Structural health monitoring

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Abstract

The monitoring of infrastructure for structural integrity continues to be a critical need. The potential for structural failure—due to phenomena related to material and component degradation over time (corrosion) as well as instantaneous occurrences such as earthquakes and terrorist attacks—is a growing concern as bridges and buildings are becoming older yet more heavily used. Structural integrity concerns are traditionally addressed through regular inspection of the structure, which may include visual, dye penetrant, ultrasonic, and/or radiographic nondestructive test methods. These methods are capable of detecting most defects of concern to authorities, but some of the methods may not detect defects (such as corrosion or cracks) in structural members that are completely hidden, and none of them are able to determine (in a single measurement) if a defect is actively growing. As a result, standard inspection techniques may not find defects that are likely to compromise integrity and could instead focus attention on defects that, while readily detectable, may be harmless to the overall health of the structure. State-of-the-art and emerging sensor technology approaches are available that can assess structural integrity in real time. Furthermore, these technologies can be integrated into a comprehensive remote monitoring system that can continuously assess the structural health of a building or a bridge, facilitating the rapid repair of potential issues.

Keywords: Structural Health Monitoring, Structural Health Management, Bridges, Corrosion, Infrastructure, Sensors, Fiber Bragg Gratings.

1 Introduction

The structural health of infrastructure has become an increasing area of concern in recent years, as age, aggressive environments, and increased traffic volume
have taken their toll on many structures. The potential for catastrophic failure of bridges in particular has instigated studies and surveys of bridge structural health, which provide a grim picture. In December 2008 the United States (U.S.) Department of Transportation (DOT) reported that, of over 601,000 U.S. highway bridges in inventory, as many as 151,000 may be either structurally deficient or functionally obsolete [1]. The criticality of the situation is underscored when one considers that a number of these bridges may be fracture critical (i.e., they may contain a single component whose failure could lead to failure of the entire structure). These studies, as well as incidents such as the catastrophic collapse of the Interstate 35 (I-35) West Bridge over the Mississippi River in Minneapolis, MN in August 2007, have refocused public attention upon the age and condition of bridges within the nation’s infrastructure. Steel bridges have become a specific concern in recent years, as metal fatigue can combine with corrosion damage to accelerate bridge health deterioration. Conditions like these have been implicated in several recent failures of steel bridges [2]. Of 503 U.S. bridges that failed over an 11-year period, 100 were found to be due to corrosion [3]. Failure may be exacerbated by catastrophic occurrences such as earthquakes, tidal waves, landslides, and terrorist attacks.

It is recognized that organizations responsible for infrastructure maintenance are constrained to some degree by current state-of-the-art inspection equipment and techniques. The engineering investigation following the collapse of the I-35 Bridge highlighted the fact that conventional inspection techniques employed during the routine assessment of steel bridges—including visual, dye penetrant, ultrasonic, and/or radiographic nondestructive testing methods—may not be capable of detecting cracks in hidden or nearly inaccessible areas (such as those in built-up structures) and may also be unable to determine if a crack in a critical location or component is actively growing.

In view of the above issues, there is an urgent need to examine and assess the latest state-of-the-art technologies and approaches to the remote monitoring of the degradation of critical infrastructure by means of strategically positioned sensors, reliable data acquisition systems, and advanced analytical software. A number of sensor technologies are available that can meet this need. Furthermore, innovative structural health monitoring (SHM) systems can incorporate several different types of sensor technologies into a single interactive system. When properly implemented on a structure, these SHM systems can provide advance warning of a growing structural problem as well as an opportunity for repair before catastrophic failure. Such a system has recently been envisioned [3], designed [4,5], and implemented on a bridge structure [6].

2 Structural evaluation

Before initiating the design of an integrated sensor system for a structure, it is essential to conduct a structural evaluation of the as-built structure. This evaluation is necessary not only to establish the current structural health of the
structure (as a baseline) but also to determine any critical failure points, load paths, and so on. This evaluation will also establish optimum areas for sensor placement.

For example, previous work to design and implement a SHM system on two bridges [4–6] was initiated with the structural analyses of the bridges to establish the current load rating, critical members, expected structural response, and any other identified characteristics necessary for the design of the SHM system for each bridge. To accomplish this, structural engineers evaluated both bridges based on three-dimensional finite element models; separate structural analyses were required for each bridge. In addition, available bridge inspection reports and maintenance reports were reviewed. Optimum sensor placement was then determined from the analyses. Using this methodology, the locations of the desired sensors for the swing span of one of the bridges, the Government Bridge at Rock Island Arsenal, IL, was developed. This bridge consists of two levels: a lower level for highway traffic and an upper level for trains. A diagram of the optimum sensor locations for the SHM system on the Government Bridge is presented in Figure 1.

Several points of interest were derived from the analyses. It was found that additional sensors (possibly two or three strain gages) would be useful to determine railroad and highway floor beam stress levels, since some of these are fracture critical members. A weigh-in-motion sensors/system was also found to be useful to determine the weight of the train while on either track.

3 Sensor selection

The sensors employed within a SHM system will be dependent upon the size, age, condition, environment, and unique needs of the structure. A number of sensor types are available to monitor and manage the structural health of infrastructure as described in the following sections.
3.1 Accelerometers

Acceleration measurement is a useful tool in SHM. These measurements are typically determined using accelerometers, placed at specific points on the structure such that the natural frequencies and vibration mode shapes can be determined. Changes in modal response, vibration, and inclination can then be measured as a function of time. Modal response in particular is an excellent method for determining changes in the overall structural behavior of bridges, in that changes in the bridge’s natural frequency may be indicative of damage to the structure [3]. A commercial off-the-shelf (COTS) accelerometer is presented in Figure 2 [3].

3.2 Strain sensors

An assessment of strain, to monitor tensile and compressive loading in critical structural members of the superstructure, can be derived using strain gages adhered directly to the structure. Important data related to stresses in critical bridge members, particularly those that are not redundant, can be obtained using strain gages.

3.3 Tilt sensors

Tilt sensors are employed to determine rotational displacement on free-standing structural members such as bridge piers. Movement at piers and expansion joints is measured and monitored using tiltmeters. COTS tiltmeters attached to a bridge structure are presented in Figure 3 [7].

3.4 Displacement sensors

Deflection/displacement sensors can be employed to measure movement between structural members, such as displacement between deck joints and...
displacements at bridge bearings. Measured deflections, like strain readings, are helpful in determining whether a structure is responding as expected and can serve as an early warning if unanticipated trends are observed.

3.5 Corrosion sensors

A number of COTS corrosion sensing technologies are available for monitoring corrosion and material degradation of structures. In general, three types of corrosion monitoring technologies have been considered for infrastructure applications [3]: linear polarization resistance (LPR) sensors, electrical resistance (ER) sensors, and test coupon racks.

The LPR technique involves the application of a small voltage (or polarization potential) to an electrode in solution. By measuring the resulting current, a corrosion rate can be derived. While this technique can provide a snapshot of how the material is degrading in real time, the disadvantage of LPR sensors is that they are designed for relatively clean, aqueous, electrolytic environments. Monitoring the portion of bridge piers that are underwater would be an optimal application for LPR sensors, whereas the monitoring of above water portions might not. The interpretation of the data can also be complex. In general, LPR is easy to use as a qualitative signal of general corrosion phenomena such as coating deterioration but not corrosion rate [8].

Conversely, ER corrosion sensors can be used to measure atmospheric corrosion rates. ER sensors measure the change in Ohmic resistance of a corroding metal element exposed to the atmosphere. The action of corrosion on the surface of the element produces a decrease in its cross-sectional area, with a corresponding
increase in its ER. The increase in resistance can be related directly to metal loss, and this loss as a function of time is by definition the corrosion rate.

An assessment of atmospheric corrosion can also be made using a test rack of metallic coupons that are exposed to the subject environment. Bare metal coupons mounted on a polymer sample card (using nonmetallic fasteners that suspend the samples above the card) can be employed to assess the visual onset of corrosion. Additional information can be obtained by removing the test coupon racks at regular intervals and analyzing the coupons for mass loss and residual surface contaminants using methods such as ASTM G11 [9] and ASTM B825 [10], respectively.

While corrosion sensors using other electrochemical techniques such as electrochemical impedance spectroscopy and zero-resistance ammetry have been developed, they have not yet been demonstrated for infrastructure applications.

3.6 Fiber Bragg Gratings (FBGs)

FBG technology can be employed as simple, low-cost, high-sensitivity sensors for infrastructure. FBGs are “mirrors” that are photo-imprinted into a fiber-optic cable that is bonded to (or embedded in) a structure. A diagram of FBGs within fiber-optic cable is presented in Figure 4 [4].

Each FBG sensor has a specific wavelength and measures a specific parameter. When a laser light source is used to project light through the fiber, a portion of the light is reflected back from the FBG. As this wavelength changes over time due to temperature and/or stress of the fiber, each FBG sensor returns
information on these parameters as a function of the state of the structure [11]. The nature of FBG sensors makes them well suited for outdoor infrastructure monitoring; they consume lower power than standard sensor systems and are immune to electromagnetic effects, corrosion, and most chemicals. Optical sensors have been previously demonstrated for infrastructure applications using this technique [12–14]. The utility of using FBG sensors to assess the structural health of buildings damaged by earthquakes or terrorist attacks was envisioned as early as 2004 [15].

The versatility of FBG sensors lends them to a number of useful applications with respect to the SHM system. An assessment of strain can be derived using FBG strain gages adhered directly to the bridge structure [6]. In addition, FBG tilt sensors can be employed to determine rotational displacement in bridge piers, and FBG deflection/displacement sensors can be used to measure displacement between deck joints and displacements at bridge bearings.

3.7 Acoustic emission sensors

Acoustic emission (AE) technology detects and monitors ultrasonic waves produced by materials when they undergo cracking [3,4,11]. As these ultrasonic waves can travel great distances, AE sensors are capable of inspecting the entire monitored area for defects, covering beams, gussets, stringers, and hidden structural members. The technique has been thoroughly demonstrated for the structural health assessment of bridge systems by Carlyle [16–20] and others.

Under past efforts [6], AE sensors were used to identify active crack growth in selected pins used to connect truss members on the Government Bridge. The AE portion of the SHM system consisted of piezoelectric sensors and specialized signal processing to separate, in real time, the acoustic defect signal from typical traffic noise. At each pin, sensors actively listened for distress or cracking. In addition, the sensor actively emitted a signal (ping) at regular intervals in order to detect cracks or changes in the pin connectors.

3.8 Additional technologies

SHM systems placed on infrastructure can incorporate additional monitoring technologies such as video cameras [21]. Cameras can be placed on and around the structure to allow remote viewing and to save video images when an event is triggered. The video cameras can be set in such a way as to allow remote viewing of the length of the structure as well as the main navigation channels. If an event is triggered, the cameras can automatically zoom in on the affected area and begin recording. Video capture from the remote computer can be made possible through the SHM software (see Section 4.1).

Laser-based measuring systems have been employed to monitor the vibration of bridge systems under road traffic conditions [21]. These systems simply measure the position of the laser on a sensitive screen and record changes in two-dimensional space.
It is envisioned that future SHM systems will incorporate technologies that have yet to be fully embraced and are therefore currently used only on a handful of applications. These include ground-penetrating radar, thermography, and impact echo as well as emerging technologies such as tiny sensors enabled by microelectromechanical systems (MEMS) and nanotechnology. These future SHM systems could also incorporate mesh or cloud data networks [22].

4 System design and integration

Two SHM systems were designed to acquire and process data from two bridges under past work [6]. On each bridge, relevant sensor technologies (primarily FBG but also incorporating AE and corrosion sensors) were incorporated into a single interactive system. Sensors were placed along the bridges in a unique, unobtrusive “single trunk” design, in which cabling from all sensors is part of a single large bundle running along the length of the bridge. This design greatly reduced required space and took advantage of the FBG technology’s ability to transmit data over long distances. A diagram of the SHM system implemented on a bridge structure in two monitoring configurations (periodic and continuous) is presented in Figure 5.

Cabling is significantly reduced for FBG sensors compared to traditional sensors. In both of the above scenarios, data is gathered from the individual sensors, sent through the cable, and transmitted through the data acquisition and analysis system (see Section 4.1) to the satellite dish where it is transmitted to the responsible parties for review.

For one of the bridges, the aforementioned Government Bridge, the overall intent of the SHM system was to monitor corrosion and detect structural irregularities and/or changes to the bridge span. The SHM system for this bridge was therefore designed to monitor modal response (accelerometers), strain response (strain gages), acoustic response (AE sensors), and corrosion (ER sensors and metal coupons). It is noted that the SHM system on this bridge was designed to operate while the swing span is in any operating position as well as while it is in motion.
4.1 Data acquisition

The control system for the integrated SHM system must provide data integration, analysis, and output for all sensors incorporated into the sensor system. The control system generally consists of two major components: a data recorder and analysis system located on the structure for recording and performing the analysis, and a remote computer to store data, perform additional analysis, send alerts via e-mail and telephone, and serve as a Web-based access portal for visualizing the data and generating reports.

Typical SHM software consists of a graphic user interface (GUI) compatible with a standard operating system. The software records and archives the data as it is generated. While standard GUIs may employ simple graphical sensor readouts, such graphs are often difficult to interpret by untrained viewers. A more useful and simple methodology would be to provide a real-time graphical presentation of the data in an innovative “color code” system. Rather than provide a typical data readout that must be interpreted and understood before action can be taken, the system would simply show a photograph or diagram of the monitored structure overlaid with a color code—green, yellow, or red—for each sensor. An example of this innovative GUI is presented in Figure 6.

In this way the software performs real-time analysis of the structure for the purpose of detecting potential problems or safety concerns. The system allows two-way communication between the data recorder and analysis system on each structure and the remote computer such that programming and querying of instrumentation may be performed remotely. If any sensor area maintains
a yellow/red status, or if an event is triggered, the system automatically trans-
mits warnings to designated personnel via e-mail and cell phone so that the
overall data can be reviewed and an appropriate response can be quickly deter-
mained. The SHM software should also be able to access archived video footage
as well as control the pan feature of video cameras (if used) and capture live
video on demand.

5 Review and interpretation of the data

Once the SHM system has been implemented on a structure, the data should
be reviewed frequently to monitor the readings from the sensors and manage
the overall health of the structure. While the system has built-in warnings to
alert users when significant events or changes occur (see Section 4.1), occa-
sional monitoring to make sure the system is functioning properly should also
occur. The readings should be monitored periodically by maintenance personnel
as well as by structural engineers who can direct the appropriate precautionary
measures on an as-needed basis.

It should be noted that the implementation of such a system will likely incur
additional costs in identifying the current state of the structure (in addition to the
initial structural analyses mentioned in Section 2) as well as tuning the structural
models used to determine triggers and conditions so that warning thresholds are
properly set. This process will occur as the results are interpreted and under-
stood as a function of time and will likely be a unique process for each structure.
Recent studies [6] have demonstrated that data must be collected and analyzed
for as much as a year to fully understand the effects of environmental factors
such as thermal strains and movements, water levels, winds, rain, and so on.

6 Summary

Existing sensor technologies can be integrated into a comprehensive SHM sys-
tem for the remote monitoring of the structural integrity of critical infrastruc-
ture. The SHM system is intended to provide advance warning of a growing
structural problem as well as an opportunity for repair before catastrophic fail-
ure. The capabilities of such systems, and the potential benefits for future pos-
sible application, continue to be of keen interest to both government and civilian
organizations. As such, it is anticipated that SHM systems will continue to be
considered for bridges, buildings, and similar load bearing structures.

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References


