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Automated structural health monitoring – helping save costly and disruptive bridge strengthening works

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ABSTRACT: Automated structural health monitoring systems have a great deal to offer those who are responsible for ensuring the ongoing suitability and trustworthiness of engineering structures such as bridges. Such a system may be used, for example, during a limited period of time to establish that a structure is not deteriorating and that no threat exists. Alternatively, a monitoring system with an alarm function (which can automatically send alarm messages via SMS or e-mail) can be used, for an indefinite period, to provide confidence in the current condition of a structure at any time, where deterioration of the structure cannot be ruled out. Examples of the use of automated structural health monitoring systems in each of these ways are presented, demonstrating the important role such systems can play in reducing the costs, and disruption to traffic, resulting from bridge remedial works.

1 INTRODUCTION

Questions may arise during the life of any structure which may cast doubt on its ability to continue to function safely and well – for instance in the aftermath of en unexpected event or where significant deterioration is noted in the course of planned maintenance inspections. Where such concerns arise, it may not be a straightforward matter to properly assess the situation and conclude that the structure is not in need of any remedial action. In such cases, modern technology can offer a means of obtaining the information required to make a sound engineering judgement, which would not have been possible even in the recent past. The use of sensibly designed automated structural health monitoring systems can thus potentially allow costly and disruptive strengthening or other remedial works to be postponed or even deemed unnecessary. Examples of such applications at two bridges in Switzerland, the Weyermannshaus Viaduct on Berne’s bypass motorway and the Pont Nanin bridge in the Alps mountains, are presented below.

2 CHANGING CONDITIONS IN AN UNCERTAIN WORLD

The conditions to which any structure is subjected may vary greatly during the course of its lifetime, for any number of reasons. Extreme weather conditions during which structures are battered by exceptionally strong winds or loaded with extraordinary quantities of snow or rainwater, seismic forces, and other natural phenomena present perhaps the greatest sources of uncertainty in the design of an engineering structure. The variability of the materials used for construction, and the reducing ability of a structure to carry loads due to deterioration can also be very significant, while the likelihood of change of use or loading at a later stage should also be considered, and of course human error can never be neglected. A combination of such factors will of course increase the risks for a structure.

This variability in loading and other conditions can and must be addressed during the design stage of the structure, with appropriately conservative design loading and other conditions chosen, and containing factors of safety to ensure the proper performance of the structure in all circumstances. A certain degree of redundancy for the unknown variables that must be considered in the design of a load-bearing structure is inevitable, but it is incumbent upon engineers to continually seek to refine their methods and reduce the amount of materials, energy and effort devoted to the construction of the infrastructure needed by society. The amount of materials and energy available for such endeavours is not limitless, and awareness of the responsibility we share in reducing waste and unnecessary use of materials and energy continues to grow every year, with “sustainability” having become a catchword of the engineering profession in recent years. Indeed any lack of effort on the part of engineers, who possess great expertise and experience in the design and construction of structures, to minimise the materials and energy required in construction must today be regarded as wasteful and unsustainable.

In order to reduce the uncertainties in their methods and thus the conservativeness of their designs, engineers must, in one way or another, increase their knowledge. Increased knowledge of performance- and safety-defining issues will decrease uncertainties and enable overly conservative approximations and safety factors to be refined, with a consequent reduction in materials, energy and effort requirements. Automated monitoring systems offer the means to increase this store of knowledge, and thus to make this contribution to the engineering profession and the world.

3 MONITORING FOR A LIMITED PERIOD TO EVALUATE THE CONDITION AND PERFORMANCE OF A STRUCTURE AT A PARTICULAR POINT IN TIME

3.1 *The purposes such an application can serve*

Even a well-designed and properly constructed structure may have questions posed of it at some stage in its life, for example under circumstances such as the following:

- in the aftermath of exceptional loading (e.g. due to extreme weather);
- where increased loading (e.g. due to increased traffic volumes on a bridge or changed use of a building) has been introduced;
- where indications of deterioration (which may or may not be structurally significant) have been observed; or
- where modern research calls into question the accepted construction methodologies and scientific knowledge of earlier times.

When questions arise regarding the ability of a structure to continue to fulfil its function properly and safely, a well-specified automated monitoring system can provide the information required to make a sound engineering judgement. While certain data may alternatively be obtained by more traditional manual inspections, this may not always be possible or practical, given the precision and power of modern technology, and even where manual measurement and observation would be possible, the use of an automated system which greatly reduces the required manpower will in many cases offer efficiency benefits and cost savings.

3.2 *The Weyermannshaus Viaduct*

All highways leading to the Swiss capital Berne are connected to the city’s bypass motorway, making it a critical element of the city’s transportation network. This motorway, long sections of which are elevated on bridge structures, is exposed to great volumes of heavy goods and commuter traffic, resulting in frequent congestion. After 30 years in operation, general renovation of several key structures along this motorway is required. A core element of this project is the renovation of the motorway’s longest bridge, the Weyermannshaus Viaduct, with the goals of ensuring the usability of the bypass for another 30 years, improving safety features in line with current standards, and minimising the environmental impact of the motorway. The main construction work was scheduled for the years 2010/2011.

Fig. 1: Weyermannshaus Viaduct, Berne - Switzerland

The Weyermannshaus Viaduct (shown in Figure 1) is 912 m long, and the height of its deck above the ground varies from 10m to 15m. The bridge is a prestressed concrete structure, with a maximum bridge width of 40m. Various renovation activities could be easily planned for this structure, including the replacement of bearings, expansion joints and drainage system. However establishing the condition and necessity for remediation of the concrete structure was less straightforward. An initial detailed visual inspection of the bridge identified localised surface cracking of the concrete, as shown in Figure 2. The cracks were concentrated at the locations of the coupling joints of the prestressing cables. The appearance of these cracks could not be explained, and it could not even be established if they appeared immediately during the construction of the bridge due to the effects of prestressing, or later during its operational phase.

The authorities decided to further analyse the overall condition of the bridge before starting the general renovation, using only non-destructive methods. The analysis would identify the cause of the cracking and assess the condition of the structure, drawing conclusions about the remaining life expectancy of the bridge.

3.3 *Concrete crack monitoring of the viaduct*

The bridge monitoring project was announced by the Swiss federal roads authority and the Swiss Federal University EPFL, and was mainly driven by uncertainty about the overall condition of the bridge. Assessment by experts could theoretically conclude that the observed cracking was superficial only and that the bridge is generally healthy, or that the structure should be considered to have a 'fully-cracked' cross section resulting from serious overloading.

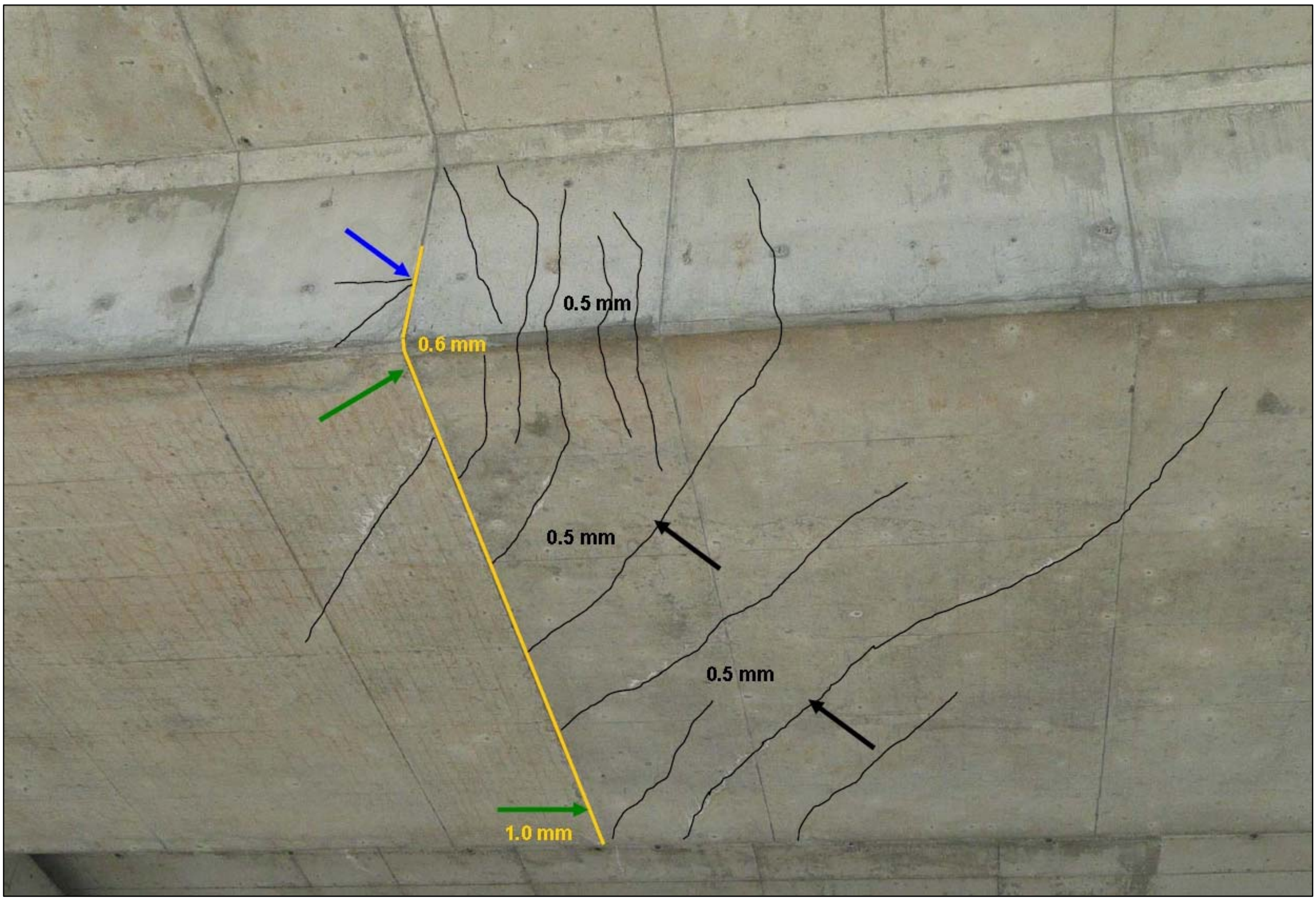


Fig. 2: Cracking at location of coupling joint of pre-stressing cables

3.4 *Goals of the project*

The authorities commissioned a local engineering firm, already involved in the overall project and known as specialists for bridge condition assessments, to manage the monitoring project. They determined that a permanent monitoring system would have to be installed to confirm their assessment model on an ongoing basis. The main purpose of this monitoring project is to give answers to the following questions:

- Should the cross-section of the bridge be considered to be "fully cracked"?
- How is the strength of the structure affected by the established cracking level?
- Are the pretensioning tendons suffering from fatigue?

The static model developed by this firm included all important key figures for both theoretically 'non-cracked' and 'fully cracked' concrete conditions. The evaluated situations represent the boundaries of the assessment, and the monitoring system installed should allow the bridge condition to be assessed much more accurately. While previous assessments by bridge experts, based on the limited information available, did not conclude that the bridge was likely to be in a poor condition, the monitoring was expected to confirm this hypothesis in a relatively easy and economical way. Failing this, the safety of the bridge may have had to be ensured by strengthening works, potentially at much greater expense.

3.5 *Main characteristics of the chosen monitoring elements*

Based on the decision that only non-destructive system could be applied, it was decided to install a *Robo*®*Control* remote monitoring system, tailored for this application to measure primarily crack widths. The system measures crack movements at 16 locations, at the pre-stressing coupling joints. The layout of the sensors at one coupling joint is indicated by their references R1 – R7 in Figure 3, while the locations of temperature sensors and meteorological stations is shown by their references T1 – T6.

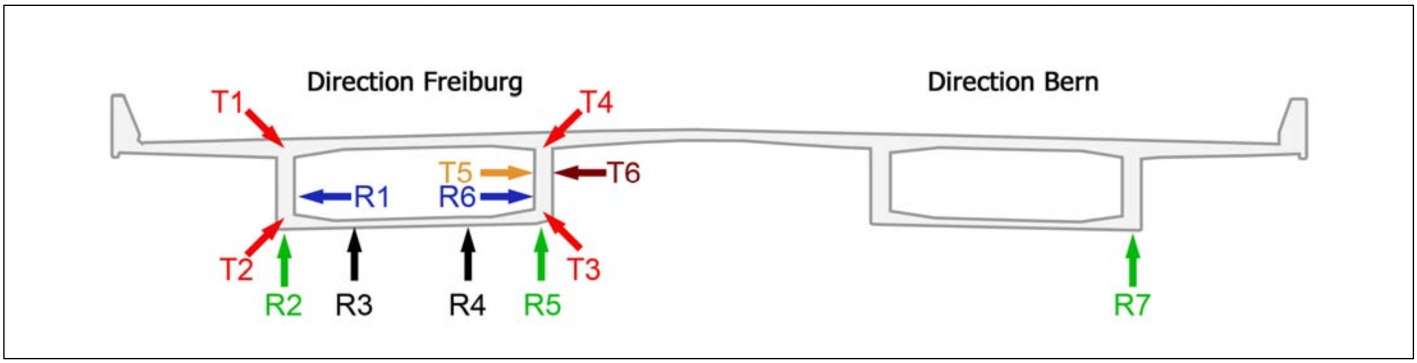


Fig. 3: Locations of movement sensors (R1 – R7) and temperature sensors (T1 – T6) at one coupling joint (Axis O)

The crack movements are measured with inductive LVDT sensors and LVDT current converter couples. The signal converter is placed close to the measurement position and transforms the physical parameter to a stable current signal according to the industrial 4 to 20 mA interface. The sensors have a measurement range from just +/-1 mm with a linearity better than 0,3% and repeatability of 0,15µm. Due to the LVDT principle the resolution is practically infinite (depending on the selected measurement range and amplification). In the project's preparation stage, test routines showed reliable resolution of 0,5µm.

Environmental conditions are monitored by four temperature sensors, which were drilled into the concrete, and two meteorological stations measuring temperature and humidity of the air. The measurement frequencies can be varied between 1 Hz and 500 Hz. A data pre-analysis can be programmed to filter the data output and to ensure an adequate data supply while limiting transmission costs.

The calculation model developed for the structure allows characteristics such as the tension in the reinforcement of the concrete and the condition of the prestressing tendons to be deduced from the measured crack widths. The analysis required a frequency of 500 Hz to ensure adequate results, as lower frequencies wouldn't permit measurement of the effects of vehicles moving at up to 120 km/h. The data was processed locally and saved on a hard disc.

3.6 *Installation and calibration*

After testing the manufactured system in the factory, all monitoring components were installed. The central computer was located inside the bridge, perfectly protected from the outside environment (Figure 4), and sensors were positioned at selected locations (Figure 5).

To facilitate calibration of the system, the bypass motorway was temporarily closed to traffic while a truck with a known weight of 40 tons passed over the critical sections of the structure at different, predefined speed levels. As expected, variation of the speed had no impact, meaning the crack width during the passing of a slow truck is comparable to the crack width during the passing of a truck travelling at 80 km/h.

Due to only minimal noise practically no digital signal conditioning was necessary. To make the manual determination of the maximum crack movement during the passage of test trucks more convenient, a gliding smoothing algorithm over 10 measurement values (at 500 Hz) was applied.

The first comparison of the measured values with the calculated figures of the static model showed an excellent correlation between the measured values and the predicted results from the 'non-cracked' concrete cross section model. This correlation is shown in Figure 6, where graphs representing measured and predicted values are presented together. This analysis provided the first solid evidence that the bridge is generally in good condition.

Fig. 4: Installation of Robo®Control computer

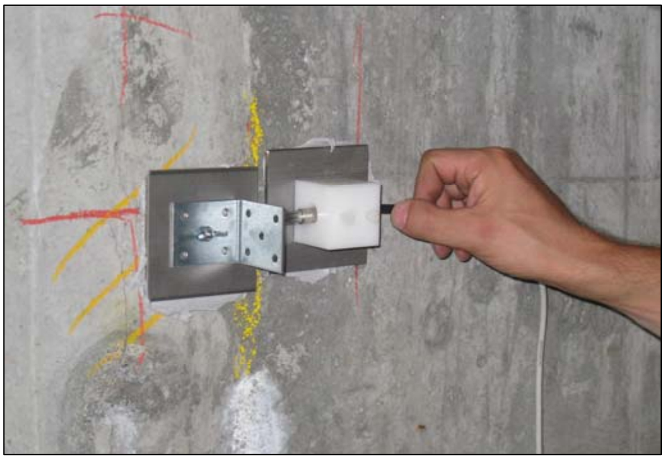


Fig. 5: Installation of an inductive sensor

In addition, the measurements clearly showed the different reaction of the bridge to different types of truck. A direct correlation between crack width and the weight of the truck could be identified, allowing counting and weight-classification of vehicles to be used directly in the fatigue assessment of the bridge's reinforcement and pre-stressing cables.

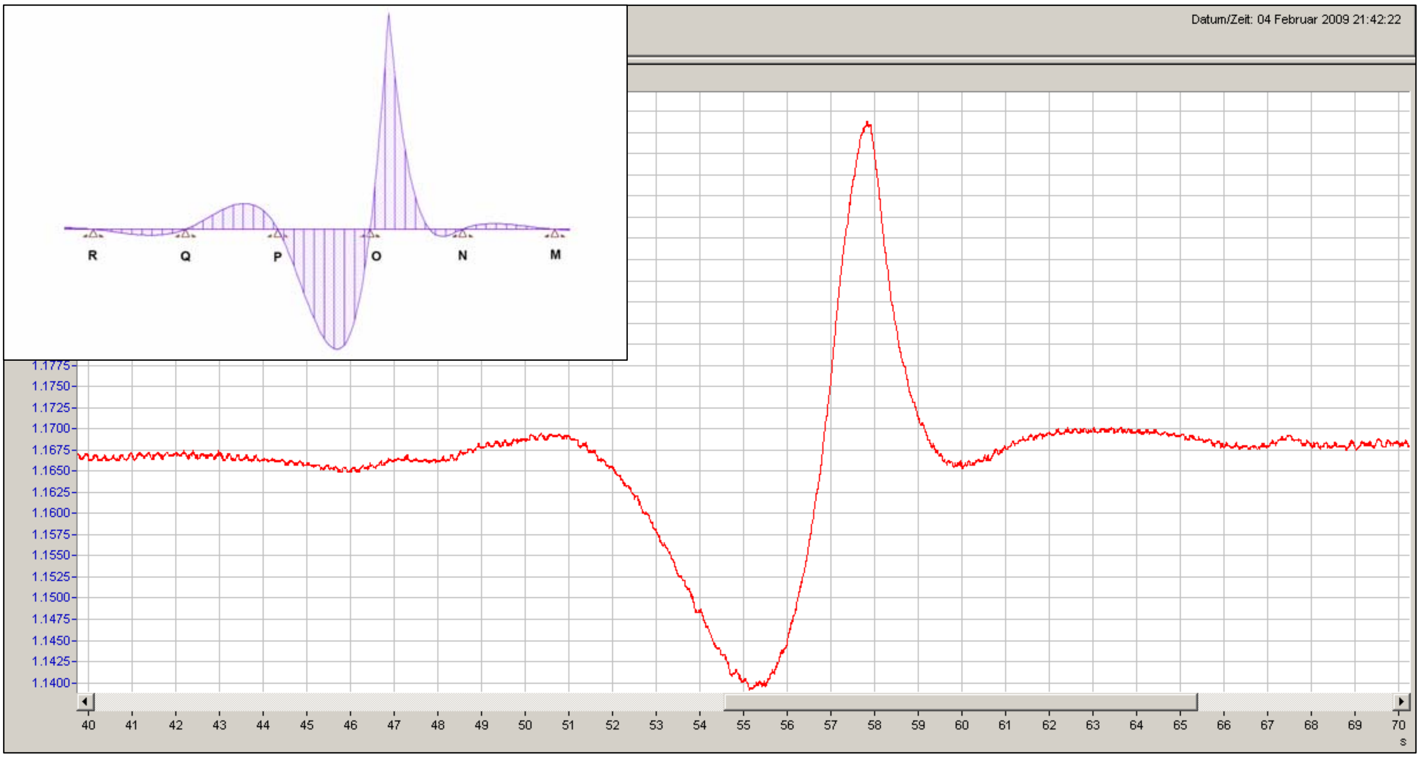


Fig. 6: Crack width measurement during system calibration (main graph), demonstrating excellent correlation with calculated influence line of static model (inset graph)

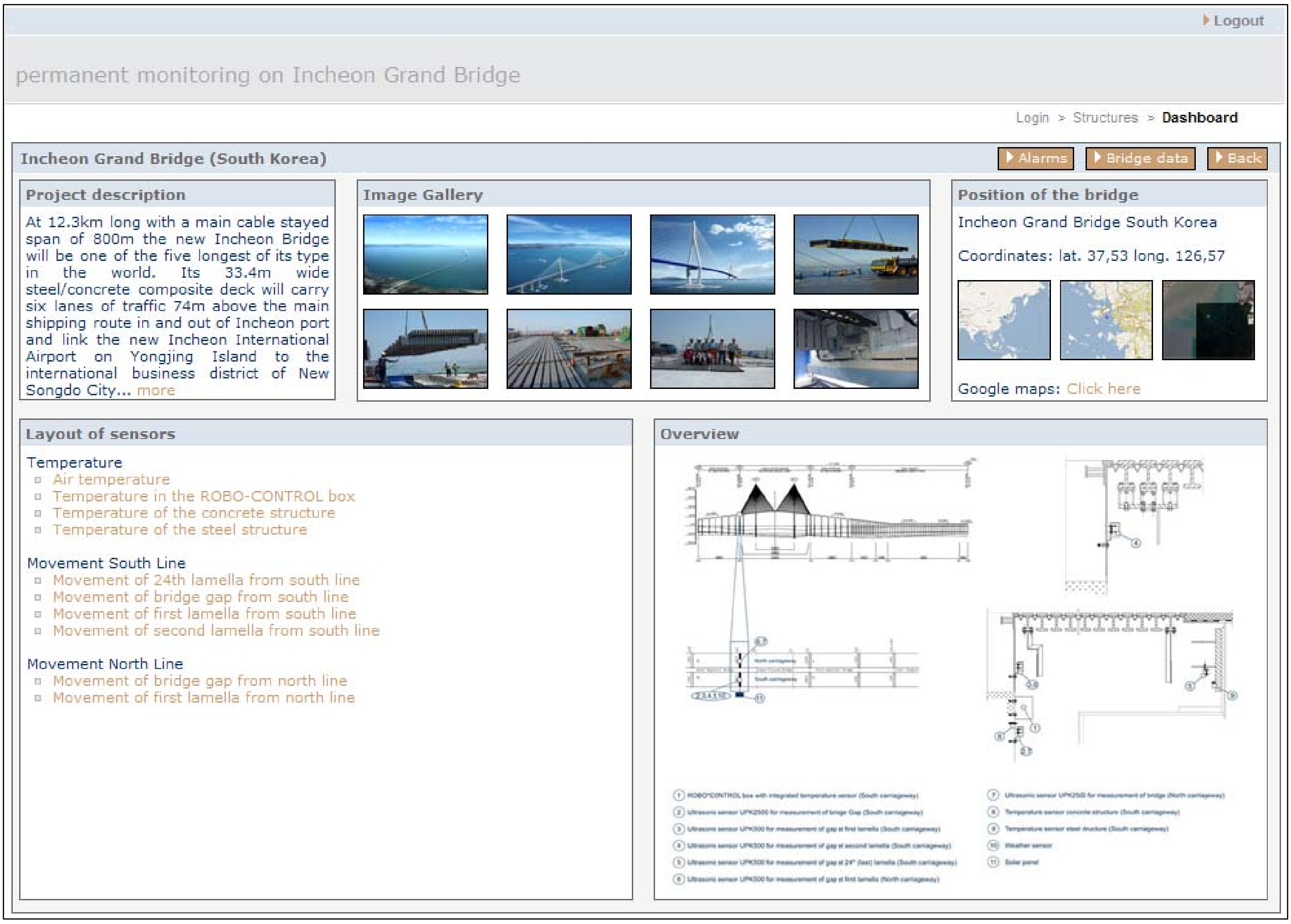
3.7 *Analysis of the impact of traffic loading*

After completion of calibration, the monitoring system was adapted to measure the effects of traffic on the structure. Due to the enormous amount of data generated at the chosen frequency of 500 Hz, and the hardware limitations of the installed computer, this assessment was conducted for one week only. All data was stored locally on the hard drive of the computer and was transmitted to the server in the office. After processing of data all values were made accessible in user-friendly format via the internet.

The results of this analysis were the same as those resulting from the calibration measurements, meaning that normal traffic conditions result in the same stresses and crack widths as observed during the calibration. Therefore the measured data could be used for the fatigue assessment of the structure - the number of peaks in the crack width measurements can be used to determine the number of trucks passing over the bridge.

3.8 *Analysis of the impact of temperature*

Finally the system was adapted, using lower measuring frequencies, to assess the impact of temperature over a period of one year. The duration was chosen to ensure that the whole range of temperatures during summer and winter times would be covered. The data processing was changed to suit the different needs of the adapted system. Continuous measurements at a frequency of 500Hz were no longer required due to the slow impact of temperature changes. The sensors still record at high frequency, but the on-site computer filters all values and only saves and transmits selected values at pre-defined intervals of five minutes, recording the average, minimum and maximum crack width values for each period. The system can be remotely controlled, to allow measurement frequency and data collection and transmission interval to be adapted as desired from the engineer's office.



Incheon Grand Bridge (South Korea)

Project description

At 12.3km long with a main cable stayed span of 800m the new Incheon Bridge will be one of the five longest of its type in the world. Its 33.4m wide steel/concrete composite deck will carry six lanes of traffic 74m above the main shipping route in and out of Incheon port and link the new Incheon International Airport on Yongjing Island to the international business district of New Songdo City... more

Image Gallery

Position of the bridge

Incheon Grand Bridge South Korea

Coordinates: lat. 37,53 long. 126,57

Layout of sensors

Temperature
- Air temperature
- Temperature in the ROBO-CONTROL box
- Temperature of the concrete structure
- Temperature of the steel structure

Movement South Line
- Movement of 24th lamella from south line
- Movement of bridge gap from south line
- Movement of first lamella from south line
- Movement of second lamella from south line

Movement North Line
- Movement of bridge gap from north line
- Movement of first lamella from north line

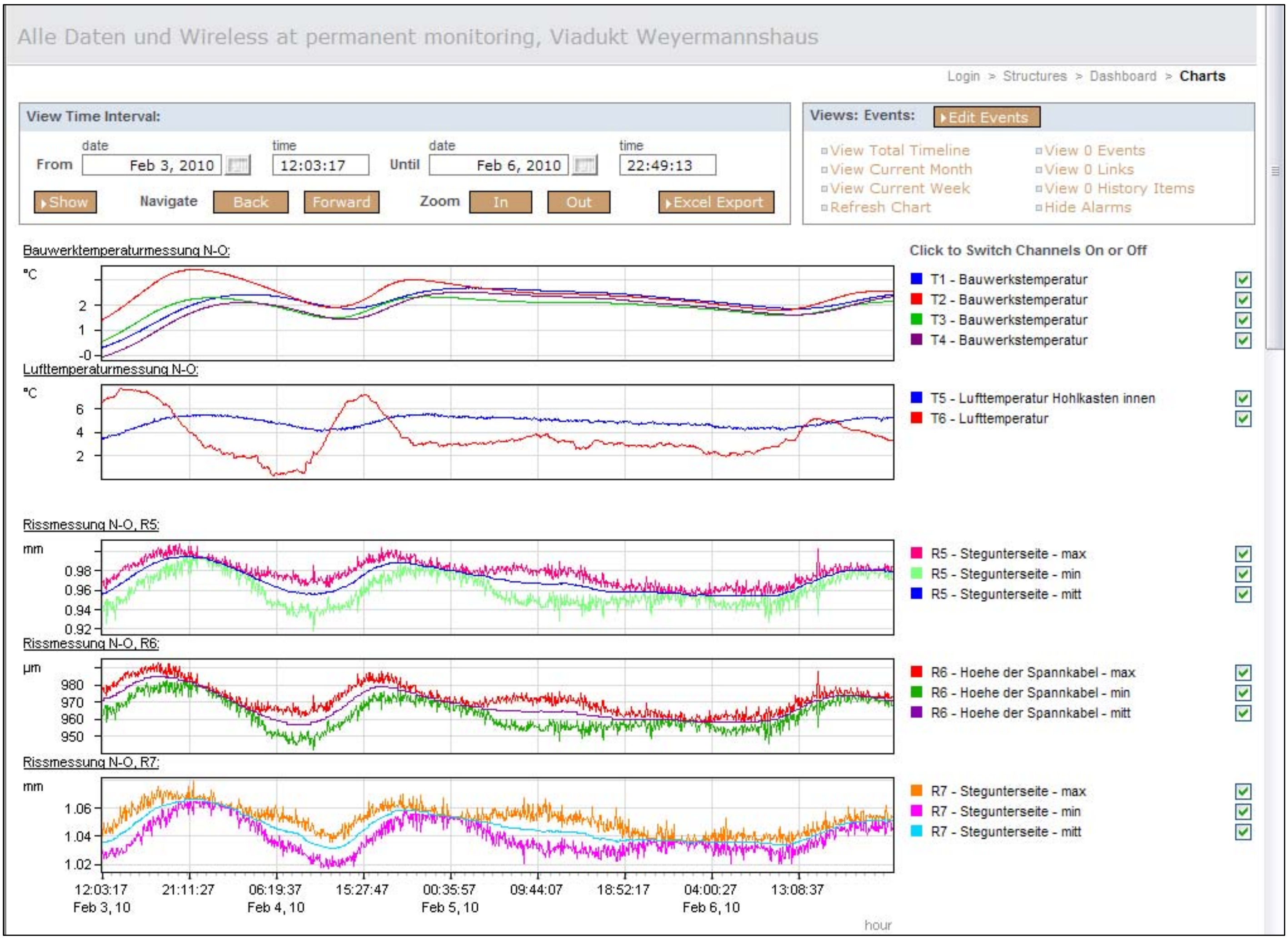
Fig. 7: Web interface of a long-term monitoring system (English language)

This approach reduces both the energy requirements of the system and, more significantly in this case, the data transmission costs. The data is transmitted to the off-site server and can be accessed in real time via the internet, allowing the authorities and engineers to analyze the data from any computer in the world with internet connection. All data can be directly downloaded in Excel format for ease of analysis. As a result the bridge can be completely monitored from the office, reducing greatly the effort and expense associated with manual methods. The web interface (in English language) of a similar long-term monitoring system is shown in Figure 7, and graphic presentation of detailed measurements by the Weyermannshaus Viaduct monitoring system is shown in Figure 8.

3.9 *Analysis of the information provided by the monitoring system*

The measurements such as those presented in Figure 8 indicate a clear correlation between temperature (of the structure and of the air) and crack widths (here shown with reference to the crack widths measured at locations R5, R6 and R7). Furthermore it could be established, by comparing crack movements during initial measurements with crack movements 6 months later, that no significant difference had developed, indicating that the cracking was not deteriorating due to increased cumulative loading. The measured values were used in the engineer’s analysis of the impact of temperature on the bridge’s condition. The hypothesis, which resulted from the computer model in advance, that the impact on bending moment from temperature is higher than that from traffic loading, was confirmed by the measurement results. The static evaluation of the structure, using the results provided by thecould thus be used by the responsible bridge engineer to conclude:

1. The critical concrete section is not fully cracked, but showing a slightly reduced resistance.
2. The strength of the structure is still adequate for current and projected loading.
3. The fatigue assessment was positive, indicating that the pretensioning tendons should continue to serve their purpose for the remaining life of the bridge.



Alle Daten und Wireless at permanent monitoring, Viadukt Weyermannshaus

View Time Interval:
From date Feb 3, 2010 time 12:03:17 Until date Feb 6, 2010 time 22:49:13

Fig. 8: Presentation of detailed measurements in graphic form (3-day period)

3.10 *Monitoring at Weyermannshaus Viaduct - Conclusions*

The installed monitoring system was used to conclude that the observed cracking of concrete on the Weyermannshaus Viaduct most probably appeared already at the time of the bridge’s construction or soon after, and is not deteriorating. The prestressing is concluded to have been adequate to give the structure sufficient strength, but insufficient to prevent cracking of the concrete at several coupling joint locations. The measurement of crack widths in combination with static calculations gave confidence to the structure’s owner and engineer that it continues to function well and safely, making costly reinforcement works such as external pre-stressing cables unnecessary.

4 LONG-TERM MONITORING TO ENSURE IMMEDIATE NOTIFICATION OF CHANGES IN A STRUCTURE'S CONDITION

4.1 *The purposes such an application can serve*

In certain cases the condition of a structure, at a particular point in time, may be known to be safe and satisfactory – for example, as a result of a short-term evaluation as described above. However concern may remain that the condition of the structure could change quickly for some reason, potentially making the structure unsafe or making accelerated deterioration likely. In such circumstances, an automated monitoring system, used purely to monitor the condition of the structure (without any further evaluation of the data recorded) can provide up-to-the-minute, precise information on the relevant variables. Where immediate notification of any change which might indicate a reduction in safety of the structure is required, manual observation is highly unlikely to be practical and provide the required level of certainty. However automated monitoring systems can monitor for any such changes and provide the required notification, immediately and efficiently, at a fraction of the cost of manual monitoring.

For such an application, a monitoring system can be designed to continually measure critical data (such as forces or movements of any part of the structure), and to immediately send an alarm signal, via SMS or e-mail, to the structure's engineers should any pre-defined alarm value be exceeded. This can allow a bridge owner to be confident that any sudden or significant change in the bridge's condition will be known immediately, allowing appropriate action to be taken to ensure the safety of the structure and its users.

4.2 *The Pont Nanin Bridge in the Swiss Alps*

The twin arch bridges of Pont Nanin (Figure 9) in the Swiss canton of Graubünden were constructed in 1967, using the same formwork, to create an important new connection in the mountainous area of the famous San Bernadino Pass. During refurbishment works some thirty years later, modifications to the bridge and road network 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 the superstructure, meaning that all movement of each bridge now occurs at one end. Therefore some of the bridge's 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 given rise to such movements in the past.


Fig. 9: Pont Nanin in the Swiss Alps

4.3 *Purpose of the monitoring project*

In order to provide ongoing confirmation that the impacts of the changes to the bridge's structural system are 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 at the bridge in 2005 in order to monitor the adapted load transfer through the structure, ensuring 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.

4.4 *Design of the system*

It was decided during consultations with the bridge owner 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 fulfil these objectives, a permanent Robo®Control "Basic" system was determined to provide the optimal solution. This member of the Robo®Control family of products is ideal for the purpose, considering the low volume of data and low measurement frequency required. The further benefits offered by a more elaborate (and more costly) "Advanced" system would not be significant in this case and was therefore not preferred.

The system measures the loads carried by bearings and the movements experienced by expansion joints at both abutments at 15-minute intervals. It also allows an authorised user, from the comfort of his office, to specify that measurements of increased frequency (for example, every second, during a period of one hour) should be recorded and transmitted for analysis via the web interface.


Fig. 10: Load monitoring at a bridge bearing


Fig. 11: Movement monitoring sensors at an expansion joint

4.5 *Features to suit remoteness of location*

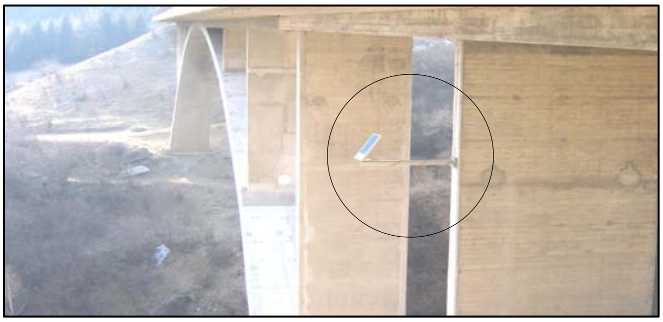


Fig. 12: A solar panel to fulfil power requirements

The choice of a low frequency "Basic" monitoring system was especially beneficial considering the remoteness of the location. The absence of a fixed power supply at the bridge necessitated the use of a solar panel (Figure 12) to satisfy energy requirements, while the lack of fixed-line telecommunications resulted in the need for transmission of data from the bridge to the system's central sever by mobile telephone network. The low frequency of measurements limited the volume of data to be recorded and transmitted, resulting in minimal power requirements and low data transmission costs, making solar power and SMS transmission of data sufficient and economical.

4.6 *Alarm notification of unexpected changes*

In addition to conclusions that can be reached regarding the bridge's structural behaviour at any time, the monitoring system also features an integrated alarm system which automatically sends notification, by e-mail and SMS, when any pre-defined alarm value is exceeded. This allows the bridge owner to have confidence that any changes in the condition of the bridge will be immediately recognised, enabling appropriate action to be taken to ensure the safety of the bridge and its users.

4.7 *Monitoring at Pont Nanin - Conclusions*

The monitoring system installed at Pont Nanin in February 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 statical system of an existing structure to satisfy updated usage requirements and conditions. The system thus validates the approach which was deemed most suitable for economic and other reasons, but which necessitated such validation in order to manage and minimise all residual risks – and does this much more efficiently and economically than could be achieved by an alternative manual inspection regime.

5 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 other structures. Questions that arise at any stage during the life of a structure, for example due to modifications to the structure or changes in its loading or condition, can be precisely analysed using data efficiently provided by such a system. And where concerns remain following any such analysis, a long-term monitoring system can provide economical real-time confirmation, with alarm notification if necessary, that the structure continues to fulfil its function properly and safely. Monitoring systems can thus potentially enable a preferred solution to be implemented, saving alternative solutions that might result in higher costs and more disruption to usage – thus playing an important part in the efforts of the engineering community to maximise efficiency and minimise the impacts of construction work on society and the environment.