in 125 micron increments. Large motion is typically experienced at the bridge expansion bearings. By deploying a number of sensors at the fixed and mobile ends of a bridge deck, a continuous readout of bridge health is available.

Other customized sensors: SmartTilt meter, Smart Accel, SmartTpRh for temperature and relative humidity, SmartWind2 and SmartWind3 sensors for wind speed and direction, SmartGPS for millimeter-scale movement of bridge structures, and SmartWIM for capturing speed and type of vehicles pass through a bridge.

Data acquisition system: a rack-mount UNIX-based PC, controlling multifunction data acquisition card and modem, and signal condition modules and anti-aliasing filters.

Bridge monitoring system (BMS) software (web-based server application, password protected). Through a web browser, a user can view the real-time data, retrieve raw data, perform advanced analysis and obtain health reports of the bridge.

Fig. 16.8 A complete FOS system (Smart Structures, LLC)

A list of projects using Smart Structures' systems are available http://www.smart-structures.com/projects.htm. Fig. 16.9 shows the design of FOS bridge health monitoring system recently implemented on a cable-stay bridge (***Zhanjiang Bay Bridge, China).*** The monitoring system includes the following measurements: stress and the strain in the structure, temperature of the structure, dynamic mode analysis, the force in stay-cables, structural space deformation, wind loads, structural loading condition, and connection joint monitoring of the steel and concrete beams.

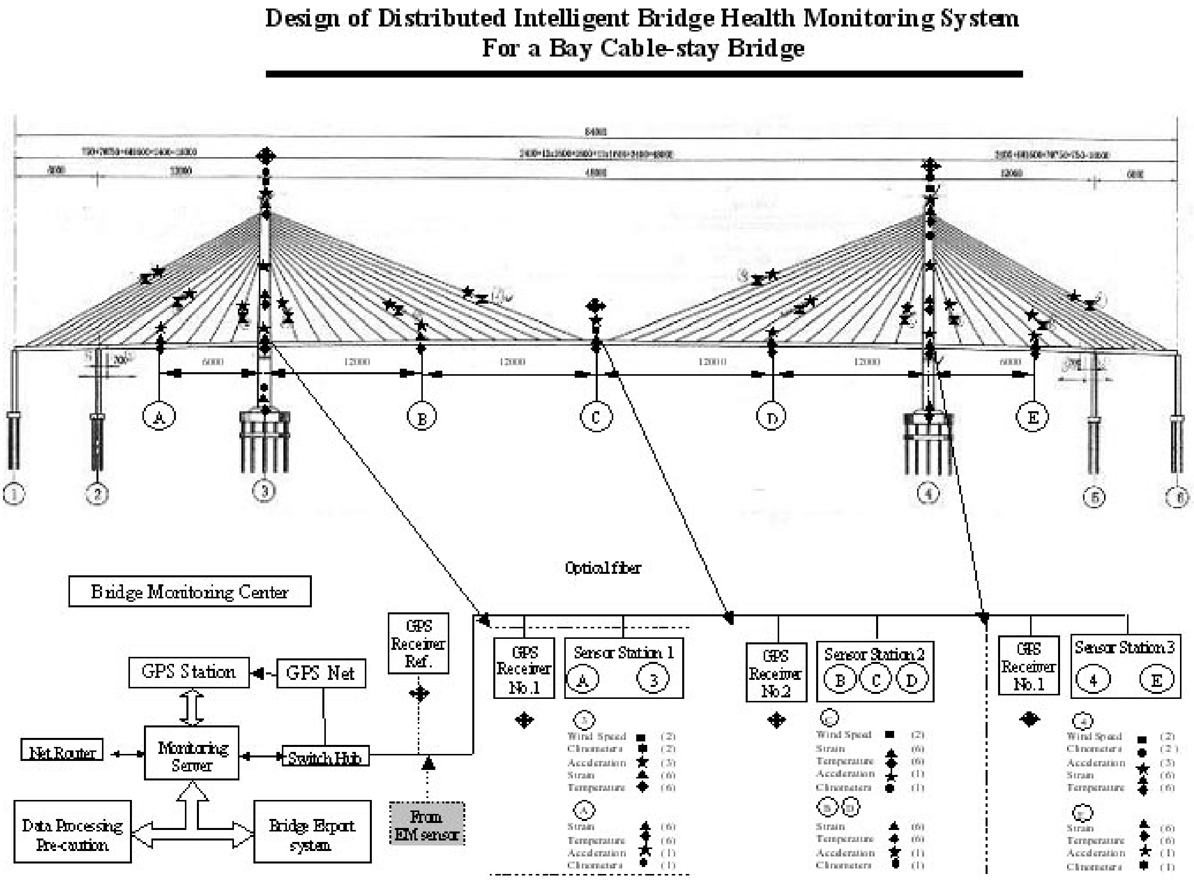


Fig. 16.9 Design of SHM system by Smart Structures

17 SHM OF CRACKING

Cracking is one of the most common damages found on bridges during inspection. Crack can occur in both concrete and steel bridge members, joint/connection, even in reinforcing bar and prestressed tendon. Cracks have caused collapses of bridges (Silver bridge, 1967, etc.) and closure of bridges for repair. Proper assessment of cracking is critical in structural health monitoring. Various aspects of cracks such as length, width, depth, and pattern should be documented. Additionally, it is important to document if any movement has occurred relative to observed cracking, such as shrinkage, displacement, or volumetric expansion.

A variety of technologies have been developed for SHM of cracks to identify and locate the crack damage, also to monitor the growth and propagation this type of damage.

17.1 Acoustic Emission (AE) Based Technologies

Acoustic emission (AE) is simply the stress waves, in the frequency range of ultrasound usually between 20 KHz and 1 MHz, generated in the materials due to deformation, crack initiation and growth, crack opening and closure, dislocation movement, twining and phase transformation, fiber breakage and delamination. The sources of AE are predominantly damage–related and AE monitoring leads to the prediction of material failure.

AE testing involves recording and evaluating AE signals to identify evolution of damage. This is usually accomplished by direct coupling of piezoelectric transducers on the surface of the structure under test and loading the structure. The output of the piezoelectric sensors (during stimulus) is amplified through a low–noise preamplifier, filtered to remove any extraneous noise and further processed by suitable electronics (see Fig. 17.1). AE tests can non–destructively predict early failure of structures. Further, a whole structure can be monitored from a few locations with additional sensors and while the structure is in operation.

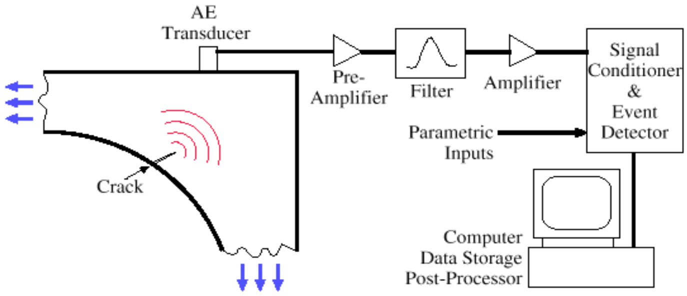


Fig. 17.1 Principle of acoustic emission process (Huang et al. 1998)

For bridge structures, AE detection may be a result of crack initiation and/or growth, crack opening and closing (i.e. fretting/rubbing of crack faces and bolts), and/or dislocation movement in steel components. AE has also been successfully used for monitoring bearings in swing and lift bridges, deteriorating reinforcing steel, concrete decks, concrete cracking and corrosion of substructure components.

17.2 ÆSMART 2000 by Dunegan Engineering Company, Inc.

One issue with acoustic emission analysis on bridges is the possible extraneous noise caused by impacts and friction. ÆSMART 2000 utilizes its own acoustic emission sensors and patented "MODAL RATIO" analysis to separate valid crack growth signals from extraneous noise and to estimate crack depth, all in real time and in 'noisy' environment. AE SMART 2000 system can:

- detect crack growth and estimate crack depth in real time,
- perform global monitoring of growing cracks in "NOISY" structures,
- monitor known cracks, without traditional guard transducers,
- do both laboratory and field measurements with the same portable instrumentation, and
- include up to 100 channels at low cost per channel.

The system needs direct wire connection. When real-time, continuous crack monitoring is not necessary, an automatic system "hold" allows to only record data when the load is present on the bridge. The system can be operated in low temperatures (for example, the H series sensors at -20 to 60°C; the M series sensors at -50 to 125°C; the P and Q series sensors at -50 to 100°C; the MUX-MODULE and Model 600 pulser at -50 to 50°C).
The system has been used to Railroad bridges in Pueblo, Colorado to detect the Crack growth at the known crack locations (THE DECI REPORT – JAN. 2002 http://www.deci.com/decireport102.pdf) and to detect the initiation and growth of new fatigue cracks in the test specimen Mason Creek Bridge, Canada (DECI NEWSLETTERS AND REPORTS, http://www.deci.com/dnlreport.htm).

17.3 Physical Acoustics Corporation (PAC)

(http://www.pacndt.com/products/Remote%20Monitoring/Civil_Structures.pdf)

Physical Acoustics Corporation (PAC) designs and manufactures the complete AE product line - AE sensors, AE measurement instruments and software. They have developed real-time, on-line, intranet based monitoring paired with remote and/or wireless acoustic emission (AE) systems. What cracks?

PAC's Sensor Highway II™ system supports 16 high speed AE monitoring channels and handles multiple parametric sensor inputs (+/- 10 volts). The system is housed in a rugged outdoor case; capable of operating in extreme weather (with a temperature range of -35º -70º C) and factory conditions. The system has been developed for un-attended condition monitoring and "Asset Integrity Monitoring" management. The key feature of this system is its highly flexible sensor fusion interface for input and processing of almost any variety of AE sensors. This interface is accomplished inside the Sensor Highway II system through the use of standard industrial, DIN Rail mounted signal conditioning modules, with options for proximity probes, pressure transducers, load cells, thermocouples, environmental sensors, strain gages, wireless sensors *and more*.

The Sensor Highway II™ has several interfaces available for data communication and remote control. The principal interface is the built-in Ethernet 10/100BT port (or optional wireless Ethernet). Other available interfaces include: cellular modem and wireless.

Fig. 17.2 Sensor Highway II System ™.

PAC AE systems have been used to a variety of projects, including:

Suspension Bridges

AE systems have been installed on a suspension bridge in Pennsylvania to monitor, record, interpret, identify and report possible wire breaks and other activities (e.g. vandalism) on main suspension cables.

Concrete Bridges

AE testing of concrete beams in controlled field conditions has been successful for sorting good from bad beams. As traffic load is applied, the systems can distinguish between background noise, new cracking, existing cracks, wire breaks in tendons and corrosion in tendons.

Cable Stay Bridges

The AE systems have successfully monitored cable stay bridges by finding broken wires in cables.

Steel Bridges

Over one hundred bridges have been tested using Acoustic Emission by MISTRAS Group (of which PAC is a member), Universities and bridge authorities. Using the Kaiser Effect, which has been incorporated into many ASTM, ASME and other codes and standards, AE can determine if load ratings for bridges are within safe load conditions.

17.4 SoundPrint Acoustic monitoring system by Pure Technologies, Ltd.

SoundPrint uses an array of sensors or distributed fiber optics acoustic sensors to measure the response of a structure caused by the energy released when tensioned wires/stand/cable fail or other event of interest occur. The system can be used in prestressed concrete, cylinder pipes, reinforcement in post-tensioned structures, or as primary supporting elements in cable-stayed or suspension bridges that can corrode and fail without any external evidence, leading to potential structural deficiency.

SoundPrint sensors are connected to a data acquisition system located in or near the structure being monitored. SoundPrint filters out acoustic events caused by ambient activity such as traffic or loose joints. Data from events that pass a primary filtering process are then automatically transmitted to a data-processing center by means of the internet. Sophisticated proprietary software is used by Pure Technologies' analysts to determine the time, location, and classification of each event.

Users can get direct access to data from their structures via Client Access portion of Pure Technologies' website. Using the website's intuitive interface, users can custom-design their own reports, which are generated in real time. They can examine and replay all acoustic events in real audio format, and view and print presentation-quality reports from multiple sites. Comprehensive security ensures that only authorized individuals can access specific sites.

SoundPrint® is currently in use or has been in use as a structural monitoring system on a variety of structures, including post-tensioned, pre-tensioned, suspension and cable-stayed bridges (Fig. 17.3). New York State Bridge Authority had commissioned Pure Technologies Ltd to install SoundPrint® at Bear Mountain Bridge at Fort Montgomery, New York since February 2001. Since commissioning the system has achieved an operating efficiency of over 99%. In addition to identify and locate blind wire cuts successfully, a number of spontaneous wire breaks have also been identified. Bear Mountain Bridge is one of the case studies installed with SoundPrint®. Others include Waldo Hancock Bridge, Bronx-Whitestone Bridge, Fred Hartman Bridge, and Quincy Bayview Bridge (Fig. 17.4). In addition to a proven track record of monitoring the deterioration of prestressing tendons, cost-effective, targeted repairs have been carried out on a number of structures based on information generated by SoundPrint.

Fig. 17.3 Wireless Sensors attached to cable (Waldo Hancock Bridge, Verona, Maine)

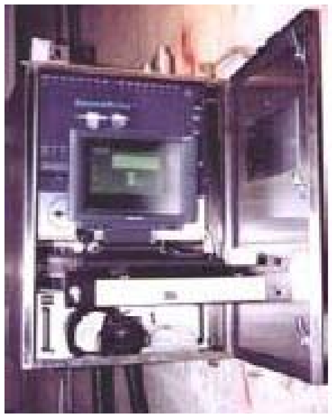


Fig. 17.4 Data acquisition system (Bronx-Whitestone Bridge, NY City)

SoundPrint provides a tool that helps ensure the long-term integrity of these bridges by detecting and locating tensioned wire failures through continuous, non-intrusive remote monitoring. The system can be designed to withstand any harsh environmental condition.

17.5 Impact-Echo Based Technology

Impact–echo (IE) is a nondestructive test method specifically developed for concrete and masonry structures. The IE method is based on the use of impact–generated stress (sound) waves that propagate through the structure and are reflected by internal flaws and external boundaries of the structure. The reflected waves are recorded by a displacement transducer placed near the impact point. The record of displacement versus time is transformed into the frequency domain for ease of signal analysis. A study of the time–domain waveform and frequency spectrum makes it possible to locate and detect subsurface flaws (see Fig. 17.5). Impact–echo method has been employed to detect flaws in concrete materials and members (Sansalone 1997) and bridge decks (Tawhed and Gassman 2002).

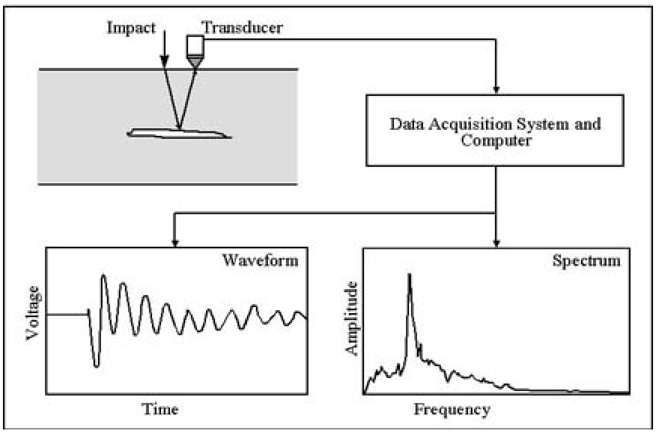


Fig. 17.5 Schematic diagram of impact–echo method (Sansalone and Streett, 1998)

The acoustic instruments by Impact-Echo Instruments, LLC. use piezoelectric transducers, an analog/digital data acquisition system, and Impact-E software for evaluation of concrete and masonry structures. The systems can measure thickness of concrete plates such as pavements, retaining walls, and tunnel walls, in compliance with ASTM Standard C1383-98a. They can also measure the depth of surface-opening cracks, and determine the location, depth and extent of cracks, voids, delaminations, honeycombing and debonding in plain and reinforced concrete structures.

Impact-Echo Instruments have been used successfully to locate flaws and defects in highway pavements, bridges, buildings, tunnels, dams, piers, sea walls and many other types of structures, and to measure the thickness of concrete slabs (pavements, floors, walls, etc.). It is claim to be able to be used in most environments (not under water).

Impact-Echo Instruments has just developed a new Wireless Echo system for 2-man forensic teams (Fig. 17.6). One operator uses the testing device (transducer) on the structure being tested, and the signals are sent by wireless to the computer, where the second operator sees the resulting signals on the computer screen just as they appear when the transducer is connected by wire to the computer. The wireless system is effective for distances up to 300M between the two operators.

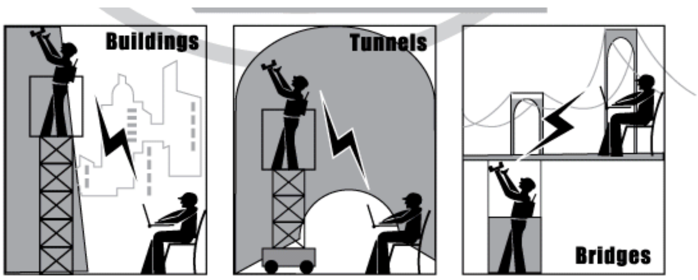


Fig. 17.6 Schematic view of Wireless Echo system

17.6 Other technologies

17.6.1 Advanced Structure Monitoring (ASM), Inc

Advanced Structure Monitoring, Inc. developed the diagnostic-network-patch (DNP) system and "interrogation-networking" or ubiquitous-transceiver-networking (UTN) methods for real-time monitoring and forecasting structural condition.

DNP sensors are one-piece dual-function devices of coin-sized thin multilayered devices containing piezoelectric disks for actuator and sensor. The thin multilayered disk is used as an extra film patch that is either bonded onto or inserted into the structure for the purpose of interrogating guided acoustic signals with structural health condition of laminated composites, plate-like metallic and concrete structures.

DNP datalogger is designed to interface with the DNP sensors and actuators. The DNP interrogator has the built-in capability to energize the piezoelectric devices embedded in the DNP patches and record the measurement signals of neighboring piezoelectric sensors and fiber-optic loop sensors. DNP Advancer is graphic-user-interface database software with plug-in capabilities for a variety of active-SHM and "interrogation networking" modules for grouping and networking DNP devices, interrogating anomalies in structures, collecting the diagnostic signal data of structural conditions and physical properties, and then displaying a variety of data in real time.

According to the manufacturer, DNP is the first scanned-image-based SHM system for damage identification. The DNP can be used on any materials (e.g., concrete, steel, timber, etc), but it appears most suitable for composite and metal structures for crack detection, degradation of material properties, debonding and delamination, impact and aging detection.

17.6.2 Fatigue Damage Sensor (FDS) by Kawasaki Heavy Industries (KHI), Inc.

FDS are made of two metal foils or leaves. On FDS, crack will propagate from the initial notch after receiving fluctuating strains on the structural members. The fatigue damage can be monitored by measuring its crack length on FDS using the fundamental characteristic of FDS; its crack growth rate is always constant independent of its crack length against the same strain fluctuating ranges (Fig. 17.7). More accuracy results will be anticipated as compact Kawasaki FDS can be attached on the stress concentrating areas as close as possible. Comparing to the fatigue damage evaluation method by strain gauges, monitoring method by FDS is a simple and easy one with low-price.

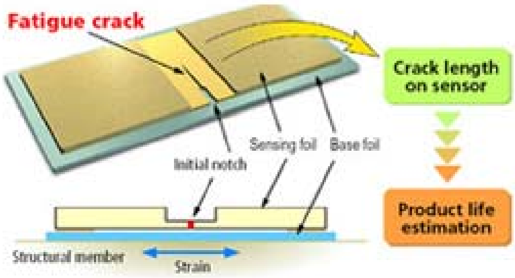


Fig. 17.7 Structure of FDS by Kawasaki Heavy Industries

FDS is very small and can be applied to local stress concentrated locations; it can sense the geometrically concentrated stress in the vicinity of welding beads or other weld locations; responds even to compressive cyclic stresses. FDS is easy to be attached with commercial adhesive; requires neither costly measuring instrument nor wiring. FDS can be used on both new and existing bridges. In a highway bridge, the remaining life evaluation by FDS was verified by comparison with the stress frequency method (Kawaguchi et al. 2003).

17.6.3 Fatigue crack sensor by Strainstall Ltd.

Strainstall designs and manufactures a fatigue sensor system, the CrackFirst™ sensor for welded joints in steel structures. The CrackFirst™ sensor consists of a thin shim of material attached to the target structure close to a critical joint.

Under the action of cyclic stress in the structure, a fatigue pre crack at the centre of the shim, introduced during manufacture, extends by fatigue crack growth. This indicates how much of the design life of the adjacent weld has expired and how much remains. It is of most benefit for structures in which fatigue is the primary limit state, especially in situations where inspection and repair is difficult or impossible, or where structural failure would have significant consequences with respect to safety and/or financial loss. Typical applications include cranes, earth moving vehicles, bridges, offshore structures, railway bogies and many more.

There are several methods of powering and interrogating the sensor, which are based on the client's requirements. The simplest method is to interrogate the sensor using a multimeter. There is a known relationship between electrical resistance and crack length. For remote location or more frequent checking, an on-board electronics unit regularly checks the sensor status and records in memory the date/time of each crack increment. Sensor data can be downloaded to a laptop PC via a wireless link or to a datalogger. The power can be obtained from an on-board battery, a remote battery pack, the vehicles power or from a mains supply.

17.6.4 Comparative Vacuum Monitoring (CVM) system by Structural Monitoring Systems (SMS) Ltd.

SMS's CVM system, consisting of an inert sensor, a regulated vacuum source, and a fluid flow-measuring device, has been developed and used mainly for the aerospace industry for in-situ, real-time monitoring of crack initiation and/or propagation (Fig. 17.8).

CVM is a measure of the differential pressure between fine galleries containing a low vacuum alternating with galleries at atmosphere in a simple manifold. If no flaw is present, the vacuum will remain at a stable level. If a flaw develops, air will flow through the passage created from the atmosphere to the vacuum galleries. Sensors may either take the form of self-adhesive polymer "pads" or may form part of the component. A transducer measures the fluid flow between the galleries.

This product is capable of being integrated with an aircraft to provide an in-flight structural health monitoring system (SHM). The In-flight structural health monitoring system developed using the CVM™ technology is able to continuously monitor the development of any cracks in predefined areas on an aircraft that are deemed to have a high risk of crack formation. The implementation of this technology will reduce the cost of mandatory structural integrity maintenance inspections, increase aircraft performance, and provide an increase in the safety of air travel. Based on this application, it seems that CVM can be well suited for monitoring bridge structures; since it measures relative vacuum flow, it works on permeable materials such as concrete, in addition to steel and other materials.

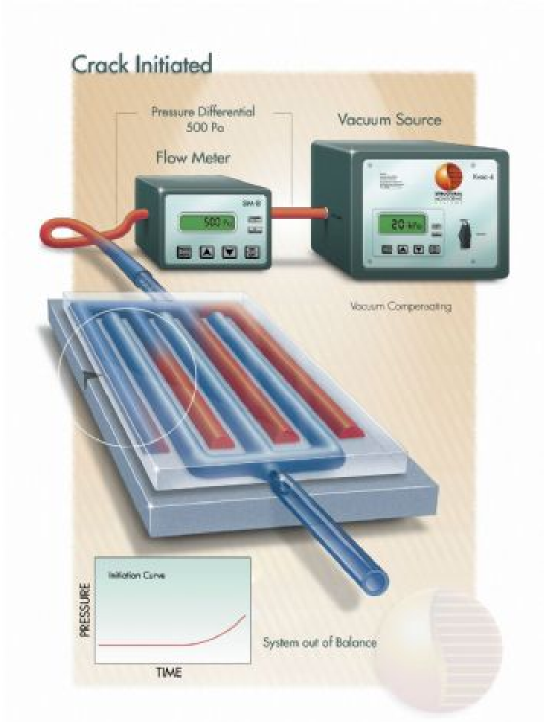


Fig. 17.8 CVM system installed on a damaged component

Installing CVM sensors is simple and quick; the test surface is pre-cleaned and the sensor removed from its release liner case and laid on the test surface and rolled firmly down. The PTFE tubes are then inserted. In particularly harsh environments, sensors are over coated with specified polymer / resins to provide extra protection to the sensor and to the parent structure. Sensors can also be embedded within the mass of a structure. Sensors can be embedded within bonded joints and lap joints to monitor for failure within the joint.

18 SHM OF CORROSION OF CONCRETE AND STEEL BRIDGES

Corrosion of rebar in concrete bridges is perhaps the most common form of deterioration found in concrete bridge structures and is difficult to detect. The steel reinforcement in concrete structures is susceptible to corrosion when chloride ions enter into the concrete from de-icing salts applied to the concrete surface, or from seawater in marine environments. If chlorides are present in sufficient quantity, they disrupt the passive film on the reinforcing steel, resulting in corrosion. Oxygen content, moisture availability and temperature also affect this corrosion rate. Corrosion of the reinforcing steel can weaken the structural strength; create cracking, delaminating and spalling of the concrete. Although periodic visual inspections are performed on bridges, they cannot reveal the early symptoms of rebar corrosion within the bridge deck. By the time external visual evidence is seen, the damage has already occurred, and the bridge deck will need replacing. Core sampling can measure the levels of both pH and chloride, but it is time consuming and expensive.

Besides reinforced concrete structures, corrosion damage also occurs in steel structure since steel oxidizes when exposed to oxygen, particularly in moist environments. Therefore it is desirable to monitor the corrosion condition of such structures, sometimes right from the construction stage, by carrying out periodic corrosion surveys and maintaining a record of data. Many electrochemical and non-destructive techniques are available for measurement of the corrosion rate of reinforcing steel in concrete and steel structural members.

18.1 Advanced Corrosion Monitoring (ACM) Instruments

For field corrosion monitoring, ACM offers Field Machine - a PC controlled and portable instrument that performs both AC and DC tests. It can be fitted with our GalvoGuard probe electronics to allow galvanostatic guard ring operation. The Field Machine may also be equipped with the potentiostatic guard ring electronics to allow all DC tests under guard ring focus. Some of ACM's other products may also be considered, the LPR Meter, the Pocket Machine and the Field Logger offer small lightweight solutions to specific problems, but without the versatility of the PC controlled instruments.

By adding internet connection either via a LAN, phone line or mobile phone, ACM offers new internet control software that the data can be retrieved from any PC connected to the internet, proving the ability to change parameters in the office. The resulting data is then plotted as a 2D or 3D contour map to help with bridge repair and operation.

Housed in a professional slim black case, fully waterproof a go anywhere instrument, from Sahara heat to the cold of Alaska. A long battery life ensures prolonged testing in the field. Operating temperature: -5°C to 72°C.

18.2 Corrosion Monitoring Systems by Force Technology

The concrete monitoring products by Force Technology include:

The CorroRisk probe consists in the standard version of 4-8 measuring electrodes and 1 combi-electrode. Initial corrosion is discovered when threshold values of the potentials or current have been exceeded. The potential of the equilibrium is measured between the combi-electrode and the individual electrodes in the concrete cover.

The CorroRisk probe has been developed for use on existing concrete structures, especially in aggressive corrosive environments and where visual inspection is difficult. This could e.g. be pillars in seawater, bridge decks, multi-storey car parking structures exposed to de-icing salt and various structures in swimming pools. The CorroRisk is usually mounted in the cover layer between the concrete surface and the outer reinforcement layer.

The ERE 20 is a true, long life Reference Electrode, which can be cast into the cover concrete to check the cathodic protection and to monitor the corrosion state of reinforcing steel or predict corrosion. Normally in newly cast concrete structures, but the electrode can also be installed in existing structures. It can be used for potential measurements in wet and dry concrete, and can be exposed to chloride or carbonation.

The **CorroWatch** is a multiprobe, which in the standard version consists of four black steel anodes and one noble metal cathode. The CorroWatch acts as an early warning system to predict the initial stages of corrosion in concrete structures. It is cast into the cover concrete, normally in newly cast concrete structures. The sensor can measure most of the relevant corrosion parameters.

Fig. 18.1 CorroWatch and ERE 20 attached to the reinforcement

The **GalvaPulse™** is a rapid, non-destructive polarization technique for the evaluation of reinforcement corrosion rate as well as half-cell potentials. The GalvaPulse™ is a lightweight system supplied with batteries for optimum portability and is designed to be operated by one man. It can be used for reliable evaluation of reinforcement corrosion also in wet, carbonated or inhibitor treated concrete.

Fig. 18.2 GalvaPulse™: Hand held computer and electrode

All the probes can easily be attached to a logger for collecting and monitoring low-potential-values. Time interval can be specified either in seconds or minutes. User-friendly Window-based software program is available for managing interval and delay for readings. Remote monitoring by modem is also possible. In recent years, FORCE has completed projects in about 60 countries all over the world. The corrosion monitoring system can be used in a temperature range of -40°C to 75°C.

18.3 Ground Penetrating Radar (GPR) for bridge deck monitoring by Geophysical Survey Systems, Inc (GSSI)

The GSSI's BridgeScan™ is a complete, affordable GPR sensing and data acquisition system that provides an effective tool for quickly determining the condition of aging bridge decks, parking structures, balconies and other concrete structures. The system can identify rebar location and depth, obtain overlay thickness, determine concrete cover depth, and define area of delamination. (Fig. 18.3)

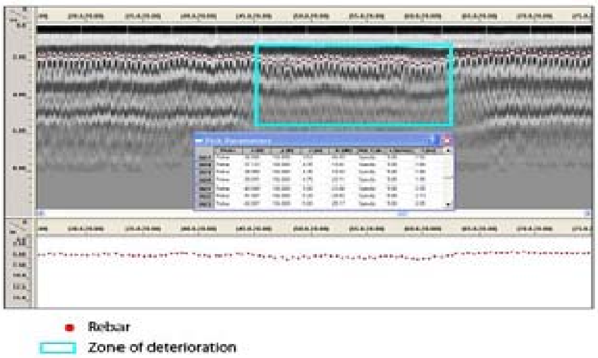


Fig. 18.3 BridgeScan for bridge deck inspection

Another complete GPR system for concrete inspection and analysis by GSSI is the StructutreScan products. The StructutreScan products can be used to locate metallic and non-metallic targets, voids concrete, to measure slab thickness, and to map relative concrete condition for rehab planning.

GSSI's GPR system has been used in a number of bridge deck evaluations. It can be used in a temperature range of -10 to 40°C.

18.4 Ground Penetrating Radar (GPR) and Infrared thermography (IR) monitoring system by INFRASENSE, Inc.

INFRASENSE's GPR bridge deck evaluation system uses various combinations of GPR air-coupled or ground-coupled antennas, and/or Infrared Thermography (IR) video cameras, to identify bridge deck conditions including: assessment of delamination and freeze-thaw damage, computation for depth of rebar, evaluation of deterioration quantities, measurement of overlay thickness, and quality control of rebar placement.

Data is collected at driving speeds by a Laptop computer with a Windows-based GRP data analysis software (Fig. 18.4). Lane closures are not required, traffic is not interrupted, and personnel are not exposed to safety hazards.

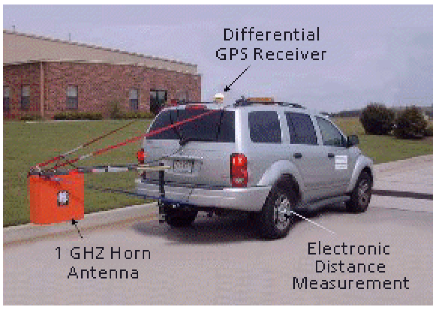


Fig. 18.4 Survey vehicle

The system has been used to a number of bridge projects which are available at the company's website.

18.5 MEMS Concrete Monitoring System by Advanced Design Consulting (ADC), Inc.

ADC combines radio frequency identification devices, or RFIDs, with its MEMS sensors in a package that can mix with Portland cement and be poured along with the concrete and embedded in a new bridge, building or roadway. The ultra-small sensor monitors moisture, temperature, pH, as well as the concentration of chloride, sodium and potassium ions within the concrete. These devices will provide critical data for evaluating concrete performance from its freshly mixed stage to its casting, through the concrete's service life, to its period of deterioration and repair. The sensors will be powered by electrical energy radiated from a hand-held monitoring device and transmit its data and identity by reradiating the signal. At other times, the sensor would remain unpowered.

18.6 Smart Aggregate by Johns Hopkins University

Smart Aggregate, based on wireless embedded sensor platform (WESP), was developed for concrete corrosion monitoring. Smart Aggregate composed of sensor, transducer and communication system can be embedded in concrete at pouring to measure the corrosion of rebars. These sensors can measure the concentration of chloride ions and the actual corrosion rate using a sacrificial sensor.

The WESP is small (about the size of a quarter), rugged (made of high compression strength ceramics) and versatile (capable of being integrated with a wide variety of sensor elements), long lasting (no battery), and wireless. It can be placed in a holder mounted on rebar. A remote transmitter powers the WESP up from a sleep mode, the sensor readings are converted in the WESP and transmitted to a receiver and once the measurement is made the unit goes back to sleep until the next request is made.

Researchers have installed several prototype Smart Aggregates in a bridge deck in Montgomery County, Maryland, and are gathering performance data.
(http://maintenance.transportation.org/Documents/MMC2009Session3B-3SrinivasanPaper028.pdf)

18.7 Smart Pebble by SRI International

Working with CalTrans (California Department of Transportation), SRI International had developed chloride threshold sensors called Smart Pebbles™ which are literally the size and weight of a pebble. Smart Pebble is a unique combination of an electrochemical chloride-concentration sensor with a wireless radio-frequency identification (RFID) chip (Fig. 17.13). It is a passive sensor activated by radio frequency waves for monitoring the level of chloride ingress into concrete bridge decks. It is designed to be inserted in the bridge deck either during the initial construction (or during refurbishment) or in a back-filled core hole.

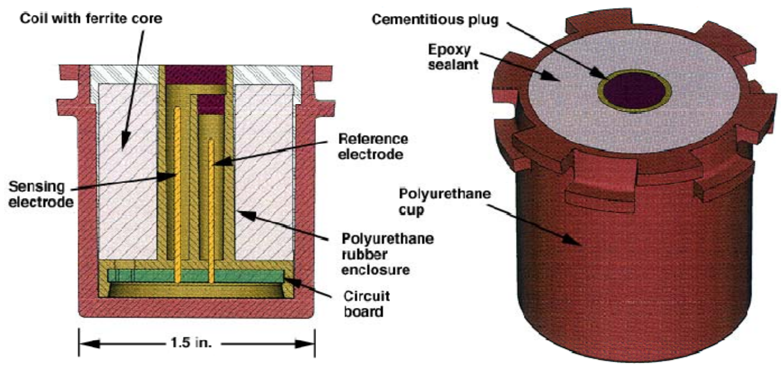


Fig. 18.5 Smart Pebble Package design

The sensors can be activated by a handheld or vehicle-mounted RFID data logger that gathers the data as it passes over them. To collect the sensors readings, the reader emits a blast of radio energy and each radio query identifies an individual pebble. And by using Global Positioning System (GPS), the health status of the bridge will automatically update in the bridge database.

Laboratory tests of Smart Pebbles have so far been very positive. It is said Caltrans is formulating plans for a long-term evaluation of Smart Pebble prototypes in both the lab and in selected bridge decks.

18.8 SoundPrint for corrosion breakage of steel rebar/tendons by Pure Technologies, Ltd.

SoundPrint uses an array of sensors or distributed acoustic fiber optics sensors to measure the response of a structure caused by the energy released when tensioned wires fail or other event of interest occur. The system could also be used for tendon monitoring, corrosion, fatigue crack, bolt/rivet failure detection.

See Chapter 17 for more information about Pure Technologies and their SHM products.

18.9 Corrosion Monitoring System by S+R Sensortec GmbH

S+R Sensortec GmbH designs corrosion monitoring systems by using moisture sensor (multiring electrodes), temperature sensor (PT 1000), corrosion sensors (Anode Ladder and Expansion Ring Anode). The Anode Ladder consisting of single steel anodes at different depths is used for monitoring of time dependent chloride ingress or carbonation progress into the concrete both for newly built and existing structures. Expansion Ring Anode comprised of individual steel anodes at staggered depths is installed into existing structures to monitor the time-dependent penetration of chlorides or the carbonation depth into the concrete.

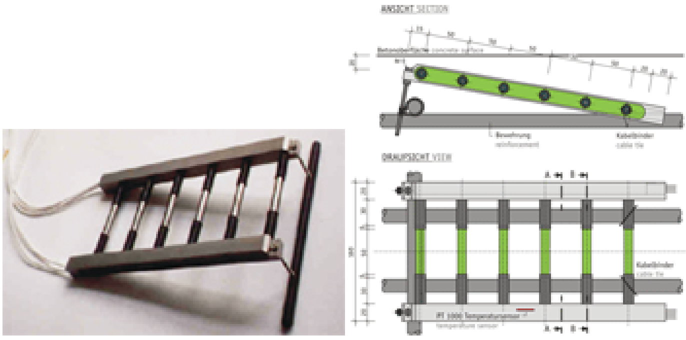


Fig. 18.6 Anode Ladder corrosion sensor

The monitoring system has been used to a variety of bridge projects. Wireless communication can be designed upon request. Operating temperature measurement range: ±99°C with ± 2°C accuracy.

18.10 Corrosion Monitoring system by Rohrback Cosasco Systems (RCS)

To prevent deterioration of the reinforced concrete infrastructure, many new structures are installed with cathodic protection (CP). CORROSOMETER probe by RCS can be used to evaluate the effectiveness of the cathodic protection system by detecting when chloride ingress is nearing the rebar, measuring and recording metal loss and the corrosion rate. Using a portable CORROSOMETER instrument such as the Checkmate, readings are taken at intervals and the metal loss recorded. These values are plotted in a spreadsheet or in CORRDATA Plus software to show metal loss over time.

The CORRATER probes are used to assess the instantaneous corrosion rate of steel in concrete by the method of Linear Polarization Resistance (LPR). The electrodes of the LPR probe are manufactured using carbon steel. Each reading gives the instantaneous corrosion rate of the electrodes in the concrete environment, and the probes are monitored frequently or continuously to track changes in corrosion rate. The automated CORRDATA range of datalogging instruments enable data to be collected on a frequent and regular basis for subsequent collection and downloading to CORRDATA Plus software. This ensures continuous monitoring of corrosion rate.

Fig. 18.7 Probe mounted just above Rebar

In concrete structures Multi Depth Sensors may be used to assess the depth of chloride or carbonation ingress, and optionally the instantaneous corrosion rate. The multi depth sensor has four galvanic couples of mild steel and stainless steel. These couples are located at four depths from the concrete surface, with the couple furthest from the surface placed above the rebar. An increase in current flow indicates the ingress of chloride contamination and increased corrosion at that electrode level. As an option, the Multi Depth Sensor can measure the instantaneous corrosion rate of steel in concrete by the method of Linear Polarization Resistance (LPR).

18.11 SmartCET Corrosion Transmitter by Honeywell International, Inc.

Honeywell's SmartCET® corrosion transmitter embeds proprietary corrosion measuring technology to provide a convenient and efficient method to bring corrosion data online to the process control system. From a standard electrode probe, SmartCET provides four corrosion measurements, which include general corrosion rate, an indicator for localized corrosion (Pitting Factor), a measured Stern-Geary constant (B value), and a Corrosion Mechanism Indicator (a capacitance value to help diagnose the condition of the probe electrode health), enabling a more complete understanding of the physical corrosion process that is occurring.

From these multiple measurements, SmartCET can differentiate if the corrosion is general, uniform corrosion or if localized pitting corrosion is occurring, indicated by the Pitting Factor output. Another key output is the B value which is a realtime measurement of the prevailing value of the Stern Geary constant. The general corrosion rate is calculated using a default B value and the measured B value can be used as an adjustment to improve the accuracy of the calculated corrosion rate. In addition to enhancing the corrosion rate accuracy, the B value measurement provides insight into changes in corrosion mechanism, which occur as a consequence of variability in the process environment.

SmartCET corrosion transmitters can be used in bridge SHM for intelligent corrosion monitoring of reinforced concrete structure and providing online, real-time monitoring of corrosion information. The transmitters can be operated in cold temperature (operation temperature range: -45°C to 85°C).

18.12 Embedded Corrosion Instrument (ECI) by Virginia Technologies, Inc. (VTI):

VTI designs and manufactures Embedded Corrosion Instrument (ECI) for corrosion monitoring of steel reinforced concrete structures (Fig. 18.8). ECI contains a chloride threshold indicator, a temperature sensor, conductivity and resistivity sensor, a polarization resistance sensor, and an open-circuit potential sensor. ECI provides comprehensive, real-time information on structural conditions by monitoring five key factors in corrosion, which are linear polarization resistance (LPR), open circuit potential (OCP), resistivity, chloride ion concentration (Cl-) and temperature.

Each ECI is a digital peripheral instrument on a local area network. It communicates with other instruments on its network and with an external data logger using the SDI-12 industry standard protocol (Fig. 18.9). By communicating digitally, the ECI guards against data corruption by electro-magnetic interference. Data can be collected on-site with a laptop computer or downloaded remotely by wireless transceiver and cellular modem. ECI provides comprehensive, real-time information on structural conditions.

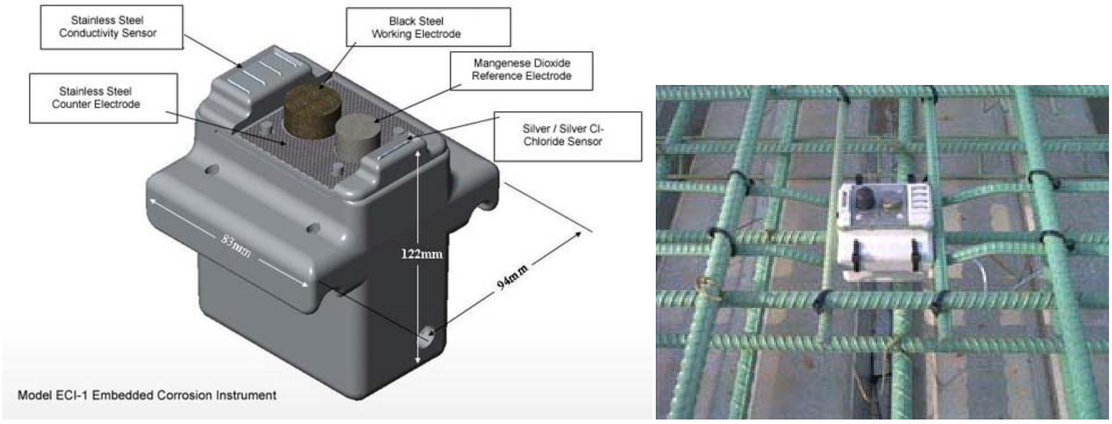


Fig. 18.8 Embedded Corrosion Instrument (EC-1).

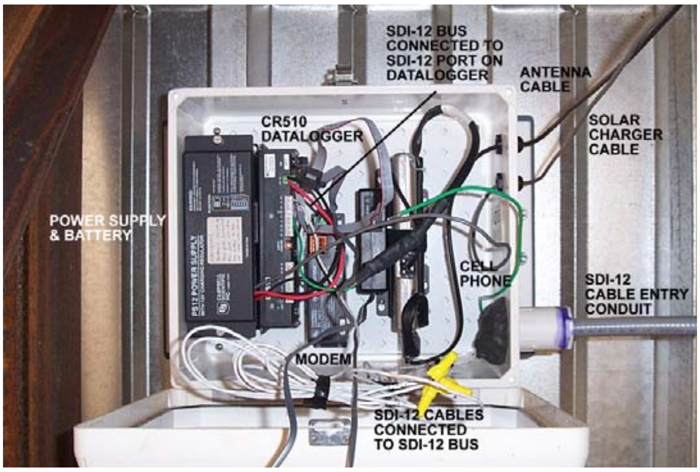


Fig. 18.9 Enclosed Datalogger, Power Supply and Telecommunications

ECI has been integrated into a wide range of structures, in regions as diverse as Australia, Singapore, and the United States. -40°C to 70°C.

18.13 Concrete Monitoring System by VETEK System Corporation

VETEK corrosion monitoring system uses monitoring electrode to determine the chloride content in concrete, Corrosion Penetration Rate Monitoring (CPMP) system to measure the rate of penetration of corrosion conditions through the concrete before it can attack the structural steel, and a Permanent time domain reflectometry (TDR) cable to determine the location and severity of corrosion of embedded or encased steel rebar and strands.

For existing structures, some destruction is required in order to install the necessary monitoring sensors/cables. -30 to 70°C.

18.14 CableScan™ by Pure Technologies, Ltd.

Corrosion of bridge cables or ropes is not always evident from visual inspection, as corrosion often originates in the interior of cables.

CableScan™ is a new cable inspection service that utilizes magnetostrictive sensing (MsS) to identify anomalies in bridge cables from a single location on each cable. Pure Technologies holds a worldwide non-exclusive license for MsS for bridge applications. The system represents a major breakthrough in bridge inspection technology. CableScan devices can generate and detect guided waves electromagnetically in ferromagnetic materials; identify the condition of cables and the location of any defects; and provide a preliminary report so that cables can be selected for close-up visual inspection, removal, load testing and/or forensic analysis.

19 SCOUR MONITORING

Scour is the erosion or removal of stream bed or bank material from bridge foundations due to flowing water. Although bridges rest on normally stable foundations of piers, abutments, and caissons, when scour occurs at a dangerous level, it causes bridges to become unstable and unsafe for traffic. According to the National Cooperative Highway Research Program (NCHRP) Report 396, *Instrumentation for Measuring Scour at Bridge Piers and Abutment*, (Lagasse et al, 1997), these stream related issues account for 60% of bridge failures in the United States. Countermeasures to mitigate these issues involve either physical means or monitoring. In cases where physical countermeasures are cost prohibitive, monitoring may be used as an acceptable alternative (Lueker et al. 2010).

The goal of this section is to review current scour monitoring technologies and instruments which could be used in a bridge SHM program. These include the methods and instruments that detect streambed elevation and the means of collecting and storing the data.

19.1 Sonar Devices

The sonar instrument measures distance based on the travel time of a sound wave through water. The data logger controls the sonar device and data collection functions. The data logger is programmed to take measurements at prescribed intervals. Sonar sensors normally take a rapid series of measurements and use an averaging scheme to determine the distance from the sonar transducer to the streambed. These instruments can track both the scour and refill processes. If scour has caused the elevation of the streambed to decrease significantly, an alert condition is initiated. The sensor requires DC power and the interface with a datalogger is wired. It is capable of multiplexing and does contain some self diagnostic routines.

Sonar sensor is not structurally robust, and may be mounted in a variety of elevations out of the way of debris. *Sonar-type systems* are the choice for coastal and bay bridges where the channel bottom may be sandy or contain riprap and there is little debris.

NexSens Technology, Inc uses Benthos PSA-916 precision sonar altimeter to measure the accurate height off the riverbed. The altimeter can be fixed to a mounting arm off a bridge structure and uses digital sonar technology to track the scour. The units output a digital RS-232 output for interfacing with iSIC or SDL500 data loggers.

Fig. 19.1 Bridge scour monitoring site

For a complete bridge scour monitoring system, a NexSens iSIC or SDL500 data logger is used for data collection and transmission. The terrestrial iSIC data loggers can be pole mounted or fastened on the top of a bridge pier. The SDL500 submersible data loggers offer a better solution when there is an elevated risk or flooding or if the monitoring system is located in a vandal-prone area. NexSens solar panels provide a continuous charge to the battery to keep the system powered without the need to continuously swap batteries. When configured with telemetry, data can be transmitted in real-time from the bridge site to a project computer, eliminating the need for periodic site visits to upload data. Options are also available for landline phone or Ethernet telemetry if the site has access to a landline or Ethernet hub.

Alarm Notification NexSens bridge scour monitoring systems offer two types of alarms: software and data logger. Software alarms are used to notify persons via SMS text messaging or email of parameters exceeding pre-defined limits. NexSens iChart Software sends the alarm when it receives data from the data logger. Data logger alarms are used to change the functionality of the data logger based on parameter inputs, such as changing sample and log intervals based on a particular logged reading.

Once the riverbed alarm limit is determined, the value is entered into NexSens iChart Software. When the river bed depth exceeds this pre-defined range from scour, a text message or email is automatically sent to a pre-defined list of contacts to take appropriate actions. Typically, this involves closing off the bridge for inspection.

Managing Data Riverbed depth and water level data is logged and transmitted at a user-defined interval (minimum 1 minute) back to the project computer running iChart Software. iChart is a user-friendly Windows-based software package that serves as the centralized interface and database for all incoming data. A single Software license can manage a virtually unlimited number of bridge scour sites. The software allows users to generate customized reports with data from all systems in an iChart database. Reports can be converted to PDF, exported to Microsoft Excel, sent to interested parties via e-mail, uploaded to a web server, and more.

NexSens WQData is an optional web-based data management solution for bridge scour monitoring systems and other environmental data. The modular datacenter interface can be easily customized to include project-specific themes and information. WQData allows users to access to bridge scour data from any web browser.

19.2 Magnetic Sliding Collars

Magnetic sliding collars (MSC) slide on rods or masts that are driven or augured into the streambed. Sensors which change in response to a magnetic field are displaced along the rod or mast. A collar with magnets is placed on the streambed around the rod and triggers sensors in the rod. If the streambed erodes, the collar moves or slides down the rod into the scour hole. The depth of the collar provides information on the scour that has occurred at that particular location. The magnetic sliding collar may be automated or manually read. The automated type is driven into the bed and is connected to a datalogger using flexible wires that convey magnetic switch closures. The manually read type requires a hollow metal tube to connect the sensor to the bridge deck. For this reason, the manually read sliding collar is very exposed to debris and ice.

Fig. 19.2 MSC scour monitoring system

Strainstall Ltd. has designed a bridge scour monitoring system using MSC (Fig. 19.2). Each time the magnetic collar passes one or more sensors, an alarm sequence is activated. This is sent as a text message warning that scour has occurred, enabling inspectors to take the appropriate action (such as closing the bridge until it can be physically examined). The scour monitoring system has been designed to be very simple and easy to install. It is battery powered, with around a two year battery life, so the monitoring system can be left unattended for several years.

19.3 Float-Out Devices

Buried at strategic points near the bridge, float-outs are activated when scour occurs directly above the sensor. Should scour occur sufficiently to release the device, the buoyant float-out rises to the water surface, activating an internal transmitter. A unique digitized signal identifying the alarming device is sent to a receiver mounted on the bridge.

Float-out scour monitoring systems only provide a measurement if the scour has progressed past a datum. There is a power requirement, but it is minimal. However, the device cannot be checked to verify operational capability and the on-board power must be reliable for long periods without use. The interface with a datalogger is wireless.

ETI Instrument Systems' Scour Tracker scour monitoring system uses ETI AS-3 Active Sonar, SMC-3 Sliding Magnetic Collar or FLT-3 Float-out Transmitter as the scour sensor. ETI's *Smart Remote Sensor Control Unit (SRSCU)* collects data every 30 minutes from the sensors. The SRSCU is mounted on a pier in the vicinity of the measured streambed. A few simple wiring connections that connect the sensors to the SRSCU and it is ready to start collecting data. It combines the data from sensors connected to it into a single record and transmits that record to the nearby Master Unit. The Master Unit can communicate with several SRSCUs. It analyzes their data and determines if a condition exists that requires notification of bridge maintenance personnel. If so, the Master Unit places a data (or synthesized voice) call to a designated office.

ETI's scour monitoring instrumentation has been installed on more than 70 bridges in 16 states. Both Magnetic Sliding Collar (MSC) and Sonar system were used to two bridge sites in a NJDOT research project (Nassif etc. 2003). Continuous scour data monitoring was initiated. It was observed that both instruments could be easily installed with the proper equipment and some technical skills by the inspection personnel of NJDOT. It was found that the MSC and Sonar devices complement each other to provide a clear and accurate picture of the scour activity at each site.

Based on the potential scour environment at the bridge site, different instrument may be used. Sonar-type systems are the choice for coastal and bay bridges where the channel bottom may be sandy or contain riprap and there is little debris. At rivers and creek beds where debris may accumulate, buried sensors such as a sliding magnetic collar and transmitting float-out devices may be better suited. Regardless of the technique used, if scour is detected each system can use its onboard telecommunications to alert responsible bridge safety personnel. Both digitized voice and digital data describe the present conditions.

19.4 Tilt Angle/Vibration Sensor Devices

Tilt and vibration sensors measure movement and rotation of the bridge itself. The X, Y tilt sensors or clinometers monitor the bridge position. Should the bridge be subject to scour causing one of the support piers to settle, one of the tilt sensors would detect the change. A pair of tilt sensors is installed on the bridge piers. One sensor senses rotation parallel to the direction of traffic (the longitudinal direction of the bridge), while the other senses rotation perpendicular to traffic (usually parallel with the stream flow).

19.5 Soundign Rods

Sounding-rod or falling-rod instruments are manual or automated gravity based physical probes. As the streambed scours, the rod, with its foot resting on the streambed, follows the streambed and causes the system counter to record the change. The foot must be of sufficient size to prevent penetration of the streambed caused by the weight of the rod and the vibration of the rod from flowing water. These are susceptible to streambed surface penetration in sand bed channels. This influences their accuracy.

19.6 Piezoelectric Film Devices

A piezoelectric film sensor is a passive electric sensor that turns deformation into an electric signal. The device uses an array of film sensors to detect the location of the bed. When a sensor is buried, it does not move and does not output a signal; when unburied the sensor is moved by the flow and outputs a small current. Thus, they can measure aggravation and degradation of surrounding soil. These devices are typically very sensitive which can lead to false measurements.

19.7 Time Domain Reflectometry (TDR)

TDR was originally used by electrical engineers to locate discontinuities in power and communication transmission lines. Later on its application was extended to measure material dielectric and electrical properties. For Civil Engineering, the applications were extended to include soil water content measurement. TDR works by sending an electromagnetic pulse down a rod buried vertically in the streambed and measuring the reflections due to the change of system geometry or material dielectric permittivity.

The ability of TDR for scour monitoring lies in the large contrast between the dielectric constant of water (around 81) and that of the air (1) or sediment solids (the dielectric constant for dry solids is between 2-7; that of saturated solids varies depending on the degree of saturation). Because of the large contrast in the dielectric properties, reflections will take place at the interfaces between 3 material layers with different dielectric properties (including the air/water interface and the water/sediment interface). (Fig. 19.3 http://filer.case.edu/xxy23/Xinbao/Print/interview/TRB-09-3056.doc) (Measurement of Simulated Scour by Time Domain Reflectometry Xianbu Yu and Xiong Yu, TDR2006, Purdue University). By monitoring the round-trip travel time of a pulse in real time, the distance to the respective boundaries can be calculated. This provides information on any changes in streambed elevation. TDR requires a complicated instrument to produce the pulse and analyze the return signal. Campbell Scientific offers such a device.

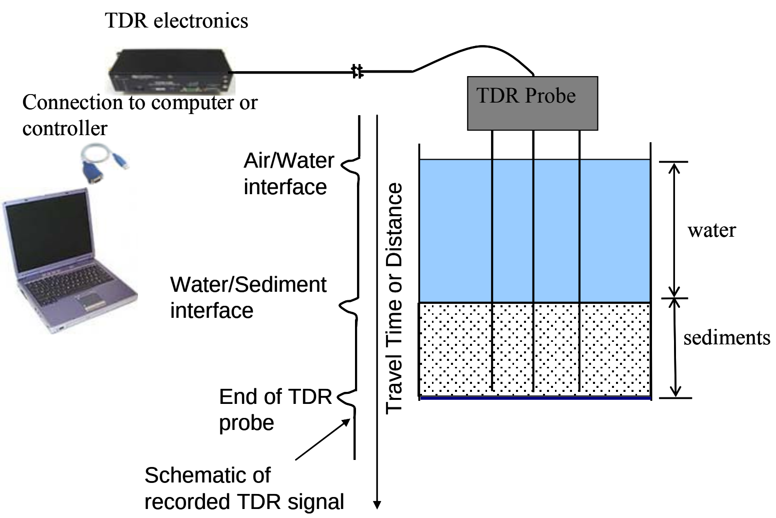


Fig. 19.3 Schematic of TDR monitoring of simulated scour

A TDR-based system has been developed at Cold Regions Research and Engineering Laboratory (CRREL) for continuous, real-time, dynamic detection and measurement of bridge scour. The system consists of a Campbell CR10X data acquisition system with a TDR100 interface and sensors that are manufactured at CRREL. It can easily be installed on new construction and retrofitted to existing structures. A computer at CRREL recovered the data daily using a modem integrated into the DAQ package. The TDR system can detect changes in river sediment depths of less than 2.5 cm (1 in.).

The CRREL system is capable of tracking, in real time, changes in channel bed elevation through the winter. It continuously monitors channel changes associated with river ice formation and breakup, as well as with flow rate changes. It allows unattended automatic operation; provides all-weather, day-and-night operation; provides high resolution of scour depth; supplies real-time, dynamic data; resets automatically, enabling measurement of multiple erosion/deposition event.

19.8 FBG sensing

Research has been exploring and testing in the laboratory to use fiber Bragg grating (FBG) sensing technology for real-time bridge scour monitoring systems. (Lin, etc, 2005).

A series of FBG sensors are mounted on a rod which is driven into the streambed. When the running water flows towards the cantilevered rod, a deformation strain will be generated by the bending moment, and this strain will be detected directly by the FBG sensor. If the FBG sensor is originally buried under the river bed surface, there is no response of the FBG sensor. The scour depth will be detected directly from the responses of the corresponding wavelengths, whenever the FBG sensor emerges from the river bed surface during scouring.

These FBG scour-monitoring systems can measure both the processes of scouring/deposition and the variations of water level. Several experimental runs have been conducted in the flume to demonstrate the applicability of the FBG systems. The experimental results indicate that the real-time monitoring system has the potential for further applications in the field.

An Illinois Center for Transportation (ICT) study developed a fiber optic scour sensor capable of monitoring and providing quantitative characteristics of both scour depth and flow processes, i.e. rate. The proposed fiber optic scour sensor includes a single Fiber Optic Bragg Grating (FBG) sensor embedded inside a rod cantilevered into the river bed. The research involved development, testing, and fabrication of the prototype sensor assembly, laboratory prototype testing, modeling, fabrication of field sensor, and field implementation. The research results proved that the simple concept for the development of a very low cost sensor with only one sensing element is sound. (F. Ansari, 2010).

20 DYNAMIC TESTING AND MONITORING

To carry out vibration-based testing for the purpose of SHM, the following equipment is need: 1) excitation hammer or shaker, or vehicle, 2) sensors to measure dynamic response of the structure, and 3) data acquisition system. Please refer to Section xx of Part I of this report for more details of vibration-based dynamic testing and analysis for bridge SHM.

The most commonly used transducers for dynamic testing of structures are accelerometers, velocity, and displacement transducers to measure acceleration, velocity, and displacement response histories of a structure, respectively.

Accelerometers are the most common and applicable sensors used during dynamic testing of civil structures, since they are capable of operation over a wide range of frequencies and are easy to install (Green, 1995). There are two types of accelerometers: piezoelectric and capacitance accelerometers. The piezoelectric accelerometer measures the acceleration of a seismic mass in the sensor through deformations in a piezoelectric crystal. In a capacitance accelerometer, semiconductor elements and a seismic mass form an active Wheatstone bridge. As the structure vibrates the Wheatstone bridge becomes unbalanced and the differential output provides a measure of the acceleration. The acceleration data from accelerometer is used to derive frequency, velocity, position, and tilt. These properties make accelerometers very versatile measurement sensors.

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*.

Other transducers include velocity and displacement transducers. An example of a velocity transducer is the scanning laser Doppler velocimeter (Stanbridge and Ewins, 1999; Ewins, 2000), which is a noncontact device that measures the velocity of a point from the Doppler shift between incident and scattered light returning to a measurement point. Displacement transducers include potentiometers and linear variable displacement transducers (LVDT). Potentiometers are limited to low frequency vibrations. The LVDT measures displacements through changes in voltage levels of the coils surrounding a free moving magnetic core.

In this section, we'll briefly review technologies provided by different manufacturers, including sensors and DAQ systems which could be used for seismic or dynamic testing and monitoring to provide important information about the structure's response to natural or man-made seismicity.

20.1 DYTRAN Instruments Inc

DYTRAN uses piezoelectric technology and manufactures dynamic transducers for dynamic testing. Its sensors include accelerometers, dynamic force sensors, dynamic pressure sensors, and impulse hammer systems. Data acquisition system for Dytran's accelerometer is provided by TMI Inc. (www.tmirep.com). Operating temperature range: -60 to 50°F.

20.2 EENTEC

EENTEC provides strong motion sensors and digital strong motion recorders, seismic/vibration sensors and recorders and digitizers, etc. for structural monitoring, earthquake engineering, and seismic research. EENTEC sensors are available in external, internal, or borehole configurations, are good for strong motion monitoring applications. EENTEC digital seismic recording systems are portable, rugged, ultra low power and high-performance. They allow multiple channels to operate synchronously up to 2,000 samples per second. Data is retrieved by removal of the PC compatible compact hard drive, or through dial up telephone access (internal modem optional), or via LAN (Ethernet card optional). The integrated display and keyboard allows for easy setup in the field and real time viewing of up to 3 waveforms. Operating temperature range: 10 to +50°C

20.3 Endevco Corporation

Endevco designs and manufactures dynamic instrumentation for vibration, shock and pressure measurements. ENDEVCO offers both piezoelectric and piezoresistive type transducers for use in dynamic, static and acoustic applications. All of these transducers are supported by a complete line of related signal conditioners, amplifiers, cables, measurement systems and accessories. Endevco systems have been used in aerospace, automotive, defense, industrial, and medical applications where accurate and reliable data is absolutely vital, though no application on bridge structures yet. The general purpose piezoelectric accelerometers can be operated in a temperature range of -55 to 177°C.

20.4 GeoSIG Ltd.

GeoSIG sensors used for structural dynamic monitoring include

- triaxial accelerometers based on MEMS technology and servo-accelerometers based on a standard exploration geophone mass-spring system designed for borehole applications regarding strong motion earthquake survey and monitoring,

- triaxial velocity sensors for field or industrial survey and monitoring applications concerning vibration or explosion, and

GeoSIG data acquisition systems and software include an Ethernet connection and optionally a 2.4 GHz Wi-Fi module to insure fast and reliable data transfer. The system can process data in real time. If triggered by a seismic event, the system calculates Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD) and Response Spectrum (RSA) at various frequencies of the event. GeoSIG Measuring System (GMS) can report these parameters, which are related to the strength of shaking, to a data centre where a synopsis (such as a shakemap) for disaster management facilities can be generated in almost real time over the Internet. An event file is also recorded in the memory, which is sent out from the instrument and also securely accessible over the Internet. The operating temperature range for GeoSIG sensors is -40 to 70°C, for the monitoring instrument -20 to 60°C.

20.5 Geo Space, LP.

Geospace Technologies manufactures and supplies seismometers which can be used for SHM. The Geospace seismometers are high sensitivity, self-generating velocity detector with extremely low natural frequencies for detecting seismic activity for structural analysis, geologic hazards, vibration isolation, etc. Its product Geospace Seismic Recorder (GSR) is designed for autonomous nodal seismic data recording. The self-contained unit includes 1 to 4 channels of 24-bit digitization, an integrated/high sensitivity GPS receiver, built-in test signal generator, up to 4 GB per channel of non-volatile solid-state data storage, and a high-speed data port. The unit is housed in a sealed case, with input connector, extended life battery connector/data port connector

The operating temperature ranges for Geo Space sensors is -40 to 100°C.

20.6 Instantel:

Instantel provides continuous and transient ground vibration monitoring technology for applications during construction. Using velocity sensors (geophones), accelerometers, microphones and overpressure sensors, Instantel's Blasmate and Minimate monitors could be used for monitoring vibration created by pile driving, construction activities, demolition activities in bridge structural monitoring and analysis. The system is capable of monitoring for extended periods of time, remotely monitoring with automatic storing of data to a PC, triggering external alarms, and programming sample rate to increase the frequency response. Operating temperature range of -10 to 50°C.

20.7 Kinemetrics, Inc.

Kinemetrics provides portable, high performing broad band triaxial seismometers, surface and borehole accelerometers, and borehole episensors and packages for a variety of seismic and structural engineering applications with its own digital recorders and sofware.

Kinemetrics systems can be used for automated system identification and monitoring modal properties (e.g., natural frequencies, damping rations, mode shapes) and their derivatives; parametric and analytical (e.g., finite element) model updating;

Kinemetrics has provided instruments and service to a variety of bridge strong motion monitoring projects. For example, in one bridge project, the system provides valuable information about the response of the structure. Induced seismic forces on the bridge superstructure and amplification effects will be calculated from acceleration data. Measured displacements in the longitudinal and transverse directions will provide information to review the criteria in the design of the central girder supports. Common reinforcing steel and pre-stressed steel strain measurements on both girders and columns will provide information on the long-term behavior of the bridge under gravity loads. The operating temperature range is -20°C to 70°C, and 0 to 100% relative humidity.

20.8 PCB Piezotronics, Inc.

PCB Piezotronics manufactures accelerometers, force sensors, load cells, microphones, pressure transducers, pressure transmitters, strain sensors, torque sensors, vibration sensors, signal conditioners, cables, and accessories. PCB's sensors and instrumentations are used for test, measurement, monitoring, and feedback control requirements in industrial, R&D, military, educational, commercial, and OEM applications. When used for bridge SHM, its accelerometers and vibration sensors can be an option for vibration monitoring.

20.9 Silicon Design Inc. (SDI)

Silicon Designs manufactures MEMS accelerometers and acceleration data acquisition system for monitoring wind effect and seismic activity. The sensors include surface mount LCC accelerometers, single axis accelerometer modules, and three axis accelerometer modules. -55 to 125°C. Model: 2210: -40 to 85°C.

20.10 Summit Instruments, Inc:

Summit Instruments manufactures uniaxial, biaxial and triaxial digital and analog accelerometers to measure acceleration, vibration, shock and gravity. Summit Instruments' accelerometers have been used to monitor the movement and position of heavy mining and construction equipment, the sway of structures to determine if design parameters are being exceeded, and the vibration of machinery for predictive and condition-based maintenance.

Accelerometers: -40 to 85°C. Temperature sensor: -55 to 125°C.

20.11 Bridge Monitoring System (BRIMOS) by Vienna Consulting Engineers (VCE)

VCE's Bridge Monitoring System (BRIMOS) offers a method for system identification and damage detection in bridges and other civil structures based on the dynamic response to ambient excitation such as wind, traffic and micro seismic activity. By instrumentation of bridges with accelerometers (Kistler sensor or EPI sensor), displacement sensors and piezoelectric sensors, etc., BRIMOS system enables accurate observation and evaluation of structural condition and damage detection, assessment of the susceptibility of cables with regard to the two most frequent cases of cable vibrations: galloping at higher wind speeds and wind-rain-vibration at lower wind speeds.

BRIMOS data acquisition equipped with internal 3-dimensional Forced Balanced Accelerometer and BRIREC software provide quick and easy data transfer to a monitoring station and provides dynamic characteristic of structure.

BRIMOS needs direct wire connect, or Internet network, and enables automatic warning for critical conditions.

VCE has designed, supervised or tested bridges of all kinds with its particular expertise in cable-supported bridges and structures. Its BRIMOS can be used for cable monitoring, hot-spot monitoring, in-depth monitoring, permanent monitoring (Fig. 20.1), web-interface/web-database, life-cycle analysis, etc. Among the many successful applications of the BRIMOS® are the Binzhou Yellow River Highway

Bridge in China, Brooklyn Bridge in U.S.A., Confederation Bridge in Canada, Kao Ping Hsi in Taiwan, Olympic Grand Bridge in Korea and etc. (www.brimos.com)

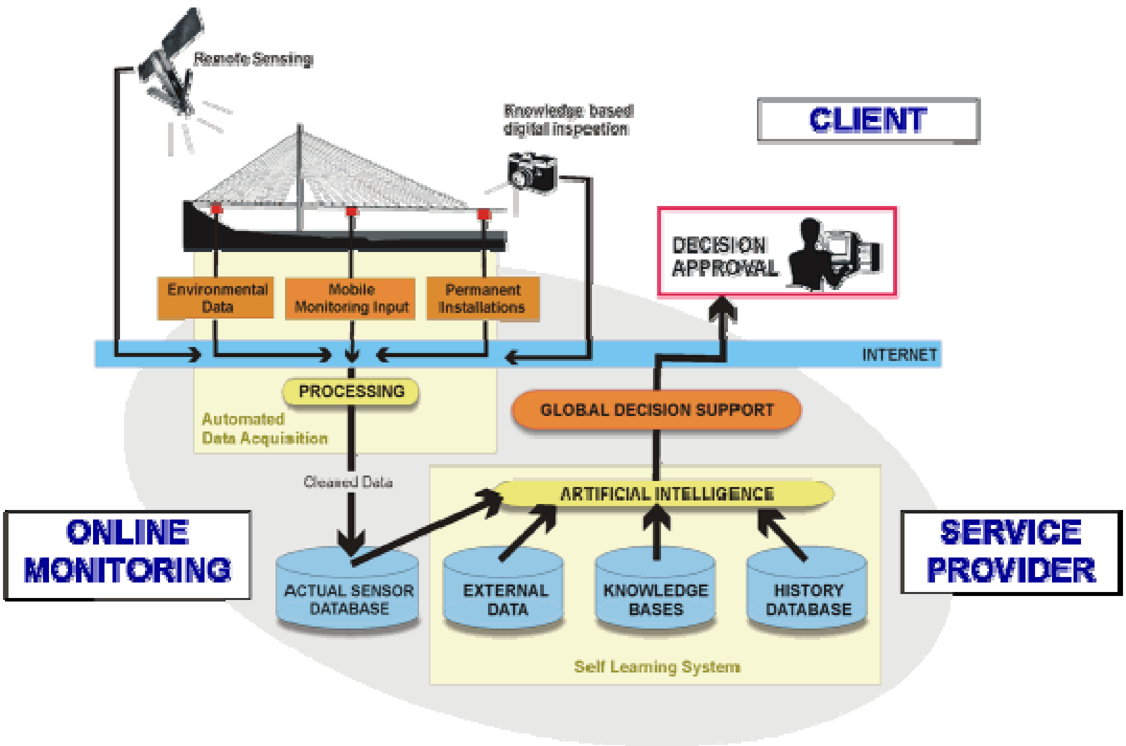


Fig. 20.1 General layout of permanent monitoring systems

20.12 Vibra-Metrics:

Vibra-Metrics (of Mistras Group) manufactures vibration sensing products: accelerometers (vibration sensors), data delivery systems and a comprehensive assortment of ancillary products. Data acquisition, the Sensor Highway is capable of collecting vibration, temperature, pressure and other parameter data from up to 4000 sensors throughout a facility and transporting the information back to the controller or a processing PC for surveillance and analysis. The Vibralarm Supervisory System is a key feature of the on-line Sensor Highway System; it allows vibration monitoring on site and from remote locations through Ethernet/Internet or other wireless communications.

20.13 Wilcoxon Research, Inc:

Wilcoxon Research manufactures and supplies accelerometers, vibration sensors, and network accessories for industrial condition based monitoring and predictive maintenance applications.

20.14 Case Studies

Example 1: UDOT I-15 South Temple Bridge (1999)

This project focused on the northbound I-15 bridge (composite construction) over South Temple Street in Salt Lake City, prior to its demolition. Initially the focus was on the entire nine-span structure and conducting a dynamic study of this structure using forced vibration. Then after the demolition of most of the South Temple overpass, leaving only a simple span, the research focused on detecting through system identification (again using forced vibration) the damage state of the smaller structure as it went through various phases of damage and repair.

The dynamic excitation of the bridge was provided by an AFB Engineered Test Systems Model 4600A eccentric mass shaker capable of providing a sinusoidal forcing function in any horizontal direction. The amplitude of the force induced by the shaker can be up to 89 kN (20,000 lbf) at up to 20 Hz.

The dynamic response of the bridge was measured utilizing Kinemetrics FBA-11 uniaxial 1g and 0.25 g accelerometers. The array of accelerometers was such that there was an accelerometer placed in the center of every span, oriented to measure the response perpendicular to the centerline of the bridge
The objective of placing the instruments on the bridge in this manner was to capture the first four transverse modes of the bridge.

The data acquisition system consisted of two main components. The accelerometers and shaker were connected to a Kinemetrics VSS-3000 vibration survey box. The second component consisted of a desktop computer that utilized data acquisition software to control the sampling rate and operation of the converter box. Once the signals were converted to digital signals they were sent to the computer where they were stored in ASCII format in preparation for later data processing and analysis.

Data processing: the response acceleration signal of each channel at each excitation frequency were used to determine the natural frequencies, mode shapes and modal damping which were used in the system identification of the bridge.

The results of this research in terms of frequencies and mode shapes for the nine-span bridge are shown as well as the changes in the frequencies and mode shapes for the simple span bridge as it went through various states of damage and repair. This study shows that system identification of large structures is possible and gives a preliminary indication that system identification has potential as a non-destructive evaluation technique for the determination of structural damage.

Example 2: Global NDE of timber bridge using impact generated FRFs (Morison 2002)
Six timber bridges of similar design have been examined. Most of the bridges are Comprised of a single span with an average overall length of about 20 feet. A heavy (12 Ib) PCB modal sledgehammer and a medium (3 Ib) PCB modal sledgehammer were used to excite the bridge structures under test. The excitation location was chosen to excite as many modes as possible. On one bridge the accelerometers were laid 3 rows of 15 lengthwise down the bridge for response measurements and modal analysis. Portable data acquisition was available in multiples of 4 channels with a maximum number of 16 channels. The polynomial cure-fitting method was employed to calculate the poles of the system and the associated mode shapes.

Example 3:FHWA-RD-03-089 September 2005 substructure
This research project was funded to investigate the possibility that, by measuring and modeling the dynamic response characteristics of a bridge substructure, it might be possible to determine the condition and safety of the substructure and identify its foundation type (shallow or deep). Determination of bridge foundation conditions with this approach may be applied to quantify losses in foundation stiffness caused by earthquakes, scour, and impact events. Identification of bridge foundation type may be employed to estimate bridge stability and vulnerability under dead and live load ratings, particularly for unknown bridge foundations.

Example 4: Hong Kong bridges Ni, etc.
In Hong Kong, a sophisticated instrumentation system has been devised by the Highways Department of the Hong Kong SAR Government to monitor the structural performance and evaluate the health and safety conditions of three long-span cable-supported bridges, the suspension Tsing Ma Bridge, the cable-stayed Kap Shui Mun Bridge and the cable-stayed Ting Kau Bridge. This integrated on-line monitoring system with a total of 774 sensors permanently installed on the bridges is deemed to be the most heavily instrumented bridge project in the world. The implementation of this system highlights the necessity for developing practical damage assessment methodologies. This paper reports the research work in the Hong Kong Polytechnic University to develop vibration-based damage detection methods in accordance with the long-term monitoring system. A particular focus is on exploring a neural network based hierarchical identification strategy for successive detection of the occurrence, type, location and extent of structural damage in the three bridges.

(Toksoy and Aktan 1993) In multireference impact testing, impacts are induced by a 12-lb impact hammer (PCB 086B50), and a total of number of seismic accelerometers (PCB 393C) are used to capture the response of the structure at reference points. The modal grid discretized the bridge into a total number of 119 points as shown in Fig. 3. A portable GenRad 2515 data-acquisition system was used to acquire the data. The post-processing was performed on a HP 300 Series workstation using a package parameter estimation program developed at the Structural Dynamics Research Laboratory of the University of Cincinnati.

In some cases it may not be possible to laterally excite a bridge by impact. If only the truck-load performance of a straight-horizontal bridge is to be evaluated, lateral-response characteristics may be excluded from structural identification. If the geometry is complex or the scope includes evaluating earthquake and other lateral vulnerabilities, the lateral-response characteristics also become critical. In such cases forced-excitation modal-testing may be required.

Part III SHM Application Examples

21 CASE STUDIES

21.1 Introduction

Field applications of structural health monitoring have become increasingly common since the last decade (Inaudi and Glisic 2008). In this chapter, several representative case studies in North America, Europe and Asia are presented to give examples of the type of monitoring that is possible with technologies currently available bridge engineering community. A number of additional case studies and application examples are usually available on the web sites of SHM system developers. Some of them have already been mentioned in the previous chapters of this report.

Bridges come in many sizes, structural systems and construction materials. Because of their very long design lifetime, sometimes exceeding 100 years, many types of bridges that are no longer considered for new construction are still in service and can become candidates for SHM. Inaudi (2009) classified bridges which have been instrumented with SHM systems or can be SHM candidates into the following main types:

- Concrete beam bridges
- Steel beam bridges
    - Concrete cantilever bridges
    - Arch bridges
    - Cable stayed bridges
    - Suspended bridges

The cited references describe examples of monitoring systems installed on each type of bridge.

Table 21.1 summarizes the main risks that are usually associated with each type of bridge. Three stars denote a risk or uncertainty that is to be considered a priority for that type of bridge. Two stars denote one that is very often relevant and one star indicates one that can be added if the budget allows or if the risk is higher than usual for that type of structures.

Table 21.2 discusses the typical expected responses and the proposed types of sensors to measure each identified risk.

Table 21.1 Typical risks and uncertainties associated with different bridge types

Risk/uncertainty	Concrete beam	Steel beam	Concrete cantilever	Arch	Cable-stayed	Suspended
Correspondence between finite element model and real behavior	**	**	**	**	*	*

Dynamic strain due to traffic,wind,earthquake, explosion,etc.		***		*	***	***
Creep, relaxation of pre-stress	***		***	*		
Change in cable forces					**	**
Correspondence between calculated vibration modes and real behavior	*	*	*	*	*	*
Non-working bearings and expansion joints	**	**	**		**	*
Cracking of concrete or steel	*	*	*	*	*	*
Temperature changes and temperature gradients in load bearing elements	***	***	***	***	***	***
Differential settlement between piers or foundations	*	*	**	**		
Change in water table or pore water pressure around foundations	*	*	*	*	*	*
Stability of slopes around foundations and abutments	*	*	*	*		
Change in the concrete chemical environment: carbonation, alkali-silica reaction, chlorine penetration	***	*	***	**	**	**
Environmental conditions				*	***	***
Traffic and overloads	*	*	*	*		
Construction schedule and specific actions	**	**	**	**	**	**

Legend: * = sometimes relevant; ** = usually relevant; *** = always relevant

Table 21.2 Risks, responses and candidate sensor types

Risk/uncertainty	Response/consequence	Proposed sensors
Correspondence between finite elemetn model and real behavior	Strain distribution and magnitude different form model	Local strain sensors, including strain gauges, vibrating wire gauges and fiber optic sensors, tiltmeters.
Dynamic strain due to traffic, wind ,earthquake, explosion,etc.	Large strains, fatigue, cracks	Local strain sensors, including strain gauges, vibrating wire gauges and fiber optic sensors, with dynamic data acquisition systems, Distributed fiber optic sensor to detect new cracks. Crack-meters.
Creep, relaxation of pre-stress	Global deformations, bending	Long-gauge fiber optic strain sensors, settlement gauges, tiltmeters, laser distance meters, topography.
Change in cable forces	Force an strain redistribution	Load cells: vibrating wire, resistive or fiber optics.
Correspondence between calculated vibration modes and real behavior	Mode shapes and frequencies different from model	Accelerometers, long-gauge fiber optic strain sensors.
Non-working bearings and expansion joints	Reduced movement, movements occur at wrong location, strain redistribution	Joint-meters: potentiometers, vibrating wire or fiber optics.
Cracking of concrete or steel	Crack opening	Crack-meters: potentiometers, vibrating wire or fiber optics
Temperature changes and temperature gradients in load bearing elements	Strain redistribution	Temperature sensors: electrical, fiber optics point sensors or distributed sensors.
Differential settlement between piers or foundations	Global movements, tilting, strain redistribution	Laser distance meters, topography, settlement gauges, tiltmeters.

Change in water table or pore water pressure around foundations	Change in pore water pressure	Piezometers: vibrating wire or fiber optics.
Stability of slopes around foundations and abutments	Slope sliding	Distributed fiber optic soil stability sensors, laser distance meters, inclinometers.
Change in the concrete chemical environment: carbonation, alkali-silica reaction, chlorine penetration	Corrosion of rebars	Concrete corrosion and humidity sensors.
Environmental conditions	Actions on bridge	Weather station, wind speed measurements.
Traffic and overloads	Actions on bridge	Weight-in-motion station, dynamic strain sensors.
Construction schedule and specific actions	Difficulty in analyzing data	Webcam, image capture and archival.

These indications should be considered as a starting point for designing an integrated bridge health monitoring system. It is, however, necessary to perform a specific risk analysis for each single bridge or at least for each family of similar bridges. For example, a concrete bridge in the Alps will see an increased risk of corrosion from the use of de-icing salt compared to an identical bridge in the Arizona desert. The ideal monitoring system will therefore be different for these two bridges.

21.2 Case Studies in North America

21.2.1 I-35W St Anthony Falls Bridge, Minneapolis, USA

Background

This first application is a good example of a truly integrated SHM system, combining different sensing technologies to achieve the desired level of monitoring for the construction and behavior of new bridges.

The collapse of the old I-3SW Bridge in Minneapolis in 2007 shook the confidence of the public in the safety of the infrastructure that we use every day. As a result, the construction of the replacement bridge (see Fig. 21.1 to Fig. 21.3) must rebuild this confidence, by demonstrating that a high level of safety can not only be attained during construction, but also maintained throughout the projected 100-year life-span of the bridge (Russel, 2008).

Fig. 21.1 The new I-35 Bridge

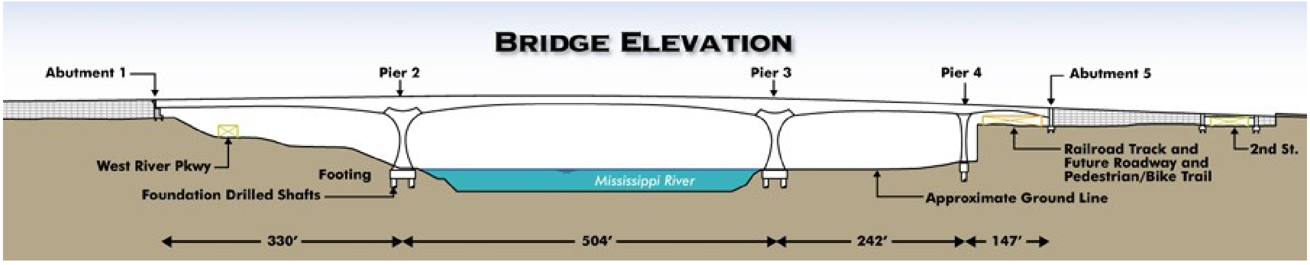


Fig. 21.2 The dimensions of the new I-35 bridge

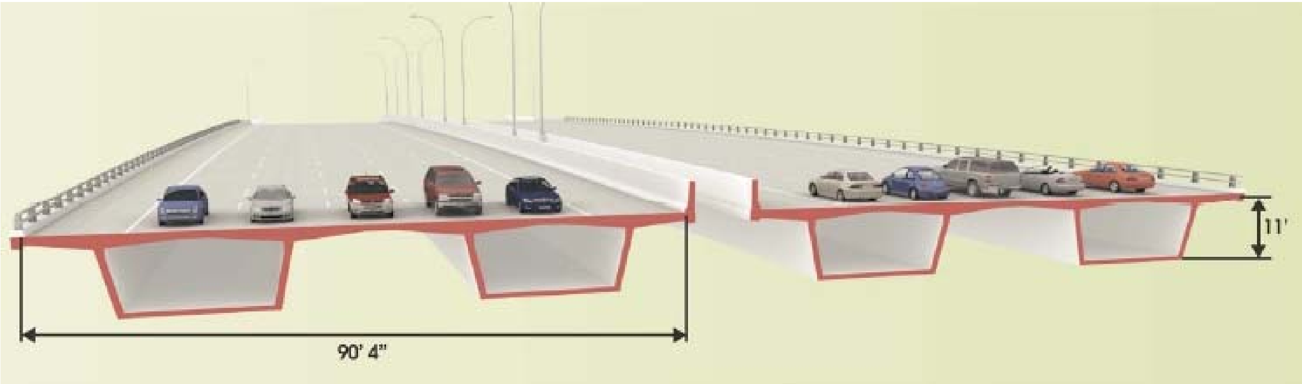


Fig. 21.3 Bridge cross-section

SHM systems

One of the central factors contributing to this project is the design and installation of a comprehensive SHM system, which incorporates many different types of sensors measuring parameters related to the bridge performance and ageing behavior. This system continuously gathers data and allows, through appropriate analysis, to obtain actionable data on the bridge performance and health evolution. The data provided can be used for operational functions, as well as for the management of ongoing bridge maintenance, complementing and targeting the information gathered with routine inspections (Inaudi 2009).

The monitoring system was designed and implemented through a close cooperation between the designer, the owner, the instrumentation supplier and University of Minnesota.

The main objectives of the system are to support the construction process, record the structural behavior of the bridge, and contribute to the intelligent transportation system as well as to the bridge security. The design of the system was an integral part of the overall bridge design process allowing the SHM system to both receive and provide useful information about the bridge performance, behavior and expected lifetime evolution.

Monitoring instruments on the new St Anthony Falls Bridge measure dynamic and static parameter points to enable close behavioral monitoring during the bridge's life span. Hence, this bridge can be considered to be one of the first 'smart' bridges of this scale to be built in the United States.

The system includes a range of sensors which are capable of measuring various parameters to enable the behavior of the bridge to be monitored. Strain gauges measure local static strain, local curvature and concrete creep and shrinkage; thermistors measure temperature, temperature gradient and thermal strain, while linear potentiometers measure joint movements. At the mid-spans, accelerometers are incorporated to measure traffic-induced vibrations and modal frequencies (Eigen frequencies). SensCore corrosion sensors are installed to measure the concrete resistivity and corrosion current.

Meanwhile there are long-gauge SOFO (Surveillance des Ourages par Fibers Optiques) fiber optic sensors which measure a wide range of parameters, such as average strains, strain distribution along the main span, average curvature, deformed shape, dynamic strains, dynamic deformed shape, vertical mode shapes and dynamic damping - they also detect crack formation. The sensors are located throughout the two bridges, the northbound and southbound lanes, and are in all spans. However, a denser instrumentation is installed in the southbound main span over the Mississippi river, as depicted in Fig. 21.4. This span will therefore serve as sample to observe behaviors that are considered as similar in the other girders and spans. Table 21.3 Summarizes the installed instrumentation and the monitoring purpose of each one.

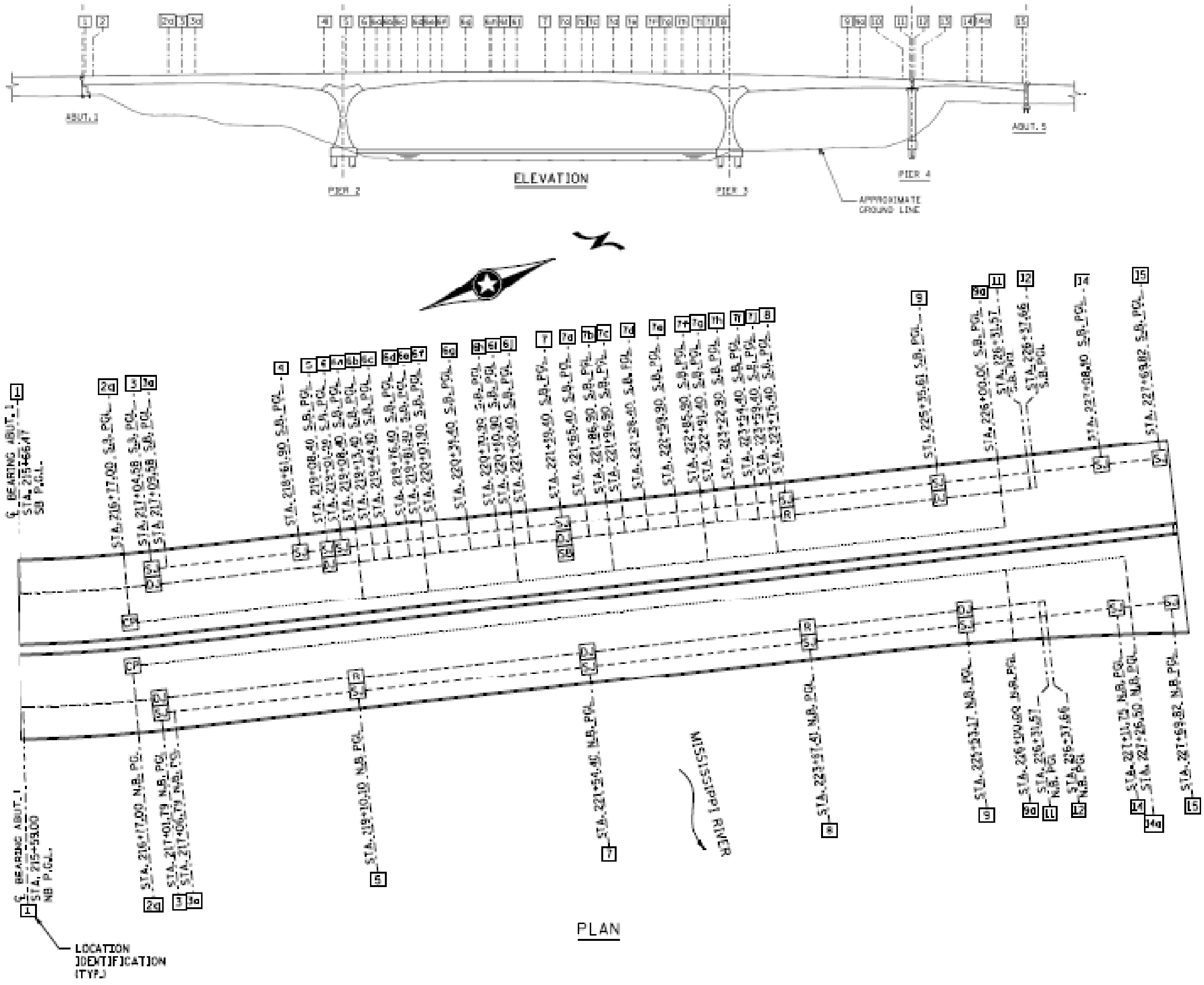


Fig. 21.4 Global overview of the I-35W Bridge health monitoring system (courtesy of Flatiron Mason)

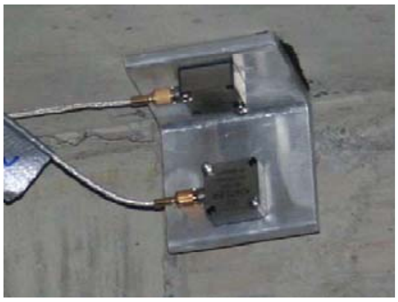
Table 21.3 Sensor types, purpose and addressed risk or uncertainty for the I-35W Bridge

Sensor type	Purpose	Addressed risk/uncertainty
Vibrating-wire strain gauges	Local static strain	Concrete shrinkage and creep.
		Correspondence with FEM
	Local curvature	Loss of pre-stress, creep
Thermistors	Temperature	Temperature induced deformations
	Temperature gradient	Temperature induced strain
Linear potentiometers	Joint movements	Stuck joints
		Anomalous global behavior
Accelerometers	Traffic induced vibrations	Excessive vibrations
		Dynamic amplification
	Modal Frequencies	Correspondence with FEM
	Dynamic damping	Stuck joints
		Anomalous global behavior
Corrosion sensors	Concrete resistivity	Water exchange in concrete deck
	Corrosion current	Corrosion of concrete deck rebars
Long-gauge fiber optic sensors	Average strains	Detection of cracks
		Correspondence with FEM
	Strain distribution	Temperature induced deformations
		Correspondence with FEM
	Average Curvature	Loss of pre-stress, creep
	Deformed shape	Correspondence with FEM
	Dynamic strains, Dynamic deformations, Mode shapes	Anomalous global behavior

Long-gauge SOFO fiber optic sensor

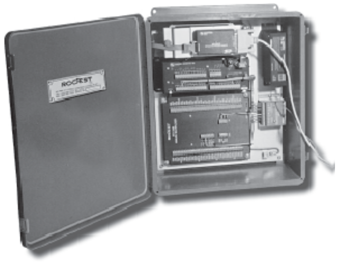
Vibrating Wire Strain Gauge

Concrete corrosion and Humidity sensors



Accelerometer

SOFO Fiber Optic Sensor Datalogger



Vibrating wire & temperature sensors datalogger

Junction boxes inside the main span of the South bound

Fig. 21.5 Some sensors and data acquisition systems installed in the I35W Bridge

System Performance and Results

Fig. 21.6 shows a simulation of the user interface implemented to display the data. The software is capable of displaying real-time information and to color-code the measurements according to pre-defined warning levels.

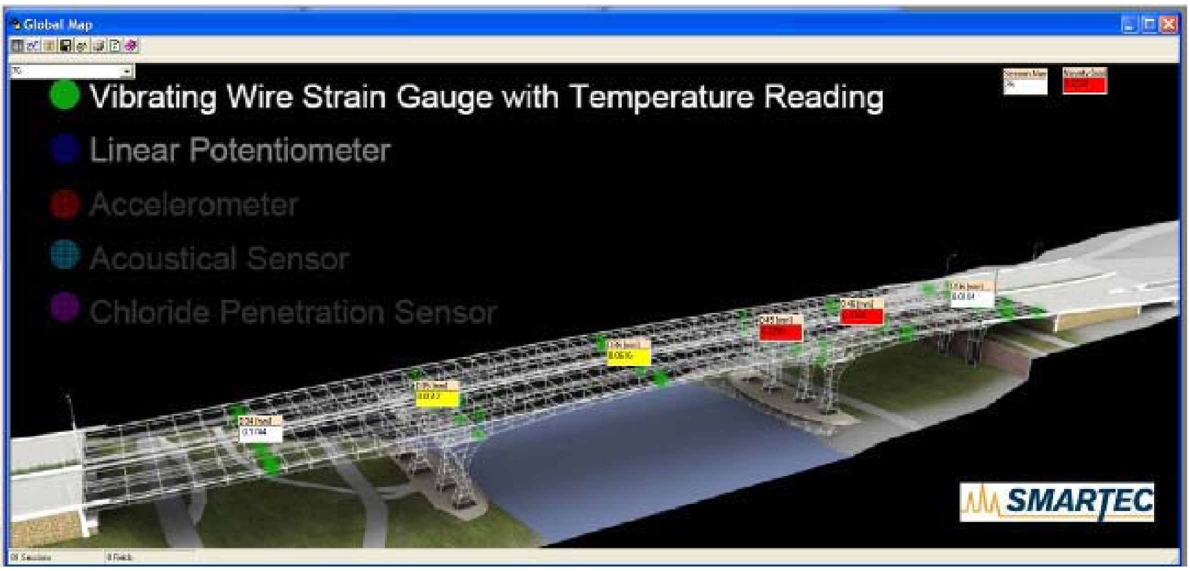


Fig. 21.6 SDB View Software interface (simulation)

All sensors and dataloggers have been installed and commissioned in the bridge. The SHM monitoring system is currently gathering data from the sensors, complementing the manual reading that were taken during construction. This data is currently being analyzed, but we will provide a few early results form the monitoring system.

Fig. 21.7 shows the measurements from the fiber optic sensors over a period of one week. The daily cycles due to the bridge expansion and contraction due to temperature changes are clearly visible.

A load test was performed on the bridge prior to its opening on September 18, 2008. Fig. 21.8 shows an example of the deformations recorded by the fiber optic sensors during one of the tests.

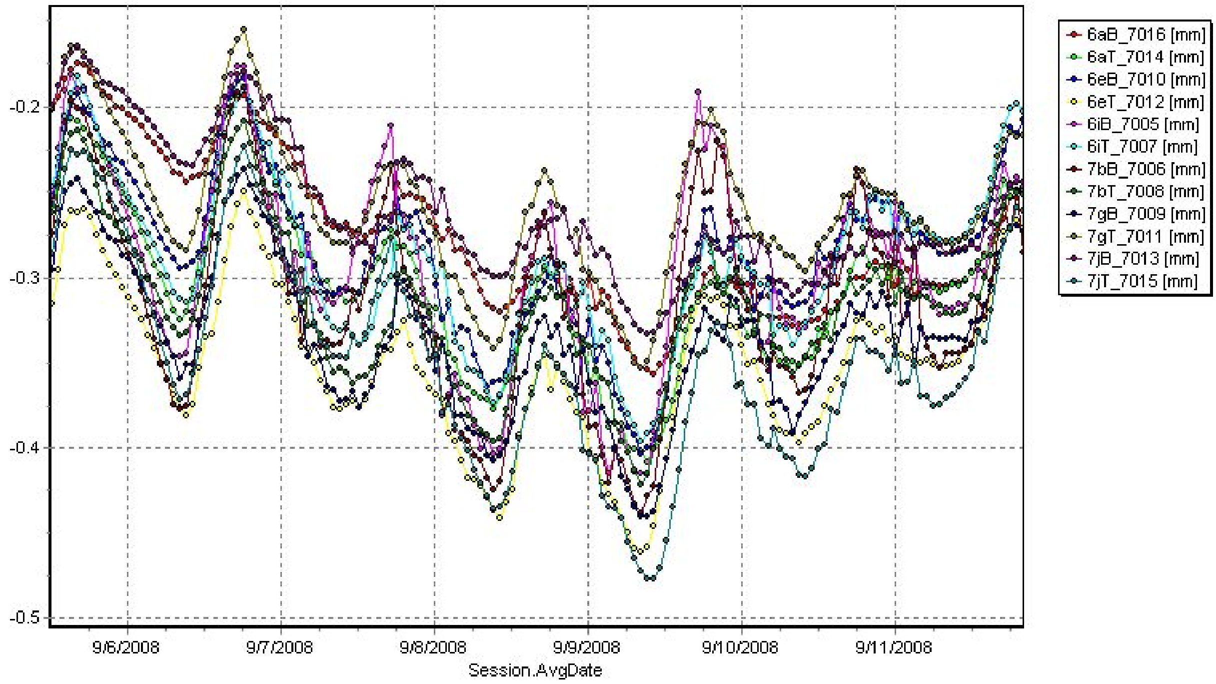


Fig. 21.7 Example of fiber optic sensor data acquired over a period of 7 days.

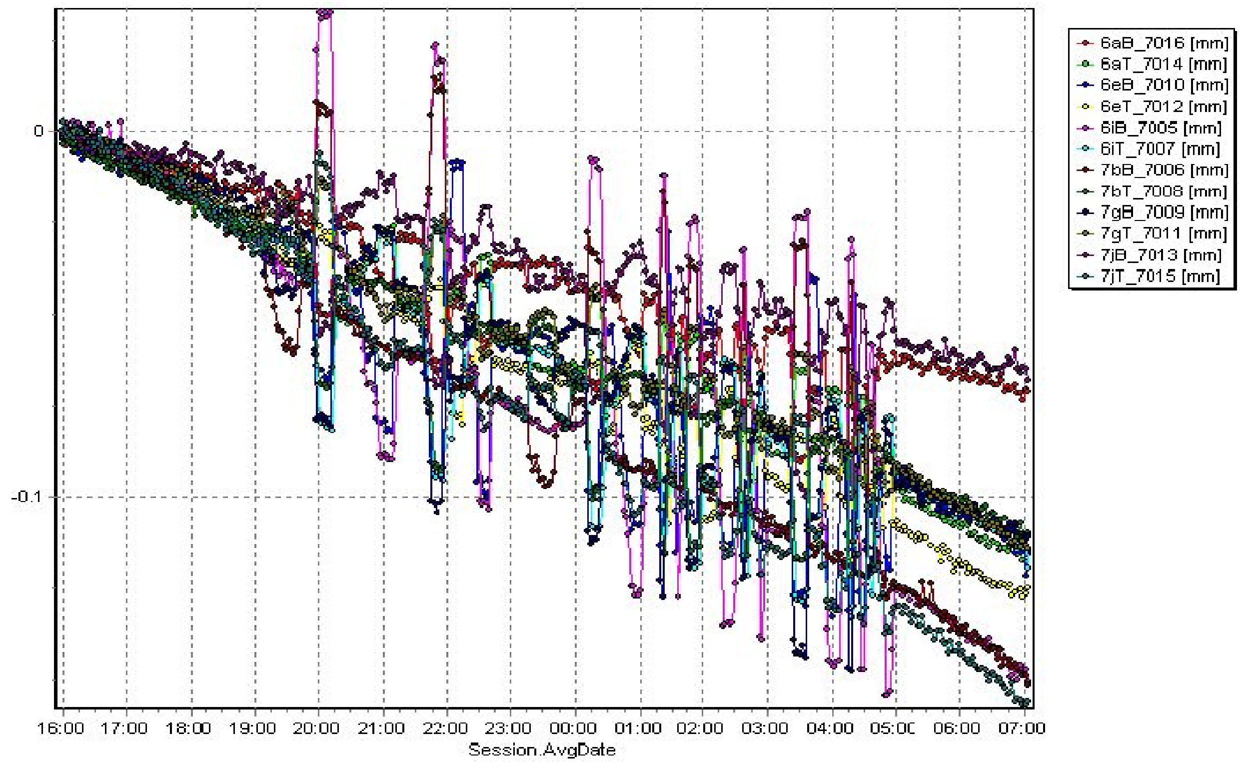


Fig. 21.8 Raw data acquired on the SOFO strain sensors during the test.

The SHM system will continuously gather data and allow through appropriate analysis to obtain actionable data on the bridge performance and health evolution. The provided data will be used for both operational functions as well as for the management of the bridge maintenance, complementing and targeting the information gathered with routine inspections.

References

- Inaudi, D., (2010)
- Inaudi, D., (2009b)
- Inaudi, D, et al. (2009)
- Web site: http://www.roctest-group.com/node/492

21.2.2 Arsenal Bridge, Rock Island, IL, 2009

This is a good example for establishing a SHM system for existing steel truss bridges.

Background

Arsenal Bridge was a steel through Pratt truss of 8 Spans, constructed 1896. It is a combined two lane highway-railway structure (Fig. 21.9).

- Length: Rail (Spans 1-8)1,848 ft, Vehicle (Spans 2-6) 1,556 ft
- 360°Swing Span 2: 336 ft, 2,000 Tons
- Swing Span Average Turn Time: 12 Min
- Traffic: Rail 1,881/yr, Vehicle 10,297/day, Barges/Boats 18,568/2,884/yr

Fig. 21.9 Arsenal Bridge

The objective is to monitor the integrity and behavior of the bridge structure, and effects due to high traffic and heavy truck loads that could cause possible damage & fatigue.

SHM Systems

Instrumentation (1) Micron Optics sm130-500 Optical Sensing Interrogator
(1) Micron Optics sm041-416 Optical Channel Switch Extension

Sensors (36) Micron Optics os3100 Strain Sensors
(21) Micron Optics os4300 Temperature Sensors
(10) Micron Optics os7100 3D Accelerometers
(1)Fiber Optic Tilt Meter
Conventional AE, weather and corrosion sensors

Project Scope Employ system on the bridge to greatly reduce risk of catastrophic failure by providing advance warning of growing structural problems caused by corrosion/materials degradation.

Demonstrate and validate state-of-the-art and emerging innovative technology approaches for remote structural health and corrosion degradation monitoring of steel bridges.

Sensors were installed along the length of the entire structure, including the rail deck above and the road deck below. The bridge is broken up into four different zones (Fig. 21.10 and Fig. 21.11).

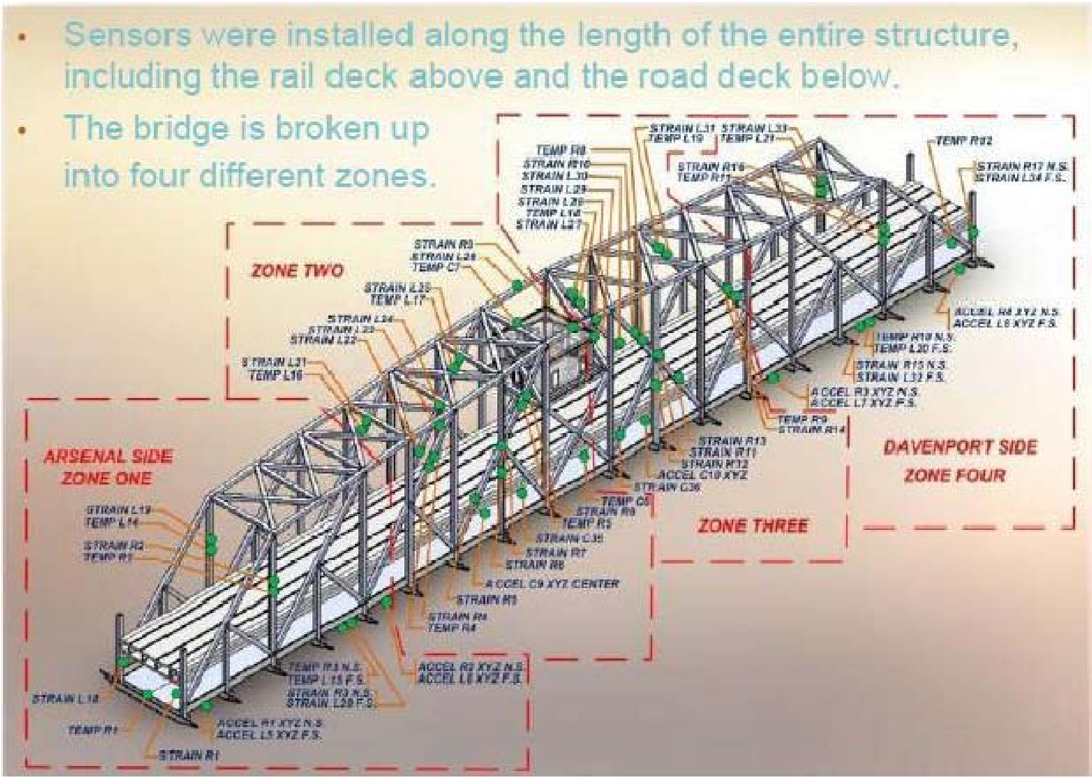


Fig. 21.10 Sensor locations on the entire bridge

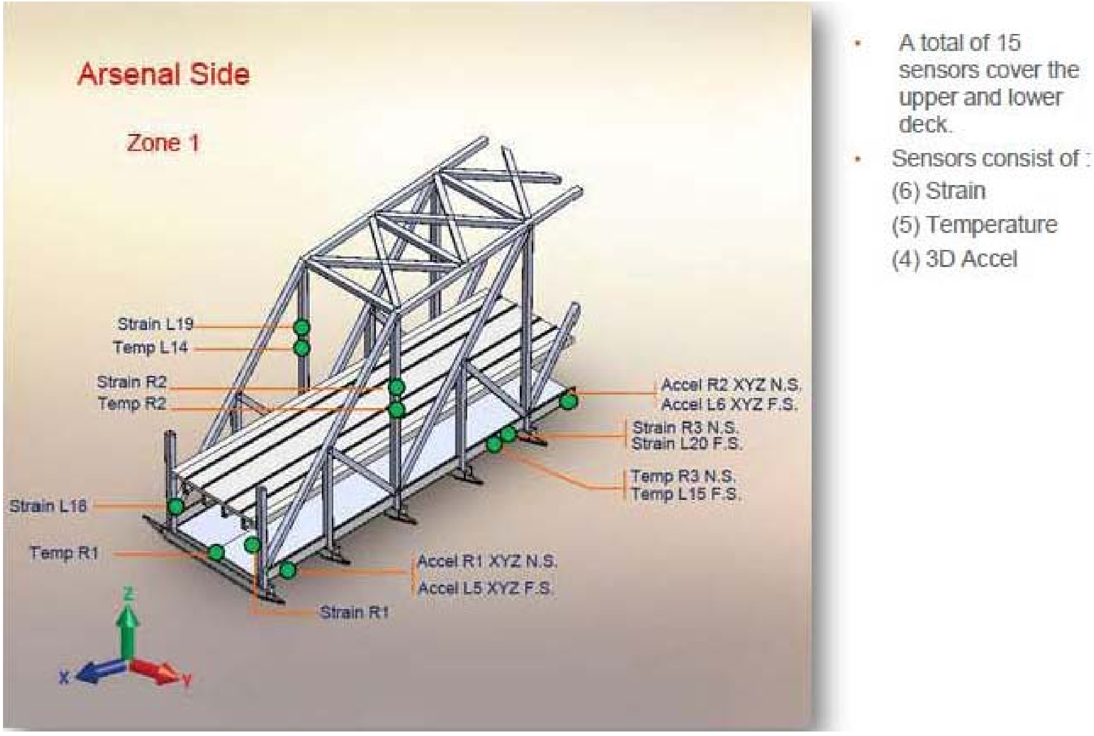


Fig. 21.11 Zone one sensor locations

The monitoring system instrumentation is composed of (Fig. 21.2 and Fig. 21.3):

- Single optical interrogator (model sm130-500), 1Khz, 4 channels
- 4x16 channel sensor multiplexer (model sm041-416)
- sp130 controller and data acquisition module

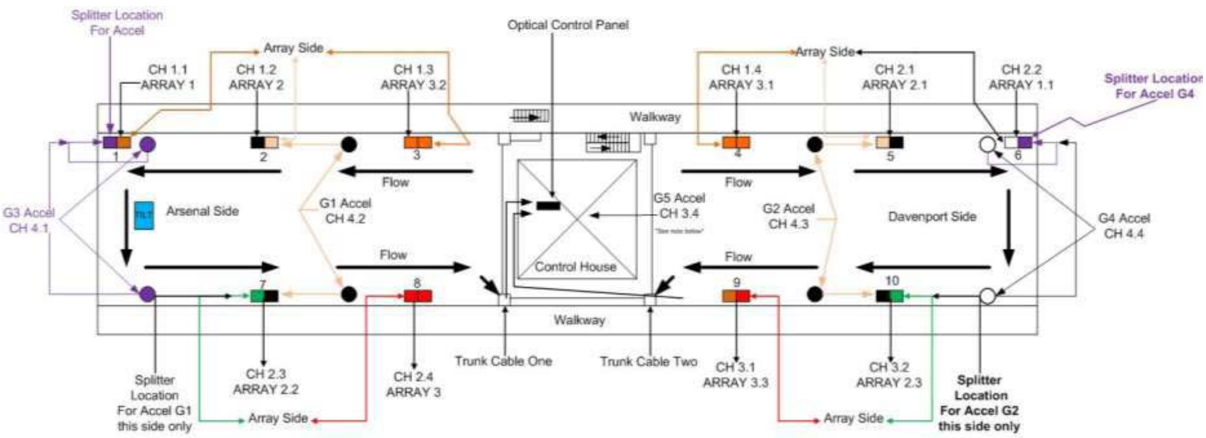


Fig. 21.12 Sensor network configuration

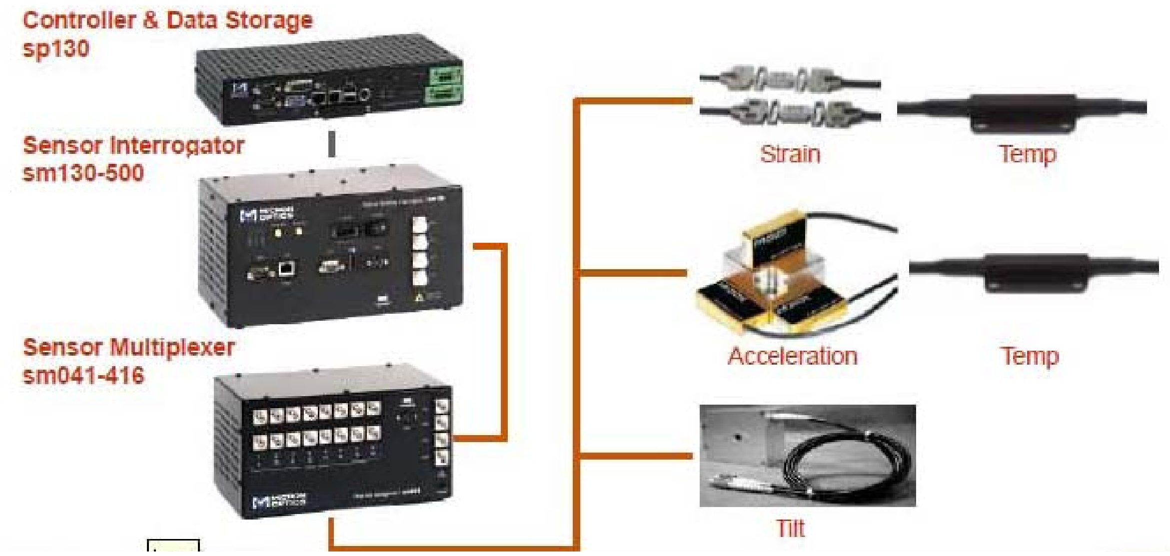


Fig. 21.13 System configuration

The optical system is housed inside a NEMA rated box with controlled temperature and humidity (Fig. 21.14).

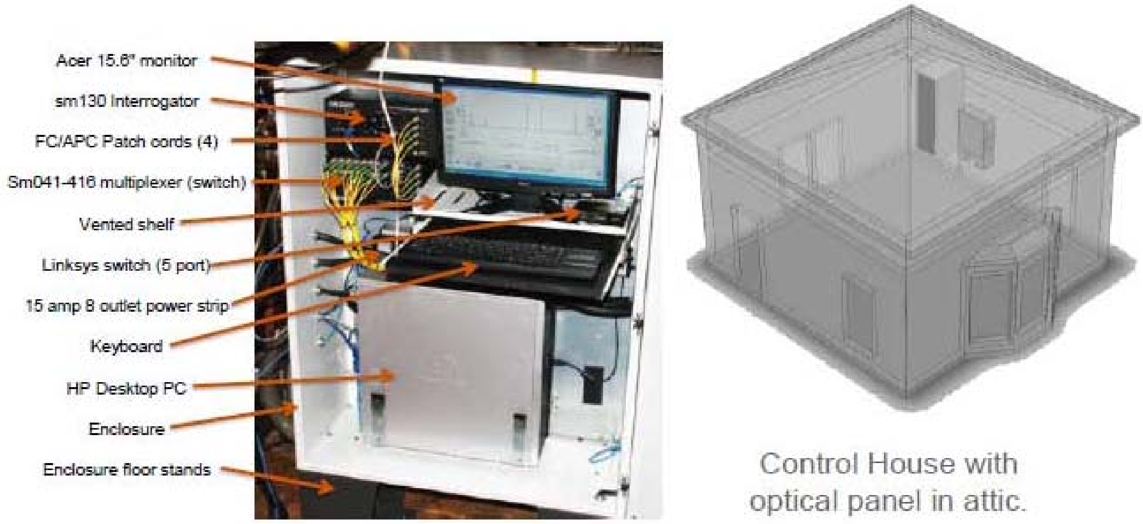


Fig. 21.14 Control house and system

The customized GUI software (Fig. 21.15)

- monitors, gathers data and provides alerts and analysis when various sensing systems approach or exceed established limits;
- communicates with numerous sensing systems to display status and provide information in one centralized user program which can be accessed remotely;

- Electrical Resistance Corrosion Sensors, Weight in Motion Sensors, Weather Stations, Security sensors, and Water depth sensors are some sensors that may be fully integrated into the IntelOptics™ software;
- Micron Optics ENLIGHT application software is used for FBG sensor setup and to stream sensor data to IntelOptics™.

System Performance and Results

The system is installed and commissioned in 2009 and 2010. The following are showing how the system performances and the reporting capabilities and report from the corrosion sensors (Fig. 21.16 to Fig. 21.19).

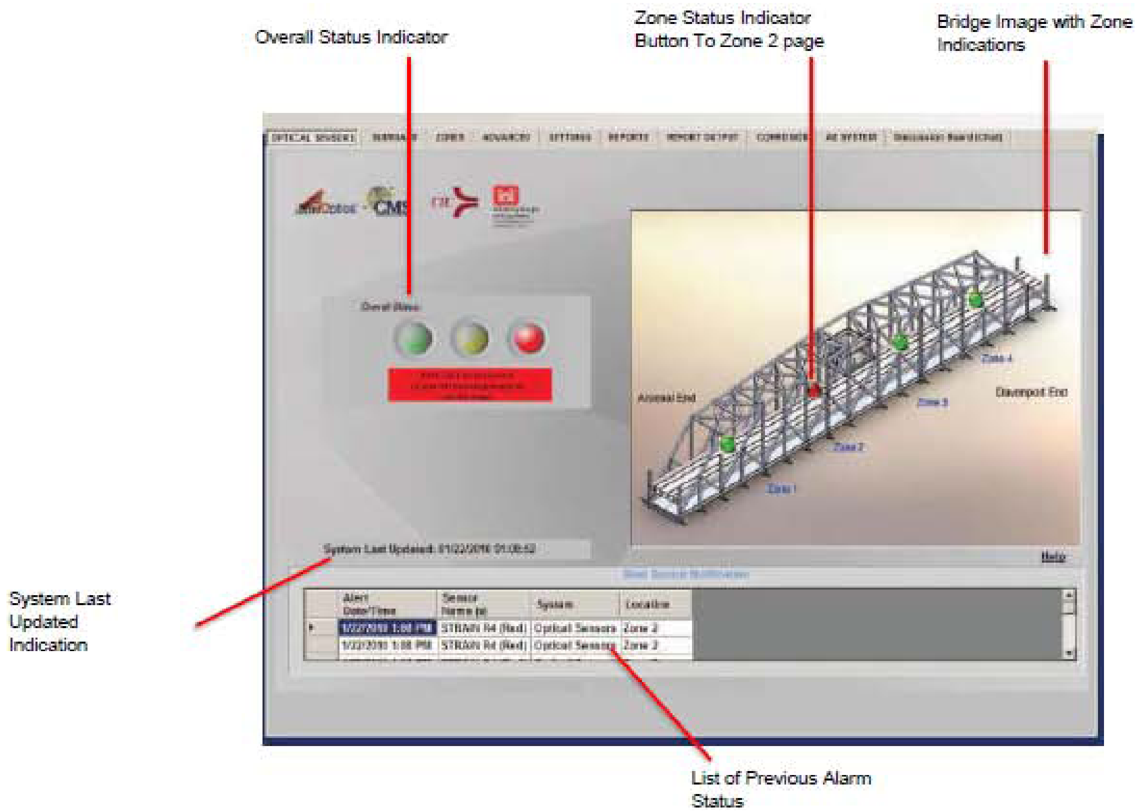


Fig. 21.15 GUI software

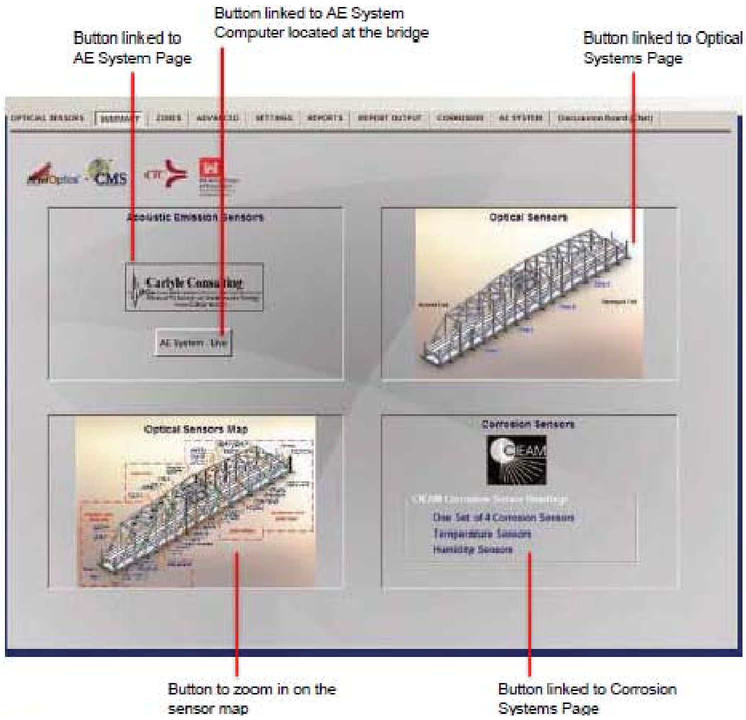


Fig. 21.16 System performance

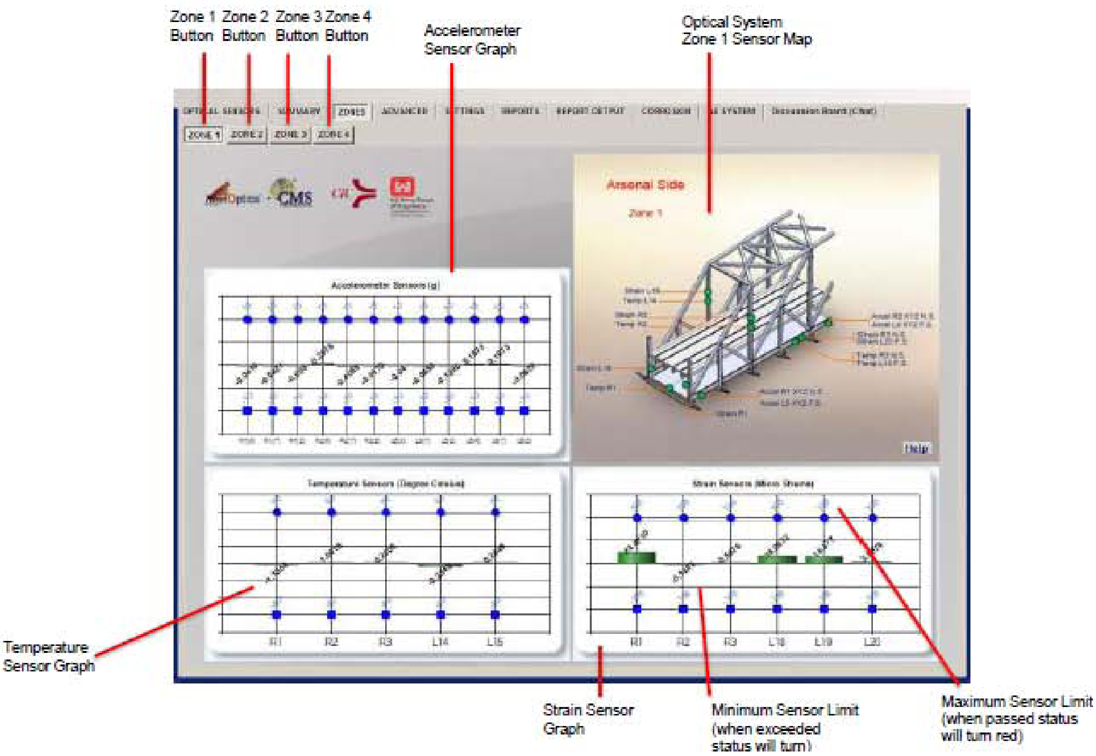


Fig. 21.17 System performance

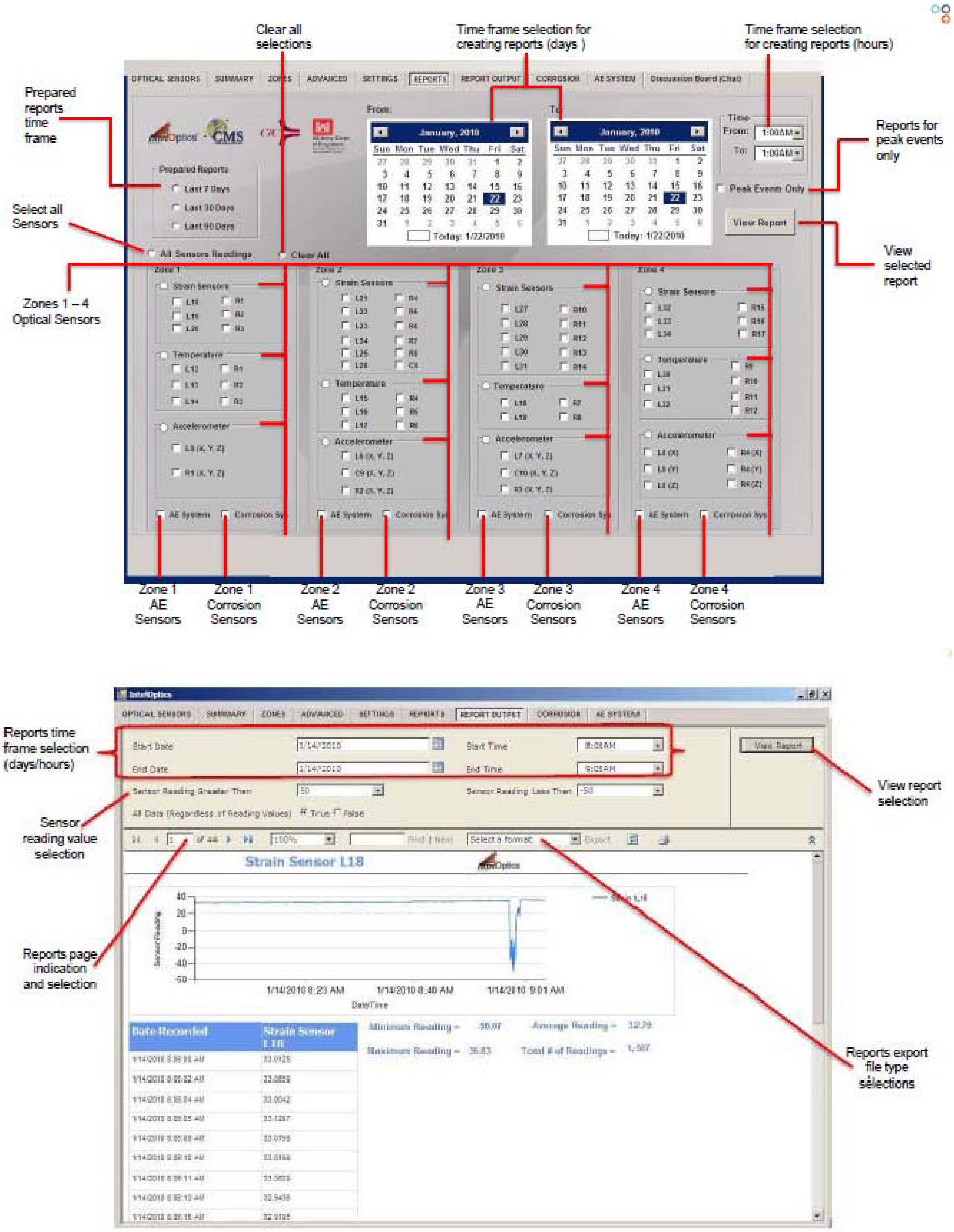


Fig. 21.18 Reporting capabilities

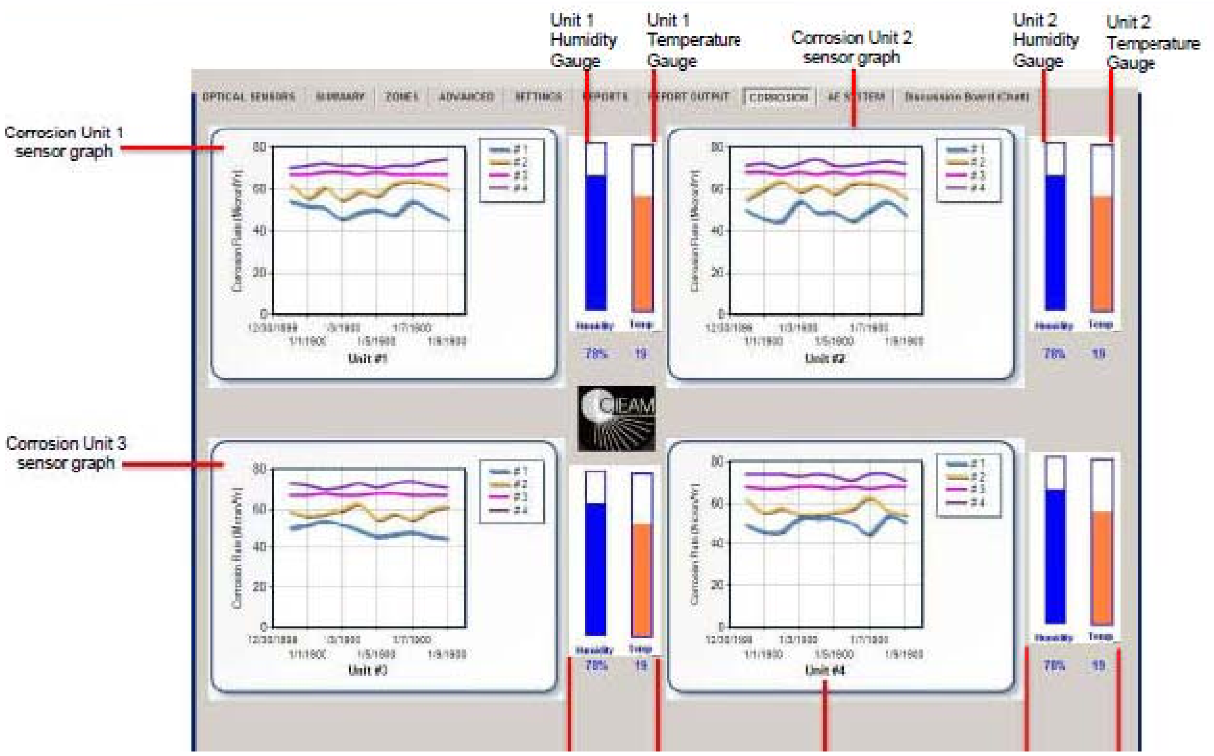


Fig. 21.19 Corrosion sensor reporting

Reference
http://www.micronoptics.com/uploads/library/documents/MicronOptics-Arsenal%20Bridge_2009.pdf

21.2.3 Kishwaukee River Bridge, Illinois, USA

Background

The Kishwaukee River Bridge is a twin pre-stressed concrete box girder structure located in Winnebago County, Illinois. The bridge was the first continuous single-cell box girder bridge with pre-cast concrete segments post tensioned and epoxied together. The box girders are five-span continuous structures with three interior spans (250 ft/ 76.2m) and two exterior spans (170ft/51.8m) with total length of 1090 ft (Fig. 21.20).

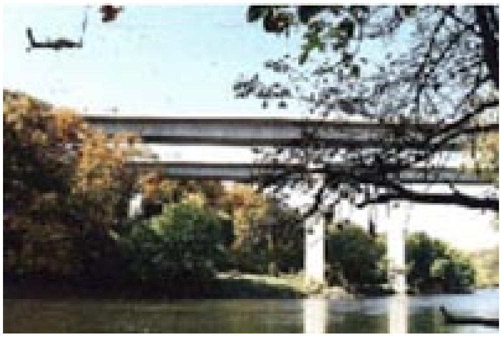


Fig. 21.20 Kishwaukee River Bridge

SHM Systems

Strain gages, accelerometers, clip gages and LVDT gages were installed on the bridge for global and local monitoring of the bridge (Fig. 21.21).

Fig. 21.21 Sensors and testing

System Performance and Results

Local strains and displacements were measured on the inside and outside of the webs, the presence and extent of crack growth and state of shear reinforcement in webs were observed. FEM model updating for global monitoring was performed. Static load test was performed on the bridge in 2000, mid-span deflection, axial strains in web closures; average strains and crack opening in webs were recorded. Shear stress/strain analysis was performed.

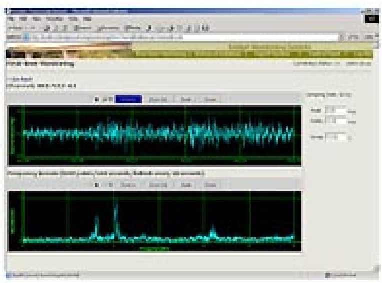


Fig. 21.22 Web monitoring and data access

A customized user-friendly remote web-based Bridge Monitoring System (BMS) to access to real time data was developed (Fig. 21.22). The BMS is a combination of sensor integration, warning and alarm system, statistical analysis and expert system. The BMS provides a password-protected access to the known users. An automated monitoring system for the bridge has been deployed since December 2001. The system provides critical information on strains, displacements, accelerations and temperature at the key segments. A multi-year system maintenance and data analysis program was considered for the bridge for identification of an effective retrofit design.

References

Web site: http://www.smart-structures.com/projects/kishwaukee.htm

21.2.4 Joffre Bridge (reconstructed 1997), Quebec, Canada

Background

The Joffre Bridge, shown in Fig. 21.23, 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 fiber 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. 21.23 The Joffre Bridge in Sherbrooke, Québec. During reconstruction in 1997

Fig. 21.24 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 fiber optic sensors and two Fabry-Perot sensors embedded in the concrete, three Fabry-Perot strain fiber 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 (Fig. 21.24). The following table summarizes sensor placement in the Joffre Bridge.

Table 21.4: Summary of SHM Sensor Placement in the Joffre Bridge

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

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 Fig. 21.25) 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. 21.25 Load testing of the Joffre Bridge with three loaded trucks

References

- Benmokrane et al. (2000)
- Bisby (2006)
- Web site: www.isiscanada.com

21.3 Case Studies in Europe

Reuss River Bridge in Wassen, Switzerland

Background

The bridge is constructed in reinforced concrete comprising a prestressed concrete box section spanning 192 m across a valley. The bridge was refurbished after its partial destruction in a flood event of 1987 and it is in pristine condition. It does not require a monitoring regime in the sense of the classical safety approach.

The objective of monitoring is to observe the bridge in order to get information of the normal structural performance for a longer period of time (up to 5 years). The monitoring should also be used to obtain information on the traffic load since the bridge is located on the heavily trafficked A2 motorway leading to Italy, it serves as transit route for most of the heavy trucks crossing the alps to Italy.

SHM System

The Osmos system with a long track record on civil structures was chosen (please refer to Chapter 16 for more information about the Osmos system).

Three types of sensors were used on the bridge:

- an optical strand with a measurement base of 5 m length (Type SI, see Fig. 21.26)
- an optical extensometer with 120mm range (Type EL, not shown)
- two optical extensometers with high resolution and 5mm range (Type EX, see Fig.21.26)

The sensors can be used between -20°C and +60°C, the temperature sensitivity ranges from 0.6×10^{-6} m/K for the optical strands and the high resolution extensometers, and it is 15×10^{-6} m/K for the EL Sensor.

Fig. 21.26 Optical Sensors; Osmos Optical strand SI 5m (left)
and Osmos EX 5mm (right)

In April 2004 four different optical sensors were installed at the bridge. The elevation of the bridge is shown in Fig. 21.27. At mid-span of the longest section (64m span), at 112m distance from the data acquisition unit at the southern abutment, an optical strand together with a temperature sensor was mounted.

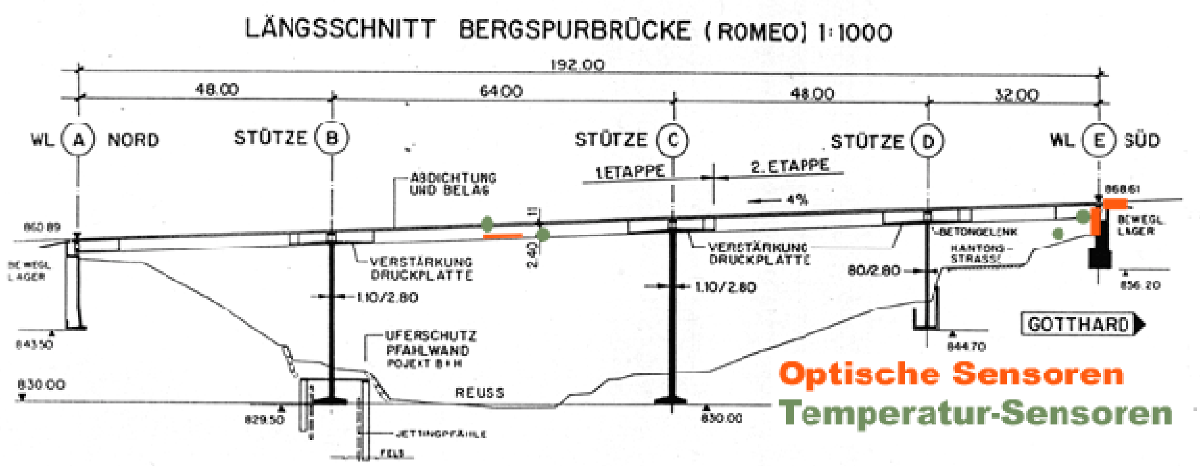


Fig. 21.27 Elevation of the bridge over the Reuss, Kt. Uri.
The lane leading to Italy was equipped with sensors.

In the southern abutment a total of 3 extensometers were installed. Two high resolution extensometers with 5mm movement capacity were placed vertically nearby the bearings. These sensors are used to measure the dynamic deformations caused by the impact of crossing traffic. This dynamic impact is typical according to the weight of the traffic. Therefore, this measurement is then used to weigh the traffic (Weigh in Motion System WIMS).

The movement of the entire bridge is measured by one extensometer, which is placed horizontally in the recess between abutment and bridge. A temperature sensor was also mounted in the recess.

Outside the recess, the Osmos data logging and transmission units are placed, together with a GMS module to transmit the data to the central data server. The power is supplied via the 220 V mains. The installation of the entire system is simple and was accomplished within two days. On the third day, the Weigh in Motion System (WIMS) was calibrated.

System Performance and Results

The bridge has been under continuous monitoring. Annual temperature changes cause equivalent changes in the deformation of the structure. This shows in annual cycles of deformation and temperature. These cycles are parallel to each other when temperature is the only contributing factor. However, should a constant shift of the deformations occur, or should the magnitude of the deformation increase, this could be a sign of beginning structural degradation.

Overall bridge movement at abutment
Fig. 21.28 shows two annual cycles measured with the extensometer located in the recess with 120mm movement capacity (red line).

It can be seen that the bridge is moving by approximately ± 15.0 mm due to the annual temperature changes. The temperature inside the bridge during the measurement period ranged from -10°C up to 25°C (yellow line).

The daily bridge movements are approximately ± 5.0 mm. This is also consistent with much smaller daily temperature variations of about Δ 10°C (day/night). The results are important in two ways. First, they can be used to draw a conclusion on the overall state of health of the bridge, or at least the directly affected components, such as the bearings. Second, in more general terms, the results facilitate a reassessment of design rules regarding bridge movements for this type of bridge.

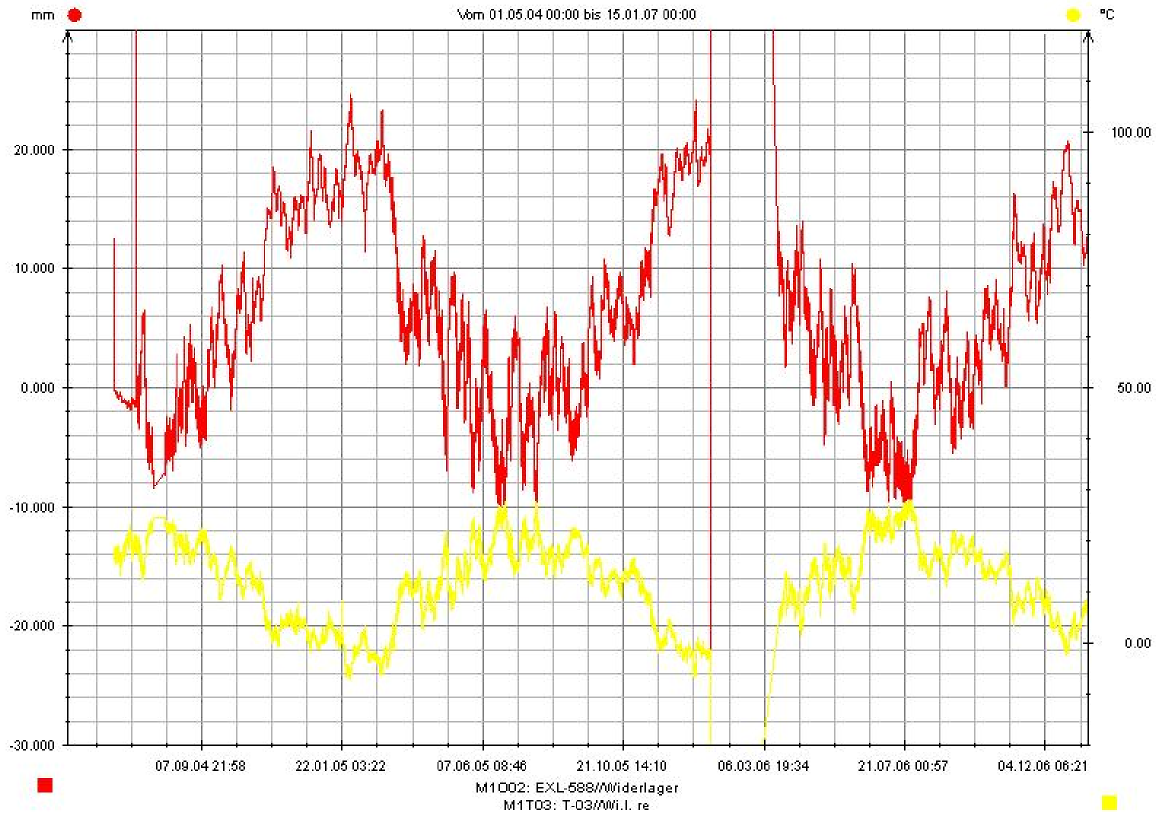


Fig. 21.28 Two annual cycles of the bridge dilation.

Vertical micro movements at abutments

The main purpose of the high resolution extensometers (5mm range) located nearby the bearings, is to measure and categorise the traffic load on the bridge. However the static measurements shown in Fig. 21.29 are also a good indication on the overall state of health of the bridge. The four bridge sections shown in Fig. 21.27 form a continuous beam. This beam shows a typical deformation due to e.g. structural restraints (from interim columns or the fixed end supports).

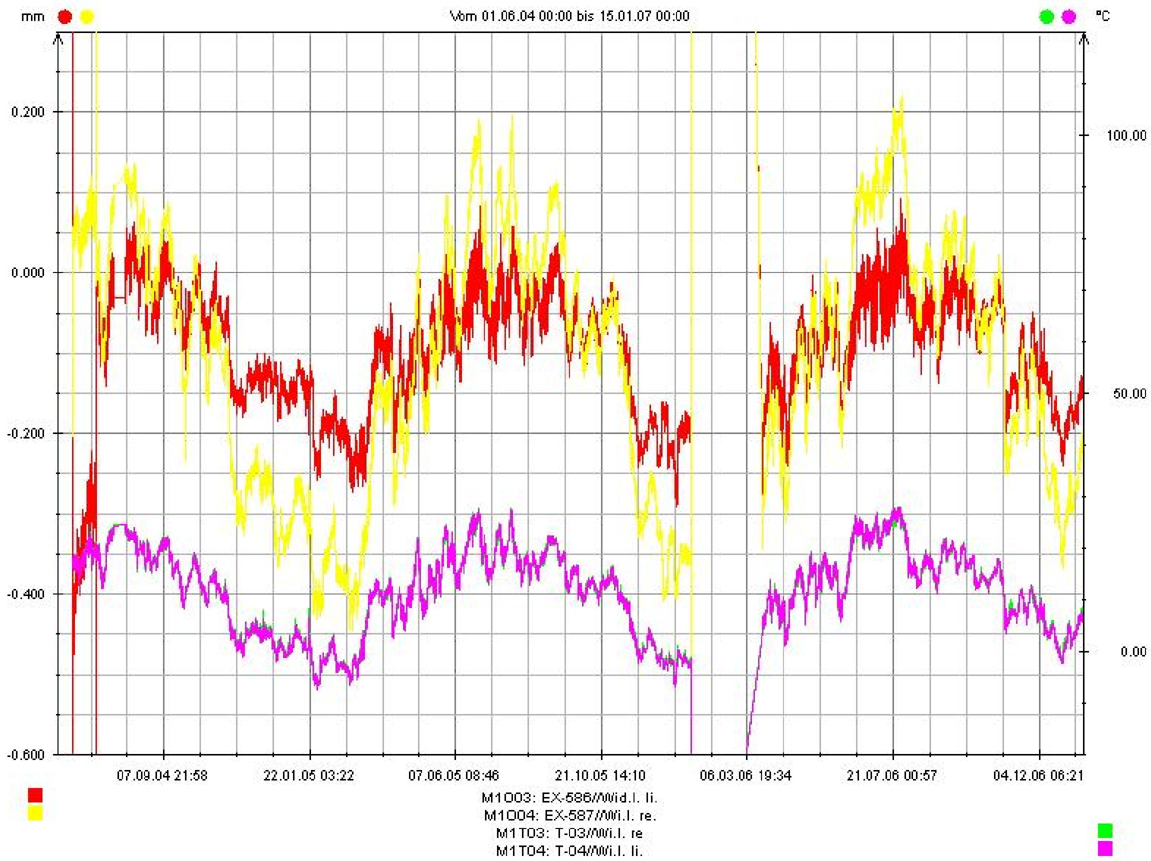


Fig. 21.29 Two annual cycles of the high resolution extensometers used on the abutments

When restraints change because of settlement of any of the columns or any other non-temperature related phenomena, this will also be shown on the deformation graph.

It is important to note, however, that the cause of such a shift cannot be determined from just observing the graph, but such a change could trigger a more detailed investigation of the bridge in order to find the reason. The temperature (green and purple lines) and deformation graphs (red and yellow lines) in Fig. 5 run parallel to each other. Therefore, the structural behavior can be classified as normal and no detailed investigation of the bridge is required at present.

Results of the Osmos WIMS (Weigh In Motion System)

The high resolution extensometers are used for categorisation of the weight of crossing traffic. As the load is transferred through the bearings, the equivalent sinking of the bearings is registered by the extensometers. While the weighing cannot be as accurate as a proper scale, the results provide a good approximation on the weight of crossing traffic.

The figures of WIMS monitoring can be used to assess the impact on the road wear course and in order to decide if any further measures against overweight vehicles are required so that the structure can be protected and offenders can be identified, e.g. by means of cameras.

Strain measurements at midspan of the longest box section

The annual cycles of strain measured at midspan of the largest bridge section is shown in Fig. 21.30. The daily temperature induced strain variations are much smaller (of the order of ± 25 µm/m. This is about the same strain than that induced by a passing truck with 35 tons (45 µm/m).

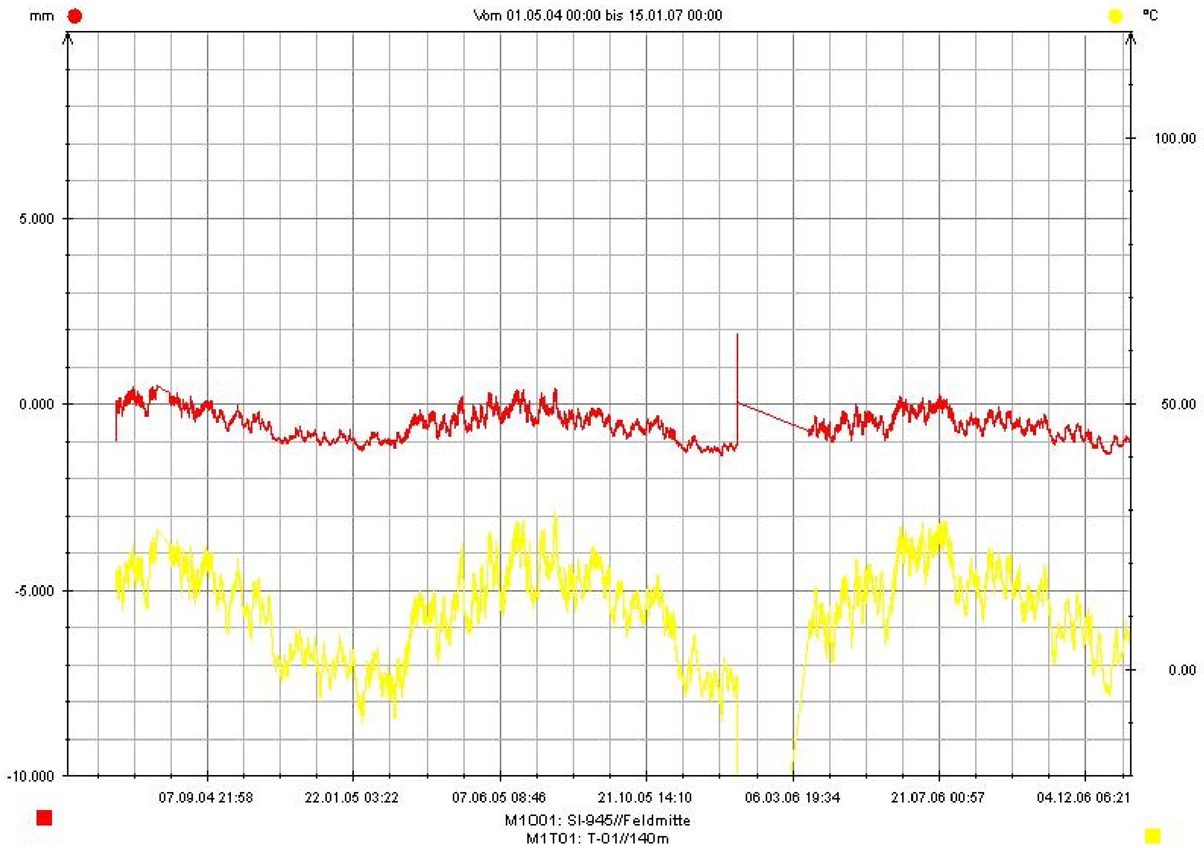


Fig. 21.30 Two annual cycles of deformation and

temperature, measured with the optical strand

First results show also that the load induced stresses are by a factor 200-300 larger than the temperature induced stresses at certain points. This kind of data could be useful in order to refine and adapt current codes of bridge design to account for the effects of traffic load.

Reference

Siegwart 2007

21.4 Case Studies in Asia

SHM in Hong Kong, China

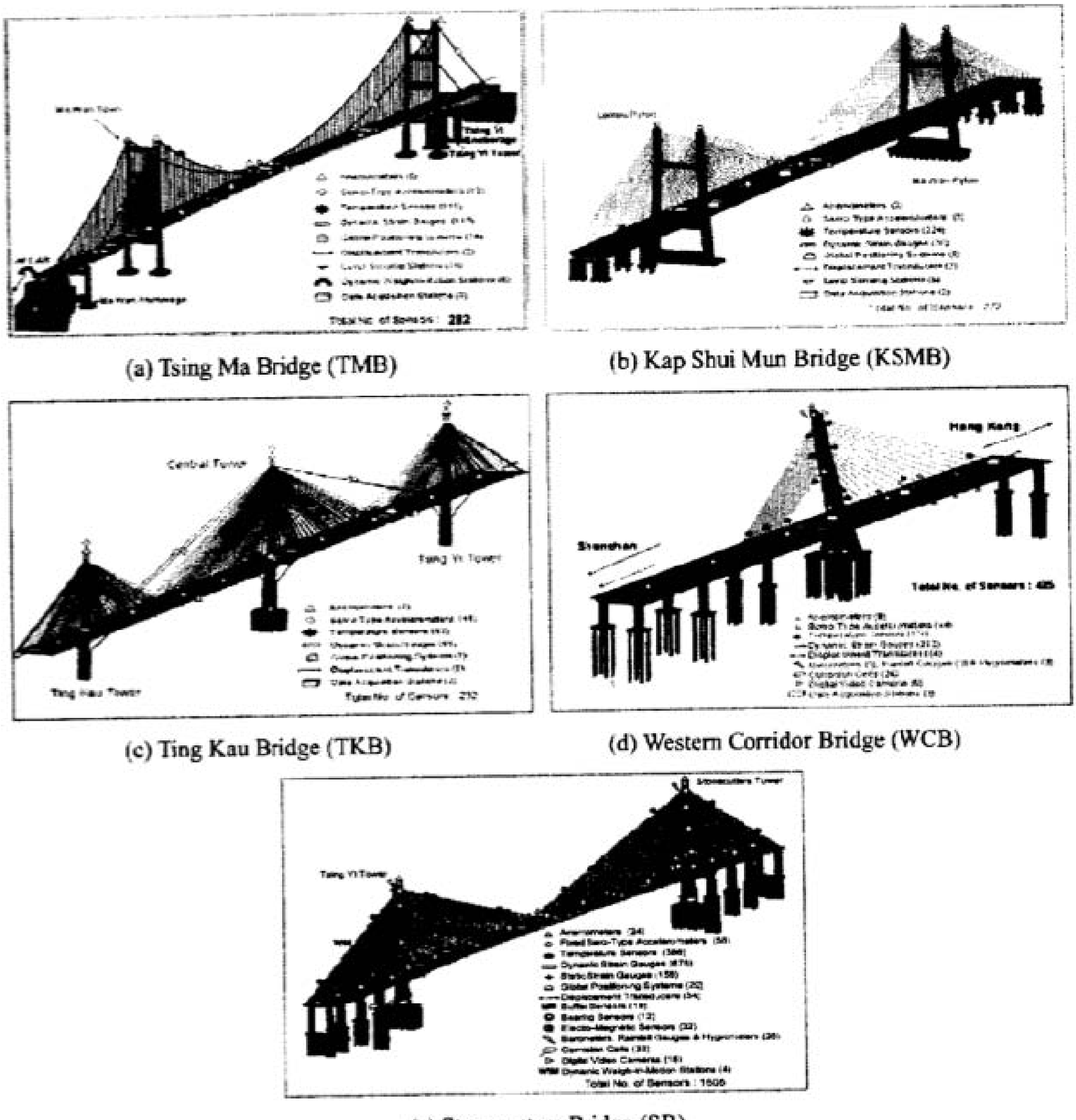
Background

The development of SHM technology for bridges has evolved for over 10 years in Hong Kong since the implementation of the so-called "Wind And Structural Health Monitoring System (WASHMS)" on the Tsing Ma Bridge in 1997 (Wong 2005, Wong 2007, Wong and Ni 2009a, and Wong and Ni 2009b). Fig. 21.31 illustrates the SHM systems deployed on the Tsing Ma Bridge (a suspension bridge with a main span of 1,377 m), the Kap Shui Mun Bridge (a cable-stayed bridge with a main span of 430 m), the Ting Kau Bridge (a cable-stayed bridge with two main spans of 475 m and 448 m respectively), the Western Corridor Bridge (a cable-stayed bridge with a main span of 1,018 m).

SHM Systems

The recently deployed SHM system for the Stonecutters Bridge consists of a total of 1,505 sensors, making it to be the most heavily instrumented bridge in the world. According to a modular design concept [4], the SHM systems have been devised to consist of six integrated modules: Module 1- sensory system; Module 2- data acquisition and transmission system; Module 3- data processing and control system; Module 4- structural health evaluation system; Module 5- structural health data management system; and Module 6- inspection and maintenance system. They are ensured to achieve structural performance objectives as well as monitoring system's performance objectives (Qian et al. 2009).

Table 21.5 lists the type and number of sensors installed on the five bridges. The SHM system for the Tsing Ma Bridge (TMB) has been implemented in 1997 when the bridge construction was completed, while the SHM system for the recently built Stonecutters Bridge (SB) has just been implemented. The evolution of SHM for TMB excludes durability monitoring, whereas the SHM system for SB includes corrosion sensors, rainfall gauges, barometers, hygrometers to monitor durability. The SHM practice over the past decade indicates that durability is a key factor which governs the condition and health of a sea-crossing bridge in its service life cycle, and therefore durability monitoring has currently become an important part of SHM systems for sea-crossing bridges, especially for those located in north China regions with heavy freezing-thawing cycling and severe saline concentration (Shao et al. 2010).



(a) Tsing Ma Bridge (TMB)

(b) Kap Shui Mun Bridge (KSMB)

(c) Ting Kau Bridge (TKB)

(d) Western Corridor Bridge (WCB)

(e) Stonecutters Bridge (SB)

Fig. 21.31 SHM Systems for large-scale bridges in Hong Kong

Table 21.5 Sensors Deployed On Large-Scale Bridges In Hong Kong

Type of Sensors	**TMB**	**KSM**	**TKB**	**WCB**	**SB**
Anemometer	6	2	7	8	24
Servo-type accelerometer	19	3	45	44	58
Dynamic and static strain gauge	110	30	88	212	836
Displacement transducer	2	2	2	4	34
Temperature senor	115	224	83	118	388
Global positioning system (GPS)	14	6	7	--	20
Level sensing station	10	5	--	--	--
Dynamic weigh-in-motion station	6	--	6	--	4
Barometer, Rainfall gauge & Hygrometer	--	--	--	9	28
Corrosion cell	--	--	--	24	33
Digital video camera	--	--	--	6	18
Elasto-magnetic sesnor	--	--	--	--	32
Buffer sensor	--	--	--	--	18
Bearing sensor	--	--	--	--	12
Data acquisition station	3	2	2	3	8
Total number of sensors	282	272	238	425	1,505

The SHM for TMB originally adopted a file-based data management system. Because the SHM system involves a large number of sensors and accomplishes 24-hour monitoring per day, the file-based approach makes the data management a labor-intensive task, and makes it extremely difficult to jointly process multiple data files. To overcome this drawback, a data repository system and a data warehouse system have been adopted to update the original data management system and to realize: (i) standardization and normalization of data, (ii) semi0automatic operation of retrieval, processing and analysis of measured data, (iii) multi-dimensional analysis of data through manipulation of appropriate software analysis tools, and (iv) integration of all historical and current measured/derived data and information.

The structural health evaluation module adopted integrates hardware and software to achieve two targets: structural health monitoring and structural safety evaluation. The former refers to continuous monitoring of performance through comparisons of measured results (e.g., structural response, structural characteristics, structural loads, and environmental conditions) to design values; while the latter refers to the structural health diagnosis and prognosis of any adverse structural effects received from the former, aiming to provide reliable information regarding the integrity of the structure after the occurrence of extreme events such as strong typhoons and earthquakes, or major vehicular and vessel collisions. The operation strategy of the performance-oriented SHM systems is defined in three levels: Level I (normal structural condition monitoring): the measurement values of the physical quantities are less than 75% of the designated values (σ_{SLS}); Level II (critical structural condition monitoring): the measurement values of the physical quantities are in between 75% and 100% of σ_{SLS}; Level III (structural degradation monitoring): the measurement values of the physical quantities are equal to or greater than 100% of σ_{SLS} (Wong and Ni 2009b).

System Performance and Results

Performance Assessment of Bridge Deck

A probability-based method for performance assessment of bridge deck making use of in-service strain monitoring data has been proposed and applied to the Tsing Ma Bridge. The proposed method consists of the structural assessment at two levels: (i) deck structural components, and (ii) deck cross-sections. As shown in Fig. 21.32, a total of 110 dynamic strain gauges have been installed on the Tsing Ma Bridge to measure strain at deck cross-sections and bearings; among them 75 gauges were developed on all the structural members of a selected deck cross-section. According to the proposed method, stress histories of individual structural members comprising the deck cross-section under in-service loads are first derived from the long-term strain monitoring data after eliminating the temperature effect with use of a wavelet multi-resolution analysis (Ni et al. 2009a). Safety indices of the structural members are evaluated through reliability analysis with use of the probability density functions obtained under different loading conditions (highway traffic, railway traffic, monsoon, and typhoon). The resultant bending moment, axial force, and shear force histories of the deck cross-section are then evaluated by synthesizing the monitoring-derived internal forces of the structural members on the deck cross-section, which are further utilized to evaluate the safety index of the whole deck section.

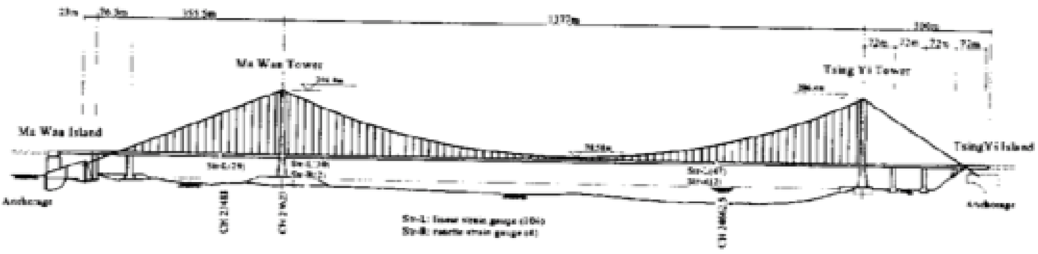
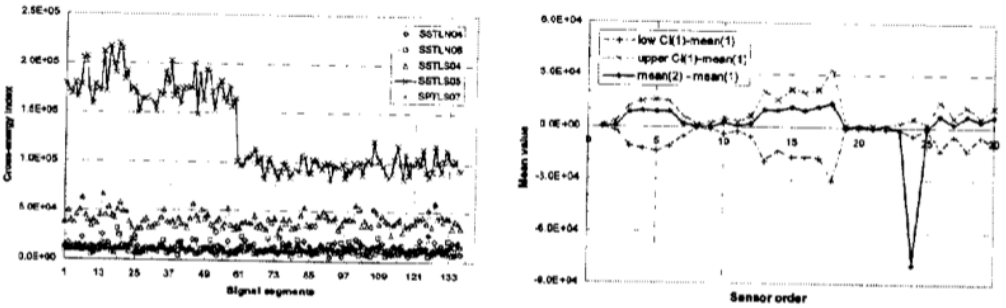


Fig. 21.32 Layout of strain gauges on Tsing Ma Bridge

Local Damage Evaluation

An energy-based local damage detection technique has been developed specific for the Tsing Ma Bridge carrying both highway and railway traffic. When a structure is subject to external excitation, an energy flow in structural components will be built up according to their effective stiffness. Any change in structural continuity, material property and connection between different components would reflect an alteration in effective stiffness and thus lead to the variation of energy distribution in structural components. In the proposed method, strain time-history segments containing railway traffic induced dynamic response are separated from the original records for analyzing strain energy and segmental statistics. The results are then utilized to extract pattern features and construct statistical parameters for damage detection. A cross-energy index has been formulated for each measurement location using the measured strain time-history segments and also the bootstrap of mean value of the cross-energy index is obtained. When the evolution of the cross-energy index at a location exhibits a shift since a time and the corresponding bootstrap exceeds its confidence interval, damage is alarmed and located. The proposed method, in the context of statistical pattern of detecting trifling and local damage as exemplified in Fig. 21.33.



(a) Evolution with time

(b) Bootstrap of mean-value

Fig. 21.33 Evoluition and bootstrap of cross-energy index

Assessment of Fatigue Life and Reliability

Fatigue is among the most critical forms of damage that may occur in steel bridges. A procedure for evaluating fatigue life and reliability of welded details based on long-term monitoring of strain has been proposed and applied to the Tsing Ma Bridge. A fatigue reliability model which integrates the probability distribution of hot spot stress range with a continuous probabilistic formulation of Miner's damage cumulative rule has been proposed for fatigue life and reliability evaluation of steel bridges with long-term monitoring data (Ni et al. 2010). By considering both the measured nominal stress and the corresponding stress concentration factor (SCF) as random variables, a probabilistic model of the hot spot stress is formulated by use of the S-N curve and the Miner's rule, which is then used to evaluate the fatigue life and failure probability with the aid of structural reliability theory. In application to the Tsing Ma Bridge, it was found that the daily stress spectra formulated using the measured strains obtained in different days were similar as shown in Fig. 21.34. As a result, a standard daily stress spectrum accounting for highway traffic, railway traffic, and typhoon effects could be derived by use of appropriate monitoring data for fatigue assessment.

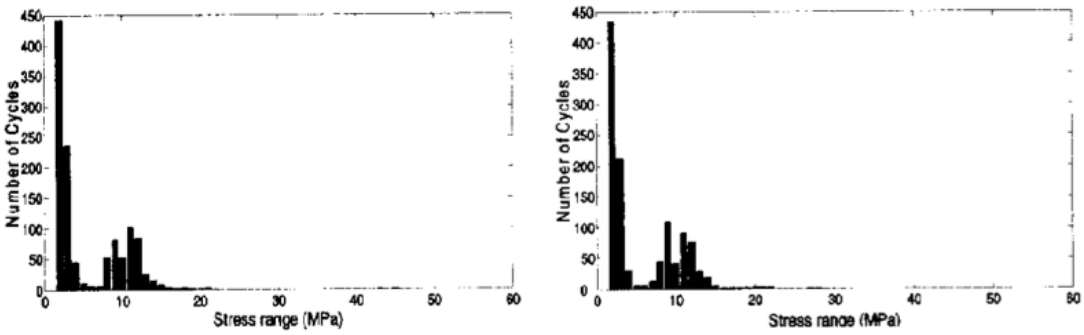


Fig. 21.34 Histograms of daily stress spectra obtained in two different days

Condition Assessment of Expansion Joints

A procedure for condition assessment of bridge expansion joints making use of long-term monitoring data has been proposed and applied to the Ting Kau Bridge (Ni et al. 2007). As illustrated in Fig. 21.35, a SHM system for a large-scale bridge usually includes the measurement of both displacement at expansion joints and temperature on deck sections. Based on the measurement data of expansion joint displacement and bridge temperature, the normal correlation pattern between the effective temperature and the thermal movement can be established. Alarm will be raised if a future pattern deviates from this normal pattern. With the established correlation pattern, the expansion joint displacements under the design maximum and minimum temperature are predicted and compared with the design allowable values. The extreme temperatures for a certain return period are derived using the measurement data for design verification. Then the annual or daily-average accumulative movements experienced by expansion joints are estimated from the monitoring data for comparison with the expected values in design. Because the service life and interval for replacement of expansion joints rely to a great extent on the accumulative displacements, an accurate prediction of accumulative displacements will provide a robust basis for determining a reasonable interval for inspection or replacement of expansion joints.

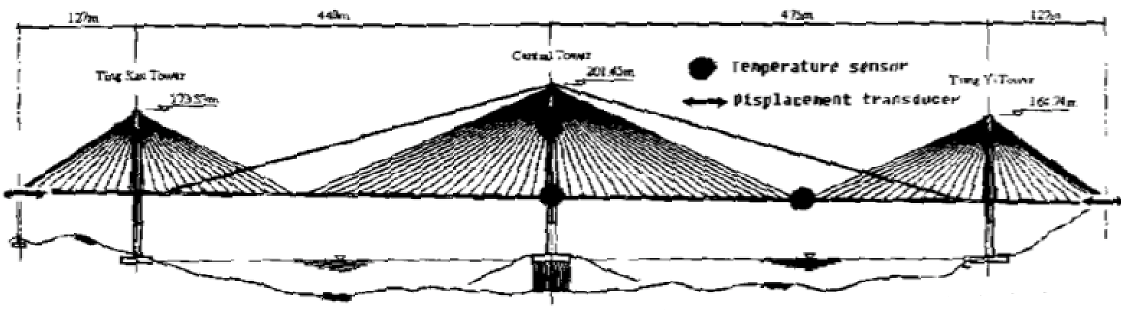


Fig. 21.35 Layout of temperature sensors and displacement transducers on Ting Kau Bridge

Vibration-Based Damage Detection

It has been shown that vibration-based damage detection approaches are only able to identify damage occurrence and localize the damage for the large-scale civil structures such as the instrumented bridges in Hong Kong, due to the extremely low modal sensitivities to local damage (Ko et al. 2009). Another pitfall limiting the successful application of vibration- or modal-based damage diagnosis methods is the environmental effects. In reality, bridges in service are always subject to varying environmental/operational conditions such as temperature, wind, traffic, humidity, and solar-radiation. These environmental effects also cause changes in dynamic and modal properties, which may mask the changes caused by structural damage or produce false indications of damage. It has been known that for bridge structures temperature is the critical source causing variability of modal frequencies with a clear correlation, but the variation in mode shapes is independent of the environmental effects.

There are both parametric and non-parametric approaches to eliminating the environmental/operational effects in vibration-based damage detection (Worden 2002, Kim et al. 2007, Deraemaeker 2008, Kullaa 2009, Oh and Sohn 2009, and Wenzel 2009). A lot of temperature sensors and accelerometers have been installed on the instrumented bridges in Hong Kong. As a result, correlation models between modal frequencies and environmental temperatures can be quantitatively formulated making use of long-term monitoring data and advanced statistical learning techniques (Hua et al. 2007, Ni et al 2009b). With the aid of the established correlation models, the modal frequencies obtained at different stages (e.g., prior to and posterior to damage) under different temperature conditions can be normalized to an identical reference temperature condition (Zhou et al. 2010a). As shown in Fig. 21.36, the novelty index sequences constructed using the normalized modal frequencies perform favorably in eschewing false-positive alarm and detecting damage under varying environmental conditions. A non-parametric method that uses generalization techniques has been developed for this purpose (Zhou et al. 2010b).

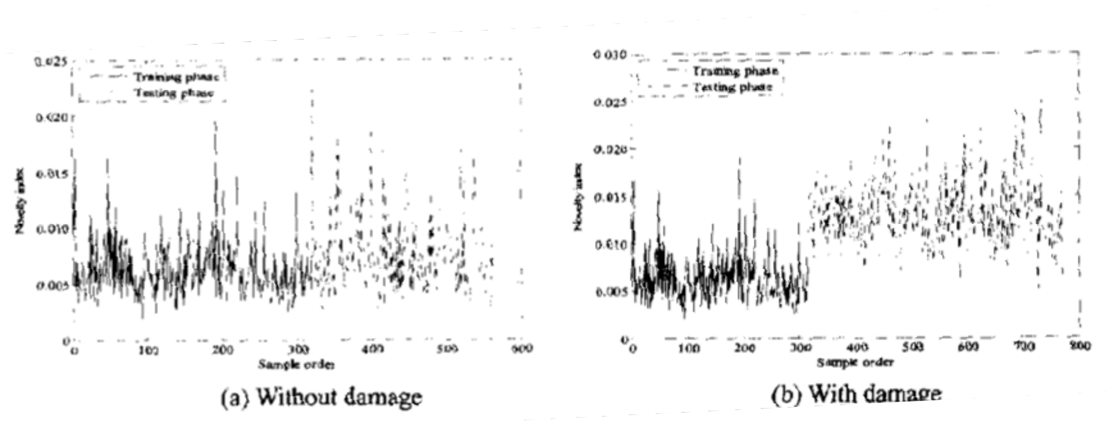


Fig. 21.36 Novelty index sequences constructed using normalized modal frequencies

References

Wang and Ni 2009b

21.5 Summary and Conclusion

Based on the potential combinations of different available sensors and systems, the range of applications is virtually endless. Application of structural health monitoring technologies to bridges has seen great increase in the past decade. Initial results from these applications have shown the capability of available SHM technologies in monitoring, analysing, and understanding the health of the monitored bridges.

Since most of case studies and applications are just in past recent years, it is necessary to examine their performance and results over a long time by continuous monitoring to determine the durability and reliability of these systems.

22 SUMMARY AND CONCLUSIONS

This study synthesize the current knowledge and technologies available for health monitoring of civil infrastructures, and to simplify the process of selecting structural health monitoring (SHM) systems for applications to bridge structures. This report focuses on (a) the state-of-the-art of SHM systems and their capabilities and (b) companies that offer particular systems and services, special attention is paid on the potentials of these systems being implemented to bridges in cold, remote regions of Alaska.

Some basic definitions about SHM, components of SHM, application scenarios, critical considerations in integrating and leveraging experimental, analytical and information technologies for SHM data analysis and interpretation are first discussed in this report. It is possible to see more and routine SHM applications in civil infrastructure due to the new advances in sensing, communication and information technologies, and the efforts of researchers and industry to develop new products and systems for specific monitoring needs.

It is seen that sensing and data acquisition technologies have advanced and are advancing significantly such that the limits of sensing are fast disappearing. A critical issue is to effectively use Internet architectural standards and associated networking protocols and technologies that offer data integration, communication, real-time visualization and archival over large distances and very long time durations such as decades. The principal challenges that remain mainly related to data analysis, timely and effectively interpretation, and information management.

Due to the variety of products offered by a variety of companies, this report tries to categorize their products in terms of their functions. Many companies specialize in a particular type of system, while others claim to offer customized complete systems that can be tailored to a specific bridge. Here a *complete system* was defined as one that comprises sensors, data acquisition units, communication tools, and software.

Based on the results of this study, majority of SHM products and systems can be used to cold regions with special care taken to tailor the system, e.g., to house the field equipment in NEMA enclosure with air-conditioning. Due to the advancement in computing, data communication and network technologies, a number of sensors and systems are able to perform wireless/remote monitoring. This means they can be used to bridges in remote regions. A number of companies offer an alarming feature. Normally, the alarm is triggered by breaching a predetermined threshold and a message is sent to the bridge owner by email or cellular.

In summary, the report explains the basic knowledge of structural health monitoring, and summarizes the commercially available SHM products and systems. Many companies claim to offer 'turn-key' systems that can be easily used to the bridge SHM. A quite number of bridges have been instrumented with SHM systems and are under monitoring, but literature of the system performance, monitoring results, and how they helped the bridge owners are often not available. It's still challenging to not only see data stream in real-time and to archive them for future use, but also to interpret, analyze, characterize the response, detect damage and deterioration and assess the condition of the bridges.

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APPEBNDIX (LIST OF COMPANIES)

Name of Company	Contact Information	
Acellent Technologies, Inc.	Address: Website: Tel:	155C-3 Moffett Park Dr. Sunnyvale, CA 94089 www.acellent.com (408) 745-1188 Fax: (408) 745-6168
Advanced Corrosion Monitoring (ACM) Instruments	Address: Website: Tel:	125 Station Road, Cark, Grange-over-Sands LA11 7NY, England www.potentiostat.com +44 (0)15395 59185 Fax: +44 (0)15395 58562
Acuity Research Inc.	Address: Website: Tel:	10624 S. Eastern Ave., Suite A-271, Henderson, NV 89052 www.acuityresearch.com (702) 616-6070 Fax: (702) 616-6071
Advanced Design Consulting (ADC), Inc.	Address: Website: Tel:	PO Box 187, 126 Ridge Road, Lansing, NY 14882 www.adc9001.com (607) 533-3531 Fax: (607) 533-3618
Analog Devices Inc. (ADI)	Address: Website: Tel:	P. O. Box 9106, Norwood, MA 02062-9106 www.analog.com (800) 262-5643 or (781) 461-3333 Fax: 781-461-4482
Advanced Optics Solutions (AOS) GmbH	Address: Website: Tel:	Ammonstrasse 35, D-01067 Dresden, Germany www.aos-fiber.com +49 (0)351 4960 193 Fax: +49 (0)351 4960 194
Applied Measurements, Ltd.	Address: Website: Tel:	3 Mercury, Calleva Park, Aldermaston, Berkshire RG7 8PN. UK. www.appmeas.co.uk +44 (0) 118 981 7339 Fax: +44 (0) 118 981 9121
Advanced Structure Monitoring (ASM), Inc.	Address: Website: Tel:	21070 Homestead #200, Cupertino, CA 95014 www.asmonitoring.com (408)-481-9030 Fax: (408)-481-9031
Advanced Telemetrics International (ATI)	Address: Website: Tel:	2361 Darnell Drive, Spring Valley, OH 45370 www.atitelemetry.com (937) 862-6948 Fax: (937) 862-7193
Bridge Diagnostics, Inc. (BDI)	Address: Website: Tel:	5398 Manhattan Circle, Suite 100, Boulder, CO 80303-4239 www.bridgetest.com (303) 494-3230 Fax: (303) 494-5027
Blue Road Research	Address: Website: Tel:	376 NE 219th Ave., Gresham, OR 97030 www.bluerr.com (503) 667-7772 Fax: (503) 667-7880
Bragg Photonics, Inc./Avensys, Inc.	Address: Website: Tel:	880 Selkirk, Pointe-Claire, Montreal (Quebec) Canada. www.braggphotonics.com www.avensys.ca (514) 428-6766 Fax: (514) 428-8999
Campbell Scientific, Inc. (CSI)	Address: Website: Tel:	815 West 1800 North, Logan, UT 84321 www.campbellsci.com (435) 750-9558 Fax: (435) 750-9540
Chen Yang	Address: Website: Tel:	Franz-Brombach-Str. 11-13, D-85345 Erding, Germany www.chenyang-ism.com +49 (0) 8122-227-4508 Fax: +49 (0) 8122-227-4509
Condor Earth Technologies, Inc.	Address:	21663 Brian Lane, Sonora, CA 95370

	Website:	www.condorearth.com or www.3d-gps.com
	Tel:	(209) 532-0361 or (209) 234-0518 Fax: (209) 532-0773
Crossbow Technology, Inc.	Address:	41 Dagget Dr., San Jose, CA 95134
	Website:	www.xbow.com
	Tel:	(408) 956-3300 Fax: (408) 324-4840
Cold Regions Research and Engineering Laboratory (CRREL)	Address:	72 Lyme Rd, Hanover, NH 03755 (US Army Corps of Engineers)
	Website:	www.crrel.usace.army.mil
	Tel:	(603) 646-4319 Fax: (603) 646-4477
Daytronic Corporation	Address:	2211 Arbor Boulevard, Dayton, Ohio 45439-1521
	Website:	www.daytronic.com
	Tel:	(937) 293-2566 Fax: (937) 293-2586
Dunegan Engineering Company, Inc.	Address:	P.O. Box 1749, San Juan Capistrano CA 92693
	Website:	www.deci.com
	Tel:	(949) 661-8105 Fax: (949) 661-3723
Digitexx Data System, Inc.	Address:	145 N. Sierra Madre Blvd. #9, Pasadena, CA 91107
	Website:	www.digitexx.com
	Tel:	(626) 568-3171 Fax: 626-568-3182
Division Projstar Monitoring Group International	Address:	Nad Dunajom 50, 841 04 Bratislava 4, Slovakia, Europe
	Website:	www.dynamag.sk
	Tel:	+421 2 654 22 432 Fax: +421 2 654 22 432
DYTRAN Instruments Inc.	Address:	21592 Marilla St., Chatsworth, California 91311
	Website:	www.dytran.com
	Tel:	(818) 700-7818 Fax: (818) 700-7880
EENTEC	Address:	625 N. Euclid Ave., Suite 404, St. Louis, MO 63108
	Website:	www.eentec.com
	Tel:	(314) 454-9977 Fax: (314) 454-9979
Encardio-rite Electronics Private Ltd.	Address:	A-7, Industrial Estate, Talkatora Road, Lucknow-226011, UP, India
	Website:	www.encardio.com
	Tel:	+91-522-2661044, 2661040 Fax: +91-522-2661043
Endevco Corporation	Address:	30700 Rancho Viejo Road, San Juan Capistrano, CA 92675
	Website:	www.endevco.com
	Tel:	(800) 982-6732 or (949) 493-8181 Fax: (949) 661-7231
Engius	Address:	1414 S. Sangre Road, IDC Building, Stillwater, Oklahoma 74074
	Website:	www.intellirock.com
	Tel:	(866) 636-4487 Fax: (866) 277-8369
Fiberpro	Address:	59-4 Jang-dong, Yusong-gu, Daejeon, 305-343, Korea
	Website:	www.fiberpro.com
	Tel:	+82-42-360-0030 Fax: +82-42-360-0040
Force Technology	Address:	Park Alle 345, 2605 Brondby, Denmark.
	Website:	www.force.dk
	Tel:	+45 4326-7000 or (713) 975-8300 in US Fax: +45 4326-7011
Fiber Optic System Technology, Inc.	Address:	4580 Dufferin Street, Toronto, Ontario M3H 5Y2, Canada
	Website:	www.fox-tek.com
	Tel:	(416) 665-2288 Fax: (416) 665-0494
Frequency Devices, Inc.	Address:	25 Locust Street, Haverhill, Massachusetts 01830

	Website:	www.freqdev.com
	Tel:	(978) 374-0761 or (800) 252-7074 Fax: (978) 521-1839
GEODEV SA	Address:	Stabile Gerre, P.O. Box 341, 6928 Manno, Switzerland
	Website:	www.geodev.ch
	Tel:	+41 91 610 1920 Fax: +41 91 610 1921
GeoIndicator Ltd.	Address:	4th floor-22 Buckingham Gate, SW1E 6LB London, UK
	Website:	www.geoindicator.com
	Tel:	+44 77 6605 5485 Fax: +44 20 7486 1830
Geokon, Inc.	Address:	48 Spencer St. Lebanon, NH 03766
	Website:	www.geokon.com
	Tel:	(603) 448-1562 Fax: (603) 448-3216
Geomation, Inc.	Address:	14828 W 6th Ave, Ste 1-B, Golden, Colorado 80401
	Website:	www.geomation.com
	Tel:	(720) 746-0100 Fax: (720) 746-1100
Geomechanics Inc.(Applied Geomechanics Inc.)	Address:	1336 Brommer Street, Santa Cruz, CA 95062
	Website:	www.geomechanics.com
	Tel:	(831) 462-2801 Fax: (831) 462-4418
GeoSIG Ltd.	Address:	Europastrasse 11, 8152 Glattbrugg, Switzerland
	Website:	www.geosig.com
	Tel:	+41 1 810 21 50 Fax: +41 1 810 23 50
Geo Space, LP	Address:	7334 N. Gessner, Houston, Texas 77040
	Website:	www.geospacelp.com
	Tel:	(713) 939-7093 Fax: (713) 937-8012
Geophysical Survey Systems, Inc. (GSSI)	Address:	13 Klein Dr, PO Box 97, North Salem, New Hampshire 03073
	Website:	www.geophysical.com
	Tel:	(603) 893-1109 Fax: (603) 889-3984
Hottinger Baldwin Messtechnik (HBM), Inc.	Address:	19 Bartlett Street, Marlborough, MA 01752
	Website:	www.hbm.com
	Tel:	(734) 944-4938 or (800) 578-4260 Fax: (508) 485-7480
Hitec Products, Inc. (HPI)	Address:	PO Box 790, Ayer, MA 01432
	Website:	www.hitecprod.com
	Tel:	(978) 772-6963 Fax: (978) 772-6966
Intelligent Fiber Optic Systems (IFOS) Inc.	Address:	650 Vaqueros Ave., Sunnyvale, CA 94085
	Website:	www.ifos.com
	Tel:	(408) 328-8610 Fax: (408) 328-8614
IMC Dataworks, LLC	Address:	4230 East Towne Blvd., #285, Madison, WI 53704
	Website:	www.imcdataworks.com
	Tel:	(608) 231-6123 Fax: (608) 244-2284
Impact-Echo Instruments, LLC.	Address:	P.O. Box 3871, Ithaca, NY 14852-3871
	Website:	www.impact-echo.com
	Tel:	(6070 738-1547 Fax: (607) 533-7667*2
Infrasense, Inc.	Address:	14 Kensington Road, Arlington, MA 02476
	Website:	www.infrasense.com
	Tel:	(781)-648-0440 Fax: (781) 648-1778
Instantel	Address:	309 Legget Dr., Ottawa, Ontario, Canada, K2K 3A3
	Website:	www.instantel.com

	Tel:	(613) 592-4642 Fax:(613) 592-4296
Institute of Civil Engineering, Technische Universitat Berlin	Address: Website: Tel:	Sekr, TIB 1-B4, Gustav-Meyer-Allee25, Berlin, Germany www.tu-berlin.de/eng/ 314 72101 Fax: 314-72110
InterCorr International, Inc	Address: Website: Tel:	14503 Bammel N. Houston, Suite 300, Houston, Texas 77014 www.intercorr.com (281) 444-2282 Fax: (281) 444-0246
Invocon, Inc.	Address: Website: Tel:	19221 IH 45 South, Suite 530, Conroe, TX 77385 www.invocon.com (281) 292-9903 Fax: (281) 298-1717
IOtech, Inc.	Address: Website: Tel:	25971 Cannon Road, Cleveland, OH 44146 www.iotech.com (440) 439-4091 Fax: (440) 439-4093
Johns Hopkins University Applied Physics Laboratory (APL)	Address: Website: Tel:	11100 Johns Hopkins Road, Laurel, Maryland 20723-6099 www.jhuapl.edu (240) 228-8309, John Bacon or (240)-228-5000
Kawasaki Heavy Industries (KHI), Inc. (US office)	Address: Website: Tel:	599 Lexington Avenue, Suite 3901, New York, New York 10022 www.khi.co.jp/index_e.html (212) 759-4950 Fax: (212) 759-6421
Kinemetrics, Inc.	Address: Website: Tel:	222 Vista Avenue, Pasadena, CA 91107 www.kinemetrics.com (626) 795-2220 Fax: (626) 795-0868
LDS Test and Measurement LLC.	Address: Website: Tel:	8551 Research Way, m/s 140, Middleton, Wisconsin 53562 www.lds-group.com (608) 821-6651 Fax: (608) 821-6691
Leica Geosystems AG	Address: Website: Tel:	Kanalstrasse 21, 8152 Glattbrugg, Switzerland www.leica-geosystems.com +41 1809 3311 or (770) 447-6361 (US) Fax: +41 1810 7937
Light Structures AS	Address: Website: Tel:	Hasleveien 38, NO-0571 Oslo, Norway www.lightstructures.biz +47 2389 7133 Fax: +47 2237 1328
LOADTEST, Inc.	Address: Website: Tel:	2631 NW 41st Street, Building D, Gainesville, FL 32606 www.loadtest.com (800) 368-1138 or (352)-378-3717 Fax: (352)-378-3934
Luna Innovations.	Address: Website: Tel:	2851 Commerce St. Blacksburg, VA 24060 www.lunainnovations.com (540) 552-5128 Fax: (540) 951-0760
LxSix Photonics, Inc.	Address: Website: Tel:	520 McCaffrey, St-Laurent, Quebec, Canada H4T 1N1 www.lxsix.com (514) 599-5714 Fax: (514) 599-5729
Micron Optics Inc.	Address: Website: Tel:	1852 Century Place NE, Atlanta, GA 30345 www.micronoptics.com (404) 325-0005 Fax: (404) 325-4082
MicroStrain, Inc.	Address: Website: Tel:	310 Hurricane Lane, Unit 4, Williston, VT 05495 www.microstrain.com (800) 449-3878 Fax: (800) 863-4093

North Carolina A&T State University	Address: Website: Tel:	1601 E.Market St., Greensboro, NC 27411 dor.ncat.edu (336) 334-7995 Fax: (336) 334-7086
Omega Engineering, Inc.	Address: Website: Tel:	One Omega Drive, Stamford, Connecticut 06907 www.omega.com (800) 848-4286 or (203) 359-1660 Fax: (203) 359-7700
Omni Instruments.	Address: Website: Tel:	120-122 King Street, Broughty Ferry, Dundee, DD5 1EW, Scotland www.omniinstruments.co.uk +44 (0)8700 43 40 40 Fax: +44 (0)8700 43 40 45
OMNISENS SA	Address: Website: Tel:	PSE-C, 1015 Lausanne, Switzerland www.omnisens.com (847) 828-6808 (Chicago office) Fax: (773) 463-9584
Onset Computer Corporation	Address: Website: Tel:	470 MacArthur Blvd, Bourne, Massachusettes 02532 www.onsetcomp.com (800) 564-4377 or (508) 759-9500 Fax: (508) 759-9100
OSMOS Inc. c/o GACC	Address: Website: Tel:	218 East North Bend Way, North Bend, WA 98045 www.osmos-group.com (www.subterra.us) (425) 888-5425 Fax: (425) 888-2725
Physical Acoustics Corporation (PACNDT)	Address: Website: Tel:	195 Clarksville Road, Princeton Jct, NJ 08550 www.pacndt.com (609) 716-4000 Fax: (609) 716-0706
PCB Piezotronics, Inc.	Address: Website: Tel:	3425 Walden Ave, Depew, New York 14043 www.pcb.com (716) 684-0001 or (888) 684-0013 Fax: (716) 684-0987
Penny & Giles	Address: Website: Tel:	1 Airfield Road, Christchurch, Dorset. BH23 3TH. UK www.pennyandgiles.com +44 (0) 1202 481771 Fax: +44 (0) 1202 484846
Pure Technologies, Ltd.	Address: Website: Tel:	10015 Old Columbia Road, Suite B-215, Columbia, MD 21046 www.soundprint.com (410)-309-7050 Fax: (410)-309-7051
RdF Corporation	Address: Website: Tel:	23 Elm Avenue, PO Box 490, Hudson, NH 03051 www.rdfcorp.com (800) 445-8367 or (603) 882-5195 Fax: (603) 882-6925
Rieker Inc.	Address: Website: Tel:	PO Box 128, Folcroft, PA 19032 www.riekerinc.com (610) 534-9000 Fax: (610) 534-4670
Roctest Telemac Ltd.	Address: Website: Tel:	665 Pine Avenue, Saint-Lambert, QC, Canada, J4P 2P4 www.roctest.com (450) 465-1113 or (877) 762-8378 Fax: (450) 465-1938
S+R Sensortec GmbH	Address: Website: Tel:	Liefenweg 15, D-52078 Aachen, Germany www.sensortec.de + 49-241-37252 Fax: + 49-241-37253
SiF Universal Pte Ltd	Address: Website: Tel:	41 Science Park Road, #01-16 The Gemini, Singapore 117610 www.sif-u.com +(65) 6773 9366 Fax: +(65) 6774 6040

Silicon Design, Inc. (SDI)	Address: 1445 NW Mall St., Issaquah, WA 98027 Website: www.silicondesigns.com Tel: (425) 391-8329 Fax: (425) 391-0446
Slope Indicator	Address: 12123 Harbour Reach Dr.,Mukilteo, WA, 98275 Website: www.slopeindicator.com Tel: (425) 493-6200 Fax: (425) 493-6250
Smart Fibers Ltd.	Address: C3 Centennial Ct, Easthampstead Rd, Bracknell, Berkshire, UK Website: www.smartfibers.com Tel: +44 (0) 1344 484111 Fax: +44 (0) 1344 423241
SMARTEC	Address: Via Pobiette 11, CH-6928 Manno, Switzerland Website: www.smartec.ch Tel: +41 91 610 18 00 Fax: +41 91 610 18 01
Smart Structures LLC.	Address: 233 N. Garrard, Rantoul, IL 61866 Website: www.smart-structures.com Tel: (217) 892-3333 Fax: (217) 893-8806
Somat Ltd.	Address: 702 West Killarney, Urbana, IL 61801 Website: www.somat.com Tel: (217) 328-5359 Fax: (217) 328-6576
SRI International	Address: 333 Ravenswood Avenue, Menlo Park, CA 94025-3493 Website: www.sri.com Tel: (650) 859-4771 Fax: (650) 859-4111
Smart Structures Research Center (SSRC)	Address: AIST Tsukuba Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki, Japan Website: unit.aist.go.jp/smart/eg/ Tel: +81-29-861-3127 Fax: +81-29-861-3126
Strain Monitor Systems (SMS) Inc.	Address: 314 Ayito Road, Southeast,Vienna, VA 22180 Website: www.strainmonitor.com Tel: (703) 938-1057 Fax: 703-938-1252
Strainstall Ltd.	Address: 9-10 Mariners Way, Cowes, Isle of Wight PO31 8PD UK Website: www.strainstall.com Tel: +44(0)1983 203600 Fax: +44(0)1983 291335
Structural Monitoring Systems (SMS) Ltd	Address: Unit 5 15 Walters Drive, Osborne Park WA 6017, Australia Website: www.smsystems.com.au Tel: +61 8 9204 4844 or (814) 234-4817 (US office)
Summit Instruments, Inc.	Address: 2236 N Cleveland-Massillon Rd, Akron, OH 44333-1255 Website: www.summitinstruments.com Tel: (330) 659-3312 Fax: (330) 659-3286
SuperLogics, Inc.	Address: 85 River Street, Waltham, MA 02453 Website: www.superlogics.com Tel: (781) 893-1600 Fax: (781) 893-0600
Texas Measurements, Inc.	Address: P.O. Box 2618, College Station, TX 77841 Website: www.straingage.com Tel: (979) 764-0442 Fax: (979) 696-2390
Transducer Techniques, Inc.	Address: 42480 Rio Nedo, Temecula, CA 92590 Website: www.transducertechniques.com Tel: (800) 344-3965 or (951) 719-3965 Fax: (951) 719-3900
University of Texas（Design	Address: 75 West 100 South, Logan, UT 84321

Analysis Associates, Inc.）	Website: Tel:	www.waterlog.com (435) 753-2212 Fax: (435) 753-7669
Virginia Technologies, Inc. (VTI)	Address: Website: Tel:	2015 Ivy Road, Suite 423, Charlottesville, VA 22903 www.vatechnologies.com (434) 970-2200 Fax: (434) 817-6170
Vienna Consulting Engineers (VCE)	Address: Website: Tel:	Hadikgasse 60, 1140 Vienna, Austria www.vce.at +43 1 897 53 39 Fax: +43 1 893 86 71
VETEK Systems Corporation	Address: Website: Tel:	6 Oak Road, Elkton, MD 21921 www.veteksystems.com (410) 398-7131 Fax: (410) 398-0312
Vibra-Metrics	Address: Website: Tel:	195 Clarksville Road, Princeton Jct, NJ 08550 www.vibrametrics.com (609) 716-4130 Fax: (609) 716-0706
Wilcoxon Research, Inc.	Address: Website: Tel:	21 Firstfield Road, Gaithersburg, Maryland 20878 www.wilcoxon.com (301) 330-8811 Fax: (301) 330-8873
Witten Technologies, Inc. (WTI)	Address: Website: Tel:	14205 Burnet Rd, Suite 210, Austin, Texas 78728 www.wittentech.com (512) 388-1112 Fax: (512) 388-1114