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STRUCTURAL HEALTH MONITORING OF BRIDGES IN SWEDEN

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Abstract

Measuring insecure parameters in constructions has taken place in the past. However, the measuring was small in scale and aimed at pure verification of desired parameters rather than for economical, security or maintenance aspects. Organized Structural Health Monitoring (SHM) activities of bridges in Sweden have begun in recent years when some innovative bridges with complicated design were constructed. Several old and/or deteriorated bridges needed upgrading and classification and benefited from SHM. Both large scale and long-term projects were initiated; as well as some more moderate projects. Planning of data acquisition, installation of sensors, data storage and analysis were very demanding and a lot of heuristic knowledge was gathered.

New techniques were also introduced and some preliminary fibre optic installations took place. A lot of practical experience was obtained when working in the field with fibre optic sensors, especially when handling distributed fibre optic sensors.

This paper introduces some projects and results in short, and highlights conclusions. Special care is paid to reasons for monitoring, issues in planning, monitoring and practices in fibre optic installation procedures.

INTRODUCTION

Sweden has a genuine tradition of measuring insecure parameters in bridges since the beginning of the 20th century (1). Organised SHM became an acknowledged concept amongst the civil engineering society in the last ten years. The need to understand some new complicated designs and material behaviour during the critical points of construction or service life profited from monitoring.

Many communities, local road and railway authorities in Sweden have the overall responsibly for the maintenance and functionality of their own bridges. These authorities are often responsible for bridges in smaller areas, and may lack experience that would guide them in decision making. In addition, finances are limited and the authorities are looking for new, economical solutions that will help them in investigations. New constructions, like bridges, are dependent on political decisions that often delay the projects and there is sometimes a need to use the old bridges even if they are badly deteriorated. SHM allows for use of such structures and guarantees the safety for users.

These reasons mentioned have been the benefiting reasons that several monitoring campaigns were initiated in the last few years. This paper presents some of the projects in short and describes issues and experiences gathered around SHM so far.

THE NEW ÅRSTA RAILWAY BRIDGE

The New Årsta Railway Bridge is 833 m long, 19.5 m wide and has a vertical clearance of 26 meters. The piers have an elliptical cross-section. The bridge accommodates 2 railway tracks, pedestrian and cycle road as well as the service road. The length of the main nine spans is 78 m. Figure 1 illustrates the bridge during its construction period. The Old Årsta Bridge can be seen in background.

Figure 1. Longitudinal view of the New Årsta Railway Bridge during construction

The slender design of the bridge required a high amount of reinforcement and in order to satisfy the needs for bearing capacity, concrete of the quality class K60 according to the Swedish standard BBK94 (2) was used.

The construction work started in the summer of 2000, and the bridge was opened for regular railway traffic in May 2005. The Swedish National Railway Administration (Banverket) initiated a monitoring campaign in order to study and understand the dynamic and static behaviour of the bridge. The main objectives are to monitor a chosen characteristic span of the bridge during 10 years including the construction phase and the testing phase.

The selected span P8 to P9 was divided into 5 sections; A, B, C, D and E; where section A is nearest to pier 9, section B the quarter span nearest pier 9, section C the mid-span, section D the quarter span nearest to pier 8 and section F nearest to pier 8. The total number of sensors can be seen in Table **1**. The system also accommodates a central cabinet for data loggers and for the broad band connection. The measurements are ongoing and have taken place from the first pouring of the concrete in January 2003 until today.

Table 1. A summary of the total number and location of the monitoring instruments installed on and/or embedded in concrete during the construction.

Sensor	Number	Location	Type
Strain Transducer	22	Sections A, B & C	KTH/HBM1XY116/120
Fibre optic sensor	40	All sections	SMARTEC, SOFO
Thermocouple	9	Sections A,C & E	SMARTEC
LVDT	1	Section B	HBM WA plunger
Accelerometer	6	Section B & C	Si_FlexSF1500S,Colibry

FUNCTION AND RESULTS

Using these new techniques in the field created a lot of problems, especially during the construction period. Serious malfunctions could jeopardise the function and quality of the system and were keenly reported in order to examine and fix them and avoid the same mistakes in the future projects.

Some sensors stopped working after casting and were probably broken by vibrating. Two sensors were not in pre-tension and therefore unable to measure. The sensors are not damaged but were either gliding after the installation or were not pre-tensioned enough during the installation. One sensor and the installed accelerometer cables were damaged by workers at the site. A few other sensors, stopped working after they were subjected to violent treatment after the installation. Water penetrated into the portable SOFO data logger and caused corrosion in some components. This caused several serious failures in the data logger and some of the problems were not detected at immediately but took place some time after and were hard to identify. In addition, the permanent Central Measurement Cabinet was standing in the water when the drainage hole had frozen in the winter and water flowed in. Coincidentally, this misadventure only damaged some transformers.

Broad band connection problems caused some loss of the data because the capacity of the data loggers for both systems is not large. Discontinuity in the measuring during construction is due to the lack of electrical power and interruption in power delivery. Many other problems occurred that are beyond this paper but important in order to gather the heuristics and will be reported in a handbook.

As the monitoring was carried out during several years, a lot of results are available. Some results are briefly presented here and more static can be seen in (3) and dynamic in (4). Figure 2 illustrates the pre-stressing steps from the 5th to the 8th of May 2003. Figure also shows when sensor AS4, that was either gliding or not pre-stressed enough in the installation phase, stops measuring after the last pre-stressing stage. The next step that can be seen in the figure is removal of the formwork on the 12th of May 2003. This activity caused additional strain changes, this time in the opposite direction and at smaller levels.

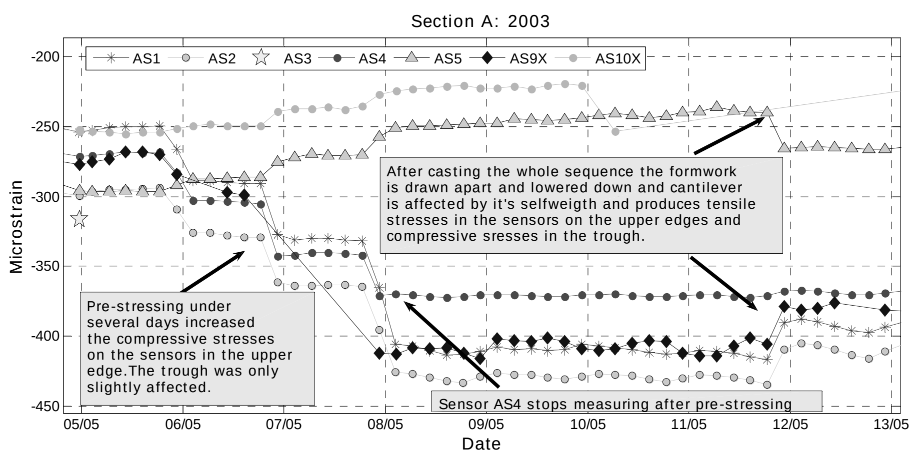

Figure 2. Strains during and after

A load test was performed before the bridge opening with one locomotive and 10 wagons filled with ballast. The train was located on the bridge and measurements were performed during this stop. The weight of the locomotive was 88 tonnes. Each wagon loaded with ballast weighted 80 tonnes. The train stopped on the western track on the bridge so that the ballast wagons filled two spans, from Pier 8 to Pier 10. The test was monitored with the SOFO sensors as well as the KTH strain transducers. SOFO sensors are commonly 4 to 6 meters long and strain transducers 0.3 meters and both measure average strain along its length. Figure 3 shows the results for sensor AS1 during the test. Measure is taken about every seven minutes that is the time to measure the whole system of 40 fibre optic sensors and thermocouples. The measured strain is expressed as microstrain, meaning a strain of $1 \cdot 10^{-6}$.

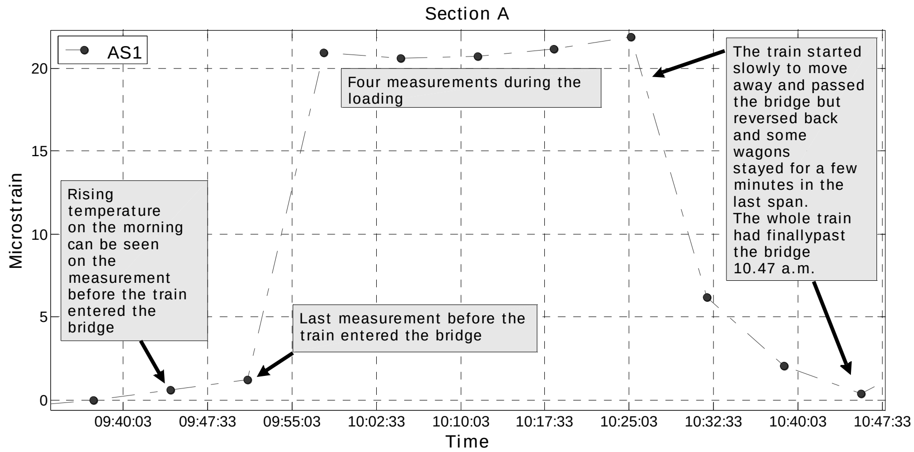

Figure 3. Strains in a 4 meter long sensor located in the outer edge of the eastern cantilever in longitudinal direction.

Figure 4 shows the maximum stresses that occurred in section A during the load test, measured with longitudinal sensors. The track slab has transversal sensors and was also measured: intimation to compression could be indicated but it is difficult to interpret at such minimal strain levels that occurred. The test showed reasonable strain and stress levels in agreement with what could be expected for this load. The test also confirmed that the measuring devices work in a satisfactory way and that the different systems in most cases show similar results.

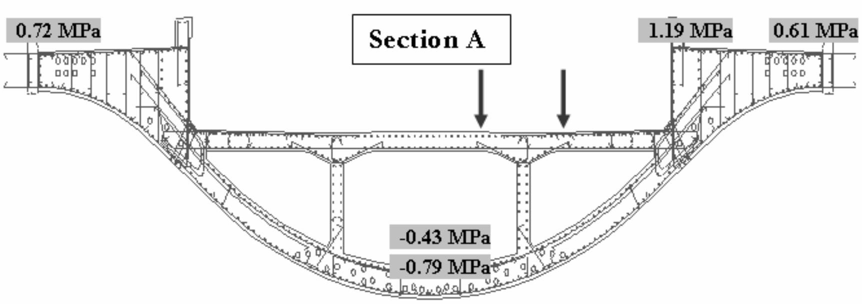

Figure 4. Maximum tensile (+) and compressive (-) stresses at section A.

GÖTAÄLVBRIDGE

Götaälvbridge is an openable, large steel beam, concrete deck construction combined for both road and light-rail traffic, built in 1939. The bridge also accommodates a pedestrian-and bicycle road on the both sides along its length of 950 meters. It is one of the most important connections for road traffic and the most important for the public transportation between the Gothenburg City and Hisingen, Sweden's 4th largest island.

Figure 5. Side view of the Götaälvbridge during bridge opening

The dense light-rail traffic causes dynamic effects and the bridge openings cause a lot of unsymmetrical static loads during boats transits. As the bridge structure was judged to be in critical condition, refurbishing work has taken place in order to upgrade the strength of the bridge to an acceptable level. A health monitoring system was also recommended to guarantee the safe usage of the bridge. Norwegian Geotechnical Institute (NGI) investigated the market in order to suggest the best solution for the purpose. They then recommended a distributed fibre optic system in order to see a total change in strain along the whole bridge.

A test installation of fibre optic sensors was made. Some selected I-beams of the bridge were installed with sensors and tested. The test also included testing the adhesion of the glue to the sensor, paint and steel clean surface. The chosen monitoring system is called DiTest and it is based on stimulated Brillouin scattering and is a unique tool for the evaluation of distributed strain and/or temperature over several tens of kilometres. The system is able to detect cracks bigger than 0.5 mm. Potential problems can be identified and localized at thousands of locations by means of a single optical fibre and in just one shot. Five longitudinal beams of the bridge are installed with sensors called SmarTapes manufactured by SMARTEC SA. There are 60 sensors and they are commonly 90 m long. Sensors are spliced together and connected to a passive multi fibre cable to build a loop that is then connected to a PC with special software designed for the project. The system will automatically send warnings to authorities by e-mail, text message or voice message.

FUNCTION AND RESULTS

The project is at the final stages during the writing of this paper. Installation procedures for distributed sensors is more complicated as the gauge length can be up to hundreds of meters. The sensors are to be checked/measured during the installation procedure with an Optical Time Domain Reflectometer (OTDR), and skills in optical engineering are an obligation for reliability. Also the advanced laser techniques for analysis of the signals require expertise to perform trustworthy measurements.

The sensors in the project are commonly around 90 meters and the initial losses are around 2 dB. After the installation the losses have increased about 0.5 to 1 dB. As minimal losses to preferred, the installation procedure is of high importance. Some sensors broke down due to the aggressive environment including a lot of dirt and hard wind. The installed sensors needed repairing in the field and this activity is very hard to perform without lowering standards, especially during the cold winter period in Sweden. Figure 6 show a preliminary measurement with DiTest for a loop consisting of 3 SmarTapes and passive cables. The measured strain is expressed as microstrain, meaning strain of $1 \cdot 10^{-6}$.

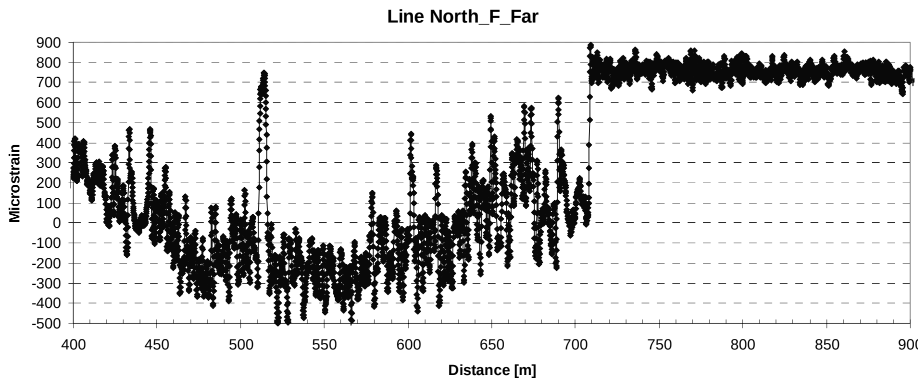

Figure 6. Strains in three SmarTapes and the passive cable in the loop.

The first sensor of approximately 60 meters starts at about 430 m. The second one of approximately 80 m starts at 520 m and ends at 600 m. The third sensor of approximately 90 meters starts at 600 m and ends at 690 meters. The passive cable can be seen at the end, starting at around 710 m, leading the light back to the DiTest. The measurement show data without reference points and to establish the local coordinates and reference levels, a load test and warming up of the desired coordinates will be performed. An algorithm for the software was also designed in order to match the conditions that may occur on the bridge. The bridge is nearing the end of its lifecycle in the near future and needs to be replaced. The monitoring system is designed to work for the next 15 years and this sets very high demands for the selected system.

THE NEW TRANEBERG BRIDGE

The Traneberg Arch Bridge built in 1934 was retrofitted by keeping the arch and reconstructing the pillars and the deck (5). See Figure 7 for a side view of monitored section; A, B, C and D. A monitoring campaign, initiated by SL, the local authorities for public transportation in Stockholm, took place during the retrofitting process of about 16 months. Temperature and static strain were continuously monitored with five thermocouples and 7 fibre optic SOFO sensors in longitudinal direction.

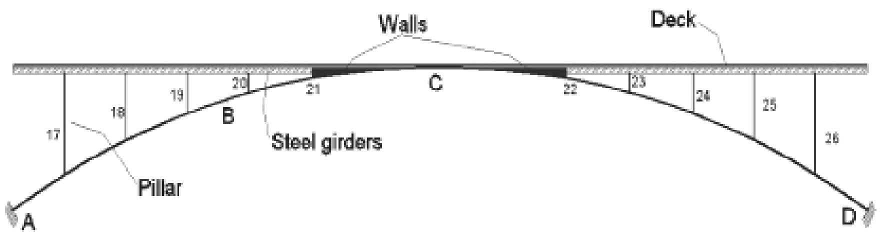

Figure 7. Side view and parts of the bridge that were rebuilt under the retrofitting

FUNCTION AND RESULTS

The function of the system was generally good, although some lack of power delivery and modem connection problems is expected. The sensor survival rate was 100 %. Monitored values were compared with calculated values and confirmed that the 70 year old concrete arc is in good condition and was not subjected to overloading during retrofitting. Cracking were also detected by comparing the daily variations of the sensors. The system remains on the bridge and can be used when needed.

See Figure 8 for four m long fibre optic sensor TA1 and for thermocouple TAT1 for the retrofitting period**.** As the temperature effects are dominating, a short study about them and reconstruction of the bridge was done and can be seen in (6).

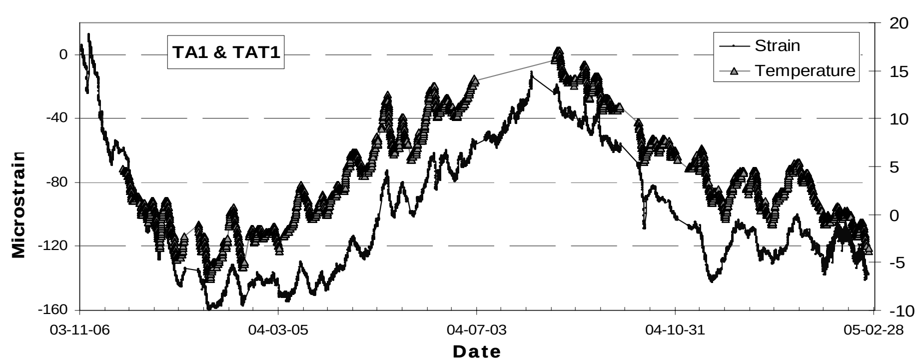

Figure 8. Strain and temperature profiles during the retrofitting period of about 16 months.

OTHER MONITORED BRIDGES

Two cantilever bridges called Gröndal Bridge and Alvik Bridge in Stockholm revealed extensive cracking in the webs of their concrete hollow box girder sections just after two years of operation (7). As the inspections showed them to be increasing, the bridges were closed. The bridges were strengthened and monitored since retrofitting and the monitoring continues for at least five more years. The monitoring confirmed that the strengthening was successful and the bridge was able to open for traffic.
The New Svinesund Bridge was built between the Swedish and Norwegian border and was opened for traffic in

2005. It is at the moment the largest concrete single-arched bridge in the world. An extensive monitoring project took place from the beginning due to the uniqueness of design, and the monitoring is ongoing. Monitoring concluded the desired parameters during the construction period. A large load test was also performed before the bridge opened, consisting of measurements with different technologies like vibrating wires, strain transducers, total station and laser (8).

Long-term dynamic monitoring like in the New Årsta Bridge is rare to find but several short-term projects took place as monitoring of the Älvsborgbridge, the Höga kusten Bridge etc. Most of the dynamic projects are aimed at measuring local as well as global parameters for classification and may be repeated periodically in order to monitor the changes of these parameters in time.

DISCUSSION AND CONCLUSIONS

Monitoring produces a lot of data that needs to be analysed. If this data is not stored in a compatible format for end users, it increases the cost of monitoring. The database where statistical studies of parameters are easily done is preferred. The statistical methods are a good tool in revealing malfunctions in long-term monitoring. In several long-term monitoring projects discussed above, statistical methods were used successfully to locate cracks and control their propagation. A lot of resources and time can be saved with cautious planning of the database related issues at the beginning of the project.

Installation procedures in the field are important for trustworthy results and for the long-term quality of the monitoring system, especially with fibre optic installation. Even if there is a lot of literature about the subject, the engineering society seems not capable of applying this information, and only the experience brings deeper understanding of the complexity of the subject. Practical issues around the installation need to be tested and proved in the field beforehand. A laboratory environment is optimal, lacks the demands of the field, and may endanger the function of the sensors. Large projects like Götaälvbridge with 60 distributed sensors to be glued to the beams demand a lot of staff. It is impossible to find trained site workers as there is no experience in the field. The need for basic handbooks and descriptions for installation staff is urgent. The bridge engineers working with advanced fibre optic, laser and other techniques also need education in the related subjects to be able to judge the reliability of these measurements.

SHM is a tool that helps in verification, decision making, maintenance and follow-up. Still, there is lot to learn and therefore all the problems and malfunctions need to be gathered, reported and discussed in detail to not be repeated. Responsible authorities need to have sound knowledge for measuring techniques and methods in order to be able to optimise the monitoring systems as well as reducing the costs. If this expertise is lacking in their own organisation, it is necessary to rely on external assistance.

REFERENCES

1. Anger, D., “Tranebergbron”, Offprint from Cement och Betong 1932-1934, (Tryckeri Aktiebolaget Thule, 341092, Stockholm 1935).
2. Boverket (The National Board of Housing, Building and Planning), “Boverkets handbok om betongkonstruktioner” (BBK 94), Band 1, Konstruktion, (Boverket, Stockholm, Sweden, 1995).
3. Enckell, M., “Structural Health Monitoring using Modern Sensor Technology – Long-term Monitoring of the New Årsta Railway Bridge” (Licentiate thesis, Royal Institute of Technology, KTH, 2006)
4. Wiberg J., “Bridge Monitoring to Allow for Reliable Dynamic FE Modelling: A Case Study of the New Årsta Railway Bridge” (Licentiate thesis, Royal Institute of Technology, KTH, 2006)

5. Enckell, M. and Larsson, H., “Monitoring the behaviour of the Traneberg Bridge during retrofitting”. In Proceedings of the ISHMII-2, the Second International Conference on Structural Health Monitoring and Intelligent Infrastructure, Shenzhen, P.R.of China (2005), 1631-1635.
6. Miranda, P., “Evaluation of the structural behaviour during retrofitting of the Traneberg Bridge by monitoring” (Master of Science Thesis, Structural Design and Bridges, Royal Institute of Technology, 2006).
7. Malm, R., James, G. and Sundquist, H., “Monitoring and evaluation of shear crack initiation and propagation in webs of concrete box-girder sections”. In proceedings of The International Conference on Bridge Engineering – Challenges in the 21st Century, Hong Kong (2006).
8. Karoumi, R., Andersson, A., and Sundquist, H., “Static and Dynamic Load Testing of the New Svinesund Arch Bridge”. In proceedings of The International Conference on Bridge Engineering – Challenges in the 21st Century, Hong Kong (2006).