

# Categories of SHM Deployments: Technologies and Capabilities

G. T. Webb, Ph.D.<sup>1</sup>; P. J. Vardanega, Ph.D., M.ASCE<sup>2</sup>; and C. R. Middleton, Ph.D., C.Eng.<sup>3</sup>

**Abstract:** The findings of an extensive literature survey focusing on bridge structural health monitoring (SHM) deployments are presented. Conventional, maturing, and emerging technologies are reviewed as well as deployment considerations for new SHM endeavors. The lack of published calibration studies (and quantification of uncertainty studies) for new sensors is highlighted as a major concern and area for future research. There are currently very few examples of SHM systems that have clearly provided significant value to the owners of monitored structures. The results of the literature survey are used to propose a categorization system to better assess the potential outcomes of bridge SHM deployments. It is shown that SHM studies can be categorized as one (or a combination) of the following: (1) anomaly detection, (2) sensor deployment studies, (3) model validation, (4) threshold check, and (5) damage detection. The new framework aids engineers specifying monitoring systems to determine what should be measured and why, hence allowing them to better evaluate what value may be delivered to the relevant stakeholders for the monitoring investments. DOI: [10.1061/\(ASCE\)BE.1943-5592.0000735](https://doi.org/10.1061/(ASCE)BE.1943-5592.0000735). This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <http://creativecommons.org/licenses/by/4.0/>.

**Author keywords:** Structural health monitoring (SHM); State-of-the-art review; Technology; Modeling; Data interpretation.

## Introduction

“Knowledge,” Richard Feynman lectured in 1963, “is of no real value if all you can tell me is what happened yesterday. It is necessary to tell what will happen tomorrow” (Feynman 1998).

The structural health monitoring (SHM) revolution is benefiting from rapid advances in sensor and data-acquisition technologies. These have made it possible to install extensive monitoring systems on structures and obtain large amounts of quantitative data. Civil engineering is often regarded as a conservative industry not receptive to change and innovation. However, recent technological developments have given the profession new opportunities to better understand and assess the behavior of the complex and valuable structures that serve modern civilization. The 21st-century civil engineer will be a professional not only versed in the mechanics that underpin the physical behavior of infrastructure but also able to understand the functioning of the communications and sensing technologies that constantly measure the performance of the infrastructure [this new reality for the profession was foreshadowed in Maser (1988)]. The implications for engineering educators that arise from this perspective are challenging and worthy of further research, but they are beyond the scope of this paper.

In the future, SHM may become a standard component of any civil engineering project; however, the civil engineering profession is still grappling with how best to use the data from SHM systems to

actually provide useful value. Infrastructure design and management may be transformed if reliable data can be generated from SHM deployments that can be related back to the actual performance of the instrumented structure and then acted on by those who are responsible for managing infrastructure. The SHM systems that have a clearly defined purpose have more chance of providing value than those that are specified simply because it is possible to measure a particular parameter but without a clear understanding of how such measurements will be used to inform decision making.

Unfortunately, many existing monitoring endeavors do not have a clearly defined objective. Instead, seemingly sensible parameters are measured without proper consideration given to how the data will be interpreted. Data interpretation is then considered at a later date, often coupled with the discovery that very little useful information can be obtained. A more rational approach to the design of SHM systems is needed. The following questions should be answered:

1. What information regarding structural performance is needed?
2. What action would actually be taken if this information were available?
3. Can this information be obtained from available sensor technologies and data interpretation techniques?

Therefore, an understanding of the range of capabilities of different SHM systems will be helpful in directing stakeholders to evaluate what output and, hence, value can actually be delivered.

This paper has two primary aims: (1) to elucidate the current state of the art of SHM (focusing on the widely reported examples used on bridges) and (2) to present a recently developed categorization system to describe the types of monitoring deployments commonly specified and aid in the design of improved future systems. Although the focus of this paper is on bridges, the findings are expected to also be applicable to many other infrastructure types.

## Why Monitor?

Monitoring requires the commitment of financial and human resources. As such, consideration first needs to be given to the role and purpose of proposed SHM systems.

Maser (1988) reviews the role of sensors for infrastructure monitoring and discusses the implications for the education of the civil

<sup>1</sup>Engineer, Parsons Brinckerhoff, 6 Devonshire Sq., London EC2M 4YE, U.K.; formerly, Doctoral Student, Dept. of Engineering, Univ. of Cambridge, Cambridge, CB2 1PZ, U.K. E-mail: [graham.webb@cantab.net](mailto:graham.webb@cantab.net)

<sup>2</sup>Lecturer in Civil Engineering, Dept. of Civil Engineering, Univ. of Bristol, Bristol BS8 1TR, U.K. (corresponding author). E-mail: [p.j.vardanega@bristol.ac.uk](mailto:p.j.vardanega@bristol.ac.uk)

<sup>3</sup>Laing O'Rourke Professor of Construction Engineering, Dept. of Engineering, Univ. of Cambridge, Cambridge CB2 1PZ, U.K. E-mail: [crm11@cam.ac.uk](mailto:crm11@cam.ac.uk)

Note. This manuscript was submitted on May 31, 2014; approved on October 21, 2014; published online on December 17, 2014. Discussion period open until May 17, 2015; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Bridge Engineering*, © ASCE, ISSN 1084-0702/04014118(15)/\$25.00.

engineering profession. Hoult et al. (2009a) outlines some recent deployments of wireless monitoring systems in the United Kingdom (including bridges) and concludes that great potential exists for these to become standard tools for the management of infrastructure. However, there has been less focus on the purpose of monitoring and the reasons a new (or existing) piece of infrastructure should have a SHM system installed. There are few examples where SHM systems have been reported to actually demonstrate value to the operators of the structure—there may be justifiable reasons for how the collected data may prove useful to someone in the future, but the actual benefit to the system owner is rarely evident. Instead, the primary purpose of the majority of deployments is simply demonstrating that a particular new sensor technology can measure a parameter of interest rather than specifically to provide information that will inform decision making. Hence, before the rush to monitor, the question should be asked, “Why monitor?” If a valid reason cannot be found for a SHM system, then the no-monitoring option should be viewed as acceptable.

### **SHM or Condition Monitoring?**

It is worth pointing out that there is a key distinction between SHM and condition monitoring, both of which are established terms. Some consider condition monitoring to include the measurement of parameters such as vehicle loading, air pressure, traffic speed, wind speed, and temperature, which are not directly related to the health of the structure, whereas SHM is related to the physical condition of the asset. Condition monitoring may still provide useful data for use in the future; this is analogous to many atmospheric measurements that are taken at meteorological stations. Perhaps a more all-encompassing term should be used to describe all metrology efforts on infrastructure; for example, structural monitoring (SM) could be used. However, SHM has now become almost ubiquitous when discussing all measurement efforts in civil engineering and as such will continue to be used in the present paper.

### **Objectives and Stakeholders**

For any monitoring endeavor to be successful, it is vital to clearly define the objectives of the monitoring at the beginning of the project (British Tunnelling Society 2011). A number of different facets must be considered. In established economies, the need to assess the residual life and performance of aging, existing infrastructure has a high priority. In rapidly developing economies, where there is a greater prevalence of new-build projects, monitoring during construction is especially relevant. Monitoring of new projects also presents the opportunity for the collection of data sets that have the potential to provide long-term validation of structural analysis and performance models. This has the potential to be of great value to design engineers and code drafters. It is also potentially easier to install a system during construction than to retrofit one later in the life of the asset.

Additionally, it is important to consider who is intended to benefit from the data generated by a monitoring system. Anderson and Vesterinen (2006) provide some brief discussion on this topic in addition to a number of the other considerations mentioned here, including identifying key stakeholders of SHM projects, namely (1) authorities, (2) owners, (3) users, (4) researchers, (5) designers, (6) contractors, and (7) operators.

Asset owners will likely obtain most value from a system that aids in decision making related to operational or safety matters. Design engineers are more likely to derive benefit from long-term monitoring, enabling them to evaluate the appropriateness of their current analysis techniques and design assumptions. This may lead to future improvements in the pursuit of enhanced safety or design efficiencies. Monitoring systems can also be installed primarily as research tools to investigate various phenomena, e.g., structural performance, testing of new sensor technologies, or refining novel construction techniques.

Camfield and Holmes (1995) review the use of monitoring efforts (in the context of design and operation of coastal installations): “Monitoring is a critical test of design tools, such as physical and numerical models, and the use of these tools. Information obtained from monitoring can be incorporated into design and construction practices on future projects to reduce costs of operations and maintenance.”

The emphasis on maintenance has particular significance for the bridge engineering community. Bridges are expensive, critical infrastructure assets that connect communities and serve as lifelines for regions. The SHM systems that allow for better planning of their maintenance have the potential to be extremely valuable.

Improvements in SHM have the potential to assist with the sustainability imperative by improving the understanding of structural performance and hence allowing for extension of the life of existing infrastructure (e.g., Hoult et al. 2009b). Sánchez-Silva and Rosowsky (2008) argue that the safety standards used in construction in developed countries are economically unsustainable and should not be adopted worldwide. Civil engineers should attempt to reduce the levels of unnecessary overspecification. It is often proposed that SHM systems can assist with this challenge.

A further potential use for SHM data is to allow engineers to better understand how structures perform from both safety and serviceability perspectives. Understanding performance is different from understanding design. Design is concerned with making decisions to ensure that a structure will be adequate according to set criteria. A good design can be achieved without necessarily fully understanding structural behavior: conservative assumptions are made during the design process for precisely this reason. Performance can be observed, but the loop between design predictions and measured outcomes is rarely closed. As a result, the opportunity to compare actual performance to design predictions and hence optimize or refine designs is often missed. Table 1 illustrates how many of these SHM objectives can be generalized. Catbas et al. (2012) provide an in-depth review of research related to structural identification, i.e., the process of calibrating a structural model using experimental data, an important step if performance is later to be compared with predictions.

### **Applications of Infrastructure Monitoring**

Many SHM systems have been deployed on a variety of geotechnical structures and other structural components, e.g., deep excavations in stiff clays (Schwamb et al. 2014); wireless sensor networks in tunnels (Bennett et al. 2010a, b); optical fiber installations in transport tunnels (Cheung et al. 2010; Mohamad et al. 2010); geophones for piled foundations (Gassman and Finno 1999); strain measurement using optical fibers for piled foundations (Klar et al. 2006; Schwamb 2010); ultrasonic testing of bridge piles (McCuen et al. 1988) and longer-term monitoring of bridge abutment piles (Huntley and Valsangkar 2014); cracking and thermal expansion in unreinforced masonry structures (DelloRusso et al. 2008); remote sensing of corrosion in bridges (Agrawal et al. 2009); and the dynamic response of sporting stadia (Reynolds et al. 2004). A distinguishing feature of the geotechnical SHM projects is that the data are primarily used during construction as

**Table 1.** General Objectives of SHM (Data from Liu et al. 2009)

Objective	Description
1	Detect structural damage
2	Estimate remaining service life of a structure
3	Optimize (based on data) the decision making process for maintenance efforts to avoid costly replacements
4	Aid in the transition of structural design methodology from current semiprobabilistic load resistance factored design to future probabilistic performance-based design

opposed to informing whole-life asset management thinking, which is often the primary goal of SHM systems deployed on bridge structures. The interpretation of monitoring data from bridges also presents some unique challenges. Bridges are often highly sensitive to varying live-load, wind, and temperature distributions. These loading forms, which are often not relevant or significant for geotechnical structures, can be extremely difficult to quantify. Additionally, bridges are often unique, complex, and indeterminate structures, making the standardization of any monitoring techniques and interpretation of data challenging.

The next section aims to briefly review some technologies that are becoming commonplace in SHM deployments. New technologies are making the collection of vast and diverse data sets more feasible but simply having the data does not imply more information is available. This will be demonstrated later in the paper when the new categorization system is presented.

## Existing Data Acquisition and Deployment Technology

All monitoring systems require the ability to collect, store and process data. Farrar and Worden (2007) explain that the technical challenges of monitoring include “the 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 these features caused 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, and performance of comparative studies of different damage identification methods applied to common datasets.”

Many review papers summarizing the literature concerning a variety of aspects of mature and emerging SHM technologies and communication systems have been published. These reviews include analysis of fiber-optic technologies (Casas and Cruz 2003; Bao and Chen 2011); vibration based monitoring (Brownjohn et al. 2011); and wireless sensor networks for SHM deployments (Lynch and Loh 2006; Stajano et al. 2010). Various authors have reviewed the use and adequacy of the range of available sensors and measuring devices for use on civil infrastructure (e.g., Dunncliff 1988; Rens et al. 1997; Ko and Ni 2005; Yanev 2007; Vaghefi et al. 2012; Wijesinghe et al. 2013).

## Conventional and Maturing Technologies

Some of the conventional technologies used in reported SHM studies include electronic resistance strain gauges (ERSGs) (e.g., Allen and Rens 2004); vibrating wire strain gauges (VWSGs) (e.g., Abudayyeh et al. 2010); laser-based deflection measurements (e.g., Fuchs et al. 2004); deflection measurements using the global positioning system (GPS) (e.g., Brown et al. 1999, 2006); acoustic emission (AE) technology for detection of prestressing wire breaks (Webb et al. 2014); and use of ground penetrating radar for inspection studies (Bungey and Millard 1993).

Fiber-optic technologies are a maturing monitoring method for civil infrastructure. Fuhr et al. (1993) present an early experimental study investigating the feasibility of using optical fiber sensors for stress monitoring of concrete. Casas and Cruz (2003) review various SHM uses of fiber-optic technology for bridge engineering, namely crack sensors, strain monitoring, temperature monitoring, inclinometers, acceleration sensors, and even corrosion monitoring. The authors anticipate an increased use of fiber-optic technology for use on bridge structures but report little about the accuracy and reliability of the technology itself.

Chen et al. (1994) compare fiber Bragg grating (FBG) measurements of concrete crack widths to those obtained from

micrometers. The comparison was shown to be very good between the readings from the two measurement devices.

Whereas the use of FBG technologies is well documented, other approaches such as the use of Brillouin optical time domain reflectometry (BOTDR) are still not standard on large-scale infrastructure projects. This technology is capable of distributed strain measurements and hence the determination of strain profiles throughout structures. Use of BOTDR for strain measurement is becoming more widespread in tunneling works, such as described in Mohamad (2008) and Mohamad et al. (2010). Klar et al. (2006) report the use of BOTDR for use in monitoring of piled foundations, as do Schwamb et al. (2014) for monitoring of deep shafts in the London clay deposit.

## Emerging Technologies

Many exciting new technologies are being used in SHM activities. It is beyond the scope of this paper to review all of them; however, three key emerging technology types are considered by the authors to have great future potential, namely (1) imaging and computer vision, (2) microelectromechanical systems (MEMS) sensors, and (3) bioinspired sensors.

### Imaging and Computer Vision

Sensors do not measure damage directly; they provide data from which it may be concluded that damage has occurred (Farrar and Worden 2007). Most conventional sensors only provide readings at point locations on a structure. Although point sensors do not necessarily have to be placed exactly on damaged locations, they must be placed in sufficient numbers to allow for reasonable interpolation to occur across the area being monitored; distributed measurement technologies avoid this problem somewhat. A camera can be used to record images of a large area of a structure, which can then be processed to detect features that may correspond to damage. One such technique uses an infrared camera to look for disrupted heat flow through a structure (Washer et al. 2010). Particle image velocimetry (PIV) [also referred to as digital image correlation (DIC)], which has its origins in fluid mechanics, can be used to track areas of concrete between different images and deduce the strain field. White et al. (2003) have shown this to work for the relatively large strains encountered in geotechnical applications. Structural applications of computer vision include crack width detection (Kabir 2010); locating structural elements such as concrete columns (Zhu and Brilakis 2010); and detecting the extent of concrete spalling in earthquake damaged buildings (German et al. 2012). Transportation applications include detection of road defects and damage using video footage taken from a vehicle (Koch et al. 2013) and vehicle height detection (Khorramshahi et al. 2008; Sandidge 2012). Construction applications include tracking resources on construction sites (Park et al. 2012) and movements of construction workers (Park and Brilakis 2012).

### MEMS Sensors

Various MEMS strain and displacement gauges have now been produced (e.g., Wojciechowski et al. 2005; Ferri et al. 2011) that operate in a similar fashion to vibrating wire strain gauges but on a microscopic scale. They have the potential to offer extremely small (and low power) sensors with very high strain resolutions.

### Bioinspired Sensor Technologies

Research work is also being undertaken to develop sensors that are informed by the characteristics of biosystems (e.g., Del Valle 2011). For example, sensor skins, inspired by the sensory properties of human skin, aim to provide a fine spatial resolution of sensors across



the whole surface of a structure. Researchers such as Tata et al. (2009) are developing a patch antenna that can be used both to sense strain and to transmit those measurements wirelessly to a data logger. The small size of such a sensor should allow dense arrays of measurement devices to be built up.

## Deployment Considerations

### Wired Sensor Networks

Wired sensor networks use dedicated cabling to provide both power and data connectivity. These systems are usually very reliable and are capable of high data collection rates. One example is the Wind and Structural Health Monitoring System (WASHMS) devised by the consultant Arup and the Hong Kong Highways Department (Wong 2004). This system has been installed on a number of long-span cable-supported bridges in Hong Kong (China), with each bridge having up to 1,000 individual sensors taking hundreds of measurements every second. The cost of cabling and installation time is a significant disadvantage with wired systems, as is the fact that sensors cannot readily be added or moved to different locations on the structure if desired. However, a wired system may be the most cost-effective solution for a SHM system intended to have a long service life, and that is installed during construction.

### Wireless Sensor Networks (WSNs)

Alternatively, WSNs have the advantage of reduced hardware costs owing to the removal of the need for large amounts of cabling. However, potential problems with radio signal propagation and the need for regular changes of batteries (for instance) mean that these systems tend to be less reliable and robust than wired systems (e.g., Bennett et al. 2010a). Therefore, WSNs may be a more cost-effective solution for short-lived systems where battery life is less of an issue. Examples might include monitoring of neighboring preexisting structures during new construction. Like wired systems, WSNs can also provide real-time measurements (Hoult et al. 2009b) that techniques such as visual inspections cannot. Lynch and Loh (2006) provide an excellent state-of-the-art review of WSNs for SHM applications; they also highlight the need for power, which is generally derived from batteries. Agrawal et al. (2009) review various remote corrosion monitoring sensors and systems for use on highway bridges. Stajano et al. (2010) outline a set of 19 operational and technical principles for developing reliable and useful WSNs.

Park et al. (2008) review a number of energy-harvesting or wireless energy transfer technologies that may eventually overcome the need for battery replacements. Examples include electromagnetic vibration energy harvesters (Sazonov et al. 2009), piezoelectric vibration energy harvesters (Challa et al. 2011), microwave wireless energy transmission (Mascarenas et al. 2009), harvesting electrochemical power from the concrete corrosion process (Ouellette and Todd 2014), and even the digestion of insect biomass using a microbial fuel cell (Ieropoulos et al. 2005; Melhuish et al. 2006).

## Data Quality Considerations: Calibration, Resolution, and Accuracy

There is a paucity of published studies that give evidence of the long-term performance of the aforementioned technologies. Calibration of sensing equipment is vital for the users of SHM data to have confidence that decisions can be made on the basis of the data. Klar et al. (2006) compared the stated technical capabilities of VWSGs, FBGs, and BOTDR (Table 2). Long-term drift of sensors is also an important consideration, as discussed by Samaras et al. (2012), who discover drifts of approximately  $200 \mu\epsilon$  using electrical resistance strain gauges over a 6-month period. Matta et al. (2008) report that in the field their BOTDR analyzer outperformed the expected accuracy of  $\pm 40 \mu\epsilon$ . Bao and Chen (2011) review the developments of Brillouin scattering-based fiber sensors; according to the outcome of their review, state-of-the-art Brillouin scattering fiber sensors can achieve: (1) 100-km sensing range without the need for inline amplification; (2) improved spatial resolutions (of 2 m) with added erbium doped fiber amplifiers (EDFAs); (3) temperature resolutions of  $1^\circ\text{C}$  (with EDFAs); and (4) down to 2.5-mm spatial resolutions (however, no data are presented to support these conclusions). The experiments reported in Ge (2013) and Ge et al. (2014) demonstrate limitations on the accuracy of VWSG and fiber-optic strain measurements on concrete beams tested in the laboratory: differences of up to 30% were found between readings taken at comparable locations using different types of sensors.

Studies describing the accuracy, sensitivity, and reliability of many sensing technologies are remarkably difficult to source (apart from the notable exceptions previously cited). More research should be undertaken to demonstrate the accuracy of sensors for use on SHM projects. Without this, asset owners will not have sufficient confidence in any monitoring data to allow decisions to be influenced, rendering the entire monitoring activity futile.

Even if the collected data are deemed acceptable for decision-making purposes, there needs to be a clearly defined use for the data so that SHM can be justified. Various deployment types do this to varying degrees, as will be shown in the following section.

## New Categorization System for SHM Deployments

This section presents the verification of a new categorization system to classify SHM deployments. All deployments studied can fit into at least one of five categories, regardless of the technologies used in the deployment.

Many SHM systems are currently capable of capturing a large quantity and variety of measurements. Novel methods to rapidly communicate and disseminate the data are being reported (Fraser et al. 2010). However, if these data are not interpreted and converted into valuable information, then (by definition) they can be of no use to the operators of the monitoring system.

Webb and Middleton (2013) initially propose a four-category categorization system to assist SHM users to better understand the

**Table 2.** Comparison of Some Strain Measurement Techniques (Adapted from Klar et al. 2006, with Permission from ICE Publishing)

Method	VWSG	FBG	BOTDR
Sensor	Vibrating wire	FBG	Optical fiber
Measurement	Discrete	Discrete	Distributed
Strain resolution ( $\mu\epsilon$ )	0.5–1	0.1–10	30
Gauge length	50–250 mm	~2–40 mm (length of grating)	~1 m
Number of measurements per sensing element	1	Typically 40 sensors per single fiber	Up to 20,000
Measurement time	Real time	Real time	4–25 min
Maximum strain ( $\mu\epsilon$ )	3,000	~10,000	~10,000
Feature	Established technique	High strain accuracy	Distributed measurements

**Table 3.** SHM Categories

Category	Description
1	Anomaly detection
2	Sensor deployment studies
3	Model validation
4	Threshold check
5	Damage detection

purpose of SHM systems. In this paper, the framework is expanded and a more complete treatment provided (see also Webb 2014). The five proposed categories (Table 3) of SHM monitoring are intended to enable users of monitoring systems to clearly understand the purpose of any specified SHM system. They explain the types of information that the data from a deployment may be converted into. As the category number increases, so does the potential for value and impact, but the complexity and difficulty of achieving the stated outcome also increases. Higher-level categories (e.g., Category 4, threshold check, and Category 5, damage detection) have the potential to yield great value to many stakeholders, but (as is demonstrated later in the paper) successfully achieving these is difficult and challenging.

The categories can also be considered as a toolkit of available interpretation techniques, each capable of producing a different type of information. The categories of SHM deployment are independent of the technology used to obtain the data. The categories will remain valid as emerging SHM technologies (including those reviewed earlier in the paper) mature; technological advances may mean that higher-level categories become easier to achieve. The categories will now be examined in turn.

### **Category 1: Anomaly Detection**

Anomaly detection is a common category of SHM studies. Any system installed to purely identify changes in measured parameters could be considered anomaly detection. This category is a completely model-free approach to SHM investigation. Examples of SHM deployments with anomaly detection components have been reported in Chang and Im (2000); Lynch et al. (2006); Staquet et al. (2007); Koo et al. (2013); Roberts et al. (2006, 2012); and Minardo et al. (2012). Chandola et al. (2009) give a detailed treatise on the fundamentals of detecting anomalies in data sets. An anomaly could be caused by a change in the loading applied to the structure, changes in the monitoring system, or changes to the structure itself.

Many analysis methods have been proposed and trialed to distinguish between anomalies caused by changing environmental conditions, structural defects, and loadings. Examples include the use of artificial neural networks (Masri et al. 1996; Zapico et al. 2003), wavelet decomposition (Hou et al. 2000), autoregressive moving average vector models (Bodeux and Golinval 2001), cointegration (Cross et al. 2011), and outlier analysis to detect damage in an unsupervised learning fashion (Worden et al. 2000). However, for anything to be detected, it must cause changes in measurable parameters that are large enough to be distinguished from sensor noise; often this does not occur.

### **Category 2: Sensor Deployment Studies**

Category 2 SHM describes studies that aim to demonstrate (or showcase) new sensor technologies rather than necessarily derive information about the performance of the structure to which they are attached (e.g., Brown et al. 1999; Gebremichael et al. 2005; Hoult et al. 2008; Hoult et al. 2010; Chen 2010; Rodrigues et al. 2010;

Minardo et al. 2012). Many research papers have been written simply describing the deployment of sensor networks without giving the *raison d'être* for the SHM system. Some of these studies present data on quantities such as temperature, strain, and deflections but offer no explanation (in the papers) of how these data are to be used or how they could provide value to the asset owner. A high proportion of the SHM installations surveyed by Webb (2014) were identified to be in this category. A deployment proposed by Webb and other coauthors was also found to be well described by this category (Fidler et al. 2013). It is conceded that in the future these data sets may prove useful, provided that the data remain available and in an intelligible, future-proofed data format.

Studies aimed at road-testing emerging sensor technologies (e.g., fiber-optic strain gauges) alongside traditional approaches (e.g., electronic resistance strain gauges) are valuable exercises. They can assist with the development of, and testing the reliability, robustness, and calibration of, new and emerging SHM technologies.

### **Category 3: Model Validation**

Model validation is the first category in the categorization system in which data are actually related back to the performance of the structure being monitored. This can be described as a model-based approach, because data interpretation involves comparing measurements with a model that can be used to predict the behavior of the structure. This could prove valuable to designers or researchers, as it can assist with the validation of the structural models and assumptions that they use. Of course, if a set of measurements are predicted by a model, then the question of whether the right answers were obtained for the right reasons is not easily answered (e.g., Hemez and Farrar 2014). More strictly, it is only model falsification that can be achieved, because no model can be completely validated with a limited number of observations. For example, Goulet et al. (2013) show the use of model falsification procedures to detect leaks in water pipe networks, and Goulet and Smith (2013) and Goulet et al. (2014) use a similar philosophy to examine the behavior of some bridge structures. Model validation studies are likely to be of less benefit to the asset owner because they have already commissioned a design that they expect will lead to a safe and serviceable structure. Model validation is a common aim of studies presented in the SHM literature.

### **Input Loading Validation**

During the design process, various assumptions are made about the magnitude and type of loadings (demands) that will be applied to structures. Measuring the actual applied loading in situ (e.g., O'Connor and Eichinger 2007) allows engineers to determine whether design loads accurately represent real conditions or are overly conservative (or unconservative). However, many loadings are difficult to characterize to the extent that they can be applied to a structural model. These include wind loads, varying temperatures, and the dynamic effects of moving vehicles. Xu et al. (2010) carry out a detailed study of the effects of temperature on the Tsing Ma Bridge in Hong Kong, finding variations to be within the range of values specified in design codes. However, a different example, presented by Shoukry et al. (2009), discovered temperature gradients throughout the depth of a bridge deck that differed significantly from the design values used. Loading models were obtained for a bridge over the Yangtze River by Ji et al. (2012).

### **Output Response Validation**

In addition to verifying the loadings applied to a structure, it is also possible to compare the structure's responses with those predicted

by analytical models. Frequently, a model is developed to predict a facet of bridge response, and this is calibrated by comparing measured responses (e.g., displacement, strain, natural frequency) with those predicted by the model. Verification of numerical models (e.g., finite-element analyses) is a common example of this category (e.g., Brownjohn et al. 1999; Brown et al. 1999, 2006; Gebremichael et al. 2005; Ni et al. 2008; Chen 2010; Roberts et al. 2012; Xu et al. 2012; Hedegaard et al. 2013; Kurata et al. 2013).

A danger is that the designer may adjust model parameters so that responses match the measured results, but this does not necessarily mean that the model has been universally validated (or if the reverse is true, then the model falsified). Frangopol et al. (2008) highlight the importance of the quantification of sensor errors for reliability studies.

### Load-Rating Analyses

Nowak and Tharmabala (1988) use bridge test data in conjunction with load-rating models to estimate what they refer to as *safety-reserve*. Similar studies were reported by Jáuregui and Barr (2004) and Staquet et al. (2007).

### Category 4: Threshold Check

A threshold check provides a very simple way of interpreting data to determine whether there is likely to be a problem with a structure that needs addressing. Deployments that can fit into this category include elements reported in Hoult et al. (2008) (humidity limit for the Humber Bridge Anchorage); Corbett et al. (2010) (settlement and vibration thresholds); and Caetano et al. (2010) (verification that vibration amplitudes meet serviceability criteria).

Thresholds for measurable parameters can be established in two different ways. First, limits can be imposed on parameters such as deck deflections, measured strains, or number of wire breaks, which are derived from predictive models. If a limit is exceeded, the monitoring system can alert the bridge's owners to the need to take immediate action. Second, limits can be imposed in a cumulative manner, such as with fatigue life of components and manufacturers' limits on bearing travel. In this case, the rate at which these thresholds are being approached can also be used to aid the bridge owners in their maintenance planning.

To be useful, the assigned threshold must have relevance: that is, reaching or exceeding the threshold will result in action or intervention. Care should be taken in determining the technical basis for selecting any assigned threshold to avoid excessive numbers of false alarms while ensuring that sufficient warning of any defects is provided. For example, Mao and Todd (2013) report efforts to use probabilistic uncertainty quantification models to select meaningful thresholds.

Irrespective of how the threshold is derived, if the threshold value is not meaningful (or does not have a valid technical basis), then the SHM deployment is more akin to an anomaly detection (Category 1) study, i.e., a change from normal behavior is observed that serves as a warning or alarm that something, somewhere may be amiss.

### Category 5: Damage Detection

The aims of damage detection monitoring are to directly determine some or all of the following damage characteristics: (1) type, (2) location, (3) extent, and (4) rate. A general framework describing the interplay between components of a damage prediction process is described in Farrar and Lieven (2007), who emphasize that any model that is predictive has an associated error. The decision maker must manage uncertainty in the collected SHM data but also uncertainty from the models used to predict the damage.

Young and Lynch (2010) discuss the visual inspection of the Severn Bridge suspension cables, the results of which were used to

develop the maintenance program involving dehumidification. Visual inspections are time consuming and intrusive and cannot provide continuous measurements. They have also been found to be unreliable and highly dependent on the individual inspectors concerned (e.g., Moore et al. 2001; Lea and Middleton 2002). However, it is currently unlikely that bridge managers will cease to rely on visual inspection as the primary method of structural evaluation, regardless of the level of sophistication of any installed SHM system.

### Global Damage Detection

Global damage detection methods aim to provide information without requiring any prior input from the designer as to what damage is expected to occur. The vast majority of such systems reported in the literature are based on modal analysis methods. A monitoring system is used to measure various properties of the vibrational response of a structure. By analyzing any changes to these properties, it is hoped that it will be possible to determine the location and extent of any damage. Despite the popularity of these techniques, modal parameters are insensitive to anything except the most extreme damage scenarios. Additionally, the techniques cannot provide any information about the type of damage occurring. Farrar and Jauregui (1998a, 1998b) attempted to implement the technique on an old composite bridge due to be demolished. They found that cutting through half of the cross section of a bridge girder resulted in only an 8% change in the first natural frequency of the bridge. Xia et al. (2006) presented data that demonstrated variations of a similar magnitude caused by only temperature and humidity changes. Brownjohn et al. (2011) reviewed vibration-based monitoring of 31 civil infrastructure projects (mainly bridges) and concluded that as far as damage detection was concerned, vibration-based methods were not suitable (as the stiffness changes inherent in all but the most catastrophic levels of damage will not be detectable) but could be useful to study structural behavior.

### Specific Damage Scenarios

A more feasible approach is to target specific damage or deterioration scenarios. In this case, the monitoring system's designers must postulate what sort of damage or deterioration might occur. They can then predict the effects that the damage will have on the structure, with the aim of identifying measurable parameters that change, allowing the extent and rate of damage development to be quantified. Postulating what damage may occur, and where, is likely to be a difficulty in this type of study and will be highly dependent on the designer's knowledge and experience with similar structures. Visual inspections will often also be needed in conjunction with the detecting technologies, although these are known to be unreliable (e.g., Lea and Middleton 2002). Ritdumrongkul and Fujino (2006) use piezoceramic actuator sensors and a spectral-element model of a simple bolted aluminum beam to see if damage could be detected in a laboratory environment. Bolts were arbitrarily loosened so that damage could be simulated. The simulated damage was then detected by the sensors. The requirement to believe the structural model was necessary for the success of this simple study. Arguably, this is a fusion of model validation and damage detection. Hoult et al. (2010) describe a monitoring installation consisting of displacement transducers arranged to measure crack widths, in direct response to a concern that cracks in the structure may be increasing in size.

### Application of the Categories

Table 4 presents examples of SHM deployments from the literature that have been classified using the new framework, and Fig. 1 shows the number of examples of each category that were identified. Examples of each category can be found in the literature and,

**Table 4.** Classification of Some Reported Bridge SHM Studies Using the New Categorization System (Five Categories)

Classification	Bridge	Location	Reported period of		Key technologies deployed in the sensor network	Stated major aims of study	Reported key outputs	Reference
			monitoring or duration of deployment	September 1996 to April 1998				
Anomaly detection/model validation	Sa-Dang Viaduct	South Korea	September 1996 to April 1998		<ul style="list-style-type: none"> <li>• Thermocouples</li> </ul>	<ul style="list-style-type: none"> <li>• Evaluate thermal loading distribution on the bridge</li> </ul>	<ul style="list-style-type: none"> <li>• Comparison of measured thermal loading with some published loading models in codes of practice</li> <li>• Design temperature distribution deemed unsuitable</li> </ul>	Chang and Im (2000)
Anomaly detection/sensor deployment/model validation	Geumdang Bridge	South Korea	December 2004 and July 2005		<ul style="list-style-type: none"> <li>• Accelerometers (wired and wireless)</li> <li>• 14 wireless sensors in network</li> </ul>	<ul style="list-style-type: none"> <li>• Monitor bridge response to truck loading</li> </ul>	<ul style="list-style-type: none"> <li>• Mode shapes determined owing to vibration loading</li> </ul>	Lynch et al. (2006)
Anomaly detection	Tamar Suspension Bridge	United Kingdom	Reported systems installed in 2006 and 2009		<ul style="list-style-type: none"> <li>• Anemometers</li> <li>• Hydraulic level sensing system for deck vertical displacement</li> <li>• Temperature sensors for main cable, deck steel members, and ambient</li> <li>• Resistance strain gauges to measure loads in additional cables</li> </ul>	<ul style="list-style-type: none"> <li>• Provide a more complete picture of bridge behavior and characterize low-frequency-vibration modes of structure</li> </ul>	<ul style="list-style-type: none"> <li>• Data reported as insufficient for identifying the normal (baseline) behavior of the bridge</li> </ul>	Koo et al. (2013)
Anomaly detection/model validation	Forth Road Bridge	United Kingdom	February 8–10, 2005 (46-h period)		<ul style="list-style-type: none"> <li>• Robotic total station</li> <li>• GPS monitoring system</li> </ul>	<ul style="list-style-type: none"> <li>• Observe effects of a 100-t lorry passing over the bridge</li> </ul>	<ul style="list-style-type: none"> <li>• Magnitudes and frequencies of bridge deflection measured and matched to a FEM</li> </ul>	Roberts et al. (2012)
Anomaly detection/sensor deployment	Musmeci Bridge	Italy	1 year		<ul style="list-style-type: none"> <li>• BOTDA strain measurement</li> </ul>	<ul style="list-style-type: none"> <li>• Field test of distributed sensors</li> </ul>	<ul style="list-style-type: none"> <li>• Discovered anomalous readings which after visual inspection led to discovery of crack in a concrete arch</li> </ul>	Minardo et al. (2012)
Anomaly detection/sensor deployment	Millennium Bridge	United Kingdom	November 22–24, 2000		<ul style="list-style-type: none"> <li>• GPS monitoring system</li> <li>• Accelerometers</li> </ul>	<ul style="list-style-type: none"> <li>• Investigate whether the GPS can be used to effectively monitor long-term bridge deflections</li> </ul>	<ul style="list-style-type: none"> <li>• Measured deflections and frequency movement</li> </ul>	Roberts et al. (2006)



**Table 4.** (Continued.)

Classification	Bridge	Location	Reported period of monitoring or duration of deployment	Key technologies deployed in the sensor network	Stated major aims of study	Reported key outputs	Reference
Sensor deployment/ model validation	Mjosund Bridge	Norway	18 months	<ul style="list-style-type: none"> <li>• FBG strain gauges</li> <li>• ERSGs</li> </ul>	<ul style="list-style-type: none"> <li>• Verify FBG sensors by comparison with data from ERSGs</li> </ul>	<ul style="list-style-type: none"> <li>• Good performance of sensors in harsh weather conditions</li> <li>• Agreement between FBG and ERSGs and FEM reported</li> </ul>	Gebremichael et al. (2005)
Sensor deployment/ damage detection	Ferriby Road Bridge	United Kingdom		Wireless sensor network including: <ul style="list-style-type: none"> <li>• Inclinometers</li> <li>• Relative humidity</li> <li>• Temperature sensors</li> <li>• Displacement transducers</li> </ul>	<ul style="list-style-type: none"> <li>• Transverse inclination of the elastomeric bearings</li> <li>• Crack widths in the soffit of the slab (at a few discrete locations)</li> </ul>	<ul style="list-style-type: none"> <li>• Sensors rated as stable enough for long-term use but not sufficient to replace visual inspection</li> <li>• Development of crack widths (which was a concern of the bridge's owners) can be monitored</li> </ul>	Hoult et al. (2010)
Sensor deployment/ model validation	Kao Ping Hsi Bridge	Taiwan		<ul style="list-style-type: none"> <li>• Servovelocitv sensors for ambient deck vibration</li> </ul>	<ul style="list-style-type: none"> <li>• Dynamic characteristics of the cable-stayed bridge</li> </ul>	<ul style="list-style-type: none"> <li>• Mode shapes determined and a matches to a FEM shown</li> </ul>	Chen (2010)
Sensor deployment	Leziria Bridge	Portugal		<ul style="list-style-type: none"> <li>• FBG-based strain displacement gauges</li> <li>• VWSGs</li> </ul>	<ul style="list-style-type: none"> <li>• Develop a baseline record so that future changes can be detected.</li> </ul>	<ul style="list-style-type: none"> <li>• Good agreement between FBG and VWSGs</li> </ul>	Rodrigues et al. (2010)
Model validation	Safti Link Bridge	Singapore	3-day period	<ul style="list-style-type: none"> <li>• Accelerometers</li> </ul>		<ul style="list-style-type: none"> <li>• Measured mode shapes and fundamental frequency of cables compared with finite-element analysis</li> </ul>	Brownjohn et al. (1999)
Model validation	Bridge on national road No. B224	Austria	June 10–14, 2002	<ul style="list-style-type: none"> <li>• Weigh-in-motion (WIM)</li> </ul>	<ul style="list-style-type: none"> <li>• Loading distribution assessment</li> </ul>	<ul style="list-style-type: none"> <li>• Influence lines determined</li> </ul>	O'Connor and Eichinger (2007)
Model validation/ anomaly detection	Railway bridge Brussels-Schuman Station	Belgium		<ul style="list-style-type: none"> <li>• Strain gauges</li> <li>• Inclinometers</li> <li>• Extensometers</li> <li>• Acoustic emission</li> </ul>	<ul style="list-style-type: none"> <li>• Assess long-term behavior under heavy loading</li> </ul>	<ul style="list-style-type: none"> <li>• Bridge was reported as continuing to operate to an acceptable standard</li> </ul>	Staquet et al. (2007)
Model validation	Ting Kau Bridge	Hong Kong, China		<ul style="list-style-type: none"> <li>• Accelerometers</li> <li>• Strain gauges</li> <li>• Displacement transducers</li> <li>• Anemometers</li> </ul>	<ul style="list-style-type: none"> <li>• Validate a three-dimensional FEM</li> </ul>	<ul style="list-style-type: none"> <li>• FEM validated</li> <li>• Various damage scenarios studied</li> </ul>	Ni et al. (2008)



Table 4. (Continued.)

Classification	Bridge	Location	Reported period of monitoring or duration of deployment	Key technologies deployed in the sensor network	Stated major aims of study	Reported key outputs	Reference
Model validation/sensor deployment	New Carquinez Suspension Bridge	California	October 20–January 10, 2011 (full installation)	<ul style="list-style-type: none"> <li>• Temperature sensors</li> <li>• WIM</li> <li>• GPS monitoring</li> <li>• Wireless sensor network including:               <ul style="list-style-type: none"> <li>• Potentiometers</li> <li>• Accelerometers</li> <li>• Climate station including anemometers</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Study the effect of seismic motion on the structure</li> </ul>	<ul style="list-style-type: none"> <li>• Mode shapes measured and good comparison with FEM reported</li> </ul>	Kurata et al. (2013)
Model validation	I-35W St. Anthony Falls Bridge	Minneapolis, Minnesota		<ul style="list-style-type: none"> <li>• Network of more than 500 sensors including:               <ul style="list-style-type: none"> <li>• VWSGs</li> <li>• ERS gauges</li> <li>• Fiber-optic strain gauges</li> <li>• Thermistors</li> <li>• Linear potentiometers</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Validate a linear-elastic three-dimensional continuum FEM</li> </ul>	<ul style="list-style-type: none"> <li>• FEM calibrated using the monitoring data</li> </ul>	Hedegaard et al. (2013)
Model validation	Tsing Ma Bridge	Hong Kong, China	1997 onwards	<ul style="list-style-type: none"> <li>• Network of more than 350 sensors:               <ul style="list-style-type: none"> <li>• Temperature sensors</li> <li>• GPS monitoring system</li> </ul> </li> <li>• Displacement transducers</li> <li>• Level sensing stations</li> <li>• WIM</li> <li>• Anemometers</li> <li>• Accelerometers</li> </ul>	<ul style="list-style-type: none"> <li>• Monitor the effect of temperature on a long-span suspension bridge</li> </ul>	<ul style="list-style-type: none"> <li>• Temperature variations (mean, maximum, and minimum values) within design code limits</li> <li>• Longitudinal movements correlate with temperature</li> </ul>	Xu et al. (2010)
Model validation/sensor deployment	Star City Bridge	West Virginia	2003–2009	<ul style="list-style-type: none"> <li>• Strain gauges</li> <li>• More than 800 VWSGs</li> <li>• Inclinometers</li> <li>• Weather station</li> <li>• WIM</li> </ul>		<ul style="list-style-type: none"> <li>• Discovery of nonuniform temperature gradient through deck</li> </ul>	Shoukry et al. (2009)
Model validation	1:150 scale model of Tsing Ma Bridge	Hong Kong, China		<ul style="list-style-type: none"> <li>• Laser displacement meters</li> </ul>	<ul style="list-style-type: none"> <li>• Comparison of vibrational properties with a FEM</li> </ul>	<ul style="list-style-type: none"> <li>• Natural frequencies and mode shapes determined</li> <li>• Suggestion that damage detection using this benchmark data may be possible</li> </ul>	Xu et al. (2012)

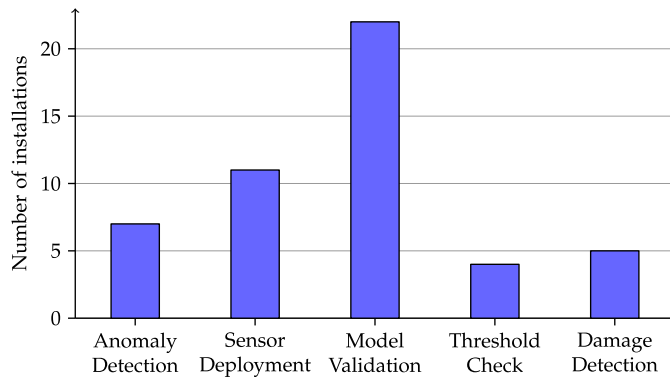
Table 4. (Continued.)

Classification	Bridge	Location	Reported period of monitoring or duration of deployment	Key technologies deployed in the sensor network	Stated major aims of study	Reported key outputs	Reference
Model validation/sensor deployment	Humber Bridge	United Kingdom	February 1998 (1 night)	<ul style="list-style-type: none"> <li>GPS monitoring system</li> </ul>	<ul style="list-style-type: none"> <li>Validation of a FEM using load testing data</li> </ul>	<ul style="list-style-type: none"> <li>Displacement data obtained</li> <li>Low-frequency vibrations characterized</li> </ul>	Brown et al. (1999)
Model validation	Forth Road Bridge	United Kingdom	February 2005 (2 days)	<ul style="list-style-type: none"> <li>GPS monitoring system</li> </ul>	<ul style="list-style-type: none"> <li>Validate a FEM using load testing data</li> </ul>	<ul style="list-style-type: none"> <li>Obtained data about movement of tower tops</li> <li>Good agreement between measurements and FEM predictions</li> </ul>	Brown et al. (2006)
Model validation	Mattawa River Bridge	Canada		<ul style="list-style-type: none"> <li>Strain gauges</li> <li>Deflection transducers</li> </ul>	<ul style="list-style-type: none"> <li>Testing bridge reliability models</li> </ul>	<ul style="list-style-type: none"> <li>Bridge reliability models updated based on sensor data</li> </ul>	Nowak and Tharmabala (1988)
Model validation	Jiangyin Yangtze River Highway Bridge	China		<ul style="list-style-type: none"> <li>Use measured traffic counts to develop equivalent traffic loading model</li> </ul>	<ul style="list-style-type: none"> <li>Determine if critical corrosion threshold is breached (based on humidity data)</li> </ul>	<ul style="list-style-type: none"> <li>Vehicle loading model obtained</li> </ul>	Ji et al. (2012)
Threshold check/sensor deployment	Humber Bridge	United Kingdom	July 2007 to present	<ul style="list-style-type: none"> <li>Wireless sensor network including: <ul style="list-style-type: none"> <li>Temperature sensors</li> <li>Relative humidity sensors</li> </ul> </li> <li>Tilt meters</li> <li>Vibration meters</li> </ul>			Hoult et al. (2008)
Threshold check	Penang Bridge (piers and piles monitored)	Malaysia	During widening works	<ul style="list-style-type: none"> <li>Accelerometers</li> </ul>	<ul style="list-style-type: none"> <li>Settlement thresholds and vibration thresholds to prevent damage to existing structures</li> </ul>	<ul style="list-style-type: none"> <li>Settlements were recorded (from precise leveling) but no action was taken, so some damage occurred that necessitated some remedial work</li> </ul>	Corbett et al. (2010)
Model validation/threshold check	Pedro e Ines Footbridge	Portugal		<ul style="list-style-type: none"> <li>Accelerometers</li> </ul>	<ul style="list-style-type: none"> <li>Validate predictions of vibrational response</li> <li>Check that vibration amplitudes are within acceptable limits for comfort</li> </ul>	<ul style="list-style-type: none"> <li>FEM validated</li> </ul>	Caetano et al. (2010)
Damage detection/model validation	I-40 Bridge	New Mexico		<ul style="list-style-type: none"> <li>Strain transducers</li> </ul>	<ul style="list-style-type: none"> <li>Load rating analysis</li> <li>Nondestructive evaluation of condition</li> </ul>	<ul style="list-style-type: none"> <li>Finite-element analysis and loading data allowed a more realistic live load model to be developed</li> </ul>	Jáuregui and Barr (2004)

**Table 4.** (Continued.)

Classification	Bridge	Location	Reported period of monitoring or duration of deployment	Key technologies deployed in the sensor network	Stated major aims of study	Reported key outputs	Reference
Damage detection/model validation	6th Avenue Viaduct	Colorado	Late January to early April 2000	<ul style="list-style-type: none"> <li>• Strain gauges</li> </ul>	<ul style="list-style-type: none"> <li>• Evaluate short-term safety of the structure</li> <li>• Evaluate long-term viability of the structure</li> </ul>	<ul style="list-style-type: none"> <li>• Short- and long-term safety was assessed</li> <li>• Overstress in three columns detected</li> </ul>	Allen and Rens (2004)
Damage detection/model validation	Millard E. Tydings Memorial Bridge	Maryland	Field test, July 27, 2006	<ul style="list-style-type: none"> <li>• Strain gauges</li> </ul>	<ul style="list-style-type: none"> <li>• Investigate reliability of sliding expansion joint design after incidents of premature failures</li> </ul>	<ul style="list-style-type: none"> <li>• Faulty sliding plate system determined to be not adequate and cause of system (sliding expansion joint) failure</li> </ul>	Fu and Zhang (2011)
Damage detection/threshold check	Hammersmith Flyover	London	2009–2012	<ul style="list-style-type: none"> <li>• Acoustic emission</li> <li>• Displacement transducers</li> <li>• Strain gauges</li> <li>• Inclinometers</li> <li>• Temperature gauges</li> </ul>	<ul style="list-style-type: none"> <li>• Determine condition of prestressing tendons and roller bearings</li> </ul>	<ul style="list-style-type: none"> <li>• Identified deterioration to a number of bearings, and locations at which corrosion of prestressing tendons was occurring</li> </ul>	Webb et al. (2014)

Note: When a study is classified into more than one category, the first one listed is considered to be the primary focus of the study, in the opinion of the present authors.



**Fig. 1.** Classification of the existing monitoring installations presented in Table 4 (note that some installations fit into more than one category)

although some studies fit into more than one category, no examples were found that could not be classified. Table 5 summarizes the value and complexity of each category. In addition to requiring a clearly defined objective for any monitoring activities, and using one or more of the data interpretation categories to assist with the selection of suitable sensors, there are a number of other challenges involved with the successful implementation of SHM systems. These are discussed in the next section.

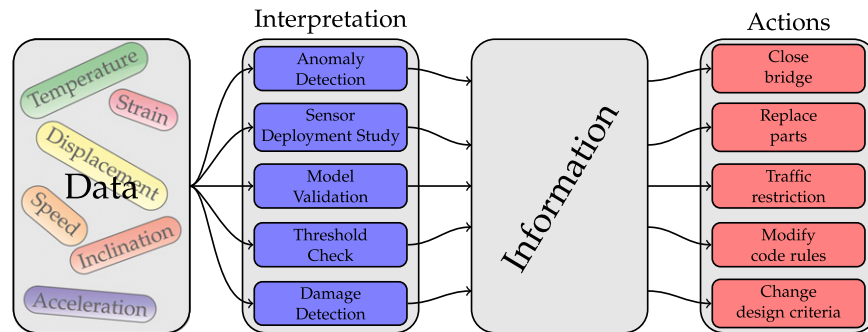
### Implementing SHM

For a monitoring system to be considered successful, it must be able to produce value to its stakeholders. Currently, guidance for designers of SHM systems is scarce, leading to many examples of poorly considered systems providing little or no real benefit. A number of important considerations have been discussed in this review. First, all monitoring systems should have a clearly defined objective; this is often missing in the examples considered. Once an objective has been established, the information required to realize it can be determined. The SHM categorization system presented here describes the different ways in which raw sensor data can be transformed into information. The information derived (which varies depending on the SHM category) can then be used by the system’s operators to aid in decision making and influence future design decisions or the actions to be taken, either during construction or during the operation of the structure. This process is represented in Fig. 2. Intervention decisions are also subject to cost and resource considerations. However, availability of relevant and reliable data will assist in making the case for cost and resource expenditure, e.g., for maintenance activities.

It should be noted that the ability to categorize a proposed SHM system does not guarantee a successful outcome; it is only one part of the process depicted in Fig. 2. It is also vital to consider how any information obtained from the monitoring activities will be used to inform actions and hence make progress toward fulfilling the original objective of the SHM system. Taking measurements from various locations on a structure and then transforming these data into a reliable representation of performance is a difficult task. It is this task that makes the more complex SHM categories very challenging indeed. Simply recognizing the category of SHM that is needed to fulfill the needs of the asset owner does not, in and of itself, mean that value can be successfully delivered. Understanding the requirements of each category is the starting point,

**Table 5.** Summary of the New Categorization System

Category	Description	Complexity	Value
1	Anomaly detection	Low complexity	Of limited value to asset owner but may initiate further investigations on the monitored asset (no immediate value)
2	Sensor deployment studies	Low complexity	Valuable for evaluating capabilities of new sensors, so may in the future lead to improvements in technical capability (no immediate value to asset owner)
3	Model validation	Moderate complexity	Useful for bridge designers but of limited value to the asset owner, as the bridge has already been constructed; may lead to improvements in future bridge designs or provide some confidence in current bridge performance (little immediate value)
4	Threshold check	Moderate complexity	Very useful for asset managers as there is a direct link to a performance criterion; moderately difficult, as establishing the performance criterion can be very challenging (immediate value)
5	Damage detection	High complexity	Extremely useful, but also extremely difficult to achieve (immediate value)

**Fig. 2.** SHM implementation process

and then the technical and implementation challenges that need to be solved can be realistically assessed.

## Summary

- Five categories of SHM deployments have been defined, namely (1) anomaly detection, (2) sensor deployment studies, (3) model validation, (4) threshold check, and (5) damage detection. Each category produces a different type of information and has different uses and value. This categorization scheme is intended to aid in describing the SHM literature, as well as clearly understanding how monitoring data can be used. It can also be considered as a toolkit of available interpretation techniques to aid those planning SHM systems.
- It is observed that SHM is rapidly becoming a standard feature of major, large-scale, civil engineering projects, attracting the attention of many researchers and practitioners. However, there are currently few examples of SHM systems that have clearly demonstrated value to their operators, and especially to the owners of the bridges they are installed on. Potential objectives for monitoring systems were discussed. This is an important, and often neglected, consideration during the design of any monitoring system, without which very little value will be obtained.
- Conventional sensors, e.g., strain gauges, accelerometers, and acoustic emission devices, have been reviewed alongside maturing and emerging technologies, e.g., fiber-optic cables and computer vision techniques. Published studies describing the calibration, accuracy, sensitivity, and reliability of sensing technologies are remarkably hard to find (with some notable exceptions). Further research should be undertaken to demonstrate the accuracy of sensors for use on bridge structures. There will always be uncertainty in data obtained from sensors,

and also in models used to predict structural behavior. This uncertainty can degrade confidence in information from monitoring systems. Where uncertainties cannot be eradicated by improvements in measurement science or analysis techniques, they need to be quantified to give asset owners the confidence to take decisions on the basis of collected data. Improvements in sensor technologies, including those that have been reviewed (BOTDR, imaging and computer vision, MEMS, and bioinspired sensor technologies), may make some higher-level categories in the categorization system more achievable, but they will not invalidate the categorization system itself.

- Deployment strategies (wired versus wireless) for sensors have been reviewed, and particular attention has been paid to the emerging use of WSNs. Although these developments are promising, there are still limitations with reliability, robustness, and power supplies which must be addressed in future research and commercialization efforts.
- Many SHM systems have been installed and may be criticized for not having clearly reported aims. It is a duty of authors to report back on the operation, use, and success (or failure) of installed systems in future years so that the value proposition for SHM may be better established.

## Acknowledgments

This work was partly funded by EPSRC Grant No. EP/K000314/1: Innovation Knowledge Centre for Smart Infrastructure and Construction. Thanks are due to Mr. P. R. A. Fidler for his helpful proof-reading of the paper and for his valuable comments and suggestions. The authors also thank the reviewers for their insightful and helpful comments on the paper.



## References

- Abudayyeh, O. Y., Barbera, J., Abdel-Qader, I., Cai, H., and Almaita, E. (2010). "Towards sensor-based health monitoring systems for bridge decks: A full-depth precast deck panels case study." *Adv. Civ. Eng.*, 2010(2010), 579631.
- Agrawal, A. K., et al. (2009). "Remote corrosion monitoring systems for highway bridges." *Pract. Period. Struct. Des. Constr.*, 10.1061/(ASCE)1084-0680(2009)14:4(152), 152–158.
- Allen, B. J., and Rens, K. L. (2004). "Condition assessment of the eastbound 6th Avenue Viaduct using strain gauges." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(2004)18:4(205), 205–212.
- Anderson, J. E., and Vesterinen, A. (2006). *Structural health monitoring systems*, COWI, Lyngby, Denmark.
- Bao, X., and Chen, L. (2011). "Recent progress in Brillouin scattering based fiber sensors." *Sensors*, 11(4), 4152–4187.
- Bennett, P. J., et al. (2010a). "Wireless sensor networks for underground railway applications: Case studies in Prague and London." *Smart Struct. Syst.*, 6(5–6), 619–639.
- Bennett, P. J., Kobayashi, Y., Soga, K., and Wright, P. (2010b). "Wireless sensor network for monitoring transport tunnels." *Proc. Inst. Civ. Eng. Geotech. Eng.*, 163(3), 147–156.
- Bodeux, J. B., and Golinval, J. C. (2001). "Application of ARMAV models to the identification and damage detection of mechanical and civil engineering structures." *Smart Mater. Struct.*, 10(3), 479–489.
- British Tunnelling Society. (2011). *Monitoring underground construction: A best practice guide*, ICE Publishing, London.
- Brown, C. J., Karuma, R., Ashkenazi, V., Roberts, G. W., and Evans, R. A. (1999). "Monitoring of structures using the global positioning system." *Proc. Inst. Civ. Eng. Struct. Build.*, 134(1), 97–105.
- Brown, C. J., Roberts, G. W., and Meng, X. (2006). "Developments in the use of GPS for bridge monitoring." *Proc. Inst. Civ. Eng. Bridge Eng.*, 159(3), 117–119.
- Brownjohn, J. M. W., De Stefano, A., Xu, Y.-L., Wenzel, H., and Aktan, A. E. (2011). "Vibration-based monitoring of civil infrastructure: Challenges and successes." *J. Civ. Struct. Health Monitor.*, 1(3-4), 79–95.
- Brownjohn, J. M. W., Lee, J., and Cheong, B. (1999). "Dynamic performance of a curved cable-stayed bridge." *Eng. Struct.*, 21(11), 1015–1027.
- Bungey, J. H., and Millard, S. G. (1993). "Radar inspection of structures." *Proc. Inst. Civ. Eng. Struct. Build.*, 99(2), 173–186.
- Caetano, E., Cunha, Á., Magalhães, F., and Moutinho, C. (2010). "Studies for controlling human-induced vibration of the Pedro e Inês footbridge, Portugal. Part 1: Assessment of dynamic behaviour." *Eng. Struct.*, 32(4), 1069–1081.
- Camfield, F. E., and Holmes, C. M. (1995). "Monitoring completed coastal projects." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(1995)9:3(161), 161–171.
- Casas, J. R., and Cruz, P. J. S. (2003). "Fiber optic sensors for bridge monitoring." *J. Bridge Eng.*, 10.1061/(ASCE)1084-0702(2003)8:6(362), 362–373.
- Catbas, F. N., Kijewski-Correa, T., and Aktan, A. E., eds. (2012). *Structural identification of constructed facilities: Approaches, methods, and technologies for effective practice of St-Id*, ASCE, Reston, VA.
- Challa, V. R., Prasad, M. G., and Fisher, F. T. (2011). "Towards an autonomous self-tuning vibration energy harvesting device for wireless sensor network applications." *Smart Mater. Struct.*, 20(2), 025004.
- Chandola, V., Banerjee, A., and Kumar, V. (2009). "Anomaly detection: A survey." *Assoc. Comput. Mach. Comput. Surv.*, 41(3), 15.
- Chang, S. P., and Im, C. K. (2000). "Thermal behaviour of composite box-girder bridges." *Proc. Inst. Civ. Eng. Struct. Build.*, 140(2), 117–126.
- Chen, B., Maher, M. H., and Nawy, E. G. (1994). "Fiber-optic Bragg grating sensor for nondestructive evaluation of composite beams." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1994)120:12(3456), 3456–3470.
- Chen, C.-H. (2010). "Structural monitoring and field test for Kao Ping Hsi cable-stayed bridge in Taiwan." *Proc., 2nd Int. Conf. on Computational Mechanics and 12th Int. Conf. on the Enhancement and Promotion of Computational Methods in Engineering and Science*, Vol. 1233, American Institute of Physics (AIP), Melville, NY, 1231–1236.
- Cheung, L. L. K., Soga, K., Bennett, P. J., Kobayashi, Y., Amatya, B., and Wright, P. (2010). "Optical fibre strain measurement for tunnel lining monitoring." *Proc. Inst. Civ. Eng. Geotech. Eng.*, 163(3), 119–130.
- Corbett, P. W., Buckley, R. J., and Wee, E. L. (2010). "Penang Bridge widening: Design and construction challenges." *Proc. ICE Bridge Eng.*, 163(3), 125–135.
- Cross, E. J., Worden, K., and Chen, Q. (2011). "Cointegration: A novel approach for the removal of environmental trends in structural health monitoring data." *Proc. R. Soc. London, Ser. A*, 467(2133), 2712–2732.
- DelloRusso, S., Juneja, G., Gabby, B., and Dusenberry, D. (2008). "Monitoring and repair of the Milwaukee City Hall masonry tower." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(2008)22:4(197), 197–206.
- Del Valle, M. (2011). "Bioinspired sensor systems." *Sensors (Basel)*, 11(11), 10180–10186.
- Dunnicliff, J. (1988). *Geotechnical instrumentation for monitoring field performance*, Wiley, New York.
- Farrar, C. R., and Jauregui, D. A. (1998a). "Comparative study of damage identification algorithms applied to a bridge: I. Experiment." *Smart Mater. Struct.*, 7(5), 704–719.
- Farrar, C. R., and Jauregui, D. A. (1998b). "Comparative study of damage identification algorithms applied to a bridge: II. Numerical study." *Smart Mater. Struct.*, 7(5), 720–731.
- Farrar, C. R., and Lieven, N. A. (2007). "Damage prognosis: The future of structural health monitoring." *Philos. Trans. Royal Soc. London, Ser. A*, 365(1851), 623–632.
- Farrar, C. R., and Worden, K. (2007). "An introduction to structural health monitoring." *Philos. Trans. Royal Soc. London, Ser. A*, 365(1851), 303–315.
- Ferri, M., et al. (2011). "Fabrication and testing of a high resolution extensometer based on resonant MEMS strain sensors." *Proc., 16th Int. Solid-State Sensors, Actuators and Microsystems Conf.*, IEEE, New York, 1056–1059.
- Feynman, R. (1998). *The meaning of it all*, Penguin Press, London.
- Fidler, P. R. A., Vardanega, P. J., Long, P. J. G., Webb, G. T., Stehle, J. S., and Middleton, C. R. (2013). "Construction monitoring constraints and challenges: A feasibility study." *Proc., 6th Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure (CD-ROM)*, Y. L. Xu et al., eds., Dept. of Civil and Environmental Engineering, Hong Kong Polytechnic Univ., Hong Kong.
- Frangopol, D. M., Strauss, A., and Kim, S. (2008). "Bridge reliability assessment based on monitoring." *J. Bridge Eng.*, 10.1061/(ASCE)1084-0702(2008)13:3(258), 258–270.
- Fraser, M., Elgamal, A., He, X., and Conte, J. P. (2010). "Sensor network for structural health monitoring of a highway bridge." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000005, 11–24.
- Fu, C. C., and Zhang, N. (2011). "Investigation of bridge expansion joint failure using field strain measurement." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)CF.1943-5509.0000171, 309–316.
- Fuchs, P. A., Washer, G. A., Chase, S. B., and Moore, M. (2004). "Laser-based instrumentation for bridge load testing." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(2004)18:4(213), 213–219.
- Fuhr, P. L., Huston, D. R., Ambrose, T. P., and Snyder, D. M. (1993). "Stress monitoring of concrete using embedded optical fiber sensors." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1993)119:7(2263), 2263–2269.
- Gassman, S. L., and Finno, R. J. (1999). "Impulse response evaluation of foundations using multiple geophones." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(1999)13:2(82), 82–89.
- Ge, Y. (2013). "Temperature effects on optical fibre strain sensors." M.Phil. thesis, Univ. of Cambridge, Cambridge, U.K.
- Ge, Y., Elshafie, M. Z. E. B., Dirar, S., and Middleton, C. R. (2014). "The response of embedded strain sensors in concrete beams subjected to thermal loading." *Constr. Build. Mater.*, 70, 279–290.
- Gebremichael, Y. M., et al. (2005). "A field deployable, multiplexed Bragg grating sensor system used in an extensive highway bridge monitoring evaluation tests." *IEEE Sens. J.*, 5(3), 510–519.
- German, S., Brilakis, I., and DesRoches, R. (2012). "Rapid entropy-based detection and properties measurement of concrete spalling with machine vision for post-earthquake safety assessments." *Adv. Eng. Inform.*, 26(4), 846–858.

- Goulet, J.-A., Coutu, S., and Smith, I. F. C. (2013). "Model falsification diagnosis and sensor placement for leak detection in pressurized pipe networks." *Adv. Eng. Inform.*, 27(2), 261–269.
- Goulet, J. A., and Smith, I. F. C. (2013). "Predicting the usefulness of monitoring for identifying the behavior of structures." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0000577, 1716–1727.
- Goulet, J.-A., Texier, M., Michel, C., Smith, I. F. C., and Chouinard, L. (2014). "Quantifying the effects of modeling simplifications for structural identification of bridges." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000510, 59–71.
- Hedegaard, B. D., French, C. E. W., Shield, C. K., Stolarski, H. K., and Jilk, B. J. (2013). "Instrumentation and modeling of I-35W St. Anthony Falls Bridge." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000384, 476–485.
- Hemez, F. M., and Farrar, C. R. (2014). "A brief history of 30 years of model updating in structural dynamics." *Proc., Special Topics in Structural Dynamics*, G. Foss and C. Niezrecki, eds., Springer, New York, 53–71.
- Hou, Z., Noori, M., and St. Amand, R. (2000). "Wavelet-based approach for structural damage detection." *J. Eng. Mech.*, 10.1061/(ASCE)0733-9399(2000)126:7(677), 677–683.
- Hoult, N., et al. (2009a). "Wireless sensor networks: Creating 'smart infrastructure'." *Proc. Inst. Civ. Eng. Civ. Eng.*, 162(3), 136–143.
- Hoult, N. A., Bennett, P. J., Fidler, P. R. A., Middleton, C. R., and Soga, K. (2009b). "Smart infrastructure: Pervasive WSNs for a more sustainable Europe." *Proc., 4th Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure*, International Society for Structural Health Monitoring of Intelligent Infrastructure, Winnipeg, Canada.
- Hoult, N. A., Fidler, P. R. A., Hill, P. G., and Middleton, C. R. (2010). "Long-term wireless structural health monitoring of the Ferriby Road Bridge." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000049, 153–159.
- Hoult, N. A., Fidler, P. R. A., Wassell, I. J., Hill, P. G., and Middleton, C. R. (2008). "Wireless structural health monitoring at the Humber Bridge UK." *Proc. Inst. Civ. Eng. Bridge Eng.*, 161(4), 189–195.
- Huntley, S. A., and Valsangkar, A. J. (2014). "Behaviour of H-piles supporting an integral abutment bridge." *Can. Geotech. J.*, 51(7), 713–734.
- Ieropoulos, I., Melhuish, C., Greenman, J., and Horsfield, I. (2005). "EcoBot-II: An artificial agent with a natural metabolism." *Int. J. Adv. Robot. Syst.*, 2(4), 295–300.
- Jáuregui, D. V., and Barr, P. J. (2004). "Nondestructive evaluation of the I-40 Bridge over the Rio Grande River." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(2004)18:4(195), 195–204.
- Ji, B., et al. (2012). "Research on stress spectrum of steel decks in suspension bridge considering measured traffic flow." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)CF.1943-5509.0000249, 65–75.
- Kabir, S. (2010). "Imaging-based detection of AAR induced map-crack damage in concrete structure." *NDT Int.*, 43(6), 461–469.
- Khorramshahi, V., Behrad, A., and Kanhere, N. K. (2008). "Over-height vehicle detection in low headroom roads using digital video processing." *Int. J. Comput. Info. Syst. Sci.*, 2(2), 82–86.
- Klar, A., et al. (2006). "Distributed strain measurement for pile foundations." *Proc. Inst. Civ. Eng. Geotech. Eng.*, 159(3), 135–144.
- Ko, J. M., and Ni, Y. Q. (2005). "Technology developments in structural health monitoring of large-scale bridges." *Eng. Struct.*, 27(12), 1715–1725.
- Koch, C., Jog, G. M., and Brilakis, I. (2013). "Automated pothole distress assessment using asphalt pavement video data." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000232, 370–378.
- Koo, K. Y., Brownjohn, J. M. W., List, D. I., and Cole, R. (2013). "Structural health monitoring of the Tamar suspension bridge." *Struct. Contr. Health Monit.*, 20(4), 609–625.
- Kurata, M., et al. (2013). "Internet-enabled wireless structural monitoring systems: Development and permanent deployment at the New Carquinez Suspension Bridge." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0000609, 1688–1702.
- Lea, F. C., and Middleton, C. R. (2002). "Reliability of visual inspection of highway bridges." *Technical Rep. CUED/D-STRUCT/TR.201*, Dept. of Engineering, Univ. of Cambridge, Cambridge, U.K.
- Liu, M., Frangopol, D. M., and Kim, S. (2009). "Bridge system performance assessment from structural health monitoring: A case study." *J. Struct. Eng.*, 10.1061/(ASCE)ST.1943-541X.0000014, 733–742.
- Lynch, J. P., and Loh, K. J. (2006). "A summary review of wireless sensors and sensor networks for structural health monitoring." *Shock Vib.*, 38(2), 91–128.
- Lynch, J. P., Wang, Y., Loh, K. J., Yi, J.-H., and Yun, C.-B. (2006). "Performance monitoring of the Geumdang Bridge using a dense network of the high-resolution wireless sensors." *Smart Mater. Struct.*, 15(6), 1561–1575.
- Mao, Z., and Todd, M. (2013). "Statistical modelling of frequency response function estimation for uncertainty quantification." *Mech. Syst. Signal Process.*, 38(2), 333–345.
- Mascarenas, D., Flynn, E., Farrar, C., Park, G., and Todd, M. (2009). "A mobile host approach for wireless powering and interrogation of structural health monitoring sensor networks." *IEEE Sens. J.*, 9(12), 1719–1726.
- Maser, K. R. (1988). "Sensors for infrastructure assessment." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(1988)2:4(226), 226–241.
- Masri, S. F., Nakamura, M., Chassiakos, A. G., and Caughey, T. K. (1996). "Neural network approach to detection of changes in structural parameters." *J. Eng. Mech.*, 10.1061/(ASCE)0733-9399(1996)122:4(350), 350–360.
- Matta, F., Bastianini, F., Galati, N., Casadei, P., and Nanni, A. (2008). "Distributed strain measurement in steel bridge with fiber optic sensors: Validation through diagnostic load test." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(2008)22:4(264), 264–273.
- McCuen, R. H., Aggour, M. S., and Ayyub, B. M. (1988). "Spacing for accuracy in ultrasonic testing of bridge timber piles." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1988)114:12(2652), 2652–2668.
- Melhuish, C., Ieropoulos, I., Greenman, J., and Horsfield, I. (2006). "Energetically autonomous robots: Food for thought." *Auton. Robots*, 21(3), 187–198.
- Minardo, A., Persichetti, G., Testa, G., Zeni, L., and Bernini, R. (2012). "Long term structural health monitoring by Brillouin fibre-optic sensing: A real case." *J. Geophys. Eng.*, 9(4), S64–S69.
- Mohamad, H. (2008). "Distributed optical fibre strain sensing of geotechnical structures." Ph.D. thesis, Univ. of Cambridge, Cambridge, U.K.
- Mohamad, H., Bennett, P. J., Soga, K., Mair, R. J., and Bowers, K. (2010). "Behaviour of an old masonry tunnel due to tunnelling-induced ground settlement." *Géotechnique*, 60(12), 927–938.
- Moore, M., Phares, B., Graybeal, B., Rolander, D., and Washer, G. (2001). "Reliability of visual inspection for highway bridges, Vol. 1." *Rep. No. FHWA-RD-01-020*, U.S. DOT, Federal Highway Administration, Washington, DC. (<http://www.fhwa.dot.gov/publications/research/nde/01020.cfm>) (Aug. 24, 2014).
- Ni, Y. Q., Zhou, H. F., Chan, K. C., and Ko, J. M. (2008). "Modal flexibility analysis of cable-stayed Ting Kau Bridge for damage identification." *Comput. Aided Civ. Infrastruct. Eng.*, 23(3), 223–236.
- Nowak, A. S., and Tharmabala, T. (1988). "Bridge reliability evaluation using load tests." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(1988)114:10(2268), 2268–2279.
- O'Connor, A., and Eichinger, E. M. (2007). "Site-specific traffic load modelling for bridge assessment." *Proc. Inst. Civ. Eng. Bridge Eng.*, 160(4), 185–194.
- Ouellette, S. A., and Todd, M. D. (2014). "Cement seawater battery energy harvester for marine infrastructure monitoring." *IEEE Sens. J.*, 14(3), 865–872.
- Park, G., Rosing, T., Todd, M. D., Farrar, C. R., and Hodgkiss, W. (2008). "Energy harvesting for structural health monitoring sensor networks." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2008)14:1(64), 64–79.
- Park, M.-W., and Brilakis, I. (2012). "Construction worker detection in video frames for initializing vision trackers." *J. Autom. Constr.*, 28(Dec), 15–25.
- Park, M.-W., Koch, C., and Brilakis, I. (2012). "Three-dimensional tracking of construction resources using an on-site camera system." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000168, 541–549.
- Rens, K. L., Wipf, T. J., and Klaiber, F. W. (1997). "Review of non-destructive evaluation techniques of civil infrastructure." *J. Perform. Constr. Facil.*, 10.1061/(ASCE)0887-3828(1997)11:4(152), 152–160.
- Reynolds, P., Pavic, A., and Ibrahim, Z. (2004). "A remote monitoring system for stadia dynamics." *Proc. Inst. Civ. Eng. Struct. Build.*, 157(6), 385–393.

- Ritdumrongkul, S., and Fujino, Y. (2006). "Identification of the location and level of damage in multiple-bolted-joint structures by PZT actuator-sensors." *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2006)132:2(304), 304–311.
- Roberts, G. W., Brown, C. J., Meng, X., Ogunidipe, O., Atkins, C., and Colford, B. (2012). "Deflection and frequency monitoring of the Forth Road Bridge, Scotland, by GPS." *Proc. Inst. Civ. Eng. Bridge Eng.*, 165(2), 105–123.
- Roberts, G. W., Meng, X., Brown, C. J., and Dallard, P. (2006). "GPS measurements on the London Millennium Bridge." *Proc. Inst. Civ. Eng. Bridge Eng.*, 159(4), 153–161.
- Rodrigues, C., Félix, C., Lage, A., and Figueiras, J. (2010). "Development of a long-term monitoring system based on FBG sensors applied to concrete bridges." *Eng. Struct.*, 32(8), 1993–2002.
- Samaras, V. A., Fasl, J., Reichenbach, M., Helwig, T., Wood, S., and Frank, K. (2012). "Long-term gage reliability for structural health monitoring of steel bridges." *Proc., SPIE 8347: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security*, A. L. Gyekenyesi, ed., International Society for Optical Engineering, Bellingham, WA.
- Sánchez-Silva, M., and Rosowsky, D. V. (2008). "Risk, reliability and sustainability in the developing world." *Proc. Inst. Civ. Eng. Struct. Build.*, 161(4), 189–197.
- Sandridge, M. J. (2012). "Truck height determination using digital video." M.S. thesis, Georgia Institute of Technology, Atlanta.
- Sazonov, E., Li, H., Curry, D., and Pillay, P. (2009). "Self-powered sensors for monitoring of highway bridges." *IEEE Sens. J.*, 9(11), 1422–1429.
- Schwamb, T. (2010). "Optical strain sensing for piled foundations at Ninewell's bridge." M.Res. thesis, Univ. College London, Univ. of Cambridge, Cambridge, U.K.
- Schwamb, T., et al. (2014). "Fibre optic monitoring of a deep circular excavation." *Proc. Inst. Civ. Eng. Geotech. Eng.*, 167(2), 144–154.
- Shoukry, S. N., Riad, M. Y., and William, G. W. (2009). "Longterm sensor-based monitoring of an LRFD designed steel girder bridge." *Eng. Struct.*, 31(12), 2954–2965.
- Stajano, F., Hoult, N., Wassell, I., Bennett, P., Middleton, C., and Soga, K. (2010). "Smart bridges, smart tunnels: Transforming wireless sensor networks from research prototypes into robust engineering infrastructure." *Ad Hoc Netw.*, 8(8), 872–888.
- Staquet, S., Kalogiannakis, G., Detandt, H., Van Hemelrijck, D., and Espion, B. (2007). "Field testing of a 30-year-old composite Preflex railway bridge." *Proc. Inst. Civ. Eng. Bridge Eng.*, 160(2), 89–98.
- Tata, U., Deshmukh, S., Chiao, J. C., Carter, R., and Huang, H. (2009). "Bio-inspired sensor skins for structural health monitoring." *Smart Mater. Struct.*, 18(10), 104026.
- Vaghefi, K., et al. (2012). "Evaluation of commercially available remote sensors for highway bridge condition assessment." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000303, 886–895.
- Washer, G., Fenwick, R., and Bolleni, N. (2010). "Effects of solar loading on infrared imaging of subsurface features in concrete." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000117, 384–390.
- Webb, G. (2014). "Structural health monitoring of bridges." Ph.D. thesis, Univ. of Cambridge, Cambridge, U.K.
- Webb, G., and Middleton, C. (2013). "Structural health monitoring of bridges." *Proc., SMAR 2013 Istanbul: 2nd Conf. on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*, Ilki, A., Motavalli, M., Goksu, C. and Havranek, B. eds., EMPA, Dübendorf, Switzerland.
- Webb, G. T., Vardanega, P. J., Fidler, P. R. A., and Middleton, C. R. (2014). "Analysis of structural health monitoring data from Hammersmith flyover." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000587, 05014003.
- White, D. J., Take, W. A., and Bolton, M. D. (2003). "Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry." *Géotechnique*, 53(7), 619–631.
- Wijesinghe, B. H. M. P., Zacharie, S. A., Mish, K. D., and Baldwin, J. D. (2013). "Design and development of in situ fatigue sensors for structural health monitoring of highway bridges." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000361, 297–307.
- Wojciechowski, K., Boser, B., and Pisano, A. (2005). "A MEMS resonant strain sensor with 33 nano-strain resolution in a 10kHz bandwidth." *Proc., IEEE Sensors 2005*, IEEE, New York, 947–950.
- Wong, K.-Y. (2004). "Instrumentation and health monitoring of cable-supported bridges." *Struct. Contr. Health Monit.*, 11(2), 91–124.
- Worden, K., Manson, G., and Fieller, N. R. J. (2000). "Damage detection using outlier analysis." *J. Sound Vib.*, 229(3), 647–667.
- Xia, Y., Hao, H., Zanardo, G., and Deeks, A. (2006). "Long term vibration monitoring of an RC slab: Temperature and humidity effect." *Eng. Struct.*, 28(3), 441–452.
- Xu, Y. L., et al. (2012). "Testbed for structural health monitoring of long-span suspension bridges." *J. Bridge Eng.*, 10.1061/(ASCE)BE.1943-5592.0000349, 896–906.
- Xu, Y. L., Chen, B., Ng, C. L., Wong, K. Y., and Chan, W. Y. (2010). "Monitoring temperature effect on a long suspension bridge." *Struct. Contr. Health Monit.*, 17(6), 632–653.
- Yanev, B. (2007). *Bridge management*, Wiley, New York.
- Young, J. S., and Lynch, M. J. (2010). "Inspection and maintenance of Severn Bridge suspension cables." *Proc. Inst. Civ. Eng. Bridge Eng.*, 163(4), 173–180.
- Zapico, J. L., González, M. P., and Worden, K. (2003). "Damage assessment using neural networks." *Mech. Syst. Signal Process.*, 17(1), 119–125.
- Zhu, Z., and Brilakis, I. (2010). "Concrete column recognition in images and videos." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000053, 478–487.