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Journal:	*IABSE Conference Cairo 2012*
Manuscript ID:	Cairo-0118-2012.R1
Theme:	Sustainable Development and Structural Engineering
Date Submitted by the Author:	30-Nov-2011
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Type of Structure:	Bridges
Material and Equipment:	Steel
Other Aspects:	Instrumentation / Monitoring, Facility Management, Quality, Safety, Reliability

SHM-informed Management of Long-span Bridges: Motivation, Approach and Challenges

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Summary

Structural Health Monitoring Systems (SHMS) are increasingly present in most modern long-span bridges. Those systems can be used to better assess the performance of structures by reducing the uncertainties associated with deterioration modelling. This can potentially lead to a reduction of the operational costs. Despite their promise and potential, a gap still remains between the outcomes of those systems and practical bridge management decisions. As a result, huge amounts of data can be continuously collected which are not readily useable, thus being of reduced interest in practical terms. Methodologies which integrate SHMS within Bridge Management Systems (BMS), need to be developed to address asset management issues traditionally informed by visual inspections and scarce Non Destructive Tests (NDT). This integration should overcome the shortcomings of current approaches and exploit the advantages offered by modern sensor technologies.

The present paper reviews the different uses of SHMS on long-span bridges. The motivation of using SHMS to inform and improve bridge management decisions is presented. The interest of a local monitoring approach targeting selected structural components is highlighted. The need of a combined approach between traditional inspection techniques, NDT and monitoring is justified in terms of spatial and temporal coverage. The relevance of probabilistic approaches to assess and update structural performance indicators is outlined. The case of the Great Belt Bridge (Denmark) is described to illustrate the use of SHMS on long-span bridges, together with an overview of ongoing research.

Keywords: structural health monitoring, long-span bridges, bridge management systems, structural reliability, inspection systems, Great Belt Bridge.

1. Introduction

In the last decades, the use of sensors in the field of civil engineering has increased significantly. Thus, the possibility of monitoring the response, load history and environmental conditions of a structure by means of a particular system, a Structural Health Monitoring System (SHMS), has received the focus of both the scientific and the professional engineering communities. In effect, the use of SHMS opens the door to a better understanding of the behaviour of structures, leading to a more accurate assessment of structural performance, thus making Structural Health Monitoring (SHM) a promising and exciting field of research. This can lead to a reduction of operation and maintenance costs of civil infrastructure, while ensuring a minimum level of performance. That is why, in a context of financial constraints, SHMS are increasingly becoming an attractive tool for bridge managers and national authorities.

Notwithstanding the potential benefits outlined above, a generalized and successful use of SHMS on long-span bridges has not yet been fully reached. Several factors can be outlined to explain this fact. From a general perspective, some authors [1] have stated, as a first cause, the different interests of the stakeholders (bridge designers, owners, researchers, etc.) in relation to SHM objectives. The multi-disciplinary approach combining knowledge in structures, electronics and computing required for designing successful SHMS has also hindered a wider deployment of such technologies. Apart from that, the complexity in integrating SHM within Bridge Management Systems (BMS) has also played its role. BMS traditionally rely on periodic visual examinations and occasional Non Destructive Tests (NDT), the outcomes of which differ significantly from the ones provided by modern SHMS in terms of quality and spatial and temporal coverage. Last but not least, the reliability and durability of the sensors themselves have prevented a faster deployment of SHMS.

Nevertheless, technological improvements and the experience gained through a number of applications have made it possible to collect real time data in modern SHMS, with high levels of reliability [2]. As a result, huge amounts of data can be collected nowadays, passing from a situation of scarce, and in many cases subjective, data to one where data is continuous and quantifiable. Paradoxically as it may seem, this can lead to information being generated that is not readily useable for practical purposes.

All in all, it can be seen there is a gap in knowledge and tools in utilising monitoring outcomes for practical bridge management decisions. Consequently, there is a need to develop methodologies to integrate effectively SHM data within traditional BMS, thus improving asset management strategies according to updated and more refined performance indicators for structural components and systems[3].

The present paper reviews the use of SHMS on long-span bridges. The motivation in using SHMS to inform and improve bridge management decisions is presented. A comparison between global and local monitoring approaches is undertaken. The potential of local monitoring targeting those structural components prone to special inspection and maintenance actions is highlighted. The treatment of uncertainties is discussed, together with the necessary interaction between monitoring outcomes and traditional inspection techniques. To illustrate the use of permanent SHMS on long-span bridges, the case of the Great Belt Bridge, in Denmark, is described. Finally, an overview of the ongoing research work is given.

2. SHMS on long-span bridges

Long-span bridges turn out to be one of the most monitored civil infrastructures. Their inherent technical complexity has made those structures attractive and convincing candidates for instrumentation. In addition, the high costs associated with their design, construction and operation make it easier to justify the use of permanent SHMS in cost-benefit terms.

In general terms, Structural Health Monitoring Systems on long-span bridges can be classified according to the purpose they serve [4]:

- *To verify design assumptions*. In many cases, the design of long-span bridges is innovative and, hence, requires to be checked in real conditions during both construction and operation phases. SHMS may be used to monitor real structural responses and loading conditions, so as to verify that the structure performs in accordance with design assumptions.
- *To identify unforeseen problems*. Long-span bridges may be subject to unforeseen structural responses, such as excessive vibrations of long hangers adjacent to the towers of suspension bridges or unexpected behaviour of expansion joints. They can also experience problems arising from water ingress due to bad drainage. If such situations are not identified and dealt with, they can lead to an increasing deterioration of the structural components in the longer term and to costly mitigation actions. Therefore, it is critical to detect those problems as early as possible. SHMS can be used to record unexpected responses and to understand the physical mechanism behind them, so as to schedule appropriate action. It is worth pointing out that some problems, such as high amplitude cable vibrations, are discrete in time and tend to occur in relatively rare adverse meteorological conditions, which make them very difficult to be reported and quantified by means other than permanent monitoring systems.
- *To ensure a safe bridge operation*. During adverse weather conditions, e.g. high winds, and exceptional situations, such as earthquakes, or during the occurrence of accidental situations, like ship impacts or traffic accidents, SHMS may be used to raise an alarm so that bridge managers can prevent or restrict the use of the bridge during unsafe conditions.
- *To assess the performance of structural components and to improve performance predictions*.

Long-span bridges are associated with increasingly long service life, up to 200 years in modern suspension bridges, e.g. the Messina Bridge. Those structures are subject to harsh environments and changing load conditions that have an impact on the performance and expected service life of different structural components. SHMS can be used to provide information on the real structural demands (traffic intensities, temperatures, wind speeds) and on the structural responses (time-series of strains, accelerations, etc…). This can be used as a valuable input to theoretical deterioration models to improve the assessment of current and future component performance and expected service life under different scenarios.

- *To optimize inspection, maintenance and repair actions*. This is closely related with the previous point, since a better assessment of component performance, aided by SHMS, can lead to an optimized and rational inspection, and more effective maintenance and repair strategies.

3. SHM-informed management of long-span bridges

3.1 Motivation

In the following, only the case concerning the use of SHM to assess structural performance as the basis for optimizing inspection, maintenance and repair will be addressed. Thus, the use of SHM for other bridge management purposes, as described in the previous section, is not further considered in the present paper.

Long-span bridges are key elements of communication networks that need to be operated under the minimum of possible traffic disturbances, due to the great impact that such situations may have, both in economic and social terms. As key nodes in highly utilised transportation networks, such structures tend to have specifically dedicated management organizations, in contrast with short and medium span bridges that are normally managed within a stock perspective.

From a bridge management point of view, it is necessary to explicitly answer two well-defined questions:

- Is the structure behaving as anticipated or, equivalently, is its deterioration rate within the design allowables?
- Are the inspection, repair and maintenance strategies appropriate or do they need to be modified?

However, those two simply formulated questions have uncertain answers. This can be understood, on the one hand, considering the inherent randomness of the environmental conditions, loads and geometrical properties of the structures and the uncertainties associated with theoretical models used to predict deterioration processes, such as corrosion and fatigue. Moreover, both the temporal and the spatial variability of deterioration processes also contribute to the unqualified level of confidence while answering the management requests, as highlighted in [5]. In this regard, SHM can provide a continuous flow of data at discrete pre-selected locations; on the other hand, visual inspections or spatially distributed NDT campaigns can give more or less accurate information over extended regions but only at particular points in time. An attempt to combine the best features and advantages offered by each of the two approaches can be seen as the motivation to combine SHM, visual inspections and NDT to capture more fully both the spatial and the temporal dimensions, as further discussed in section 3.4 below. This turns out to be especially relevant on long-span bridges, associated with both long service life (temporal domain) and large dimensions (spatial domain).

Bearing in mind the above, it is reasonable to add a third question:

- With what confidence can we answer the previous questions?

Bridge management strategies strongly depend on the perceived precision in answering those questions. In most cases, those strategies are based on visual inspections that are inherently associated with some degree of subjectivity and are intermittent in time. SHMS provide objective data that can be used to reduce the uncertainties associated with deterioration modelling. This can be used to update continuously structural performances predictions during the service life of the structure according to observed outcomes [3]. As a result, SHMS can contribute in better answering the usual bridge managers' requests, providing valuable support to decision-making. It is relevant to point out that, from an economic point of view, an improved structural assessment leading to a justification of an extension of service life or to a reduction of operation costs can easily prove the cost-effectiveness of SHMS.

In addition, the use of monitoring systems has some other advantages in practical terms [6]. For instance, traffic flow is not interfered when monitoring and structural elements with difficult access can be monitored, once the installation of the sensors is carried out.

All these considerations have motivated a shift in the conceptualisation of modern SHMS of long-span bridges [4, 7]. In those structures, SHMS are an integrated part of management systems instead of just a tool to be used exclusively under exceptional circumstances, highlighting a shift from a reactive to a proactive management. Monitoring outcomes are hence used to assess continuously structural condition or performance and subsequently update service life predictions of a number of structural components. This leads to *SHM-informed* Management Systems, where SHMS outcomes may guide inspections, maintenance and repair actions, resulting in a safer and optimized bridge management.

Nonetheless, the abovementioned integration is not straightforward. The choice between a local or a global monitoring approach, the selection of locations, components and durations to monitor, the data collection, processing and interpretation, the treatment of uncertainties and the interaction between qualitative and quantitative techniques are issues that need to be addressed and understood and still limit the use of SHMS in informing Bridge Management Systems.

3.2 Monitoring approach

Two general approaches to monitoring can be distinguished when implemented in long-span bridges: a global and a local approach. In general terms, the former aims at assessing the global response of the structure by, for example, characterizing the eigenfrequencies and mode shapes of the structure. It is then assumed that any damage on the structure will have and impact on those parameters and, thus, by monitoring their evolution in time, damage can be detected, located and quantified [8]. In contrast, the local approach does not aim at identifying damage locations but is more akin to assessing the extent of potential damage/deterioration in critical areas. Thus, monitoring efforts are directed towards structural components that are prone to deteriorate in time and, therefore, can be expected to be the object of costly inspection, maintenance and repair actions. In this case, damaged or deteriorating locations are assumed to be reasonably well known or anticipated. Despite the promise of global methods in detecting unexpected behaviours and long-term global deterioration, local methods seem more appropriate in better assessing the condition of expected deterioration mechanisms at experience-driven critical locations; thus, they seem more likely to have a practical impact on bridge management strategies for long-span bridges, which are, on the whole, designed, constructed and operated with particularly high levels of expertise and care.

3.3 Choice of structural components

In the following, the components of long-span bridges that are the most prone to maintenance problems are described. Focus is given to bridges with steel girders. For further details, one could refer to [9].

- *Main cables and hangers*. The main cable of suspended bridges, the hangers and the stays of cable-stayed bridges constitute one of the key structural elements of long-span bridges. Their inspection and maintenance is very difficult and, therefore, their structural assessment needs to be accurate. The deterioration of hangers and stays is generally associated with corrosion or vibration-related events inducing fatigue problems, whereas the deterioration of main cables is essentially associated with corrosion.
- *Steel girders*. Together with main cables and hangers, they constitute the main structural elements. They are exposed to fluctuating loads that, in time, could lead to fatigue problems. Although good design should account for these considerations, a number of reasons, for instance a traffic increase higher than expected, may raise concerns regarding the fatigue resistance within a service life time horizon. It should also be pointed out that the economic implications of repairs in this component can be very important. Monitoring turns out to be

a powerful tool in assessing realistically the remaining fatigue life by means of recording time series of strains and concomitant actions (traffic, temperature, etc.).

- *Connections between main girders and transverse elements.* A number of connecting elements, such as tranverse beams, bracings and diaphragms, with either welded or bolted ends, exist between main girders. Some of the most critical and difficult to predict and assess fatigue issues can be related to such members and their connections.
- *Mechanical replaceable devices*. Although they represent only a small fraction of the main cost during the construction phase, their associated maintenance and repair costs during the operation of the infrastructure may constitute a considerable percentage of the total costs during this second phase. Moreover, long-span bridges are flexible structures that experience higher movements than other structural typologies. Therefore, their moving components, such as expansion joints, have special requirements in terms of durability against wear and tear. In contrast with most other components, bearings and expansion joints are expected to be maintained or replaced during the life of the structure and require, thus, intense inspection efforts. Being able to avoid unprogrammed repairs/replacements or, conversely, being able to synchronise the timing of such actions over part of the bridge could lead to cost savings, and, more significantly, to less traffic disruptions.
- *Deck paint and deck surfacing.* In spite of not being structural-resistant elements, they are always included in the maintenance agenda. Their degradation may lead to increased structural damages in the long-term. For example, a loss of the deck paint may result in corrosion of steel sections, whereas a deterioration of the pavement over an orthotropic deck may increase the stress ranges at the steel plates and, thus, reduce fatigue life.

Within a SHM-informed management approach, those are the components that should be the target of local monitoring.

3.4 Treatment of uncertainty

Both aleatoric (due to the randomness in loads, material properties, etc.) and epistemic (due to lack of knowledge) uncertainties have motivated a shift in the approach used when predicting the structural performance of long-span bridges: deterministic methods are gradually being replaced by probabilistic approaches. This has lead to an increasing use of the structural reliability theory, through which the performance of a structure or structural component is assessed by computing the probability of failure in relation to a particular limit state.

A limit state or performace function needs to be specified, which in general terms can be seen as the safety margin between the component's capacity or resistance, R(t,x), and its demand or load, L(t,x). Time (t) and space (x) index variables refer to the potential temporal and spatial variability in both resistance and loading terms. In general:

$$g = R(t,x) - L(t,x) \quad (1)$$

Where g is the limit state function and g<0 constitutes the failure domain. This leads to the formulation of a structural reliability problem, namely

$$p_f = p\left[R(t,x) < L(t,x)\right] = p\left[g(R(t,x), L(t,x)) < 0\right] \quad (2)$$

In many applications, such limit states functions have been developed for evaluating fatigue resistance in steel structures, as well as bending/shear/bond resistance in deteriorating concrete structures etc. Moreover, in considering performance indicators that are not immediately linked to safety, limit states associated with corrosion initiation times in concrete structures have also been investigated extensively.

In simple terms, the random resistance and loading terms appearing in equations (1) and (2) are, in turn, dependent on a number of basic random variables with specified probability density functions. SHM data may be used, among other approaches, to reduce epistemic uncertainties by better characterizing the distributions of these basic random variables or by providing directly information on the resistance or the loading terms. An increasing number of references suggest the use of SHM data in a reliability analysis of long-span bridges, showing the benefit of including SHMS outcomes in the probabilistic framework [10, 11].

3.5 Interaction with traditional inspection techniques

Due to the spatial and temporal limitations of the monitoring systems and inspection techniques outlined in paragraph 3.1, SHMS cannot be regarded as a substitute for classical inspection strategies, but as a tool to be used in conjunction with traditional systems, in order to capture more fully both the temporal and the spatial dimensions of the deterioration mechanisms and the associated performance state. This combined use is also relevant since bridge management of long-span bridges has historically been undertaken successfully without SHMS. In this respect, an effective integration of this technology strongly depends on a synthesising strategy which combines well-understood and 'tried and tested' approaches with their innovative counterparts. Bearing in mind the above discussion, it would appear that a continuous local monitoring sensor network, which can improve performance assessment at discrete critical locations, can be used to adapt the frequency and the scope of the different inspection types or NDT campaigns. An application of such an approach could be developed in the fatigue assessment of the welds of steel girders: SHM can provide quantitative input to the underlying engineering models at pre-defined critical 'hot spots', thus guiding inspection intervals. At the same time, visual inspection can provide a level of assurance on the spatial domain around the hot spots, where it may become necessary to deploy a NDT technique, should the design or operating assumptions be challenged at some point during the operation.

4. The Great Belt Bridge SHMS

4.1 Description of the bridge

The Great Belt Bridge (Figure 1) is a suspended bridge in Denmark that opened in 1998. It has a main span of 1624m and a maximum hanger length of 177m. Its main section is formed by a closed steel box with an orthotropic steel deck. It constitutes a key element of the Danish transportation system, ensuring both the national traffic as well as the road connection between northern Europe and Scandinavia. Since bridge inauguration, the traffic has been continuously increasing, reaching an annual bi-directional traffic flow above 10 million vehicles since 2006.

4.2 Structural Health Monitoring System

Fig. 1: The Great Belt Bridge (Denmark)

Two main different reasons have motivated the use of a SHMS on the Great Belt Bridge. The first is that the number of vehicles crossing the structure has turned out to be much higher than initially expected. Several monitoring campaigns have been used to reassess the fatigue capacity of the orthotropic deck considering also an updated traffic forecast. However, because of the uncertainties associated with short-term monitoring periods due to the influence of temperature on the amplitude of the recorded strains, it has been decided to install a permanent fatigue monitoring system. In total, there are 24 strain gauges continuously recording time series of strains at both longitudinal and transverse welds. An example of stress time-series recorded during one day can be seen in Figure 2. The sampling frequency is 100 Hz to effectively capture the stress cycles and intensity ranges, mainly induced by the flow of vehicles. Additionally, a number of sensors record temperature variations in the pavement and in some sections inside the steel girder.

With regard to the second reason, observations of unacceptable cable vibrations in some of the longest hangers, especially during winter conditions, also motivated the use of SHMS. In this case the object was to record cable accelerations, to understand the excitation mechanism, to check the effectiveness of mitigation measures and to assess remaining fatigue life. Because of this, selected hangers have been monitored during the last 10 years. The abnormal situations have been reported and various mitigation measures have been taken. In 2010, the system was further extended with more cables being monitored. Nowadays, the system consists of 16 accelerometers: 14 to measure hanger vibration and 2 to measure transversal deck oscillations. It can be seen that the monitored structural components and the means of monitoring are in accordance with the considerations outlined in section 3.2.

5. Ongoing research

The development of methodologies to update performance predictions for different types of structural components of long-span cable-supported bridges according to SHMS outcomes and inspection observations is currently under research. Since SHMS can continuously collect new data, more information is potentially always available. Bayesian techniques are effective tools in combining prior knowledge with new observations, so as to update deterioration models and, subsequently, reduce the uncertainties of the predictions, which constitutes the basis for an optimized bridge management. Those updating schemes should contribute to assess cost-effective monitoring durations and time intervals between successive updates of the model, as well as to assess spatial densities of sensors to account for the spatial variability of deterioration.

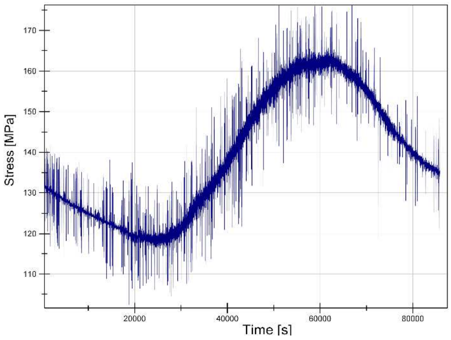

Fig.2: Stresses on 30/07/2011

In order to develop effective updating schemes it is essential to understand the interaction between different measured parameters since, in many cases, it is the combined effect of several parameters what determines future performance. In those cases, SHMS outcomes may be used to establish joint probability distributions for some of the key variables, so as to assess more accurately structural performance in the future. To illustrate this concept, one can refer to the fatigue assessment of the welded joints in orthotropic steel decks where temperature can have an important impact in reducing the load spreading effect through the pavement during warm conditions and, consequently, increasing the intensity of stress variations [2]. In such a case, to predict remaining fatigue life, attention has to be paid to the joint effect of temperature and traffic distributions in time.

Figures 3 and 4 show the asphalt temperature and the computed daily histogram of stress ranges of one weld monitored through the SHMS of the Great Belt Bridge during two days of similar heavy traffic. The stress ranges have been computed applying the rainflow algorithm to the time series of stresses, according to ASTM E1049-85 (2005). The influence of temperature on stress ranges can be seen in Figure 4, with a very clear shift of the stress range distribution towards higher values.

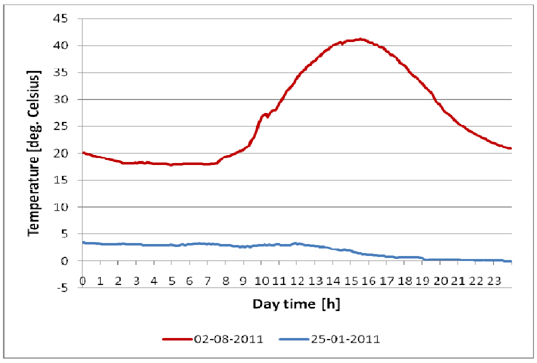

Fig.3: Asphalt temperatures

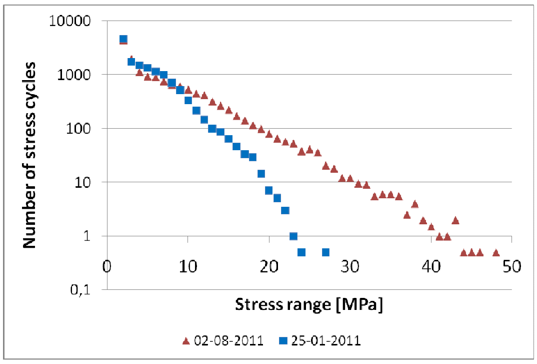

Fig.4: Stress range histograms

Other examples of a joint use of SHM is the prediction of cumulated displacements of expansion joints, resulting in wear and tear, where attention has to be given to both temperature distributions, affecting long-term movements, and traffic distributions in time, affecting the short-term component of displacements. The risk of cable vibrations inducing fatigue can be also tackled considering a similar approach.

6. Concluding remarks

SHM has a high potential to better assess present and future structural performances, which constitutes the basis for a safer and optimized bridge management of long-span bridges. It is therefore needed to develop methodologies to integrate effectively SHMS within BMS, avoiding a situation where huge amounts of collected data cannot be readily used and, thus, lead to a reduced interest in practical terms. An identified way to bridge that gap is to focus on local monitoring approaches, targeting those structural components prone to known deterioration problems. The structural reliability theory constitutes an appropriate probabilistic framework for integrating SHMS outcomes into performance predictions. Due to the different characteristics in terms of temporal and spatial coverage, SHMS cannot be regarded as a substitute for classical inspection strategies, but as a powerful tool to be used in conjunction with them. The development of updating methodologies considering SHM and inspection outcomes using Bayesian techniques is currently under investigation. It is believed that long-term monitoring data will be extremely useful to check new research approaches in field conditions and contribute to transparently assess the benefits of a SHM-informed management of long-span bridges. They will also help improve our understanding of underlying phenomena through the establishment of joint probability distributions, and may also lead to some unexpected correlations and dependencies become apparent with the course of time.

7. Acknowledgement

The authors would like to acknowledge the European Commission for funding the SmartEN research project under the Marie Curie ITN FP7 program, since the ongoing research work is carried out within this project. The authors would also like to thank Storebælt A/S for allowing access to the Structural Health Monitoring Systems of the Great Belt Bridge in the context of this research project. The research findings, views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the authors' organisations or the European Commission.

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Summary

The present paper discusses the benefits of using Structural Health Monitoring (SHM) to inform and improve bridge management decisions. The different uses of SHM on long-span bridges are reviewed. The interest of a local monitoring approach targeting selected structural components is highlighted. The need of a combined approach between traditional inspection techniques, Non Destructive Tests (NDT) and monitoring is justified in terms of spatial and temporal coverage. The relevance of probabilistic approaches to assess and update structural performance indicators is outlined. The case of the Great Belt Bridge (Denmark) is described to illustrate the use of SHM on long-span bridges, together with an overview of ongoing research in the field.

Keywords: structural health monitoring, long-span bridges, bridge management systems, structural reliability, inspection systems, Great Belt Bridge.

Abstract

Structural Health Monitoring Systems (SHMS) are increasingly present in most modern long-span bridges. Those systems can be used to better assess the performance of structures by reducing the uncertainties associated with deterioration modelling. This can potentially lead to a reduction of the operational costs. Despite their promise and potential, a gap still remains between the outcomes of those systems and practical bridge management decisions. As a result, huge amounts of data can be continuously collected which are not readily useable, thus being of reduced interest in practical terms. Methodologies, which integrate SHMS within Bridge Management Systems (BMS), need to be developed to address asset management issues traditionally informed by visual inspections and scarce NDT. This integration should overcome the shortcomings of current approaches and exploit the advantages offered by modern sensor technologies.

On long-span bridges, which tend to be one of the most popular candidates for monitoring amongst civil infrastructures, SHM systems can be classified according to their intended purpose namely: to verify design assumptions, to identify unforeseen problems, to ensure a safe bridge operation, to assess both present and future performance of structural components, and to optimize inspection, maintenance and repair actions.

As key nodes in highly utilised transportation networks, long-span bridges need to be operated with the objective of minimizing possible traffic disturbances, due to the great impact that such situations may have, both in economic and social terms. These structures usually have specifically dedicated management organizations, in contrast with short and medium span bridges that are normally managed within a stock perspective. From a bridge management point of view, it is necessary to explicitly answer two well-defined questions:

- Is the deterioration rate of the bridge within the design allowables?
- Are the inspection, repair and maintenance strategies appropriate or do they need to be modified?

However, due to both aleatoric and epistemic uncertainties, those two questions have uncertain answers. Therefore, it is reasonable to add a third question:

- With what confidence can we answer the previous questions?

Bridge management strategies strongly depend on the precision in answering those questions. SHMS can provide objective data that can be used to reduce the uncertainties associated with deterioration modelling. As a result, SHMS can help in answering better bridge managers' requests, through their integration in rational decision-making support tools. This has motivated a shift in the conceptualisation of modern SHMS of long-span bridges, for which the aim is to make them an integrated part of the overall management systems. Monitoring outcomes are hence used to continuously assess structural condition and subsequently update service life predictions of a number of structural components, giving place to *SHM-informed* Management Systems, where SHMS outcomes may guide inspections, maintenance and repair actions, resulting in a safer and optimized bridge management.

Nevertheless, the choice between a local or a global monitoring approach, the selection of locations, components and durations to monitor, the data analysis, the treatment of uncertainties and the interaction between qualitative and quantitative techniques are issues that need to be addressed and understood. Such issues, which currently restrict the more widespread use of SHMS to inform Bridge Management Systems, are highlighted in the following.

Local monitoring approaches seem more appropriate to better assess the condition of deterioration-prone components and thus are more readily useable in terms of their practical impact on bridge management strategies. In this context, SHMS should focus on main cables and hangers, steel girders, connections between main girders and transverse elements, mechanical replaceable devices and deck paint and surfacing.

Within a temporal and spatial domain, SHM can provide a continuous flow of data at discrete pre-determined locations, whereas visual inspections or spatially distributed NDT can give more or less accurate information over extended regions at particular points in time. Therefore, SHMS cannot be regarded as a substitute for classical inspection strategies, but as a tool to be used in conjunction with traditional systems, in order to capture more fully both the temporal and the spatial dimensions of the deterioration mechanisms. Moreover, this combined use is also relevant since bridge management of long-span bridges has historically been driven without SHMS and, thus, an effective integration of this technology strongly depends on a complementary approach combining well-known approaches with innovative ones and understanding the interaction between them.

An important methodological issue is the treatment of the uncertainties, and the establishment of an appropriate probabilistic framework within which the data provided by SHMS can be incorporated and utilised in determining current and future structural reliability estimates. Since SHMS can continuously collect new data, more information is potentially always available. Bayesian techniques are effective tools to combine prior knowledge with new observations, so as to update deterioration models and, subsequently, reduce the uncertainties of the predictions, which constitutes the basis for an optimized bridge management. Those updating schemes incorporated within the overall probabilistic framework, could be used to assess cost-effective monitoring durations and time intervals, determine appropriate performance update schemes, and suggest relevant spatial densities of sensors.

To illustrate the potential use of SHMS on long-span bridges, and to focus on some of the above issues through a particular structural system, the case of the Great Belt Bridge, in Denmark, is briefly discussed. The importance of understanding the interaction between several monitoring parameters is highlighted and illustrated by considering fatigue in orthotropic decks, where daily damage at a specific detail depends both on the temperature and traffic temporal distributions.