Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Remote structural health monitoring systems for bridge expansion joints and bearings

Gianni Moor[1], Niculin Meng[2] and Colm O'Suilleabhain[2]

[1] mageba USA, New York, USA
[2] mageba SA, Bulach, Switzerland

ABSTRACT: The story of a bridge's bearings and expansion joints does not end with the installation of these critical structural components. Rather, it continues until the bridge is removed from service, with regular inspections and occasional replacements required. Although far less robust than the main bridge structure, which tends to consist of mass concrete and steel, the bearings and expansion joints are also subjected to impacts and fatigue-inducing forces and movements. This unfavourable combination results in these parts having a life expectancy which is considerably less than that of the bridge itself. The inspection and maintenance effort, and the effort required for remedial works of such elements, can be greatly reduced through the application of modern automated monitoring systems. These can be used to continually report on the condition of these important components, and precisely diagnose and assess any problems that arise, enabling both planned and non-scheduled works to be optimised. Examples of such applications are discussed and presented.

1 INTRODUCTION

The features and benefits of structural health monitoring systems, such as that shown in Figure 1, are many and varied (refer, for example, to Spuler et al (2007) and Wenzel (2008)). They can provide continuous, real-time records of almost any variable in a bridge's condition, analyse the data gathered, present it in tabular or graphic format, and make it available to an authorised user anywhere in the world via the internet (Figure 2). Such systems can also be used, for example, to provide structural engineering or bridge usage data, or immediate notification of the reaching of predefined values of any measured variable.

Figure 1. Bridge computer of a monitoring system, with connections to all measurement sensors.

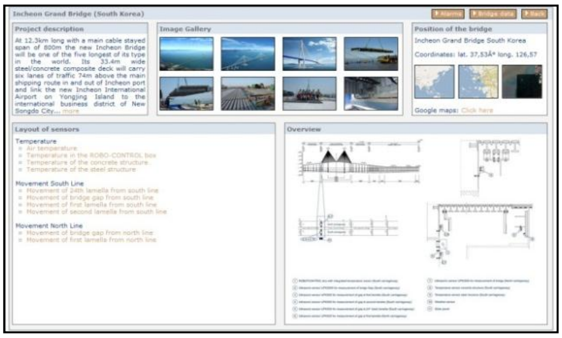

Figure 2. User interface on internet of a typical monitoring system.

Such benefits make structural health monitoring systems of potentially great use in relation to any part of a bridge, or the bridge as a whole, at any time during the bridge's life. A bridge's bearings and expansion joints are no exception – and indeed, it is generally truer of these critical bridge components than of any other part of the bridge. Despite being mechanical components, which must facilitate movements and/or rotations while subjected to fatigue loading, they are far less robust than the main bridge structure, and thus more prone to wear and damage.

And automated monitoring of bearings and expansion joints does indeed have much to offer right throughout a bridge's life-cycle. The following examples of the use of such a system at various stages illustrate this – starting with a case study from the very start of a bridge's life.

2 CASE STUDY 1: FOLLOWING CONSTRUCTION OF A NEW BRIDGE – THE INCHEON GRAND BRIDGE, SOUTH KOREA

With its main span of 800 m, the Incheon Grand Bridge in South Korea, which opened in 2009, it is one of the world's longest cable stayed bridges. Exceptional bridges like this require exceptional components such as the extremely large expansion joints (Figure 4) needed by this structure to facilitate its deck's movements.

Figure 3. The Incheon Grand Bridge, with an overall length of 12.3 km.

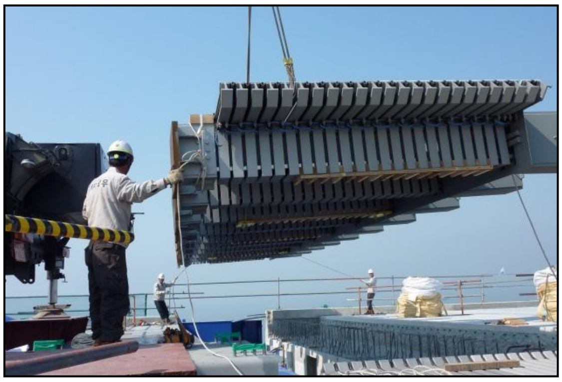

Figure 4. A 24-gap modular expansion joint during installation on the Incheon Grand Bridge.

It was decided at the time of the bridge's construction to install an automated monitoring system to enhance the responsible engineers' understanding of the precise movements of the new bridge, and enable long-term maintenance efforts relating to the bridge's very large and complex expansion joints to be optimised. At the same time, the system would detect damage or unexpected changes that might arise at any time, enabling repair or preventative work to be quickly arranged. The joints are 24-gap modular joints, with 23 lamella beams forming the driving surface of each [Spuler et al (2009)]. A permanent Robo®Control system was tailored to provide detailed information about the movements and performance of the expansion joints, and consequently of the connecting bridge deck also. This data would be used to ensure that the bridge performed as intended, especially during the first months and years of its life, and to allow optimisation of the expansion joints' life-cycle costs. Experience shows that the life-cycle costs of a bridge's expansion joints, during the life of the bridge, are many times greater than the initial costs of supply and installation, especially when consequential impacts such as traffic disruption during replacement works are considered [Spuler et al (2012)]. Gaining a full understanding of the demands on the bridge's expansion joints, and how well they are performing, can enable adjustments and maintenance measures to be tailored to maximise the length of service life with a minimum of maintenance effort.

Of primary importance in this is the evaluation of expansion joint movements in the bridge's longitudinal direction. To assess this, the total bridge gap width is monitored using ultrasound sensors. Temperature sensors located at different points on the structure enable allowance to be made for thermal effects. An example of the presentation of the measured movements at one expansion joint, together with relevant deck temperature data, is shown in Figure 5.

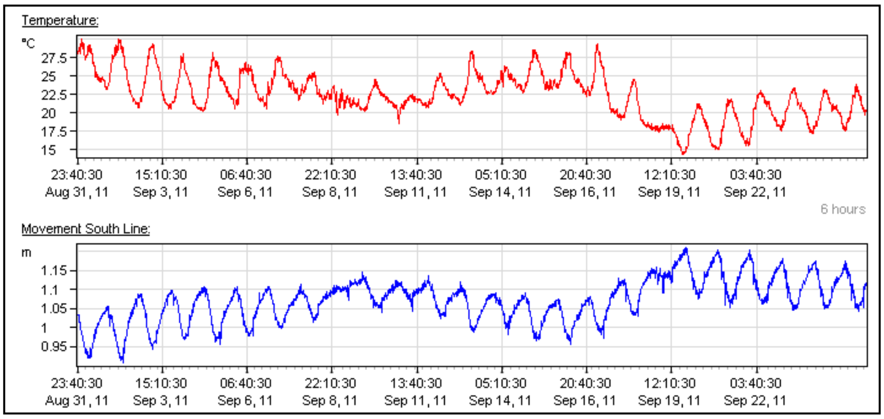

Figure 5. Presentation of the longitudinal movements of an expansion joint (and thus also of the connecting deck), showing the correlation between deck temperature and movements.

To improve damage detection on the expansion joints, environmental effects can be eliminated using regression models, generated from the correlation between temperature or humidity and the movements of the bridge. The resulting movements recorded by the system do then not include movements resulting from temperature or humidity, enabling abnormal influences (due to damage or other unexpected events) to be easily recognised. This is illustrated by Figure 6, which shows on the lower graph, with normalised values, the bridge movements that are due to traffic etc. and not due to temperature. Any abnormal shift on this graph would be immediately recognisable, enabling the need for repair or preventative action to be assessed.

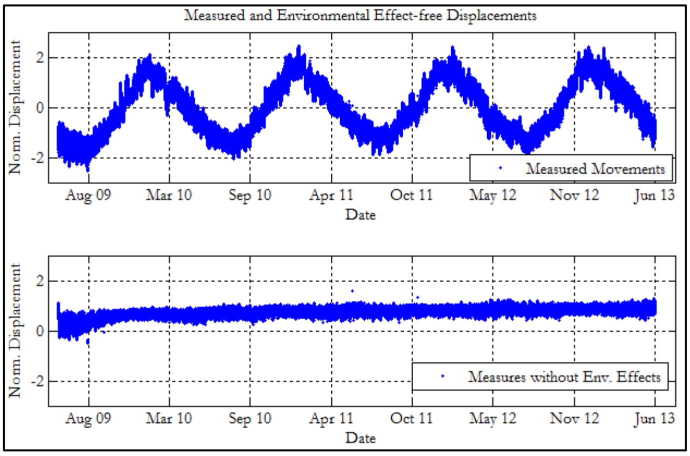

Figure 6. Temperature effect elimination for clear detection of damage or other unexpected developments.

As well as recording the overall joint and deck movements based on changes in the width of the bridge gap, the proper functioning of the expansion joint is confirmed by additionally measuring individual gap widths at both sides of the expansion joint (specifically, at the first, second and 24th of the joint's 24 gaps). Since the lamella beams of the Tensa®Modular joint installed are all interconnected to form a single dynamic mechanism, the movements of one depend on the movements of all others – enabling the proper functioning of the joint as a whole to be verified by comparing the movements of the beams at each side of the joint, as shown in Figure 7.

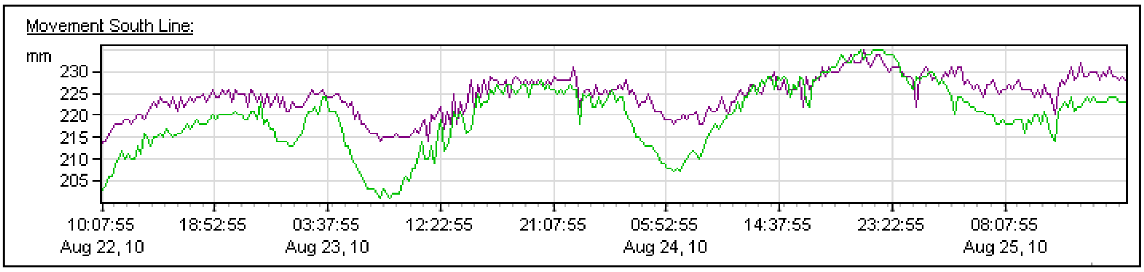

Figure 7. Presentation of movements of first and last of joint's lamella beams, showing very similar behaviour (with differences explained by the elasticity of the joint's control system, and the build-up of friction forces across the joint) - thus confirming the proper functioning of the expansion joint.

Thanks to low-energy technologies and a "power on measurement" design, the energy requirements of the system could be minimised, enabling it to be powered by a solar panel with a buffer battery, and thus requiring no external power supply. Measured data is transmitted, using the locally available UMTS (mobile phone) technology, to a central computer system, where it is processed and made available to the user via a web interface. The results can either be viewed in graphic form, or downloaded in tabular format as a CSV file.

As a result of the use of the monitoring system on this structure, the responsible engineers could conclude, most critically in the months following the bridge's construction and opening to traffic, that its deck exhibits movement and rotation behaviour in line with what had been expected based on theoretical models and calculations. The system also provides ongoing confirmation that the structure's exceptional expansion joints are well suited to fulfill the structure's needs, and continue to perform excellently. The data generated by the system in relation to the movements and rotations experienced by the joints is also being used to assess fatigue and to improve the planning of maintenance efforts – for example, by enabling the timing of replacement of wear parts such as sliding materials to be optimised.

3 CASE STUDY 2: FOLLOWING BRIDGE MODIFICATION WORKS – PONTE NANIN, SWITZERLAND

The twin arch bridges of Ponte Nanin (Figure 8) in the Swiss canton of Graubünden were constructed in 1967 to create an important new connection serving the San Bernardino Pass. During refurbishment work some thirty years later, modifications were carried out to accommodate increased traffic demands. These changed the static system of the bridge, with several of the bridge's pillars newly monolithically connected to its deck, meaning that all movement now occurs at one end. Considerable impacts on the bridge's bearings and joints were expected. Some of the bearings, which were originally designed to allow sliding movement of the deck, were modified to now act as fixed bearings, preventing movements and thus resisting the forces that would have caused such movements in the past.

Figure 8. Ponte Nanin in the Swiss Alps.

Figure 9. Load monitoring at Ponte Nanin bearing.

In order to provide ongoing confirmation that the impacts of the changes to the bridge's structural system were as anticipated, and that the structure continues to function properly and safely, a monitoring regime was instigated. Benefiting from the most suitable modern technology available, a remote monitoring system was installed in 2005 to monitor the adapted load transfer through the structure and its bearings. This would ensure that the performance of the structure is fully understood and that any changes in the structure, which could affect its performance or safety, are immediately recognised, allowing appropriate action to be taken.

It was decided during consultations with the bridge engineer that records of forces and movements within the structure at 15-minute intervals would in general provide an appropriate level of information. However the ability to obtain more frequent values (for example, every second instead of every 15 minutes) was also desirable for more detailed analysis as required. In order to fulfill these objectives, a low-frequency permanent Robo®Control system was determined to provide the optimal solution.

The system measures the loads carried by hydraulic bearings (Figure 9) at both abutments. It also monitors the movements experienced by the structure's expansion joints, by means of ultrasonic displacement sensors which continually determine the position of the last lamella beam of each joint. The monitoring system is also equipped with meteorological devices to measure air temperature and humidity and concrete temperature (Figure 10).

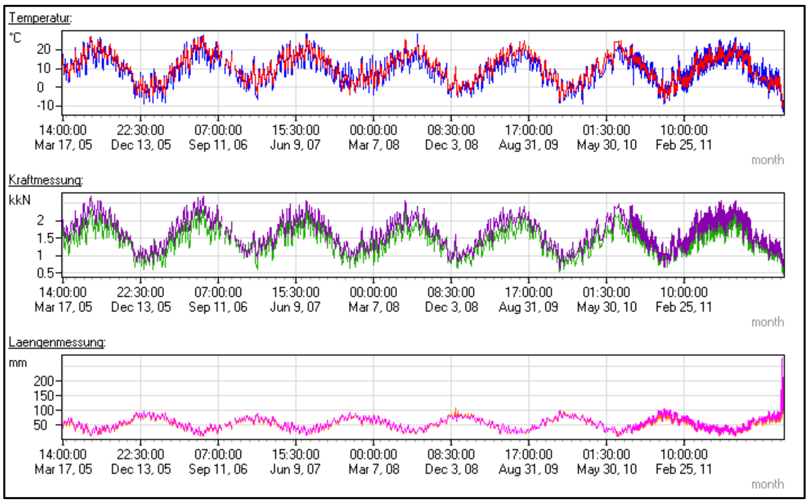

Figure 10. Temperature, load and displacement measurement at Pont Nanin.

The remoteness of the bridge's location had a significant impact on the selection and low-frequency design of the monitoring solution. The lack of fixed line telecommunications resulted in the need to transmit data from the bridge to the system's central server via the available mobile telephone network - limiting the amount of data which should be transmitted in order to avoid excessive transmission costs. And the absence of a local power supply necessitated the use of a solar panel to satisfy energy requirements - limiting the power that would be available to the system, and thus the amount of data that could be recorded and transmitted. The low frequency of measurements required and facilitated by the system's design limits the volume of data arising, making powering by solar panel and transmission of data by SMS both sufficient and economical. However, to accommodate special needs, the system is also designed to enable an authorised user, from the comfort of his office, to increase the frequency of measurements being recorded and transmitted for analysis. The design of the monitoring system is thus a sensible compromise between the low power, low data transmission requirements of standard usage and the increased power and data transmission requirements that arise only occasionally.

The main concern following the refurbishment of the bridge related to the “flow of the forces” through the structure. By measuring the loads in the bearings and observing the force distribution in the bridge structure, this concern could be immediately allayed after initial measurements. Since then, ongoing measurements have been used to assess the thermal behaviour of the structure and the effects of increasing traffic. And as an added benefit, the system also features an alarm capability which automatically sends notification, by email and SMS, when the pre-defined boundary value of any variable is exceeded. This allows the bridge owner to have confidence that any changes in the condition of the bridge will be immediately recognised, enabling action to be taken to ensure the safety of the bridge and its users.

The monitoring system, initially installed in March 2005, still provides confidence on an ongoing basis that the structure continues to function safely and well. It therefore confirms the design of the engineers who were faced with the challenge of adapting the static system of an existing structure. The system thus validates the approach which was deemed most suitable for economic reasons, but which necessitated such validation in order to minimise all residual risks, more thoroughly and efficiently than could be achieved by any manual inspection regime.

CASE STUDY 3: PLANNING BRIDGE RENOVATION WORKS - THE ALVSBORG BRIDGE, SWEDEN

The Alvsborg Bridge (Figure 11) is a suspension bridge across the Göta Älv river in Gothenburg. Built in 1966 with a main span of 417 metres, it is one of the few structures connecting the north and south parts of the city across the river, and is therefore one of Gothenburg’s most important traffic arteries. And with its 107-metre pylons, it is also one of the city’s most prominent landmarks.

Figure 11. The Alvsborg Bridge in Gothenburg.

Figure 12. Existing finger joint of Alvsborg Bridge.

During planning of major renovation works, to be completed in the coming years, it was decided to use an automated structural health monitoring system to provide detailed information on certain key aspects of the bridge’s condition and performance, allowing the works to be optimised. One part of the project involves the replacement of the bridge’s expansion joints (Figure 12), which are in a poor state of repair as might be expected after a respectable service life of over 40 years. Due to the substantial maintenance effort required by the existing steel finger joints to date, questions have been posed as to whether an alternative type, such as a modular joint, might be more durable and cost-effective considering the particular demands of this structure.

In order to optimise the selection and design of the replacement joint, and thus reduce future maintenance and replacement effort, an SHM system was proposed. It was designed to precisely quantify the bridge's actual movements and rotations, which would be likely to differ from the theoretical values estimated at the time of the bridge's construction. The system, which was installed in 2011, measures absolute longitudinal and transverse movements, horizontal and vertical rotations, and accumulated longitudinal movements (at high measurement frequency to include all micro-movements). It also records the structure temperatures needed to form a frame of reference for the movements and rotations, enabling these to be fully understood. In this way, movements due to traffic can be decoupled from temperature effects, for better understanding.

An example of the data generated by the system is presented in Figure 13, in graph form, and in Figure 14, exported in tabular form for detailed analysis.

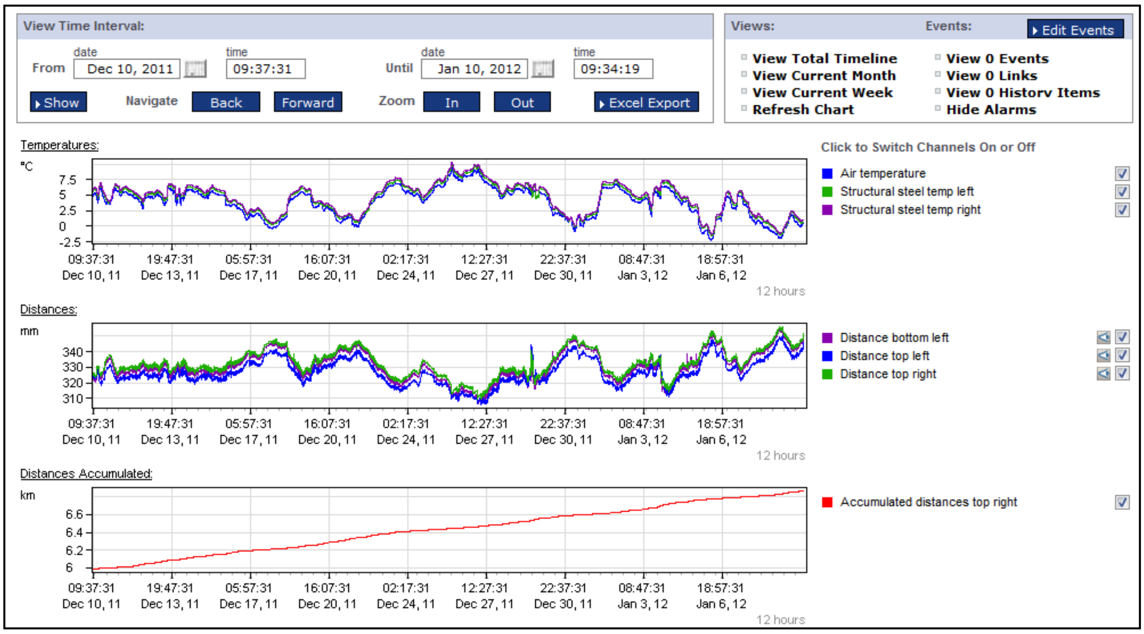

Figure 13. Presentation of measured data (graph form).

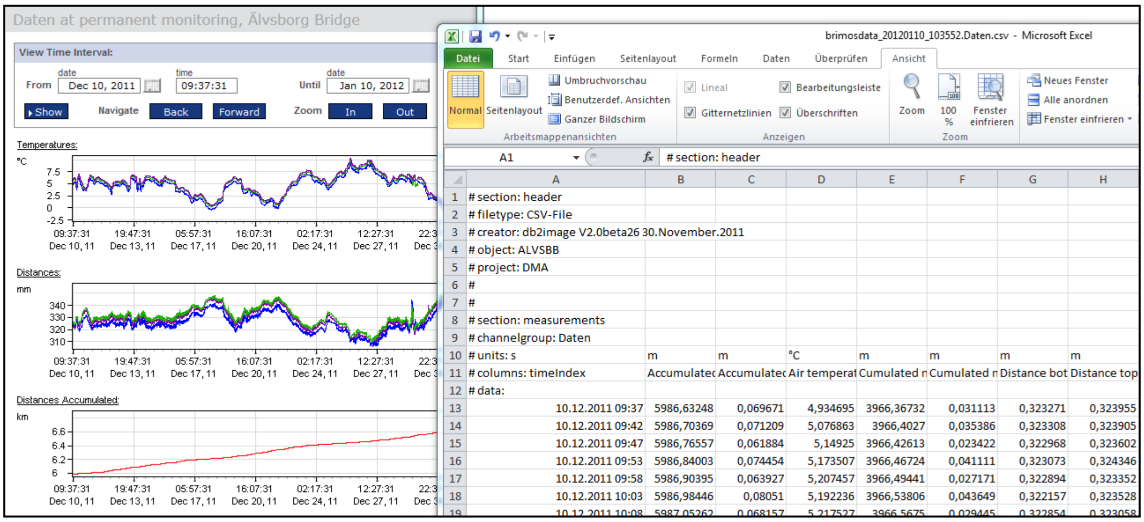

Figure 14. Presentation of measured data (converted to tabular form and exported as a CSV file).

This example shows the correlation between longitudinal deck movements and temperature, and also the accumulated deck movements (including micro-movements as well as daily thermal cycles) as they add up over time. Figure 13 shows that the total accumulated movements between 10th December 2011 and 6th January 2012 came to approximately 800 m, from which it might be deduced that the deck experiences total longitudinal movements of over 10 kilometres in a year. A more accurate value, reflecting seasonal variations, can be gained by considering data from a 12-month period. For yet more precise information, the data in tabular form can be used. The first line of data in the exported table in Figure 14, for instance, shows that accumulated movements of 0.069671 m, or approximately 7 cm, were recorded in a 5-minute period starting at 9.37am on 10th December. Such a level of information, generated from high-frequency measurements, could never be provided by manual methods alone.

The data generated by the system provides a detailed understanding of the structural behaviour of the bridge deck, in particular in relation to thermal impacts and secondary bending moments. It can also be used to provide quantification of the new joints' required movement and rotation capacities, enabling the most suitable type of expansion joint to be selected (finger, modular or other). And it will enable the design of the joints to be optimised, eliminating overly conservative safety margins and facilitating the selection of the most suitable sliding materials. Considering the high accumulated movements which have been recorded to date, it can be concluded that a standard sliding material such as PTFE would be worn away within only a few years, and that an alternative material that offers exceptional durability and performance must be used.

In addition to providing continuous records of selected variables, the system can also be programmed to send an alarm message should any measured variable exceed a predefined boundary value. Although not a particular concern in the case of this structure, the presence of an alarm system can help guard against any developments which might result in partial or complete closure of such a critical transportation link – especially one which is considered to require renovation works in the coming years.

4 CONCLUSIONS

It can be seen from the examples presented above that automated structural health monitoring systems have a great deal to offer the engineers who are charged with the construction and maintenance of bridges, and specifically in relation to their bearings and expansion joints. Such systems can efficiently provide data required for almost any purpose, at any stage of the life-cycle of these critical mechanical components. Whether used during the installation, inspection, maintenance or replacement of the components, or to facilitate assessment of unexpected events or planned modifications, automated monitoring systems are thus sure to play an increasingly important role in maintenance and renovation in years to come.

REFERENCES

Spuler, T, Moor, G and O'Suilleabhain, C. 2007. Remote monitoring: New cost-effective, self-sufficient and versatile systems will change the way bridges are monitored. *Proc. IABSE Congress*. Weimar, Germany.

Spuler, T, Moor, G and Savioz, P. 2009. High performance expansion joints for the Incheon Grand Bridge. *Proc. International Commemorative Symposium for the Incheon Bridge*. Incheon, Korea.

Spuler, T, Loehrer, R and O'Suilleabhain, C. 2012. Life-cycle considerations in the selection and design of bridge expansion joints. *Proc. IABSE Congress on Innovative Infrastructures towards human urbanism*. Seoul, Korea.

Wenzel, H. 2008. *Health Monitoring of Bridges*. Chichester, England: J. Wiley and Sons Ltd.