Comparison of Visual Inspection and Structural-Health Monitoring as Bridge Condition Assessment Methods

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Abstract: This paper presents the results of a research project aimed at examining the capabilities and challenges of two distinct but not mutually exclusive approaches to in-service bridge assessment: visual inspection and installed monitoring systems. In this study, the intended functionality of both approaches was evaluated on its ability to identify potential structural damage and to provide decision-making support. Inspection and monitoring are compared in terms of their functional performance, cost, and barriers (real and perceived) to implementation. Both methods have strengths and weaknesses across the metrics analyzed, and it is likely that a hybrid evaluation technique that adopts both approaches will optimize efficiency of condition assessment and ultimately lead to better decision-making.

INTRODUCTION

The recent series of natural disasters that affected the US has brought substantial attention to national infrastructure and identified its vulnerability. Perhaps the most significant natural disaster of the last decade was Hurricane Katrina (IBRD, 2010) and the resulting levee failures in Louisiana. Following Hurricane Katrina—when infrastructure failure was mostly associated with extreme events—in 2007 the I-35W Bridge in Minneapolis collapsed under daily loading conditions, causing substantial economic losses, disruptions to the day-to-day activities of citizens, and more importantly loss of many lives (Zhu et al., 2010; NTSB, 2008). While these failures are not isolated (Wardhana and Hadipriono, 2003), they are the most significant of the recent events in the US that highlight the deficiencies of the infrastructure. The term infrastructure is defined by Egan (2007) as ”systems that provide critical support services to a country, geographic area for a corporate entity; when they fail, there is potentially a large cost in human life, the environment or economic markets”. This broad definition, like its counterparts (i.e. definitions by the US Department of Homeland Security etc.), encompasses power and communication infrastructure in addition to the environment; however, the discussions in this article will be limited to infrastructure.

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Perhaps, the most visible example of the discrepancy between the infrastructure rehabilitation and renovation needs of the US and the capital investment requirement is the *Infrastructure Report Card* published by American Society of Civil Engineers (ASCE, 2013). The organization characterizes the US infrastructure as deficient, with a symbolic grade of “D+”, and calls for a medium-term plan to improve it to an acceptable standard. The projected total cost of these necessary improvements is $3.6T by 2020. Assuming a linear distribution of the needed funds over the next seven years, this is an additional investment requirement of ~$500B, and in the US total volume of construction industry (for both public and private) is approximately $800B (US CENSUS, 2013). Although these numbers are just estimates, it is clear that the available resources are likely to fall short of the necessary investment to renovate the infrastructure as a whole. This puts a tremendous amount of pressure on improved decision-making in infrastructure investment to sustain the infrastructure in a proper condition to maintain its functionality.

Transportation networks are one of the most critical components of infrastructure systems. A functional transportation network is crucial for supporting interstate trade, providing logistics support for daily commute of residents, and providing accessibility for relief efforts during and after natural disasters. The role of transportation networks in disaster recovery is, generally, an overlooked functionality. However, there are clear evidences in reduced effectiveness of recovery operations, i.e. slow recovery after Katrina, following natural disasters due to reduced accessibility as a result of damaged transportation network (Holguin-Veras et al., 2007).

Infrastructure vulnerability and its necessary investment extend beyond susceptibility to natural disasters. A natural response to the I35W bridge collapse was the added emphasis on condition assessment methods and structural adequacy of the bridges. The most vulnerable component of the US transportation network, there are 607,380 bridges in the US, 66,749 of which have been assessed to be structurally deficient as reported by the *Infrastructure Report Card* by the American Society of Civil Engineers. With aging structures and increased user demands, proper maintenance and monitoring of the bridges is more of a national priority than it has ever been, and condition assessment is the cornerstone of improved decision-making of efficient maintenance and rehabilitation programs.

RESEARCH MOTIVATION

This research was undertaken to provide baseline information on both visual bridge inspection and health monitoring of bridges, elaborate on predetermined characteristics (i.e. feasibility, cost, practicality) of each approach, and provide comparisons across these fundamental aspects of both alternatives. Specific examples of monitored bridges are presented to demonstrate how monitoring systems provide information to inform maintenance and mitigation strategies. Additionally, the formulas and methods for calculating inspection costs are given. Improved decision-making—under the current condition of the infrastructure and the funding discrepancies—in allocating funds for infrastructure maintenance and renovation is a necessity, and this article should fill a significant knowledge gap that exists in the literature about state-of-practice bridge inspection and health monitoring systems as they pertain to decision-making.

BRIDGE INSPECTION

General Guidelines

The governing document in the US that provides guidance in bridge inspection procedures is the *National Bridge Inspection Standards (NBIS)* published by Federal Highway Administration (FHWA, 2004). This document serves as a guideline and sets certain standards to be met in bridge inspection processes of both federal and state owned structures. The sections of the document that relate to this article are the quality control and assurance discussions of visual inspection and frequency of inspection—a maximum of 24-month inspection frequency is suggested. Although there is no explicit statement of visual inspection as the suggested inspection method, from the language of the FHWA document, it can be inferred that visual inspection is the *de facto* method of routine inspection. The state and federal agencies are given the flexibility to establish best practices for more frequent inspection.

FDOT Bridge Inspection Process

In constructing the discussions on the details of routine bridge inspection processes and the decision-making process for rehabilitation and maintenance, input from Florida Department of Transportation (FDOT) bridge inspection personnel and engineers was sought. This was done through structured interviews with a large number of FDOT personnel both at the central and district level. Information collected was used to determine the systems boundaries for the analyses conducted. Although there are federal guidelines for bridge inspection procedures such as NBIS, the interpretation and implementation at the District level depends on the decision-making criteria of the inspection personnel and engineers. Thus, it is necessary to obtain state-level information and FDOT is one of the largest highway agencies in the US with a bridge inventory of over 10,000 structures. The State of Florida also maintains a large number of structures that are located in aggressive marine environments and more vulnerable to environmental degradation that require more intensive inspection and health monitoring. The experience and expertise of individuals working in these environmentally aggressive marine mediums provided insight on day-to-day details of bridge inspection and condition improvement decision-making process.

FDOT is composed of eight jurisdictional/operational districts, each responsible for its individual bridge inspection process, which is monitored by a centralized governing body. Although there are minor procedural differences among districts, meeting federal guidelines such as routine inspection frequency as a minimum is the accepted practice for all districts and structures. This decentralized and independent decision-making system is the cornerstone of the agile support system for bridge inspection and maintenance. Below are some highlights from FDOT bridge inspection processes:

- *Method:* Bridge inspection—either in-house or through contracts given to qualified consultants—is done mostly through visual inspection as part of routine procedure maintenance process. More advanced and detailed inspections, and destructive and non-destructive testing, are also executed provided the visual inspection results indicate any irregularities with the structure. Although the majority of the inspection is outsourced, in-house equipment and personnel are retained for QA/QC of the contracted inspection and limited in-house inspection. The type of equipment retained depends on the structures in the inventory and environmental conditions. For instance, if there are known scour related issues, it is likely for the districts to have underwater inspection personnel and capability.

- *Frequency:* A maximum of a 24-month interval—as suggested by FHWA—is allowed between inspections. However, depending on the condition assessment of the structure and environmental conditions, inspections can be carried out more often. A flexible decision-making on inspection frequency is granted to the inspection office personnel provided the bridge inspected has known structural issues or the recent inspection reports have some problematic findings.
- *Monitoring:* Although full-scale, permanent structural health-monitoring systems are sparingly used, monitoring for known problems such as corrosion and scour is common practice. Possible redundancies in the structural design for simpler bridges seem to have reduced the necessity and practicality of a full monitoring system for the majority of the state bridges. The monitoring systems have been designed on an ad-hoc basis using different technologies (i.e. sonar sensors for scour, cameras for displacement, strain gauges for deformations, etc).
- *Costs:* Inspection costs are projected for standardized inspection activities. There are guidelines to estimate expected costs of routine inspection operations. However, when there are added inspection elements to routine procedures (i.e. underwater inspection, use of a snooper etc.) additional costs are incurred for the added work.

Potential Limitations of Visual Inspection

Visual inspection is the default bridge inspection methodology; however, there are some limitations that might affect the efficiency of decision-making and resource utilization. Some of these concerns have been summarized in an FHWA report (Moore et al., 2001). The report mainly focuses on the subjective nature of inspection outcome.

- *Timing:* Although the inspection frequency can be adjusted according to the structural details and environmental conditions, the static nature of condition assessment may reduce the agility of the response in maintenance and rehabilitation decisions. A good analogy would be the continuous nature of possible structural issues with a bridge (i.e. crack propagation) as opposed to discrete observations made during visual inspection at a single point in time. Thus, the timing of the visual inspection becomes, perhaps, the single most important parameter for (near) structurally deficient bridges.
- *Interpretability:* As discussed in the FHWA report, because visual inspection is dependent on inspectors' subjective assessment, inappropriate and inadequate condition assessments are quite possible. Discrepancies in training and general inspection guidelines used by different agencies can add to the subjectivity of assessments.

- *Accessibility:* Perhaps the most significant shortcoming of the visual inspection is the reliance on the necessity for having a clear line of sight to conduct condition assessment. Any internal problems that are not visible or not interpretable from surface irregularities of the structure will not be identified. Regrettably, there are no universally accepted non-destructive testing methods or equipment to compliment visual inspection in situations where visibility is an issue. Thus, accessibility is a major consideration in assessing the effectiveness of visual inspection in general.

STRUCTURAL HEALTH MONITORING

The term structural health monitoring (SHM) encompasses a range of methods and practices designed to assess the condition of a structure based on a combination of measurement, modeling and analysis. Non-destructive evaluation (NDE) approaches can be incorporated into the inspection process to evaluate hidden defects, such as reinforcing steel corrosion or crack propagation. Though early NDE research represents the origins of SHM, SHM has recently emerged as a separate field. While NDE seeks to discover flaws at the material level, and is thus limited to local damage assessment, SHM encompasses a more global approach to the assessment of civil infrastructure. The size and complexity of civil structures often requires global SHM methods; information from small, limited portions of the structure may not provide a complete picture of the structural condition. In an SHM system, data generated by sensors deployed on the structure is processed and analyzed to capture structural response information, detect anomalous behavior, or track known issues. Many bridges worldwide are instrumented for a variety of purposes; however, a large majority of these systems are deployed with the sole purpose of monitoring an identified defect or deficiency. SHM technology has not been widely adopted as an approach to routine bridge monitoring in the US; however, recent improvements in the functionality and performance of SHM systems make it a viable approach for reliable and potentially real-time bridge assessment.

Components and SHM System Types

While SHM systems can be applied to a wide range of civil infrastructure components such as buildings, dams, pipelines (Brownjohn, 2007), the focus of this paper is their application to bridges. Specific SHM components are application-dependent and can vary significantly; however, most SHM systems have the same fundamental elements (as shown in Figure 1): 1) measurements by sensors and instrumentation, 2) structural assessment (such as peak strains or modal analysis), and 3) condition assessment to support maintenance and rehabilitation related decision-making (Alampalli and Ettouney, 2008).

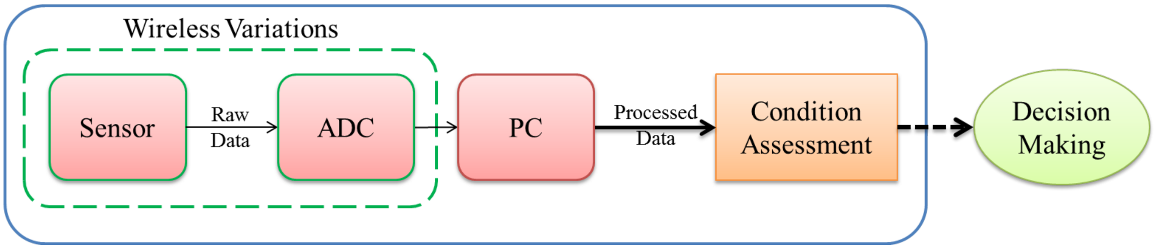

Figure 1. SHM approach to bridge assessment and decision support.

Sensors

The functionality of an SHM system depends heavily on the types and number of sensors used. A monitoring system may rely on a single or multiple sensor types, which can be tailored to capture a variety of physical measurements associated with: loads, environmental conditions, and bridge responses (Wong, 2007). There are countless SHM sensing technologies, both emerging and established, that may be considered for bridge monitoring (i.e. Ko and Ni, 2005; Webb et al., 2014). Standard strain gages and accelerometers have been in wide use for decades to measure structural responses. More recently, optical fiber sensors have been applied for strain, temperature and vibration measurement. Fiber optic sensors are less susceptible to electrical noise and can provide distributed measurements along the structure, in contrast to the discrete nature of strain gages and accelerometers (Li et al., 2004; Lopez-Higuera, 2011). Researchers have also proposed the use of applied coatings that can indicate structural changes. These coatings may provide visual cues resulting from property changes in response to structural changes [i.e. triboluminescence (Dickens et al., 2011)] and would be most appropriate for use in the framework of visual inspection. Measuring bridge deflections is can be problematic due to the need for a fixed reference point. Proposed approaches to directly measuring deflection include differential GPS (Cosser et al., 2003), radar-based systems (Guan et al. 2014; Guan et al. 2015), video (Chan et al., 2009), and laser-based systems (Rossi et al., 2002). Directly measuring the loads that structures experience can be challenging thus loads are often inferred from limited measurements of the external conditions (i.e. ambient temperature, wind speed/direction, wave heights).

In many cases, monitoring the condition that leads to damage can prove to be more meaningful than using loading or response data. For example, in Florida, where a significant number of bridges are in coastal regions, monitoring and control of corrosion and scour are of critical importance and makes up the majority of existing monitoring systems in the state. Corrosion may be tracked by monitoring the electrical outputs of a cathodic protection system, while scour monitoring involves the use of acoustic, pier-mounted sensor to directly track scour depth in the regions of bridge piers and abutments. Table 1 outlines common sensor/sensor systems and their measurement capabilities.

Table 1. Bridge monitoring sensors and measurement functionality.

Sensor/Sensor System	Measurement/Functionality	Potential Purpose
Accelerometer	Vibration	Modal analysis
Strain Gauge	Surface or reinforcement strain	Strain/stress response
Anemometer	Wind velocity/direction	Wind load assessment
Tiltmeter	Slope	Pier settlement detection
Thermometers	Temperature	Thermal load assessment
GPS Receivers	Displacement/motion	Model validation, load rating
Sonar	Pier-tip elevation	Scour detection
Reference Electrodes	Voltage potential of steel	Corrosion monitoring

Data Acquisition and Aggregation

Generally, the electrical output of sensors must be digitized by an analog-to-digital converter (ADC) for further processing by a central computer. The ADC and computer allow for on-site data collection, and enable data to be interpreted and stored for retrieval and potential diagnosis of a bridge's condition. A real-time or near real-time SHM system provides sensed data and/or processed results immediately as they become available. Non-real-time systems may possess a latency resulting from data processing and communication delays.

Until recently, most SHM systems relied on cables to connect sensors on bridges to a centralized power and data acquisition source. Such cabled monitoring systems have been used for over 60 years to capture the response of structures during normal loading conditions and to report the state of a structure after natural and man-made hazards (Brownjohn, 2007). The primary disadvantage of cabled monitoring systems is the amount of hardware required for installation in a full-scale deployment. Data and power cables, along with supporting conduit, remain the primary implementation and cost obstacle for these traditional systems, especially when deployed on an in-service structure.

Over the past few decades, wireless sensors have become a viable option to alleviate the cost and labor associated with cabled monitoring systems (i.e. Kurata et al., 2012; Rice et al., 2010a). Wireless sensor nodes typically include a number of on-board sensors (or ports for external sensors) in addition to radio communication, and computational and processing capabilities—these additional capabilities make scaling the SHM systems to large structures economically feasible. By collocating the measurement and the data processing at each sensor node location, new possibilities for an intelligent monitoring system may be realized. Wireless sensors often rely on battery power; however, energy harvesting, such as solar panels, has also been successfully implemented (Jang et al., 2010).

Example SHM Applications

SHM systems are tailored for each application by careful sensor selection and placement. In general, past and current bridge monitoring applications can be subdivided into two primary categories: 1) short-term deployments to assess a specific aspect of bridge performance or to validate a sensor/sensor system and 2) long-term installations for permanent bridge monitoring to assess a wide range of bridge health conditions. Another critical distinction is between monitoring systems deployed to track a previously identified concern (such as corrosion or scour) and monitoring systems that are deployed preemptively, either during original construction or to track general structural health. An example of a general and extensive long-term SHM system is the one installed on the newly constructed I-35W Bridge in response to its tragic collapse. With a variety of sensor types distributed throughout the structure, this "smart bridge" identifies material parameters such as concrete creep/shrinkage and corrosion, environmental effects including temperature gradients, and dynamic responses such as traffic induced vibrations and modal frequencies (Inaudi et al., 2009).

The following bridge monitoring examples are typical of systems installed in the state of Florida to address specific performance concerns. These examples illustrate the types of sensors that are used and detail the types of information that the systems provide along with how the information is used in an overall bridge maintenance strategy.

Scour Monitoring of a Coastal Bridge

A bascule bridge located over an inlet in south Florida is currently instrumented to protect against scour damage. Built in 1966, the bridge is approximately 350 ft. in length and is subject to hydraulic and foundation conditions that result in scour vulnerability at the pier foundations. Bridges such as this, are surrounded by consistently strong tides or demanding currents, may experience high erosion rates at the piers, resulting in a "scour critical" classification. While the bridge is expected to undergo scour remediation in the next several years, more immediate action has been taken to monitor the conditions that lead to scour vulnerability. The bridge is instrumented with four sonar sensors that measure seabed elevations at critical locations along with water elevation and velocity. Also installed is a weather station tracking environmental conditions including wind speed/direction, air temperature, and humidity. All sensors are hard-wired to data acquisition hubs known as remote-monitoring units (RMUs) mounted at the bridge and the data is available wirelessly via an Ethernet connection. The overall cost of the described sensor equipment, including labor and miscellaneous hardware, is roughly $29,000. The primary purpose of the monitoring system is to continuously observe the scour elevation at pier locations, and verify it is still a safe and usable structure until the replacement of the bridge or other remedial action can occur. Specifically, when a maximum scour threshold, as determined by an experienced bridge engineer, is indicated as breached by the installed monitoring system, a diving inspector is deployed for confirmation and a subsequent closure of the bridge or emergency repair operations.

Example data shown in Figure 2 originates from a bridge that has been reconstructed as a result of scour. This data illustrates the water and scour elevation levels around the base of one of the bridge piers as well as the known a pile tip elevation. The +/- 6 inches of periodic variation of *Sensor #1* is expected and illustrates the disturbance of seabed sand as a result of the periodical change in tide direction. As indicated in the figure below, the maximum scour elevation has reached the original pile tip elevation and subsequent crutch pile reinforcements have been installed. This reactionary measure to the "scour critical" classification of the bridge is implemented to extend the service life of the structure until reconstruction occurs.

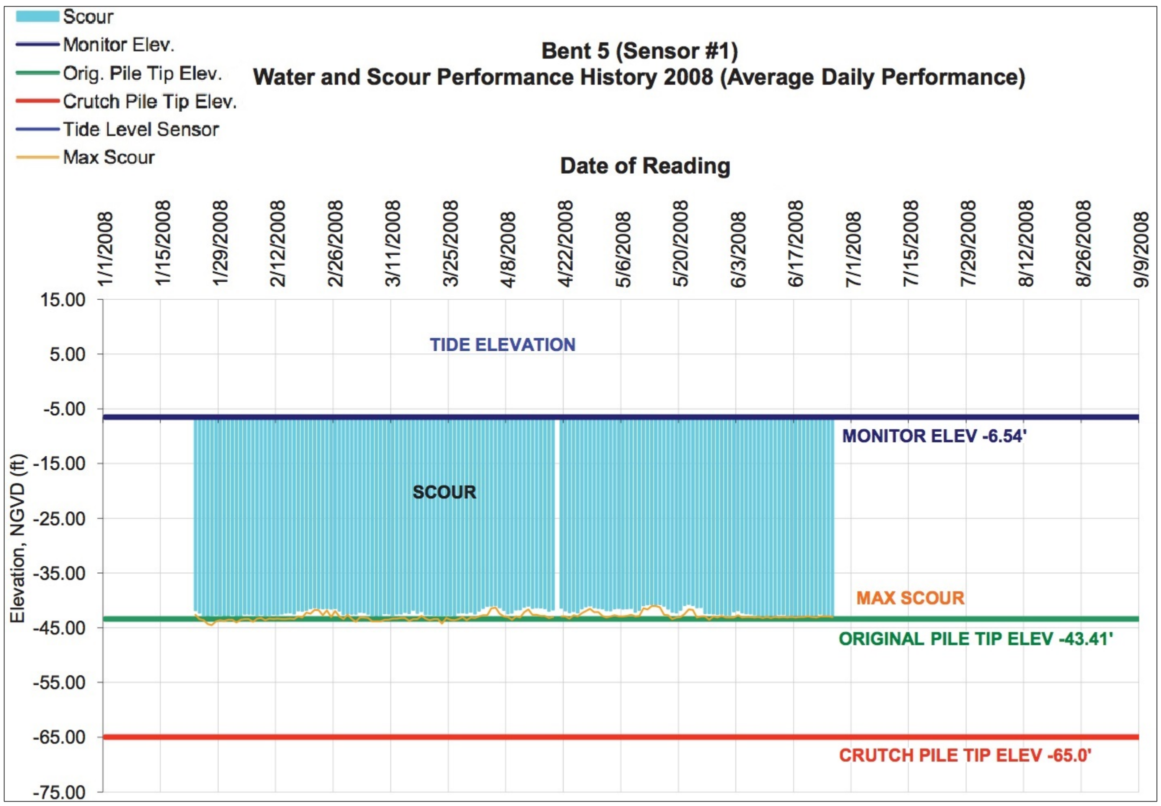

Figure 1. Scour elevation levels (Courtesy of FDOT: State Materials Office)

Corrosion protection and monitoring

The Howard Frankland Bridge caries I-275 to span Old Tampa Bay in Florida, linking St. Petersburg and Tampa. The 15,900-ft bridge has two separate spans; the older, northbound span was opened in 1960 while the southbound span was completed in 1990. This particular bridge is indispensable for the communities it serves and had an average daily traffic of 135,000. Reinforcement corrosion is of particular concern in the piers of the older bridge span. Cathodic protection has been installed on 20 critical piers as a measure to extend the life of the structure until it can be replaced in sometime between

2020 and 2025. Costs for this monitoring system have been broken down to $11,900/pier and includes both equipment and labor.

The fundamentals of cathodic protection are described in detail in Page and Sergi (2000); however, a general description is briefly provided here. Corrosion is dependent on two types of reactions: an anodic reaction, where electrons are released into the metal, and a cathodic reaction, where electrons are removed from the metal. The electric potential is of critical importance because it signifies how much of each reaction is needed to prevent corrosion, i.e. to keep the reactions in balance. The initial measurements of a cathodic protection system determine the natural potential of a pier's internal reinforcing steel and record this voltage as a baseline value. Current is then applied to the steel with the intention to polarize the metal to a higher magnitude of voltage than the natural potential that was initially measured. As long as the reinforcing steel is polarized to a more negative voltage than the natural potential, then corrosion protection is in place. Corrosion systems like the one installed on the Frankland Bridge output rectifier voltage, current and rebar potential data and are checked twice daily to monitor that the values are adequate to prevent corrosion.

Skyway Bridge: Model Predictions

The Skyway Bridge, another critical lifeline, serves motorists commuting between St. Petersburg and Terra Ceia. Stretching 21,877 ft across the southern portion of the Tampa Bay waterway, this Florida landmark is vulnerable to high open channel winds particularly at its 1,200 ft mid span. Multiple sensor types are distributed throughout the structure providing real-time measurements on wind velocity and direction, concrete temperature, and overall bridge position. Indicated in Figure 3 is the profile of the Skyway Bridge as well as the location of global positioning systems (GPS). Weather stations are installed at the *Mid Span* and *1 South* locations and additional automatic total stations (ATS) are deployed on select concrete impact barriers. Additionally, periodic vibration measurements are performed on stay cables to provide cable tension estimates.

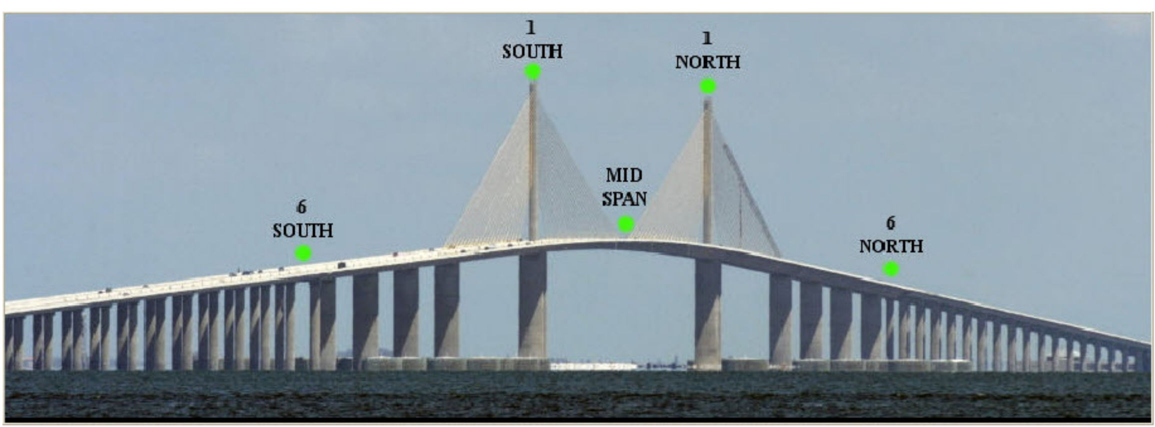

Figure 2. The Skyway Bridge structural health monitoring system (Courtesy of FDOT: D7)

One goal for bridge engineers of the Skyway Bridge is to use translated sensor data acquired through this monitoring system to calibrate an interactive Finite Element Model (FEM) predicting the movement of the bridge as a function of temperature and wind variances. This innovative step forward will result in FEM predictions that can be used to determine bridge response thresholds allowing for sensor alarm systems to be adjusted accordingly.

Potential SHM Limitations

There are a number of critical considerations that must be addressed to achieve a successful monitoring system, some of which have been barriers to the adoption of SHM systems as part of a routine bridge maintenance strategy. The following list outlines these important challenges and considerations.

- *System complexity*: The complexity of SHM systems varies based on the size and complexity of the structure being monitored and also depends on the desired functionality characteristics. For example, an autonomously operating, multi-functional SHM system with embedded data processing algorithms and automated decision making and system alerts requires complex and robust network software (Rice et al., 2010b). The required system complexity may also depend on the expected remaining service life of the structure.
- *System maintenance*: SHM systems will invariably encounter hardware and software failures and require routine, on-site maintenance to sustain long-term operation. There are some measures that can be taken to reduce maintenance needs, such as building in system redundancy and providing renewable power sources (thereby eliminating the need to change batteries in wireless sensors); however, adequate IT and maintenance personnel and resources must be provided to ensure ongoing functionality.
- *Automated data analysis*: To truly operate as an SHM system, and not just a network of data generating sensors, the system should provide actionable information that locates potential damage to target maintenance. Another important consideration is the dedicated personnel requirement for monitoring and analyzing the system output. The existence of an SHM system alone without the necessary organizational commitment cannot deliver the cited benefits and perhaps can lead to creating a false sense of security.
- *Liability/Responsibility*: The ability of an SHM system to continuously generate data has the potential to create liability issues and raises the question of who is responsible for the data and information potentially buried in the data. Should a structural change leading to bridge failure be missed, which party, if any, holds the responsibility?

MONITORING VS. INSPECTION

Functionality

Although full-scale SHM and visual inspection have distinct characteristic differences, their overall functionalities are not mutually exclusive and their functional differences can be leveraged for a complementary approach to bridge monitoring. One of the most obvious distinctions between SHM and visual inspection is the frequency or time scale on which they are carried out. Inspection events are discrete and infrequent, while SHM systems have the potential to generate information on a daily basis, if not continuously. Likewise, there are certain types of structural faults that are detectable by only one approach or the other. An advantage of inspection is that is not limited to the detection or assessment of a specific type of damage or a component of the bridge; it involves a broad evaluation of the entire structure without a priori knowledge of structural defects. An example of this would be the assessment of cracks in a bridge superstructure, where both formation and propagation must be considered. Neither inspection nor automated monitoring systems can successfully and efficiently address both problems (Harada and Yokoyama, 2007). Visual inspection is effective in the initial identification of crack locations (once they have become sufficiently large), whereas a similar functionality with an automated system would potentially require an immensely dense sensor network. On the other hand, crack propagation is a dynamic/continuous process and visual inspection alone will not capture the dynamic changes to the existing cracks; however, there are low-cost, easy to implement sensor-based solutions to track crack propagation (Yi et al., 2011).

Cost

The perceived cost of implementation and operation for SHM systems is a significant barrier to its widespread adoption. SHM system costs will depend on the functionality and the level of system integration. A comprehensive SHM system is likely to require a significant initial investment; however, the operation and maintenance costs are expected to be less than the initial investment. In the case of visual inspection, the costs are positively correlated to the level of detail of the inspection and inspection frequency. Inspection of a structurally deficient bridge with known and complex issues (i.e. scour, corrosion of post tensioning tendons) can be financially problematic. In both alternatives, the costs will depend on the characteristics of the structure analyzed. Drawing conclusions in overall costs figures is a challenging task due to the nature of variability of the contributing factors. However, it should be noted that there are some fundamental differences in the nature of cost structures.

Assessing the true cost of both inspection and SHM requires examining up-front and ongoing expenses, as well as the anticipated return on investment. In SHM, the majority of the up-front system costs are associated with hardware and software while ongoing expenses such as system maintenance and data management must be considered. SHM is a proactive approach designed to increase the overall longevity and health of bridges; the return on investment will be significantly improved if the SHM system can help identify structural deficiencies to enable proactive maintenance. Visual inspection, on the other hand, can be seen as both proactive and reactive. Prescribed biennial inspection may identify new damage but the inspection frequency and rigor will be increased once the bridge has known issues. The major component of the visual inspection costs is labor with added costs resulting from advanced equipment utilization. Proactive strategies to anticipated long-term structural problems (or benefits) are perhaps the more preferable to increase the resilience of infrastructure; however, justification of the expenses of such systems is may be more challenging, especially when the likelihood and severity of the anticipated structural damages are unknown.

User (Organizational) Resistance

SHM falls under the larger Information Technology (IT) umbrella, and although not specific to SHM, *user resistance* to IT-based systems has been identified in earlier literature (Agdas and Ellis, 2010). The need for organizational learning and shifting the focus to operational expenses (mostly in database management and hardware maintenance) are some of the few examples of factors that might add to user resistance in implementing SHM. SHM is an attempt to compliment/alter the existing bridge inspection processes and there are no guidelines and benchmarks to ensure proper implementation at the agency/company level. Because widespread SHM implementation will influence day-to-day business practices, it is imperative that proper attention is given in assessing user resistance. To overcome this potential resistance, Hartman and Fischer (2009) suggest that users should be involved in, at the earlier stage of implementation, on-going discussions about potential implementation benefits of the new technology.

CASE STUDY

To illustrate the discussion in earlier sections on the functionality and costs associated with visual inspection and SHM, a case study bridge is presented to compare both alternatives. A specific example structure enables a reliable and consistent comparison between the two approaches. The model structure, representative of a typical pre-stressed concrete girder bridge in a coastal region, is shown in Figure 4. This non-continuous bridge has three 65-ft spans and an 8-ft girder spacing making up a 56-ft wide deck. The bridge is assumed to have some known issues with corrosion of the pretensioning steel and has been identified as scour-critical.

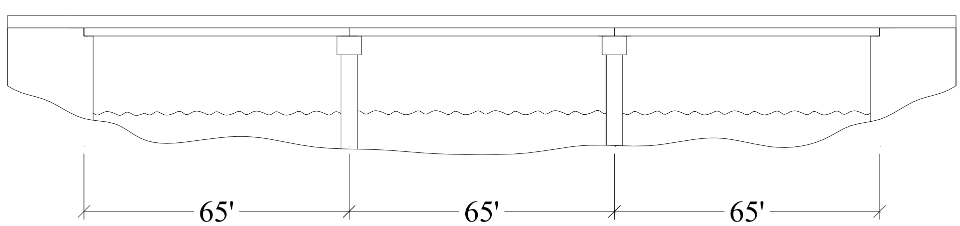

Figure 3. Case study bridge.

Visual Inspection Costs

District-wide historic costs—using a cost estimation spreadsheet provided by FDOT that serves as the basis for assessing inspection bids—were used in estimating typical routine inspection costs for the case study bridge described above. The cost development was based on adjusting unit costs of inspection-related costs using the model bridge's characteristics. A similar actual structure (in size and type) to the model bridge developed for this study was used to calculate the unit cost items that are related to routine inspection. For instance, the *routine field inspection* cost item describes the consulting costs associated with actual inspection and the payments are based on a standardized measure of the bridge size. Similarly, *maintenance of traffic (MOT)* costs are expenses related to necessary temporary *traffic control* devices and are expressed in number of days they are present at a construction/inspection site. Some of the basic assumptions in estimating the inspection costs were:

- Visual inspection is expected to take approximately one day.
- Underwater inspection is carried out due to the possibility of scour.
- A snooper (to access the underside of the bridge deck) is used for one day.
- Traffic control devices are used for one days.
- The presented unit costs are district wide average prices paid for the services.

The cost figures for visual inspection are limited to a single, routine inspection and are provided in Table 2. As discussed earlier in the article, the frequency and the details of the inspection largely depends on the specifics of the structure. It is likely the visual inspection costs of bridges will increase as the structure ages due to increased deterioration of the structure (Harada and Yokoyoma, 2007). Combined with the volatility of the bridge visual inspection cash flows because of the changes to the structure's condition, are the likely more frequent inspections in future and assumptions (i.e. discount rate used in computations) needed to be made for calculating the life cycle costs. Occasionally spurious in nature, discounted cash flow (DCF)—the main tool used in life cycle cost analyses—assumptions chosen by analysts play a major role in conclusions drawn. This is particularly problematic when the analysis period is longer, which is applicable to structures such as bridges (Prevatt et al., 2012). Considering these inherent difficulties in assessing exact dollar figures associated with bridge monitoring throughout the life cycle of a structure, the cost figures in this article—for both visual inspection and SHM systems—are limited to initial and periodic costs only.

Table 2. Case study bridge estimated inspection costs.

Cost Item	**Unit Cost**	**Unit**	**Quantity**	**Case Study Cost**
Routine Field Inspection	$ 232	Eq. Span*	4.91	$ 1,140
Routine Inspection Report	$ 155	Eq. Span	4.91	$ 762
Underwater Routine and Sub-marine cable	$ 185	Eq. Span	4.91	$ 909
MOT	$ 1500	Day	1	$ 1500
Snooper	$ 2500	Day	1	$ 2500
QA bridge inspection	$ 63	Eq. Span	4.91	$ 310
Snooper mobilization	$ 1285	Ea.	1	$ 1285
Safety Boat	$ 80	Hour	5	$ 400
			Total	**$ 8,806**

*Equivalent Span is a dimensionless measure of bridge size that includes superstructure and substructure with all incidentals.

Monitoring Costs (SHM)

Cost estimation for bridge monitoring systems is fairly complicated due to a virtually infinite number of potential system compositions, monitoring frequency and method; thus, even simplified monitoring cost cash flow estimates can become complex problems over the life cycle of the structure (Frangopol et al., 1997; Kim and Frangopol, 2011). As previously discussed, a monitoring system's capability largely depends on both type and number of sensors used and subsequently becomes one of the factors effecting system cost. The case study bridge illustrated in Figure 4 is equipped with dynamic, static, corrosion, and scour sensing hardware whose locations are displayed in Figure 5. The corrosion and scour sensors are implemented to track known concerns (as is the current practice in Florida), the strain gages are intended for use in load rating and for tracking load sharing between the girders and the accelerometers are included as part of a study to investigate the changes in the modal properties of the structure over time. Although this combination of sensors and their deployment topology are unique to this case study, the cost values presented in Table3 are retrieved and scaled from actual applications for both wired and wireless SHM systems.

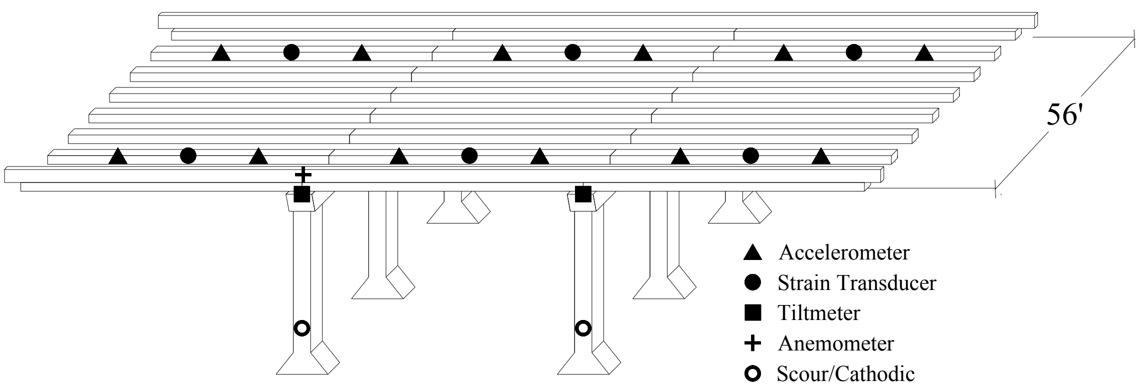

Figure 4. Proposed sensor layout.

Table 3. Wired and wireless SHM costs for case study bridge.

	Hardware	Unit Cost	Unit	Quantity	Wireless	Wired
	Wireless Processing Unit w/ Embedded Accelerometer	$ 600	Node Location	14	$ 8,400	-
	Accelerometers	$ 750	Sensor	14	-	$ 10,500
	Strain Gauge	$ 550	Sensor	6	$ 3,300	$ 3,300
	Anemometer	$ 2,600	Sensor	1	$ 2,600	$ 2,600
	Cathodic Protection	$ 5,450	Bent	2	$ 10,900	$ 10,900
	Scour	$ 7,000	Bent	2	$ 14,000	$ 14,000
	Base Station	$ 6,500	System	1	$ 6,500	$ 6,500
	Software License	$ 1,000	System	1	$ 1,000	$ 1,000
Initial	**Installation & Power**					
	Wired Installation	$ 20,000	Bent	2	-	$ 40,000

	Wireless Installation	$ 8,000	Bent	2	$ 16,000	-
	Conduit	$ 1,020	Span	3	-	$ 3,060
	AC Power	$ 6,240	Span	3	-	$ 18,720
	Solar Power	$ 185	Panel	6	$ 1,110	-
			Initial Cost:		**$ 63,810**	**$ 110,580**
Ongoing	**Bridge Service**	**Unit Price**	**Yearly Occurrence**		**Wireless**	**Wired**
	Data Analysis	$ 2,000	1		$ 2,000	$ 2,000
	Maintenance	$ 5,000	2		$ 10,000	$ 10,000
			Ongoing Cost / Year:		**$ 12,000**	**$ 12,000**

Note: The expected life expectancy of typical system components are approximately 10 years with proper maintenance.

Sensor hardware (i.e. strain gauge, anemometer, and accelerometers) costs were determined using average market prices. A sensor/wireless communication platform with embedded triaxial accelerometers was used and priced according to previous academic applications (Rice et al., 2010). Installation costs, including equipment rentals and labor, were retrieved from comparable standardized industry applications based on the size and type of bridge. Ongoing costs such as IT personnel, software management, and general SHM system maintenance are reported in a cost per bridge, per year basis and were developed based on current methods of fund allocation for existing monitoring systems in Florida—this information was obtained by research team via personal communication with FDOT. For the presented case study, a wireless SHM system results in over a 40% reduction in initial costs versus an equivalent wired SHM system. The cost benefit of wireless system is expected to increase with bridge length as the conduit and power requirements make up a relatively large percentage of wired SHM system costs. These figures make a strong case for moving towards wireless SHM. Wireless SHM also provides additional functionality over wired systems, such as in-network data communication and processing.

Cost Variations and Life Cycle Cost Considerations

The cost figures provided here are baseline estimates; some deviations from these values are expected in most cases. Moreover, the cost of visual inspection and SHM system implementation and maintenance on road users is not presented. Any disturbances to the flow of traffic will incur additional travel time, resulting in monetary losses. However, there are too many unknowns to accurately compute these costs for this case study, thus they were excluded from the analyses.

The SHM costs presented in Table only reflect the hardware and installation of sensors and ongoing maintenance for an SHM system. Unpredictable costs associated with bridge restoration and rehabilitation that may be required for in-service bridge monitoring applications, are not included in these estimates. These restoration costs may add an additional 75-150% in price and are dependent on various factors such as height and length of the bridge, location, and existing damage.

The life cycle cost considerations are of great importance in long-term decision-making when adapting monitoring methods. The cost comparisons provided here are intended to give readers an estimation of typical, on-going monitoring costs. As the structure gets older, the level of detail and frequency of visual inspection will increase—with the added potential requirements for (non) destructive testing. This is a stark contrast to structural health monitoring systems, as the initial capital investment requirements are significantly more substantial than the maintenance costs, although the latter is likely to increase as the hardware and software components become obsolete or need to be replaced. Given these unknowns regarding the life cycle cost considerations, the reliability of comparisons is low and thus not considered in this article.

DISCUSSIONS

Both SHM and visual inspection have limitations and relying solely on either is not prudent; however, with advancements in sensing and networking technology, visual inspection can be augmented with an SHM system to streamline structural data acquisition and processing. This combined approach has the potential to enable early identification of structural problems while minimizing human error. The use of the wireless SHM to monitor the progression of deficiencies identified during a visual inspection is also considered a great value to bridge owners. Such a system allows for the continuous monitoring of identified problems while maintaining a safe use of the structure and provides time for permanent repairs to be budgeted, designed and constructed. Increased understanding of the benefits and shortcomings of each approach for different bridge characteristics is the first step in achieving such augmented systems. Another necessary step is to improve the functionality of SHM system components while reducing production and operational costs.

While this paper is an attempt to present realistic cost figures for both visual inspection and SHM. The benefits of both approaches, and even a combined strategy, must be evaluated in terms of a full life cycle analysis. Assigning value to more intangible aspects of bridge maintenance poses a challenge. For example, the value of an SHM system deployed on a bridge that does not experience significant deterioration in its lifespan is difficult to quantify, as is the value of an SHM system that provides daily information that results in action that saves lives. Such analyses require a statistical analysis framework that examines the aggregate life cycle value of number of SHM systems in a transportation network.

CONCLUSIONS

As a result of the destruction caused by recent natural disasters in the US as well as countless reports on infrastructure deficiencies and need for condition improvement, bridge inspection and maintenance efficiency is a clear national priority. In this article, a review of both visual inspection and structural health monitoring of bridges—that encompass multiple attributes of each method—was provided. Each method has its own strengths and limitations, making the case for and a hybrid/augmented system design for optimal functionality. Visual inspection has proven to be effective for general inspections. For smaller bridges with no known structural problems, this method can be sufficient in identifying preliminary issues. For larger structures and structural problems that require more in-depth understanding of their nature for effective maintenance, structural health monitoring may be more appropriate. Perhaps the best solution is an augmented, coupled visual inspection and structural health monitoring system. The visual inspection can be instrumental in identifying potential problems and areas, which are more suitable for a more sophisticated monitoring system deployment. Advances in monitoring technology and reduced hardware costs, coupled with increased awareness on the potential shortcomings of visual inspection, create the motivation for a combined approach to bridge maintenance. While the initial costs of an SHM system, which can be reduced through the use of wireless sensors, may be higher than each inspection episode, the added functionality and timeliness of decision support it provides can justify the additional investment.

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REFERENCES

Agdas, D. & Ellis, R. (2010) "The potential of XML technology as an answer to the data interchange problems of the construction industry", *Construction Management and Economics*, 28:7, 737-746

Alampalli, S., & Ettouney, M. (2008) "Role of structural health monitoring in bridge security." *Bridge Structures: Assessment, Design and Construction,* 4(3-4), 143-154.

ASCE (2013). "Report card for America's infrastructure," Available at: <http://www.infrastructurereportcard.org/>

Brownjohn, J.M.W. (2007). "Structural health monitoring of civil infrastructure." *Philosophical Transactions of the Royal Society A,* 365(1851) 589-622.

Chan, T. H., Ashebo, D. B., Tam, H., Yu, Y., Chan, T., Lee, P., and Gracia, E. P. (2009), "Vertical displacement measurements for bridges using optical fiber sensors and CCD cameras – a preliminary study", Structural Health Monitoring, 8(3), 243-249.

Cosser, E., Roberts, G. W., Meng, X., & Dodson, A. H. (2003). "The comparison of single frequency and dual frequency GPS for bridge deflection and vibration monitoring," *Proc. of the Deformation Measurements and Analysis, 11th International Symposium on Deformation Measurements*, International Federation of Surveyors (FIG).

Dickens, T. J., Olawale, D., Sullivan, G., Breaux, J., Okoli, O. O., & Wang, B. (2011). "Toward triboluminescent sensor realization for SHM: statistical modeling of triboluminescent composites," *Proc. SPIE Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring* (pp. 79810J-79810J).

Egan, M. (2007). "Anticipating Future Vulnerability: Defining Characteristics of Increasingly Critical Infrastructure-Like Systems," *Journal of Contingencies and Crisis Management*, 15(1):4-17.

Federal Highway Administration (FHWA) (2004). National Bridge Inspection Standards. 23 CFR Part 650. *Federal Register.* 69(239), 74419-74439.

Frangopol, D.M., Lin, K.Y. & Estes, A.C. (1997) "Life-cycle cost design of deteriorating structures." *Journal of Structural Engineering,* 123(10):1390–1401. doi:10.1061/(ASCE)0733-9445(1997)123:10(1390).

Gastineau, A., Johnson, T. & Schultz, A. (2009). "Bridge Health Monitoring and Inspections- A Survey of Methods." *Technical Rep. No. MN/RC 2009-29,* University of Minnesota, Minnesota Department of Transportation, MS.

Guan, S., Rice, J.A., Li, C. and Wang, G. (2014). "Bridge Deflection Monitoring using Small, Low-Cost Radar Sensors," Proc. Structures Congress 2014 , Boston, MA.

Guan, S., Rice, J.A., Li, C., Li, Y. and Wang, G. (2015). "Dynamic and Static Structural Displacement Measurement Using Backscattering DC Coupled Radar," Smart Structures and Systems (in press).

Harada, T., and Yokoyama, K. 2005. "Optimization of maintenance strategies for road pavement by considering flexibility of alternatives", in *Life-Cycle Cost and Performance of Civil Infrastructure Systems, eds Cho, Frangopol and Ang.* Taylor and Francis, Hoboken, NJ.

Hartmann, T. & Fischer, M. (2009) "A process view on end-user resistance during construction IT implementations", *ITcon - Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning* , 14(353-365).

Holguín-Veras, J., Pérez, N., Ukkusuri, S., Wachtendorf, T., & Brown, B. (2007). Emergency Logistics Issues Affecting the Response to Katrina: A Synthesis and Preliminary Suggestions for Improvement. *Transportation Research Record*, *2022*(-1), 76–82.

Inaudi, D., Bolster, M., Deblois, R., French, Cathy., Phipps, Alan., Sebasky, J., & Western, K. (2009). "Structural Health Monitoring System for the New I-35W St Anthony Falls Bridge." *Proc. 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure.* 2-10.

International Bank for Reconstruction and Development (IBRD) (2010). "Natural Hazards, Unnatural Disasters: The Economics of Effective Prevention." <http://www.gfdrr.org/sites/gfdrr.org/files/nhud/files/NHUD-Report_Full.pdf> (Dec. 10, 2012)

Jang, S., Jo, H., Cho, S., Kirill, M., Rice, J.A., Sim, S., Jung, H., Yun, C., Spencer Jr., B.F and Agha, G. (2010). "Structural Health Monitoring of a Cable-Stayed Bridge Using Smart Sensor Technology: Deployment and Evaluation," *Smart Structures and Systems,* 6(5-6), 439-459.

Kim, S. & Frangopol, D.M. (2011). "Cost-effective lifetime structural health monitoring based on availability." *Journal of Structural Engineering,* 137(1): 22–33. doi:10.1061/(ASCE)ST.1943-541X.0000280.

Ko, J.M. and Ni,, Y.Q. (2005) Technology developments in structural health monitoring of large-scale bridges, *Engineering Structures*, 27(12): 1715-1725.

Kurata, M., Kim, J., Lynch, J. P., Van Der Linden, G. W., Sedarat, H., Thometz, E., ... & Sheng, L. H. (2012). Internet-enabled wireless structural monitoring systems: development and permanent deployment at the New Carquinez Suspension Bridge. Journal of Structural Engineering, 139(10), 1688-1702.

Li, H. N., Li, D. S., & Song, G. B. (2004). "Recent applications of fiber optic sensors to health monitoring in civil engineering". *Engineering structures*, 26(11), 1647-1657.

López-Higuera, J. M., Rodriguez Cobo, L., Quintela Incera, A., & Cobo, A. (2011). Fiber optic sensors in structural health monitoring. Lightwave Technology, Journal of, 29(4), 587-608.

Moore, M., Phares, B., Graybeal, B., Rolander, D., & Washer, G. (2001). *Reliability of Visual Inspection for Highway Bridges, Volume 1: Final Report(No FHWA-RD-01-020).*

National Transportation Safety Board (NTSB) (2008). "Collapse of I-35W Highway Bridge, Minneapolis, Minnesota, August 1, 2007." *Highway Accident Report*. <http://www.dot.state.mn.us/i35wbridge/ntsb/finalreport.pdf> (Dec. 10, 2012).

Page, C. and Sergi, G. (2000) "Developments in Cathodic Protection Applied to Reinforced Concrete." *J. Mater. Civ. Eng,*. 12(1), 8-15.

Prevatt, D., van de Lindt, J., Back, E., Graettinger, A., Pei, S., Coulbourne, W., Gupta, R., James, D., and Agdas, D. (2012). "Making the Case for Improved Structural Design: Tornado Outbreaks of 2011." *Leadership Manage. Eng.*, 12(4), 254–270.

Rice, J.A., Mechitov, K.A., Sim, S. H., Spencer Jr., B.F and Agha, G. (2010a). "Enabling framework for Structural Health Monitoring Using Smart Sensors," *Structural Control and Health Monitoring*, 18(5):574-587.

Rice, J.A, Mechitov, K., Sim, S.H., Nagayama, T., Jang, S., Kim, R., Spencer Jr., B.F., Agha, G. and Fujino, Y. (2010b). "Flexible Smart Sensor Framework for

Autonomous Structural Health Monitoring," Smart Structures and Systems 6(5-6): 423-438.

Rossi, G., Marsili, R., Gusella, V. and Gioffre, M. (2002), "Comparison between accelerometer and laser vibrometer to measure traffic excited vibrations on bridges", Shock and Vibration, 9(1), 11-18.

Stiros, S. and Psimoulis, P. (2012), "Response of a historical short-span railway bridge to passing trains: 3-D deflections and dominant frequencies derived from Robotic Total Station (RTS) measurements", Engineering Structures, 45, 362-371.

US CENSUS (2013). "U.S Census Bureau News." U.S Dept. of Commerce, <www.census.gov/const/C30/release.pdf>.

Wardhana, K. and Hadipriono, F. (2003). "Analysis of Recent Bridge Failures in the United States." J. Perform. Constr. Facil., 17(3), 144–150.

Webb, G., Vardanega, P., and Middleton, C. (2014). "Categories of SHM Deployments: Technologies and Capabilities." *J. Bridge Eng*ineering?

Wong, K. (2007). "Design of a structural health monitoring system for long-span bridges." *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 3(2),* 169-185.

Yi, X., Wu, T., Wang, Y., Leon, R. T., Tentzeris, M. M., & Lantz, G. (2011). "Passive wireless smart-skin sensor using RFID-based folded patch antennas." *International Journal of Smart and Nano Materials*, *2*(1), 22–38.

Zhu, S., Levinson, D., Liu, H. X., & Harder, K. (2010). "The traffic and behavioral effects of the I-35W Mississippi River bridge collapse." *Transportation Research Part A: Policy and Practice*, *44*(10), 771–784.