THE WIDE RANGE OF APPLICATIONS OF STRUCTURAL HEALTH MONITORING – A SOLUTION FOR EVERY NEED

Pascal SAVIOZ[1], Niculin MENG[2] and Colm O'SUILLEABHAIN[2]
[1] Mageba (Shanghai) Ltd., Shanghai, China
[2] Mageba SA, Bulach, Switzerland

ABSTRACT

Those who are responsible for the construction, maintenance and renovation of structures of any kind can potentially make use of the enormous assessment power of modern structural health monitoring (SHM) systems. Indeed, as SHM technology and the capabilities of practitioners rapidly improve, with new functionalities, increased performance and enhanced reliability available at lower costs, the usage of such systems can only increase in the future. Examples of the use of a modern automated system are presented, demonstrating its usefulness and ease of use, and the enormous gains in efficiency it offers over alternative manual monitoring methods, with information of far higher quality and usefulness provided in real time rather than just periodically. These examples shall include applications from stages right through the typical life of any structure: its initial construction; normal inspection and maintenance work during its service life; the investigation of specific concerns that may arise at any time in its life due to unforeseen events etc.; and renovation when the time comes to replace part or all of the structure. The great diversity of possible applications of SHM systems is also illustrated, with examples including both temporary and permanent applications, both passive and active, ranging from relatively simple to extensive and powerful, installed on small natural structures and large man-made ones – thus also demonstrating, perhaps, that modern SHM systems can offer a solution to any significant need for information that may be required in relation to any structure.

KEYWORDS

Structural health monitoring, applications, diversity, efficiency, reliability.

INTRODUCTION

Structural engineers often require detailed information in order to form a full and continually up-to-date understanding of the condition and performance of their structures, and such information is generally provided by some form of inspection or monitoring process or regime. An increasingly important role in this regard is played by modern automated structural health monitoring (SHM) systems, which can detect and immediately report any changes in selected monitored parameters. Knowledge of such changes can be used to draw conclusions about related changes such as structural deterioration or damage, or other events of interest. SHM systems offer many benefits over traditional manual observation and measurement methods: they are typically much more efficient, having far lower "running costs"; they are capable of an extraordinary level of detail and accuracy, e.g. in measuring high-frequency vibrations that would scarcely be registered by human touch; and they can be set up to operate 24 hours a day, 7 days a week, for as long as required, and can thus be relied on to immediately record and report unexpected / serious events, no matter when they might occur (Spuler *et al*. 2011). Thanks to these benefits, such systems can be used to serve many purposes in relation to bridges and other structures. For example, assessment of actual structural behaviour by means of experimental and theoretical investigations 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.

Applications can arise at any stage in the life of any structure, including as follows:

1. Initial construction
2. Normal inspection and maintenance work during its service life
3. Investigation of specific concerns that may arise at any time in its life (e.g. due to unforeseen events)
4. 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 demonstrated below with reference to various case studies.

APPLICATION #1: INITIAL CONSTRUCTION OF STRUCTURES

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.

Case study 1: Monitoring of the River Suir Bridge, Waterford, Ireland

The River Suir Bridge on the N25 Bypass of Waterford city was opened in 2009, with an overall length of 475 metres and a main span of 230 metres. An SHM system was installed during the construction of the bridge, to fulfil a series of functions. The system's first task was to optimise completion of the bridge's construction – in particular, the fine-tuning of the load distribution among the structure's stay cables. Then, before the bridge was opened to traffic, it served quality assurance purposes, providing a detailed record of key variables which helped prove the proper construction of the bridge. And with the bridge in service, the system finally took on the role of monitoring the bridge's condition on an ongoing basis.

A key element of the monitoring system's design is the monitoring of vibrations, which can tell so much about any cable supported structure's health at any time. Any significant change in the condition of a cable supported bridge, whether as a result of normal, gradual deterioration or a sudden, unexpected event, is likely to result in changes in the vibrations experienced by its cables – changes which can be picked up and reported by a high-frequency monitoring system. Evaluation of these vibrations can be used to assess dynamic behaviour by identification of principal modal frequencies and to determine cable forces in real time.

Figure 1 shows the system's "Cockpit" – a graphic display presenting a summary of the current values of all main variables, in a format which makes it easy to form a quick overview. Figure 2 shows an example of the data recorded by selected sensors over any selected period of time – in this case, the vibrations experienced by three stay cables. Anomalies in the data, such as the very prominent peaks, can be looked at to ensure that their cause is understood and no reason for concern.

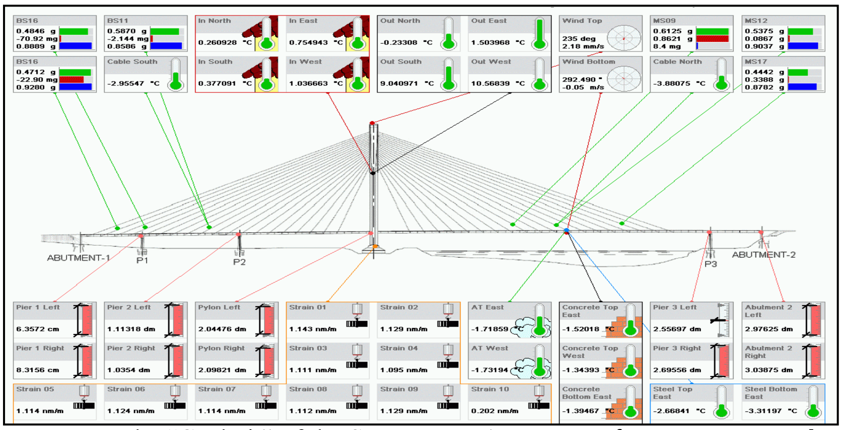

Figure 1. The "Cockpit" of the SHM system's user interface – presenting the current values of all main variables for an immediate overview

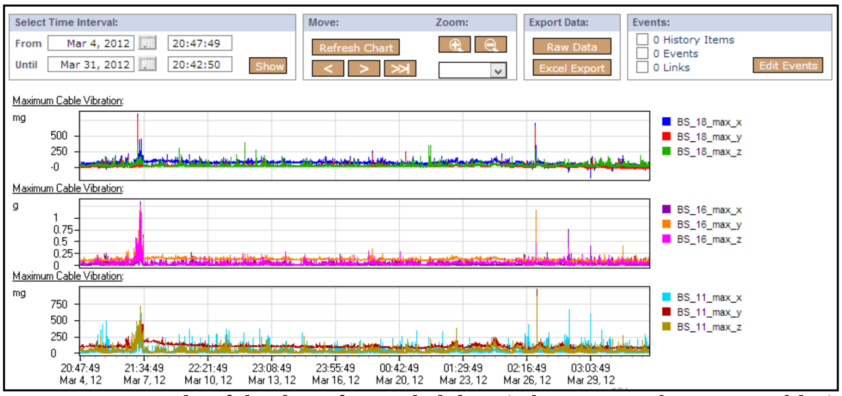

Figure 2. Example of display of recorded data (vibrations in three stay cables)

The system continues to give confidence, on an ongoing basis and with minimal effort by the responsible engineers, that the structure continues to fulfil its purpose safely and well.

APPLICATION #2: INSPECTION AND MAINTENANCE OF STRUCTURES

Automated SHM systems have a great deal to offer those who are charged with the inspection and maintenance of all types of structure, as demonstrated by the following case studies. The first presents a relatively simple application which serves a single easily-defined purpose.

Case study 2: Monitoring of rock face stabilisation at Rhine Waterfalls, Switzerland

The Rhine Falls (Figure 3) in Schaffhausen, Switzerland is visited by hundreds of thousands of tourists every year. It is one of the region's most important tourist attractions, and visitors can enjoy the spectacle from a terrace and viewing platforms on the rock face beneath the castle of Laufen.

Figure 3. The Rhine Falls in northern Switzerland

Figure 4. Rock wall with public terrace on top

Rock anchors installed to stabilise the 20m-high rock face (Figure 4) showed unexpected force changes, leading to concerns that some sliding surfaces had developed. To ensure the ongoing safety of the terrace above, 11 additional rock anchors were installed. A permanent SHM system was then connected to the newly installed anchors to constantly monitor the loads arising in them and continually transmit all measured data to a web interface for analysis at any time. The system also features an alarm function, designed to automatically send immediate notification should any pre-defined force value limitation be exceeded. The alarm values were chosen in accordance with the designer's requirement that the force arising in any anchor should not vary from its initial design force by more than 15%. This alarm function allows the site owner to have confidence that any changes in the condition of the rock wall will be immediately recognised and notified, enabling appropriate action to be taken to ensure the safety of the public.

It could already be concluded that the rock face has been well stabilised by the additional anchors, with only negligible movements observed. The measured data (Figure 5) demonstrates this, with forces shown to vary by just +/- 0.5%, and perfectly in line with temperature changes. The SHM system thus enables the owner to safely manage one of Switzerland's most frequented and most spectacular public terraces.

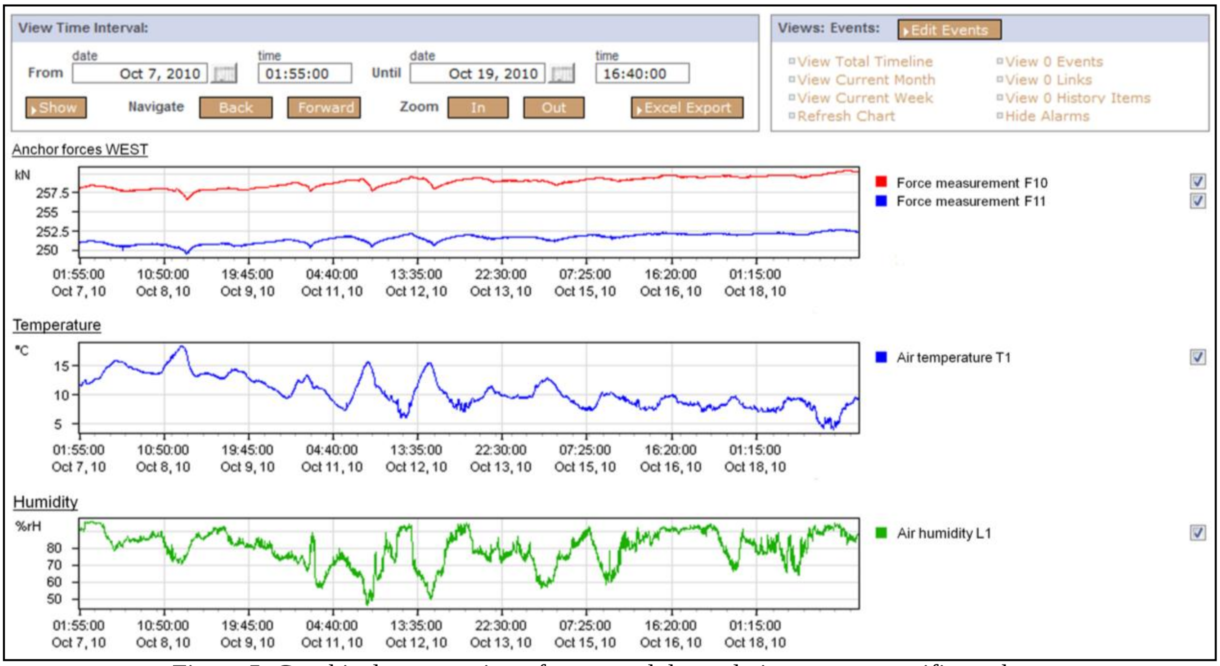

Figure 5. Graphical presentation of measured data relating to two specific anchors

The above project is an example of a simple, passive application on a small natural structure. The next is quite the opposite in some respects: an extensive and powerful, active application on a large man-made structure.

Case study 3: Monitoring of the Signature Bridge in Wazirabad, Delhi, India

A new cable stayed bridge is currently under construction across the Yamuna River in Wazirabad, Delhi (Figure 6). The bridge will have a total length of 675 metres, with a main span of 251 metres. Its steel-concrete composite deck, with a total width of 35 metres, will carry four lanes of traffic in each direction. Its dramatic inclined steel pylon, at 154 metres high, and elegant stay cable design, will make it a particularly attractive and imposing addition to the Wazirabad skyline. In addition to this pleasing aesthetic impact, the shape of the pylon enables it to provide, to a substantial extent, the stress balance required to support the deck.

Figure 6. The new Signature Bridge at Wazirabad, Delhi

The bridge will be equipped with a sophisticated SHM system (described by Furtner *et al*. 2013), which shall monitor the structure's behaviour, performance and condition. The system shall fulfil three major purposes:

- structural health monitoring and damage detection;
- monitoring of weather loading (e.g. temperature, storms); and
- earthquake monitoring.

It will do this by monitoring specific environmental factors, load factors and the bridge's structural response, using a wide array of sensors (Figure 7).

Sensor	Logo	Sensors according to Specifications	Channels according to Sensors
		Sensors	Channels
Structural Temperature	T	20	24
Strain gauge boltable	S	10	10
Strain gauge weldable / glueable	S	10	10
Wind sensor 3D	W	1	4
Wind multisensor (Wind 2D directrion and speed, ambient temperature, precipidation levels, barometric pressure, relative humidity)	WT	1	6
3D accelerometers, cables	A3w	18	54
3D accelerometer, deck & pylon	A	8	24
Seismic accelerometers	As	4	12
Displacement sensor	DI	4	4
Inclination, tilt	I	4	8
Corrosion	C	3	6
DV Camera	V	4	
Traffic analyzer	TA	8	
Electromagnetical sensors	E	9	9
Sum		104	171

Figure 7. Summary of the monitoring system's sensors

The integration of a fully automatic system identification algorithm, in the frequency domain, will allow the continuous tracking of the principal vibrational modes of the structure in order to detect any deterioration or other significant change or event. Once any such change or event has been notified by the system, its effects can be analysed in detail using the dense network of sensors recording acceleration, strain, corrosion, electromagnetic charge, etc.

The automated monitoring system will thus provide enormous amounts of information which will enable the conditions to which the bridge is subjected, and the structure's condition and performance, to be precisely evaluated with a minimum of effort. It is thus a good example of the type of comprehensive service which can be provided by modern SHM systems, if sensibly conceived, detailed and implemented.

The above case studies present permanent, long term applications - but temporary, short-term applications are also possible when data is required to assess a particular aspect of a structure's performance. Where the period during which data is to be gathered is short, use of a portable system may present an attractive alternative.

Case study 4: Short-term monitoring of the Danube Bridge, Sinzing, Germany using a portable system

The River Danube is crossed near the town of Sinzing by a bridge carrying the German Autobahn No. 3. The bridge has a total length of approximately 800m and consists of nine spans. The steel bridge deck is composed of two separate constructions, each consisting of two main girders and smaller transverse members. It was observed by the bridge owner that the bridge moves significantly under normal traffic loading, and that the PTFE sliding material of a number of the bridge bearings had been worn away to the point that it required replacement, as shown in Figure 8. This condition was reached after only five years of service, although PTFE sliding material can be expected to last at least twenty years under "normal" conditions. Therefore, it was surmised that the unusually large movements of the bridge had resulted in the early wearing away of the PTFE. But rather than simply replacing the PTFE discs of the bearings, the bridge owner decided to gain a fuller understanding of the movements and characteristics of the bridge, so that a lasting solution could be implemented, saving the effort and expense of replacing PTFE discs in the future.

One possible solution would involve replacing the PTFE sliding discs of the bearings with discs of a new, improved sliding material. The material, known as *RoboSlide*, is a special high-grade polyethylene which has been tested over a sliding distance of 60 km with no signs of abrasion. It was anticipated that this would be a suitable sliding material, even giving the demanding movements of the bridge. However, if the accumulated sliding distance would significantly exceed 60 km over the life of the bearing, then an alternative solution such as the addition of dampers or strengthening members to reduce the bridge movements might also be considered. A monitoring system was proposed to record movements of the bridge deck (to an accuracy of 0.1mm), strain in the bridge deck girders, acceleration of the bridge deck (in all three principle directions), rotations of the deck and temperatures (of the structure itself and ambient temperature).

Considering the short-term nature of the monitoring project, a portable system, consisting of a suitcase-held computer and sensors with cables, was selected. The system, powered by battery alone, was installed to collect data during three periods of approximately one day each. Figure 9 shows an example of the measured longitudinal movement at three sensors during the first measurement period. The expansion of the bridge due to daytime warming can be easily recognised.

Figure 8. Wear of PTFE sliding discs

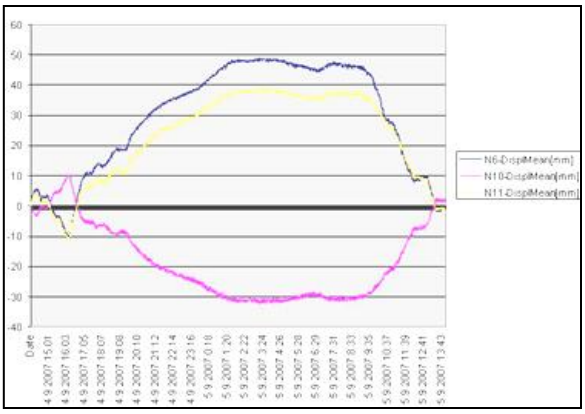

Figure 9. Longitudinal displacement at three locations

Based on the measured data, it could be established that the total longitudinal movement of the bridge deck over its bearings came to 6,350mm during a period of 22.5 hours. Extrapolating this, it could be concluded that the total accumulated longitudinal sliding distance in a year would be approximately 2,500m. This meant that total sliding movements of up to 12 kilometres had likely already occurred after five years of service. It is known that PTFE sliding material is susceptible to deterioration already after 10,000m, and no further exceptional conditions were observed at the bridge which could explain such early deterioration of the sliding surface material. Therefore, it was concluded that the high movements of the bridge were indeed the primary cause of the wearing away of the PTFE discs.

Based on the results from the monitoring project, it was decided to replace the sliding discs of the bearings with the new *RoboSlide* material, which not only exhibits far higher resistance to wear than PTFE, but also offers lower friction values. It can thus now be expected that the new sliding discs will perform well for the remaining life of the bearings.

A further application arises at any specific time during the life of the structure, should a specific concern arise. An example of such a concern, and how it was addressed using an SHM system, is presented below.

APPLICATION #3: INVESTIGATION OF SPECIFIC CONCERNS THAT MAY ARISE

Case study 5: Monitoring of the Weyermannshaus Viaduct, Berne, Switzerland

The Weyermannshaus Viaduct is 912 m long, and the height of its deck above the ground varies from 10m to 15m. The bridge is a post-tensioned, pre-stressed concrete structure, with a maximum width of 40m. Several decades after construction, a detailed visual inspection of the bridge identified localised surface cracking of the concrete, concentrated at the locations of the coupling joints of the pre-stressing cables (see Figure 10). The appearance of these cracks could not be explained, and it could not even be established if they appeared already during construction of the bridge due to the impact of post-tensioning of the pre-stressing cables, or later during its operational phase.

The authorities decided to further analyse the matter using only non-destructive methods (Spuler *et al*. 2010). The analysis would identify the cause of the cracking and assess the condition of the structure, drawing conclusions about the remaining life expectancy of the bridge. Assessment by experts could theoretically conclude that the observed cracking was external only and that the bridge was generally healthy, or that the structure should be considered to have a ‘fully-cracked’ cross section resulting from serious overloading. While previous assessments by bridge experts, based on the limited information available, did not conclude that the bridge was likely to be in a poor condition, the monitoring was expected to confirm this hypothesis in a relatively easy and economical way. Failing this, the safety of the bridge may have had to be ensured by application of external reinforcement, at great expense.

Based on the decision that only non-destructive methods could be applied, it was decided to install a permanent SHM system to monitor crack widths. The high frequency system selected was designed with 16 inductive movement sensors, situated at the post-tensioning coupling joint locations at three different axes of the structure. In order to measure with the required accuracy, these sensors had a tolerance of 0.0001 mm, were temperature compensated, and were highly resistant to pollution by any kind of dirt and to magnetic disturbance. Weather conditions were monitored by four temperature sensors, which were drilled into the concrete, and two meteorological stations measured temperature and humidity of the air. The measurement frequencies could be varied between 1 Hz and 500 Hz. A data pre-analysis could be programmed to filter the data output and to ensure an adequate data supply while limiting transmission costs.

A calculation model developed for the structure by the responsible engineer allowed characteristics such as the tension in the reinforcement of the concrete and the condition of the pre-stressing cables to be deduced from the measured crack widths. This required a measurement frequency of 200 Hz to ensure adequate results, as lower frequencies wouldn’t permit measurement of the impacts of vehicles moving at up to 120 km/h. The data was processed locally and saved on a local hard disc.

To facilitate calibration of the system, the bridge was temporarily closed to traffic while a truck with a known weight of 40 tonnes passed over the critical sections of the structure at different, predefined speeds. As expected, variation of the speed had no impact, meaning the crack width during the passing of a slow truck is similar to the crack width during the passing of a truck travelling at 80 km/h.

The first comparison of the measured values with the calculated figures of the static model showed an excellent correlation between the measured values and the predicted results from the ‘non-cracked’ concrete cross section model. This correlation is shown in Figure 11, where graphs representing measured and predicted values are presented together. This analysis provided the first solid evidence that the bridge is generally in good condition, and not deteriorating under the effect of traffic loading, saving the need for strengthening works.

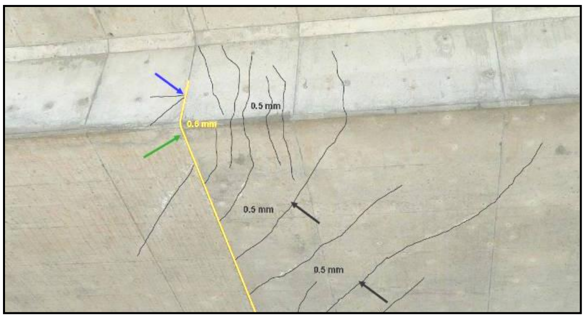

Figure 10. Cracking of concrete on underside of deck at coupling joint of cables

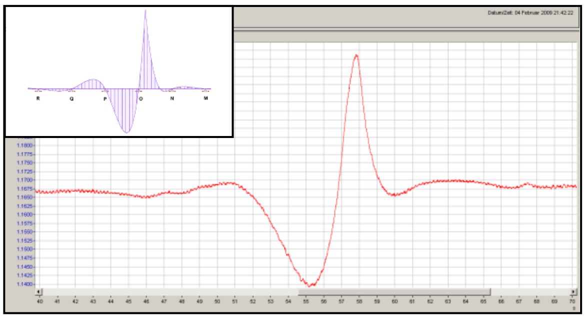

Figure 11. Crack widths (main graph), demonstrating excellent correlation with calculated influence line of static model for non-cracked condition (inset graph)

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.

APPLICATION #4: RENOVATION OF STRUCTURES

Case study 6: Monitoring of the Angus L. MacDonald and A. Murray Mackay bridges, Halifax, Canada

The city of Halifax, capital of the Canadian province of Nova Scotia, relies heavily on two structures in particular - the Angus L. Macdonald Bridge (Figure 12) and the A. Murray MacKay Bridge (Figure 13), both of which connect the city across the sea inlet that divides it in two. Having been opened to traffic in 1955 and 1970 respectively, both structures have already provided several decades of service. The A. Murray MacKay Bridge was renovated in recent years, and similar renovation works, with similar changes to the bearing support of the bridge deck, are currently being planned for the Angus L. Macdonald Bridge. It is proposed that it will receive an entire new deck, and computer modelling of the deck, verified by measured data, will play a key role in the design process.
It was determined that a structural health monitoring system should be used to measure and record the movements and rotations of the deck of the Angus L. Macdonald Bridge at its expansion joints, providing the data needed by the computer modelling. It was also decided to monitor the movements of the previously renovated deck of the A. Murray MacKay Bridge, so that the effects of the renovation works (and in particular, the changes to the deck support system) can be accounted for in the planning of the proposed works. An example of some of the data provided by the system, for a specified period of time, is presented in Figure 14. This particular data enables rotations and displacements (both longitudinal and transverse) to be easily related to temperature, and to wind strength and direction.

Figure 12. The Angus L. Macdonald Bridge

Figure 13. The A. Murray Mackay Bridge

Although the system is still gathering data which will be used by the bridge's design engineers in any way they see fit, it has already provided a very interesting insight into the movements of the deck of the A. Murray Mackay Bridge. It could already be established that the deck moves a great deal in the longitudinal direction, with accumulated movements of up to 35 kilometres per year at a single expansion joint. Such enormous accumulated movements are extremely rare, and many times higher than the movements experienced by the decks of the great majority of long span bridges. For comparison, the movements of the existing deck of the neighbouring Angus L. Macdonald Bridge are estimated by the same monitoring system to amount to less than 700 m per year at each joint, or just 2% of the accumulated movements at the A. Murray Mackay Bridge. This gives a strong indication of how the movements of the new deck of the Angus L. Macdonald Bridge will increase if it is supported in the same way as the previously renovated deck of the A. Murray Mackay Bridge. The understanding of deck movements provided by the SHM system will thus play a crucial role in supporting the planning of renovation works of one deck and maintenance and possible adaptation works of the other. For instance, all mechanical parts of the bridge, such as its expansion joints and bearings, must be capable of accommodating and withstanding these extreme movements; and ways of controlling and minimising the movements may also be considered – for example, through the use of hydraulic dampers. By recognising and understanding the challenge, the responsible engineers are well equipped to plan and implement effective, durable solutions.

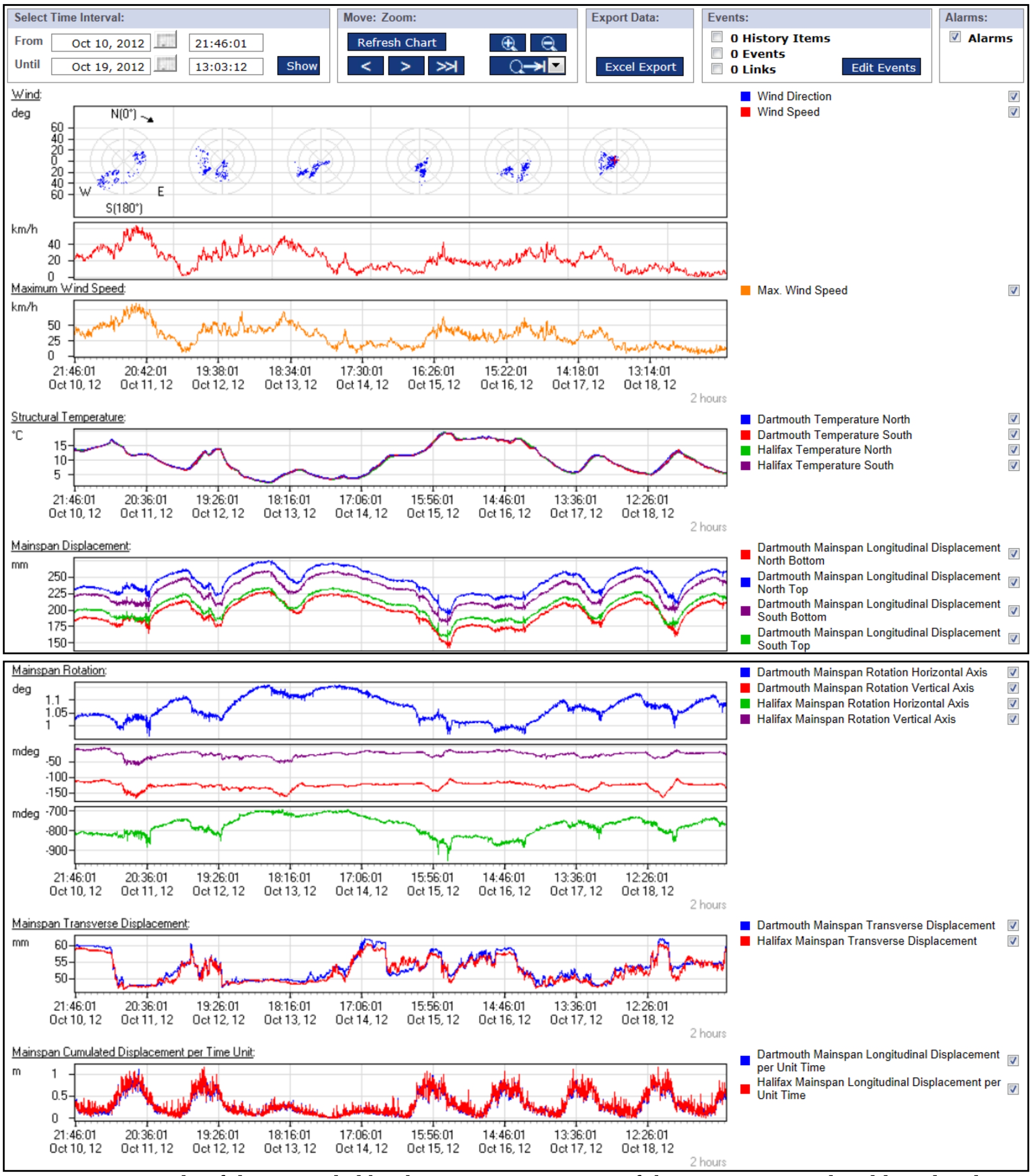

Figure 14. Example of data recorded by the monitoring system of the Angus L. Macdonald Bridge during a selected 9-day period. Rotations and displacements (both longitudinal and transverse) can be easily related to temperature, and to wind strength and direction

The greatest challenge posed by the very large accumulated movements of the Mackay Bridge, which have been identified and quantified by the monitoring system, may relate to the expansion joints which must facilitate the movements while providing a driving surface at each end of the deck. Fortunately, the supplier of the monitoring system, also a supplier of bridge expansion joints and other components, has experience of supplying large modular joints for another bridge which imposes even greater accumulated movements. The New Lillebaelt Bridge in Denmark was equipped in 2002/2003 with modular expansion joints at 6 bridge axes, with up to 16 gaps per joint. The total annual movement at one joint has been estimated to amount to 98 kilometres per year – a truly exceptional figure. Having developed a lasting solution to that particular challenge, incorporating adaptations to the design of the joint and the use of special high-performance sliding and control components, it is possible to have confidence in at least one solution to this particular challenge.

The use of the monitoring system has thus already enabled a highly unusual demand, and a significant potential problem in the performance of the renovated bridge's expansion joints, to be identified in advance, ensuring that it is properly addressed right from the start.

CONCLUSIONS

The potential applications of automated SHM systems are almost unlimited and very varied. They 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. Monitoring solutions can be short- or long-term, passive or active, and can be tailored to fulfil the specific needs of any particular structure at any time in a highly efficient, effective manner.

This makes SHM systems a very useful tool in many circumstances, and indeed, often an essential one 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 and management of structures in years to come.

REFERENCES

Furtner, P., Della Ca', D. and Ghosh, C. (2013). "Structural health monitoring of Signature Bridge in Delhi - the BSHMS for the Wazirabad Bridge Project", *Proc. IABSE Symposium on Long Span Bridges and Roofs, Kolkata*.

Spuler, T., Moor, G. and Berger, R. (2010). "Automated structural health monitoring – filling a knowledge gap", *Proc. 3rd fib International Congress, Washington D.C*.

Spuler, T., Moor, G., O'Suilleabhain, C. and Berger, R. (2011). "Modern remote structural health monitoring - providing long-term confidence in a structure's condition", *Proc. Middle East Conf. on Smart Monitoring, Assessment and Rehailitation of Civil Structures, Dubai*.