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SMART INFRASTRUCTURE – ARE WE DELIVERING ON THE PROMISE?

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Abstract

Many bridges across the world have very extensive structural health monitoring (SHM) systems that generate vast quantities of data. There are many engineers and researchers who envisage a brave new world of smart bridges with ubiquitous sensors providing real time information on all aspects of bridge performance. How realistic is this aspiration? How do we currently utilise the data generated in existing bridge SHM systems? How are such SHM systems designed in the first place?

A major research programme at the Centre for Smart Infrastructure and Construction (CSIC) at Cambridge University in the UK has been at the forefront of some of these smart technology developments, specifically in fibre optics, wireless sensor networks, MEMS sensors, computer vision techniques and data interpretation tools.

A recent PhD study by Webb [10] in which he investigated the manner in which such monitoring systems are currently designed, deployed and utilised for bridges has led to a re-evaluation of their effectiveness. A new framework which provides guidance for bridge engineers on how to design such SHM systems has been developed and will be presented in this paper.

Introduction

Many of the world's largest bridges have extensive SHM systems installed at the time of construction, with the cost being justified since it is only a small percentage of the overall cost of what are critical strategic infrastructure links. The assumption is that these systems will provide a form of "insurance policy" for the structure by giving early warning of safety or performance problems. However a review of the literature demonstrates that it is very difficult to find papers in which these systems have been shown to provide genuine value to the bridge owner or manager.

With small span bridges, it is rare to find examples of SHM systems installed from new. Far more commonly, an SHM system is introduced retrospectively to an existing structure to investigate a specific problem that has been identified by visual inspection.

In the last 10 years there have been quite dramatic developments in sensor technology that offer the prospect of ubiquitous monitoring of structures. The challenge for SHM academics and contractors is to demonstrate the benefits that such systems can deliver. In addition, the limitations of visual inspection are more widely recognised and thus more objective alternatives are being sought [6][7].

Fibre optic sensor systems can now measure strain and temperature over large distances, wireless sensor networks provide flexible, low cost means for deploying a large number of sensors, and MEMS (micro-electromechanical systems) technology allows extremely small, low cost and low power sensors to be produced. Computer vision tools can now provide visual information in a format that was inconceivable even 5 years ago, and data analytics and signal processing algorithms are able to extract useful information from complex large data streams to assist in the diagnosis of problems.

Cambridge University's CSIC has now been involved with a large number of SHM deployments on a range of structures. In particular the team has installations on a large number of tunnels and geotechnical structures as well as several bridges. The bridges include the UK's largest bridge, the Humber, and also the adjacent Ferriby Road Bridge, Nine Wells Bridge in Cambridge and the Hammersmith Flyover in London. Specific issues relating to the SHM systems on each of these structures are discussed in other publications [1-5][8-11].

Case study of SHM system design – Walton-on-Thames Bridge

When faced with a blank piece of paper and the task of selecting and designing a new monitoring regime, what should be the objectives? In practice, this process tends to involve asking the questions "what might go wrong and over what time scale" and hence "what sensors might be included to give forewarning of failure or deterioration". A case study of this design process is presented here to illustrate some of the key issues to be faced.

The new Walton-on-Thames Bridge is a 90m span, steel arch structure that replaced two older bridges over the River Thames (Fig.1). It was completed in 2013. The client was a local county council that had retained an experienced in-house engineering team able to fulfill the role of an "informed and intelligent" client who also had an enlightened approach to innovation. Back in 2011, the client, consultant and contractor, all of who had previously worked together successfully, joined with Cambridge University to explore the feasibility of deploying a state-of-the-art structural monitoring scheme to provide information and long term value to the stakeholders. It was a strong, close-knit team, brought in early in the design process so that a system could be incorporated during construction.

Fig. 1 Walton-on-Thames Bridge (photo taken by authors in Sept. 2015)

In practice this proved to be an extremely difficult task. The team members all had experience of the types of problems that bridges might encounter over time. The primary concern was with deterioration of materials and components with time. This might arise due to fatigue of steel elements or corrosion of the main structural members or reinforcement, or deterioration of key components such as bearings and joints, although as a general philosophy joints were to be avoided wherever possible for the very reason that these have historically proved problematic.

So what did we consider? We could envisage that some key steel components such as the steel arch or cable hangers might eventually suffer from fatigue cracking. All these components had of course been designed for fatigue criteria but this would be based on an assumed loading profile and stress cycle range that will inevitably not reflect the actual stresses the bridge will encounter in service. Whether the actual stress cycles will be higher and more frequent or lower and less frequent is impossible to predict. Therefore, the stress range of key components would seem to be a valid and sensible parameter to measure. And here the process started to unravel. Who should pay for measuring the stress range and the ongoing monitoring? The owner would expect that the designers had taken fatigue into account and that the design would be sufficient for the full design life of the bridge (120 years in the UK) so he/she should not have to worry about premature life expiration. The designer was interested in validating his/her structural model but the long term nature of the monitoring required would mean they would really not know the outcome for many years and by then they would not be contractually involved in the bridge so not responsible for processing or using the information obtained. The contractor had no long-term interest in such information. So it was unclear what the real benefit would be, who would be the main beneficiary and who would be willing to pay for recording this information over such a long time period.

The next issue related to the practicality of such monitoring. Whatever sensors might be deployed and embedded in the bridge, e.g. strain gauges linked up to a wireless sensor network (WSN) which communicated data back to a computer back at someone's office, the reality is that the fatigue issue is only likely to be of interest in thirty, forty, fifty or even more years' time. The one thing that can be guaranteed is that any monitoring system deployed today will be long obsolete and unlikely to last anywhere near this period of time. So it was concluded that this may not be a very practical option.

It was recognised that the consequences of not knowing the stress range history could be very costly. If fatigue cracks were identified during a routine visual inspection long before the expected design life had been reached then the owner would be under an obligation to check and confirm that the bridge was safe. Without a stress range history, they may be obliged to undertake extensive and expensive inspections and testing to validate the condition, and possibly even repair or replace the bridge. So there is an incentive to deploy a monitoring system for the client but the client would need to be willing to consider a whole life perspective and even then, using typical discount rates over such long periods, the present value of the future repair options would likely be relatively low. The challenge comes when bridges designed for 120 years start to exhibit extensive fatigue cracking after, say, 10 or 20 years, as has happened on some of the larger steel box bridges around the world. In these circumstances having the fatigue history gives some indication of whether the problem is due to reaching the stress cycle limit or some other design or detailing error. But even if the stress history is to be measured, how many sensors and locations should be monitored? On a long span structural steel bridge the potential number of fatigue locations is very large so at best you can only put discrete sensors at a few locations.

So the combination of the very long period before stress range data is likely to be useful, discrete nature of any sensor readings taken, and inevitable obsolescence and need to replace any sensor system several times over its life all made the economic case for monitoring difficult to justify.

What about other types of potential failure? Corrosion of reinforcement in the concrete deck slab and abutments is always a potential cause of performance failure. But where and what should you measure? At present, there are various methods for measuring corrosion, or more correctly the likelihood of corrosion, but these are almost all discrete point measurements, indirect and rather questionable in accuracy. Do we measure the cover and chloride profiles at many locations? Even if we did, what would be the action taken if the chloride profile exceeded some acceptable threshold adopted by the client?

It can also be argued that if the bridge is properly designed, which one assumes from a top consultant, no problems should arise. Similarly, with a top contractor, the plethora of quality assurance (QA) systems in place on such projects should ensure no problems of workmanship or material properties arise over the lifetime of the bridge so why should we monitor. In practice we all know that issues will inevitably arise but it is nigh on impossible to predict exactly what, where and when such problems may arise. Any problem that arises is likely to be due to a specific incident where, for example, the operative building the bridge did something badly, or a poor quality batch of materials slipped through the quality assurance system. Even the best and most rigorous QA system is not perfect. We also must examine the responsibility for any problems that might arise. The client might quite justifiably say that if a problem arises then s/he would seek redress with the consultant if it were a design fault or the contractor if it were a construction fault so why pay for a monitoring system. The consultant usually has no long-term responsibility so s/he would not want to pay. And of course the contractor is mainly interested in the immediate short-term delivery of the bridge and has little interest in what happens in 50 years' time.

This scenario can change with a different procurement model, such as a PFI or Alliance model where the consortium designing and building the bridge picks up liability for all repairs for, say, a 30 year period. But herein lies another problem. Most concrete problems only arise long after construction so it might be 40 years or more before these issues are identified. At that stage they may indeed be quite severe and might even compromise the safety or performance of the bridge, but they are unlikely to be picked up long before that. Unless there is whole life responsibility for the structure there is no real incentive for any of the parties to monitor performance.

The reality is that although we might have a reasonable idea of which components are more likely to exhibit problems with time, we are still not able to predict accurately exactly what, where and when structural problems will occur.

In the end, no structural monitoring system was deployed on this bridge. The whole team came to the conclusion that it was very difficult to justify the business case for a substantial investment now when it was not at all clear what the benefits would be and to whom, and who should pay for any monitoring system. In practice the client nearly always pays. But it is not clear that the client is always the recipient of any benefits to be derived from the structural monitoring system and information obtained.

It is suggested here that this is not a dissimilar process to most situations when a SHM system is envisaged for a new structure. The consultants would try to identify what might go wrong with time and put in some sensors to measure some parameters that might help inform that expected outcome. It is extremely difficult to find any example in the literature where a system has been designed and the full interpretation of potential measured outputs has been evaluated in advance and decisions based on potential outcomes identified.

The limitations of this SHM design exercise led to the initiation of a PhD research project in which the simple question posed was "what should we measure and why?" The outcome of this study, by Cambridge PhD student Graham Webb, has had a profound effect on the first author's approach to the design of SHM systems. Webb's thesis [10] gives a framework which allows stakeholders to ask the appropriate questions and understand what could be monitored and why. This transparency is essential if an effective SHM system is to be deployed. As a result of applying this new framework retrospectively to the Walton-on-Thames bridge, the authors would now recommend that a SHM system should have been deployed, but with a clear understanding of what benefits could be derived by each of the stakeholders.

Webb undertook an extensive literature survey investigating published accounts of SHM deployments. The question he posed was "on which of these deployments was value obtained as a result of an action being taken or a decision being made on the basis of the data provided by the SHM system?" The results, shown in Figure 3, are quite enlightening. Of the 44 papers reviewed, only 5 provided any information that could be or was acted upon by the relevant stakeholder. The vast majority were, in reality, simply demonstrators of the technology to show that a particular parameter could be measured. How the parameter or parameters obtained would then be interpreted and translated into information and hence value was not addressed.

This failure to demonstrate real value to the owners and managers of the bridges in most of the cases examined reinforces the point that the SHM industry needs to focus on demonstrating how the data measured can be converted into information, knowledge and value. Instead, at present it seems that most SHM deployments fall into the monitoring category the authors have defined as "Sensor Deployment Studies" which might more realistically be called "sensors for sensors sake".

Webb, in association with the other authors, undertook a profound rethinking exercise to challenge the current approach to SHM and try to design a structured framework which would guide all parties involved in designing such a system and understanding the benefits that could be derived from SHM.

The results of this exercise are summarised below.

New framework for the design of Structural Health Monitoring systems

When developing a SHM strategy, the key stakeholders should consider all of the items listed below. This assists in providing clarity and transparency to what can realistically be measured, the value that might be obtained and the key beneficiaries of any measurements taken.

1. *Stakeholders – client/owner, designer, contractor, operator.*
One must identify the desired outcomes/objectives for each stakeholder. For example, the client might want to know how long the asset will last, be safe and provide the service for which it was designed. The designer might want to compare the actual performance (e.g. deflection, strains, vibrations) with the design models and hence calibrate his/her assumptions. The contractor may wish to measure deformations of key components during construction and the operator may wish to know when and what maintenance actions should be undertaken.

2. *Primary objectives – safety, performance and cost.*
Consider the main objectives of the SHM system being designed. In practice the primary objectives of all stakeholders should be first and foremost to ensure the bridge is safe, then to ensure the bridge delivers the functionality and performance required and finally that this performance is delivered at a reasonable cost. Different parameters will need to be measured to determine the ultimate strength capacity when compared to serviceability and performance problems. Within this item, certain key considerations may be relevant to the local environment e.g. earthquakes are a dominant factor in some countries whereas material deterioration is of more concern in other jurisdictions.

3. *New versus Existing* – is the system for a new build structure or is it to be retrofitted to an existing bridge? If new build, is the primary goal to measure parameters during construction only or to embed sensors in the bridge for long term performance monitoring?

4. *Structural Health Monitoring Classification system (5 categories)* – all deployments of SHM systems from Webb's literature review [10] can be classified into one or more of the following 5 categories. These provide a focus for understanding what outputs are likely to be achieved by any SHM system. See Figure 2.

(i) Anomaly detection
(ii) Sensor deployment study
(iii) Model validation
(iv) Threshold check
(v) Damage detection

These are discussed in detail in Webb's PhD thesis [10].

5. *Expected outputs* – it is of critical importance to consider the likely data that any sensor will produce, in particular the accuracy, resolution and frequency of measurement and what will actually be done with the specific data derived.

6. *Decisions/actions* – what actions/decisions would be influenced/made as a result of obtaining specific data from the SHM system?

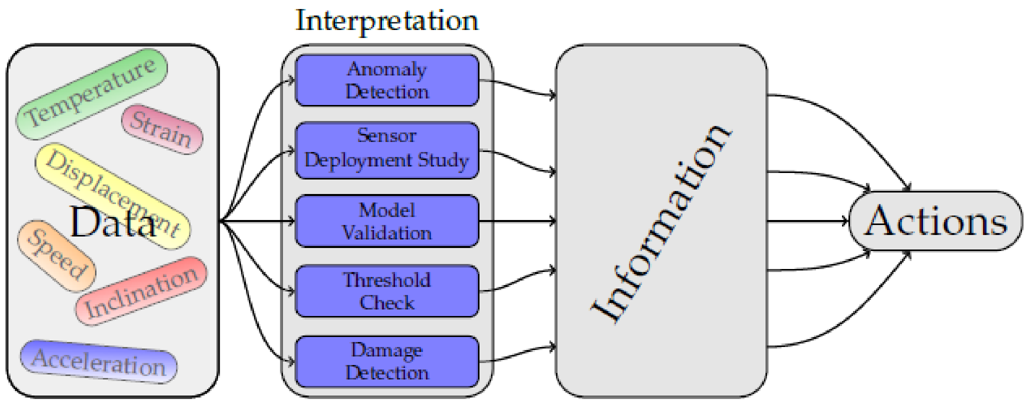

Fig. 2 SHM classification system (from Webb [10])

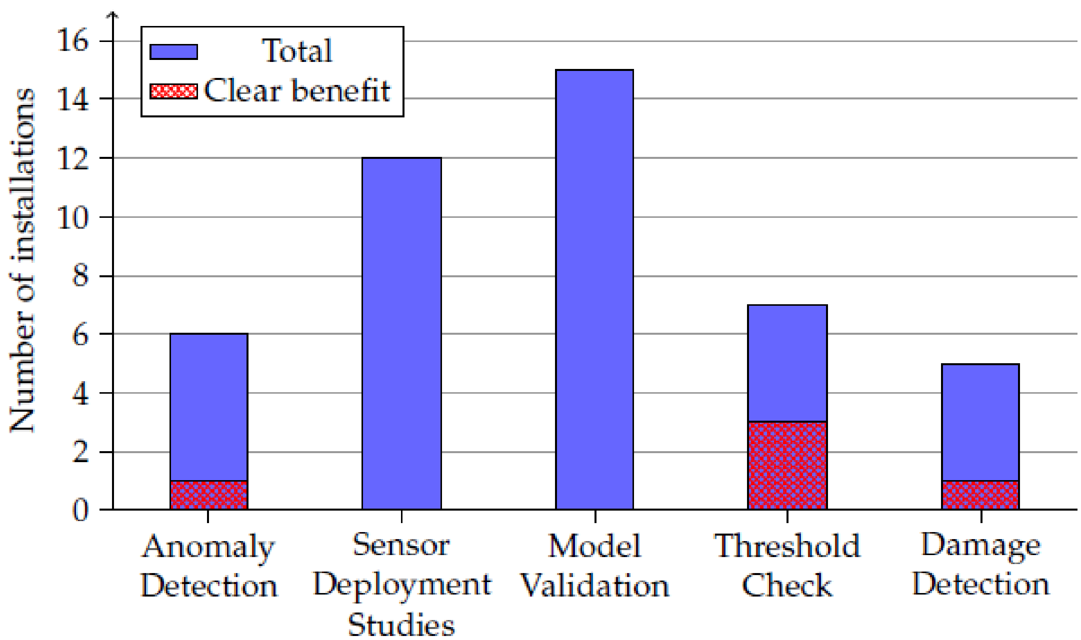

Fig.3 SHM deployments by category and number with demonstrated value (from Webb [10])

Conclusions

To date, in the majority of cases examined, SHM systems have not delivered on the promise of providing reliable, objective, real-time information that can be used to inform decision-making and actions for all the different stakeholders responsible for our bridge infrastructure. However with a clear framework to define what outcomes may be obtained, and with the rapid improvement in sensor technology and reduction in the cost of hardware and data transmission and storage, it may well be possible to achieve this goal in the not too distant future. Perhaps the greatest challenge is to develop new sensors that can measure the key parameters that bridge engineers require, rather than other parameters that are simpler and more convenient to measure. These would include a sensor to determine the location, extent and rate of corrosion on reinforcing bars embedded in concrete as well as corrosion of steel prestressing cables, a concrete strength sensor, a steel yield stress detector and a reliable fatigue monitor that can cover a large area rather than a single point location. All these challenges offer exciting opportunities for research engineers.

References

1. Hoult, N. A., Fidler, P. R. A., Wassell, I. J., Hill, P. G. & Middleton, C. R. (2008). Wireless structural health monitoring at the Humber Bridge UK. *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, **161(4):** 189-195.
2. Hoult, N. A., Bennett, P. J., Fidler, P. R. A., Middleton, C. R. & Soga, K. (2009a). Smart Infrastructure: Pervasive WSNs for a more Sustainable Europe. *Proceedings 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4)*, 22nd to 24th July 2009, Zurich, Switzerland.
3. Hoult, N., Bennett, P. J., Stoianov, I., Fidler, P., Maksimović, Č., Middleton, C., Graham, N. & Soga, K. (2009b). Wireless sensor networks: creating 'smart infrastructure'. *Proceedings of the Institution of Civil Engineers – Civil Engineering*, **162(3):** 136-143.
4. Hoult, N. A., Fidler, P. R. A., Hill, P. G. & Middleton, C. R. (2010a). Long-Term Wireless Structural Health Monitoring of the Ferriby Road Bridge. *Journal of Bridge Engineering,* **15(2):** 153-159.
5. Hoult, N. A., Fidler, P. R. A., Hill, P. G. & Middleton, C. R. (2010b). Wireless structural health monitoring of bridges: present and future. *Smart Structures & Systems*, **6(3):** 277-290.
6. Lea, F. C. & Middleton, C. R. (2002). *Reliability of Visual Inspection of Highway Bridges*. Technical Report CUED/D-STRUCT/TR.201, Department of Engineering, University of Cambridge, UK.
7. Moore, M., Phares, B., Graybeal, B., Rolander, D. & Washer, G. (2001). *Reliability of Visual Inspection for Highway Bridges*, volume 1. US Department of Transportation, Federal Highway Administration, Washington, United States.
8. Stajano, F., Hoult, N., Wassell, I., Bennett, P., Middleton, C. R. & Soga, K. (2010). Smart Bridges, smart tunnels: Transforming wireless sensor networks from research prototypes into robust engineering infrastructure. *Ad Hoc Networks*, **8:** 872-888.
9. Webb, G. & Middleton, C. (2013). Structural Health Monitoring of Bridges. *Proceedings Second Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*, Istanbul, Turkey, 9th to 11th September 2013.
10. Webb, G. (2014). *Structural Health Monitoring of Bridges*. Ph.D. Thesis, University of Cambridge, United Kingdom.
11. Webb, G. T., Vardanega, P. J., Fidler, P. R. A. & Middleton, C. R. (2014). Analysis of Structural Health Monitoring Data from Hammersmith Flyover. *Journal of Bridge Engineering (American Society of Civil Engineers)*, **19(6):** 05014003, http:dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000587