

What added value can SHM bring to my construction project or structure maintenance programme?

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ABSTRACT: Although the numerous benefits of using modern structural health monitoring (SHM) technology in the construction of bridges and other structures, and for subsequent inspection, maintenance and renovation work, are well established, they are not fully appreciated and exploited by many with responsibilities in these fields. Even engineers that have used SHM in the past may fall within that category, considering the wide range of possible applications and the rapid rate of development of SHM technology. This paper seeks to address this by presenting the many benefits offered by SHM, in terms of efficiency, cost-effectiveness, precision, reliability and continuous coverage, and by illustrating the wide range of purposes that can be served by SHM in the construction, maintenance and renovation of bridges and other structures.

1 INTRODUCTION

The cost of restoring deficient infrastructure to an adequate level is significant for structural owners and transport authorities across the globe. As an example of the situation in the USA (but reflective of the worldwide situation), it is estimated that USD 48.7 billion is needed to replace the country's structurally deficient road bridges, or USD 33 billion to rehabilitate the current stock (Table 1). In order to prioritise intervention work, those with responsibility for the construction, maintenance and renovation of such structures can benefit greatly from the potential offered by modern SHM systems to better understand the structural behaviour. Today's SHM technology offers numerous benefits over traditional manual methods of inspecting, assessing and recording relevant data, as described in the next section. As a result of these benefits, SHM is in many cases an ideal tool for inspection and maintenance activities etc., which have evolved, in some fields in particular, from a prescriptive and time-based approach to a risk-based approach – as exemplified, for example, by European standard EN 16991 (CEN, 2018). The range of purposes that can be served by SHM, right throughout the life-cycle of a structure, is very broad – as will also be illustrated below. These technologies can bring significant added value to infrastructure owners and allow more economic use of already scarce resources.

Table 1. Estimated costs of replacing/repairing structurally deficient (SD) road bridges in USA (FHA, 2017)

Bridge type	Total no. of SD bridges (2017)	Estimated cost of replacing all SD bridges (mUSD, 2017)	Estimated cost of rehabilitating all SD bridges (mUSD, 2017)	Average replacement cost per bridge (mUSD, 2017)	Average rehabilitation cost per bridge (mUSD, 2017)
National Highway System	5,010	26,322	17,899	5.25	3.57
non-National Highway System	49,550	22,430	15,252	0.45	0.31

2 ADVANTAGES OF SHM RELATIVE TO MANUAL METHODS

SHM systems typically offer many benefits over traditional manual monitoring, inspection and measurement methods, including those mentioned below – as a consequence of which the use of SHM can greatly increase the usefulness and reliability of the critical information provided for use on a particular structure or project.

2.1 *Far higher sensitivity and precision*

Modern SHM technology is capable of achieving an extremely high degree of precision – for example, being able to measure the tiniest changes in forces, dimensions and other parameters of interest. It can also be used to detect and analyse high-frequency vibrations, at frequencies of 200 Hz or more, that would scarcely be registered by human touch and would clearly be impossible to analyse by purely manual methods.

2.2 *Improved inspection cover*

Once installed, a suitably designed SHM system will continually measure and record the required data, 24 hours a day and seven days a week, for as long as required – clearly a huge advantage over the sporadic/periodic nature of manual methods. Where appropriately designed, an SHM system can thus be relied on to provide immediate notification (warning) of unexpected / serious events, no matter when they might occur – increasing structure and user safety, and potentially enabling a structure for which residual risks have been identified to remain in service.

2.3 *Automatic recording of data and immediate analysis by powerful software applications*

The enormous analysis power provided by modern computing technology can be used to generate very useful insights and information from the vast amounts of data recorded by SHM. For example, the histogram shown in Figure 1 (left) shows, as a distribution curve, the number of times a certain parameter (displacement) was measured with each particular value. The graphs in Figure 1 (right) show how regression models can be used to improve damage detection etc. by eliminating the influence of environmental effects and the like.

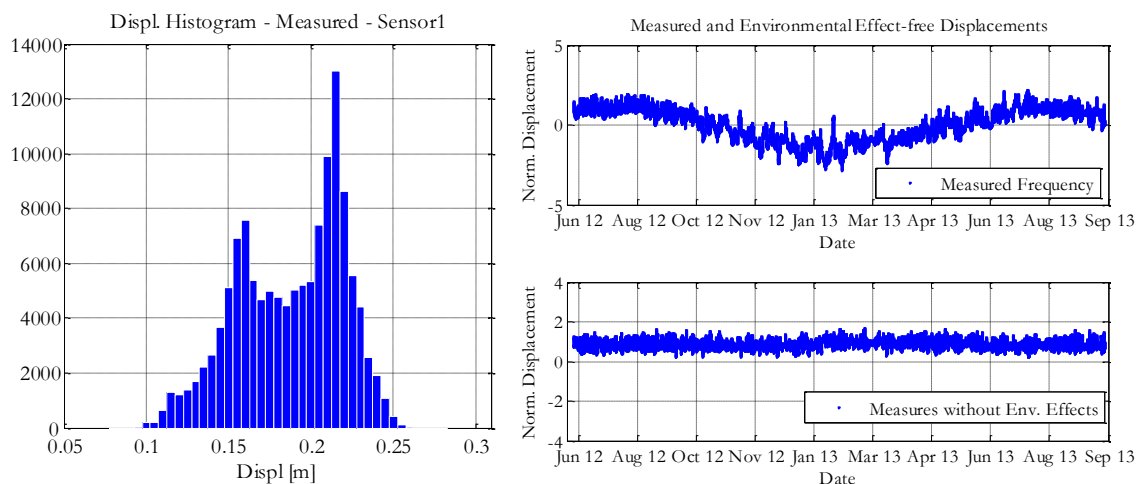


Figure 1. A typical histogram showing the frequency at which measurements of each value arose (left), and the usefulness of a typical regression model in eliminating the effects of normal environmental effects on the parameter of interest – with the original measured data on top and the adjusted data on the bottom (right).

2.4 *Greater efficiency, lower inspection costs, faster reporting*

In many cases, the use of SHM is likely to offer considerably greater efficiency and cost-effectiveness than manual methods (Figure 2). If a structure requires particular parameters to be measured on an ongoing basis, and this need could be fulfilled by either a manual or an SHM approach, the costs of the SHM approach will often be considerably lower – especially in the case of long-term applications when the initial set-up costs of SHM are more than reimbursed by the savings in “running costs”. Furthermore, the cost of the SHM system relative to the cost of the structure or even the cost of structural intervention works in many cases is extremely small.



Figure 2. Traditional approach to measurements during inspection visits (left), and continuous automated measurement by means of SHM (right).

3 POSSIBLE BENEFITS THROUGHOUT A STRUCTURE’S LIFE CYCLE

Thanks to these benefits, modern SHM systems can be used to serve many purposes in relation to bridges and other structures. Applications can arise at any stage in the life of any structure, including:

- Initial construction
- Normal inspection and maintenance work during its service life
- Investigation of specific concerns that may arise at any time in its life (e.g. due to unforeseen events)
- Renovation when the time comes to replace part or all of the structure

The use of SHM systems to provide important data in each of these application areas is illustrated below.

3.1 *Benefits during a structure’s initial construction stage*

A suitably designed SHM system can provide essential assistance to constructors of bridges and other structures, e.g. where loads, stresses and strains must be sensitively balanced. It can also be used by the constructor or client as a quality assurance tool in proving construction in accordance with specifications, and by the designer to verify the proper functioning of the newly-built structure as expected – for example:

- Verification of structural performance as designed – e.g. as described by Meng et al (2019) in relation to the construction of the Kota Chambal Bridge in northern India, whose design presented particular design and construction challenges. The system was used, for example, to measure the accelerations associated with forced vibrations of stay cables, enabling the proper distribution of forces among the cables to be verified and the cables’ natural frequencies to be determined, supporting the bridge’s construction and providing the base information needed for data evaluation throughout the bridge’s service life.

- Optimising construction of structures – e.g. as described by Moor et al (2014) in relation to the construction of the Gleisbogen Bridge in Zurich, Switzerland, where a temporary monitoring solution was used to verify the correct distribution of tension forces in the bridge’s suspension cables.
- Optimisation of design of key components – e.g. as described by Spuler & Moor (2013) in relation to the design and supply of the replacement sliding finger expansion joints of the Alvsborg Bridge in Gothenburg, Sweden, where SHM was used to evaluate the actual movements of the existing joints – information that was very useful in the design of the new joints.
- On the Greek National Opera in Athens (Figure 3), to avoid the need for conventional heavy lifting, an alternative solution was developed using the building’s 30 column head assemblies of shock absorbers and spring devices by injecting compressible elastomer into the spring devices in a very controlled manner, making it possible to lift the roof enough to remove scaffolding after just ten days – a fraction of the time that would have been needed for conventional heavy lifting. The whole process was closely monitored using an SHM system, which monitors the pressure in the spring and damper elements.

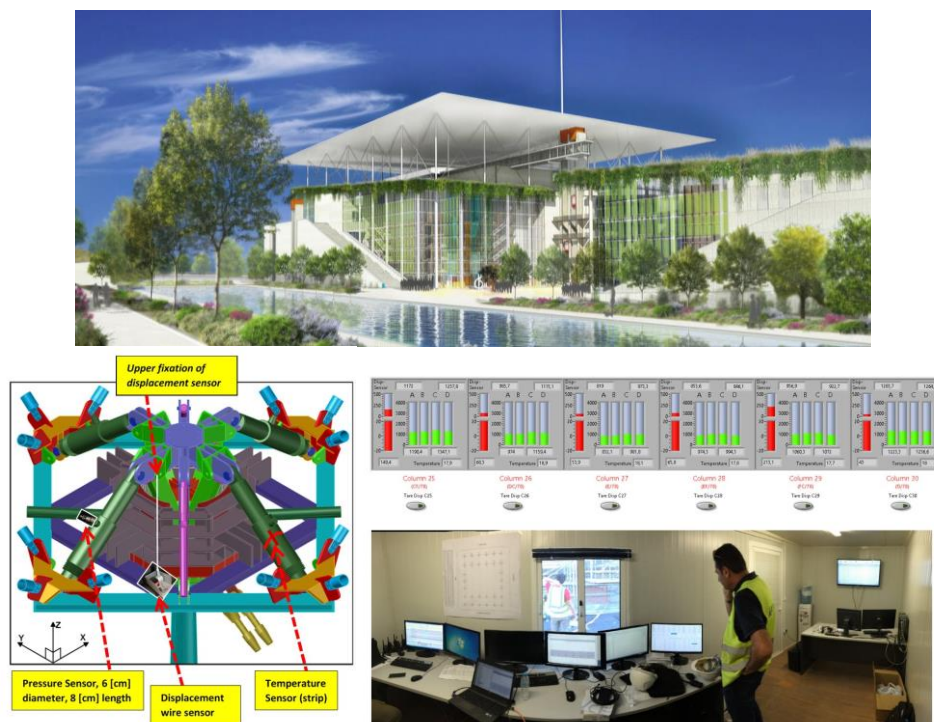


Figure 3. Stavros Niarchos Foundation Cultural Centre in Athens (top), SHM system integrated on roof spring and damper system (bottom left), and monitoring control room during construction (bottom right).

3.2 Supporting normal inspection and maintenance work during a structure’s service life

Automated SHM systems have a great deal to offer those who are charged with the inspection and maintenance of all types of structure – for example:

- Detection of long-term structural deterioration – e.g. as described by Malekzadeh et al (2018) in relation to SHM system of the New Champlain Bridge in Montreal, Canada, whose wide range of sensors includes, for example, corrosion sensors embedded in the structure’s concrete.

- Monitoring of condition and performance of special structures – e.g. as described by Islami & Meng (2015) in relation to the SHM system of the unique roof of Zurich Zoo’s elephant house, Switzerland, a spectacular wooden shell structure whose condition is sensitive to the hot, humid environment maintained within the building and its contrast with the external local climate.
- Monitoring of applications where high reliability and low maintenance are especially important, and high confidence is required – e.g. as described by Meng et al (2018) in relation to the construction of the Johan Sverdrup oil platform facility in the North Sea off the coast of Norway, where the performance of the special bearings supporting the bridges connecting the facility’s various platforms must be assured at all times, especially considering the remoteness of the location and the harshness of the environment.
- Confirmation of remedial measures / safety – e.g. as described by Savioz et al (2013) in relation to the monitoring of rock anchors securing the viewing area cliff faces at the Rhine Falls near Schaffhausen, Switzerland, where an SHM system will provide immediate notification of any change in the stress in any monitored anchor, indicating a possible risk of sudden collapse and thus enabling the area to continue to be used in safety (Figure 4).

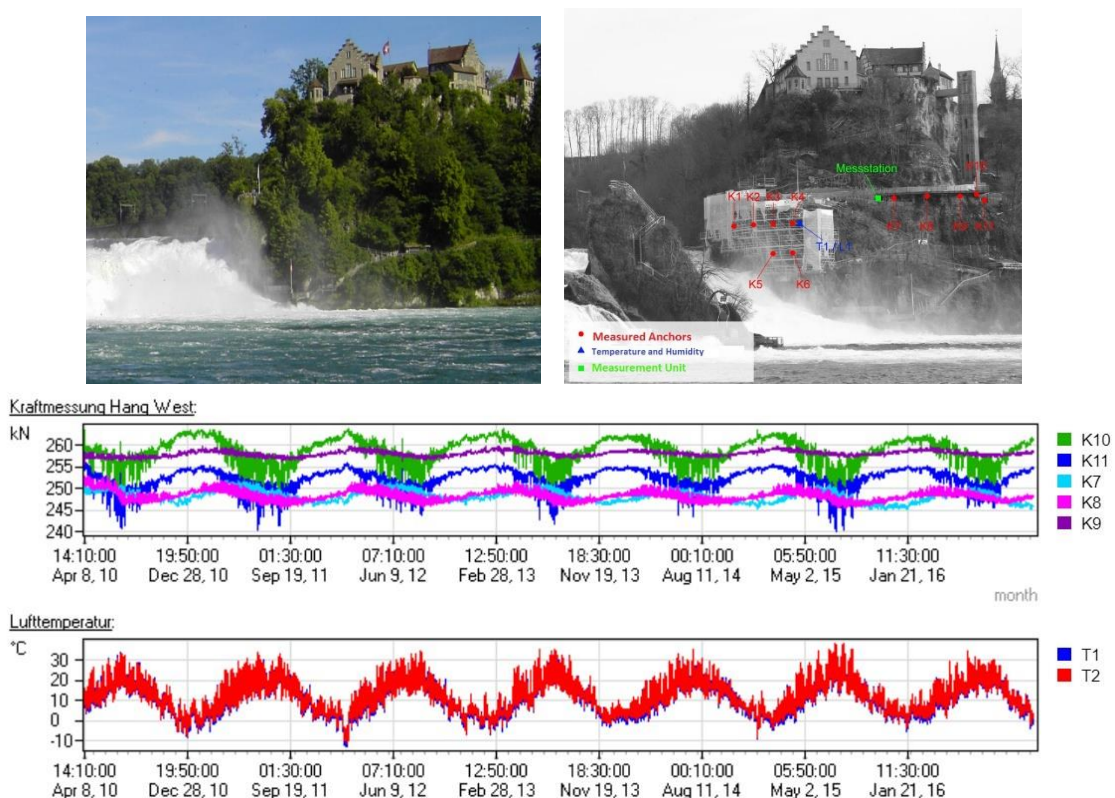


Figure 4. Laufen Castle at the Rhine Falls (top left), rock face with instrumented rock anchors (top right), and almost seven years of measured force data from the rock anchors (bottom).

- Enabling a structure for which residual risks have been identified to remain in service, with automatic immediate notification (“warning”) of exceeding of predefined threshold values – e.g. as described by Creighton et al (2018) in relation to the monitoring of the Hunter Expressway in New South Wales, Australia, where a significant risk of ground subsidence was identified due to mining activities in the area.

- Confirmation of proper ongoing performance of critical protection devices – e.g. as described by Meng et al (2019) in relation to the very large, very special shock transmission units (STUs, or lock-up devices, LUDs) of the Halogaland Bridge in northern Norway.
- And in general: Supporting of data-driven approaches to inspection and maintenance, in line with modern standards such as EN 16991 (CEN, 2018), with load monitoring of bearings now being specified by some standards – e.g. as was the case for the spherical load cell bearings used in the construction of Doha’s Orbital Highway in Qatar, as described by Islami et al (2018).

3.3 Supporting investigation of structural performance, specific concerns, etc. that may arise at any time in its life

Further applications may arise at any specific time during the life of the structure, should a specific need arise (e.g. due to unforeseen events) – for example:

- Understanding of real structural behaviour of structures – e.g. as described by Spuler et al (2012) in relation to the SHM system of the Dintel Harbour Bridge in Rotterdam, Holland, which provided data for use in updating the structure’s Finite Element Analysis (FEA) model.
- Investigation of matters of concern (for example, from structure inspections etc.) – e.g. as described by Moor et al (2010) in the case of the Weyermannshaus viaduct in Berne, Switzerland (Figure 5), where an SHM system was used to investigate the origin and significance of cracking of concrete, enabling a rebar fatigue analysis to be carried out and the expectation of a significant remaining service life to be confirmed.

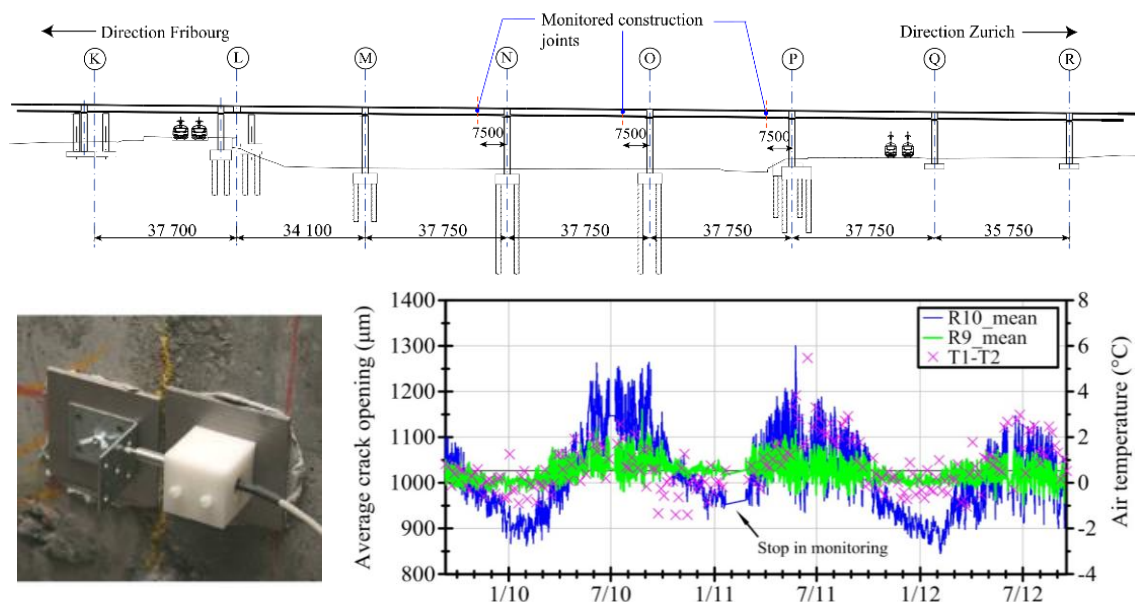


Figure 5. Weyermannshaus Viaduct typical span arrangement (top), crack opening sensor (bottom left), and three years of crack opening data (bottom right).

3.4 Supporting renovation/modification/strengthening work etc. as required

Finally, at the end of a structure's life as originally constructed, an SHM system can provide very valuable information which can be used to plan and optimise adaptation or renovation works. For example, assessment of actual structural behaviour can help to select the optimum approach to repairs or adaptations where these are required, and such methods can also be used to calibrate systems and update numerical models. For example:

- Adaptation of a structure's static design – e.g. as described by Spuler et al (2011) in relation to modification work carried out on the Pont Nanin Bridge in the Swiss Alps, where the fixities of certain bearings was changed, limiting movements that were previously facilitated.
- Modifications to improve safety in line with modern demands and design standards (such as seismic) – e.g. as described by Bd&e (2016) in relation to the retrofitted bearings and STUs of the elegant Lavoitobel arch bridge in eastern Switzerland, which improved seismic safety and accounted for the considerable increase in traffic since the structure was built.
- Optimisation of planning of remedial works and of renovation design work– e.g. as described by Moor et al (2014) in relation to the renovation of the Angus L. Macdonald Bridge and the A. Murray MacKay Bridge in Halifax, Canada (Figure 6) – for which an SHM system was used to measure and record the movements and rotations of the bridges' decks, providing the data needed by the computer modelling of the new deck of one bridge, and assisted in the planning of remedial works of the existing deck of the other.



Figure 6. Angus L. Macdonald Bridge and A. Murray Mackay Bridge, Halifax, Canada.

4 CONCLUSIONS

Thanks to the advantages that modern SHM technology offers over traditional inspection and data acquisition methods – such as its far higher sensitivity and precision, the non-stop inspection cover it provides, its automatic recording of data and immediate analysis using powerful software and its much greater efficiency – SHM has enormous potential for use on construction projects of all kinds and in the inspection and maintenance of bridges and other types of structure. As demonstrated by the examples mentioned, possible applications are very varied and can arise during all stages of a structure's life-cycle: initial construction and acceptance; normal inspection and maintenance; investigation of concerns that may arise at any time (with an alarm function if desired to provide immediate notification of any deterioration in the structure's condition or safety); or planning and execution of renovation works. A common result of the use of SHM in a structure's construction or maintenance is the minimising of costs and the optimising of life-cycle performance. Of course, this can be financially very significant for the owner/constructor, but the benefits for the structure's users and the public are liable to be even greater – for example, with

less traffic disruption associated with maintenance and repair works. In some cases, the use of SHM may even enable a structure's service life to be substantially extended – as in the case of the Weyermannshaus viaduct, as referred to in Section 3.3 above, for example.

Therefore, SHM is a very useful tool in many circumstances, and indeed, often an essential one where high degrees of precision and accuracy are required and where efficiency, reliability and cost-effectiveness must be optimised. It is thus clear that modern SHM systems, continually developing and improving, will play an increasingly important role in the construction, management and maintenance of structures in the future.

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