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Modern Remote Structural Health Monitoring - providing long-term confidence in a structure's condition

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ABSTRACT: Remote monitoring of bridges and similar structures can serve a wide range of purposes, providing continuous records of almost any variable in a structure's condition. This may be of special interest to owners of older bridges, who must ensure the ongoing safety of their structures – not only because of the unavoidable deterioration that comes with age, but also due to the greatly increased traffic loading of recent decades, and the fact that many older bridges may not necessarily satisfy today's increasingly rigid safety demands. Very often, an assessment of the risks affecting a structure may not be able to conclude that the structure will continue to be safe in the future – for example where a risk, however small, of rock or slope instability has been identified. In such a case, a failure which could be catastrophic for the structure cannot be ruled out, and such a failure could occur at any time. To avoid having to undertake what might be prohibitively expensive or disruptive strengthening or replacement works, a comprehensive monitoring regime is then required to ensure that any change in the condition of a structure will be recognised in good time, in order that the safety of the structure and the public can be guaranteed. An automated monitoring system can be utilised to provide real-time information on any structure's condition, allowing gradual changes over a period of time to be identified and offering immediate notification by SMS or e-mail of any sudden changes in a chosen variable, or exceeding of predefined alarm values. Having such a system in place enables a structure's owner to be sure that any changes in its condition will be recognised immediately, allowing appropriate strengthening work to be planned or, if necessary, the structure to be closed. Examples of the use of monitoring systems to provide such peace of mind are presented - at the Pont Nanin Bridge in the Swiss Alps and a rock face stabilisation and monitoring project at the famous Rhine Waterfall on the Swiss/German border.

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 an 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 are presented below.

2 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.

3 THE PONTE NANIN BRIDGE IN THE SWISS ALPS

3.1 Bridge description

The twin arch bridges of Pont Nanin (Figure 1) 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 Bernardino Pass. During refurbishment works some thirty years later, modifications to the bridge 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 of each bridge now occurs at one end. 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 caused such movements in the past.

Figure 1. Pont Nanin in the Swiss Alps.

3.2 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 recognized, allowing appropriate action to be taken.

3.3 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 fulfill 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 authorized 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.

Figures 2 and 3. Load monitoring at bearing and movement monitoring at expansion joint.

3.4 Technical description of the Structural Health Monitoring (SHM) system

The system contains hydraulic bearings at both abutments, each of which is equipped with a reading display (see Figure 2) and a load cell. The pressure measured corresponds linearly to the force acting on the bearings. Displacement sensors continually determine the position of the last lamella beam of each of two modular expansion joints, and also monitor the joint opening movements. The monitoring system is completed with two meteorological devices to measure air temperature and humidity and concrete temperature.

Ultrasonic displacement transducers were selected to determine the position of the joint's last transverse beam. These have several advantages over alternative devices: they are absolutely free from abrasion; they are easy to install as no complex fixing parts have to be adapted; and they do not physically connect the structure's parts as would be the case with wired sensors, resulting in no restrictions to the movements of personnel during future inspections.

All sensors are attached to an ultralow power A/D conversion device which collects values from the sensors, stores them on an SD card and transmits data via the local GPRS network. Data blocks are transmitted using file transport protocol (ftp) to a central data server, where the data is processed and stored for client analysis and use.

The ultra-low power design of the SHM system enabled the system's power supply needs to be fulfilled by means of a single solar panel.

3.5 Features to suit remoteness of location

The choice of a low frequency "Basic" monitoring system was especially beneficial due to the remoteness of the location. The absence of a local power supply necessitated the use of a solar panel (Figure 4) 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.

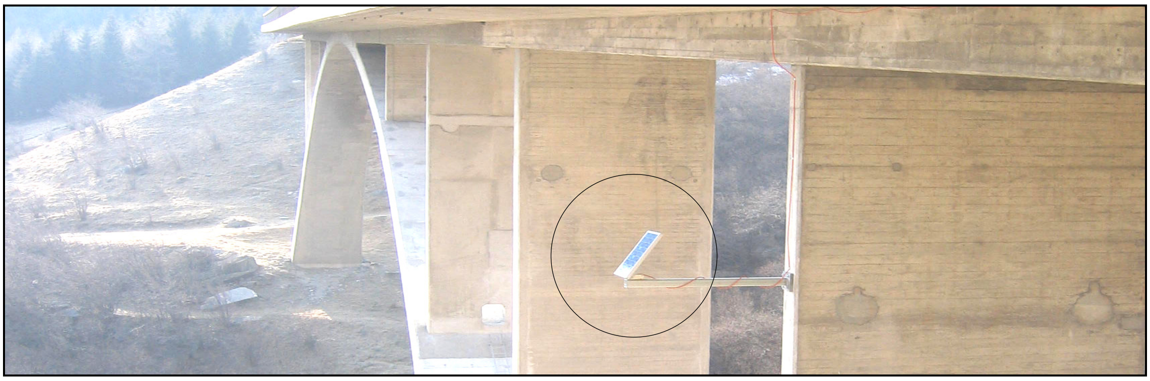

Figure 4. A solar panel to fulfill power requirements.

3.6 Alarm notification of unexpected changes

In addition to conclusions that can be reached regarding the bridge's structural behavior at any time, the system also features an 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 recognized, enabling action to be taken to ensure the safety of the bridge and its users.

3.7 Monitoring observations during operation

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, these concerns could be immediately allayed after the initial measurements. However ongoing measurements have now for six years measured the effects of increasing traffic and the thermal behaviour of the structure. Figure 5 shows a graphical presentation from the system's the web interface of force measurements at one abutment, where two pot bearings are monitored.

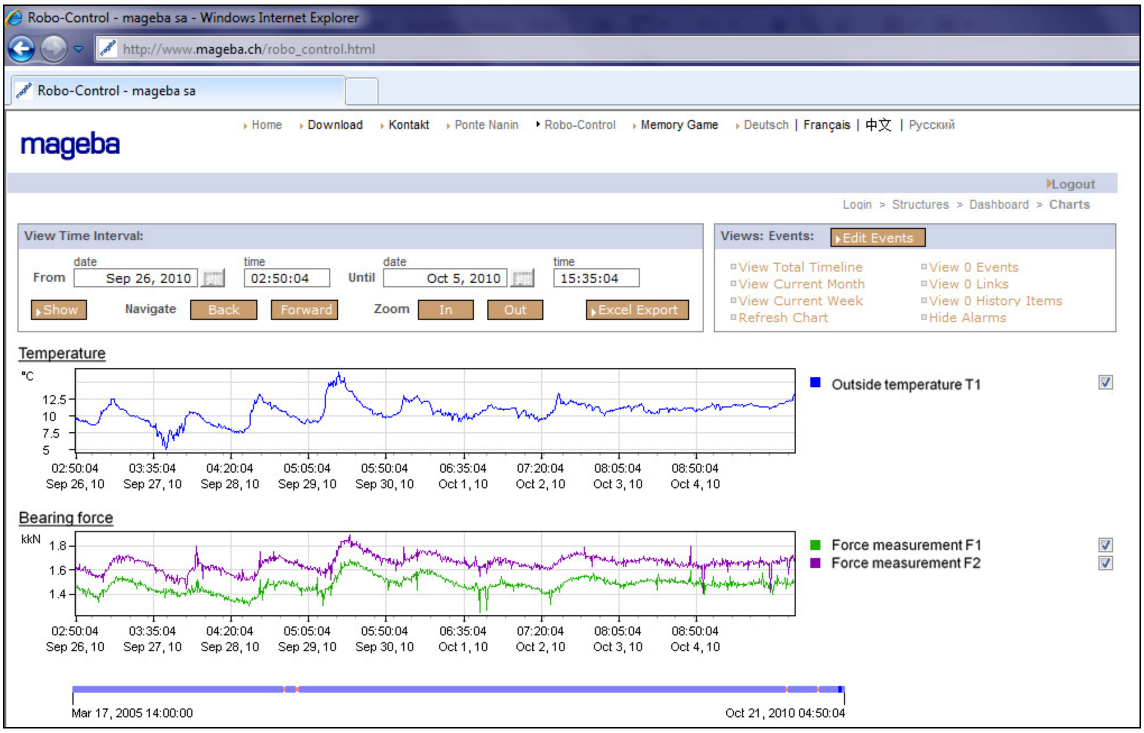

Figure 5. Graphical presentation of measured data at Ponte Nanin bridge.

3.8 Monitoring at Pont Nanin Bridge - Conclusions

The monitoring system installed at Pont Nanin 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 statical 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 minimize all residual risks, more efficiently than could be achieved by an alternative manual inspection regime.

4 THE FAMOUS RHINE WATERFALL

The Rhine Falls (Figure 6) in Schaffhausen, Switzerland is visited by hundreds of thousands of tourists every year. It is one of the region's most important tourist attractions and visitors marvel at the beautiful scenery from a terrace located close to the castle of Laufen.

Figure 6. The Rhine Falls on the Swiss/German border.

4.1 Situation and problem statement

Rock anchors installed to stabilise the rock wall below the castle showed unexpected force changes, leading to concerns that some sliding surfaces had developed. To ensure the ongoing safety of the terrace above, additional rock anchors with measuring devices were installed, with a Robo®Control system monitoring anchor force changes. This enables the responsible design engineer to draw conclusions about the wall's movement behaviour. The rock wall of particular interest (Figure 7) is below the castle of Laufen and about 20m high, and was stabilised with 11 additional rock anchors. The installation conditions were challenging due to high exposure, noise and dampness.

Figure 7. Rock wall of main interest with public terrace on top, stabilised with 11 new rock anchors.

4.2 Design and installation of the system

It was determined that a permanent Robo®Control "Basic" system should be connected to the newly installed rock anchors, to measure the loads arising in the anchors. The system should continually transmit all measured data to a web interface for analysis at any time, and additionally provide an alarm function to notify immediately of any sudden change in the forces acting on the anchors. As the system is independent of external measurement technology, flexible adaptations to suit commonly available load cells are possible.

It was decided during consultations with the bridge owner and engineer that records of forces at 30-minute intervals would in general provide an appropriate level of information. However the ability to obtain more frequent values is possible; the measuring frequency can be adapted according to the end user's requirements at any time.

4.3 Description of the SHM system

The system primarily comprises eleven load cells, which are directly connected to the installed rock anchors, and two meteorological devices to measure air temperature and humidity. A permanent power supply was locally available, but the client chose to have the system equipped with a buffer battery to overcome any potential power supply interruption of up to three hours. Data is transferred at defined intervals via the local GPRS network, with the system connecting itself to the internet and sending its data files per ftp to a central data server before disconnecting again. Just one value is measured per hour for each variable, keeping the transmitted data volumes, and thus the transmission costs, very low. The system's central computer is housed in a high quality outdoor cabinet to withstand the harsh climatic conditions of the mountain location, where very low temperatures in combination with high humidity can be expected to arise in winter. The system is also to facilitate possible expansion at a later date, with spare measurement channels.

A key feature of the installed monitoring system is the integrated alarm system which will automatically send alarm notification should any pre-defined force value limitation be exceeded. The alarm values were chosen in accordance with the designer's requirement anchors that the force arising in any anchor should not vary from its initial design force by more than 15%. This allows the site owner to have confidence that any changes in the condition of the rock wall will be immediately recognized and alerted, enabling appropriate and immediate action to be taken to ensure the safety of the public.

4.4 Monitoring of rock stability at Rhine Falls – observations to date

It can be concluded that the rock wall has been well stabilised by the additional rock anchors, with only negligible movements observed. The measured data (see Figure 8, showing forces recorded at anchors K10 and K11) demonstrates this, with forces shown to vary by just +/- 0.5%, and perfectly in line with the temperature changes recorded by sensor T1. It can be concluded that the rock wall continues to be very stable, giving the local authority the confidence it needs to safely manage one of Switzerland's most frequented and most spectacular public terraces.

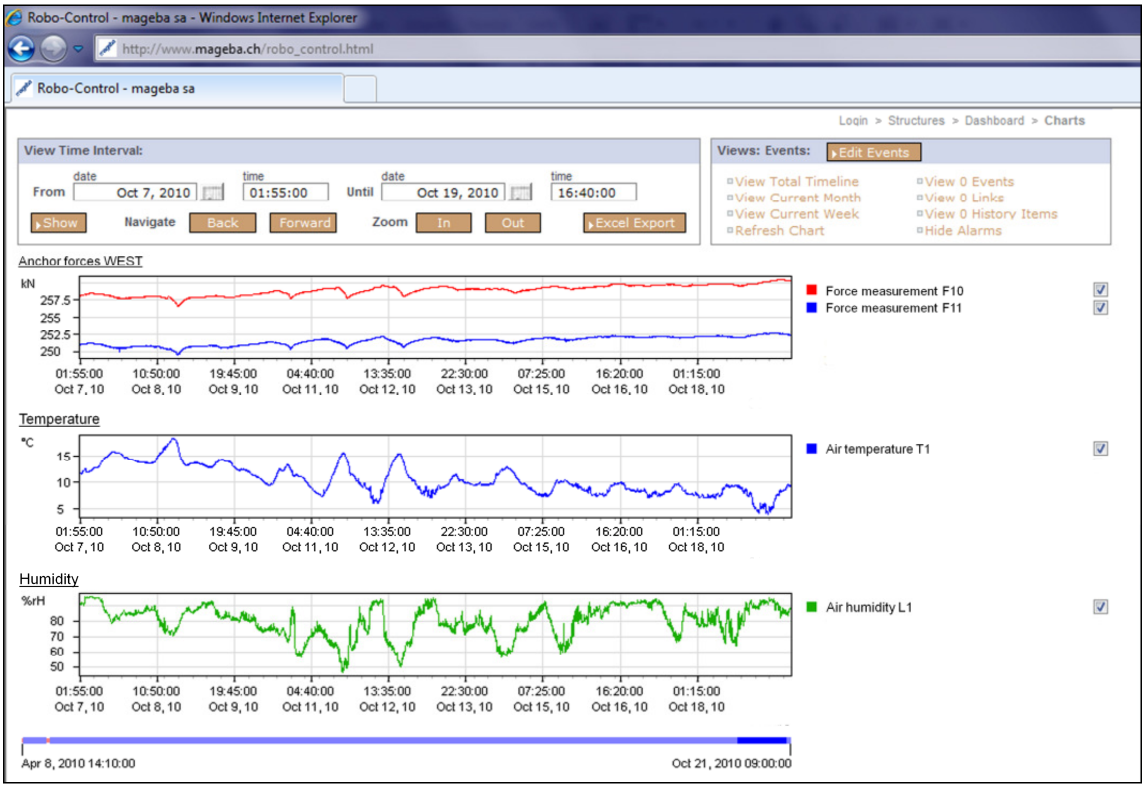

Figure 8. Graphical presentation of measured data relating to anchors K10 and K11.

5 MAIN 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 analyzed 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 fulfill 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 maximize efficiency and minimize the impacts of construction work on society and the environment.

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