SMAR 2019 – Fifth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2019

New SHM applications in cable-supported bridges – Case studies

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ABSTRACT: As the technical capabilities of structural health monitoring (SHM) continue to increase rapidly, the benefits it can bring to bridge construction and maintenance projects also increase accordingly. This is especially true of cable-supported bridges and other complex structures, where the potential benefits of using a suitably designed SHM system are particularly compelling. This paper describes current SHM applications on cable-supported bridges that have recently started providing data or that are expected to in the coming months, providing an insight into the value they bring to the projects or structures on which they are used.

1 INTRODUCTION

Modern structural health monitoring, with its enormous data collection and evaluation power, has great potential to play a valuable role in civil and structural engineering – especially as it relates to critical infrastructure such as road and railway bridges. Continually improving SHM technology can greatly increase the effectiveness and efficiency of bridge construction, inspection, maintenance and renovation work – for instance, as described by Moor et al (2014). The designs of cable-supported bridges are typically considerably more complex than those of other bridge types, increasing not only the importance of appropriate construction techniques, inspection and maintenance, but also the challenge of carrying out these activities efficiently and well. Bridge design, technology and practice continues to push the limits of what was previously considered possible and practical, with spans increasing while further optimising the use of materials. Fortunately, the tools available for use by those with responsibility for bridge construction, maintenance and inspection activities are also continually improving, keeping pace with the increasing challenges posed by modern bridge designs. For these tools to be used to full effect requires their value to be recognised by the responsible engineers. Examples of the use of modern SHM technology in the field of cable-supported bridges are presented below.

2 THE KOTA CHAMBAL BRIDGE, INDIA

The Kota Chambal Bridge, recently constructed in Rajasthan, northern India, carries a bypass highway of the city of Kota over the Chambal River, just outside the city. It has a main span of 350 m, spanning the full width of the river to avoid any impact on wildlife in this designated sanctuary area, and lateral spans of 175 m at either end. The bridge presented particular design and construction challenges, so it was decided to use an SHM system to assist already during the bridge construction phase, and subsequently, permanently, for inspection and maintenance purposes.

The initial temporary functionality of the system, during the bridge construction phase, required the following sensors:

- 2D accelerometers on cables: Vibration frequency and force in cable
- 3D structural accelerometers on deck: Measuring frequencies of deck vibration and determining natural frequencies
- 2D inclinometers on pylons: Inclination of pylons during construction phase
- 2D inclinometers on deck: Inclination of deck during construction phase
- Air temperature and humidity: For correlation with structural parameters

An example of the usefulness of the system during the construction phase is shown in Figure 1. Measurement of accelerations associated with forced vibrations of cables enabled the proper distribution of forces among stay cables to be verified and the cables' natural frequencies to be determined using automated dynamic identification – supporting the bridge's construction.

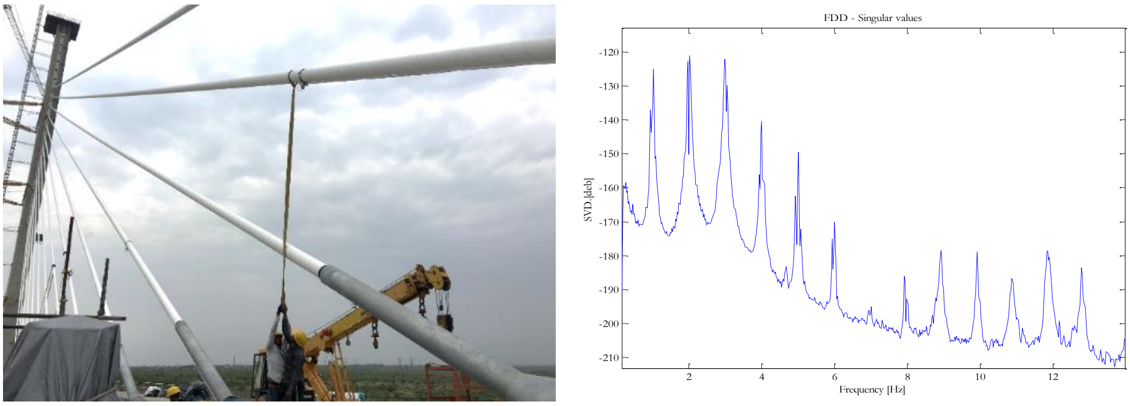

Figure 1. Forced vibration of a stay cable that is equipped with an accelerometer (left), and the cable's natural frequencies (horizontal axis, Hz) as determined from the measurements (right).

Following completion of construction, the system was modified to suit its permanent functionality requirements. The permanent system is designed to continuously record the dynamic movements and accelerations of the bridge, along with the environmental factors (including traffic, wind, etc.,) that may cause or affect these. It is also designed to, in real time, process, analyse, and interpret the data, display the data and analysis results, and provide warnings when there is a safety risk. This permanent functionality required sensors as follows:

- 2D accelerometers on cables: Vibration frequency and force in cable
- Structural accelerometers at pier and deck (2D and 3D): Vibration frequency
- 2D inclinometers on pylons: Inclination of pylons when bridge in service
- Displacement sensors at expansion joints: Superstructure movements
- Wind speed and direction: For correlation with structural parameters
- Air temperature and humidity: For correlation with structural parameters

The positioning of selected permanent sensors on part of the cable-stayed structure is shown in Figure 2, and examples of the data now being provided by the system following the recent completion of installation and commissioning are presented in the following images.

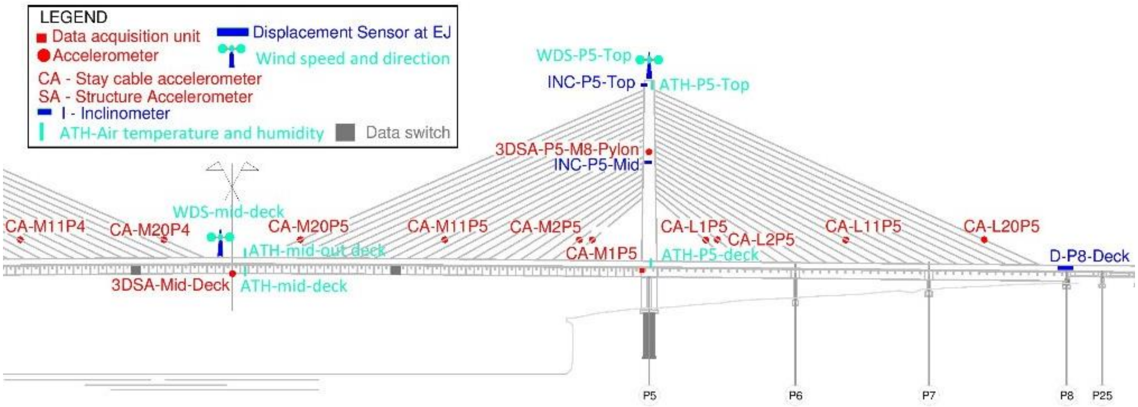

Figure 2. Positioning of selected sensors on roughly half of the Kota Chambal Bridge's cable-stayed structure, with data acquisition units at deck level.

Considering the importance of the bridge's stay cables to the structure's ongoing condition and performance, the accelerometers on selected cables continue to serve an important purpose. These can provide confidence that the structure's load distribution remains in the right range and has not become distorted by settlements or thermal, traffic, seismic or any other forces, and can provide information on the cables' damping performance and remaining service lives. The determined frequency values are displayed in time-frequency graphs, in order to continuously record the behaviour of the structure and detect any possible damage, and the values are used to derive the tension forces in the cables. Figure 3 shows an example of the tension force in a cable (approximately 7000 kN) associated with the cable's first natural frequency (approximately 1.1 Hz).

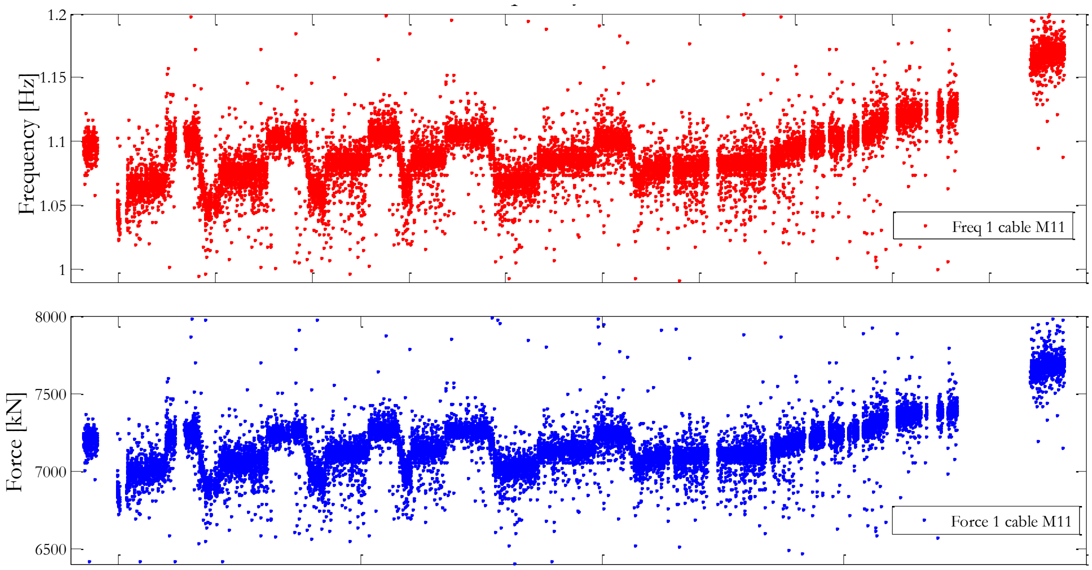

Figure 3. First natural frequency of one stay cable (above), and the derived tension force (below).

Another key assessment factor is the movements (displacements) of the pylons, which are monitored by means of 2D inclinometers on each pylon. These measure inclinations at high resolution, enabling deviations due to non-uniform load distribution, foundation settlements or cable malfunction to be identified.

Further data is provided, for example, by sensors measuring deck displacements, to an accuracy of less than 0.1 mm, at the expansion joints at both ends of the bridge. This data may be used for checking against expected values from design calculations, and in particular assessing the bridge's behaviour under varying environmental and traffic conditions. Analysis of movement data from one expansion joint, as presented in Figure 4, shows a clear correlation between joint opening/closing movements and temperature, as expected. This can, for example, provide verification of the bridge's structural design model and of expansion joint designs.

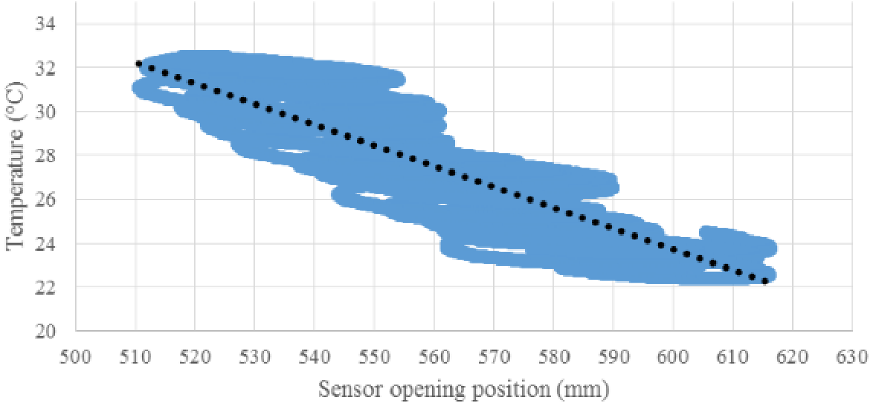

Figure 4. Plotting of correlation between expansion joint movements and temperature, at one end of the superstructure (Sensor "D_P1_Deck"), sampled at 2 minute intervals. The dotted line is a linear trend line of the data. In this example a temperature increase of 10°C corresponds to a reduction in bridge gap width in the order of 105 mm.

Analysis of the cumulative movements of the expansion joints, as shown in Figure 5, can also provide important information relating to the long-term performance of sliding interfaces, which are subjected to increased wear and tear. The data shows that both joints experience very substantial accumulated sliding movements (additional high frequency vehicle-induced measurements are not included here), with one moving 2200 m in a single month while the other moves 1400 m. Extrapolated to a 12-month period, this would be equivalent to approximately 26 km at one joint and 17 km at the other, in a single year – already exceeding the typical durability of PTFE sliding material which was traditionally used in bearing and joint applications. This type of data justifies the real need for more suitable sliding materials such as Robo-Slide, a modified UHMWPE which exhibits far superior wear resistance, to be specified.

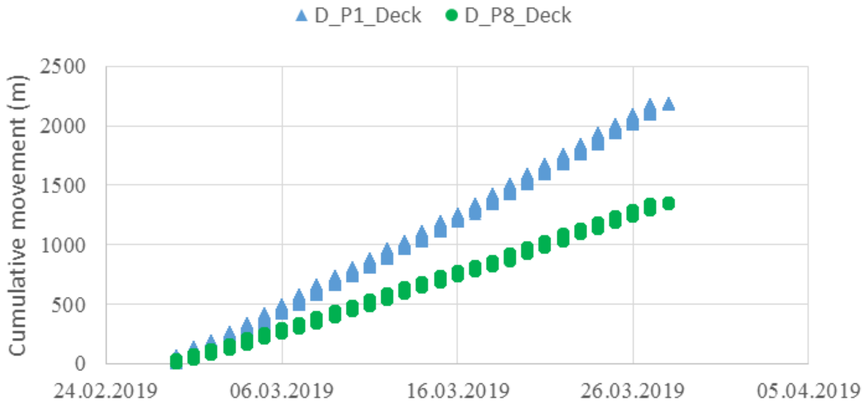

Figure 5. Evaluation of cumulative movements of the bridge's two expansion joints (one-month period).

As a result of the use of SHM technology throughout this bridge's life cycle – starting during the structure's construction, and continuing following its recent adaptation into the bridge's service life – the construction and life-cycle performance of the bridge can by optimised, benefitting the owner, the constructor and the bridge's users in different and significant ways.

3 MONITORING OF THE WAZIRABAD SIGNATURE BRIDGE, DELHI, INDIA

Installation of the SHM system on the Wazirabad Signature Bridge across the Yamuna River in Delhi, with a total length of 675 m and a main span of 251 m, is currently ongoing. Its dramatic inclined steel pylon, at 154 m high, and elegant stay cable design, make it a particularly attractive 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.

The bridge is being equipped with a sophisticated SHM system, installation of which has recently recommenced following a lengthy interruption to the bridge construction programme. The system will monitor the structure's behaviour, performance and condition, fulfilling three major purposes during the bridge's service life:

- structural health monitoring and damage detection (the specific approach to which is still under development by the responsible engineers).
- monitoring of environmental loading (e.g. temperature, storms); and
- seismic monitoring.

Its design includes:

- a total of 111 sensors, using in excess of 170 data channels, to measure environmental, load and structural response factors (see Table 1);
- a data acquisition system
- data processing to create reports, prompt control actions and provide alarms as required;
- data storage; and
- a user-friendly interface to facilitate necessary operational intervention, maintenance optimisation and high-level analysis such as finite element.

Table 1. Summary of sensors included in the Wazirabad Signature Bridge SHM system.

Sensor type	**Location**	**No.**
2D ultrasonic wind sensor	Top of pylon	1
3D ultrasonic wind sensor	Centre of deck	1
Structural temperature sensor	Various	20
Temperature and humidity sensor	Various	4
3D seismic measurement	Pylon base	4
Concrete temperature	Support columns	3
Corrosion of reinforcement	Support columns	3
Stay cable accelerometer	Stay cables	18
3D acceleration	Deck and pylon	8
Traffic cameras	Various	4
Traffic analyser	Various	8
Strain gauge	Pylon	10
Strain gauge	Deck	10
Tiltmeter	Deck	2
Tiltmeter	Pylon	2
Displacement sensor	Deck	4
Electromagnetic force sensor	Stay cables	9
Total		**111**

The layout of the sensors on the bridge, and the bridge's design, are illustrated in Figure 6.

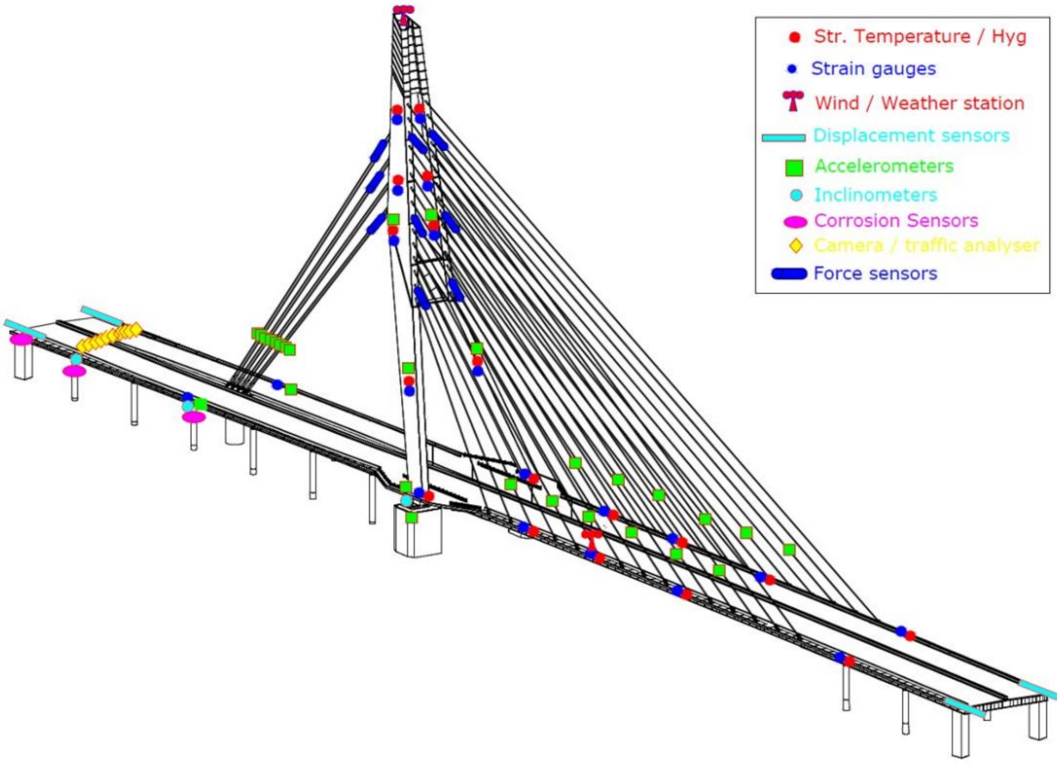

Figure 6. Layout of sensors on the Wazirabad Bridge, as designed.

The recent installation of electromagnetic sensors on selected stay cables, to measure cable tension force at any time, is shown in Figure 7.

Figure 7. Installation of electromagnetic sensor on stay cable to measure cable tension force.

Once fully installed and commissioned in the coming months, the automated monitoring system will provide valuable 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.

4 HALOGALAND BRIDGE, NORWAY

The Halogaland Bridge (Figures 8 and 9) is currently being constructed in northern Norway, within the Arctic Circle, and will form part of European Route E6. The suspension bridge will have a main span of length 1.1 km, crossing one of Norway's many fjords. Its design required the installation of shock transmission units (STU) at each of the bridge's pylons (Figures 8 and 9), to protect the bridge by transmitting sudden large forces (e.g. braking or seismic forces) directly where they can be readily resisted without damage, thus reducing the impact on other, less robust parts of the structure. The enormous STUs – each approximately 7000 kg and with a stroke of +/-450 mm – required to be specially designed, due to the limited space available, with two separate chambers with different volumes of oil in each, and two external accumulators to accommodate oil movements.

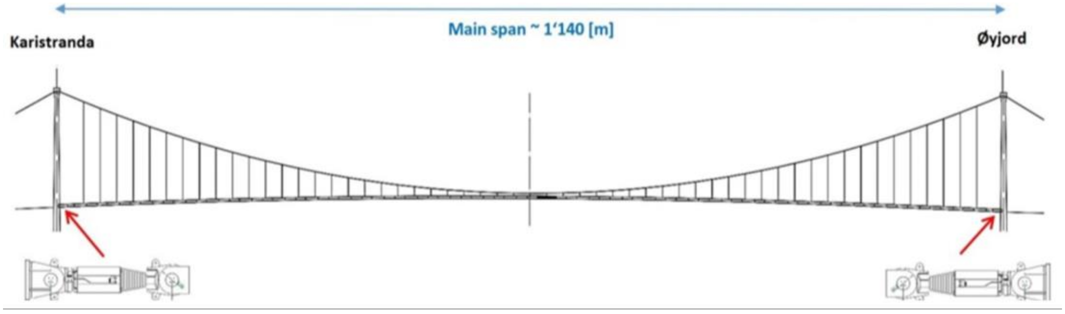

Figure 8. Elevation of the Halogaland Bridge and locations of its STUs at both pylons.

Figure 9. The Hålogaland Bridge (left), and installation of one Reston-STU shock transmission unit at a pylon to control deck movements – designed for axial force of 10,400 kN and with a stroke of +/-450 mm.

Considering the vital role to be played by the STUs throughout the bridge's life cycle, and their special design, it was decided to equip them with sensors integrated within an SHM system. Each STU is equipped with one sensor for measuring displacements, two sensors for measuring oil pressure within the device, and one sensor for measuring internal temperature. All sensors were pre-integrated in the design and fabrication of the STUs before they left the factory, maximizing durability and ensuring reliability. The system measures the pressure inside the STUs at a frequency of 100 Hz, correlating the data against similarly monitored temperature. This enables STU condition to be checked at any time, and for additional peace of mind, and to optimise maintenance work, the system is also designed to provide immediate notification should pre-defined threshold values for movement be exceeded. For example, the system features an alarm function which will send immediate notification to the owner if the pressure in an STU ever drops out of the correct working range.

The performance of these "smart" STUs is illustrated by the data from one STU shown in Figure 10. The graphs show that the opening value (movement) of the STU generally reflects the device temperature, as expected, and that the STU's reaction force (base value, neglecting fluctuations) remains relatively constant, as it should. This indicates that the system is working properly and that the STUs are contributing to protecting the bridge as designed – fulfilling a very important function for this very remote structure.

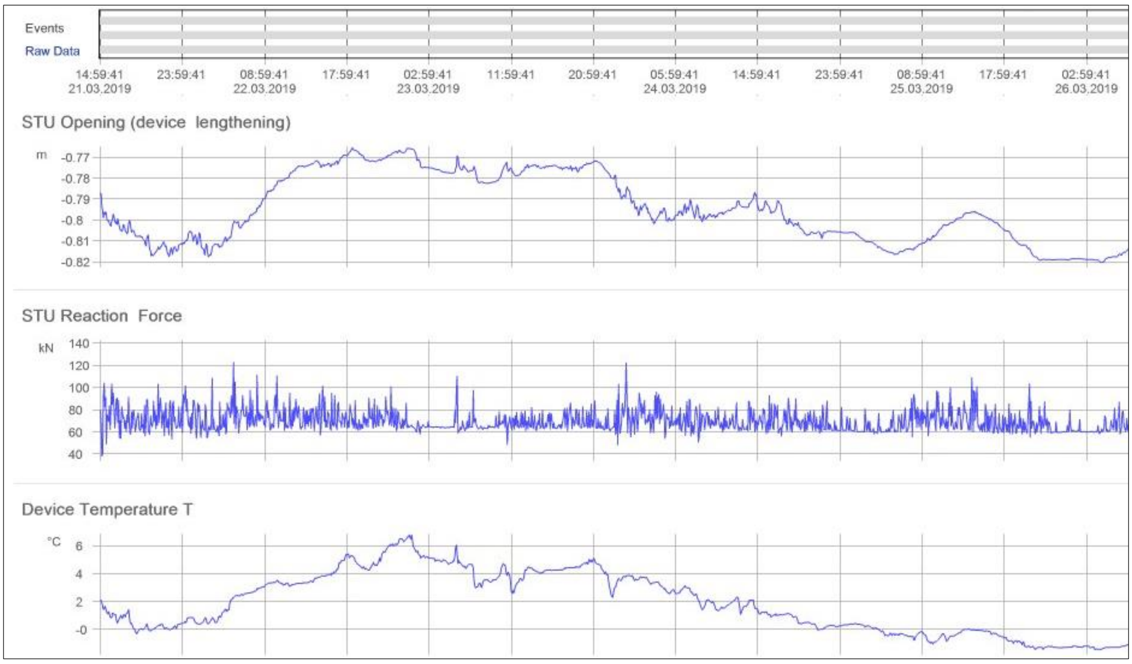

Figure 10. Data correlating STU opening value (top), force (middle) and temperature (bottom).

5 CONCLUSIONS

Automated SHM systems clearly have a great deal to offer engineers with responsibility for construction, inspection and maintenance of bridges. Elaborate systems, such as those of the Kota Chambal Bridge and the Wazirabad Signature Bridge in India, can be used to monitor a wide range of variables, giving a comprehensive record of an entire structure's condition and performance. Simpler systems, focused on the condition and performance of key components such as the STUs of the Halogaland Bridge in Norway, can also provide very useful data – not only about the components themselves, but also, thanks to the movement data etc. that they provide, about the structure as a whole.

As also illustrated, it may be very beneficial to consider the need for, and the needs of, an SHM system early in a structure's design and construction process. This is especially true where the system can already play an important role in supporting the bridge construction process (as in the case of the Kota Chambal Bridge), or where a system's sensors should ideally be integrated on site in the bridge's construction (as in the case of Wazirabad Signature Bridge). It is also true if the SHM system's sensors require to be pre-integrated in the factory into key structural components such as STUs (as in the case of the Halogaland Bridge) – a process which is optimised if the SHM supplier is also a manufacturer of such structural components. Far greater quality control can be achieved by integrating the sensing technology during production.

REFERENCES

Moor, G. Islami, K. and Meng, N. 2014. Construction and maintenance of bridges – the contribution of automated monitoring. *Proc. 9th International Conference on Short and Medium Span Bridges*, Calgary, Canada.