AUTOMATED STRUCTURAL HEALTH MONITORING – FILLING A KNOWLEDGE GAP

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ABSTRACT

Our imperfect knowledge of materials technology and the variability of the world in general, leave a gap in the scientific approach to construction. We can predict, usually with great and justified confidence, that a well-designed structure will perform as desired under the conditions to which it will be subjected. However this approach is largely statistical, having to account for uncontrollable variables such as climate and other environmental factors, the loading which may apply at any time during the lifetime of a structure, or ground conditions. Add to these the variability in properties of a material such as concrete, which depend on such factors as workability of the fresh product, method and care of placing and compaction, and proper curing, and the potential for unforeseen results can be recognised.

New technologies which can be used to complement the currently widespread construction methods have been developing quickly in recent years. Automated structural health monitoring systems offer efficient and affordable collection and transmission of almost any type of data that may be required in relation to a structure. This may serve, for example, to increase the confidence of a structure's owner or engineer that the structure continues to function well and safely, potentially making costly strengthening or replacement works unnecessary. This paper describes an application of such a monitoring system on a pre-stressed concrete structure, demonstrating how such systems have great potential to contribute to the further development of how concrete, and other construction materials, are used in making the world a better place in which to live.

Keywords: Bridge, Structural Health, Monitoring, Safety, Crack Width

INTRODUCTION

Our imperfect knowledge of materials technology, and the variability of the world in general, leave a gap in the scientific approach to construction of bridges and similar structures. The basis of most design work in this area is largely statistical, initially assuming laboratory conditions and perfect installation processes and adding safety factors to make allowance for deviations and arrive at design values which are generally conservative. However, uncontrollable variables in disadvantageous combinations can lead to circumstances not covered by the design values, a serious. Automated monitoring systems offer a means of evaluating uncertainties which may remain or arise at any time during the life of a structure. The monitoring project *Weyermannshaus Viaduct* in Berne, Switzerland, which combines a remote controlled bridge monitoring system with a static calculation model, demonstrates how non-destructive investigation and assessment of a concrete structure can shed light on issues which can not be confirmed by visual inspection alone.

THE ONGOING RENOVATION OF BERNE'S BYPASS MOTORWAY

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 will be carried out in 2010 and 2011.

THE WEYERMANNSHAUS VIADUCT

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 Figures 2 and 3. 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 analyze 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.

Fig. 1: Weyermannshaus Viaduct, Berne - Switzerland

CONCRETE CRACK MONITORING OF THE VIADUCT

The bridge monitoring project was announced by the Swiss federal roads authority and the Swiss Federal University EPFL. It was mainly driven by the 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: Detail of an observed crack

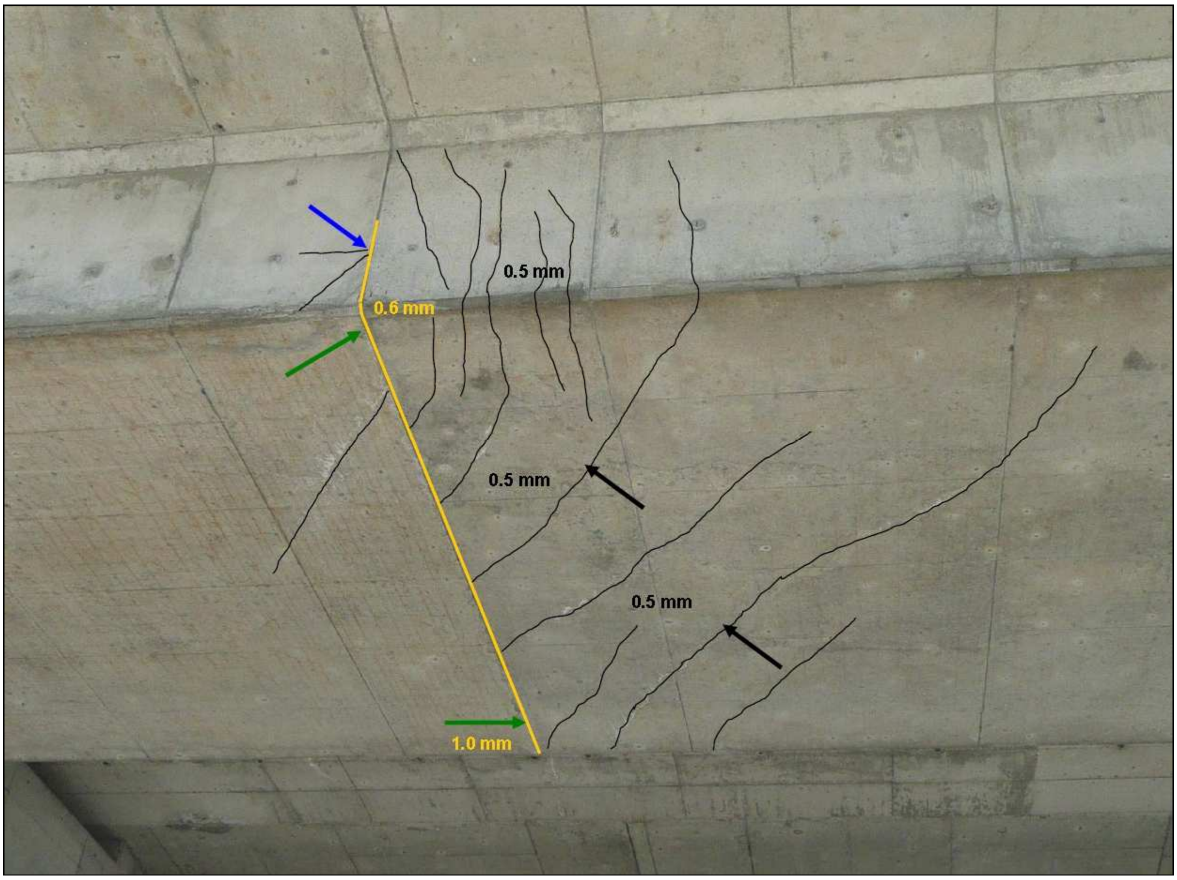

Fig. 3: Cracking at location of coupling joint of pre-stressing cables

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. 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.

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 remote monitoring system (*Robo®Control* by Mageba SA, Switzerland), 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 – R6 in Figure 4, while the locations of temperature sensors is shown by their references T1 – T6.

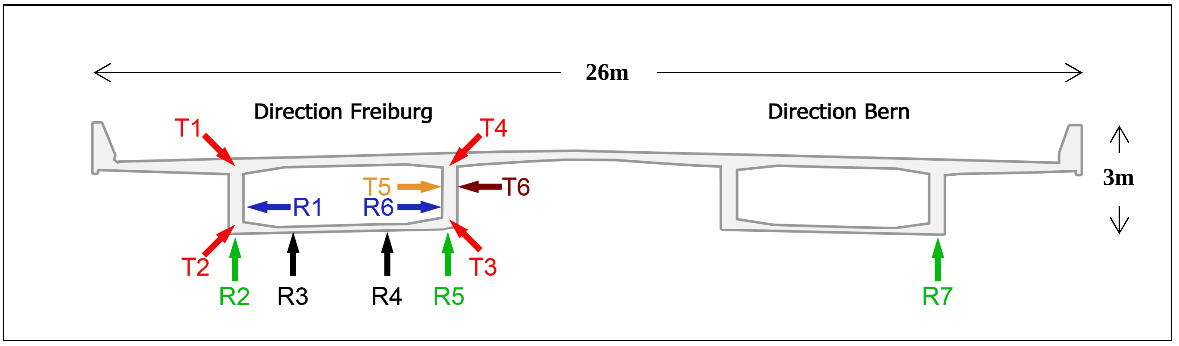

Fig. 4: Locations of movement sensors (R1 – R6) and temperature sensors (T1 – T6) at one coupling joint (Axis O)

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.

INSTALLATION OF THE MONITORING SYSTEM ON THE BRIDGE

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 5), and sensors were positioned at selected locations (Figure 6).

Fig. 5: Installation of Robo®Control computer

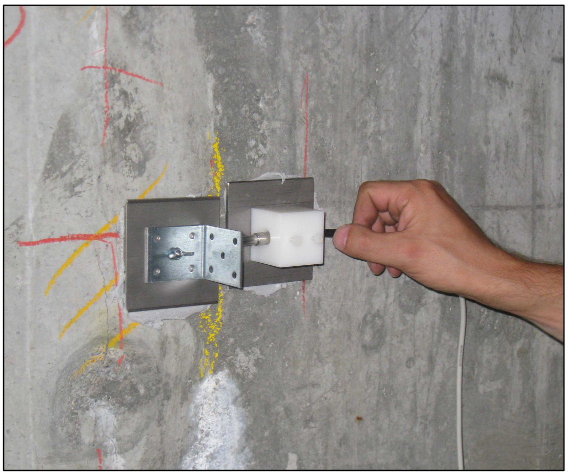

Fig. 6: Installation of an inductive sensor

CALIBRATION OF THE SYSTEM

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 is 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 (@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 7, 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.

In addition, the measurement clearly showed the different reaction of the bridge to different types of truck. A direct correlation between the 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.

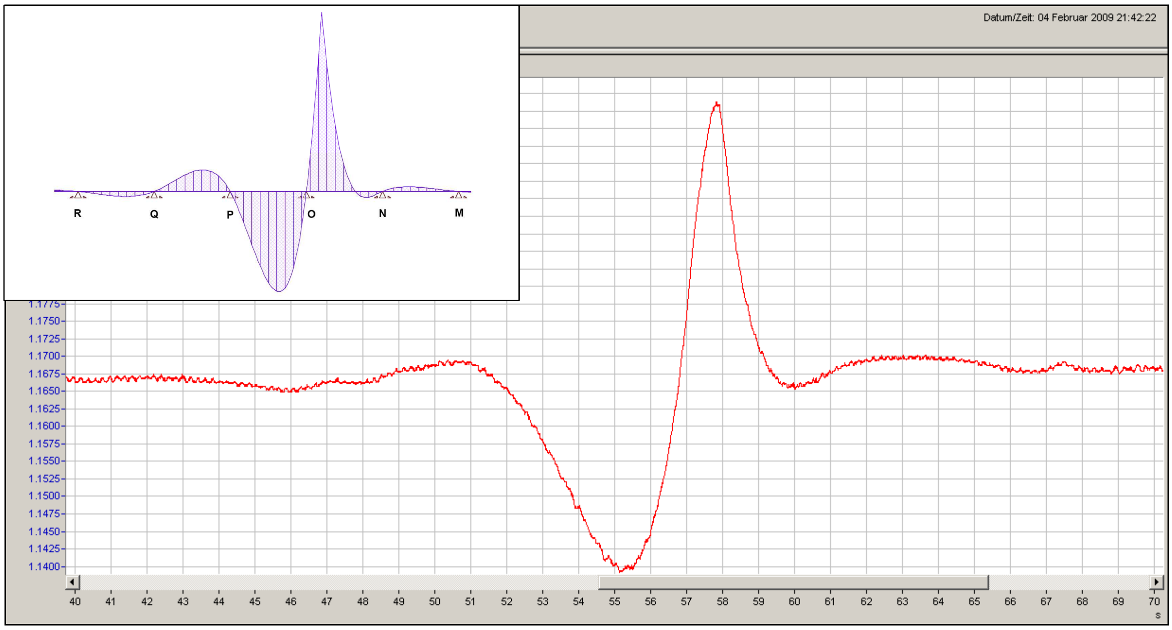

Fig. 7: Crack width measurement during system calibration (main graph), demonstrating excellent correlation with calculated influence line of static model (inset graph)

SHORT-TERM 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 by satellite 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.

LONG-TERM ANALYSIS OF THE IMPACT OF TEMPERATURE

Finally the system was adapted, using lower measuring frequencies, to assess the impact of the 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.

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 8, and graphic presentation of detailed measurements by the Weyermannshaus Viaduct monitoring system is shown in Figure 9.

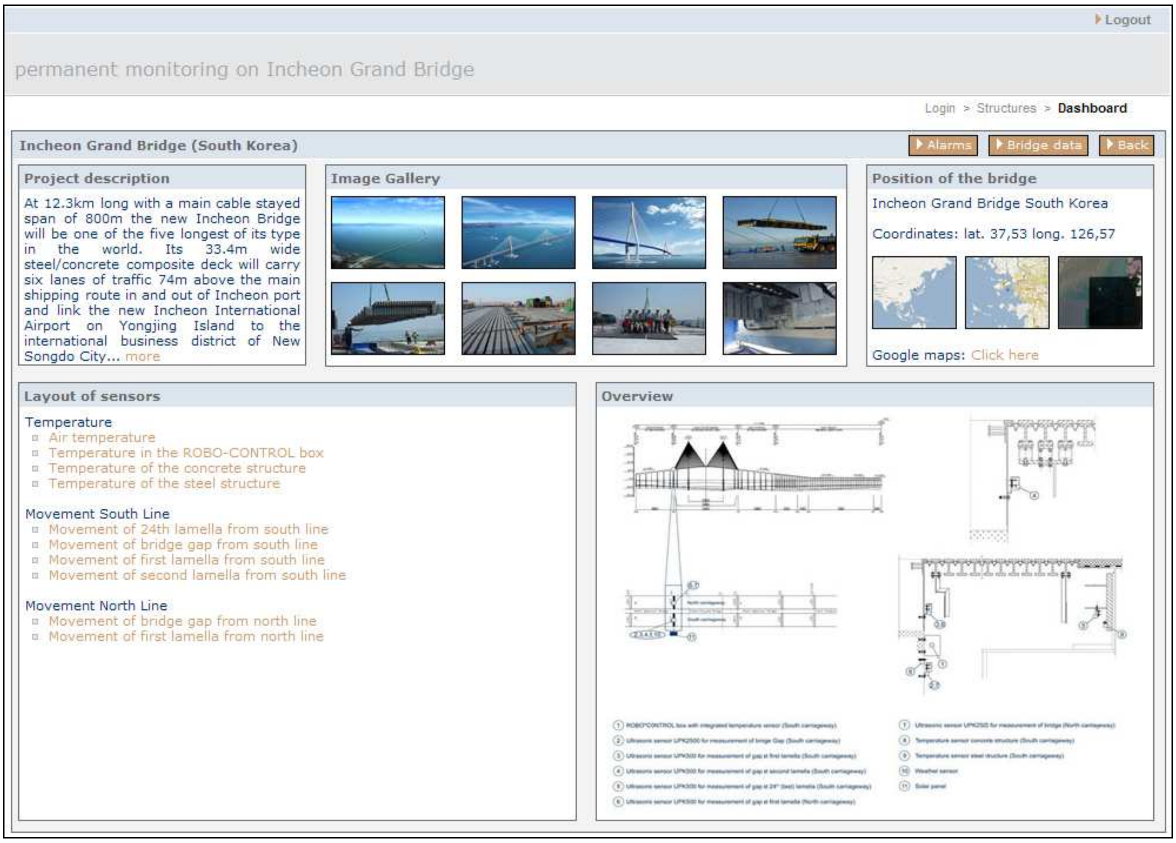

Fig. 8: Web interface of a long-term monitoring system (English language)

ANALYSIS OF THE INFORMATION PROVIDED BY THE MONITORING SYSTEM

The measurements such as those presented in Figure 9 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 at 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 the monitoring system could 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.

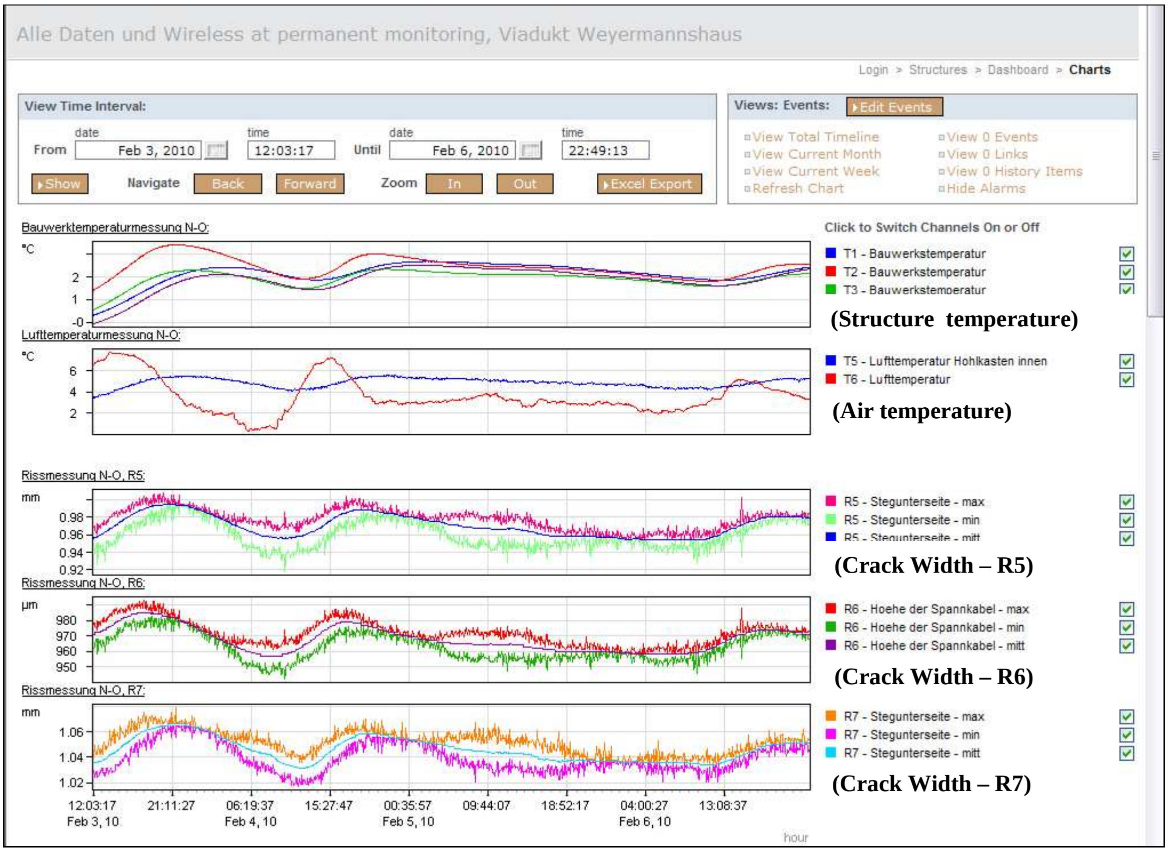

Fig. 9: Presentation of detailed measurements in graphic form (3-day period)

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.

It can be seen that automated structural health monitoring systems such as the one used offer efficient collection and transmission of data that may be required in relation to a structure. Such monitoring systems therefore have great potential to contribute to the further development of how concrete, and other construction materials, are used in making the world a better place in which to live.