



Smart bridge components (expansion joints, bearings and seismic devices) for intelligent infrastructure

Kleidi Islami, Niculin Meng, Colm O'Suilleabhain

mageba SA, Bülach, Switzerland

Contact: kislami@mageba.ch

Abstract

Modern automated structural health monitoring (SHM) systems have much to offer the responsible engineers in the construction, inspection, maintenance and renovation of structures in general, and of key structural components such as bridge bearings, expansion joints and seismic protection devices in particular. In the past, monitoring of such components generally involved the use of separate, independent sensors, connected not to the component but to the main structure and provided, to all intents and purposes, as an afterthought to the design and use of the components themselves. Improving technology is changing this, however, with “smart” components now available, with sensors pre-integrated in their design and fabrication before they leave the factory, and data analysis capabilities improving to include automatic identification of component damage based on general testing and teaching of the system.

Keywords: bridge components; SHM; automated monitoring; damage detection; expansion joints; bearings; dampers.

1 Introduction

Recent technological developments in the field of structural health monitoring (SHM), particularly in relation to sensors and data logging, have greatly increased the potential of such technology to play a valuable role in civil and structural engineering – especially as it relates to critical infrastructure such as road and railway bridges. Continually progressing research work, and the innovations of suppliers, have resulted in the development of systems and solutions which can greatly increase the effectiveness and efficiency of bridge construction, inspection, maintenance and renovation work [1].

One such area of innovation relates to the key components which, if present, are generally critically important to a bridge's efficient design and proper functioning: its bearings, expansion joints and seismic protection devices such as

dampers. This has led to the development of “smart” components, which feature pre-integrated SHM sensors already when fabricated, enabling bridge engineers to optimise the efficiency of their work as it relates to their structures' key components (Figure 1).

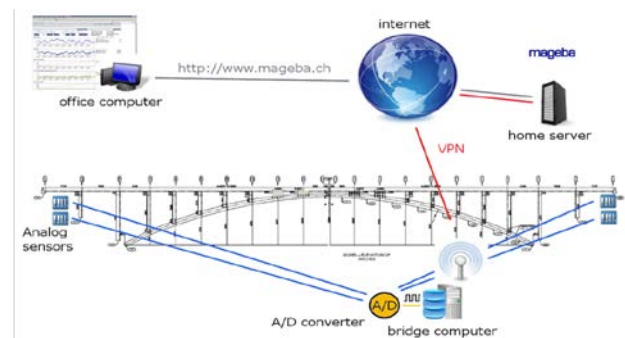


Figure 1. An SHM system with sensors integrated in key structural components can optimise inspection and maintenance activities

2 Typical uses and benefits of SHM in construction and maintenance

Modern SHM systems can be used to provide reliable, precise data on virtually any variable of interest – e.g. forces, movements or rotations of any part of a structure. The data can be automatically measured and recorded around the clock, all year round, and at high frequency if required (e.g. to analyse vibrations), making the use of SHM much more capable, and also more efficient and cost effective, than traditional manual methods in many cases. By presenting the recorded data on a graph (for example, as shown

in Figure 2), typically on a secure web interface, the effects of selected factors (e.g. temperature) on particular variables (e.g. superstructure movements, absolute or accumulated) can be easily analysed and understood.

Where specific concerns exist about a structure’s safety or performance, an SHM system can be designed to provide notification, by email or SMS, to the responsible engineer of any exceeding of defined threshold values – for example, should movements of any part of the structure exceed expected values, or the width of a crack suddenly increase.

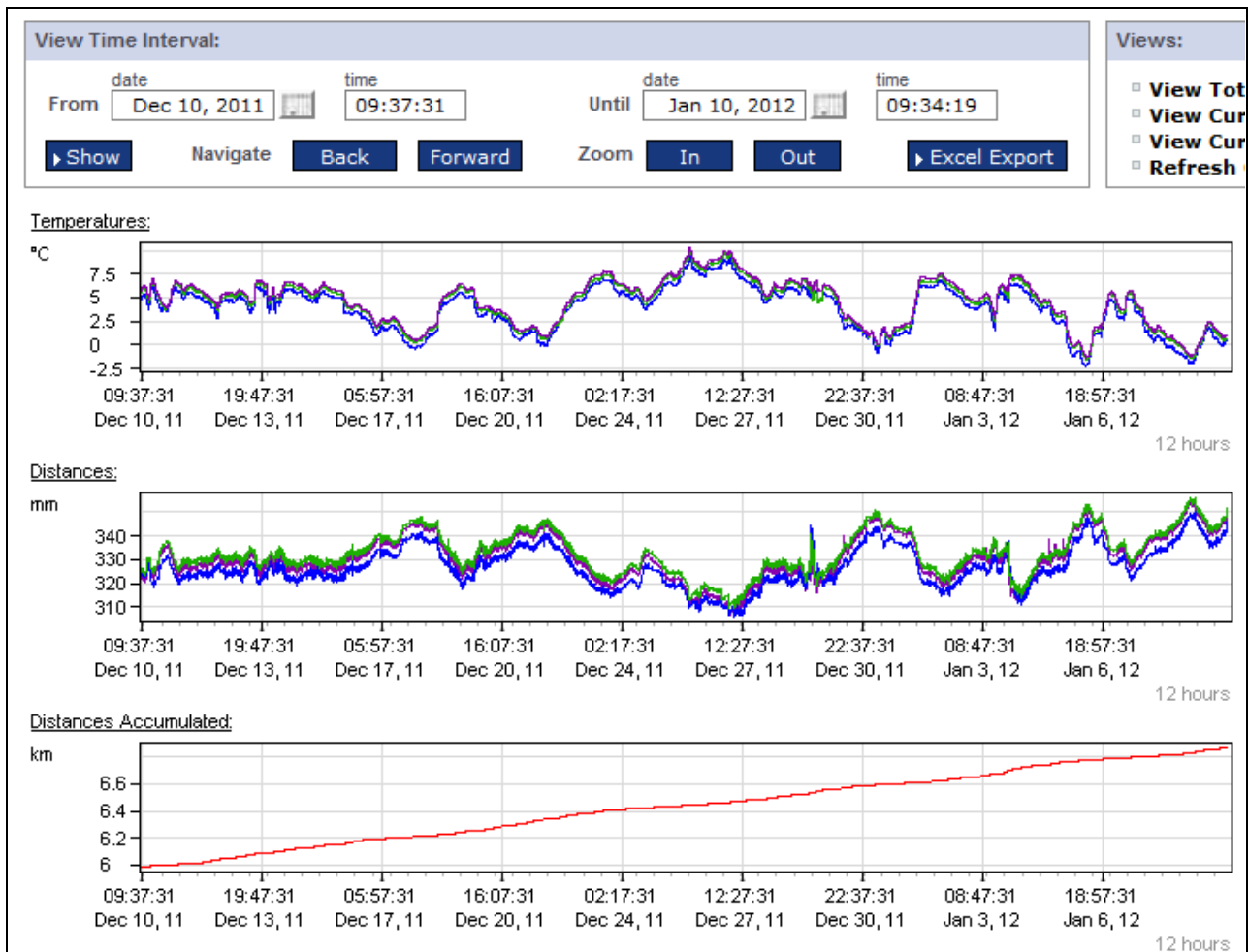


Figure 2. Presentation of measured data (graph form) on web interface

Modern SHM systems can also be programmed to statistically analyse the data they record for easier evaluation. For example, histograms such as that shown in Figure 3 can be generated to visually present the frequency of occurrence of values in any given variable during a selected period of time, enabling anomalies to be readily identified.

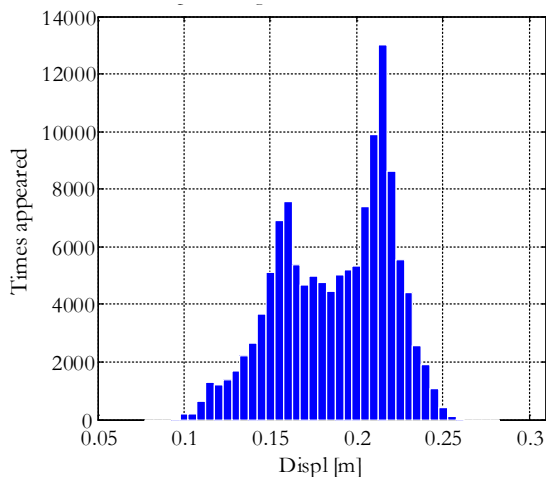


Figure 3. Example of a histogram presenting frequency of occurrence of all measured values

Presentation of selected data on a single graph, e.g. as shown in Figure 4, can also enable correlations to be established and significant deviations to be identified.

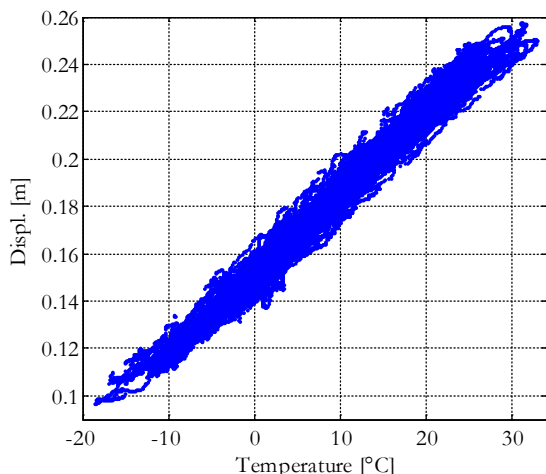


Figure 4. Example of a graph showing the correlation between an influence (temperature) and a measured effect (displacement)

It may also be helpful to be able to assess the static or dynamic behaviour of a structure due to certain influences but not others. By eliminating the influence of dominant, less relevant factors, small changes due to the factors of interest can be much more easily detected. For example, the effect of minor structural damage on a specific variable may remain unnoticed when clouded in data that includes the effects of temperature changes, but readily identifiable on a graph when the influence of temperature is excluded. Or the exclusion of temperature effects may enable the effect on deck displacements of other influences such as traffic to be more easily understood. Such analysis is made possible by the use of regression models as described by Islami & Modena [2]. The usefulness of this technique is illustrated by the graphs in Figure 5, which show how displacements at one point in a structure vary with time. The upper graph presents the measured data, unmodified, while the lower graph presents the data as modified to exclude the influences of environmental factors such as temperature but still showing the influence of traffic loading. As can be seen, the exclusion of particular data in this way makes analysis of the data far easier, with any irregular values being immediately recognizable, enabling the need for repair or preventative action to be assessed.

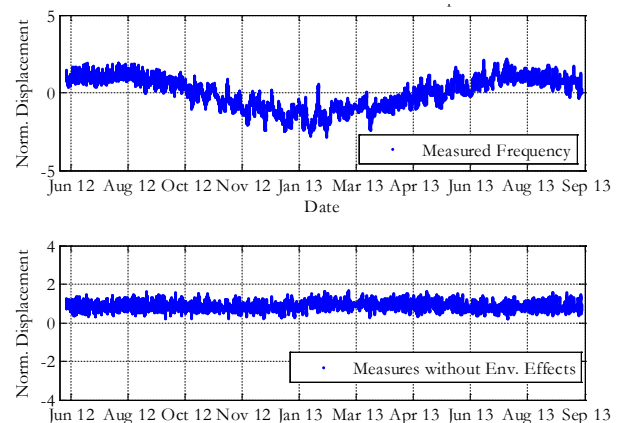


Figure 5. Example of regression analysis, showing displacement data, both before (above) and after (below) the elimination of environmental effects

3 Monitoring of bearings

A structure's bearings are critically important for its proper long-term performance, and any loss of functionality can quickly develop into a serious problem for the structure. For example, if a bearing no longer enables a bridge deck to expand/contract or move as required by its design, enormous constraint forces can build up, potentially causing severe damage to the structure. It is therefore essential that the proper condition and functioning of a structure's bearings be adequately monitored, to ensure that any such loss of proper functioning, through deterioration, accidental damage or otherwise, is recognised in good time and appropriate actions taken to protect the structure. Where the condition of a structure's bearings has been found to be questionable or where further confidence in the ongoing performance of the bearings is required, the use of an SHM system is an attractive alternative to traditional manual inspections. Not only are automated SHM systems far more accurate and precise than manual measurements, they can be designed to operate 24 hours a day, 365 days per year, thus ensuring that any sudden deterioration or damage is immediately recognised and reported to the responsible engineer or authority. And if frequent visits to a bridge are required to perform manual inspections, the investment in an SHM system can be quickly paid off and easily justified.

3.1 Case study: Modification of a bridge's static design concept

The Lavoitobel Bridge (Figure 6) in Switzerland, which opened to traffic in 1967, is an arch bridge with a main span of 105 m. During the planning of extensive renovation and strengthening works to be carried out in 2014/2015, it was decided to adjust the structure's static design by introducing longitudinal fixity to the deck at one end. This was achieved by the installation of new vertically oriented bearings to transfer longitudinal deck forces direct to the abutment and prevent movements at this end of the deck. In order to verify that the adjusted structural design and load distribution operated as planned, both in the short term and on an ongoing basis, the

responsible engineers decided to install an automated SHM system (Figures 7 and 8) to monitor the forces acting on the new bearings. The bearings (Figure 9), which are of the pot type and thus contain elastomeric pads between their steel pot and piston parts, were equipped with pressure sensors at the elastomeric pad, enabling the force acting on each bearing to be readily calculated by the connected SHM system. An example of the recorded data from a user-specified period of time is shown in Figure 10. In the event of any sudden or unexpectedly significant change in the force acting on a bearing, or in the load distribution among the different bearings, the SHM system would provide immediate alarm notification to the responsible engineers.



Figure 6. The Lavoitobel Bridge, Switzerland



Figure 7. Abutment at one end of bridge, showing access hatch to internal area with bridge bearings



Figure 8. The heart of the SHM system, installed externally at one abutment, complete with integrated solar panel on its cover for power supply and a separate weather sensor



Figure 9. One of the new vertically oriented bearings at one abutment, retrofitted to provide longitudinal fixity to the deck at this end

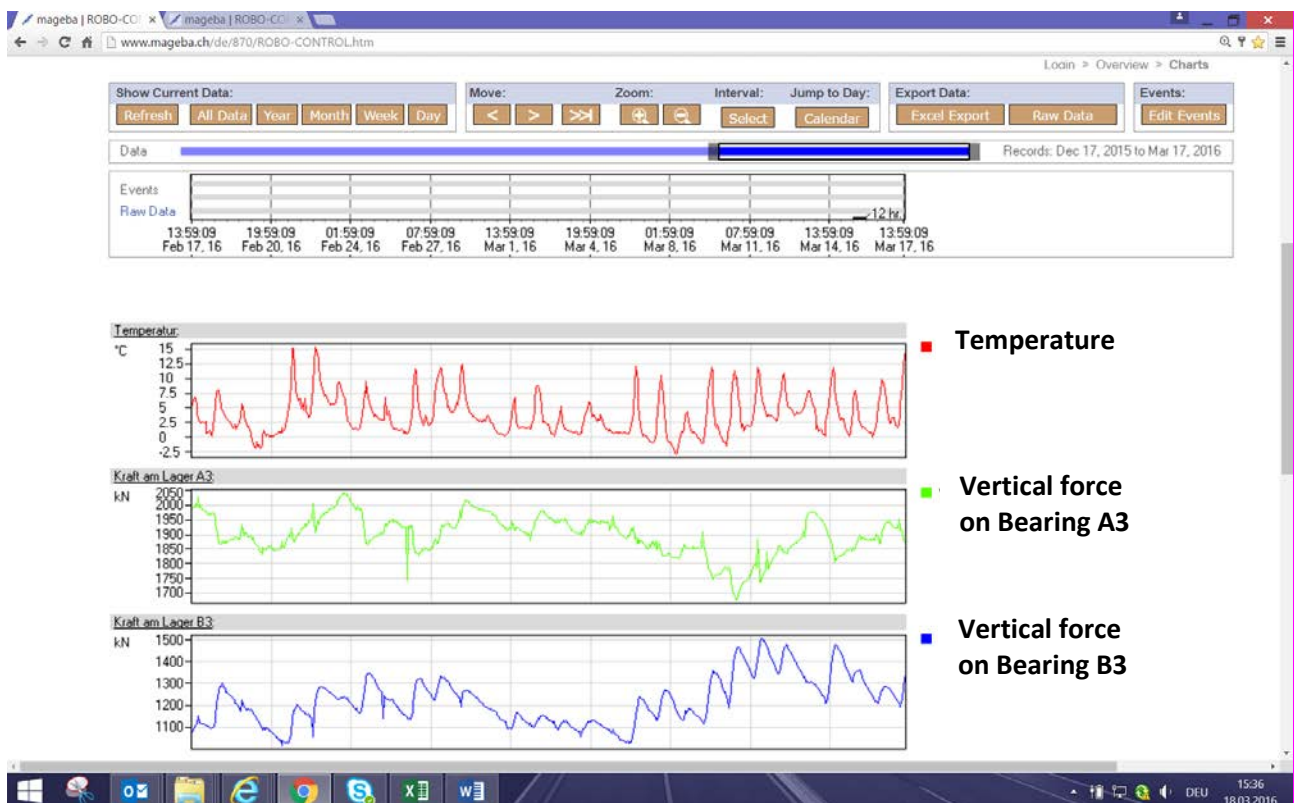


Figure 10. Monitored data from a selected time period, correlating temperature with the forces acting on the two vertically oriented bearings at one abutment

4 Monitoring of structural protection devices such as dampers and STUs

Like bearings, structural protection devices such as dampers and shock transmission units (STUs) must also perform reliably when required by the structure’s design, otherwise the consequences for the structure could be catastrophic – especially when used to protect the structure from seismic ground movements. Dampers must, as the name suggests, dampen large sudden forces or vibrations at a certain point in a structure, reducing the impact on the structure and enabling the structure to respond as designed or even to survive the event without damage. STUs, also known as lock-up devices (LUDs), protect a structure by transmitting sudden forces directly where they can be readily resisted without damage, thus reducing the impact on other, less robust parts of the structure. In order to provide confidence that these critical components remain ready to perform their vital function when the time comes, SHM systems can provide an efficient, cost-effective, round-the-clock solution – especially when the required sensors are pre-integrated in the devices during their fabrication.

4.1 Case study: Retrofitted STUs of an arch bridge for improved seismic protection

Following the construction of the arch bridge shown in Figure 11, which crosses a deep valley, it was decided to retrofit it with STUs, four at each end (Figure 12), to protect it in the event of an earthquake.



Figure 11. The monitored bridge, crossing a valley

The effect of these devices is to transfer seismic loading directly to the abutments in a safe and controlled way. They do this by locking up and not allowing movements above a certain velocity, but by expanding/contracting normally with the bridge during everyday movement cycles. This technique is widely used by bridge engineers, but in this case, the performance of the STUs is monitored by an automated SHM system. Using pre-integrated sensors, the system measures the pressure inside the STUs at a frequency of 100 Hz, correlating the data against similarly monitored temperature and deck vibration data. This enables STU condition to be checked at any time, and for additional peace of mind, the system is also designed to provide immediate notification should pre-defined threshold values for movement or differential settlement be exceeded. And to enable the actual seismic performance of the STUs to be evaluated following an earthquake, the system also correlates the pressures inside the STUs against recorded seismic data.

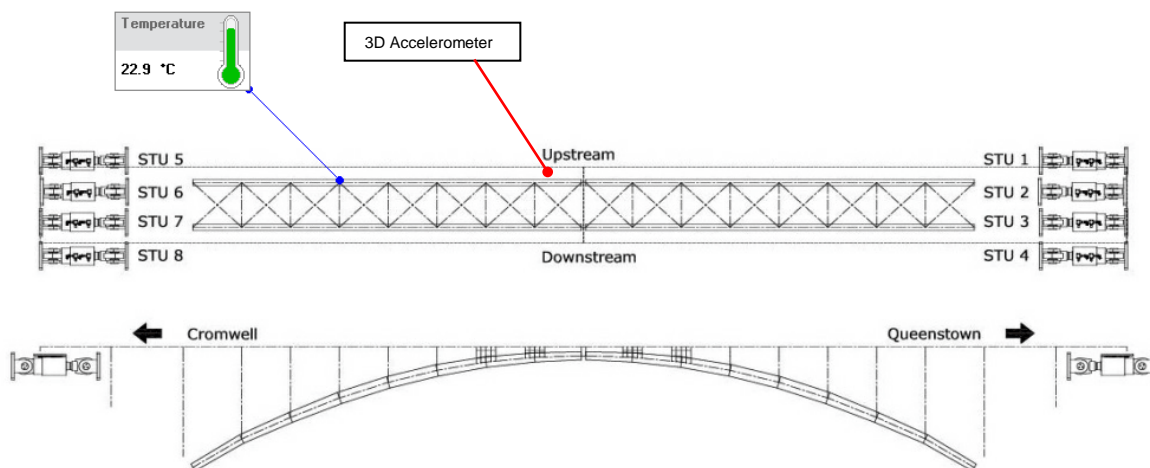


Figure 12. Layout of STUs (with pressure sensors) and acceleration (vibration) and temperature sensors

Analysis of the data shows that the seismic devices are sensitive also to vehicles crossing the bridge. Figures 13 and 14 correlate pressures inside the STUs with deck accelerations during the passage of heavy vehicles. It is interesting to note how one can follow the progress of each vehicle as it crosses the bridge, from the first abutment

(shown by STU pressure peaks) to mid-span (shown by acceleration/vibration peaks) and on to the second abutment (shown by further STU pressure peaks). This indicates that the system is working properly and that all of the STUs are contributing to protecting the structure against external excitations.



Figure 13. 100 Hz data measurements showing influence of traffic (indicated by deck vibrations) on STUs

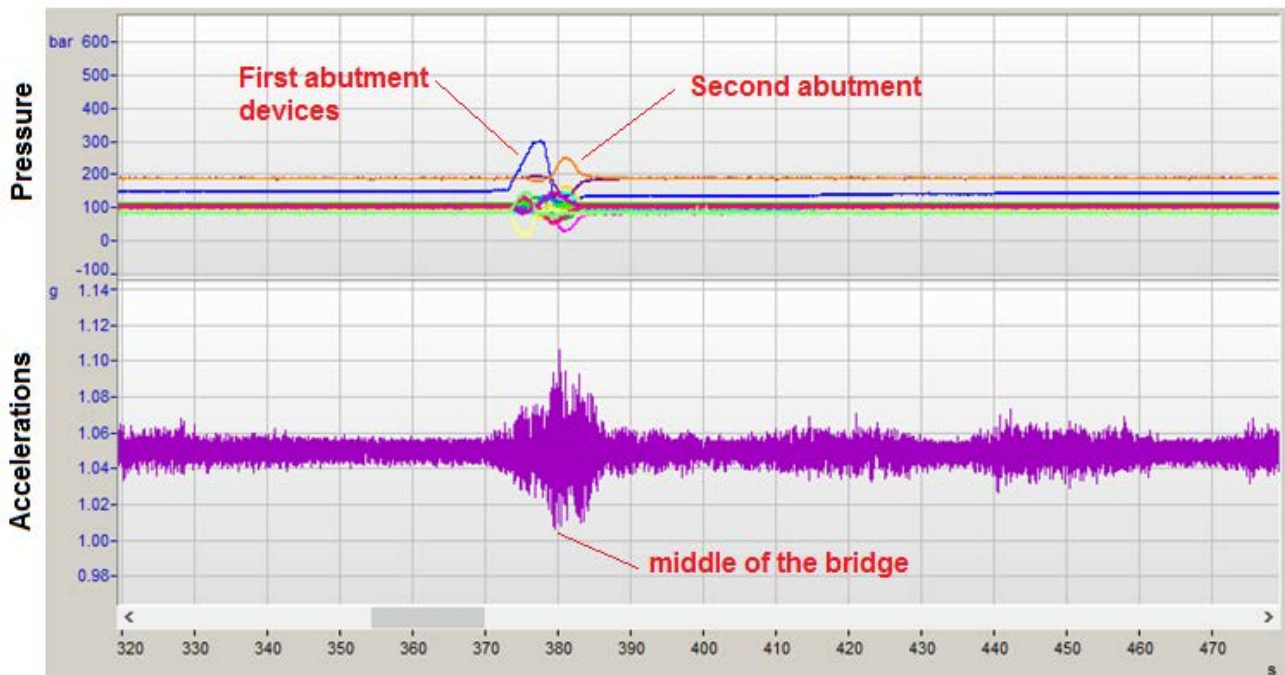


Figure 14. Close-up view of data (extract from Figure 13) showing the correlation of pressure and acceleration during the passage of a single truck

5 Monitoring of expansion joints

Although a bridge's expansion joints may not be as central to the structure's strength and stability as its bearings or dampers, the condition and performance of its expansion joints are critically important to a bridge's proper functioning as a transportation link. And given that expansion joints, very often mechanical devices with sliding interfaces, are typically subjected to direct impact loading from traffic millions of times a year, they are generally far more prone to wear and damage, and management of life-cycle costs can benefit enormously from the availability of good information relating to condition and performance [3]. Therefore, of all a bridge's key components, it is probably the expansion joints that can benefit most from the sensible use of SHM.

To maximize the benefit that can be gained from such technology, a worldwide supplier of both expansion joints and SHM systems has developed and combined the technologies, so that expansion joints can now be delivered with pre-integrated sensors for connection to a tailored SHM system. Not only that, the data analysis capabilities of the combined system have been greatly developed, based on the high-frequency measurement of structure-borne vibrations. This enables damage or deterioration to be clearly identified based on general testing and teaching of the system. As a result, unexpected damage can be immediately recognized and automatically notified, enabling the timing of replacement of components to be optimised and disruption to service to be minimized.

5.1 Case study: Large-movement expansion joints of a new bridge

The Taizhou Yangtze River Bridge (Figure 15), constructed at a cost of USD 400 million and opened in 2012, is the world's longest-span bridge of its type: The three-tower suspension bridge, with two main spans of 1,080 m each and side spans of 390 m, crosses the Yangtze River where it has a width of 2.1 km. The ambitious construction project represented the first attempt to create a long-span multi-tower suspension bridge.

This extraordinary bridge required some extraordinary key components such as the expansion joints which accommodate deck movements while providing a driving surface for traffic. Modular joints with 18 gaps each (able to facilitate 1440mm of longitudinal movement) were installed at each end of the deck (Figure 15).

An SHM system was installed on the bridge to provide the type of data that is likely to be of interest to the owner of any exceptional structure. The basic system measures and records the movements and rotations of the deck at the expansion joints, and thus gives a valuable impression of the performance of the structure, enabling the need for maintenance or adaptation work to be quickly identified and planned.



Figure 15. The Taizhou Yangtze River Bridge and one of its expansion joints, viewed from below

To maximize in particular the system's ability to monitor the condition and performance of the expansion joints, the above-mentioned newly developed technology was applied. By recording movements, inclinations, temperature and structure-borne vibrations at a frequency of 25.6 kHz, even very tiny changes in the joint or its performance can be detected and visually represented by changes in a curve on a graph. This will enable any sudden damage or deterioration to

be immediately detected, based on testing and “teaching” of the system.

As a first step, many artificial failures were created simulating damages. This was done by temporarily removing stirrups which form sliding connections between the lamella beams at the joint’s surface and the support bars beneath (see Figure 16). High-accuracy accelerometers and ultrasonic displacement sensors (Figure 17) were then used to evaluate the effects of these “failures” on the movements of specific elements, giving the system the data it needed to “learn” what data might be significant in terms of damage detection.



Figure 16. An accelerometer at the location of a temporarily removed stirrup during fault simulation and measurement of resulting vibrations and modal analysis



Figure 17. An ultrasonic displacement sensor

In service, the system sends data to a remote server, including daily records of vibrations due to heavy traffic together with the associated modal frequencies. If established limits which might indicate the occurrence of damage are exceeded, an alarm notification is sent by email and also appears on the system’s web interface, prompting

a site inspection. As a result of the system’s ability to automatically consider such information, therefore, planning of maintenance activities in general, and the timing of replacement of components in particular, can be optimized.

6 Conclusions

The integration of SHM systems in key components (bearings, expansion joints and seismic protection devices) of bridges and other structures can offer great benefits to their asset management programs. Such systems can efficiently provide data required for almost any purpose, at any stage of a structure’s life cycle.

In the case of expansion joints, in fact, the technology has already been brought another step forward, with the SHM system designed to clearly identify component damage based on general testing and teaching of the system. This enables any unexpected behaviour of the component (or the bridge) to be immediately recognised and notified, thus enabling the timing of component replacement, or other maintenance/repair work, to be optimised. With similar developments being planned for bearings and dampers, making them yet smarter and more efficient and useful in the construction, inspection, maintenance and renovation of structures, the potential benefits of the use of SHM technology in bridge asset management programmes continue to grow.

7 References

- [1] Moor, G. Islami, K. & Meng, N. Construction and maintenance of bridges – the contribution of automated monitoring. *Proc. 9th International Conference on Short and Medium Span Bridges*. Calgary, 2014.
- [2] Islami K. & Modena C. Life-cycle assessment by dynamic diagnosis and long term monitoring of old bridges in northeastern Italy. *Proc. 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII)*. Hong Kong, 2013.
- [3] Spuler, T., Loehrer, R. & O’Suilleabhain, C. Life-cycle considerations in the selection and use of bridge expansion joints. *Proc. 18th IABSE Congress*. Seoul, 2012.