SMART EXPANSION JOINTS OF LONG-SPAN BRIDGES: SELF-EVALUATING BY ADVANCED MONITORING SYSTEM

Kleidi Islami, Gianni Moor and Niculin Meng

Biography: Kleidi Islami, born in 1983, received his Master's degree in civil engineering in 2009 from the University of Padua, Italy, and his PhD degree from the same university in 2013. He is currently the manager of mageba's Structural Health Monitoring department.

Gianni Moor, born in 1968, received his civil engineering degree from the Swiss Institute of Technology in Zurich, Switzerland (ETHZ), and was later awarded an MBA degree by the Business School IESE (Barcelona, Spain). Today, he is Deputy General Manager and COO of Mageba Group, and CEO of Mageba USA.

Niculin Meng, born 1980, received his civil engineering and master's degrees from the Swiss Federal Institutes of Technology in Lausanne (EPFL) and Zurich (ETHZ) respectively. Today, he is Head of Sales of mageba.

ABSTRACT

This paper presents the installed structural health monitoring (SHM) systems of three long suspension bridges, which measure high-frequency movements, inclinations, temperature and vibrations and thus enable a proper understanding of the bridges' behavior to be developed. These case studies, based on both static and dynamic approaches, demonstrate the usefulness and ease of use of such systems, and the enormous gains in efficiency they offer over alternative manual monitoring methods. The availability of such systems has now led to the development of smart expansion joints: expansion joints that feature an integrated advanced monitoring system, already when fabricated.

Keywords: Expansion joints, damage detection, smart monitoring.

INTRODUCTION

Multi-span and long-span bridges are essential links in transportation networks, and must be inspected and maintained accordingly. They are more likely to experience large deck movements than other bridge types, and these movements must be accommodated by deck expansion joints and bridge bearings. The performance and life expectancy of such components are strongly dependent on the movements to which they are subjected, so the movement and vibration data that can be provided by modern automated SHM systems can play a pivotal role in improving their performance and extending their service lives. This is demonstrated below with reference to the SHM systems of three major suspension bridges.

To maximize in particular the ability to monitor the condition and performance of a bridge's expansion joints – perhaps the parts of the bridge that are subjected to the highest dynamic impacts – an upgrade to the standard monitoring system of a leading supplier has been realized in one of the bridges. A brand new application incorporates sensors at the expansion joints, providing clear information about the condition of the joints and supporting the planning of maintenance activities. The functioning of the new feature is based on the measurement of structure-borne vibrations. Damage can be clearly identified based on general testing and teaching of the system, facilitating very sensitive, highly robust damage identification. As a result, unexpected damage can be immediately recognized and appropriate personnel automatically notified, enabling the timing of replacement of components to be optimized.

The implications of the development of techniques of monitoring, of statistical modelling of the response of structures, and of gathering and processing data in real time, are important - especially in the context of particularly sensitive structures. It is desirable to verify whether the effects of various environmental variables measured in situ influence the static or dynamic behavior of the structure. Therefore, it is important to eliminate the influence of these factors, so that small changes due to damage can be detected. This is made possible by the use of regression models, which can determine the static variables starting from a predefined input.

All of these techniques have been used in the present study, and more importantly, have been applied to important suspension bridges that exhibit high movements.

MONITORING OF THE TAIZHOU BRIDGE, JIANGSU PROVINCE, CHINA

The Taizhou Yangtze River Bridge (Figure 1), 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 accommodate 1440mm of longitudinal movement) were installed at each end of the deck (Figure 2).

A SHM system was installed on the bridge [1] 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, repair or modification work to be quickly identified and planned. It also reports accumulated sliding movements over time – a key indicator in evaluating and predicting the condition of key mechanical components such as expansion joints and bearings.

An example of the recorded data is presented in Figure 3, showing overall displacements. Figure 4 shows a correlation between the displacements of a particular lamella beam (on the surface of an expansion joint) and the overall movements of the bridge. A 45° inclination of the correlation graph would indicate that these values are equal.

To maximize in particular the system's ability to monitor the condition and performance of the expansion joints – perhaps the parts of the bridge which deserve the most inspection and maintenance attention – an upgrade to the monitoring system has been applied. A brand new damage detection feature has been installed, incorporating sensors at the joints to provide clear information about the condition of the joints and support the planning of maintenance activities. The functioning of the new feature is based on the measurement of structure-borne vibrations recorded at a sampling frequency of 25.6 kHz, with even very tiny changes in the joint or its performance being detectable and visually represented by changes in a curve on a graph.

The installed "smart" expansion joint measures high-frequency movements, inclinations, temperature and vibrations enabling a proper understanding of the joint's and bridge's behavior. The main purpose of the project is not only to monitor the condition and performance of the expansion joints due to extensive movement or rotation (basic) but also to detect damages at an early stage by recording the level of accelerations and natural frequencies (advanced) caused by traffic.

As a first step, many artificial failures were created in order to simulate damages. This was done by temporarily removing stirrups (see Figures 5 and 6), which form a sliding connection between the lamella beams at the joint's surface to the support bars beneath which support them. The different setups of sensors (Figure 6) covered most of the joist beams of the expansion joint, with high-accuracy accelerometers fixed at the main supporting beams and ultrasonic displacement sensors installed to monitor movements.

During the tests there was a good distinction by the system between damaged and undamaged joint conditions. This enabled the system to be fine-tuned before permanent installation. The permanent monitoring sends data to a remote server, including daily levels of vibrations due to heavy traffic together with the modal frequencies. If established limits are exceeded, this indicates the occurrence of damage, causing an alarm notification to be sent by email and to appear on the system's web interface. The next step is a site visit in order to verify the damage and avoid further damage or deterioration.

Figure 7 presents an example of one month of data sent to the server from the smart expansion joint, at four positions. The appearance of dense clouds of measurements outside the normal trend would mean failure of a component.

This new application will provide better information about the condition of the joints and support the planning of maintenance activities. Damages can be clearly identified based on general testing and tuning of the system. This will allow very sensitive, but also reliable, damage identification. As a result, unexpected damage can be immediately recognized and notified, enabling the timing of replacement of components to be optimized.

PLANNING BRIDGE RENOVATION WORKS – THE ALVSBORG BRIDGE, SWEDEN

The Alvsborg Bridge (Figure 8) is a suspension bridge across the Göta Älv River in Gothenburg. Built in 1966 with a main span of 417 m, 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. Moreover, with its 107 m pylons, it is one of the city's most prominent landmarks. During planning of major renovation works to be completed in the coming years, it was decided to use an automated SHM system to provide detailed information on certain key aspects of the bridge's condition and performance, allowing the works to be optimized. One part of the project involves the replacement of the bridge's expansion joints (Figure 9), 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 optimize the selection and design of the replacement joints, 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.

Figures 10 and 11 show the correlation between longitudinal deck movements and temperature, and Figure 10 also shows accumulated deck movements (including micro-movements as well as daily thermal cycles) as they add up over time. It can be seen that the total accumulated movements in the 4-week period shown came to approximately 800 m, from which it might be deduced that the deck experiences total longitudinal movements of over 10 km in a year. For yet more precise information, data measured at a frequency of 10 Hz can be used. For instance, Figure 12 shows typical movements experienced by the structure in 24 hours, describing the behavior with nearly 900,000 values. Such a level of information, generated from high-frequency measurements, could never be provided by manual methods alone.

More statistical analysis was carried out using histograms (see Figure 13). Regression models, generated from the correlation between temperature or humidity and the movements of the bridge, were then also used to improve damage detection at the bridge's expansion joints by eliminating environmental effects [2]. The resulting movements recorded by the system do not then include movements resulting from temperature or humidity, enabling abnormal influences (due to damage or other unexpected events) to be easily recognized. This is illustrated by Figure 14, which shows on the lower graph, with normalized values, the bridge movements that are due to traffic etc. and not due to temperature. Any abnormal shift on this graph would be immediately recognizable, enabling the need for repair or preventative action to be assessed. These provide the responsible engineer with optimal information to assist in the planning of renovation works for the expansion joints and for the bridge as a whole.

The data generated by the system provides a detailed understanding of the structural behavior 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 optimized, 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 and analyzing them as described above, the system can also be programmed to send an alarm message should any measured variable exceed a predefined value after temperature effects have been eliminated.

MONITORING OF THE TAOHUAYU BRIDGE, ZHENGZHOU, CHINA

The Taohuayu Zhengzhou Yellow River Highway Bridge (Figure 15) is the fourth bridge of the Xixia Wuzhi Highway over the Yellow River in the city of Zhengzhou, China. The structure, which has a full length of 7,691.5 m, opened to traffic in October 2013. The main structure is a two-tower, three-span self-anchored suspension bridge with spans of 160m, 406m and 160m. The stiffening girder was erected by computer controlled one-way, multi-point and synchronous incremental launching.

A permanent SHM system was installed with a focus on the horizontal movements of the bridge deck under environmental and traffic influences, with movements measured at a modular expansion joint at one end of the bridge's deck (Figure 16). In particular, the system measures the longitudinal movements of the first, second and last lamella beams of the expansion joint, and the corresponding changes in the full width of the bridge gap at this location (Figure 17). It also measures deck rotations, and air and structural temperatures. Autonomous data processing and alarming is provided, with online access to data and reports via the web interface.

The system thus enables the behavior of the structure to be continuously monitored, for the purposes of condition assessment, quality control and environmental effects analysis.

CONCLUSION

The integration of sophisticated structural monitoring systems in the expansion joints of newly built and existing suspension bridges 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.

The newly developed "smart expansion joint" application installed on the Taizhou Bridge provides clear information about the condition of the joint and supports the planning of maintenance activities. It enables damage to be clearly identified based on general testing and teaching of the system. As a result, unexpected damage can be immediately recognized, enabling the timing of replacement of components to be optimized.

Whether used for installation, inspection, maintenance or replacement purposes, or to facilitate assessment of unexpected events or planned modifications, automated monitoring systems are thus sure to be increasingly used in bridge construction and maintenance in years to come.

REFERENCES

1. Islami K. et al., Life-Cycle monitoring and maintenance of Bridges: The role of remote SHM Systems, Istanbul Bridge Conference, Istanbul, 2014.

2. Islami K. & Modena C., Life-cycle assessment by dynamic diagnosis and long term monitoring of old bridges in northeastern Italy, ISHMII, Hong Kong, 2013.

TABLES AND FIGURES

List of Figures:

Fig. 1 – The new Taizhou Yangtze River Bridge.

Fig. 2 – A modular expansion joint on the Taizhou Bridge, viewed from below.

Fig. 3 – Example of lamella beam movements during a certain period of time (Taizhou Bridge).

Fig. 4 – Correlation between lamella beam movements and bridge movements.

Fig. 5 – Locations of removed stirrups (simulating damage) and sensors during preliminary vibrational tests and modal analysis on the large expansion joint.

Fig. 6 – A sensor at the location of a temporarily removed stirrup during fault simulation (left), and an ultrasonic displacement sensors (right).

Fig. 7 – Example of one month of data from the smart expansion joint, at four positions.

Fig. 8 – The monitored Alvsborg Bridge.

Fig. 9 – The monitored finger expansion joint.

Fig. 10 – Presentation of measured data (graph form) in the web interface.

Fig. 11 – Correlation of displacement (blue) with temperature (red).

Fig. 12 – Expansion joint movements during a period of 24 hours.

Fig. 13 – Histogram of expansion joint movements from Figure 12, showing distribution of displacements.

Fig. 14 – A regression model showing displacement, before and after the elimination of environmental effects. The lower graph, therefore, does not include the effects of temperature changes.

Fig. 15 – The Taohuayu Bridge over the Yellow River.

Fig. 16 – A modular expansion joint on the Taohuayu Bridge, viewed from above.

Fig. 17 – Overall movements of lamella beams of a modular expansion joint on the Taohuayu Bridge, and entire bridge movements, as shown on the web interface.

Fig. 1 - The new Taizhou Yangtze River Bridge.

Fig. 2 - A modular expansion joint on the Taizhou Bridge, viewed from below.

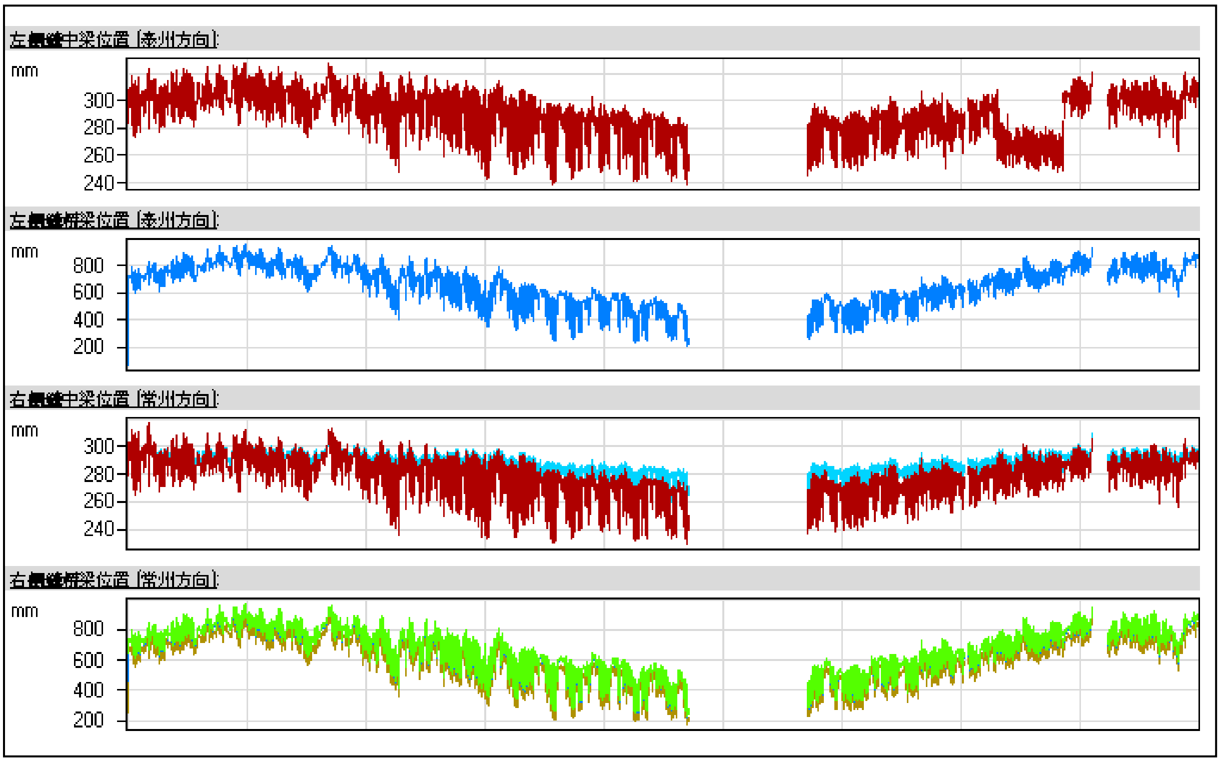

Fig. 3 – Example of lamella beam movements during one year of measurements (Taizhou Bridge). Starting at the top, the graphs show movements of the first lamella beam at left of joint, of the bridge deck at left of joint, of first lamella beam at right of joint, and of bridge deck at right of joint.

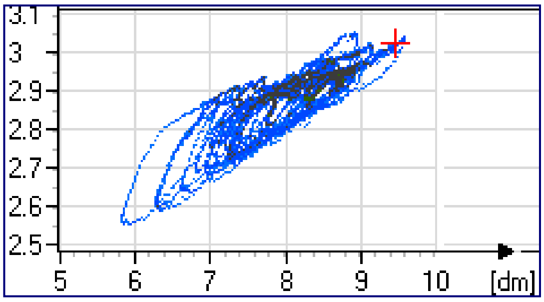

Fig. 4 – Correlation between lamella beam movements and bridge movements.

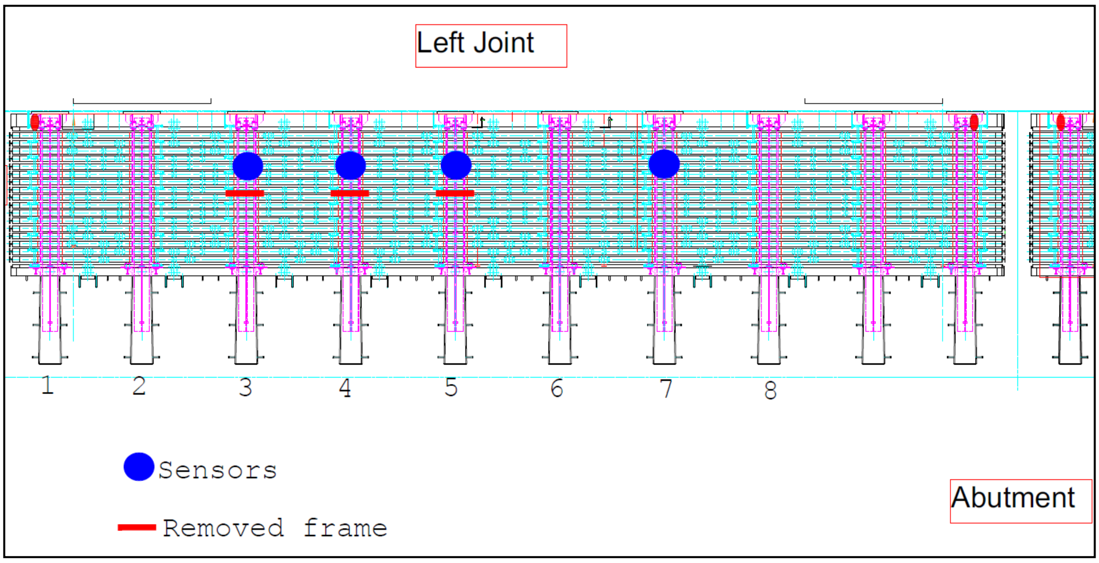

Fig. 5 – Locations of removed stirrups (simulating damage) and sensors during preliminary vibrational tests and modal analysis on the large expansion joint.

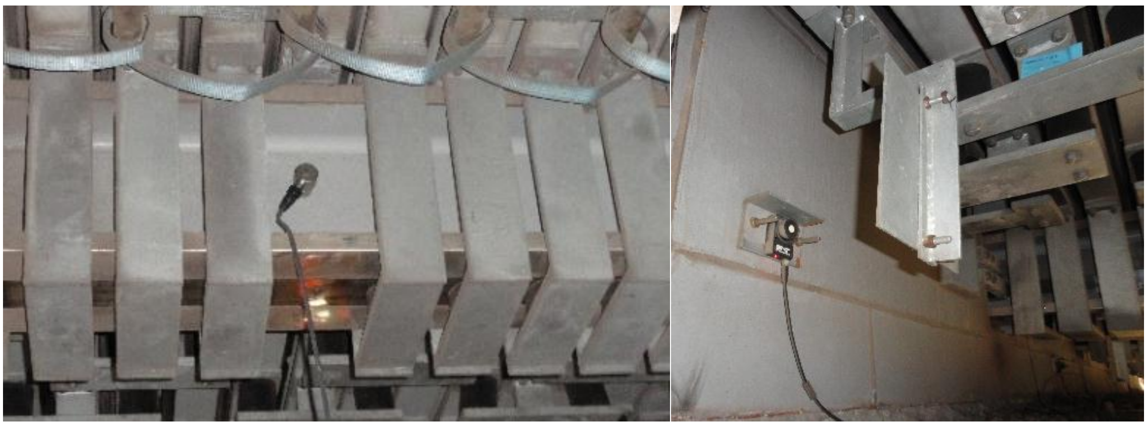

Fig. 6 – A sensor at the location of a temporarily removed stirrup during fault simulation (left), and an ultrasonic displacement sensors (right).

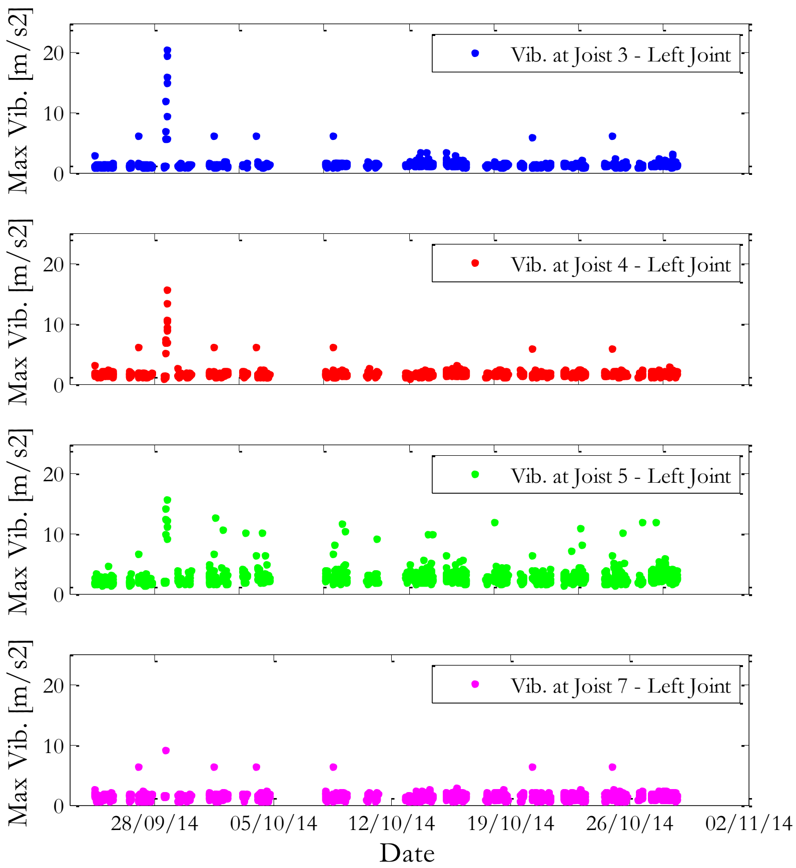

Fig. 7 – Example of one month of data from the smart expansion joint, at four positions.

Fig. 8 – The monitored Alvsborg Bridge.

Fig. 9 – The monitored finger expansion joint.

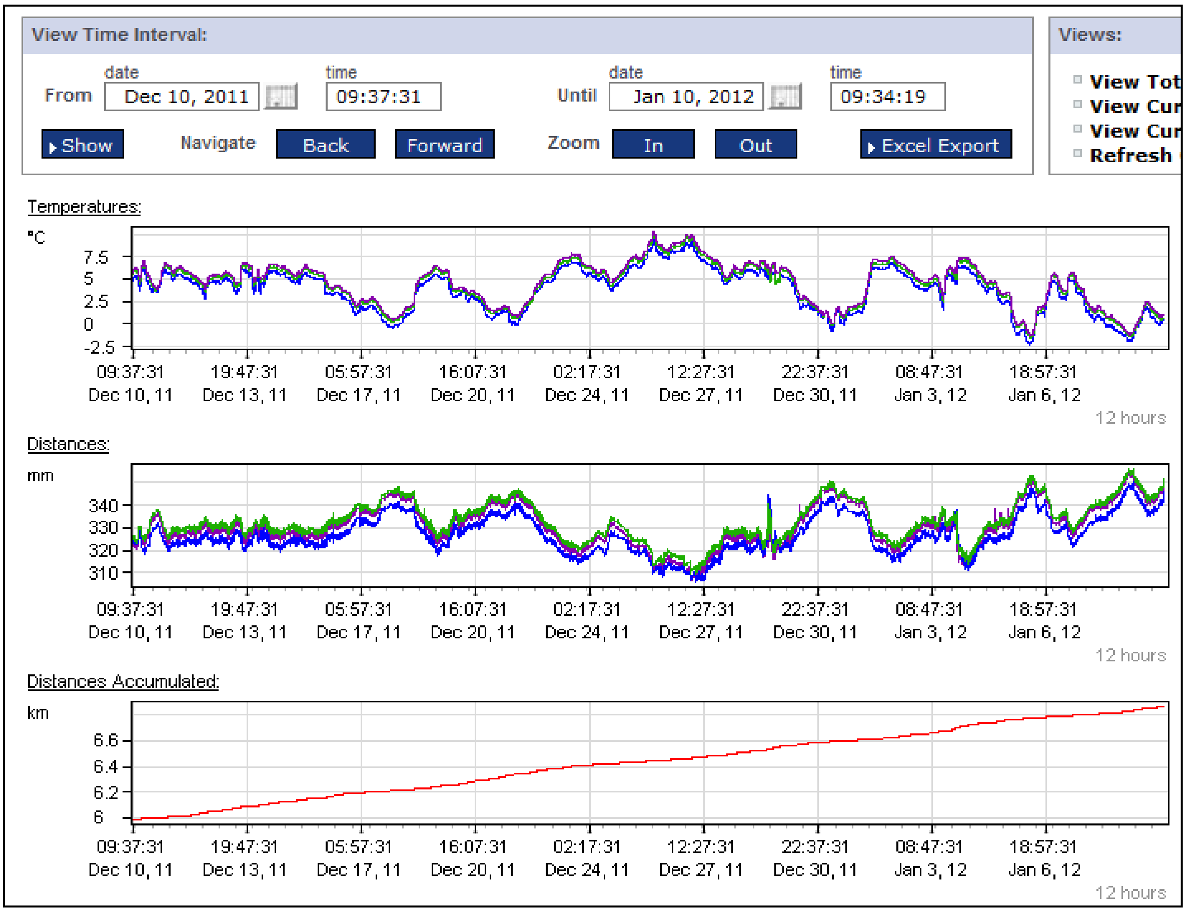

Fig. 10 – Presentation of measured data (graph form) in the web interface.

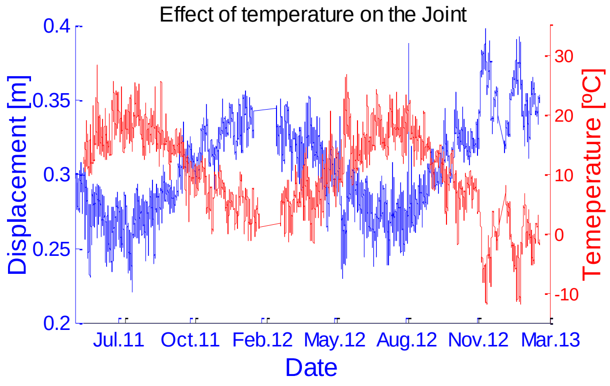

Fig. 11 – Correlation of displacement (blue) with temperature (red).

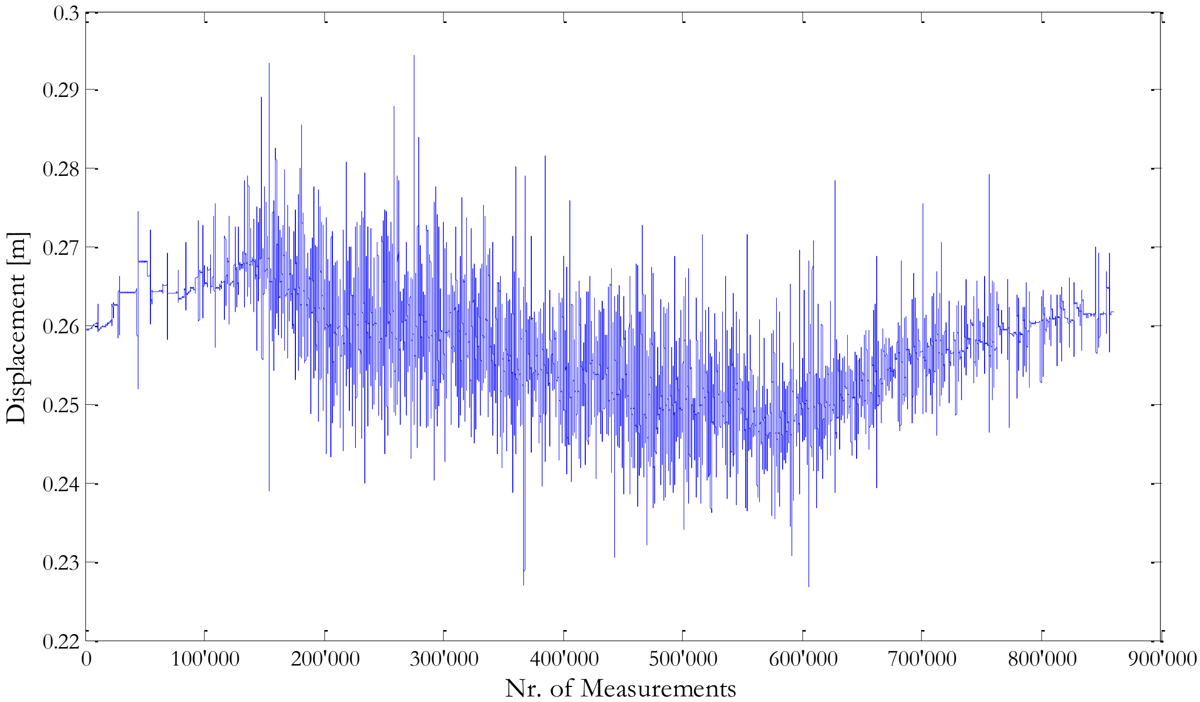

Fig. 12 – Expansion joint movements during a period of 24 hours.

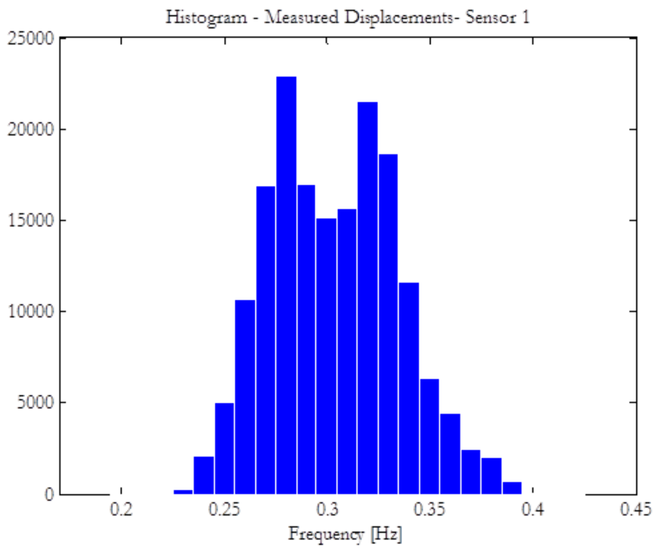

Fig. 13 – Histogram of expansion joint movements from Figure 12, showing distribution of displacements (number of incidences on vertical axis).

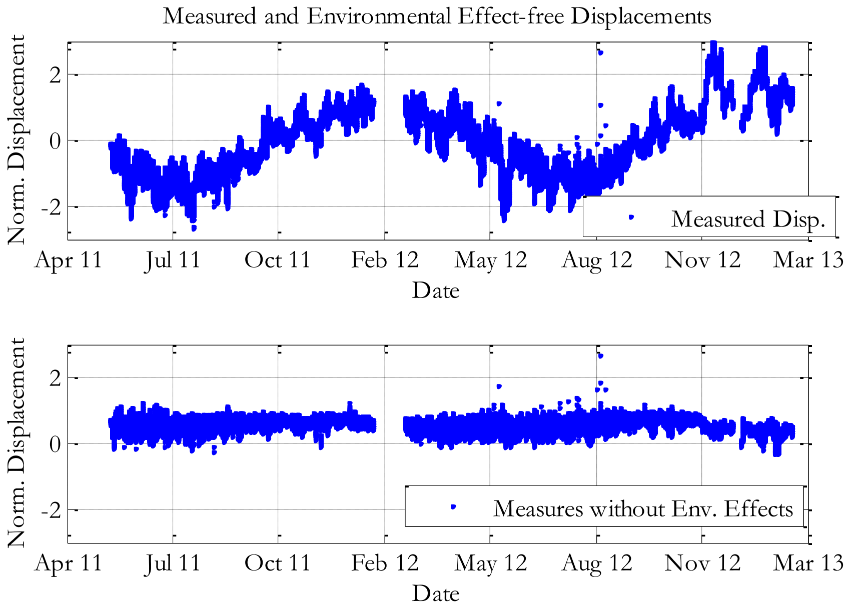

Fig. 14 – A regression model showing displacement, before and after the elimination of environmental effects. The lower graph, therefore, does not include the effects of temperature changes.

Fig. 15 – The Taohuayu Bridge over the Yellow River.

Fig. 16 – A modular expansion joint on the Taohuayu Bridge, viewed from above.

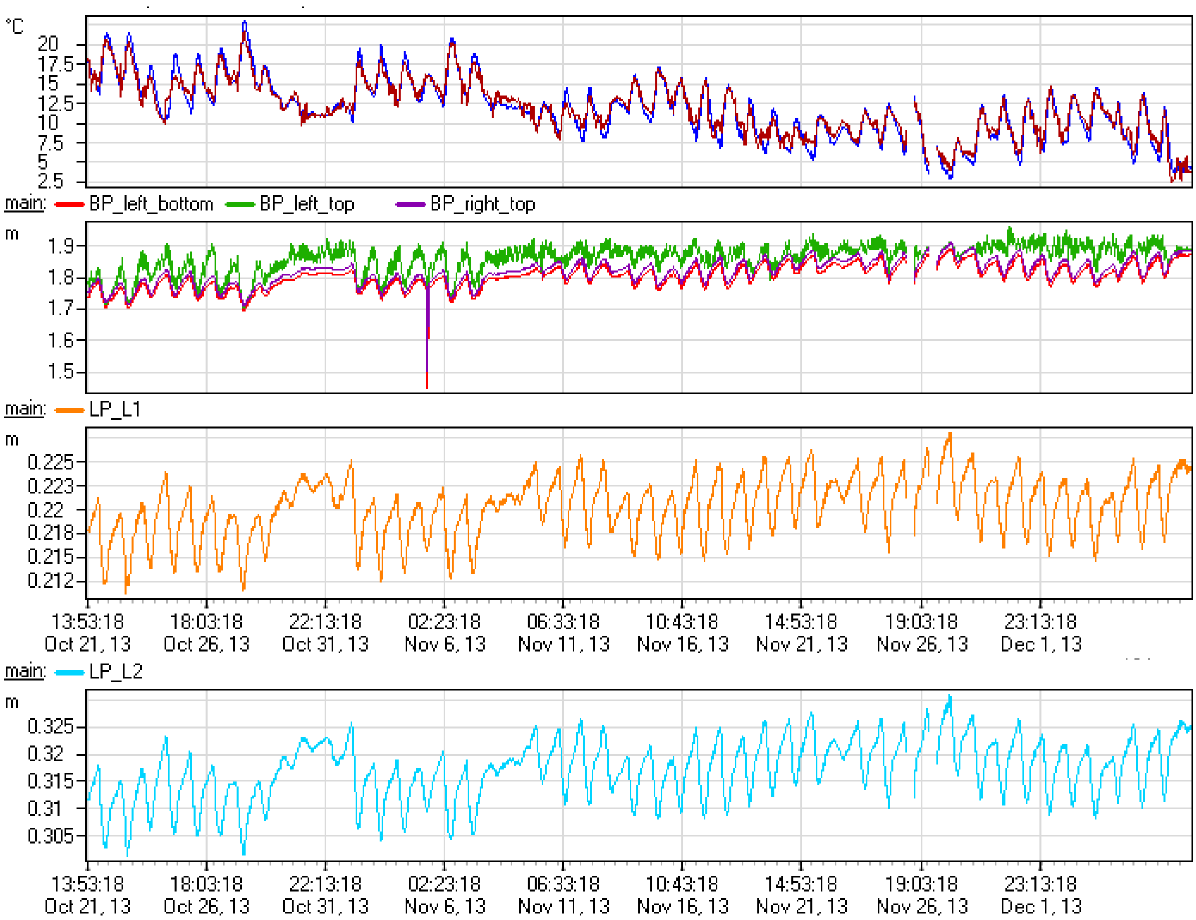

Fig. 17 – Overall movements of lamella beams of a modular expansion joint on the Taohuayu Bridge, and entire bridge movements, as shown on the web interface.

(LP_L1 = Lamella Position of Lamella 1, BP = Bridge Position)