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SMART STRUCTURAL MONITORING OF LONG-SPAN BRIDGES

John St Leger[1], Matthew Anderson[2] and Sarah Babin[3]

ABSTRACT

The paper considers the following from a practical perspective:

1) Current effective monitoring systems and how new sensor technology and future developments will help.

2) The fast moving world of web based applications for the delivery of structure information.

3) Derivation of meaningful and timely information from structural health monitoring systems to enable effective bridge management and informed decision making.

4) An overview of state-of-the-art structural health monitoring systems for bridges.

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Introduction

For a Structural Health Monitoring System (SHMS) to be smart, it cannot simply employ sensors on a bridge to record data that is delivered directly to the end user. The development of a smart SHMS starts with close liaison with the end user to establish the exact output and display requirements. Subsequently, appropriate data processing, check and interpretation scripts must be created to extract useful information from the captured sensor data. Finally, logical feedback loops are used to ensure that the end user is supplied with reliable evidence to allow them to make timely informed decisions and implement mitigating actions where required [1].

Bridge types considered include both suspension and cable-stayed bridges, an example of which is the İzmit Bay Bridge in Turkey as illustrated in Fig. 1. This bridge is currently under construction and will comprise a main span of 1,550 metres; making it the fourth longest suspension bridge in the world. The site of the bridge is one of the most seismically active. At the outset, a SHMS has been specified which will comprise of some 430 sensors to monitor loading on the bridge (wind, highway, temperature, seismic) and effects on the bridge (strain, acceleration, displacement, temperature).

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Figure 1. Artist’s impression of Izmit Bay Bridge, Turkey.

Current Effective Monitoring Systems

SHMSs can provide extremely powerful and cost saving information if they are specified with an appropriate level of quality, robustness and with the end user’s requirements in mind. It is essential to ensure that the procurement of SHMSs is not just based on the installation of the maximum number of sensors for the lowest price, as this approach results in poor quality unreliable systems which produce excessive volumes of data. The industry needs to be alert to the issues involved.

Current effective monitoring systems are capable of providing the bridge owner and operator with important information regarding the behaviour, condition and safety of the structure, thus assiting with the development of operation and maintenance plans as outlined in Fig. 2.

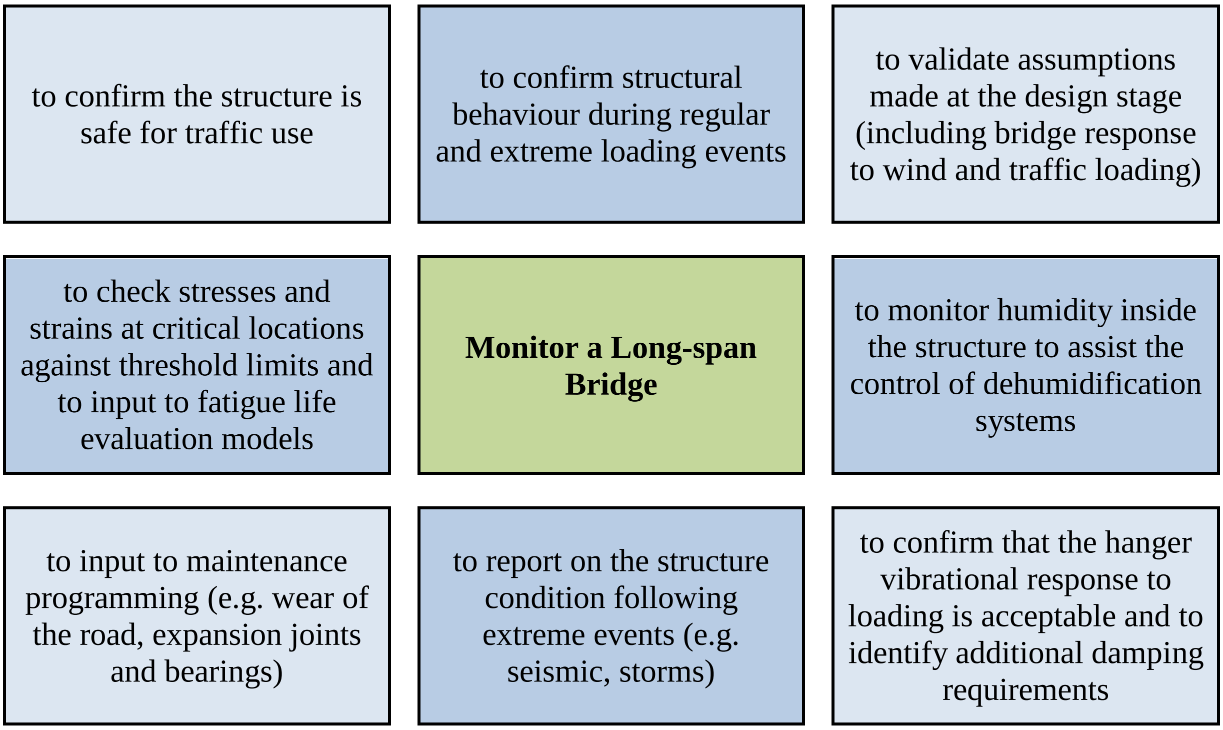

Figure 2. Example information from a Structural Health Monitoring System.

Meteorological Monitoring

Correlation of monitored meteorological conditions with the behaviour of a long-span bridge can enable the assessment of whether a structure is performing within its design parameter allowances; thus enabling the early detection of unexpected structural responses and conditions which exceed those assumed at the design stage. Such behavioral monitoring also provides for the development of an understanding of a bridge's response to meteorological parameters thus enabling future long-span bridge designs to be further refined and optimised. In addition, meteorological monitoring can support the safe operation of a bridge through the restriction of its use during periods when defined thresholds are exceeded.

Frequently, long-span bridges are considered to be suitable locations to install weather stations that monitor parameters such as atmospheric pressure (using barometers), rainfall (using tipping bucket rainfall gauges) and solar radiation (using pyranometers) The data from these sensors assists management of the structure and provides valuable supporting information for local weather records and forecasts.

Wind

Prevailing winds can exert significant loading on long-span bridges, resulting in dynamic structural deformation, translation and vibration. In particular, wind induced resonant responses in the deck, towers and cables can result in flutter instability, buffeting excitation and vortex shedding. It is therefore essential that for behaviour correlation and design validation purposes, sensors to measure wind speed and direction are installed at critical location on a long-span bridge.

Furthermore, wind speed and wind direction data can automatically be compared against predefined thresholds, which when exceeded results in the generation of a message to relevant control centres to alert them to the requirement for traffic signs limiting access to the bridge deck. This system thus provides for the safety of the travelling public and helps ensure that the bridge structure is not put at risk as a result of collision damage from errant vehicles.

Modern SHMSs include three-dimensional ultrasonic anemometers, as illustrated in Fig. 3, that are capable of measuring wind speed in three orthogonal directions at a high sampling rate, making them ideal for the real-time monitoring of wind turbulence. In addition, as ultrasonic anemometers do not have mechanically moving parts, maintenance requirements are low and the sensor does not usually need recalibration following the initial setting. Typically, on a long-span bridge, these sensors are installed on bridge deck booms and tower top masts to monitor crosswind speeds and wind direction during both the construction and operational phases.

Nonetheless, more traditional methods of wind monitoring including mechanical (cup and propeller) anemometers and weather vanes as shown in Fig. 3) are still employed today in situations where initial low cost and low system power requirements are important and a shorter sensor life cycle is acceptable.

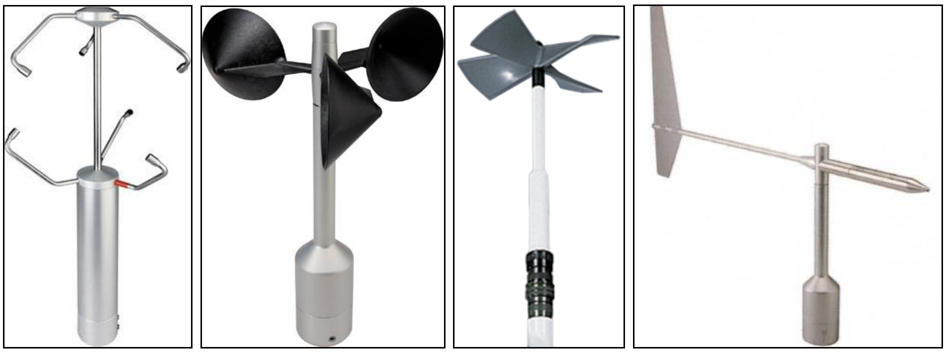

Figure 3. (Left to right): Typical 3D ultrasonic anemometer, mechanical cup anemometer, vertical propeller anemometer and wind vane

Air Temperature and Humidity

Thermal variations are responsible for significant expansion and contraction of long-span bridge decks and structural components. Daily and seasonal changes in shade air temperature, solar radiation and reradiation cause the effective temperature and temperature differences of a bridge superstructure to change. It is therefore essential that for behaviour correlation and design validation purposes, sensors to measure air and structure temperature are installed.

Temperature sensors used on bridge structures include thermocouples, thermistors, resistance temperature detectors and temperature integrated circuits. While thermocouples are rugged and comparatively inexpensive, they offer a wide measurement range, but are the least stable form of temperature sensor. Thermistors respond quickly but only over a limited temperature range. Resistance temperature detectors are the slowest to respond, but are stable and accurate and are comparatively expensive. Temperature integrated circuits are inexpensive sensors, and are the most linear but are slow to respond.

Relative humidity sensors are used to monitor the humidity inside a structure to enable control and performance assessment of dehumidification systems.

Highway Live Load Monitoring

Long-span bridge decks are required to carry a wide variety of vehicles each day and hence bridge decks are subjected to a wide spectrum of axle loads and axle configurations, vehicle numbers, gross weights, all of which may be applied at different speeds depending on traffic flow conditions.

The most effective method of monitoring the highway live loading which a bridge deck carries over a period of time is by using a Dynamic Weigh-in-Motion System (DWIMS) which records the axle weights of traffic crossing a measurement site. The recorded data can be processed to derive information regarding the number and type of vehicles using the bridge and when compared with the highway loading allowed for in the design will yield a basis from which the safety of the bridge can be assessed.

Seismic Load Monitoring

Real-time seismic monitoring of long-span bridges located in earthquake zones is essential so that information can be provided to structure operations teams undertaking safety evaluations of structural components after seismic events.

Accelerometers and dynamic displacement and positional sensors are used to monitor the dynamic response of the structure to seismic loading and the settlement of foundations, respectively. The monitoring results captured can be used to evaluate the actual loading applied to the structure and can be rapidly evaluated against predetermined thresholds to provide a basis to support damage assessment and the rapid reopening of the bridge after the event. The ability to interrogate and relate data traces as necessary both during and after an event, even by staff working remotely using a web browser can play a major role in the recovery effort.

Figure 4. (Left to right): Typical linear variable displacement transducers, magnetostrictive sensor, and GPS/GNSS receiver.

Position Monitoring

Displacement sensors (e.g. ultrasonic sensors, linear variable displacement transducers and magnetostrictive sensors, reference Fig. 4) can be used to track the movement of bridge bearings and expansion joints and hence record their cumulative travel, which provides a very valuable guide to the amount of bearing or joint wear which has taken place and provide an estimate of the remaining life available. In addition, displacement sensors measuring expansion joint movements are capable of detecting the deck movements induced by combinations of vehicles travelling across a bridge, and thermal effects. From this the cumulative travel of the joint can be calculated, thus providing a measure of the remaining fatigue life of the joint. GPS equipment (reference Fig. 4), is now used to monitor the dynamic position of long-span bridge decks and towers and in conjunction with inclinometers (reference Fig. 5), is capable of assisting with the monitoring of structural movement and the deflected shape of the deck and towers.

Hanger Load Monitoring

Measurement of the actual in service loads experienced by the bridge hangers can be undertaken using load pins which are installed in place of the conventional pins (reference Fig. 5).

In addition, linear variable displacement transducers and magneto-elastic sensors (reference Figs. 4 and 5) can be fitted to hangers and individual hanger cable strands to provide a measure of the induced forces.

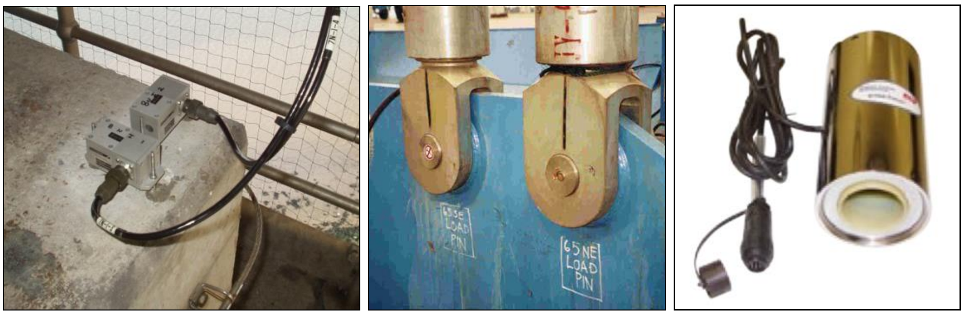

Figure 5. (Left to right): Inclinometers, load pin and magneto-elastic sensor.

Tower Settlement Monitoring

During construction, settlement of the bridge towers may result in the requirement for height correction using additional materials. To provide a measure of the height correction required, vibration wire pressure sensors can be used. In addition, sensors can be provided to measure settlement effects induced during seismic events at tower bases relative to a base station.

Strain Monitoring

Current SHMSs employ fibre optic sensors to monitor the strain and temperatures in structural components, including the deck structure and hanger cables.

Highway live loading over time gives rise to repeated application of stress cycle patterns which for fatigue-susceptible structural members is critical to assessing the level of fatigue loading to which they have been subjected. Dynamic strain gauges are used to capture high frequency strain measurements; allowing a more accurate estimation of the actual stresses in the structure to be derived and subsequently compared with the stresses calculated at the design phase. The strain measurements obtained enable calculation of the number and intensity of fatigue cycles particular structural members have been subjected to and if installed from the outset, will yield a basis from which the proportion of the bridge fatigue life used to date can be predicted.

How New Sensor Technology and Future Developments will Help

Monitoring system technology is continually developing with a view to optimising service quality, cost, efficiency and environmental impact. For example, SHMSs for long-span bridges frequently comprise multiple data acquisition units for the capture of sensor data which can be located many kilometres apart. New technical developments using GPS and Precision Time Protocol technology now enable each computer clock within a network to be time synchronised to sub-millisecond accuracy. In addition, the availability of fibre optic cable to implement high-speed data communication networks is transforming the capacity and ability of SHMSs to effectively provide real-time monitoring of large numbers of sensors on bridge structures.

Dynamic data denotes information that changes continuously as further updates become available. As sensor, logger and network communication systems are developed, the frequency at which data is captured can be increased to suit requirements. Notably, dynamic positional information accurate to 0.1 mm on long-span bridges could soon become a reality.

Developments in the provision of active aerodynamic control surfaces for bridge decks suggest that it is possible to raise the critical flutter speed of a long-span deck by significant amounts. The provision of adaptive damping control in bridges could lead to an improvement in the fatigue service life of critical structural components. Likewise the provision of smart control systems could in the future provide improved damping of wind induced vibrations in cables and active mass damping using multimodal control to improve a bridge structure's performance during an earthquake.

Brillouin optical time domain reflectometry (BOTDR) optical fibre sensing systems are being developed and proven. Of significance to bridge engineers is the work currently being undertaken to enable the use of fibre optic systems for the monitoring of dynamic strains and to reduce the cost of optical sensing cables and spectrum analysers [2].

Micro-Electro-Mechanical Systems (MEMS) combine conventional SHMS components into a single miniature integrated device resulting in a system that is smaller and less intrusive, has lower power consumption requirements, is value for money and has a longer service life. Combined with new wireless sensor network technology, MEMS could provide the industry with a low cost system that can be rapidly installed [2]. Also, energy harvesting developments are assisting with the capture of renewable energy such as vibration.

Computer vision tools are under development with a view to replacing visual structural inspections for the detection of structural abnormalities, such as cracks. The development of new change detection software will enable the rapid, quantified and objective assessment of structural deterioration and new anomalies [2].

Electrically conductive paint is now available and can be applied to almost any surface. This combined with the future development of surface coating technology based on the use of 3D printers makes it possible to print a sensor based "nervous system" on the surface of critical structural components which opens up significant opportunities in the provision of "intelligent" monitoring systems. Likewise, wide scale monitoring systems will become increasingly possible through the development of super-fast quantum computers.

The Fast Moving World of Web Based Applications for the Delivery of Structure Information

Traditionally, web based applications are used to deliver monitoring system data and graphs to the user; however, it has long been recognised that unprocessed data is of little value when it comes to making reliable, timely and informed decisions for bridge management.

More recently, there has been a move to better understand the end user's requirements, which has enabled the design of a new effective IT system architecture that uses the latest web technologies to present information in a simple and intuitive format with appropriate levels of decision support information. Cost effectiveness is achieved through the use of open source code and clever scripting that ensures a rapid system response time without the requirement for expensive hardware [3].

Furthermore, the new system architecture is configured as a scalable and flexible framework that provides a core data processing engine and user interface that can be rapidly customised to meet the requirements of a specific structure (reference Fig. 6).

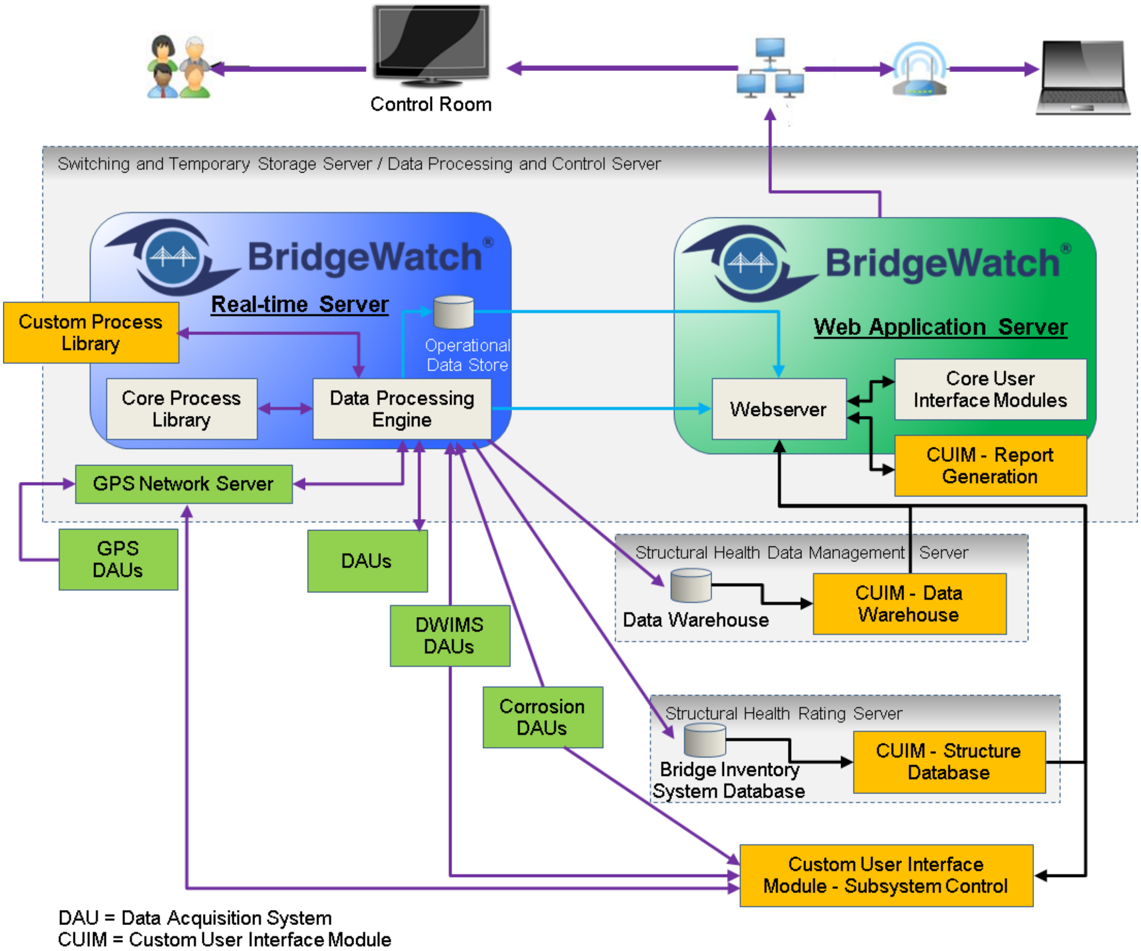

Figure 6. Web Based Application Framework Logical Architecture View (Strainstall BridgeWatch®).

State-of-the-art web application technology is now rapidly developing and complex algorithms are being used to process and further interpret sensor data; promptly delivering user-friendly information to multi-platform devices. In addition, real-time data is being combined with dynamic two and three-dimensional structure graphics to provide the end user with a visual representation of the bridge movement (reference Fig. 7).

Typically, monitoring using GPS, corrosion sensors and DWIMS is undertaken using specialised proprietary systems; each utilising individually designed display software making structure performance reviews disjointed and cumbersome. However, modern web applications are capable of integrating these monitoring subsystems so that the comparisons and analyses required for decision making can be undertaken.

Going into the future, it is likely that monitoring web applications will include, as standard, finite element analysis software that uses real-time monitoring data in conjunction with a bridge computer model, allowing analyses to be verified and the significance of specific movements to be quantified and assessed.

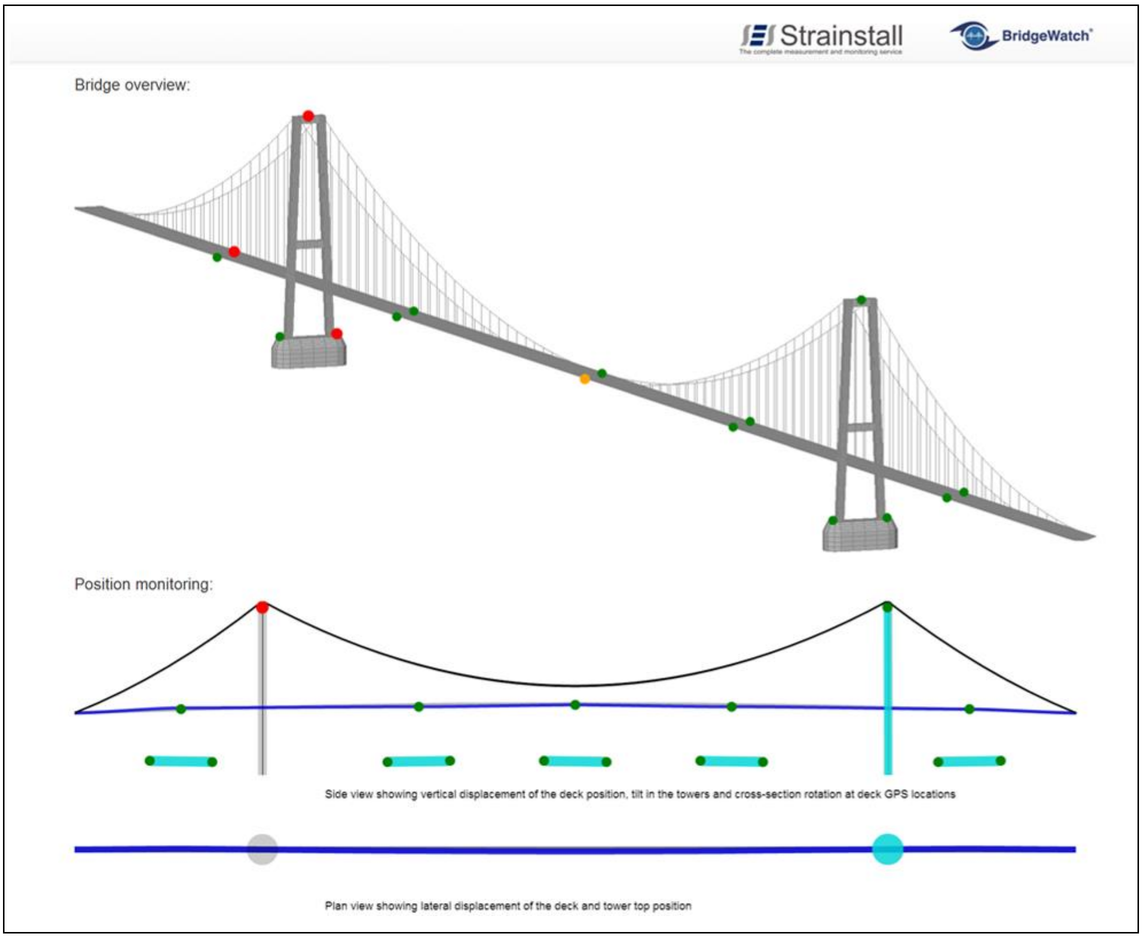

Figure 7. State-of-the-art Web Based Application Screenshot (Strainstall BridgeWatch®).

Derivation of Meaningful and Timely Information from Structural Health Monitoring Systems to Enable Effective Bridge Management and Informed Decision Making [4]

When setting out to design a SHMS, it is essential to first establish what information will be required from it and how it will be used to provide for the efficient management of a structure. Once decided, it is then possible to carefully define what data will be required, how it will be collected, analysed and interpreted. Finally, very careful thought must be given to establish how the data will be processed and 'distilled' to provide relevant timely information which must then be communicated in an easily understood format to the structure operations team to enable appropriate relevant decisions to be made by them regarding the operation and maintenance aspects of the structure.

While many structure operations teams use a wide variety of computer based systems and techniques designed to help them make better, more informed decisions, we are still told by many that they are 'drowning in data, whilst thirsting for information'. In order to extract the maximum information out of the data that is available, a structured approach to working with data to inform decision making must be adopted. In addition, where computer based systems and techniques are used, they need to be supported by appropriate processes, properly trained staff, an effective supporting infrastructure and a culture where actions and the intended behaviour or outcomes are established and understood.

Other important factors which must be considered as they can limit the decision making process, include the following:

- The context and purpose for which data is collected as this can significantly affect the data and its interpretation and care must be taken when using such data in a context or for a purpose not originally intended.
- The degree of alignment between the as-built structure, the data-capture model and the decision makers' mental model.
- The fact that people do not necessarily take a rational approach to decision making.

As opposed to monitoring applications where sensors are used in a passive manner to measure structural responses, feedback control systems require real-time system decision making based on structural response measurements. When a SHMS is installed to monitor the effects of extreme events, major maintenance work or construction, the availability and real-time use of monitoring information is vital. Accurate information about how a structure is actually performing compared to that predicted by analysis results in better informed decisions being made; allowing work to proceed during critical phases.

An Overview of State-of-the-Art Structural Health Monitoring Systems for Bridges

Appropriate SHMSs are deployed on long-span bridges to quantitatively assess their operational lifetimes, to ensure their safe operation and to enable optimisation of their management based on actual measured behaviour and are successfully used to:

- Monitor the bridge's response during construction;
- Confirm design assumptions;
- Monitor the structure before, during and after the passage of abnormal loads;
- Support the research and development of new monitoring techniques;
- Measure actual in service loads;
- Reduce the number of site visits for inspections and hence reduces working at height, in confined spaces or in carriageways;
- Assess the health of the structure by undertake special investigations and monitoring the deterioration of specific structural defects identified during inspection;
- Safely extend the lifetime of sub-standard bridges[5];
- Monitor the structure during maintenance work;
- Postpone expenditure on strengthening, reconstruction and repair; and
- Monitor the safe decommissioning and demolition of the structure.

References

1. The Royal Academy of Engineering, (2012), Smart infrastructure: the future (www.raeng.org.uk/news/publications/list/reports/smart_infrastructure_report_january_2012.pdf).

2. Cambridge Centre for Smart Infrastructure and Construction (CSIC), Annual Review 2014, Transforming Infrastructure (www-smartinfrastructure.eng.cam.ac.uk/news/20140327csicannualreview2014released).

3. Scullion, A., Day, C., Brownjohn, J., Koo K. (2013), Developing an IT-Based SHM System for Bridge Management, The 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure, Hong Kong.

4. St Leger, J., Anderson, M., Babin, S (2013), Smart Structural Monitoring Giving Data the Green Light, The 8th International Cable Supported Bridge Operators Conference, Edinburgh.

5. Design Manual for Roads and Bridges, Volume 3: Highways Structures: Inspection and Maintenance, Section 4: Assessment, Part 18, BD 79/13: The Management of Sub-standard Highway Structures.