VTT Technical Research Centre of Finland

Monitoring of bridges

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Monitoring of Bridges

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Confidentiality: Public

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Summary

The report is final report of SIMO (Monitoring of bridges) TEKES (Finish Funding Agency for Technology and Innovation) project composed by VTT and also written by other project partners.

The report describes common sensors and monitoring device which have been installed and used in five selected road bridges in Finland. The monitored bridges have been Kirjalansalmi suspenson bridge in Parainen, Boxby concrete bridge in Sipoo, Hännilänsalmi suspension bridge in Viitasaari, Jylhänranta concrete bridge in Pulkkila and Siikajoki bridge in Revonlahti. The sensors used for monitoring have been deflection transducers, laser sensors, accelerometers, strain gauges, thermometers, humidity sensors, optical fibres, corrosion sensors and weather stations. Most of the measuring devices and sensors have been obtained from normal dealer, only some measuring sensors and measuring device have been developed before the project beginning. The aim was also to test wireless connections and data transfer to laboratory. The measured data have been verified to physical models e.g. FE (Finite Element) and life cycle models in order to develop and improve existing models.

The sensors and measuring device have been working quite well for one or two years. Most of measured data could have been copied to laboratory using ADSL or GSM modems. In most cases the copied data have been afterwards analyzed in laboratory, but also in some cases analyzing have been executed on site using running programs in measuring device. Monitoring device in Kirjalansalmi suspension bridge have been connected to network using ADSL modem and all the data could be copied to laboratory and also triggering values can be included to send alarm messages. In Boxby bridge the temperature, humidity and weather conditions have been measured to estimate the deterioration of the concrete and also to make quality control after restoration. In other bridges measurements have been performed to research the conditions of the bridge or to develop the strength model of the bridge.

The benefit of measured and analyzed data have been estimated in maintenance work of the bridges.

Confidentiality	Public

Espoo 16.12.2008

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Preface

The SIMO (Monitoring of bridges) project is national TEKES (Finnish Funding Agency for Technology and Innovation) project with 15 partners, which are mentioned below. The report is written together with project partners and compiled by VTT, Ilkka Hakola. The chapters of introduction, recommendations, conclusions and summery have been written by project manager Ilkka Hakola/VTT. The other authors and corresponding chapters are mentioned below.

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FuktCom AB, Hemming Paroll (4.2, 4.3, 4.4)

Project for monitoring of bridges has been planned for many years, the first ideas to get long-term information of bridges via monitoring has been presented by Timo Tirkkonen from FINNRA and VTT developed and continued the efforts to start the project. Risto Kiviluoma, WSP has written the final project plan of SIMO.

The SIMO project has executed during years 2006 - 2008 by monitoring five different kind of bridges and by collecting data using ADSL or GSM modems. The data has been used to analyze bridges and structures using FE and life cycle models.

The assembler of this report will thank TEKES, Finnish Road Administration, engineers in Road Administration Regions and other project partner, who have given resources and funding for the project and to start the monitoring research in Finland. I will also thank all Simo project partners for good co-operation, good advice and help for writing this report with excellent expertise. I will also thank foreign universities and institutes (prof. Feltrin, EMPA; Prof. Kruger, MPA) for interesting presentations in SIMO workshops and seminars. Especially I will thank for university of Yamaguchi and prof. Miyamoto for the fine co-operation, expertise and help, concerning the bridge monitoring subject, presentations and publications.

Espoo 16.12.2008

lkka Hakola, SIMO project manager

Contents

1 Introduction

For many years the bridge inspections have been done in Finland manually, but for some years ago there have been ideas to use also sensors to help inspection, to have information inside the bridge structure and to get measuring results continuously. Nowadays all the design and maintenance data concerning bridges is saved in electrical format in bridge register. Finnish Road Administration (FINNRA) has ordered and carried out loading tests for bridges for many years and during the tests deflection, strain and temperature measurements have been done. Only in some cases long-term measurements (e.g. 2 weeks) have performed to measure deflections or fatigue of joints in bridges.

Simo project was established to test sensors, monitoring device and data transfer to find out if long-term monitoring is possible and how long time measuring device are working. Also the purpose was to develop post analyzing methods for measured data to be able to predict the condition and service life of the bridge and bridge structures. In Finland in Oulu region the maintenance of bridges has been given to outside companies using maintenance agreement (SILTOPA). This means the FINNRA does not have anymore a close contact to bridges and monitoring may give further knowledge during the period of maintenance agreement. Also in other countries there have been many examples of monitored bridges and analyzing results. In Finland the life-cycle model was included in the bridge design process and monitoring could give more information to develop analyzing of long-term data. At the beginning of project it was found, monitoring is quite complex process including sensors, measuring device, programming of devices, installation of sensors, data transferring, data saving and analyzing of data. The process is so complicated that no company was ready to perform it. Therefore co-operation was needed between companies and research institutes. SIMO project was established in 2006 to research bridge monitoring, to test monitoring devices and to analyze methods for long-term administration.

2 Goal

The goal of the SIMO project was to test monitoring equipment, sensors and measuring programs in different kind of bridges to have an idea the applicability for a long-term monitoring. Also the goal was to develop methods and programs to utilize measuring data for life cycle calculations. The project was carried out by selecting five different kind of bridges, which were monitored and loaded by heavy vehicles to calibrate measuring sensors. Project partners have developed during the project knowledge about monitoring of bridges. Also the aim of the project was to have co-operation with partners and foreign universities and institutes.

3 Important and long-span suspension bridge (Kirjalansalmi)

Kirjalansalmi suspension bridge is situated in southern part of Finland in Parainen near Turku. The bridge has two pylons, the main span of 220 m and it has been constructed using longitudinal and transversal lattices. The bridge has been rehabilitated in 2004 e.g. repairing the deck by installing rubber bearings between the longitudinal beams and transverse lattices. The bridge has selected one of the monitored bridges in SIMO project, because it includes number of joints being sensitive for fatigue. Also several heavy trucks and other heavy carriages are crossing the bridge and the behaviour was wished to model and monitor. The bridge is shown in *Figure. 3.1.*

Figure 3.1. Kirjalansalmi suspension bridge in Parainen.

3.1 Wired monitoring system

The wired measurement system was designed by Savcor Futurtec (Savcor Tempo Oy) to test and gather experience from components that have worked on other projects and observe them in more controlled environment. The software part of the wired measurement system was intended to test in a real life situation different free open source based tools and protocols together for the data handling. Monitoring system consisted of a serial measurement network, an embedded computer and a database positioned off site. The user interface was built using dynamic web-pages with real time display based on vector graphics.

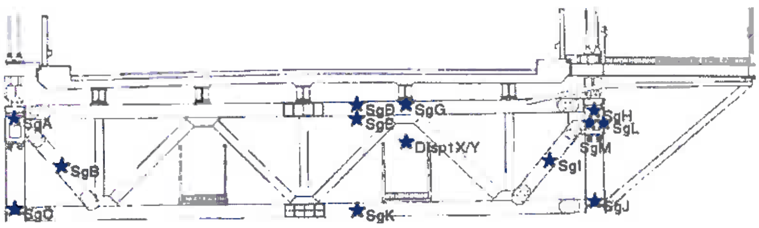


Figure 3.1.1. Location of sensors in the cross-section of Kirjalansalmi bridge.

The wired measurement and monitoring system was divided into two parts. The first part is the local RS-485 based measurement network and the second part the Internet connection over Symmetric Digital Subscriber Line (SDSL) based data link to a larger database that was located off site.

The original wired measurement system consisted of thirteen strain gages named SgA-SgM in the picture. Eleven of these are 350 Ω strain gages in bridge formation that are glued to the steel beams and protected against weather and impacts. The two last gages are weldable strain gages welded to the suspension bar anchor points. Later the customer (Finnish Roadworks) asked for some more measurements in another part of the support structure and measurement points SgN-SgQ were added in a one day post installation job.

3.1.1 Strain gages and displacement sensor

Figure 3.1.2. Strain gage installation.

Most of the strain gages are paired with a temperature sensor named TempA-K (eight units). Temperature measurements were done using digital temperature measurement chips for improved reliability. The chip based units may withstand better the effects of vibrations and impacts. The units were placed next to the strain gages. The temperature data collected by the units is then transported to the main measurement unit using the RS-485 based differential serial network. Having the temperature and strain information running in the same single cable further simplified the installation and lowered the number of cables and connections that could break or go wrong.

System has also a two dimensional displacement sensor. The infra red transmitter was placed on the immovable concrete end support of the bridge and the reflector (named DispX/Y in the picture) was placed on the maintenance walk way hanging from the bridge structure. The place on the walkway was chosen because of the straight undisturbed view from the transmitter on the end support to the reflector. The maintenance walkway is closed to normal pedestrians and is rarely used by the maintenance persons. Thus, it is a good compromise for the infra red based displacement measurement system. The unfortunate side effect of positioning the reflector in the middle of the walkway was that when other projects needed to work in the area the reflector had to be moved temporarily on the side. Effect which gave us several scary moments as it happened without warning and all the alarm systems went solidly on the red for the duration of the work. Luckily the 2D displacement unit is a very robust design and after the workers placed the reflector back roughly to it's original position normal measurements could proceed without any need for recalibration or manual fine tuning of the displacement sensor.

The monitoring installation includes also a road monitoring camera which was integrated to the general data feed and user interface pages during 2008. Currently the camera takes a picture every 15 minutes and places that into the off site database. All the images can be linked to measurements done at the same time. In the future the system will be changed to take an image every time something unusual happens on the bridge and link the relevant measurements to that image.

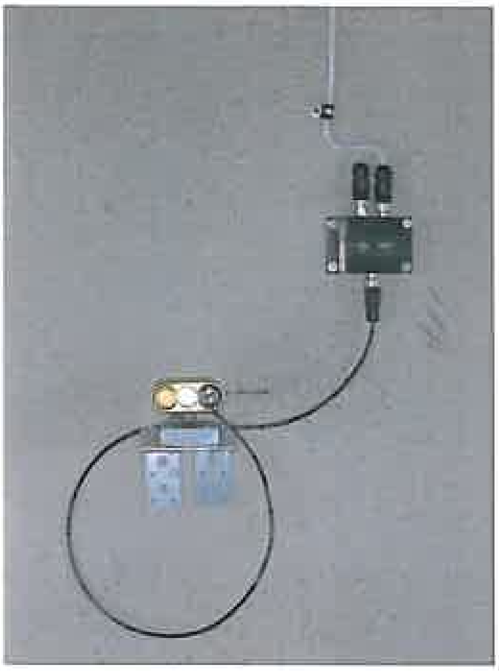


Figure 3.1.3. Displacement transmitter.

The local measurement network was divided into three cable segments to simplify the installation. Strain gages with their temperature units were on the first and second segments and the displacement unit was placed on the third segment. The three segments meet at one point where a small all weather embedded computer collects and synchronizes the segments to a single measurement heartbeat. After synchronization the collected data will be referenced to "wall time" by to data collection computer. The computer keeps itself set to accurate atomic clock time which it receives from the Internet using the Network Time Protocol (NTP) time protocol and service which is free. This gives accuracy of ±1 ms to Coordinated Universal Time (Greenwich Mean Time) which is acceptable for this kind of application.

3.1.2 Measurement archive

Final data archival was divided into two parts and locations. Daily data of approximately 1.1 GB is collected on site. The data is written on a Universal Serial Bus (USB) based flash disk. Choice of a USB memory stick for this job was an unfortunate one. Due to problems with bigger IDE-Flash disks it was considered better to use an external USB-flash. It is a workable solution, but not a recommended one. For long term use the USB memory sticks are problematic and a bit too slow on generic database use.

The data format for the collected data is an Extensible Markup Language (XML) based text file. During the night hours the daily measurement file is losslessly compressed to approximately 150 MB and sent to main archival computer 200 km away in Helsinki using the available 2 Mbps SDSL line. The compression program used is GNU zip which is an old well known and reliable compression method. It was chosen for its predictability and stability as the data will be archived for years so it is desirable after a decade to be able to find software that still can open the compressed files. In the tests more modern compression methods like BZip2 and 7Zip achieved compression ratios that were even twice as good for compression of the structural strain measurements, but their relative youth dropped them from the list of compression technologies to use in this project. In future installations we will probably start using BZip2. It has better compression ratio than GNU zip but more importantly it has a better set of recovery and error correction tools.

The received data is analyzed and appended to a larger database in Helsinki for easy handling. The XML based text files which contain the daily measurements are archived and are the main source for the analysis. The down sampled copy of the collected data inside the fast database is intended only to simplify searching and analyzing the measurements. The database can always be re-created from the larger text files if something happens to the database or changes in its structure are needed. The database engine used was an extremely simple database named SQLite. Both GNU zip for compression and SQLite for database are open source software giving better immunity from software provider made changes for the measurement archive.

3.1.3 Real time user interface and event reporting

In addition to the data collection, the wired measurement system on site was tasked to give a graphical real time user interface to a remote observer about the events on the bridge and to give alerts and warnings about unusual and excessive results of the measurements on the bridge.

The real time user interface is done using Extensible Hypertext Mark-up Language (XHTML). It is offered to the user as a web page from the on site computer which links directly to the larger archival computer in Helsinki if needed. The user does not need to know at which part of the data, the small-(real time) or the large-(archived) database, he is looking because of the automatic connection and link to the correct part of the database.

Real time measurement data traffic between user and the measurement computer is made using XML and stripped down version of Extensible Messaging and Presence Protocol (XMPP) protocol. Again the main idea was to use open standards and non proprietary versions of the protocols to maximize reliability and to keep the system compatible in future. The web pages holding the user interface are sent to the user by a small Hypertext Transfer Protocol (HTTP) server that is a small side thread of the main data collection and archiving process. Due to security reasons the HTTP connection is done with a very small stripped down HTTP server thread that is special built to allow and understand only a very limited subset of the HTTP protocol. The programming code for that part of the server could be made so small that it was possible to harden it against the threats happening in modern Internet.

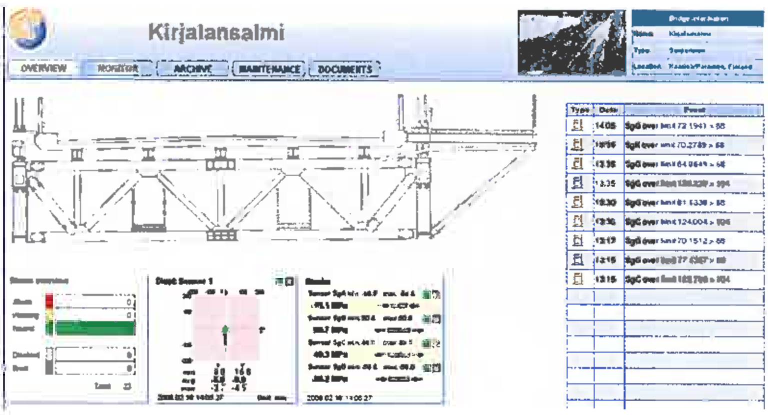


Figure 3.1.4. Web based user interface.

The web based user interface is made using modern web technologies like XHTML for text, Scalable Vector Graphics (SVG) for graphics and AJAX to handle the XMPP and data traffic to make it fit through the 2 Mbps Internet connection. To the user it feels like the monitoring application is running on his local computer.

The main element on the user interface is a picture of the cross section of the bridge. A set of square visualization modules and an event list on the right. On the first page there is a visualization for the current state of the measurement network. It shows the number of sensors which are in normal, in warning or in alarm state.

The other two visualizations show the output of the displacement sensors and four strain gages. Other sensors can be seen on later pages. These box visualizations are updated roughly once in every second. The first page gives only part of the measurements. On it has been collected those measurements that have been considered to be most interesting or useful.

The list on the right is the scrolling event list and it shows when one of the sensors has gone over a set alert or alarm limit. In this example strain gages SgC, SgG and SgK have reached values classified as alert (yellow) but have not crossed to alarm (red) levels. Main point of this interface module was to provide to the user a quick way to see at a glance the current events on the bridge.

3.1.4 What we learned from the wired installation

Keeping the strain gages and displacement sensor bound to the same measurement heart beat made it easy to cross correlate between strain and displacement measurements. Because the strains and displacements are physically completely different phenomena, the simultaneous study of the results gave us an easy way to check if the effect seen on one type of measurement was real or an artifact.

The small on site measurement computer has sufficient computing power to run Linux as an operating system and a small stripped down HTTP server to send the web pages to users. Fitting a normal web-server into such a small embedded computer would have posed several problems. So it was decided to write a stripped down version that still stays compatible with HTTP 1.0 specification. This proved to be easier than expected and the web-servers needs for memory and processor are negligible in comparison to the measurements and synchronization parts of the software. The added benefits on the security side proved themselves during the online use.

The moving graphics were done using embedding SVG vector graphics inside the web-page. This was a rather controversial choice as an Adobe Flash based visualization would have been a more traditional one. Unfortunately Adobe Flash is a proprietary technology and as such incompatible with the original goal of using only Open Source based tools. Adobe Flash is under a process to be partially or completely open sourced, but that still does not solve the other problem that it is often blocked or forbidden in companies and governmental intranets. Whereas SVG is allowed everywhere where the basic browser is allowed. On the down side unlike other software components used here SVG is very new and still shaky web-technology and needs attention and care when using it in a user interface design. Fortunately most of the browser manufacturers are including it in their products and during last two years the implementations have stabilized considerably.

Using XML as the data collection and archival format gives a neutral common ground for applications to access the data and improved protection against disk problems and transmission errors. Later proved invaluable as the USB flash disk developed a hard to debug problem and corrupted part of the files. On an XML-text file the problems were trivial to notice with eye only and repair. This sped up finding the original hardware based reason for the flask disk problem as it was easy to rule out a software based reason for the errors.

On programming side contrary to expectations the open source software libraries proved to be easy to use and easy to approach. Especially the SQLite database which has a very simple and no nonsense approach to data handling and interfaces.

3.2 Wireless monitoring system

One of the primary goals of the SIMO project was to explore and experiment on the latest technology in the field of monitoring. This is why a part of the VTT monitoring system installed in the Kirjalansalmi suspension bridge was implemented with wireless sensors. The wireless system was installed to measure four strain gages and one tri-axial accelerometer.

The required technology was acquired from Microstrain, inc (USA, Vermont). They have created a MicroStrain Agile link product family, which is a wireless measurement system designed to measure strain gages, acceleration sensors, thermo couples and many other millivolt level sensors. The product family operates in the 2.4 GHz ISM band and uses the 802.15.4 protocol for data transmission.

Accelerations can be measured with a G-Link node (Fig 3.2.1). It has a built-in tri-axial accelerometer and the node is packed in a (58 x 43 x 26) mm^3 enclosure weighing 46 grams. The node has a 12 bit A/D converter and the measurement accuracy is reported to be Δa =±0.1 m/s^2, with the maximum measurable acceleration being 2 G.

Figure 3.2.1. G-Link node.

The other node type used in the VTT system is the V-Link voltage node. It has four differential input channels that can be used with strain gages, thermocouples or any other millivolt level sensor.

Figure 3.2.2. V-Link node.

All of the MicroStrain nodes have 2 Mb of flash memory that can be used for data logging. The duration and sampling frequency of the measurements can be changed programmatically. The nodes can also be used in a streaming mode, in which data is measured and sent continuously. MicroStrain provides software with which stand-alone measurements with MicroStrain product family can be handled. If the MicroStrain system is to be used as a part of a larger measurement system, it is suggested that a software development kit is bought. It contains example code for many of the major programming languages (for example LabVIEW and C++).

Communication with the nodes is established with a USB base station connected to a PC. In streaming mode, one base station is required per sensor node but the data logging mode allows up to 16 nodes per base station.

The MicroStain products were purchased from a Swedish retailer, Load Indicator AB. They are offering starter kits, which include a base station, one G-link and one V-link node with all the required accessories for about 2100 €. Individually the G-Link nodes cost 600 € and V-Link nodes 800 €. The software development kit is priced at 380 €.

The VTT measurement system (Fig 3.2.3) includes both wired and wireless sensing. The wired system uses a CompatRIO (National Instruments, USA, Texas) system. It is a modular measurement and control device with a FPGA I/O and a real-time controller. With this particular application, the CompatRIO is equipped with a four channel strain gage module and a 16 (differential) channel analog input module. It is measuring four strain gages and three displacement transducers. The measurement system also includes a camera to capture images of the measurement events. This is handled by a Compact Vision (National Instruments, USA, Texas) system, a programmable computer vision device.

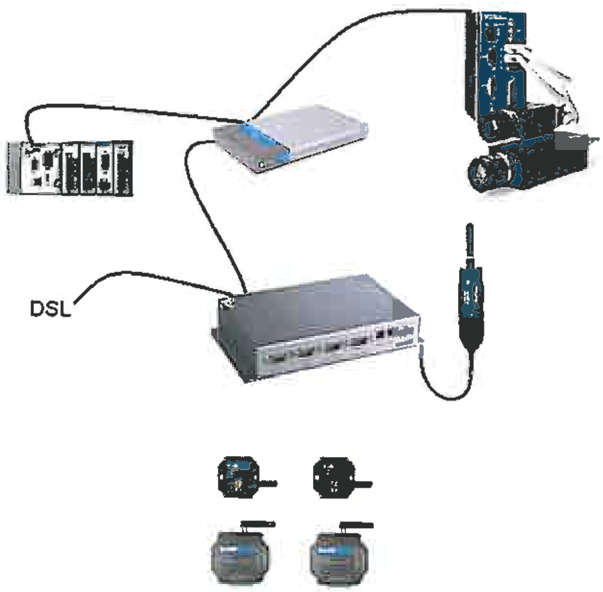


Figure 3.2.3. The VTT measurement system on Kirjalansalmi suspension bridge.

In the CompactRIO system data is measured at 100 Hz sampling rate, but only the maximum, minimum and average value of every minute is saved. This reduces the amount of data considerably and makes post processing easier. The data is logged on a flash drive in the CompactRIO. The host PC, running a Windows XP OS, is scheduled to download the measurements once an hour from the CompactRIO via FTP. The same procedure is done with the Compact Vision system. Examples of measured data from a strain gage and a displacement transducer from one month of measurements can be seen in figures 3.2.4 and 3.2.5. Picture taken from the vehicles responsible for the maximum strain and displacement of the month in question can be seen in figure 3.2.6.

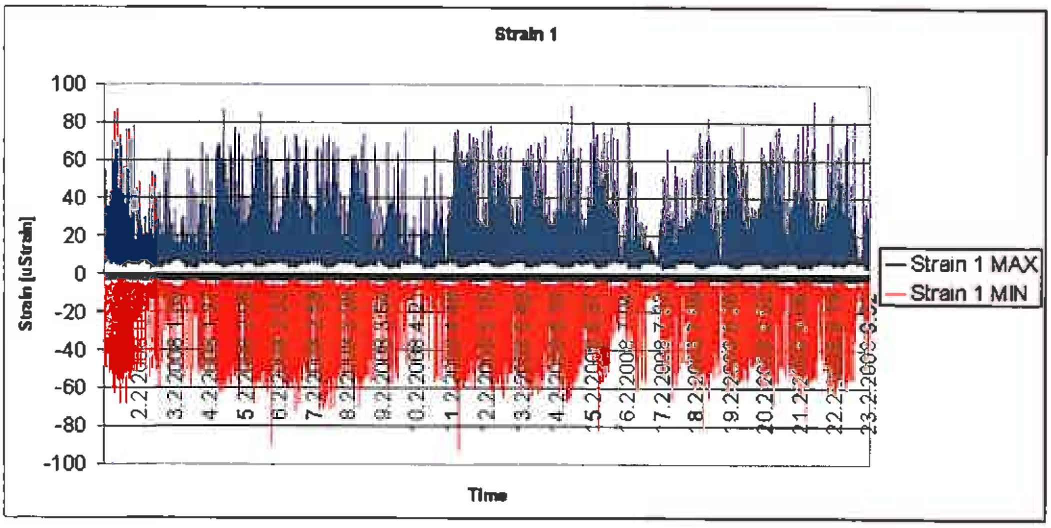


Figure 3.2.4. One month's measurement data from a strain gage. X-axis is time in minutes and Y-axis is relative strain [uStrain].

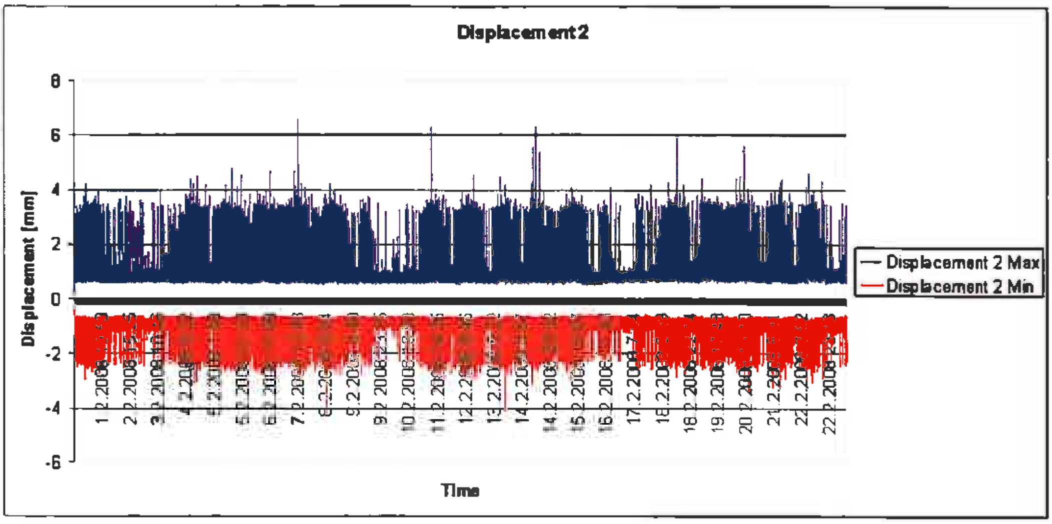


Figure 3.2.5. One month's measurement data from a displacement transducer. X-axis is time in minutes and Y-axis is displacement [mm].

Figure 3.2.6. Vehicles responsible for the maximum measured values in February 2008 on the Kirjalansalmi suspension bridge.

The wired part of the measurement system also acts as a trigger for the wireless one. When a certain threshold is exceeded in the strain gages attached to the CompactRIO, a trigger command is sent from the CompatRIO to the wireless measurement program running in the host PC. This in turn makes the base station send a trigger command to the nodes. The nodes then log data for 25 seconds with a 125 Hz sampling frequency. After the measurement period is over, the data is transmitted back to the base station, node by node, and stored in the host PC. The PC has an ADSL connection which makes remote management and data gathering possible. The remote connection is established with a SSH tunnelled VNC connection.

The wireless nodes are situated at the 22nd suspension post of the bridge and they are measuring strains from steel beams on upper and lower K-crossings. The acceleration node is connected to the lower K-crossing. The strain gages in the CompactRIO are measuring the same places as the wireless system. This is done for the sole reason that it was not known how reliable the wireless system would turn out to be.

The CompactRIO is also measuring three displacement transducers (Fig 3.2.7), which are attached to measure the displacement of rubber plate bearings at three positions on the bridge: the halfway point, quarter point and pylon.

To ensure the communication between the sensor nodes and the base station, an 18 dB directional antenna was attached to the abutment, where it has line of sight with the sensor nodes. The distance between the antenna and the nodes is roughly 40 meters.

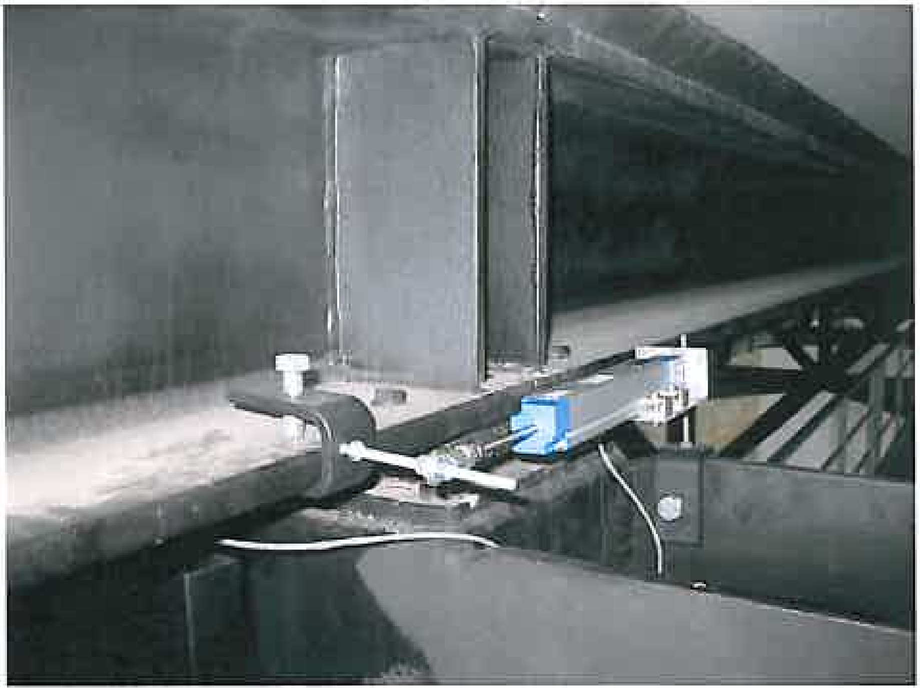


Figure 3.2.7. Displacement transducer measuring the displacement of a rubber plate bearing.

The temperature and weather conditions were a major concern in the design process of the measurement system. This is why the measurement nodes were encapsulated in additional, moisture proof enclosures (Fig 3.2.8 and 3.2.9). These enclosures include a connector for an antenna and for an external power supply. The V-Link enclosures also have a connector for two strain gages.

It was suspected early on that the lithium-ion batteries of the wireless nodes wouldn't hold their charge for long periods of time, especially in the winter time. Because of this, a solar panel was installed to power up the nodes. The solar panel is charging a 12 V lead-gel battery, and power to the nodes is fed from the battery through a 9 V regulator.

All in all, the experimentation with wireless sensor technology showed that it is not yet a feasible option for long term bridge monitoring. All the work required with ensuring an uninterrupted operation of the wireless nodes is not worth the trouble when compared to installing a few wires for traditional sensors. Because of the line of sight and external power requirements, this particular wireless setup turned out to require more wiring than the wired one. The transmission of data from sensor nodes to the base station is also not instantaneous, but rather takes 10 - 15 seconds per node. This makes fast, back to back measurements impossible, at least with the current setup.

Figure 3.2.8. V-Link enclosure.

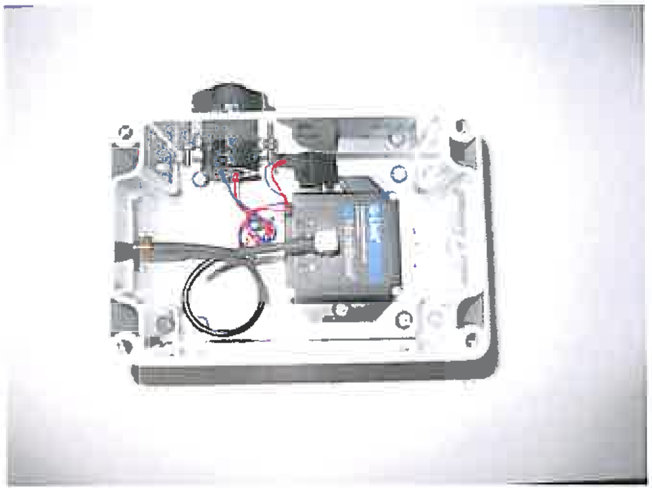


Figure 3.2.9. G-Link enclosure.

3.3 Results of the monitoring of Kirjalansalmi bridge

3.3.1 Introduction of the measurements

Kirjalansalmi bridge locates in south-western Finland and connects Kuusisto and Kirjala islands and further, the town of Parainen to the mainland. The bridge was built in beginning of sixties, thus having been in service now about 45 years. The bridge is a suspension bridge with a main span of 220 m and the side spans of 25 m in both ends of the bridge. The bridge has a line for vehicles in both directions. An additional line for pedestrian traffic has been added in the beginning of nineties. Two main beams in the main and side spans are trusses composed of I-sections with partially welded and partially riveted connections. Transversal beams are placed at distances of 7.9 meters and they are truss structures made of I-sections, also. A concrete deck plate placed on transversal trusses, carries through the local traffic load. The deck of the pedestrian line is made of glue laminated wooden elements.

Regular heavy traffic rolls over the Kirjalansalmi bridge due to the industrial activities in Parainen. Especially in Summer time, the bridge is a link to the archipelago of Parainen and Åland, thus, carrying through intensive traffic of passenger cars. The height of the free waterway at mid-span of the bridge is about 12 m, thus, allowing the sailing in the strait between Kuusisto and Kirjala islands. In the course of the years, the bridge has become a local landmark. Therefore, it is important to follow the behaviour and condition of the bridge to keep it in good order long time onwards.

Several repairing actions have been made during the years. The latest one was completed in 2005 including repainting, repairing of the bearings between the load-bearing transversal trusses and the concrete deck and improving some structural details. Because of the long service time and the repairing actions, the determination of loading histories of the different structural members of the bridge is rather difficult.

The measurements in the SIMO project include

- vertical and horizontal displacements at the 22nd suspension bar using a infra red beam,
- strains of the upper and lower chords of the main truss at a distance of 1 m from the 22nd suspension bar to the mid-span,
- strains of the upper and lower chord and of two end diagonals of the transversal truss at 22nd suspension bar,
- a strain of the lower surface of the secondary steel beam between the 21st and 22nd suspension bars,
- strains of a u-shaped connection bar at the lower end of the 22nd suspension bar,
- strains in two diagonals of the upper and lower K-shaped horizontal stiffening truss between the 27th suspension bar and the end of the main span,
- displacements in reinforced elastomeric bearings in mid-span, at 22nd suspension bar and at the end of the main span,
- temperatures at the points of strain gauges in the main truss,
- temperatures in four strain measurement points in chords and diagonals of the transversal truss and
- a temperature in a diagonal bar in the upper horizontal stiffening truss.

The measurements include altogether 2 displacements of the main truss, three displacements of the elastomeric bearings, four strains in the main truss, six strains in the transversal truss, one strain in the secondary beam, two strains in the connection bar of the 22nd suspension bar, four strains in the horizontal stiffening truss and nine temperatures. In addition, environmental data is collected separately.

The exact points of measurements have been chosen in order to measure the main stresses of the bridge for an easy control of the behaviour of the complete structure. The gauges are mainly fixed close to the mass center to show the axial forces of the truss structures. Thus, the strain gauges are not in points of probable highest stresses like the connection plates or the edges of the open sections, which are loaded by multi-axial stresses and in which the analysis of the stress state may require the use of many strain gauges. The points of measurements can be seen in Fig. 3.3.1 and in Fig. 1 in Section 3.1 Fig.1. The responsible partners of the measurements are Futurtec Oy (now Savcor Tempo Oy) and VTT. The figure 3.3.1 shows also the responsible partner of a specific measurement.

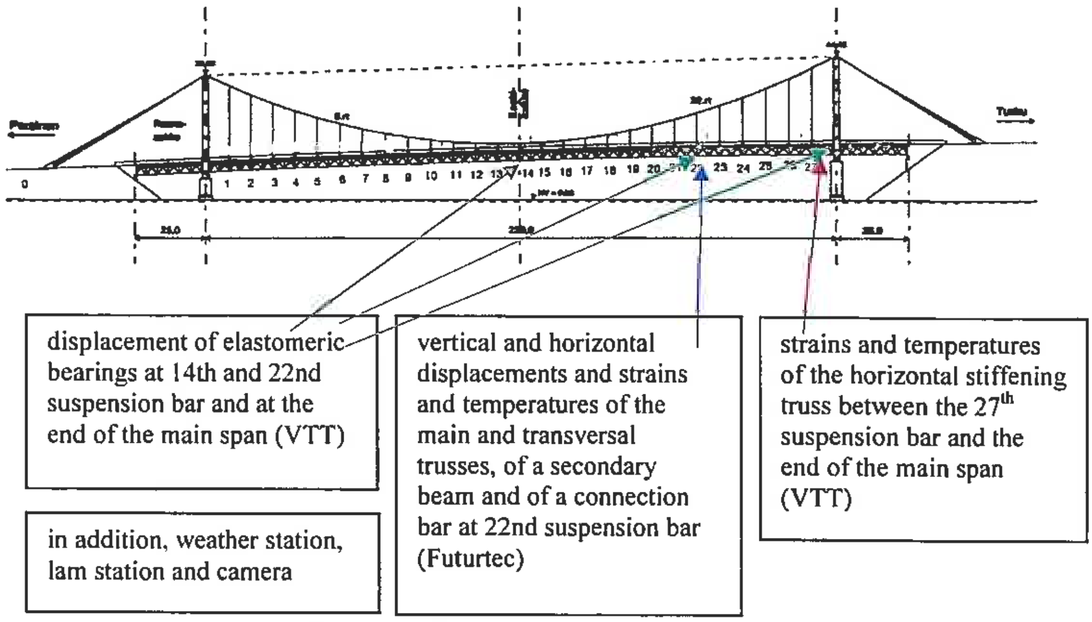
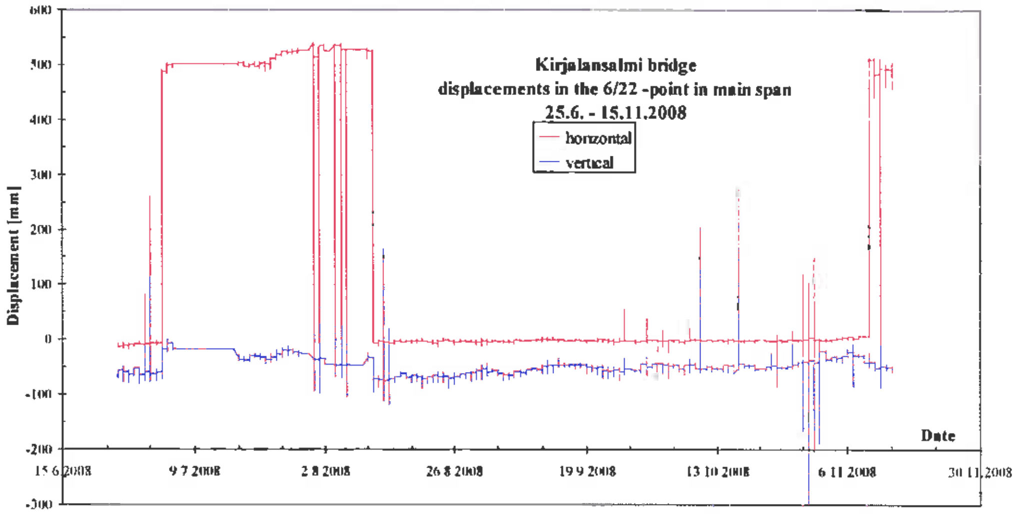


Figure 3.3.1. Location of points of measurements in Kirjalansalmi bridge.

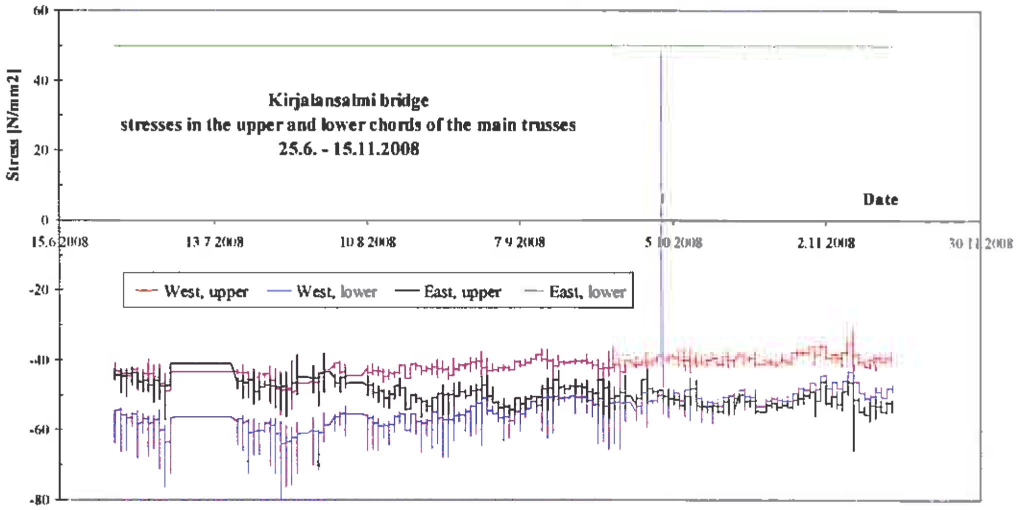
For the control and analysis of the results performed by Futurtec Oy, a special real time user interface has been build by Futurtec Oy. The interface serves for everyday control but gives also the possibility to load data of specific sensors covering a specific time for further analyses in on-line. The interface has been in use from the beginning of the monitoring. The systems to measure, to transfer and to record the data have been introduced in Sections 3.1 and 3.2. The data measured by VTT has not been available during the project. Thus, the analysis and evaluation of the data in this section is based on the results of the measurements performed by Futurtec Oy, only.

3.3.2 Quality of the measurements

Monitoring of the Kirjalansalmi bridge was started in May 2007 and it has been running continuously up today. The sensors measure the global response of the bridge in the points of the measurements. The results include all possible action effects caused by the traffic, change of temperatures and wind pressures. It includes the immediate action effects of the vehicles as well as the vibrations, which damp down during a certain course of the time. The influence of the permanent load such as the self-weight can not be seen in the results of measurements.



a).



b)

Figure 3.3.2. Results of the measurements of displacements and stresses in the 6/22 -point in the main span. Sampling rate 1/10 min.

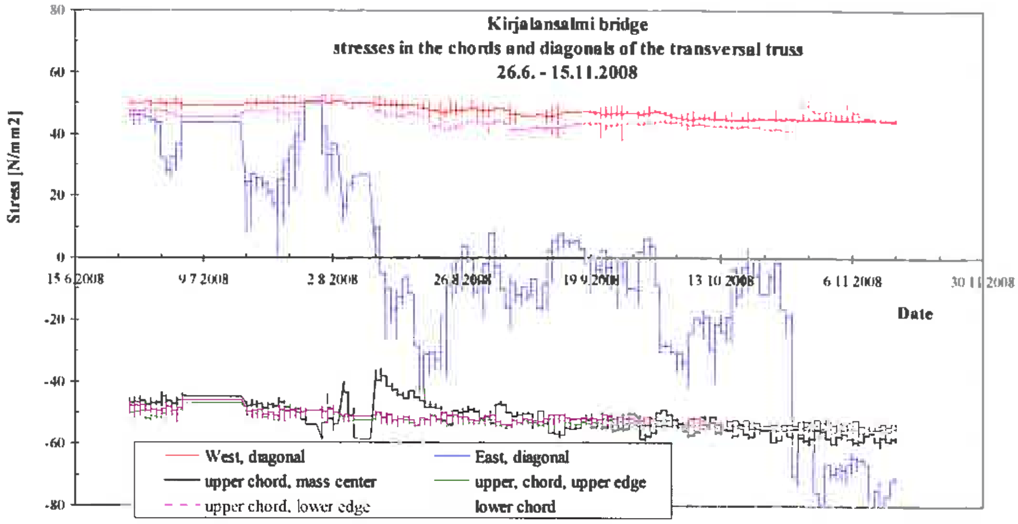
A brief analysis of the quality of the data results from the users point of view in the following conclusions. The horizontal and vertical displacements of the 6/22 = 0.27-point of the main span show the global flexibility of the suspended span of the bridge (Fig. 3.3.2 a). The measurement instrument, the infra red beam has been placed on the service line below the concrete deck. During the service works, the disturbing sharp red point ray has been turned away from the line and returned back to its original position after the works. Because the times of all service works and the times, when the infra-red beam has been in a turned position, has not always been known, the erroneous data has caused some unnecessary reactions. Thus, a manual turning of the infra-red beam should automatically result in information in the control interface in order to report about unusual arrangements in the measurement.

Strain gauges have been fixed by gluing in the surface of the webs of the upper and lower chord of the main truss. If the steel truss were the only load-bearing member, the stress in the lower chord should be opposite value to the stress of the upper chord, which fact serves an easy check to the results of the measurements (Fig. 3.3.2 b). During the installation of the strain gauges, the surfaces of the webs of the lower chords were wet, which has caused problems to the contact between the gauge and the steel surface. At the moment, the gauge in the lower chord in the eastern truss does not react in loads and the gauge in the lower chord in the western truss shows compressive stresses, which can not be the case in reality. The erroneous results of measurements in the lower chords can be easily noticed and the cause to the erroneous results is clear. Thus, the annoyingly missing results can be disclosed in the analysis of the results.

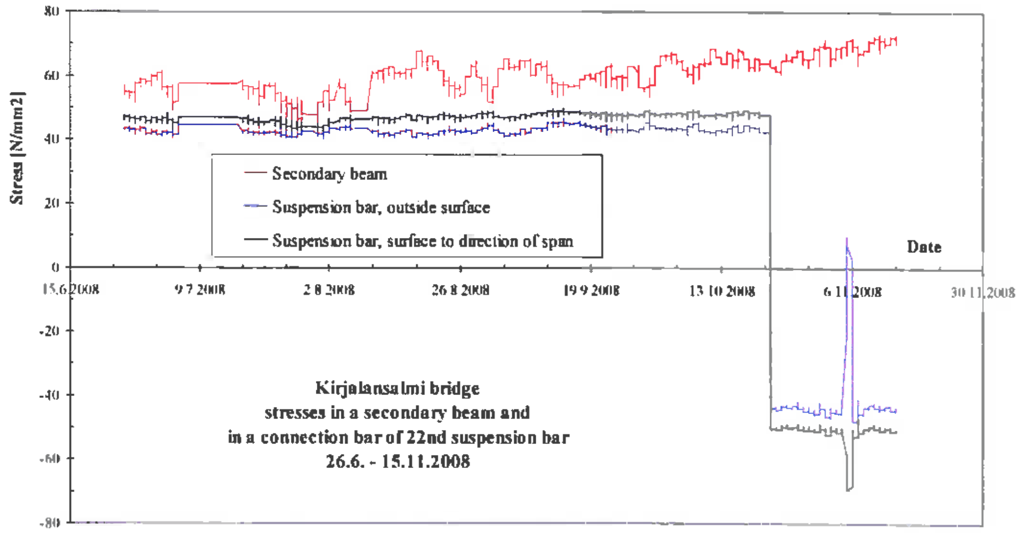
Six strain gauges were installed in the 22nd transversal truss in the main span. Two of those were fixed in the first western and first eastern diagonals of the truss. The results of the measurements in the gauge in the western diagonal are acceptable but the measured results in the eastern diagonal show during the last half a year continuous changes, which might be caused by a losing contact between the gauge and the steel surface (Fig. 3.3.3 a). The stresses in the both chords are acceptable. Differences in the stresses in the three different parts in the upper chord are small. It indicates, that the upper chord is loaded mainly by the axial compressive force and the influence of the bending moments is small.

Measurement of the strains in a connection bar of the eastern 22nd suspension bar shows two sudden changes during the last half a year (Fig. 3.3.3 b). Relative large changes from tensile stresses to compressive stresses can not take place in reality at the same time in both points of measurements. The reason of the sudden changes may be contact of the gauge not in the physical behaviour of the connection bars.

Temperature of the structural members of a suspension bridge is an important design parameters. Temperatures of the main truss and the 22nd transversal truss have been measured in four points in both structures. In average, the results show good correspondence to the environmental conditions. The differences between the upper and lower chord of the main truss and between the members of the transversal truss are typically less than five degrees of Celsius, only. However, the measurements show sudden very large steps to positive and negative directions, which results can not represent real changes of temperatures in the members (Fig. 3.3.4). The steps are characteristics of the instruments used in the measurements and they are easy to observe. Thus they should not cause problems in the analysis of the results of the measurements. The erroneous points can be removed from the data after the measurements.

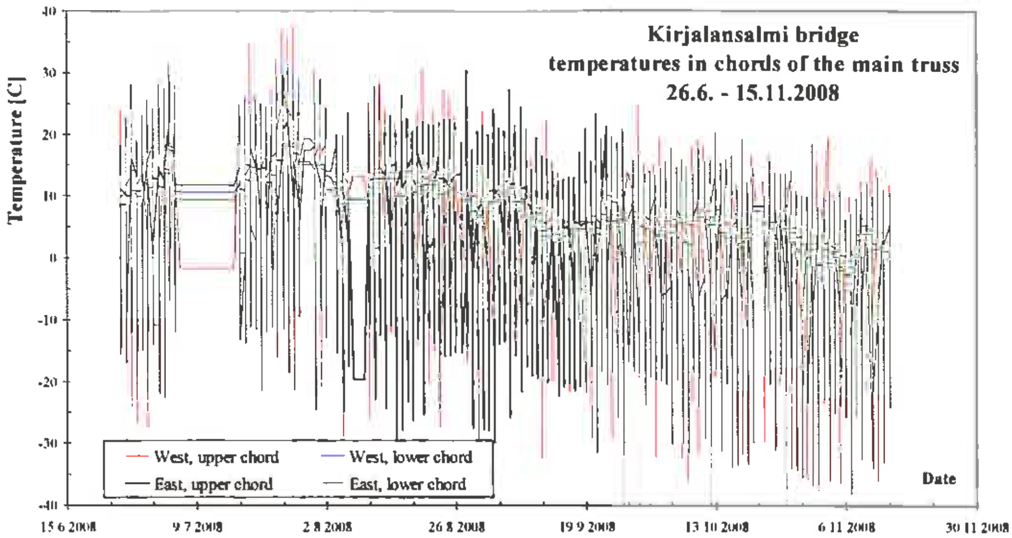


a)

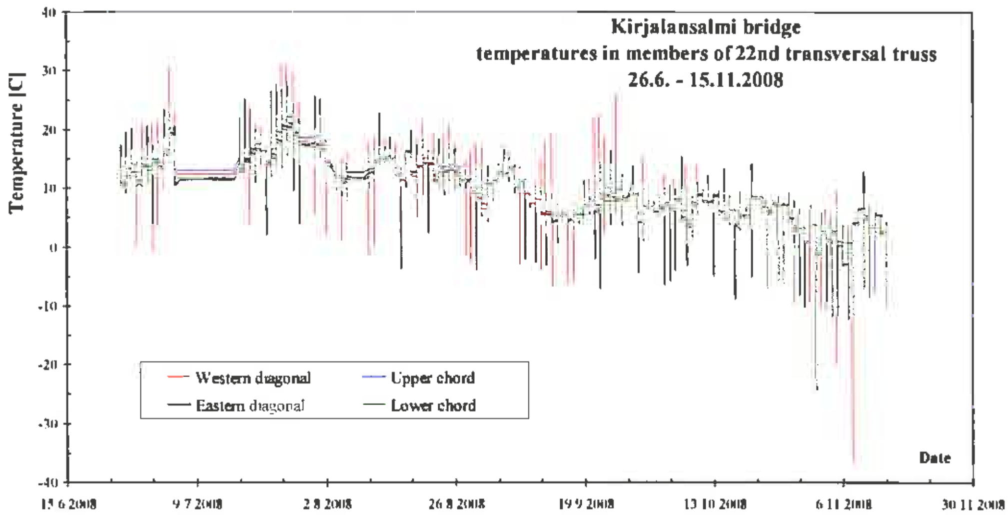


b)

Figure 3.3.3. Results of the measurements of stresses a) in the 22nd transversal truss and b) in the connection bar of the 22nd eastern suspension bar and in the lower surface of the secondary beam between the 21st and 22nd suspension bars in the main span. Sampling rate 1/10 min.



a)



b)

Figure 3.3.4. Results of the measurements of temperatures a) in the chords of the main truss and in the end diagonals and chords of the 22nd transversal truss. Sampling rate 1/10 min.

3.3.3 Verification

Loading test was made in 30.8.2007 in order to study the behaviour of the bridge and to verify the measured data. Loading arrangements and loading history followed an earlier loading test of Kirjalansalmi bridge to make the support the comparison between the results after and before the latest repairing actions. In the test two seven-axle vehicles were used (Fig. 3.3.5). The total measured weight of the vehicles were 62.25 and 63.56 tons, and the distances between the end axles 16.8 and 17.0 m, respectively.


a) b)

c)

Figure 3.3.5. Vehicles used in the loading test in 30.8.2008. a) Vehicle No 1, b) vehicle No 2 and c) vehicles in the loading test 1F.

In the test, the test vehicle drove over the bridge at a certain speed making stops at ¼, ½ and ¾ points of the main span. The test programme included tests with one vehicle driving along the center line or along the normal lines of the bridge. It included also tests with two vehicles driving after each other or side by side over the bridge. The most tests were kvasi-static tests at a low speed but also tests at higher speeds were done calling dynamic effects of the bridge. The responses of the bridge were measured with all instruments installed by Futurtec Oy and VTT in the bridge structures.

In the Section, the experimental response of the bridge is compared with the calculated response based on an analytical solution of a suspended structure. In the analytical model, the load-bearing beam includes the main steel truss, only. The concrete deck supported by elastomeric bearings is excluded in the model. The comparison includes two tests, the test 1B and 1F, in which the vehicle No 1 or the vehicles No 1 & 2 run side by side over the bridge. The both cases are symmetric to the center line. So, a plane model can be used in the calculations. In the section, characteristic behaviour of the main trusses is studied, only.

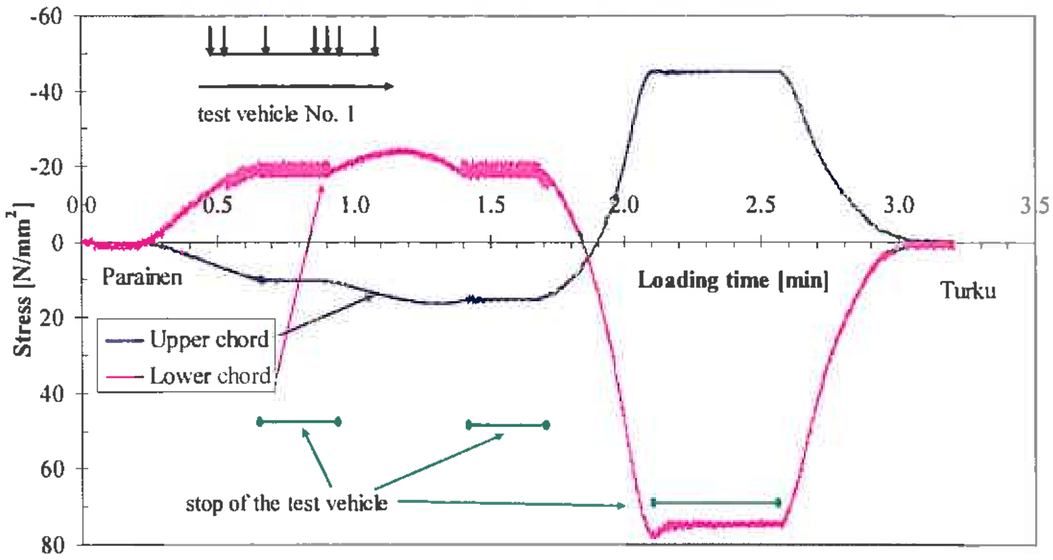


Figure 3.3.6. Measured stresses in the chords of the western main truss in the loading test 1B, in which the test vehicle No 1 crossed the bridge along the center line at a walking speed making stops at 1/4, 1/2 and ¾ points of the main span.

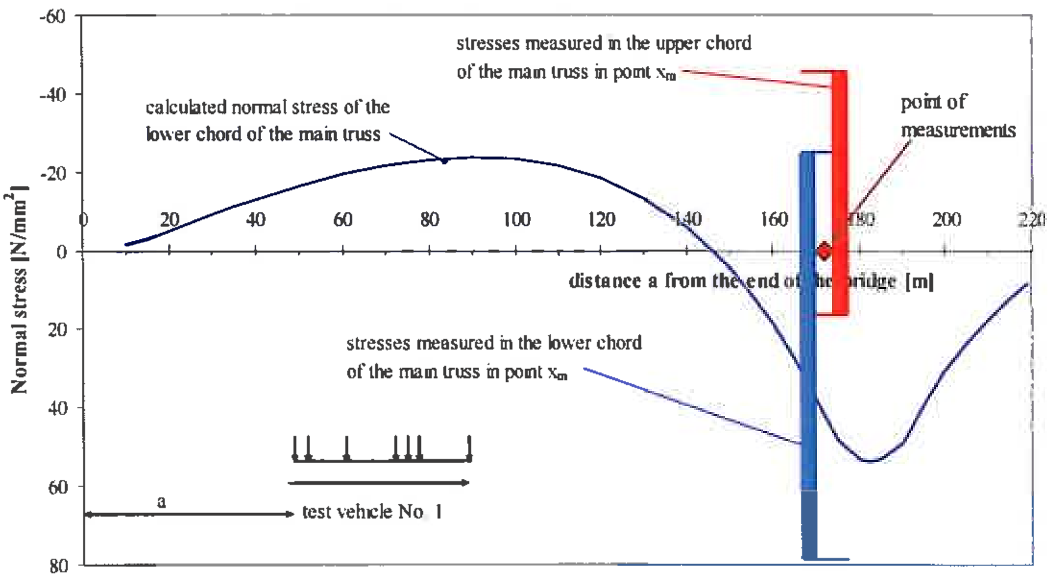


Figure 3.3.7. Comparison between the measured stresses and calculated stresses of the chords of the main truss in the loading test 1B.

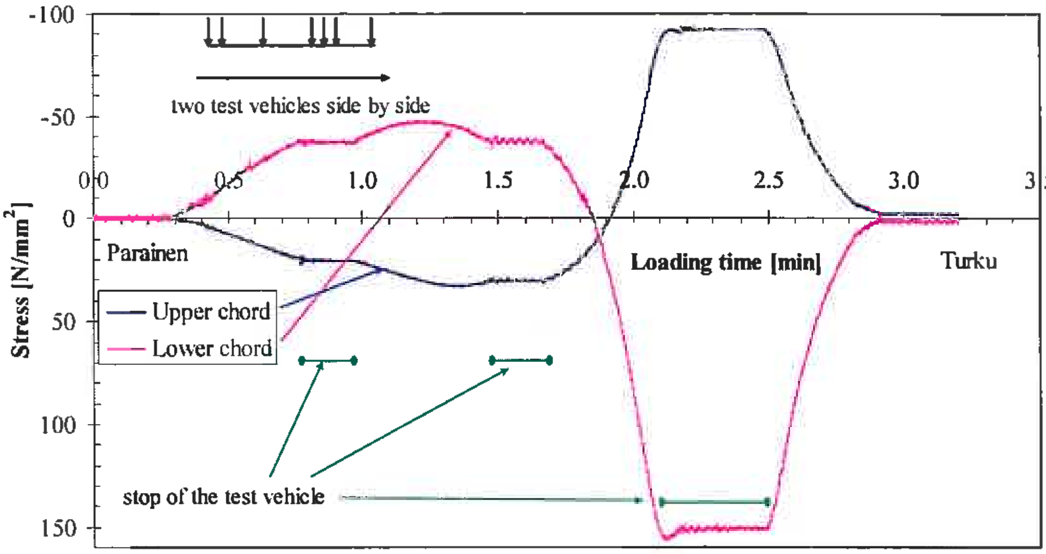


Figure 3.3.8. Measured stresses in the chords of the western main truss in the loading test 1F, in which the both test vehicles crossed the bridge side by side at a walking speed, making stops at 1/4, 1/2 and ¾ points of the main span.

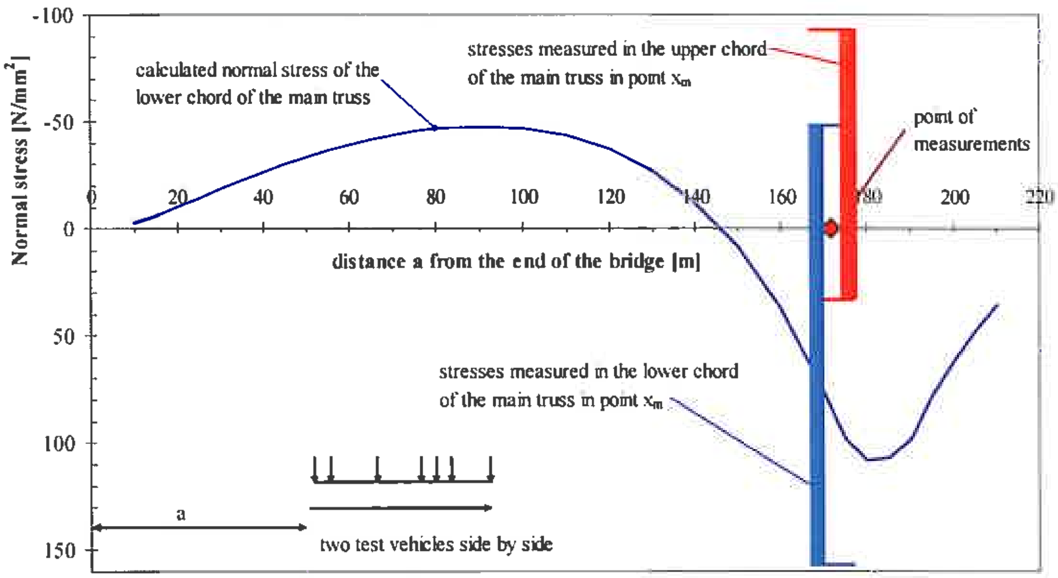


Figure 3.3.9. Comparison between the measured stresses and calculated stresses of the chords of the main truss in the loading test 1F.

The results of the loading tests include the influence of the test vehicles, only. Position of the moving test vehicle is not coupled in the measured data. The connection between the position of the vehicles and the measured response is known in the points, at which the stops were made.

Analysis based on experimental data shows non-symmetric normal stress state between the upper and lower chords of the main truss (Fig 3.3.6 & 3.3.8). Comparison of the experimental stresses to the calculated stresses confirms the finding about a composite action between the steel truss and the concrete deck plate (Fig. 3.3.7 & 3.3.9). Thus, the behaviour of the elastomeric bearing, which are the acting connection members between the steel truss and the concrete deck, is essentially important. The analysis of the displacements measured in the bearings may verify the finding explained above.

3.3.4 General information about the results

Stresses of the real structures include the influence of the permanent loads. The influence has been added in the experimental data by moving the initial level of the measured results. The influence of the permanent loads shown now in the results in the interface is at the moment based on very preliminary analysis. However, it shows the way to improve the value of the measurements.

In design of structures, limits to the ultimate and to the serviceability state shall be defined. The limits of members of steel structures concern typically yielding and fracture of the materials and connections, buckling of thin plates and slender bars, fatigue of members exposed to repeated loading and displacements and deflections. Rough limits have been determined to the members of Kirjalansalmi bridge, in which the instruments have been placed at the moment. The limits represent alarm limits, the crossing of which causes signals in the interface. Because of the very preliminary determination of the limit values, the interface produces alarms regularly today.

3.3.5 Conclusions

This report concerning the monitoring of Kirjalansalmi bridge, has been written from the designer's and user's point of view. Kirjalansalmi bridge is a good example of an existing important bridge, the structural condition of which can be followed in real time with modern monitoring systems. The results of the measurements can be fully utilized in decision making concerning the next actions of repairs or limitations to the use of the bridge.

The installation and recording work on site has been done well and the interface provides the real-time information to a user, which was a target of the project. Based on this experience, the following tasks and challenges can be listed for the development of the monitoring work in future

- continuous maintenance and development of the measuring and recording system in order to offer real and relevant data in the interface,
- more accurate definition of limits for alarms taking into account also the fatigue of welded and riveted connections,
- definition of actions to be made in case of alarms including the recognition of the difference between the erroneous and real data,
- development of methods of analysis of the data in real-time and
- analysis of the service life of the bridge on the base of the measured data, possibly continuously in real-time.

4 Rehabilitated concrete bridge (Boxby)

Boxby concrete bridge is situated in southern part of Finland and is one of the bridges crossing the highway from Helsinki to Porvoo. The bridge has the main span of 68 m and has been rehabilitated in 2007 e.g. by widening the deck of the bridge. The bridge has been selected one of the monitored bridges in SIMO project, because it is a typical concrete bridge in Finland and could be monitored before concrete casting. The bridge is shown in *Figure. 4.1.*

Figure 4.1. Boxby concrete bridge in Sipoo during rehabilitation.

4.1 Temperature and water content measurements using optical fibres

The fibre optic sensor technology used in this study is a relatively inexpensive method for measuring temperatures and a moisture content of large concrete structures. The sensor system consists of an optical fibre cable and an electrical heat pulse cable, which are integrated and embedded in concrete during the construction phase. The sensor system and the analysis software of the moisture content measurement were developed by Fortum.

The developed fibre optic sensing is a potential new method for monitoring of large structures. The attractiveness of this method is based on

- advantageous price of the basic optical fibre sensor cable,
- the possibility to use the sensor cable for measuring sensors of hundreds of metres or kilometres in length,
- possibility to measure several parameters with a single sensor,
- the fibre optic sensing system for temperature and water content can be used both for quality control of the construction (e.g. temperature, water-cement ratio, holes, homogeneity and quality of compaction and injection) and for detecting damages (e.g. erosion, cracks, leakages, increasing moisture or water content) of the structure.

The method combines temperature and water content measurements using heat pulses. Depending on the local heat conductivity of the surrounding material, a specific temperature increase over time is measured as a response to the applied heat pulse. As the moisture content or amount of water in concrete increases, the thermal conductivity increases. The distributed fibre optic sensor system gives moisture content information along the fibre cable length and has been tested in concrete at spatial resolutions as small as 0.25 m. Depending of the actual requirement the sensor installation can be easily extended for full 3-dimensional sensing of the structure.

Six fibre optic sensors (VK1E1, VK1E2, VK2E1, VK2E2, VK3E1 and VK3E2) were installed in the bridge reinforcement before casting. The total length of a single sensor was about 40 - 60 m (over 60 measuring points/sensor).

Two sensors, VK1E1 and VK2E1, were installed close to the joint area of the new and old part of the bridge. The specific aim of this joint area monitoring was to detect local leakages. One sensor, VK2E2, was installed in the corner near to the edge beam. The sensors VK1E2 and VK3E1 were installed close to the bottom of the edge beam, and sensor VK3E2 was installed close to the top of the edge beam.

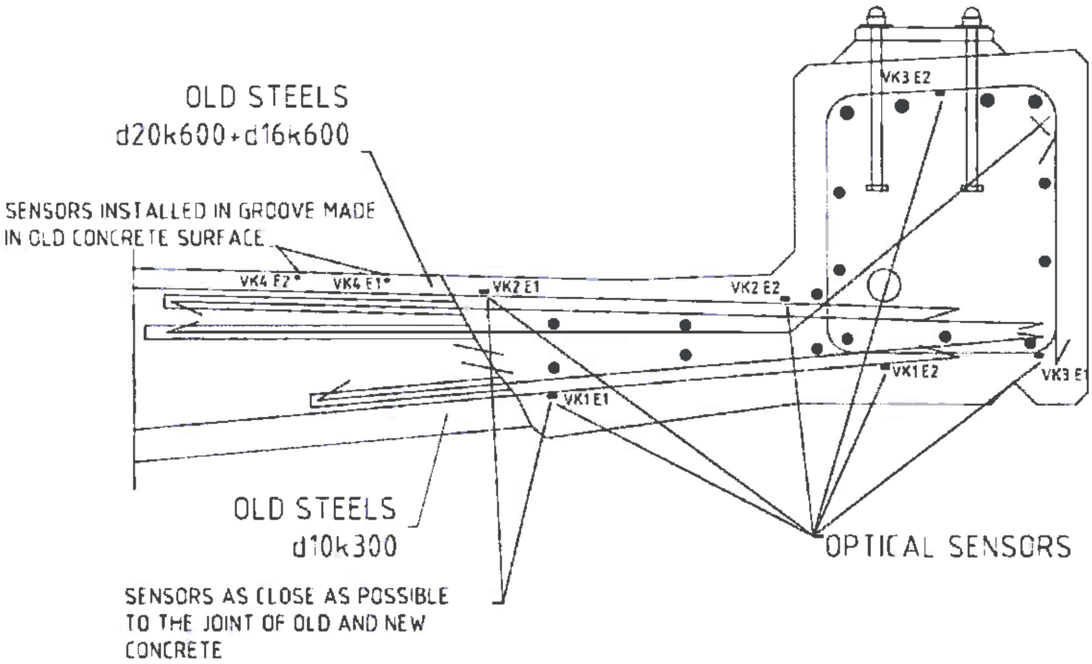


Figure 4.1.1. Locations of the installed fibre optic temperature and moisture content sensors at Boxby.

Figure 4.1.2. Two fibre optic temperature and moisture content sensors (red and black cables), VK1E1 and VK2E1, installed close to the joint area of the new and old part of the bridge.

Figure 4.1.3. A 40 m long fibre optic sensor (VK3E2) and a Sahlen sensor were installed close to the same reinforcement.

Two additional fibre optic temperature sensors (VK4 E1 and VK4 E2) were installed into the groove made close to the edge of the old part of the bridge deck. Total lengths of these two sensors were about 120 m (over 120 measuring points). The aim of this joint area temperature monitoring was to check if there is any significant temperature difference between new and old concrete parts as a result of cement hydration.

Figure 4.1.3. Fibre optic temperature sensors (VK4 E1 and VK4 E2) installed to the old part of the bridge deck.

Casting of concrete was performed on 15th of October 2007. The first temperature measurement period with optical sensors started at 15th October. The second measurement period was about one month after casting, on 15th of November 2007, and the third measurements on 13th of October2008.

The temperature and water content measurement results are presented in figures 4.1.4 - 4.1.9.

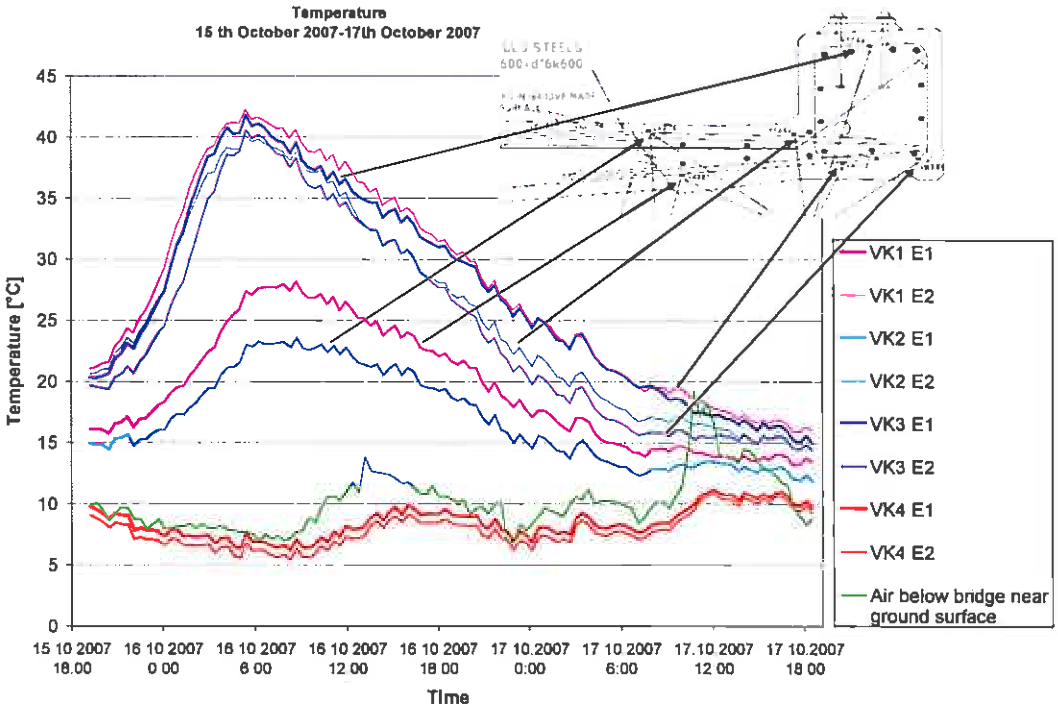


Figure 4.1.4. Temperature measurement results from Boxby bridge during 15th October and 17th October. The maximum temperature rice observed by fibre optic sensors (average temperature value along the length of a single fibre sensor), as a result of cement hydration, was 42 °C.

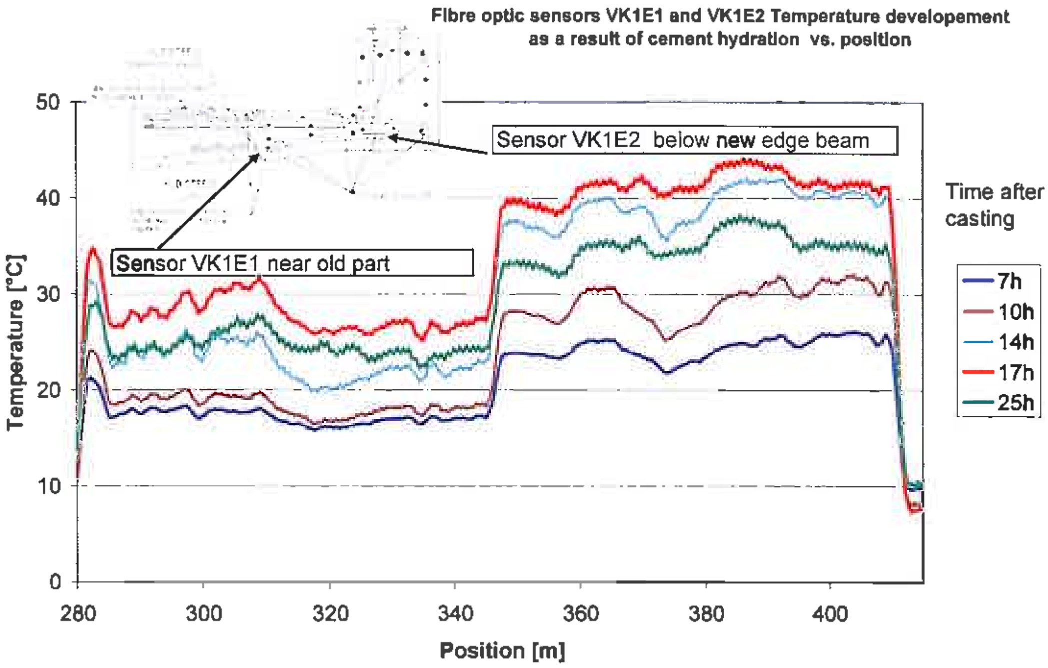


Figure 4.1.5. Temperature measurement results vs. position (7 h, 10 h, 14 h, 17 h and 25 h) after casting. The maximum temperature rice observed by VK1E2 fibre optic sensors as a result of cement hydration was 45 °C. The maximum temperature rice observed by VK1E1 fibre optic sensors as a result of cement hydration was 32 °C.

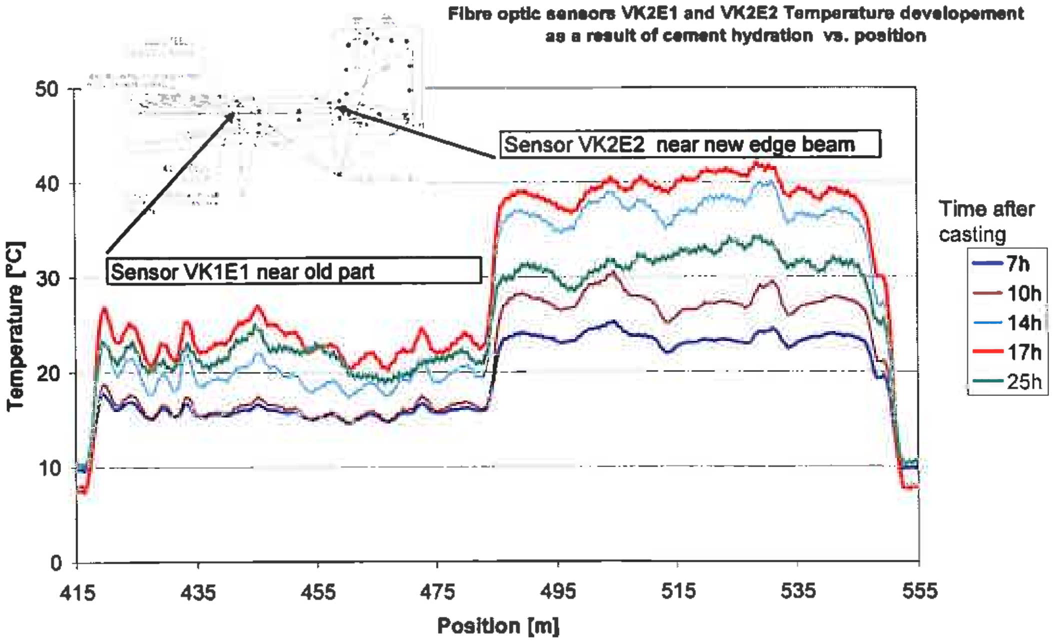


Figure 4.1.6. Temperature measurement results vs. position (7 h, 10 h, 14 h, 17 h and 25 h) after casting. The maximum temperature rice observed by VK2E2 fibre optic sensors, as a result of cement hydration, was 41 °C. The maximum temperature rice observed by VK1E1 fibre optic sensors, as a result of cement hydration, was 27 °C.

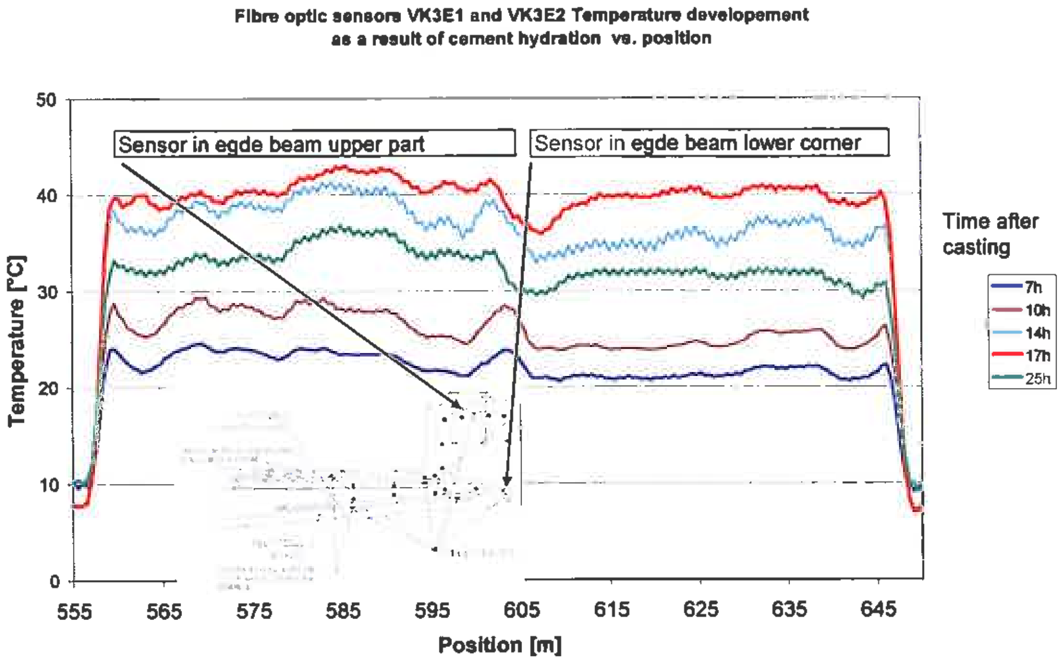


Figure 4.1.7. Temperature measurement results vs. position (7 h, 10 h, 14 h, 17 h and 25 h) after casting. The maximum temperature rice observed by VK3E1 fibre optic sensors as a result of cement hydration was 42 °C. The maximum temperature rice observed by VK3E2 fibre optic sensors as a result of cement hydration was 40 °C.

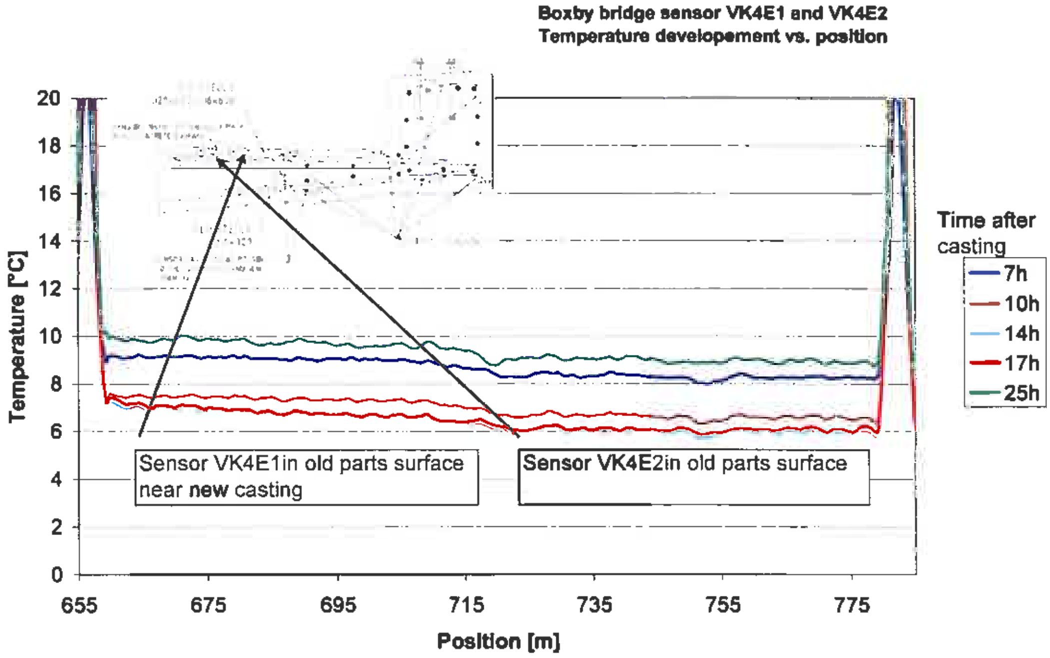


Figure 4.1.8. Temperature measurement results vs. position (7 h, 10 h, 14 h, 17 h and 25 h) after casting. The maximum temperature rice observed by VK4E1 fibre optic sensors as a result of cement hydration was 10 °C. The maximum temperature rice observed by VK4E2 fibre optic sensors as a result of cement hydration was 9 °C.

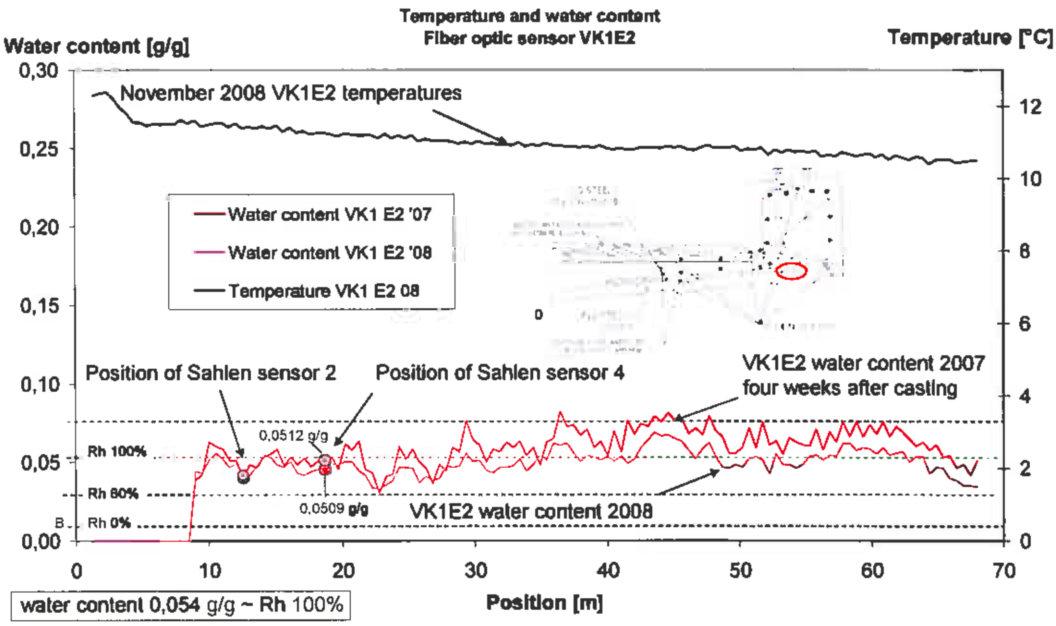


Figure 4.1.9. Temperature and water content measurement results vs. position close to the bottom of the edge beam (sensor VK1 E2) on 15th of November 2007 and 13th of October2008. The positions of the Sahlen sensors 2 and 4 are marked to the graph with red spots. E.g. water content near Sahlen sensor 4 was 0.0521g/g on 15th of November 2007and 0.0509g/g on 13th of October2008.

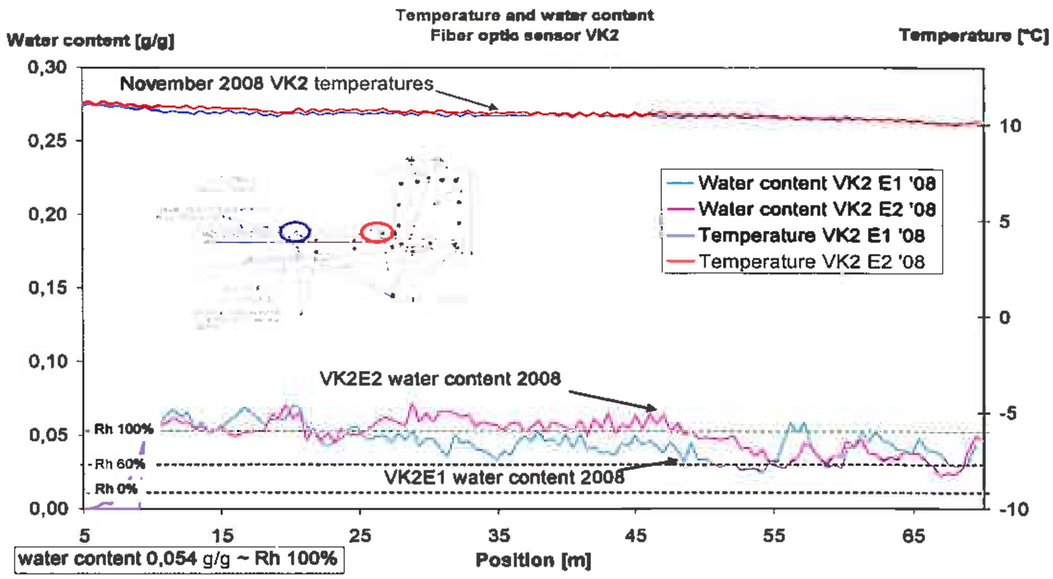


Figure 4.1.9. Temperature and water content measurement results vs. position close to the upper surface (sensor VK2 E1 and VK2E) on 13th of October2008.

The water content measurement results (close to the bottom of the edge beam and the upper surface of the bridge deck observed by fibre optic sensors VK1E2, VK2E1 and VK2E1) indicates that water content was in some positions still high (over 0.054 g/g ~ Rh 100%) after one year of casting.

The measurement results confirmed earlier experiences that the fiber optic measurement technique is effective for monitoring temperatures both for quality control of the construction and for life cycle analysis of the bridge. In addition, these measurements appear to be feasible for evaluating the local leakages and high volumetric water content. The test parameters, the main results and costs of the installations are summarized in Table 4.1.1.

Table 4.1.1. The fiber optic sensor installations at Boxby bridge and the results.

Parameter	Bridge deck	Edge beam
Purpose of fiber optic measurement	Quality control of casting Condition monitoring of waterproof sealing Location of possible leakage through the sealing materials Joint area leak detection	Quality control of casting Abnormal water content detection Erosion and degradation detection
Installation geometry and sensor location	Three horizontal levels (5 sensors): - two sensors installed in a groove made on the old part of the bridge deck - two sensors installed close to the joint area of the new and old part of the bridge - one sensor installed in the corner near to the edge beam	Two horizontal locations (3 sensors): - two sensors installed close to the bottom of the edge beam - one sensor installed close to the top of the edge beam.
Length of single sensor cable (m) /total length (m)	on average 60/300	on average 60/180
Number of measurement points	400 - 800	150 - 300
Spatial resolution (m)	0.25 - 1	0.25 - 1
Number of data collection periods	3	3
Duration of each data collection period (h)	6 - 72	6 - 72
Main results and observed events	Effects of hydration, temperature differences throughout cement hydration. Water content was in some positions still high (over 0.054 g/g ~ Rh 100%) after one year of casting.	Water content was in some positions still high (over 0.054 g/g ~ Rh 100%) after one year of casting. Temperature differences throughout cement hydration
Capital costs of sensor system Installation costs (sensors, boxes and connections) Other installation costs (groove, cable under the bridge for electricity)	3000 € 3500 € 3100 € (bridge deck and edge beam)	2000 € 3000 €
Man hours per test/condition monitoring7 data collection periods	4 - 21 hours	4 - 10 hours

4.2 Humidity measurement using moisture sensors

The durability of concrete structures is influenced by temperature and moisture content of concrete and the dynamics of heat and moisture transfer in concrete. Thus to be able to predict the degradation in a concrete structure it is important to be able to measure the temperature and moisture variations continuously in concrete. As a second step, it is necessary to develop computational methods with which it is possible to predict the rate of different degradation mechanisms that depend on temperature and moisture. In this research the continuous temperature and moisture measurements were carried out and these measurement results were used for calibration of a computer simulation program (ref. 4.5.).

The test structure was the southern edge beam of Boxby bridge which was repaired in autumn 2007. The cross section of the edge beam is presented in figure 4.2.1. The temperature and moisture sensors were installed in the edge beam before casting the concrete and provisions were made for remote monitoring of the measurement results. Similar measurements with cast-in-place sensors were successfully conducted for bridge structures in late 1990's /1, 2, 3/.

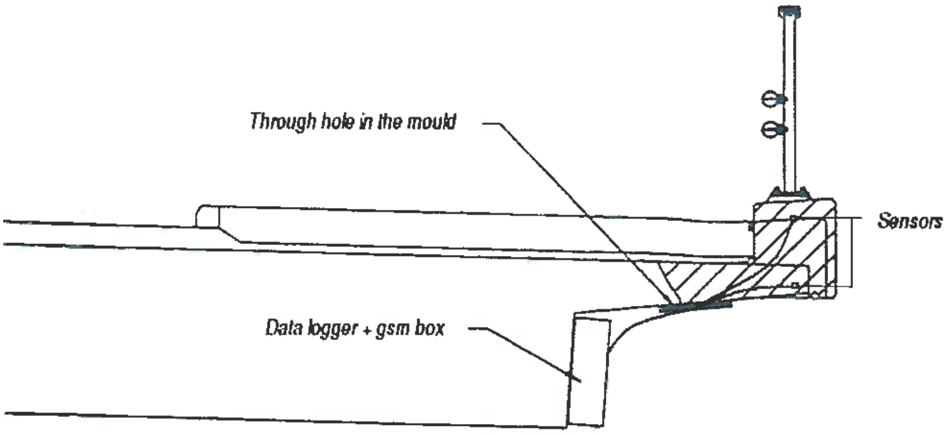


Figure 4.2.1. Repaired edge beam of Boxby Bridge.

Four cast-in-place resistive Sahlen-sensors were installed in the bridge reinforcement before casting and connected with wires to the data logger (Fig. 4.2.2). FuktLog is a 16 channel moisture and temperature data logger with a gsm modem for wireless data transmission. The data was transmitted to FuktCom AB, Malmö, Sweden and to VTT, Otaniemi. A capacitive sensor FC 100 to measure ambient air relative humidity and temperature was also connected to the data logger. Both types of sensors were manufactured by FuktCom AB.

Figure4.2.2. Installed Sahlen sensor (white device in the middle of the photo) close to the reinforcement.

In situ measurements started at Boxby bridge on 9th of October. Casting of concrete was performed on 15th of October 2007. On 16th of October a temperature rise up to 45 °C as a result of cement hydration was observed. At the same time a RH rise to 100% caused by fresh concrete mass was observed.

Table 4.2.1. Data on repair concrete.

Property of concrete	
Strength class	K50
Compressive strength, MPa	68
Frost resistance index (P)	P50
Cement type	Cem II A 42,5
Cement amount, kg/m^3	413
Water-cement ratio	0.40
Air content, %	5.0 - 5.8
Max. size of aggregate, mm	16
Consistency	S2

The Sahlen-sensors were placed close to the top and bottom of the edge beam as presented in table 4.2.2. One FC 100 sensor was installed on concrete surface under the bridge deck to measure ambient air relative humidity and temperature.

Table 4.2.2. Location of Sahlen-sensors in the edge beam.

Spot 1	Sensor 1	13 cm from top surface	540 cm from abutment
	Sensor 2	8 cm from buttom surface	610 cm from abutment
Spot 2	Sensor 3	12 cm from top surface	1030 cm from abutment
	Sensor 4	9 cm from buttom surface	1090 cm from abutment

The measurement results are presented in figures 4.2.3 and 4.2.4. From May to August there is a decrease in RH measurement values recorded by sensor 1 at 13 cm depth from the top surface. This RH variation follows the corresponding variations in temperature. Sensor 2 at 8 cm from bottom surface shows RH decrease in January and February. Sensors 1, 2 and 4 show temporarily 64% resulting from a "Time Out" function in the logger and not from malfunction of sensors. These values were neglected.

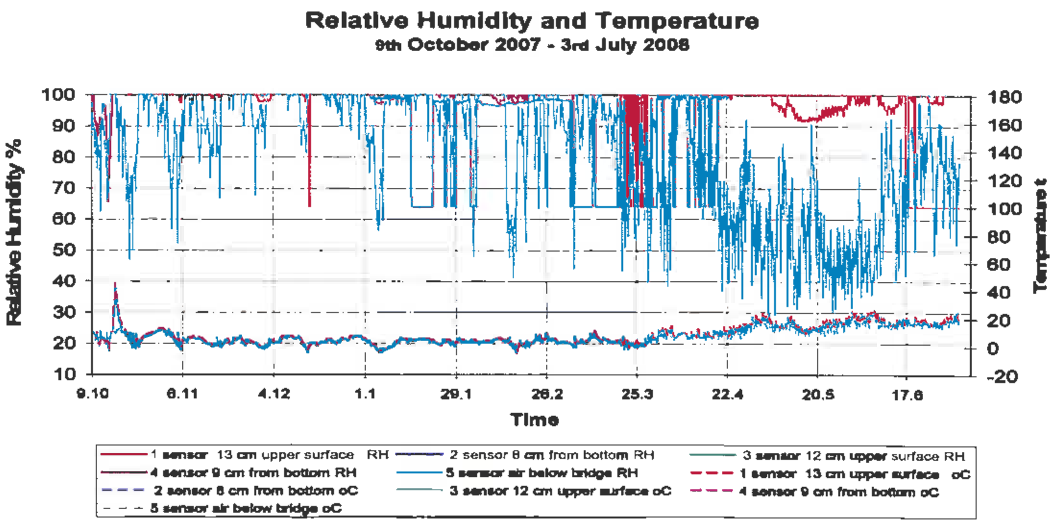


Figure 4.2.3. Measurement results from Boxby bridge during 9th October and 3rd July.

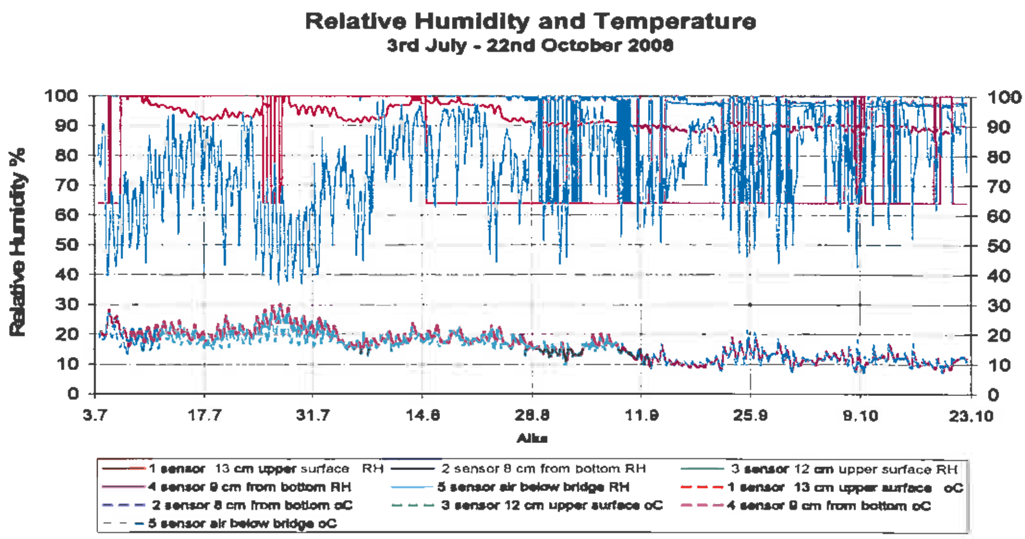


Figure 4.2.4. Measurement results from Boxby bridge during 3rd July and 22nd October.

The sensors were placed rather deep in concrete (8 - 13 cm) as it was desired that the sensors are at the level of reinforcement. Although located 13 cm from the top surface drying to 94% from May to August could be observed. During this period rapid increase in the moisture content was measured repeatedly due to rain water penetrating into concrete.

One criteria for correct measurement of moisture content is that the relative humidity must follow the temperature variation in concrete, i.e. with rise of temperature the relative humidity must also rise and vice versa /4/. This criteria was fulfilled with the used sensors as can be seen in Fig 4.2.5.

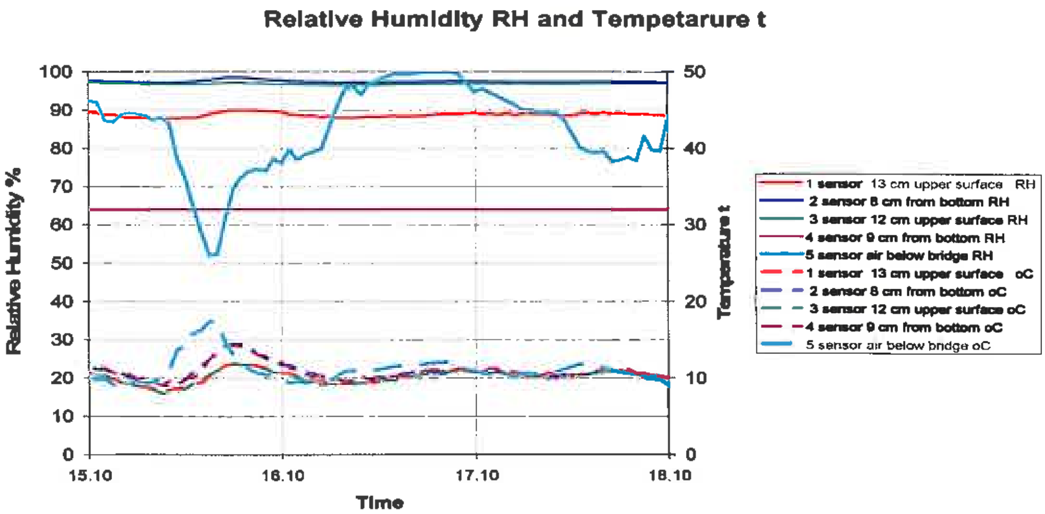


Figure 4.2.5. Detail of the measurements.

In Fig. 4.2.5 it can be seen that the RH in concrete is following the temperature while in the ambient air the RH (light blue line) is behaving in the opposite way as expected.

References

1. Paroll, H., Measurement of relative humidity and temperature in new concrete bridges. Nordic Mini-seminar of the Nordic Concrete Federation, VTT Symposium 174, Espoo, Finland 22.8.1997. p. 51 - 65.

2. Paroll, H. & Nykänen, E., Measurement of relative humidity and temperature in a new concrete bridge vs. Laboratory samples. Nordic Concrete Research No. 21. 1998. p. 103 - 119.

3. Paroll, H. & Nykänen, E., Measurement of relative humidity and temperature in a new concrete bridge vs. Laboratory samples. Proceedings Nordic Concrete Research Meeting. Nordic Concrete Research Projects 1999. Reykjavik, Island 1999. Nordic Concrete Federation. p. 116 - 118.

4. Nilsson, L-O., Hygroscopic moisture in concrete - drying, measurements & related material properties. Lund. 1980. Lund Institute of Technology, Division of Building Materials. Report TVBM-1003. 162 p.

4.3 Climate monitoring

The weather data was measured by automatic weather station which was mounted on top of the bridge. The weather station was Vaisala WXT510. A pyranometer Perel CMP 3 was attached to the weather station for measurement of solar radiation (total radiation including both direct, disperse and reflected radiation).

The weather station was capable of determining the following data:

- Wind direction average [deg]
- Wind speed average [m/s]
- Wind speed max [m/s]
- Air temperature [deg C]
- Relative humidity [%RH]
- Air pressure [hPa]
- Rain amount [mm]
- Rain duration [s]
- Solar radiation [W/m^2].

The meteorological data was recorded automatically at 20 minutes intervals using industrial computer UNO 2171. The data recording was started on 16th February 2008. The data of the weather station were used for calibration of the computer simulation.

Figure 4.3.1. Automatic weather station.

Figure 4.3.2 shows an example of the measurement results from the weather station above the bridge. The data is from 1st of March 2008. The temperature of the air is about 0 °C. The relative humidity changes between 80 and 90%. The average wind speed ranges between 0.5 and 5 m/s. The amount of rain is less than 0.1 mm.

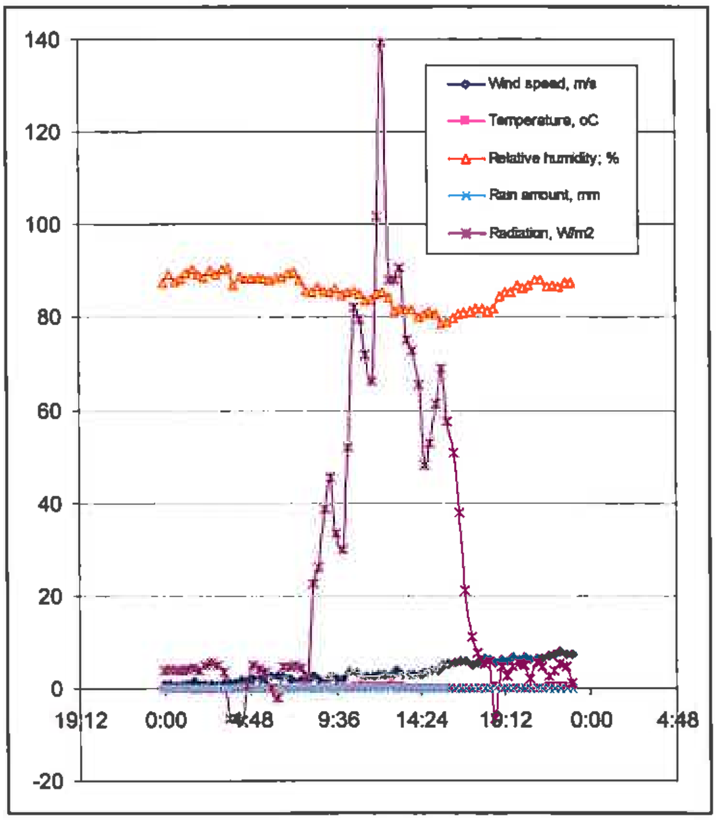


Figure 4.3.2. Example of the weather station data from one day.

4.4 Computer simulation of temperature and moisture content in concrete and comparison with measurement results

Computer simulation was used to determine the temperature and moisture contents of concrete in the edge beam from the measurements results of the weather station. Simulation in this research means numerical emulation of heat and mass transfer in concrete by the finite difference method. The temperature, relative humidity and moisture content are determined at various depths of the structures continuously. The time increment is 1 hour or less.

The relevant climatic stresses on the edge beam are temperature and relative humidity of the air, solar radiation, wind and rain. The rain water is assumed to be absorbed into concrete by capillary suction in two phases. First the capillary pores are saturated with water and after that the air pores are slowly filled. Phase transitions such as cement hydration and freezing and thawing which effect on the temperature and moisture content are also considered.

The computer simulation program that was used in the research was developed in VTT in 1996 - 1998 /1, 2, 3/. The simulation program determines theoretically temperature and moisture variations in concrete using ambient climatic data as initial data and further evaluates the degradation rate with regard to different degradation mechanisms such as carbonation, chloride ingress, corrosion of reinforcement and frost attack. The degradation can be followed step-by-step until the maximum allowable degradation (= service life) is attained.

The edge beam was modelled for the simulation as presented in figure 4.4.1. The problem was that the simulation program was 1-dimensional and thus only 1-dimensional grid could be used in the calculations. To take into account the effect of the four sides of the edge beam a 2-dimensional grid would be preferable. However, for the lack of resources the computer program could not be modified 2-dimensional.

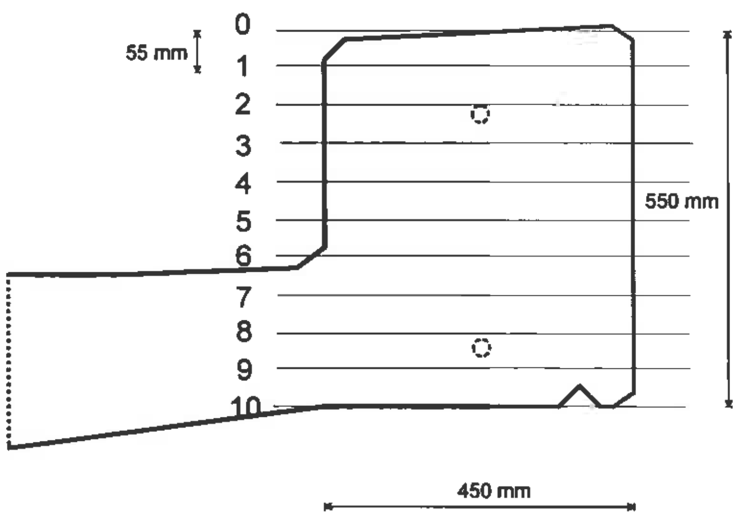


Figure 4.4.1. 1-dimensional nodal network for the edge beam in Boxby bridge. The measurement points have been marked with dotted rings.

Every nodal point in the structure represents a certain volume around the point. The law of conservation energy is assumed to apply in every nodal point. This law can be presented by the following equation:

$$\dot{E}_{st} = \dot{E}_{in} + \dot{E}_{g} - \dot{E}_{out} \quad (1)$$

where $\dot{E}_{in}$ is amount of energy tranferred to the nodal volume in a time unit, W
$\dot{E}_{out}$ amount of energy tranferred out of the nodal volume in a time unit, W
$\dot{E}_{g}$ amount of energy generated in the nodal volume in a time unit, W and
$\dot{E}_{st}$ amount of energy stored in the nodal volume in a time unit, W.

The amount of energy stored in the nodal volume increases the temperature of the nodal point. The change in the temperature can be determined when the volume of the nodal point and the thermal capacity of the material is known.

The law of conservation of species is applied in every nodal volume in calculation of the moisture content. Accordingly to the formula of energy balance we get:

$$\dot{w}_{st} = \dot{w}_{in} + \dot{w}_{g} - \dot{w}_{out} \quad (2)$$

where $\dot{w}$ means the change of moisture content of a nodal volume in a time unit and the subscripts have the same meaning as with formula 1 above.

The nodal regions at the edge of the structure gain energy and moisture from outside as they also lose energy and moisture to the outside environment. Inside the structure the heat and moisture is be transferred by diffusion. In numerical calculation the physical equations are replaced by differential approximations. The results of the calculation are obtained step-by-step at each time increment and at each nodal point.

In figures 4.4.2 and 4.4.3 some results of the simulation are presented together with the measured results. The treated time interval is September 2008. The point "Meas Top" refers to measured values close to the top surface presenting the average value of sensors 1 and 3. The point "Meas Bottom" refers to the measured values close to the bottom surface showing the average value of sensors 2 and 4. The notations "Calc Top" and "Calc Bottom" refer to the corresponding calculated values.

Generally the calculated and measured values of temperature were consistent. Only the daily variation of "Calc Bottom" values was slightly smaller than the measured variation. This is probably due to the effect of solar radiation at the sides of the beam that is not accounted for in the 1-dimensional numerical calculation.

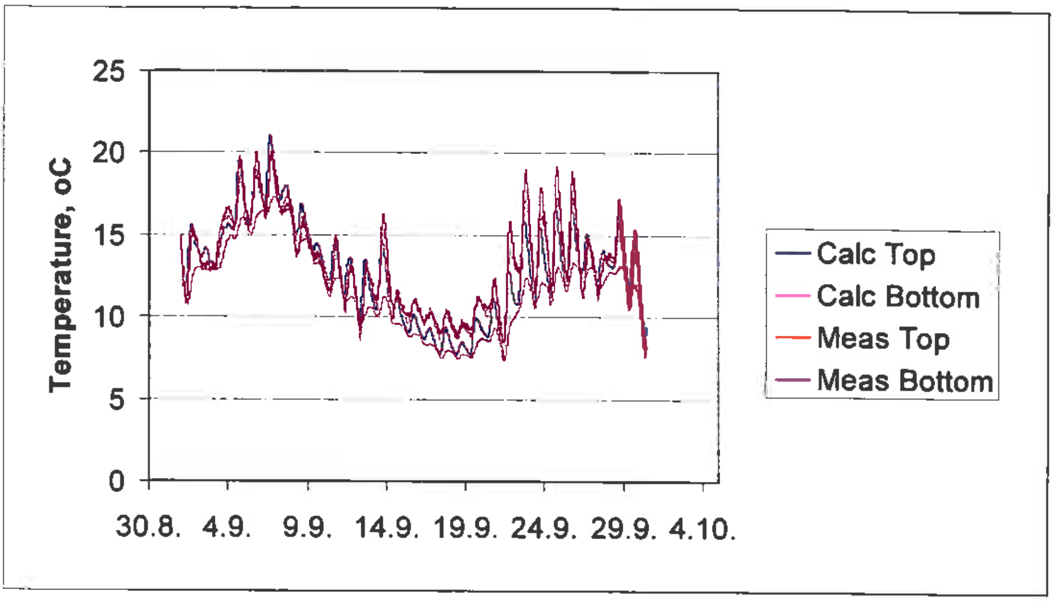


Figure 4.4.2. Calculated and measured temperatures in the edge beam.

In case of relative humidity sensor 4 did not work satisfactorily during September 2008. That is why sensor 2 alone represented the measured values at the bottom of the beam. When comparing the measured and calculated values of relative humidity the consistency was not as obvious as it was with temperatures. The daily variation in the relative humidity was conservatively taken into account in the numeric calculation (in reality the ambient temperature may affect even more on the sorption curve). The fit between calculated and measured values might be improved by determining the real porosity properties of the repair concrete from a concrete sample.

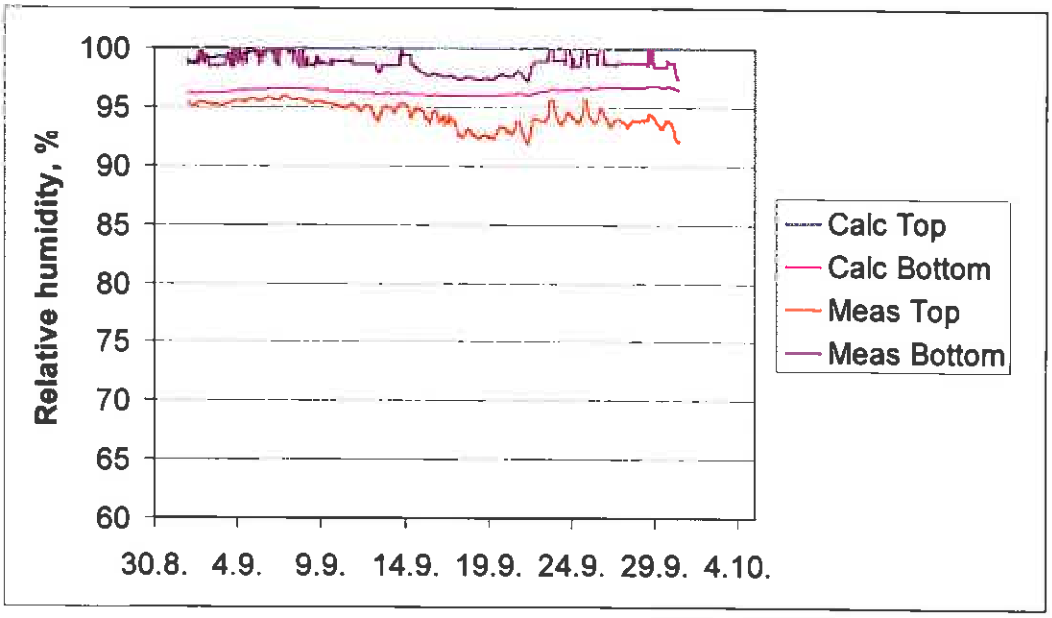


Figure 4.4.3. Calculated and measured relative humidity inside the edge beam.

To be able to properly calibrate the simulation program, it is necessary to continue the comparative calculations using test data from different seasons of the year. Also the 2-dimensional model of the edge beam should be developed.

References

1. Vesikari, E. (1998), Prediction of service life of concrete structures by computer simulation. Helsinki University of Technology. Faculty of Civil and Environmental Engineering. Licentiate's thesis. 131 p. (in Finnish)

2. Vesikari E. 1999. Computer simulation technique for prediction of service life in concrete structures. Proc. Int. Conference on Life Prediction and Aging Management of Concrete Structures. RILEM Expertcentrum. Bratislava 1999. 7 p.

3. Vesikari E. 1999. Prediction of service life of concrete structures with regard to frost attack by computer simulation. Proc. Nordic Sem. on Frost Resistance of Building Materials, Aug. 31 - sept. 1 1999, Lund. Lund Institute of Technology, Division of Building materials. 13 p.

5 Exhaust suspension bridge (Hännilänsalmi)

Hännilänsalmi suspension bridge is situated in the middle part of Finland near Viitasaari. The bridge has two pylons and the main span of 125 m. The bridge has been repaired many times and e.g. the deck of the bridge has been fixed to the main beams. The bridge has selected one of the monitored bridges in SIMO project in order to check the remaining condition of the bridge. A new bridge will substitute the old bridge in 2009. The bridge is shown in *Figure. 5.1.*

Figure 5.1. Hännilänsalmi suspension bridge in Viitasaari.

5.1 Measuring device and sensors

In Hännilänsalmi bridge the purpose of the measurements were to test portable monitoring device, which was also capable to operate without power supply. The logger used in monitoring was Campbell micrologger CR23X and storage module SM16M (*Fig. 5.1.1*). The data could be copied to laboratory with the GSM Siemens modem. The measuring equipments included battery and charger. The power supply was installed for the SIMO project using cable and socket on abutment.

The measuring device and sensors have been working very well, only a couple of times the wireless telephone connection have been cut off, but almost all the data could have been copied and saved. The micrologger is using own programming language which also includes post triggering capabilities. The logger includes direct supply for strain gauges and no extra amplifier is needed. The logger has been tested in a quite severe condition of -40 °C and power saving property has designed carefully.

The FINNRA has installed near the bridge under the road cables to measure vehicle velocities and to classify their types. These values can be used when estimating the remaining life age of the bridge.

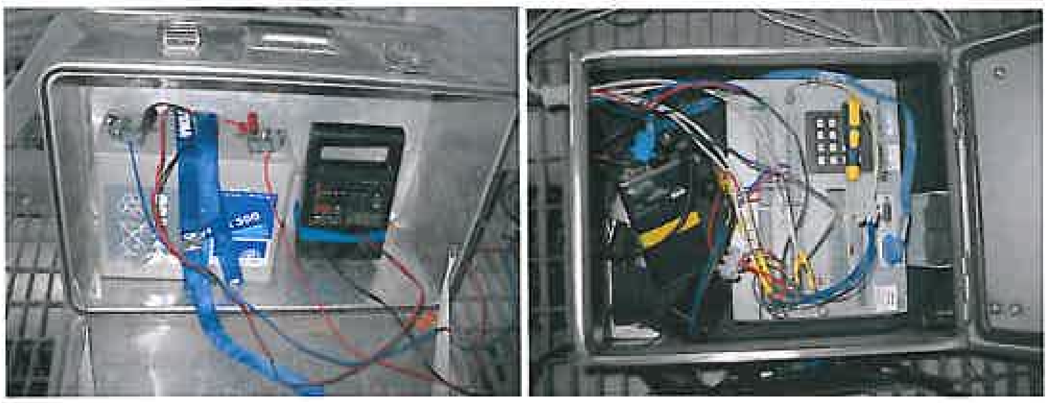


Figure 5.1.1. Micrologger, storage module, charger and accumulator in Hännilänsalmi bridge.

The sensors used for monitoring have been strain gauges, which have been glued on a longitudinal and cross beams of the bridge. The gauges have been installed on the point of 0.25*L (L = main span) according to *Figure 5.1.2*. The gauges have been fixed on the flanges of I shaped beam sections. The bridge deck has design to behave as a composite structure in the last restoration. Therefore the stresses on the upper flange are quite small due to place of neutral axis. The strain gauges are shown in the *Figure 5.1.3*.

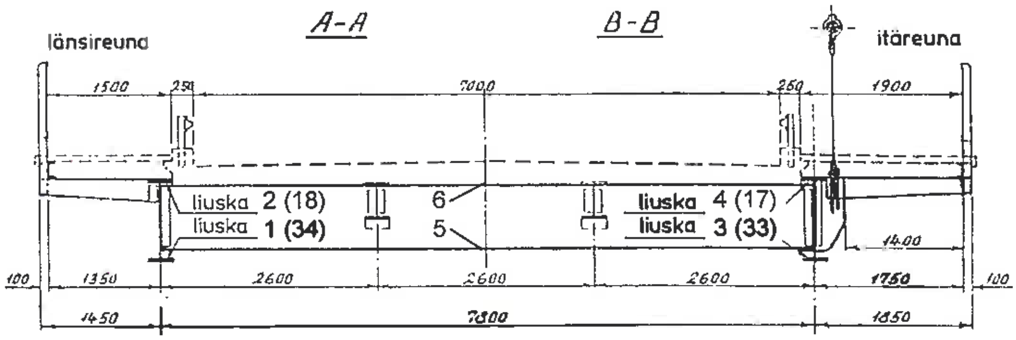


Figure 5.1.2. The places of strain gages in Hännilänsalmi bridge in loading tests. 4 strain gages have been selected for long-term monitoring.

Figure 5.1.3. In the Hännilänsalmi bridge the strain gages have been fixed on the flanges of I-shaped beams.

5.2 Classification of strains and Fatigue calculations

In Hännilänsalmi bridge the measuring device logger is running all the time but all the stress-time series are not saved due to limitation of memory size. Instead maximum and minimum values during every minute is calculated and saved. In *Fig. 5.2.1* is shown an example of calculated maximum amplitudes (μ strains) and temperature (°C) in May 2007. In the weekends there is less heavy traffics which can be seen in the *Figures* (e.g. dates 8.4, 16.4, 22.4 and 30.4). The fluctuations of the temperature do not have significant effect on the strain values in the suspension bridge. The data series above can be used to search exceptional strains or trend of strain-time series. The data series above does not include possible static strains, because all the values are reset once in a day, when no traffic is on the bridge. The reset values are saved for research if needed.

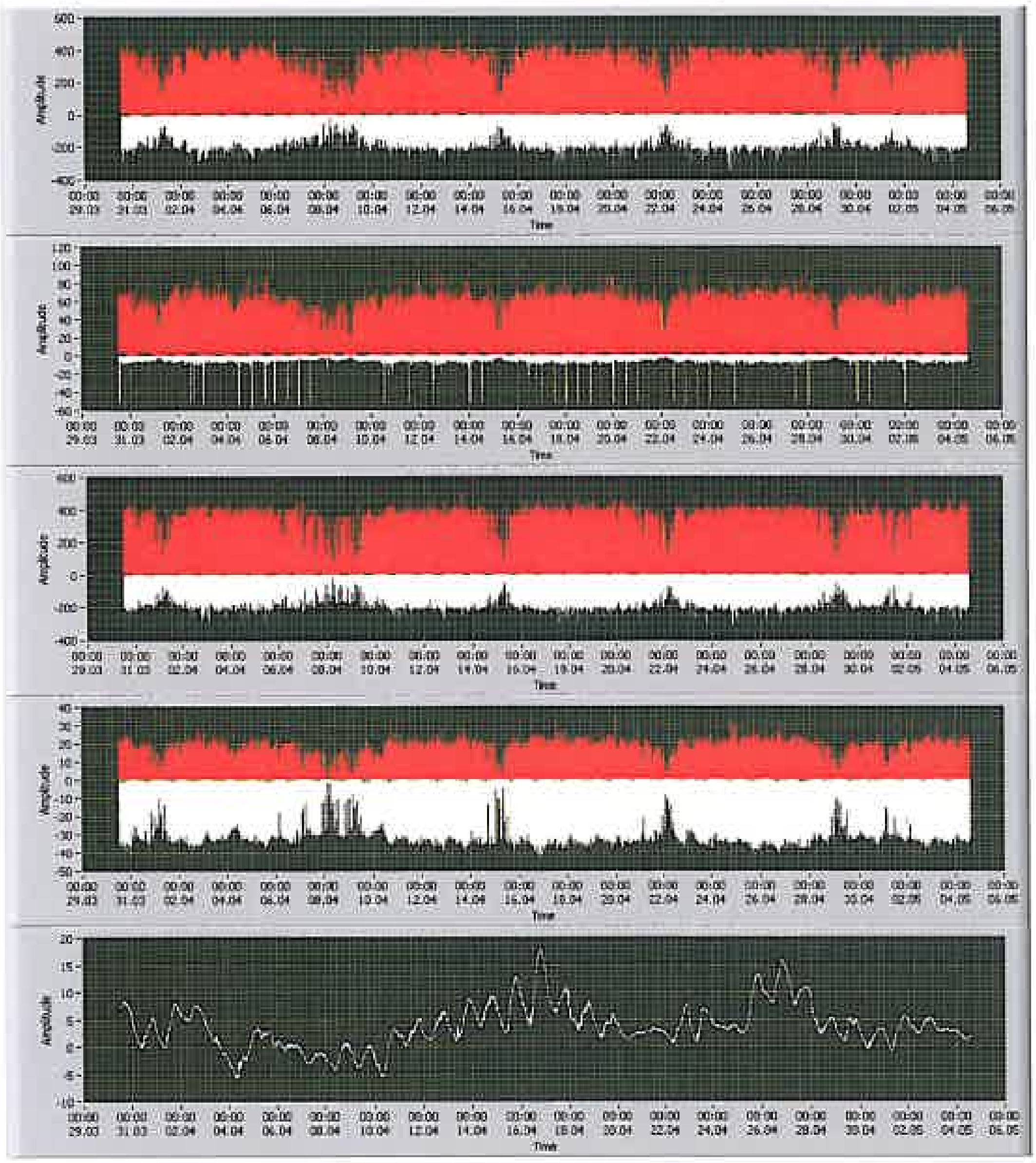


Figure 5.2.1. Maximum and minimum strains (μ strains) and temperature (°C) in May 2007 in Hännilänsalmi suspension bridge.

Better estimation of the today's condition of the bridge can be seen, if the max-min data is sorted. In *Table 5.2.1* the above data of strain gages is sorted using classes of 100 μ strains (25, 125, 225 ... μ strains), e.g. the strain gage 1 includes 30 samples of class between 475 and 525 μ strains. The same classification is shown with graph in *Figure 5.2.3*.

Table 5.2.1. Classification of maximum and minimum strains (μ strains) of strains (gauges No 1, 2 and 3) in May 2007 in Hännilänsalmi suspension bridge.

Class μ strains	Max Strain 1 samples	Min Strain 1 samples	Max Strain 2 samples	Min Strain 2 samples	Max Strain 3 samples	Min Strain 3 samples
25	22355	24152	32700	38688	22430	24569
75	2604	5932	6000	15	3198	5994
125	3638	5313	3	0	3082	4675
175	2441	2776	0	0	3015	2837
225	3297	494	0	0	2456	611
275	2049	34	0	0	1114	17
325	1189	2	0	0	1329	0
375	904	0	0	0	1581	0
425	192	0	0	0	462	0
475	30	0	0	0	33	0
525	3	0	0	0	2	0
625	0	0	0	0	0	0
725	0	0	0	0	0	0
775	0	0	0	0	0	0

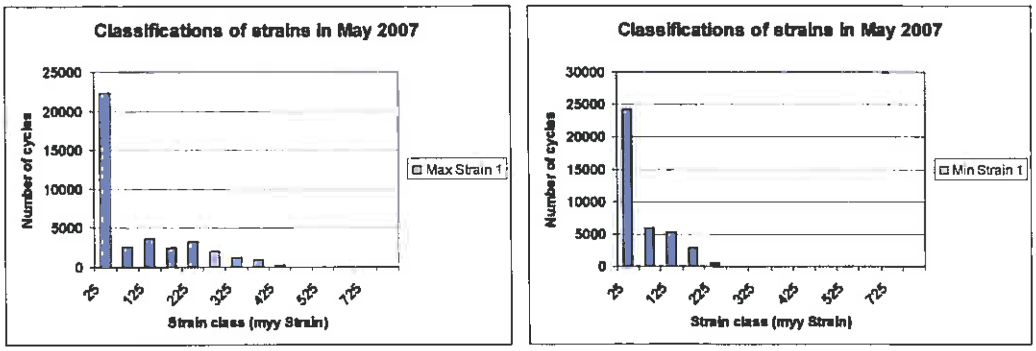


Figure 5.2.2. Classification of maximum and minimum strains (μ strains) of strain gage No 1 in May 2007 in Hännilänsalmi suspension bridge.

The speed of the heavy vehicles crossing the bridge has a significant effect to the vibration of bridge. In *Fig. 5.2.3* is shown an example of effect of crossing speed. The figure left is measured during load testing using heavy lorry with the speed of 25 km/h and figure right with the speed of 90 km/h.

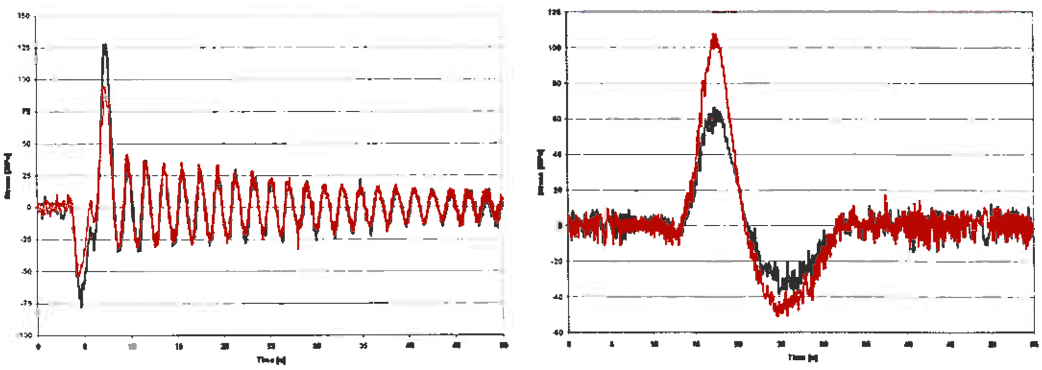


Figure 5.2.3. The vibration of the bridge after heavy vehicle crossings. In the left figure the speed have been 25 km/h and in right figure 90 km/h.

6 Typical short concrete bridge (Jylhänranta)

Jylhänranta concrete bridge is situated in middle part of Finland in Pulkkila and has the main span of 32 m. The bridge has been repaired by cluing steel plates on the bottom of concrete beams. The bridge has been selected one of the monitored bridges in SIMO project, because it is a typical concrete bridge in Finland and has a slight vibration problem. The bridge is shown in *Figure. 6.1.*

Figure 6.1. Jylhänranta concrete bridge in the middle part of Finland in Pulkkila.

6.1 Automation based monitoring systems

In the recent practice structural monitoring is mainly used for big or otherwise significant bridges, whose maintenance costs are significant. In most countries and bridge owning organizations, demography of bridge stocks show great number of small bridges, making them of special interest in bridge management. Annual maintenance budget is spent on repairing ordinary bridges, while renovation of individual big bridges may need extra funding. Regardless the size of the bridge, the renovation of the bridge will harm users of the traffic corridor.

Recently, an European research project Sustainable Bridges (Olofsson *et al.* 2005, 2007), addresses structural monitoring in this respect. It focused to special issues of European railway bridges, as summarized by Kiviluoma 2005. Development of the structural monitoring systems has been as one of the key issues of developing assessment methods and methodology to keep old bridges in use for increased traffic volume and upgraded axle loads. Need for assessing bridges per traffic corridor (railway line) bases is pronounced. A recent example in Finland is the railway line upgrade between Seinäjoki and Oulu, which contains 172 bridges (SB 8.2 Demo). Bridges needs to assessed in relatively short time before the investment. Similar issues could be faced on road bridges, e.g. when special heavy transport routes are studied.

The importance of ordinary bridges in terms of future development of structural monitoring system is addressed by Kiviluoma 2007a and the specific needs in Finland by Kiviluoma *et al.* 2007b. In Finland, most of the annual management budget is spent on ordinary bridges and will be taken care by the owning organizations. Maintenance issues are addressed by means of regular visual inspection and bridge management system. Finnish bridge management system is well established and described by Söredqvist 2004 for Finnish Road Administration's bridges. In specific pilot projects named Regional Bridge Management Contracts visual inspection results are used as contractual bases indicating contractor's performance (Kiviluoma *et al.* 2008). Bridge management system, or its specialist expert software, is used to forecast so called optimal maintenance budget. It appears that such prediction has been underestimate, which have been attributed to quality of visual inspection data (Söredqvist 2004). This has in recent years taken into account in certification and education of bridge inspectors.

A topical question arises, whether or not structural monitoring could be integrated to bridge management systems (Kiviluoma 2006), to improve quality and accuracy of theoretical models for deterioration and resistance. In this respect, a group of ordinary bridges could be monitored to form "an instrumented bridge group" in bridge management systems. This may serve purpose similar to the Reference Bridge Group (Söderqvist 2004), which are used to study the reliability of theoretical models imbedded in the bridge management systems.

Rapid process in information and communication technology (ICT) and structural monitoring systems reveal that it is possible to develop bridge monitoring systems, which may be useful on widespread application to ordinary bridges. This means in practice reduced cost and size, making the systems available for multiple and vandal-proof installations. As outcome of the Sustainable Bridges project two recent technologies have been identified as promising in the context of ordinary bridges (Kiviluoma 2007c,d), namely, the automation based monitoring systems and wireless sensor networks. In the Sustainable Bridges project, both were developed as prototypes (Kiviluoma 2007a and Bischoff *et al.* 2007). Similar developments are conducted independently elsewhere as well, including Kawamura et *al.* 2008 in Japan and the present project. In the present project, two specific workshops have been hold: wireless sensor networks and automation bases monitoring systems. It further appears that automation controller manufacturers understand this point of view, and start providing reduced-price system feasible for service provider's own developments and cloning.

6.2 Automation based monitoring systems

Automation based monitoring system is the name taken in use in the Sustainable Bridges Project (SB 8.2 Demo). The concept stands for replacing measurement computer (PC) of structural monitoring system by automation controller. Automation controller is a type of computer which is designed for measurement use. It has weaker central processor (currently of order 400 MHz), than PC. This is to reduce heat generation to allow solid state (moving-part-free) configuration.

Automation controller is typically controlled over the Internet and contains web and file transfer (FTP) interface. Result is an Internet server, which basically operates like PC based web servers do.

The bottleneck of using automation based structural monitoring systems for bridges has been the speed of measurements needed in identification of dynamic parameters (natural frequency, mode shapes, modal damping, stress cycles in fatigue etc.).In recent years, the Field-Programmable Gate Array (FPGA) has remedied this defect (SB 8.2 Demo). This technique is recently licensed by the US-based market-leading supplier of measurements hardware. Regardless or not their products are most useful and cost effective for the bridge monitoring systems, the important aspect is easy availability of products, which is needed in wide-spread usage by difference organizations, bridge locations and countries. Automation based monitoring systems could be seen as "open standard" in this respect - the technology could be utilized by every organisation. The drawback is extensive development effort needed (Kiviluoma 2007c). Whilst this is done by the organization, cloning of the system is low cost and easy. This type of cloning is one of the key issues in future development and utilisation of structural monitoring.

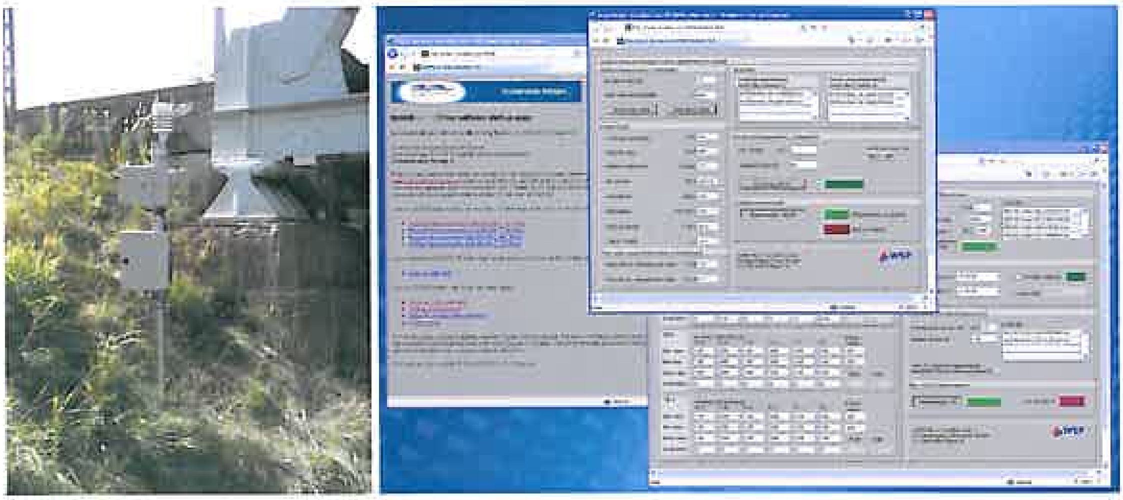


Figure 6.2.1. WSP's prototype of automation based monitoring system in a Sustainable Bridges Project. System is built in a small box allowing concealed and vandal proof installation. It is controlled over wireless Internet using the web driver software (courtesy WSP).

6.3 Jylhäranta Bridge case study

Within the present project, WSP's prototype system has been slightly modified and demonstrated on the Jylhäranta Bridge. System has been upgraded by replacing the automation controller, which doubles the processor clock speed from 200 MHz to 400 MHz and reduced the power requirement. Also upgraded was the network switch, as it turned out the industrial grade switch is needed in low temperatures. These remedy the minor unreliability problems reported for the earlier versions (SB8.2-Demo) without need to change the core driver software.

Jylhäranta Bridge (*Fig. 6.3.1*) is two-lane concrete bridge having main span 28 m and usable width 10.5 m. Bridge is situated on the busy road E75 in middle-part of Finland, in Pulkkila. The performance of the bridge for the preset traffic demands is doubted, and the bridge has been strengthened with glued steel plates. Vibration has been found to be an issue in a sense that a separate vibration level study has been conducted by the owner, Finnish Road Administration.

Figure 6.3.1. Jylhäranta Bridge. Glued steel plates under the main girders are shown in left picture.

Testing on the system has been conducted by temporary installation illustrated in *Fig. 6.3.2*. Sensors contained capacitive accelerometers of 1 V/g sensitivity and a weather sensor. Vertical acceleration has been measured at the edge beam by mounting the accelerometer by magnet on steel base plate of the rail post (*Fig. 6.3.3*). Monitoring unit has been mounted on a pipe, which is a standard traffic sign pole used in Finland. In the present setup, the system has been located relatively far away from the bridge (about 50 m) for arranging power for the units. In permanent installations, the preferred location of the system is on the bridge to minimize sensor cable lengths.

Accelerations were measured with1 kHz sampling rate, while the weather monitoring was conducted with 3 Hz. Recording was conducted in runs, 10 min in length each. Typical acceleration traces are shown in *Fig. 6.3.4*. Whether data is relatively unimportant for the present test, showing steady temperature around 15 °C and calm conditions.

Figure 6.3.2. WSP's prototype of automation based monitoring system (circled) on the Jylhäranta Bridge.

Figure 6.3.3. Accelerometers location (circled).

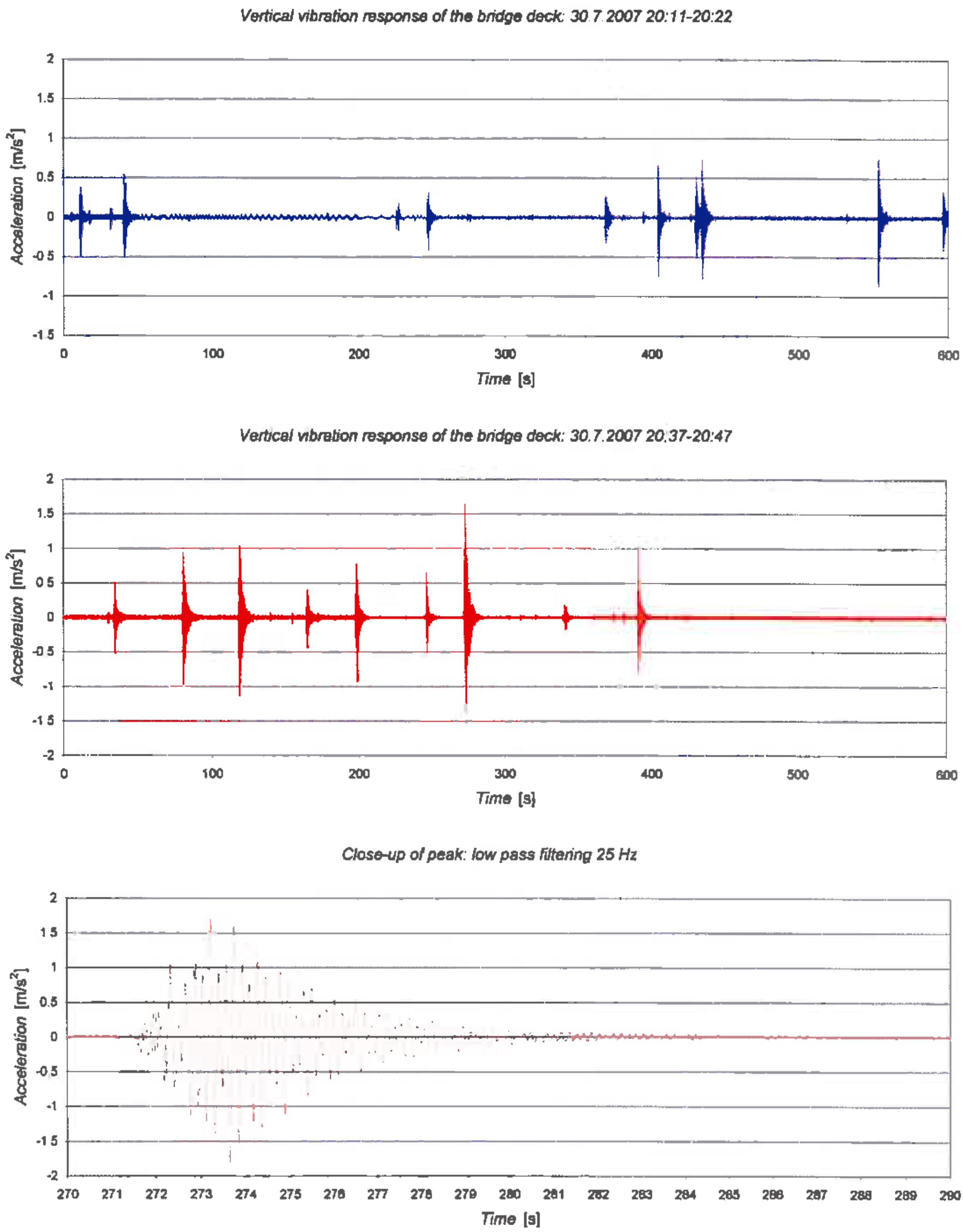
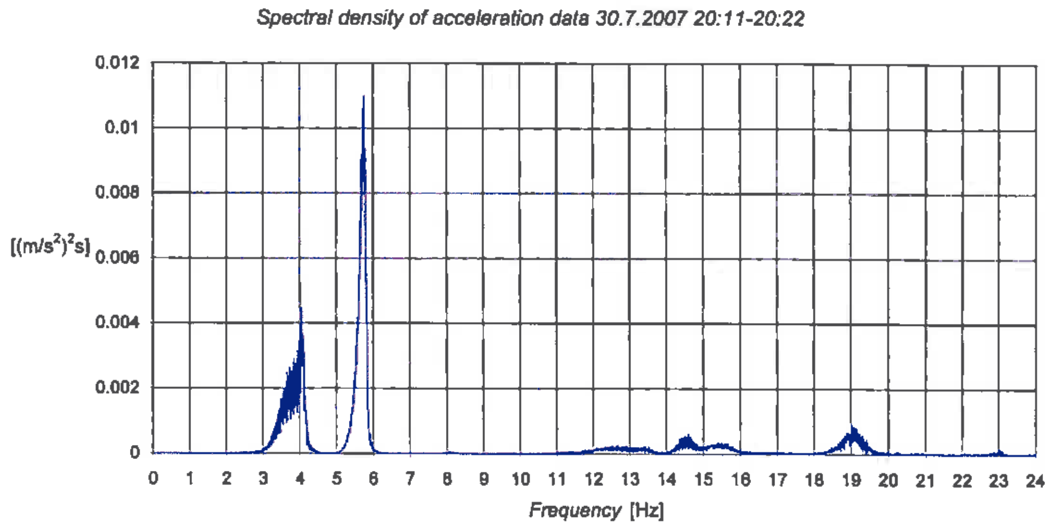


Figure 6.3.4a. Typical acceleration traces. Heavy vehicle crossings are seen as peaks.



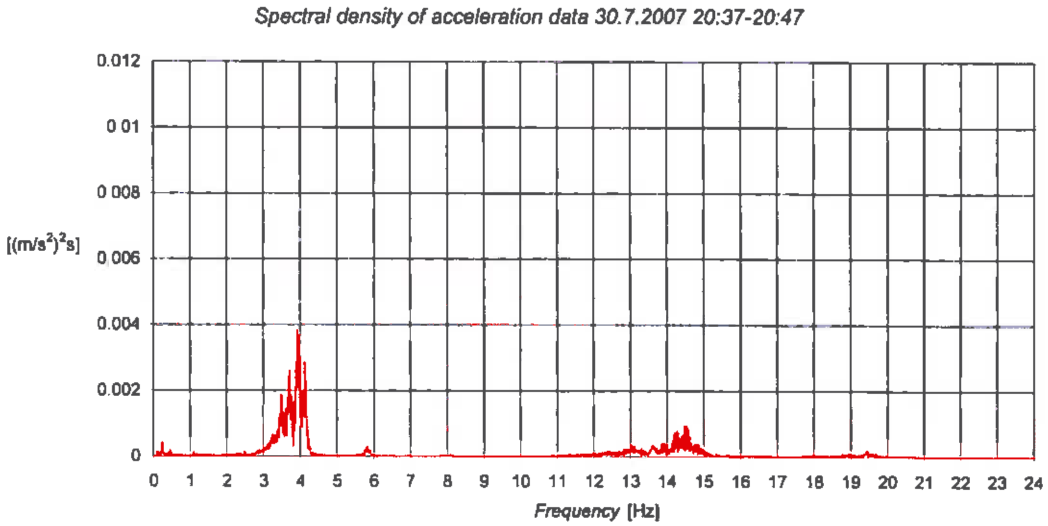


Figure 6.3.4b. Spectral density analysis of the vibration records.

6.4 Discussion of the results

The present project further reinforces the view that automation based monitoring systems are important in widespread utilization of structural monitoring. The prototype system performs in vibration monitoring as traditional computer based systems with low sensor counts do, but have obvious advantages in size, vandal proof and conceal installation and reduced cost. In fact, alike "gray boxes" already exists beside roads in telematic and road weather detection purposes, making structural monitoring systems easy to imagine as an extension.

For vibration recordings on the Jylhäranta Bridge, it could be observed that vibration levels are high in the case of heavy vehicle crossings as reported earlier by the owner of the bridge. Vibration signatures include typical "activity" in 3 - 4 Hz related due to tires of vehicles, and at high frequency content up to 20 Hz. Heavy vehicle has invoked one vibration mode shape with frequency 5.8 Hz, which is obviously one of the fundamental natural frequency of the bridge (first bending or twisting mode). It could be observed that a heavy vehicle is needed to excite the mode and making it easily identifiable. Obviously, vibration recordings should be conducted in sufficient long period (days to weeks) to properly characterise the dynamic behaviour in normal traffic. In low volume roads is even more important. Usage of structural monitoring is favourable in this respect.

The present project didn't go in detail on considerations of utilisation possibilities and new assessment models that take into account structural monitoring. It appears that is the trend and deficiency in international projects as well. Structural monitoring discipline is relatively young, and main interest has been in testing and selling the systems, rather than producing useful results and added value for the bridge owner. Development of structural-monitoring-aware assessment models and design standard is a tedious process where contribution of all parties (researchers, bridge engineers, monitoring service providers, owners, officials) is needed.

At the moment, it appears that the most promising way to take benefit of structural monitoring in bridge engineering is to concentrate on extracting simple engineering parameters, with simple instrumentations, which have counterpart in the present structural assessment models. These include e.g. dynamic amplification factors, peak responses, stress-cycle counting, load distribution parameters, weather measurements during repair works and calibration of FEM models. Considering bridge management, integration to bridge management systems is challenging due to established routines and state-of-the art. Countries and organizations who do not have comprehensive existing bridge management systems are perhaps more interested in look after new technologies. Nevertheless, it may be assumed that individual service providers, including bridge engineers, will start improving the quality of their service be developing and starting using structural monitoring systems on their specific needs. In this way the bridge owners will also start taking benefit of structural monitoring. An automation based monitoring systems is a useful tool for this.

References

1. Bischoff, R., Meyer, J. & Feltrin G. (2007). Low-power wireless sensor network for long term structural health monitoring. Sustain-able Bridges, Assessment for Future Traffic Demands and Longer Lives, Bień J. & Elfgren, L. & Olofsson, J. (eds.), Dolnośląskie Wydawnictwo Edukacyjne, Wroclaw Poland, pp. 397 - 407.

2. Kawamura K., Ogawa, T. & Miyamoto A. (2007). Development of an advanced data collecting system for bridge health monitoring. Proc. of the 2nd International Workshop on Lifetime Engineering, Ube, Yamaguchi, Japan, 28-29 Nov-2007, 10 p.

3. Kiviluoma, R. (2005), European railway bridge sustainability. Lifetime Engineering of Civil Infrastructure: Proc. of the International Workshop on Lifetime Engineering of Civil Infrastructure, Ube Yamaguchi Japan, November 9-11, 2005, Miyamoto, A. & Sarja, A.& Rissanen T. (eds), Practical Maintenance Engineering Institute of Yamaguchi University, pp. 127 - 135.

4. Kiviluoma, R. (2006), Integrating bridge health monitoring into bridge management. Proc. of the Third International Conference on Bridge Maintenance, Safety and Management, Porto, Portugal 16-19 July 2006, Cruz, P.J.S. & Frangopol, D.M. & Neves, L.S. (eds). Taylor & Francis, London 2006, pp. 609 - 610 (pp. 8 paper P_219 on CD).

5. Kiviluoma, R. (2007a), Automation based structural monitoring systems for ordinary bridges. Proc. Improving Infrastructure Worldwide, IABSE symposium, Weimar, Germany Sept 19-21, 2007. pp. 374 - 375; full paper on CD 7 p.

6. Kiviluoma, R. and Rissanen, T. (2007b), Bridge health monitoring in Finland. Proc. of the 3rd Choshu-London Memorial Symposium in Lifetime Engineering of Civil Infrastructure, Ube, Yamaguchi, Japan, 18 Jan-2007, Miyamoto, A. & Tarighat, A. (eds), pp. 79 - 93.

7. Kiviluoma, R. (2007c) Bridge monitoring demonstrations in the Sustainable Bridges Project - synthesis of results. Sustainable Bridges, Assessment for Future Traffic Demands and Longer Lives, Bień J. & Elfgren, L. & Olofsson, J. (eds.), Dolnośląskie Wydawnictwo Edukacyjne, Wroclaw Poland 2007, pp. 389 - 396.

8. Kiviluoma, R. (2007d) New technologies for easing deployment of structural monitoring projects. Lifetime Engineering of Civil Infrastructure, Proc. of the 2nd International Workshop on Lifetime Engineering of Civil Infrastructure, Ube, Yamaguchi, Japan 28-30 November 2007, Miyamoto, A. & Zhou, X. & Shao, X., (eds), pp. 119 - 131.

9. Kiviluoma, R. & Tervo, M. (2008) Use of information technology in a regional bridge management contract. Bridge Maintenance, Safety, Management, Health Monitoring and Informatics. Proc. of the Fourth International Conference on Bridge Maintenance, Safety and Management, Seoul, Korea 13-17 July 2008, Koh & Frangopol (eds), Taylor & Francis Group, London 2008, pp. 340 - 341 & 1585 - 1591.

10. Olofsson, I.& Elfgren, L. & Bell, B. & Paulsson, B.& Niederleithinger, E. & Jensen, J.S. & Feltrin, G. & Täljsten, B. & Cremona, C. & Kiviluoma, R. & Bien, J. (2005), Assessment of European railway bridges for future traffic demands and longer lives - EC project "Sustainable Bridges". Structure & Infrastructure Engineering: Maintenance, Management, Life-Cycle Design & Performance, 1(2005)2, pp. 93 - 100.

11. Olofsson, I.& Elfgren, L. & Bell, B. & Paulsson, B.& Niederleithinger, E. & Jensen, J.S. & Feltrin, G. & Täljsten, B. & Cremona, C. & Kiviluoma, R. & Bień, J. (2007), Sustainable Bridges - A European Integrated Research Project. Background and overview. Sustainable Bridges, Assessment for Future Traffic Demands and Longer Lives, Bień J. & Elfgren, L. & Olofsson, J. (eds.), Dolnośląskie Wydawnictwo Edukacyjne, Wroclaw Poland 2007, pp. 29 - 49.

12. SB8.2 Demo (2007): Demonstration of bridge monitoring. Deliverable 8.2. Prepared by Sustainable Bridges - a project within EU FP6. Available from: www.sustainablebridges.net [cited 30 November 2007]

13. Söderqvist, M-K. (2004) Experience in The Finnish Bridge Management System Development. Proc. Bridge Maintenance, Safety, Management and Cost, IABMAS 2004, Kyoto 2004, 8 p.

7 Gradually monitored concrete bridge (Siikajoki)

Siikajoki concrete bridge is situated in middle part of Finland in Revonlahti in highway No 4 and has the main spans of 20 m + 25 m + 25 m + 20 m (total length of 90 m). The bridge has been build in 1958 and has monitored also in the project of 'Sustainable Bridges' and the tested with heavy vehicles in 2007. The bridge has been selected one of the monitored bridges in SIMO project, because it is a typical concrete box-type bridge. The bridge is shown in *Figure. 6.1.*

Figure 7.1. Siikajoki concrete bridge in the middle part of Finland in Revonlahti.

7.1 TOF sensor measurements

The study tested and developed bridge monitoring system for the Siikajoki bridge concerning dislocations, degradations and load control. Furthermore, the results have been intended to apply for the bridge register, condition assessment methods and procurement processes of the Finnish Road Administration. The project has been connected with Sustainable bridges research programme as well as national SIMO research project.

The TOF device and methods of structural analyses were developed in the project in 2006-2007. Six TOF (time of flight) sensors were installed on the bridge in two steps. A fiber-optic interrogation device is based on a pulsed time-of flight (TOF) for the structural health monitoring of bridge decks. The apparatus is capable of measuring time delays between wideband reflectors, such as connectors, along a fiber path with a spatial resolution of about 3 ns (0.3 m). By using a fiber loop sensor with a reference fiber, it is possible to achieve a strain precision below 1 μstrain and a measurement frequency of 4 Hz. System performance proved adequate for the study of both static and dynamic phenomena in a bridge deck. Application areas include measuring integral strain and its derivatives such as cracks, deflections and displacements. In engineering calculations the elongation of the TOF sensor has been interpreted with rotation angle in the beam which produces stresses for each distance from the deflection curve to the edges of the bridge. The measurements of the cracks can be observed directly using a shorter sensor.

The latter step included the mounting of two sensors. One is located on the upper ceiling of the bridge deck and one on the surface of the lower slab. Vertical dislocations were measured with tachaeometer. In fall of 2007 the test loadings were carried out. The results were analysed with Finite element method (FEM) and Exact point method (EPM). The calculations were compared with measured deflections of the sensors and tachaeometer measurements. The tachaeometer results were incomplete due to lack of results on support points

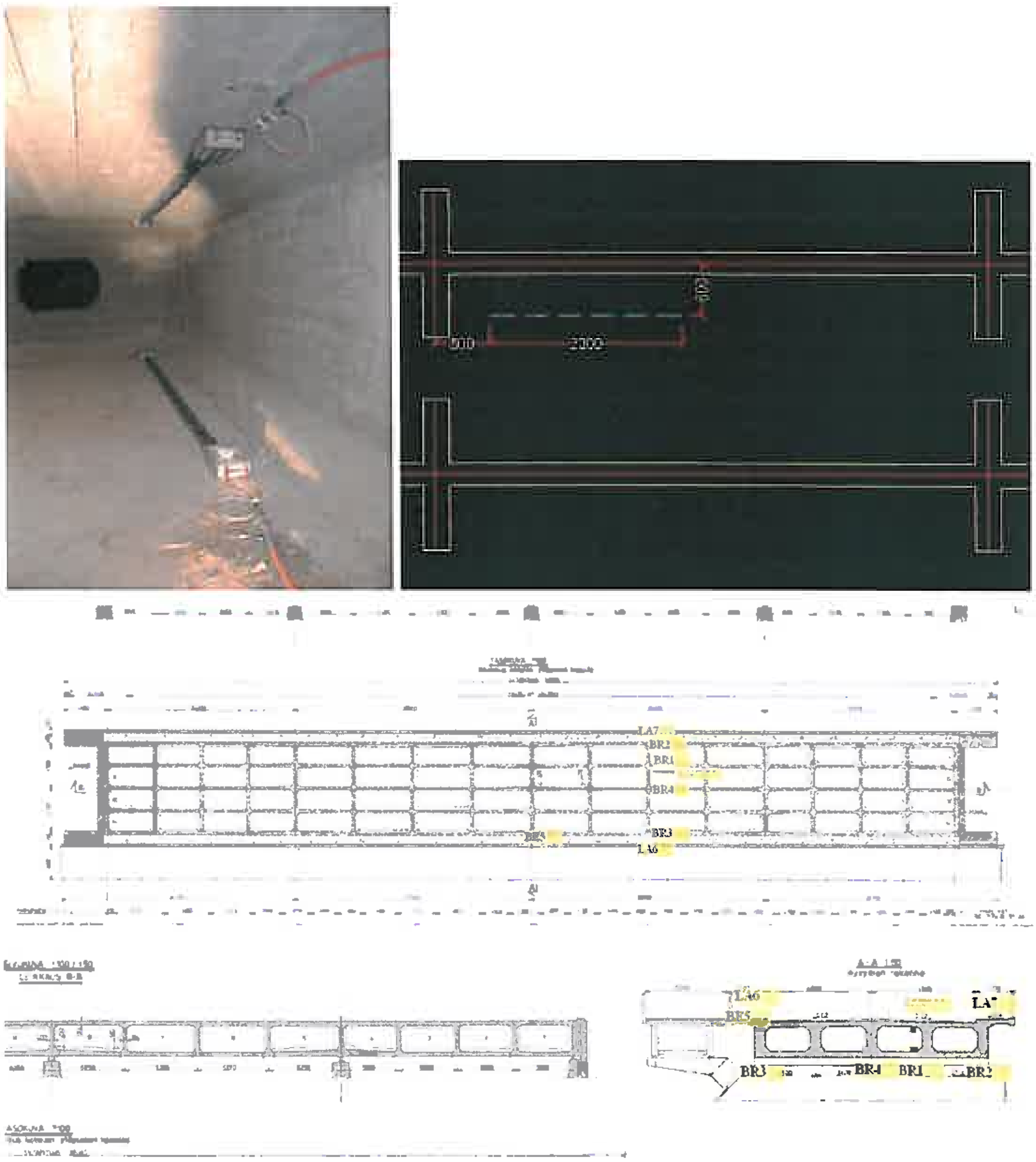


Figure 7.1.1. Siikajoki Bridge (on Revonlahti) test with TOF sensors in 2007.

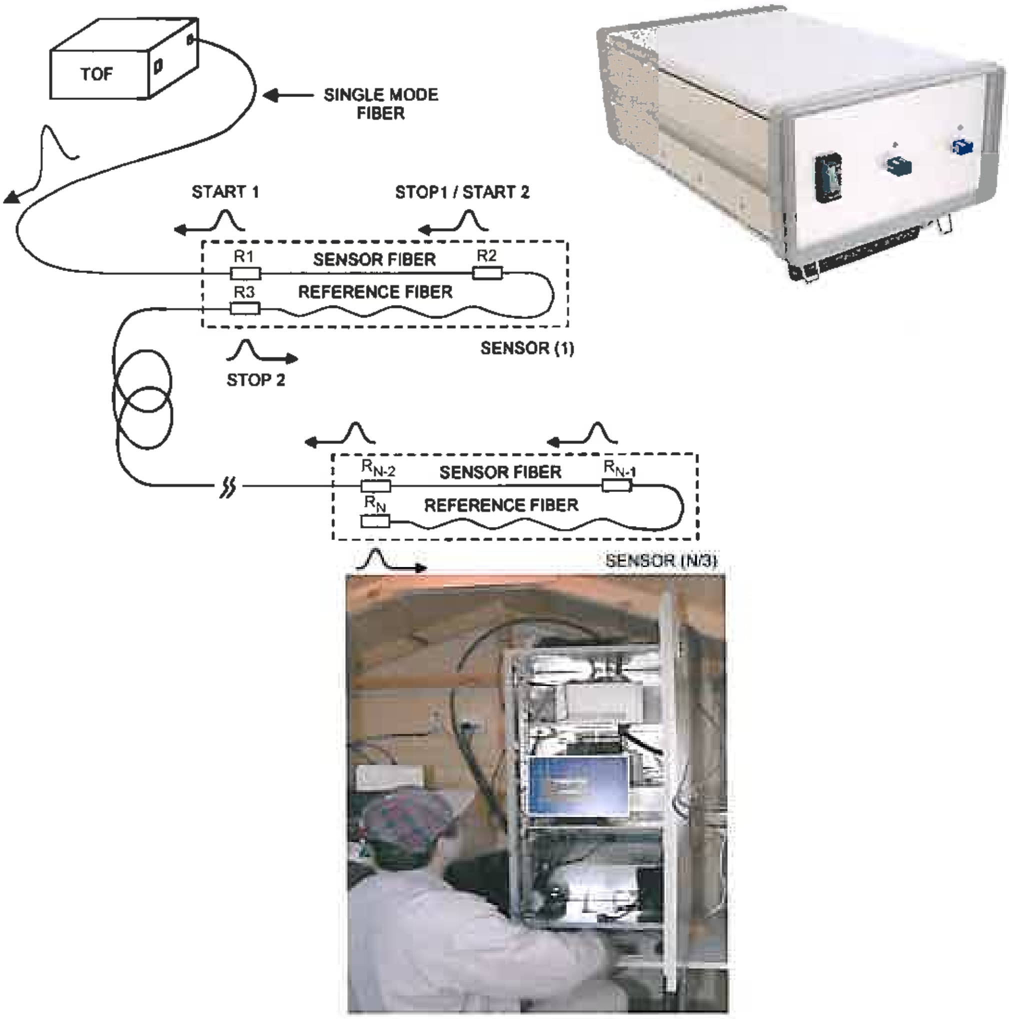


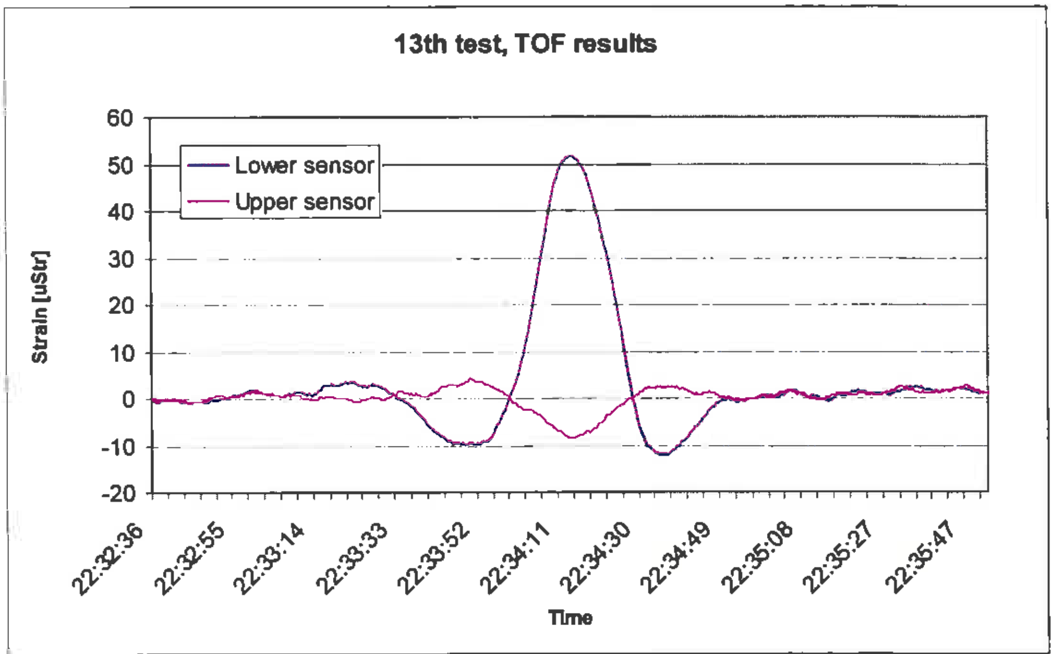
Figure 7.1.2. TOF Measurement principle and photographs of TOF interrogation device and Siikajoki field observatory.

Both calculations revealed considerable differences with observed elongations of the sensors. Furthermore, the study continued the calculations and made an assumption that there will grow slib surfaces on the deck under loading. EPM calculations match the measured elongation results in this case. The compression of upper slab was -71 µS. The assumption was that the bridge was in good condition. As to the worse condition of the bridge calculated compression value -5.8 µS was a minimum. The deviation range between -71µS - -5.8 µS reflects the condition rate of the bridge deck. VTT`s length gauges on the lower side of the bridge slab confirmed the results of the EPM calculation functions.

This will conduct to two deductions. Upper sensor fixings may have been loosed. The second explanations will argue that an existence of slib surfaces formation on the upper slab of the bridge will be a real phenomenon. This explains small compression of the sensor due to vertical dislocations that replaces the horizontal compressions. EPM analysis takes into consideration the length variation in the deflection curve. The observations of the lower sensor matched better calculated results using both calculation methods. Difference of FE method results and measured elongations differed +48%. EPM gave the same result as measured values of the sensor.

FE-calculations were made without the angel bevel lings of the concrete chambers. This assumption may have some affect to the results. Space model of the bridge might be worth applying in FEM-calculations. The calculated elongations on lower Slab matched with fair accuracy with measured results. A Difference was +48%. The calculated compressions on the upper slab were much more than measured results. The difference was -228%. The symmetric profile of the lower and upper parts of the bridge may prove that the compression and tension sides are equal. This assumption is fulfilled in FE model.

In FE model the Modulus of Elasticity was taken as a constant value in whole structure that can produce the largest errors in calculations. Cracks were observed in the bridge. The Modulus of Elasticity for cracked concrete is about 30% of uncracked concrete. In FE calculations trials were done with different values of the Modulus of Elasticity considering strains in the lower deck. Ratios were linear. When the Modulus of Elasticity was 17 000 MPa the lower TOF-sensor gave 51 μS.



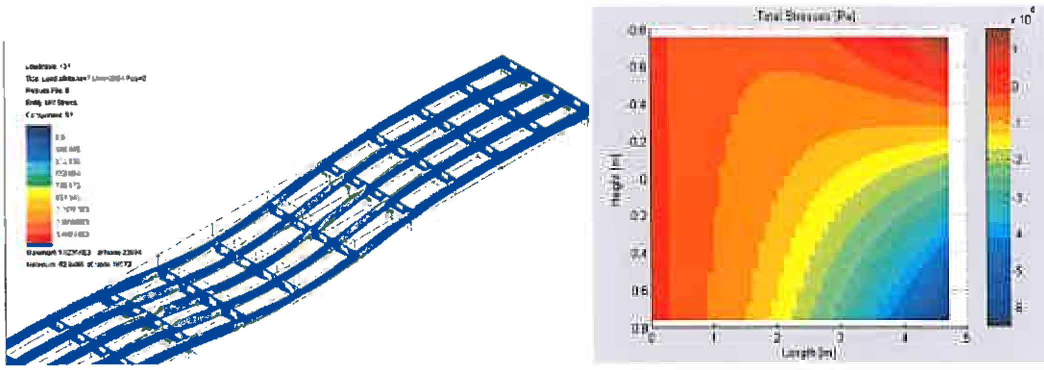


Figure 7.1.3. Upper TOF Sensor reached 51 μStrain elongations and lower sensor compressed 9 μStrain. Lower pictures illustrates deformations, compressions and stresses in calculation models (FEM-model, left. Kivelä 2008 and EPM-model, right. Kinnunen 2006, 2007).

Smaller errors can be found due to section geometries. All changes in the profile were not taken into account. EPM model gave somehow similar results. With the aid of dynamical loading and the sensor of the lower deck the zero points for moment were verified. Those points can also be found via calculations without the calibration of the bridge. Comparison with the results of VTT verified also the calibration. The Modulus of Elasticity was defined with special calibration method that need test loading and TOF measurements.

Challenges in the future are to estimate the need for transmission of support points to optimize stress-strain distribution using calculations from EPM. Simulation of repairs with composites (FRP) and post tension tendons can be analyzed and developed. In addition, monitoring of repair functionality is an important task. New bridges could be manufactured with the reverse use of bending functions, producing innovative structures.

Table 7.1.1. Calculations and measurements of Siikajoki bridge loading test using TOF sensors. Load 192.4 t (LC 101). 4.10.2007.

TOF Sensor	(1) Measured elongation µS	(2) Measured vertical dislocation, tachaemeter accuracy 0.1 mm mm	(3.1) Calculation elongation FEM µS	(3.2) Calculation elongation EPM µS	(3.3) Calculated EPM (Slib surface assumption) µS	(4) Comparisons (4.1) = [(1) - (3.1)]/(1) %	(4.2) = [(1) - (3.2)]/(1) %	(4.3) = [(1) - (3.3)]/(1) %
TOFv	-9		-29.5	-71	-5.8	-228	-689	36
TOFa	51		26.6	51	51	48	0	0
Vertical dislocations								
Vertical dislocation on center point of the slab, middle on the TOF sensor (mm)		-3.69	-3.89	-2.5				

References

1. Kinnunen, J. (2006). *Exact Parametric Differential Equations of Plane Section Rotations for Beams with Small and Large Deformations*. Luleå. Luleå University of Technology. Department of Civil and Environmental Engineering. Division of Structural Engineering. 2006:022 CIV-ISSN 1402-1617. 19 p. + app. 29 p.

2. Lyöri V., Kilpelä A., Duan, G., Kostamovaara, J. & Aho T. (2006): *Monitoring of a bridge-deck using long-gage optical fiber sensors with a pulsed TOF measurement technique*. In: Cruz P., Fragopol D., & Neves (ed). IABMAS. Bridge Maintenace, Safety, Management, Life-Cycle Performance and Cost. Porto 16 -19 July. 2006. pp. 905 - 906. London, Leiden & New York, Philadelphia, Singapore. Taylor & Francis 905.906. ISBN 10 (Book+CD - ROM): 0415403154.

3. Aho,T.,Kinnunen, J., Lyöri, V., Kilpelä, A., Duan G. & Kostamovaara J. 2007. A new time of flight sensor for measuring strain in large structures. IN: Bien, J., Elfgren, L. & Olofsson, J. (ed). Sustainable Bridges. EU Sixth Framework Programme. Wroclaw. Dolnoslaskie Wydawnictwo Edukakyjne. ISBN 978-83-7125-161-0. p.181-190. 490 p. (Book + CD - ROM): ISBN 978-83-7125-162-7.

4. Timo Aho, Timo Kivelä, Jukka Kinnunen, Kai Öörni, Veijo Lyöri, Ari Kilpelä & Duan Guoyong Siikajoen siltamonitorointi II. Tiehallinto. Työraportti. 25.2.2008. 55 s.

7.2 Corrosion measurements

Savcor has used anode-ladder sensor systems to monitor the corrosion risk of the reinforcement of new concrete structures. The anode-ladder system is installed during casting of concrete.

Similar system is also needed for existing structures. The corrosion measurements at Siikajoki bridge were performed to evaluate one such system, namely the Expansion Ring system (named ER from now on). The electrodes are installed into drilled holes of an existing structure. The measurement electrode consists of 6 measurement rings and a cathode bar. Both electrodes are installed into holes drilled into the concrete and fixed by special expansion mechanisms.

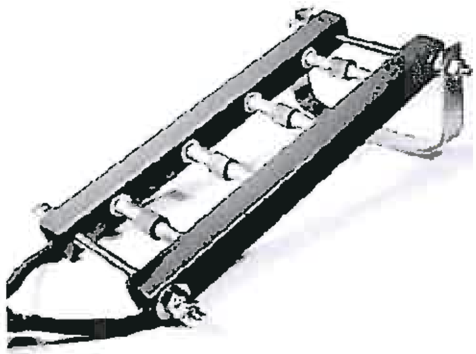



Figure 7.2.1. Anode-ladder probe (left), ER anode (right, bigger) and cathode bar (right, smaller).

Both anode-ladder and ER electrode measure the onset of corrosion at different depths related to the concrete surface. The measuring electrodes are made of steel with a similar composition as the reinforcing steel.

The aim of the corrosion measurements at Siikajoki bridge was to evaluate a new type of corrosion rate sensor (ER system) as well as to evaluate the current corrosion condition of the bridge.

7.2.1 Corrosion monitoring system at Siikajoki bridge

The corrosion monitoring system at Siikajoki bridge consists of two LPR electrodes (at two locations), and one ER system with ERE-20 reference electrode. The half cell potentials were measured from each ER anode ring (at six different depths) against ERE-20 reference electrode. Additionally, non-destructive surface measurements (corrosion rate with galvanostatic pulse method, potential mapping with surface ERE-20 reference electrode) were performed.

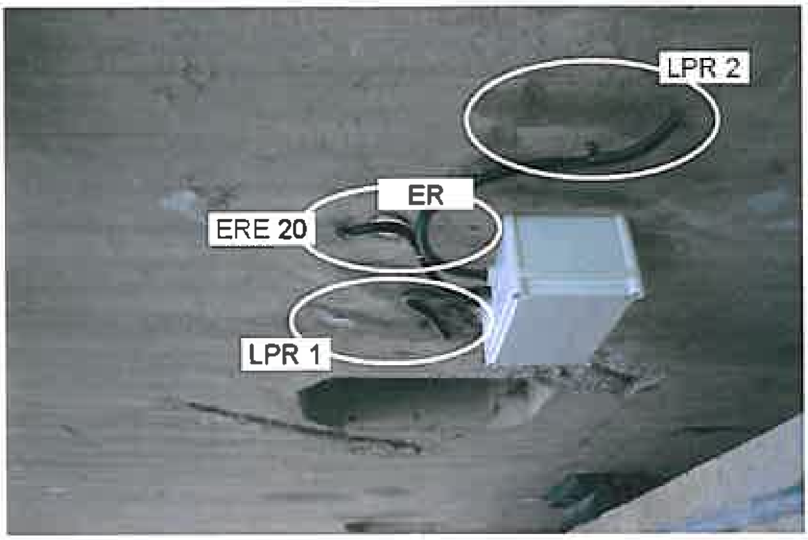


Figure 7.2.2. Corrosion monitoring system at Siikajoki bridge.

7.2.2 Potential mapping

The schematic presentation of the measurement locations (light blue squares) is shown below. One location (the upper-right corner in the figure 7.2.3) was not measured due to reinforcement being visible. The grid spacing was 20 cm. The ER system with ERE-20 reference electrode was installed in the middle and the LPR probes at different sides of the measurement area.

The half cell potential mapping was performed by measuring the reinforcement potential (contact at LPR 1 and LPR 2 locations) against an ERE-20 reference electrode, placed on the surface of the concrete at each measurement location.

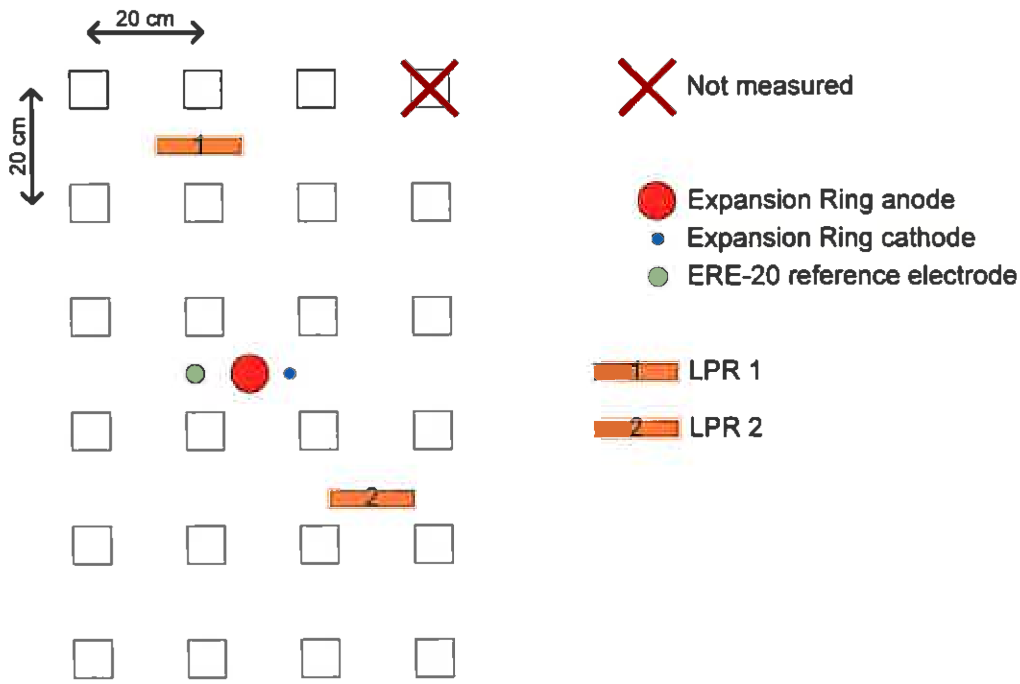


Figure 7.2.3. Schematic presentation of the measurement locations.

Table 7.2.1 shows the ASTM C876-91 standard for corrosion of steel in concrete.

Table 7.2.1. ASTM C876-91 guidelines for evaluation of half cell potentials on concrete structures.

$Cu/CuSO_4$ (mV)	Corrosion condition
≥ -200	Low (10% risk)
-200 ... -350	Intermediate
≤ -350	High (< 90% risk)
≤ -500	Severe condition

The reinforcement potential against ERE-20 reference electrode was measured. Table 7.2.2 and 7.2.3 show the potential mapping results. The reinforcement contact was taken both from LPR 1 and LPR 2 locations.

Table 7.2.2. Reinforcement potential to $Cu/CuSo_4$ (LPR 1) (mV).

-188	-219	-181	-
-180	-190	-160	-128
-143	-137	-87	-57
-129	-146	-91	-104
-31	-51	-27	-24
-30	-29	-29	-36

Table 7.2.3. Reinforcement potential to $Cu/CuSo_4$ (LPR 2) (mV).

-155	-183	-146	-
-152	-156	-124	-94
-101	-99	-51	-27
-104	-114	-60	-78
-7	-19	-3	10
-5	-11	-8	-9

Comparing the results to the ASTM C876-91 standard the corrosion condition of the Siikajoki bridge at measurement locations is estimated as low. That is, there is less than 10% risk of corrosion at the reinforcement.

7.2.3 Corrosion rate measurements

Corrosion rate measurements were performed by using GalvaPulse equipment with handheld electrode (surface measurement), which uses the galvanostatic pulse method. The following guidelines (table 7.2.4) are used when evaluating the corrosion rates.

Table 7.2.4. Evaluating the corrosion rates according to FORCE Technology.

Corrosion rate ($\mu A/cm^2$)	Corrosion condition
< 0.5	Negligible
0.5 - 5	Slow
5 - 15	Moderate
> 15	High

Table 7.2.5 shows the corrosion rates of the measurement locations, measured with the GalvaPulse unit.

Table 7.2.5. Corrosion rates at measurement locations (µA/cm²).

0.298	0.303	0.186	-
0.408	0.368	0.435	0.279
0.401	0.492	0.264	0.216
0.367	0.437	0.662	0.438
0.318	0.330	0.315	0.282
0.272	0.160	0.274	0.269

Comparing the corrosion rates to the evaluation table (table 7.2.5) we can estimate that the present corrosion status of the reinforcement is negligible. This corresponds very well to the potential mapping measurements.

7.2.4 Evaluating the Expansion Ring system

The ER system was installed into the bottom of the bridge deck by drilling a 56 mm hole into the concrete and inserting the anode into the cleaned and moist hole. The tightening of the anode was performed according to the manufacturer instructions. The cathode bar was also installed into a 16 mm hole. The ERE-20 reference electrode was also installed into a drilled hole with diameter of 25 mm.

Table 7.2.6 shows the results of half cell potentials of the ER ring electrodes vs. ERE-20 reference electrode. The rings 2 - 5 did not give reliable results due to poor contact to concrete, so they are omitted.

Table 7.2.6. Half cell potentials of ER anode rings vs. ERE-20 reference electrode.

Ring	E vs. ERE-20 (mV)
1	-227
2	-
3	-
4	-
5	-
6	-116

The measurements showed that only the top and the bottom electrode rings were in good enough contact to concrete, while the four middle electrodes were not. This presents the problem that reliable readings can be obtained from only the top and bottom electrode rings.

These measurements also showed that the corrosion condition of the reinforcement is low.

The ER system failed to give reliable results for all depths. The reason for this is poor contact of the ring anodes to the concrete wall of the drilled hole. The reason for this is one (or combination) of the following

1. Inaccurate hole for ER anode
2. Impurities in the hole before ER anode installation
3. Poor expansion of the ER anode rings.

The ER anode requires a very exact hole to be drilled into the concrete. The diameter of the hole must be 56.0 - 56.5 mm and the hole must be very straight. The drill machine used in the installation was Weka DK-12 drilling machine, which was bolted into the concrete to ensure an exact hole. The impurities were cleaned from the hole prior to the anode installation.

The expansion mechanism of the ER anode is too complicated and unreliable and can therefore produce extra problems in the installation. Due to this uncertainty/unreliability of the ER system a corresponding system is being evaluated by Savcor. This system (CorroRisk by FORCE) consists of e.g. 4 carbon steel electrodes with a known surface area. Otherwise the measurement system is quite similar to that of the ER system.

The CorroRisk system is being evaluated by Savcor at the moment.

7.2.5 Conclusions

The life span analysis of existing concrete structures requires reliable corrosion status analysis of the reinforcement. Normally a healthy concrete reinforcement is passivated and no corrosion takes place. When the passivation layer is destroyed - due to carbonation or ingress of chlorides - corrosion is initiated. Detecting this change is possible by performing various measurements on the concrete structure. These measurements include half cell potential mapping and corrosion rate measurements using galvanostatic pulse method. The half cell potential mapping is performed as initial measurements to locate the most active areas. The potential mapping method is a rapid and easy process that quickly gives a general overview of the corrosion condition of the system. The corrosion rate measurements should be performed on the most active areas that potential mapping measurements indicate. The corrosion rate measurements should be performed on various depths above the reinforcement. This way the progress of the "corrosion front" into the concrete can be monitored in real time.

The goal of the corrosion monitoring project at Siikajoki bridge was to evaluate one corrosion rate sensor that is capable of measuring the corrosion rate at six different depths above reinforcement. The Expansion Ring system is embedded into the concrete by drilling an exact hole and expanding the measuring electrode system so that the connection to the surrounding concrete wall is established. The measuring electrode consists of six different measuring electrodes 1 cm apart from each other. The goal of the measurements were to evaluate the reliability of the corrosion rate measurements using the Expansion Ring system against corrosion rate measurements performed by GalvaPulse unit using its external, surface measuring electrode. The GalvaPulse unit uses state-of-the-art galvanostatic pulse method when measuring and calculating the corrosion rate of the reinforcement.

Additionally, standard half cell potential mapping measurements were performed to evaluate the corrosion risk of the reinforced concrete of the Siikajoki bridge. The potential mapping was performed by measuring reinforcement half cell potentials of two locations against an ERE-20 reference electrode placed on the concrete surface. This is a supportive measurement method that gives a general overview of the corrosion status of a concrete structure - easily and quickly.

Reinforcement half cell potentials were measured on two locations against an ERE-20 reference electrode placed on the concrete surface. The values were compared to the ASTM C 876-91 standard test method for half-cell potentials of uncoated reinforcing steel in concrete. The measured values were above -200 mV of all measurement spots (with exception of one spot), which indicates that the corrosion risk of the measured area is low. According to the corrosion mapping, the present corrosion risk of the bridge deck low.

The corrosion rate measurements were performed by using the GalvaPulse device with both embedded Expansion Ring electrode as well as handheld electrode (surface measurement). However, the Expansion Ring electrode did not have good contact to the concrete thus giving unreliable results. In fact, only top and bottom electrodes gave realistic values whereas the four middle electrodes did not give real values at all. The corrosion rate measurements were performed with the GalvaPulse unit using its handheld electrode. The corrosion rate threshold values were given by the manufacturer of the GalvaPulse unit. These threshold values were used when evaluating the present corrosion condition of the bridge deck. All measurement spots (with exception of one location) gave negligible corrosion rate readings. This indicates that the corrosion condition of the bridge deck is good. There are no corroding areas at the measured area.

The corrosion mapping measurements correspond well with the corrosion rate measurement. This indicates that the bridge deck is at good condition and there are no corrosive active areas at the measured location.

One goal of the project was to evaluate the use of the Expansion Ring system in corrosion rate measurements in existing concrete structures. Since the corrosion rate measurement is essential for the life span analysis of concrete structures, a reliable and foolproof system for corrosion rate measurements at different depths is required, the Expansion Ring system failed these requirements. There are too many wild cards in the installation of the ER system. The drilled hole must be VERY EXACT in dimensions and clean from dust and other particles in order to create a good and reliable contact with the concrete. The fixing mechanism to the concrete (= expanding the electrode) is not reliable and it can worsen the contact to the concrete. It is difficult to evaluate the size of the hole and the fixing procedure so that the user could be absolutely sure about the functionality of the system. Therefore the Expansion Ring system cannot be recommended as the multi-depth corrosion rate sensor for existing concrete structures.

The multi-depth corrosion sensor is essential for the corrosion condition survey for existing structures. Therefore a new type of corrosion rate sensor has been sought out. The new multi-depth corrosion sensor has been found to replace the Expansion Ring system (FORCE Technology, CorroRisk sensors). At the moment they are being evaluated by Savcor.

8 Wooden bridge measurements (Vihantasalmi Bridge)

8.1 Background

The Vihantasalmi Bridge is situated on the Main Road number 5 in Mäntyharju, approximately 180 km north from Helsinki. The spans of the bridge are 21 + 3 x 42 + 21 = 168 m in total. The effective 14 m width of the bridge consists of a two-lane carriageway and one 3 m wide lane for pedestrians. The load-carrying system of the bridge is unique. It consists of kingpost trusses in the three main spans and simple supported beams in the two side spans, all made of glued-laminated timber. In all spans the timber beams are connected to the concrete deck slab by special connectors forming a composite superstructure. The bridge was taken into service in September1999 (Fig.8.1.1).

Figure 8.1.1. The Vihantasalmi Bridge.

The strength and stiffness properties of the composite structure, used in beam members, were tested under static and dynamic laboratory tests already at the design phase /1, 2/. Also for long-term tests were prepared by storing two composite beams outside without shelter for several years.

8.2 Continuous monitoring

A pilot project for continuous remote monitoring of the Vihantasalmi Bridge was started in 2002.

The bridge was instrumented by several types of sensors measuring,
- humidity and temperature variations in glulam beams,
- humidity and temperature variations of ambient air,
- longitudinal displacement variations of the girder at one (movable) end,
- strain variations (swelling) in transversal direction of glulam,
- slip between wooden beams and concrete slab and
- relative displacement between wood and steel parts in a connection.

The principle of the instrumentation and data transfer are shown in Figs 8.2.1 and 8.2.2. Detailed description of the instrumentation and equipments can be found in report /3/.

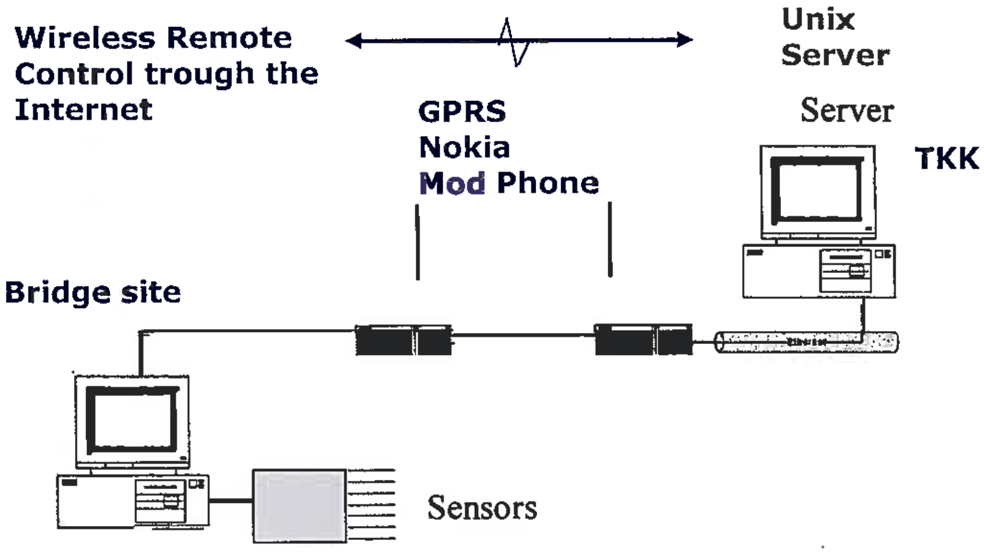


Figure 8.2.1. The principle of data acquisition and transfer.

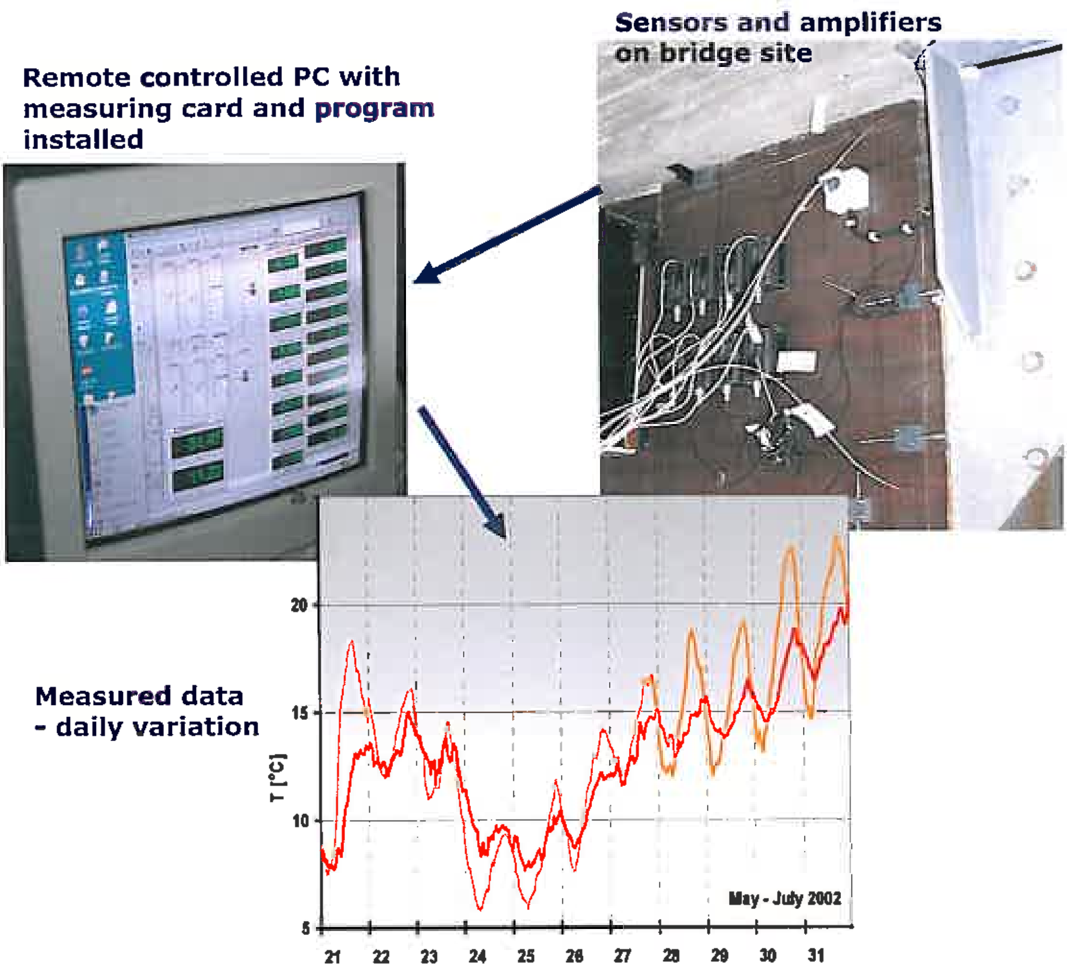


Figure 8.2.2. The principle of continuous data measurement in 2002.

The moisture content at the ends of glulam girders was noted to be quite high according the measurements during the year 2002. The relative humidity of the air, measured from a hole bored in glulam beam near the beam end, was observed to be even as high as 100 RH %, which corresponds saturated absolute moisture content (28 - 30%) of wood. This was the reason why it was decided to repeat the temperature and humidity measurements in 2005.

8.3 Temperature and humidity measurements of wood

The measurements by using long-term continuous monitoring were mostly done during the time period 18.6. - 31.12.2005.

8.3.1 Location of the measuring points

Temperature and humidity measurements were made using the same arrangement as was done in 2002. The girder and the locations, in which the measurements were recorded, are shown in detail in report /3/. Four sensors were used to measure temperature and humidity in wood and one girder end. Four of the sensors measured variation of temperature and humidity in wood and one in ambient air, respectively. The longitudinal location of the sensors at the end of selected girder is shown in Fig.8.3.1.

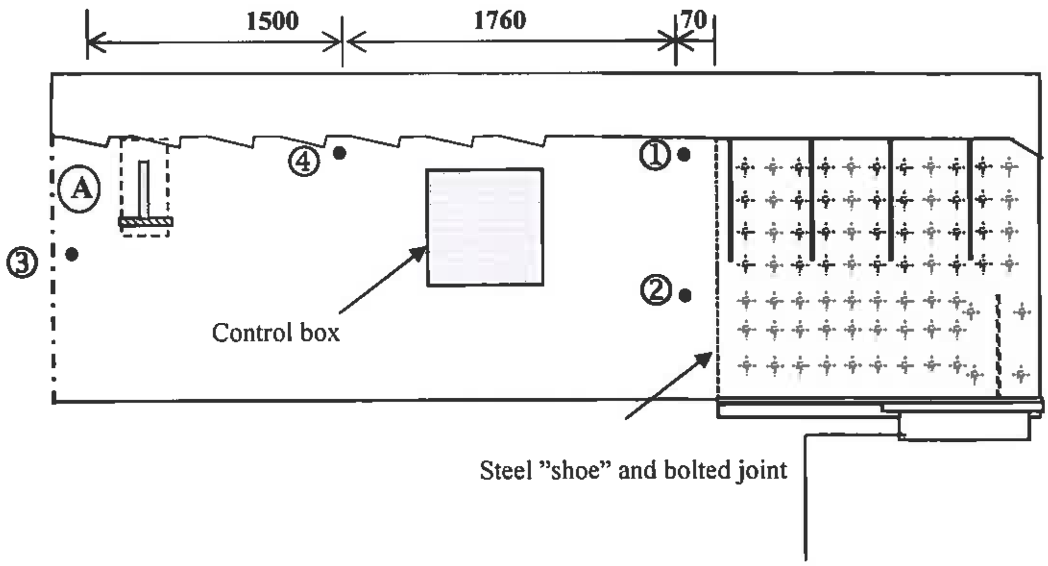


Figure 8.3.1. Longitudinal location of the sensors at the end of the examined girder.

The sensors were installed into holes, bored horizontally in girder, to measure the tempeature and humidity in the middle of the glulam web of the girder. Respective air quantities were measured using a separate sensor, fastened on outer surface of the beam. The location of the five sensors is shown in fig. 8.3.2.

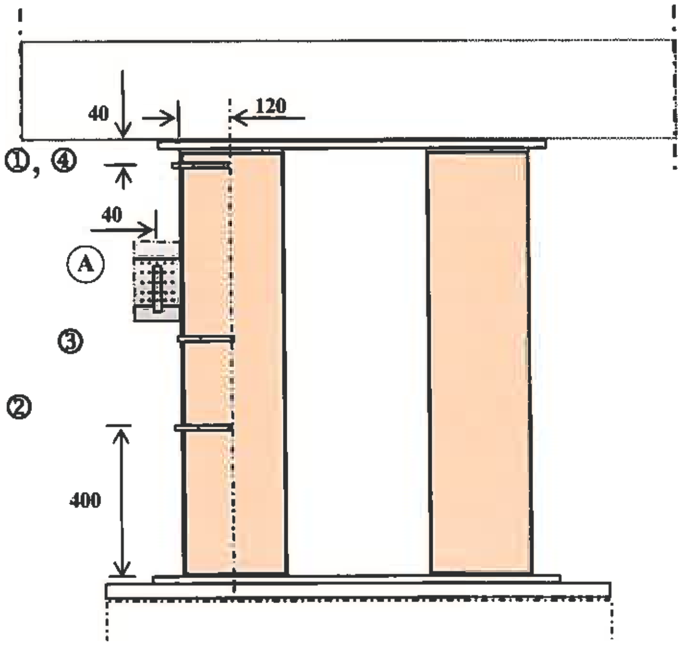


Figure 8.3.2. Transversal location of the sensors near the end of the examined girder.

8.3.2 Measured temperature variation

In figure 8.3.3 are shown the measured temperature variations of glulam wood and ambient air between time periods 18.6. - 30.10.2005.

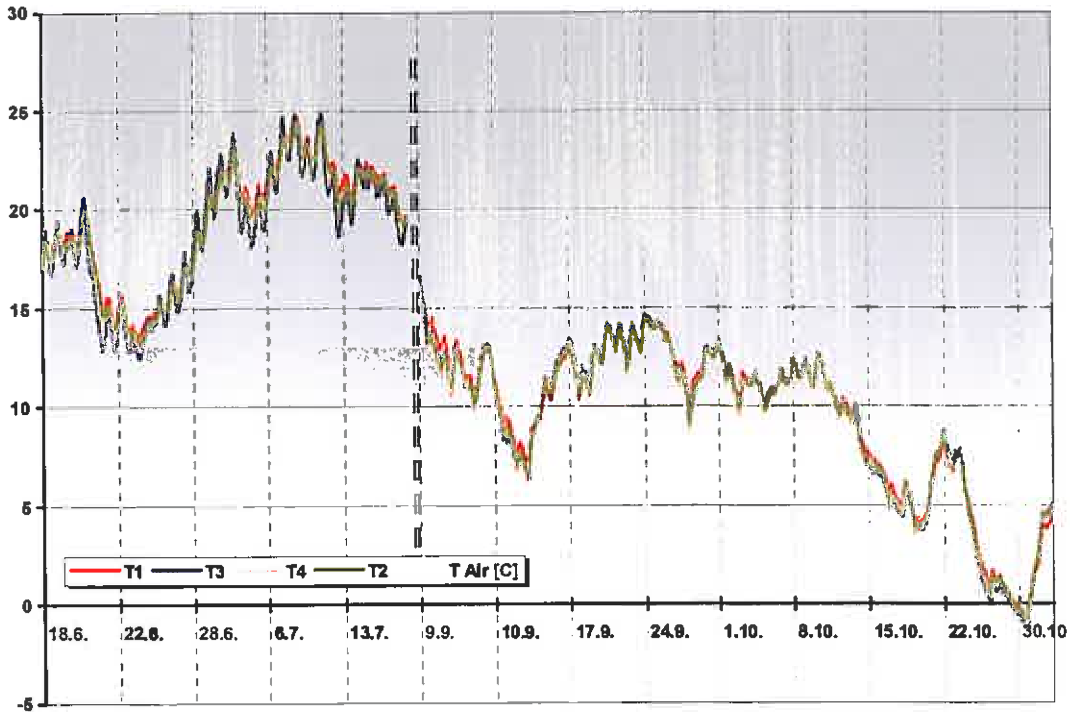


Figure 8.3.3. Temperature variations in wood and air (yellow dashed line) in 2005.

It can be seen that the temperature of wood during this period varied between +25 °C and -1 °C. There was not much difference between the recorded values of four measuring points in wood. The temperature of glulam beams followed smoothly the daily variation of the lowest air temperature, which varied strongly during the test period between limits +30 °C and -2 °C.

In Fig. 8.3.4 is shown the mean temperatures of wood and air of two10 day's period in 2005. The daily variation of wood temperature follows air temperature in summer, but in autumn, the daily variation of wood temperature is not very clear.

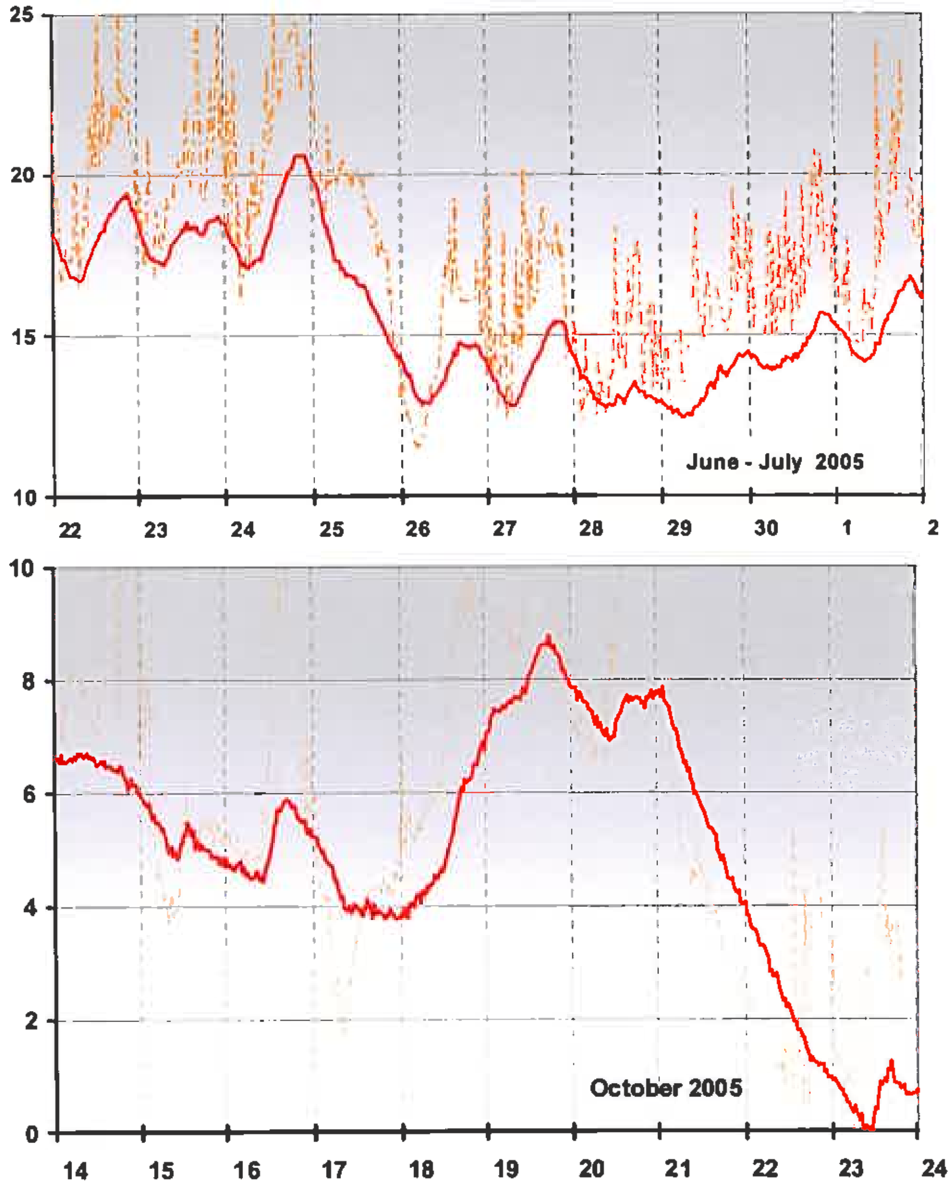


Figure 8.3.4. Measured temperature variation of wood and air during ten days period in spring and autumn 2005.

8.3.3 Measured humidity variation

Measured humidity variations during time period 18.6. - 30.10.2005 are presented in Fig. 8.3.5.

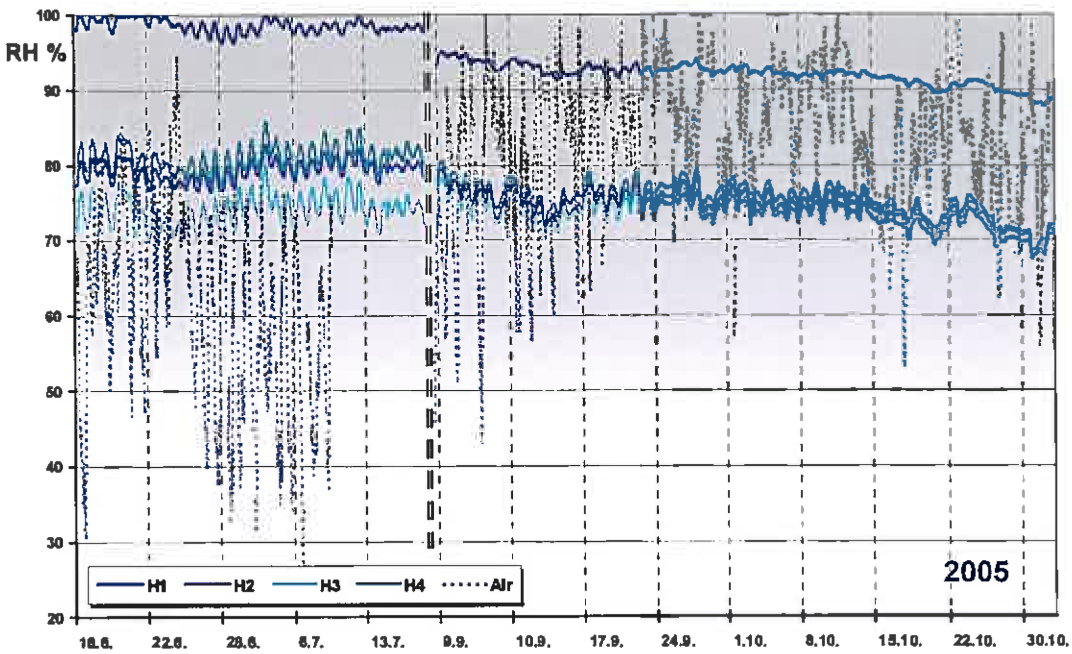


Figure 8.3.5. Measured humidity variations (RH %) in wood of (sensors 1 - 4) and air in 2005.

Measured relative humidity of the air varied strongly during measuring period. Instead, the variation of humidity was not remarkable in individual measuring points. As was already noticed from the results obtained in 2002 the measured RH % values were lowered gradually during autumn period and were reduced 5 - 10% from the values of summer period. As in 2002 in measuring point ① very high humidity values were measured. Sometimes as high as 100% RH values in the summer but at the end of October the maximum values were reduced to level 90% RH. This corresponds approximately 20 - 21% absolute moisture content of wood.

In measuring points ② to ④ the humidity varied between 70 - 80 RH %. This was also the case in 2002. The humidity corresponds 17 - 18% absolute moisture content of wood and can be considered normal in impregnated wooden material in a girder over open water surface of a lake.

In Fig. 8.3.6 is shown the measured relative humidity variations of wood and air during two10 day's period in 2005. The daily variation of wood temperature follows air temperature in spring, but in autumn, the daily variation of wood temperature is not very clearly seen.

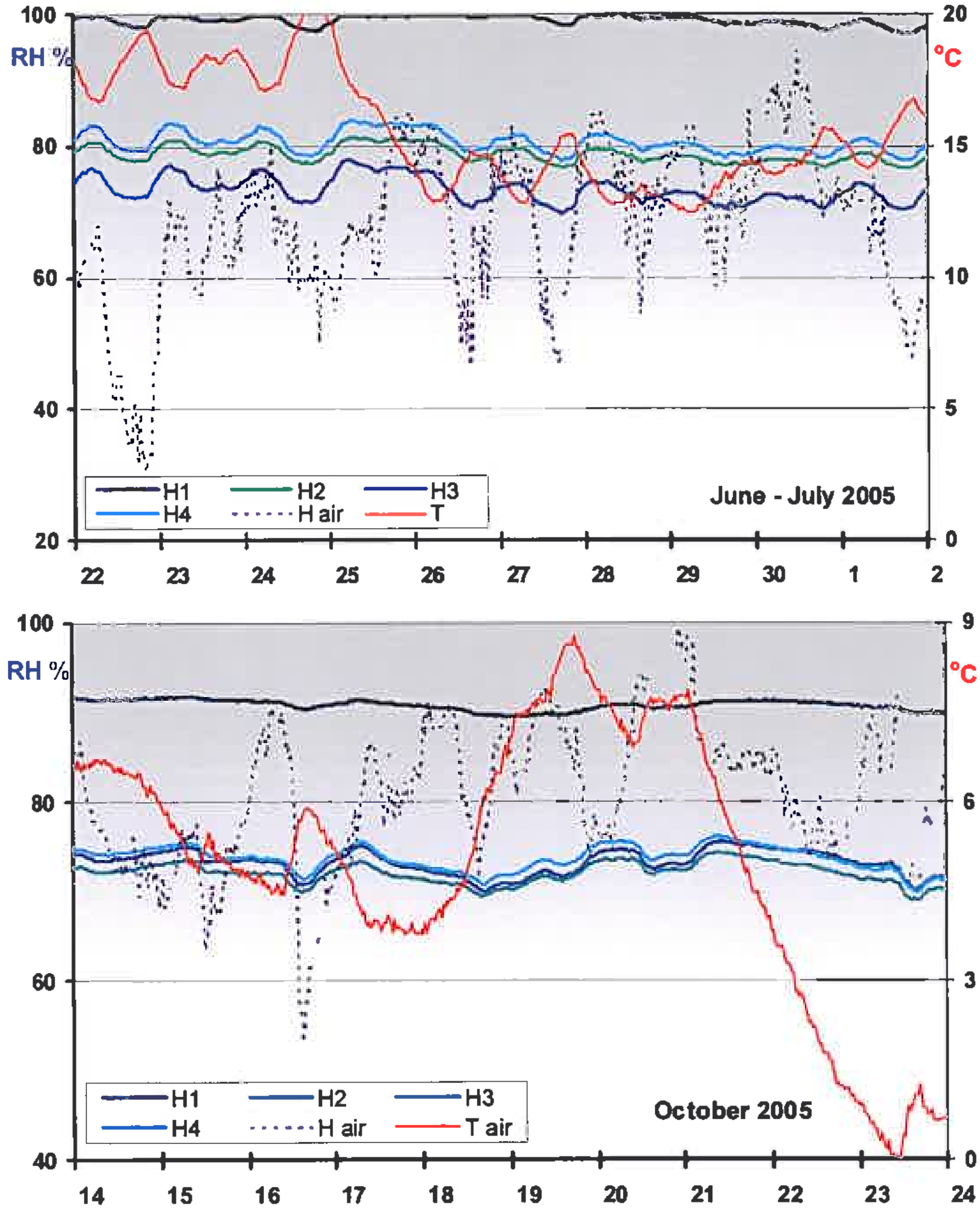


Figure 8.3.6. Measured humidity and temperature variation of wood and humidity and temperature variations (red line) of ambient air during two 10-day's periods, one in spring and the other in autumn 2005.

The daily variation in humidity of the beam was minor degree and in summer period it was approximately 5% at maximum. The humidity values were approximately 10% lower during autumn compared the values obtained in spring.

8.4 Conclusions

The measurements show the long-term variation in temperature and humidity in wooden web of the examined girder. Daily variations of the two quantities can be seen in spring, but in autumn daily variations are of minor degree. High values in humidity were obtained at measuring point ①, which located at the upper part of the end of the glulam girder (Figs 8.3.1 8.3.2). This was also noted in the measurements in the year 2002. High values were also verified by measuring the moisture content with electrical moisture measuring device.

The temperature of the ambient air effected to the values of humidity. In autumn, when the outside temperature sank near to zero (centigrade), the humidity values lowered approximately 10% RH.

The second long-term monitoring of the humidity showed, that the high measured values in moisture content of wood at the end of the glulam beam is permanent phenomena. One reason for the high values at the end of the girder might be the leaking expansion joint at the end of the span. The structure of the joint is probably another reason. The steel joint enclosing the end of the wooden girder forms closed structure from which the water content of wood cannot freely evaporate.

References

1. *J. Tommola, L.* Salokangas, A, Jutila., Tests on Shear Connectors. Nordic Timber Bridge Project. Nordic Wood. Nordic Timber Council. Stockholm 1999.

2. Jutila, A., Salokangas, L., Research on and Development of Wooden Bridges in Finland. Structural Engineering International (SEI) Vol 10, 3/2000.

3. Salokangas L., Jutila A., Vihantasalmen sillan seurantatutkimus. TKK-SRT-32. Feb. 2003. 40 p.

9 Integral abutment bridge measurements (Haavistonjoki)

The Institute of Earth and Foundation Structures at Tampere University of Technology (TUT), has been involved in the implementation of a number of applications related to traffic infrastructure monitoring technologies. In the following is an example of them, monitoring of bridge structure-soil interaction.

9.1 Overview

Instrumentation of the Haavistonjoki Bridge (implemented by TUT in 2003) in the Town of Orivesi, about 50 km north-east of Tampere on Highway 9 leading to Jyväskylä, may serve as an example of a monitoring site where the main emphasis was soil-structure interaction (SSI) and thermal behaviour of bridge superstructure. The 50 m instrumented concrete slab bridge is by type an integral abutment bridge founded on large diameter steel pipe piles (Fig. 9.1.1).

Figure 9.1.1. Instrumentation of the integral abutment bridge on Highway 9 in 2003.

The bridge instrumentation of the measurement site summarised in Table 9.1.1 was rather comprehensive. As can be observed on the basis of Figure 9.1.1 and the number of measurement sensors indicated in Table 9.1.1, the site was used specifically to study the mobilisation of earth pressures against the integral abutment bridge end screens due to thermal movements of the bridge as well as the resulting stresses on the bridge structure itself. The results of the research project have been reported in more detail by Laaksonen and Laaksonen & Kerokoski /1, 2, 3, 4/.

Table 9.1.1. Summary of measurement sensors installed and measurements made at the Haavistonjoki Bridge site.

Sensor type	Measurement quantity	Installed amount
Pressure cell	Earth pressure against bridge structure	14
Displacement gages	Displacement between approach embankment and bridge structure	18 (manual) 4 (automatic)
Laser	Bridge length	1
Temperature probe	Temperature of bridge structure, approach embankment and air	61
Strain gage	Strains in steel piles and bridge superstructure	56 *)
Manual tachymeter measurements	Displacements of the bridge and approach embankment slopes, settlement of road surface	41 locations

*) Did not work properly on long term.

Temperatures were measured from both embankments and from concrete superstructure. The places of temperature gauges at concrete bridge deck are presented in Fig 9.1.2. Temperature gauges are installed to the bridge cross section based on the approximated temperature distribution in the cross section. In total 16 temperature gauges were installed at the top, centre and bottom of the deck slab.

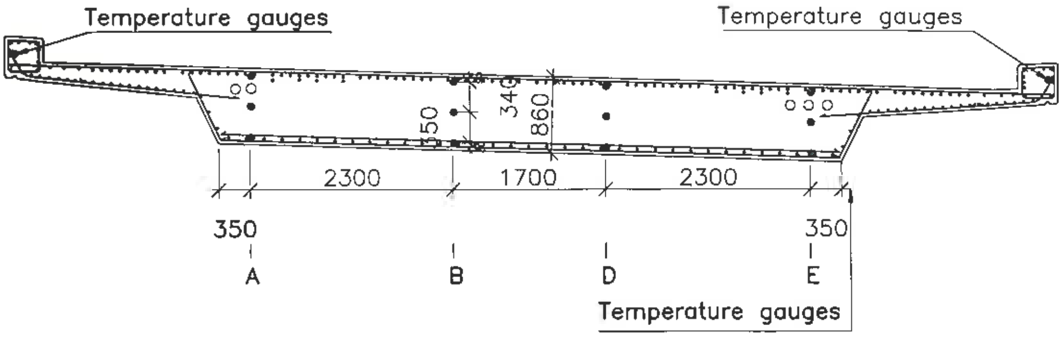


Figure 9.1.2. Temperature gauges at bridge deck [1].

One of most important reasons for monitoring Haavistonjoki Bridge was to study the cyclic displacements of the whole bridge and the longitudinal changes in bridge length. Abutment displacements and rotations were observed by installing ten long steel bars at three levels through the eastern abutment and at two levels through the western abutment /1/. These bars were anchored to the embankment, see Fig. 9.1.1 left and right bottom corners of end screen.

9.2 Results

9.2.1 Earth pressures

Figure 9.2.1 shows a 3D view of the displacements of the eastern abutment (T4) of the bridge and earth pressures induced against the eastern end screen at a depth of 1.65 meters below the road surface during the time period 10.10.2003 - 10.10.2005. Without delving any deeper into the measurement results here, one can easily determine based on the measurement results of Figure 9.2.1, for instance, the cyclic daily fluctuations in earth pressure and the occurrence of distinct earth pressure peaks at fairly small bridge displacements in early spring while the approach embankment against the end of the bridge is still frozen. Consequently, the maximum earth pressure may not necessarily occur at the time of maximum displacement. Meantime, in coldest winter, contact between end screen of the bridge and embankment has become practically non-existent which is indicated by the fall of measured earth pressures to almost zero.

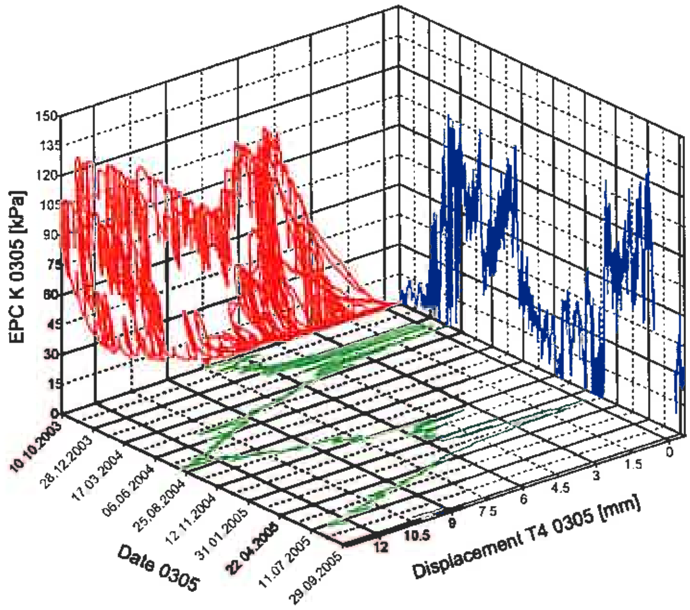


Figure 9.2.1. Displacements at eastern end screen of Haavistonjoki Bridge and earth pressures acting on it from autumn 2003 to autumn 2005 [2].

These observation leads to a phenomenon where maximum earth pressure may not occur at time maximum displacements.

9.2.2 Displacements

The displacements due to thermal expansion at the opposite abutments varied remarkably. Eastern abutment (T4) displacements were much bigger compared to western abutment (T1) displacements. The abutment T1 was much stiffer than the abutment T4 and occasionally the expansion length of a 50 m long bridge was more than 35 meters, see Figure 9.2.2.

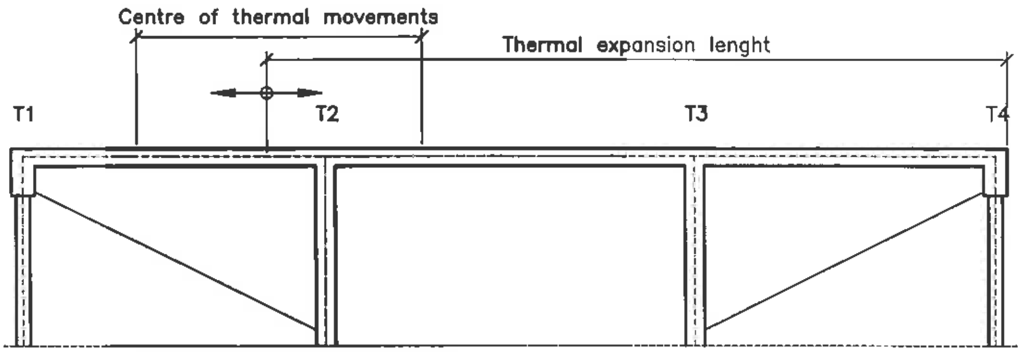


Figure 9.2.2. Variation of the centre of thermal expansion /2/.

9.2.3 Temperatures

The deck top and the edge beams follow air temperature more clearly than the other parts of the superstructure. The temperatures from a one-week summer period are presented in Fig. 9.2.3.

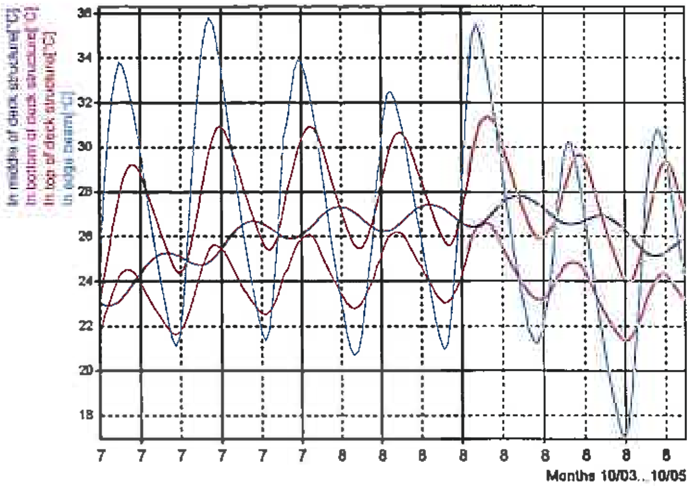


Figure 9.2.3. The bridge deck temperatures at the top, middle and bottom of the deck slab and at the edge beam during the one week period between June and July 2004 /4/.

In the middle of the deck, the temperature follows air temperature slowest. The difference between temperature changing rate at the top and at the bottom of the deck structure can be clearly seen. The bottom of the deck is colder at daytime than the top of the deck.

9.3 Discussion and Conclusions

The Haavistonjoki Bridge was extensively instrumented in the summer of 2003. Almost all the gauges were functioning correctly and the results of field test measurements were reliable and logical. The data of all the gauges can be collected simultaneously in every 15 minutes for several years and the long-term follow-up of the bridge behaviour will continue at least until year 2009.

Due to the non-linear behaviour of the soil close to integral or semi-integral bridge abutments, the thermal expansion is not at all symmetrical, which causes non-symmetrical displacements at the abutments. The location of the centre of thermal movement varies along the bridge length, see Fig. 9.2.2. The bridge temperature change causes abutment displacements. Temperature varies also in bridge cross section, see Fig. 9.2.3. The changes in the air temperature influence the bridge temperature diurnally after a little delay time and with minor amplitude. Soil-structure-interaction is strongly influenced by the earth pressure hysteresis. The meaning of quality in construction work is remarkable especially in earth construction, which was observed during the construction of the Haavistonjoki Bridge.

References

1. Laaksonen, A. (2004). Soil-structure interaction of jointless bridges. Instrumentation of Haavistonjoki Bridge. Master's thesis. Tampere University of Technology. 160 p. + app. 76 p. ISBN 952-15-1338-1. Internet 13.11.2008: http://alk.tiehallinto.fi/sillat/julkaisut/silta_ja_maa_yhteistoiminta.pdf **(In Finnish).**

2. Laaksonen, A. & Kerokoski, O. (2007) Long-term Monitoring of Haavistonjoki Bridge. IABSE Symposium, Weimar, Germany. Sept 19 - 21, 2007. 6 p.

3. Kerokoski, O. & Laaksonen, A. (2006). Monitoring of Haavistonjoki Bridge Abutment Performance. TRB 85th Annual Meeting, January 22-26, 2006, Washington DC, 19 p.

4. Laaksonen, A. (2006). Long-term Monitoring of Haavistonjoki Bridge, intermediate report from period between 10.10.2003-10.10.2005(In Finnish, unpublished on 27.2.2007).

10 Loading test and monitoring

10.1 Loading test methods

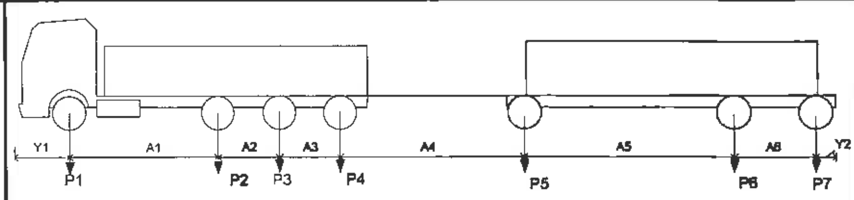
The bridge is quite complicated structure and therefore the sensors installed in the bridge are recommended to test and calibrate using loading tests. In many cases the behaviour of the bridge cannot be assumed elastic due to e.g. friction, joints, indefinite structure or concrete material properties. Usually the sensors are installed in the bridge after the bridge has been build and therefore the sensors (e.g. strain gages) are not capable to include the effect of the own weight.

In Finland most of the bridges are concrete bridges or at least the deck of bridge is made of concrete. That means the new and unloaded bridge is behaving elastic, but later on after the heavy loads have crossed the bridge, part of the concrete has been cracked due the tension stresses and the position of neutral axes has been changed. When the weights of the vehicles have been calculated using measuring results, the cracking of the concrete has to be taken into account.

In the *Figure 10.1.1* are shown the pictures of lorry used in the loading test of Kirjalansalmi. The amount of axels, the axle spacings and the axle weights of the lorry above is shown in *Figure 10.1.2*. The axle weights haven measured by axle weighing machine during loading tests.

Figure 10.1.1. The heavy lorries used in the loading test in Kirjalansalmi bridge in 2007.

Table 10.1.1. Axle spacings and axle weights of the loading lorry used in Kirjalansalmi.

Tractor 4 axles Trailer 3 axles								
Axle spacings [m]	Y1	A1	A2	A3	A4	A5	A6	Y2
		3.35	1.35	1.35	4.85	4.09	1.82	
Total spacing [m]	n.		16.81					
		P1	P2	P3	P4	P5	P6	P7
Axle loads [ton]		8.27	6.92	8.99	7.69	10.32	10.62	9.44
Total weight [ton]	62.25		Tractor		31.87	Trailer		30.38

Compared to design load of the bridge, the total weight of the lorries used in the tests is quite light and inelastic behaviour of the bridge has to be taken into account if the bridge loading capacity is estimated. It is not practical to increase the number of heavy vehicles to have a maximum axle or bogie load, because they cannot be placed near enough due to outer dimensions of the vehicles. Instead the carriage can be used to achieve more concentrated point load. In *Figure 10.1.2* is shown the tractor and carriage used in the loading test in Jylhänranta bridge. The total weight of the carriage and tractor is 140 tons or 170 tons depending of the weights on the platform. The maximum total weight of 170 tons could be used, if the vehicle was driven in the middle white line of the bridge.

Figure 10.1.2. The heavy lorry and carriage used in the loading test in Jylhänranta bridge in 2007.

When lorries are used during the loading tests the speed of the vehicle has been quite low as walking velocity. The vehicle has been stopped in the selected points on the bridge deck such as in the middle points of bridge spans. By stopping the vehicle the vibration of the bridge can be eliminated and also the deflection in concrete bridges has become stabile.

During normal traffics the velocities of the vehicles are varying and this should be included if the stresses of bridge is measured and used in analysis. Therefore it is recommended some of the loading tests are done using different crossing velocities. The measurements can also be used to define the impact factor for each velocities and vehicle types. In the *Figure 10.1.3* is shown the post vibration of the Jylhänranta bridge after dynamic loading tests. The vibrations are stronger when the speed of 80 km/h has been used.

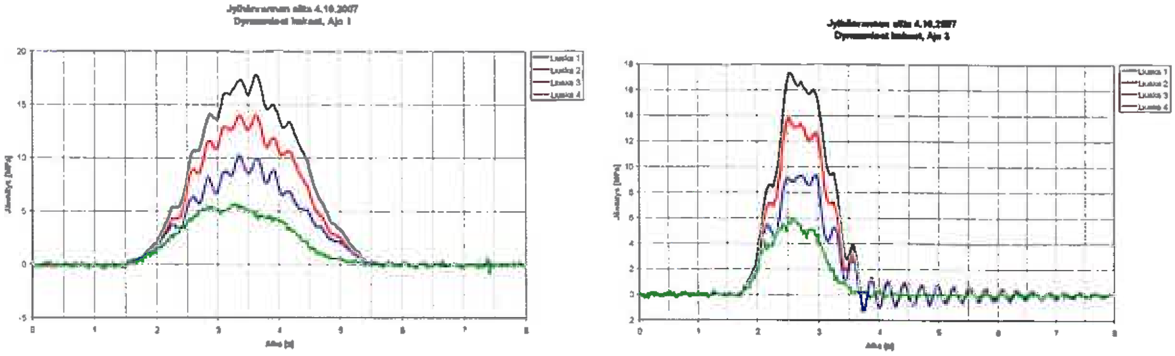


Figure 10.1.3. The stresses of steel plates clued on concrete beams in Jylhänranta bridge. The crossing speed has been 40 km/h (left) and 80 km/h (right).

The loading tests of the bridge will give valuable information of the behaviour of the bridge. When the exact weight of the vehicle is known the stresses of the bridge can be measured and the strength model (e.g. FE model) can be calibrated to behave as accurate as possible. The load testing of the bridge is not easy to perform, the tests lorries and carriages have to be obtained and usually the heaviest loads have to be loaded on site due the maximum allowable loads of other bridges. On the other hand, the normal traffic has to be stopped during testing, which may be possible only at night.

10.2 Monitoring and analysis methods

SIMO project has been concentrated on the sensors and measuring device used on monitoring. In most cases the data could have been copied to server to laboratory. Only in some cases the data analysis methods has been applied e.g. when calculating the deterioration of concrete and the fatigue life of steel beams. Actually the data analysis is the most important phase during monitoring the analysis and methods will be applied on the next phases of monitoring project.

IN SIMO project the following methods are used during monitoring:

1. All the data are saved from all sensors using defined sampling speed. The method can be used, if the measuring device is connected to network or the capacity of mass storage on site is big enough to save the measured data. If all the data have been saved, the analysis methods can be developed or selected afterwards and also complicated and processor capacity demanding methods and algorithms can be used. On the other hand, if permanent monitoring is going on, the collected data has to be analyzed to be able to perform simplified results and curves for bridge administration people. The weather information and e.g. temperature and moisture data values can be saved with a quite low sampling speed, because values are not changing very rapidly.
2. The data are saved only if one or more vehicles are crossing the bridge. The method is implemented by selecting triggering values for the measuring channels. The data can be saved for a fixed time or when the data values are

permanently lower than triggering values. If the amount of data is wished to limit, the triggering value can be changed higher. The triggering value can be set on one or several measuring channels. The failures on sensors or wires have to be included in the measuring program to avoid permanent data collection.

3. The maximum-minimum values during time period can be saved, if only the max-min. values are used in the analysis. The method can be used for the wind speed e.g. the maximum and minimum wind speed during one minute. If the measured data is changing between two values, like vibration of the bridge, the intermediate valued do not include much information. The method is also used for the long term change (trend) for maximum values.
4. Again, if the values are changing between maximum and minimum values like in item 3, the collected amplitude values can be classified by summarizing all the values belonging to same class. The method can be used to calculate the number of heavy vehicles crossing the bridge during a month or year.

Above is explained some basic methods to collect or analyze data. The more advanced analyzing methods are explained in the corresponding chapters above. The *Figure 10.2.1* is showed an example of the triggered time series data in Hännilänsalmi bridge while one (left figure) or two vehicles (right figure) are crossing the bridge.

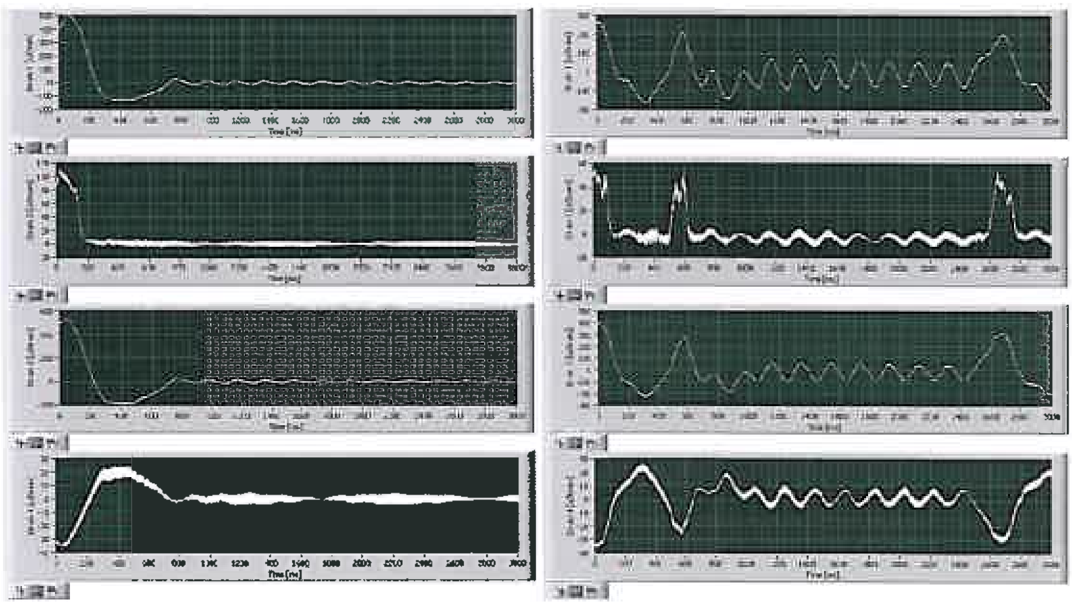


Figure 10.2.1. The stresses of steel beams in Hännilänsalmi bridge. One vehicle (left) and two vehicles (right) crossing the bridge.

11 Wireless monitoring of bridge measurements

11.1 Short range wireless data transfer for monitoring applications

One of the technologies used in wireless nets for data transmission is chirp spread spectrum modulation. This type of modulation is interesting as a technology to be used in environment monitoring tasks due to high robustness against disturbances and also low power consumption per transmitted bit.

The applications of wireless technologies of data acquisition and control have been growing rapidly in the last few years. Such systems can be used for remote measuring, ecological monitoring, vehicle tracking, remote registration of physical parameters in medicine, household devices, power saving applications, etc.

Working in the worldwide 2.4 GHz license-free ISM band (Industry, Science, Medicine), a developer can choose a standardized technology of data transfer (e.g. Bluetooth, WiFi, ZigBee, nanoNET, etc.) basing on such requirements as "visibility", distance, and robustness against disturbances, that perfectly meets the clients' needs.

NanoNET standard (in 2006 adopted as IEEE 802.15.4a) was developed by Nanotron Technologies GmbH (http://www.nanotron.com/, transceiver module costs approximately $50) and was positioned on the market as "the last mile" wireless network which in particular can be applied for the data acquisition from the various types of sensors and devices. Maximum announced bit rate is equal to 2 megabits per second (2 Mbps). There are not so many publications concerning the use of nanoNET and containing the corresponding advices, but obviously in few cases it is reasonable to use 1 Mbps and 500 Kbps modes for the purpose of increasing the distances and providing more reliable data transfer.

The other unique features of this technology are:

- Chirp Spread Spectrum (CSS) signal coding with one symbol transmission time equal to 1 microsecond;
- MAC-addressing scheme with possibility of organization of the broadcast packets;
- adaptable means of medium access control and procedures of error detection/correction and encryption;
- hardware possibility to organize synchronized network (support of real time clock generator in each node);
- supply current of the transceiver module does not exceed 78 mA (maximal signal level is 8 dBm, sensitivity of receiver is 92 dBm);
- communication distances up to 900 meter on open area and 60 meter in office without additional amplifying (as stated by Nanotron Technologies GmbH);
- radio modules programming and control are organized through SPI clocking at less than 16 MHz.

NanoNET supports two medium access methods: TDMA (based on time division) and CSMA/CA (carrier sense multiple access with a collision avoidance). The use of TDMA implies the need of software and hardware organization of arbiter node, which will issue permissions to start the data transfer in certain moments for other nodes. In CSMA/CA mode the starting time of the transmission is not externally defined therefore in the transceiver's working cycle there have to be special procedures of the most effective avoidance of the concurrent transfer by many nodes (for example, randomizing a waiting interval between the two frames).

11.2 Applications

The applications are focused on environment sensor networks based on chirp modulation radio technology. The primary application of nanoNET modules is low consumption sensors networks and this technology was announced to be low cost, easy to be installed, having long working period and high robustness to noises.

In order to design real-time application it is not enough to choose the proper data communication hardware (nanoNET transceivers); strong attention must be paid to the development of routing algorithm which utilizes all the useful features of nanoNET and designing the corresponding embedded software.

It should be noted that nanoNET radio hardware meets all the requirements for designing routing algorithms because these radio chips have the following peculiarities: the possibilities to swap the memory buffers between receiver and transmitter, to act as a bridge and retranslate the frames, and to use two MAC-addresses for this purpose.

11.2.1 Hardware developed and used in applicatios

The wireless platforms being used in experiments were based on Atmel AVR (8 bit RISC) processor and nanoNET transceivers nanoPAN 5361 (see Fig. 11.2.1).

Figure 11.2.1. Wireless nanoNET modules.

Hence, publication overview suggests that experimental research into the issue under discussion be of much importance. Except for simple peer-to-peer networks, there are 3 types of nodes.

The first type of nodes is a **master** node (a sink, a base station) that collects data from all sensors. In every network there can be only one master node. The second type of nodes is a **sensor**. The number of sensors varies from a couple to hundreds of thousands and depends on a coverage zone, range, network configuration and functioning, data collection, task specifics, and other factors. The third type of nodes is a **router** node. In addition, there are so called mixed nodes - sink-sensor and router-sensor.

Nodes of each type perform their specific task. Sensor nodes measure some physical parameters (temperature, pressure, humidity, vibration of different mechanisms, illumination, etc.) and transmit packets containing results of the measurements to the sink node, either directly to it or to the nearest router node. Router nodes form a backbone of the network; their task is to forward information from sensor nodes to the sink node (possibly with data accumulation/aggregation).

As a rule, a sink is connected to a computer that processes, visualizes, collects and transfers data via global nets to ultimate users of a sensor network. A sensor node consists of 4 components: a power source, a sensor with a digital converter, a microcontroller (in majority of cases), and a transceiver. Sometimes a sensor node also includes a module for determining geographical location (e.g. GPS) as well as some specific modules such as, for example, a mobilizer.

Designing a wireless sensor network, one should take into account some peculiarities of this type of networks.

First of all, as it is often the case, network topology and location of sensors are not determined. For instance, sensors may be dropped from an airplane. Second, sensors, routers and sinks can be mobile.

These two factors require an algorithm of network self-configuration (self-organization) - there should be at least a route-establishing algorithm when the number of nodes and their location are not fixed. Here, a route is a set of routers through which data passes from a sensor to the sink node.

Third, a more urgent problem (compared to wired networks) is how to organize transmission - if one node simultaneously receives 2 signals from other 2 nodes (collision of signals), in most cases, it can process neither of them. More than that, wireless networks are less robust against interference; consequently, signal reception is less accurate.

Another important factor to consider when designing wireless networks is that nodes have often limited resources. Among those, the most crucial one is, probably, energy supply. Therefore; network hardware and algorithms should include energy saving solutions. For instance, transformers of light or vibration energy into electricity may be used as an additional power source. Or, if the task permitting, there can be standby periods when both a node transceiver and a computing device are off.

It should be noted that a lot of publications discuss the issue of energy conservation. Further more, sensor nodes should not be expensive; otherwise, there will be no economical efficiency of maintenance of wireless infrastructure. Therefore, processing power of microcontrollers in a node is very limited - dozens of flash-memory kilobytes available for a software code and 0.5 - 4 KB of RAM for data (here, microcontrollers with Harvard architecture, e.g. Atmel's AVR). Obviously, resource limitations shrink functional capabilities of nodes in a network - a solution is to accurately select algorithms of sensors net functioning and optimize a code.

11.2.2 How to establish a wireless network

The network is comprised of one master node (the sink) and a number of sensor nodes and router nodes. There are 3 stages in its operating. The timing is set according to client's needs.

The first stage is route establishing. During this stage, the sink node broadcasts "time beacon" packet (sink announcement packet, or SAP), this feature is implemented in nanoNET transceivers. All routers and sensors are in a listening mode. Along with the time stamp and the address of the sink, the packet should contain route information - hop count set at 0 by the sink. We suppose that the broadcast from the sink packet will contain a special field - hop count (zero for the sink). Upon receipt of the packet, router nodes increment hop count and rebroadcast the packet. Besides, each node (both sensors and routers) synchronizes its timer and updates a list of nearby routers. Other parameters, such as router nodes' energy supplies and signal output, may be used as route establishers. In this case, sensors and routers will choose among nearby router a node that has the largest energy supply characteristics in order to balance energy consumption, or a node with the strongest signal to increase network functionality.

If a sensor node receives more than one of sink announcement packets, it could set up a table of all available routers and mark one of them as a default router on the base of hop count. If a router that is n hops from the sink receives a packet from routers that are more than n hops from the sink, it simply ignores such packets and does not update its table of nearby routers.

Number of hops is obviously limited. If a router receives an announcement packet with maximal hop count, it updates its table but does not rebroadcast the packet. Maximal hop count may be predefined or indicated in the sink announcement packets.

Route establishment is accompanied by sink-proximity zones determination (I, II, III, and IV in Fig. 11.2.2). A sensor or a router in n zone transmits data to a router in n-1 zone or directly to the sink when n = 1.

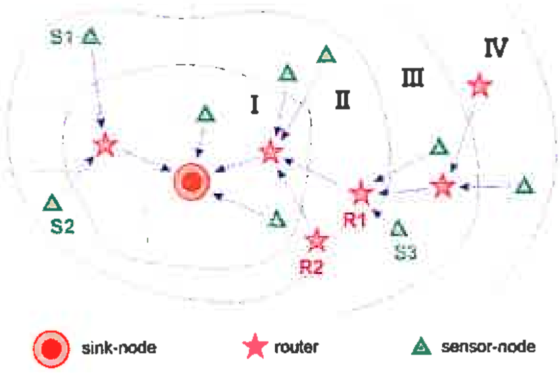


Figure 11.2.2. Wireless data collection scheme.

The second stage is data collection (data is being transmitted to the sink). Here, there are several possible algorithms for transmission timing. One of the options is sink-proximity schedule: sensors and routers that are one hop from the sink (zone

I) transmit their data packets first, after that, sensors and routers from zone II, zone III, etc. Transmission priority is determined by either CSMA algorithm or predefined schedule, or both.

In the simplest scenario, routers work all the time, since they must deliver packets to the sink from all sensor nodes. The latter may sleep between data transmission in order to save their energy.

During the second stage, routers should also broadcast "router announcement packet" once in a couple or tens of seconds so that sensors are always updated on the status of the route to sink. Besides, it ensures errorless joining of a new node or its re-registration in case of mobile sensor network.

The third stage is setting a more accurate transmission schedule. Having collected the information on a number and zone distribution of the farthest nodes (each router has a database of all connected to it sensors), the sink can arrange the schedules of all nodes and send out the recommendations on time marks of working mode, standby, listening mode, etc. This process requires a lot of computer resources and cannot be performed only by a microcontroller core; therefore, the sink has to be connected to a computer that runs major processing and has enough memory to store changing network configurations.

It is important to note that occasionally the sink itself has to initiate the first and the second stages to ensure stable network functioning. This will also allow keeping correct synchronization among all nodes and dealing with emergency situations (e.g. nodes are off due to energy depletion).

If routers are electrically supplied by autonomous sources, the load of a router will increase with the proximity to the sink be-cause the closer is a router to the sink, the more packets it has to transmit. Therefore, it is recommendable to provide heavily loaded routers with more capacious accumulators or place a cluster of routers close to the sink.

Below, there are approximate durations of the mentioned above stages with the use of nanoNET technology (data rate 2 Mbit/s). For other transmission technologies, the results will vary due to different data rates, data frame formats, characteristics of transceivers, and other factors.

If the area is not overcrowded by transceivers, we suppose that there should not be any signal collisions and low boundary for the duration of the first stage (T1) may be estimated as follows:

T1 = Ts + H*(Tp + Tt)

Here, Ts is a time period that the sink needs to prepare SAP-packet, H is the maximal number of hops, Tp is the time that a router needs to process data (time synchronization, route updates, and preparations for data transmission), Tt is time beacon transmission.

In all nanoNET systems, the transfer of 1 data symbol (2 bits at 2 Mbit/s) unit takes 1 microsecond. In small-size networks, delays are insignificant; therefore, in the first stage, transfer of an SAP-packet (of no more than 40 - 50 bytes) is about 400 microseconds. Taking into account the time for packet processing, we estimate that each router needs one millisecond to receive a frame, prepare next frame and start transmission. Let Ts ~ 1-2 ms, H = 16, Tp + Tt ~ 1 ms, then T1 ≤ 20 ms.

In reality, T1 will be longer due to collisions, interference of external electromagnetic signals and retransmission.

Consequently, the first stage is worth repeating every 5 - 10 seconds; thus, more time can be spent on data trans-mission from remote sensors.

5. Broadcast periodically "router announcement packet" (RAP).
6. Go back to step 1.

11.2.3 Problems in wireless networking

There are some challenges or problems in wireless solutions. The first of these ones is setting transmission power if distances between sensors are not fixed. The second one is power consumption in measuring systems in case if available power is limited and long measurement time has been requisite. The third one is a hidden node problem.

11.2.3.1 Setting transmission power

Theoretical analysis of algorithms of sensor net functioning is usually based on the assumption that transmission power of a sensor can be set according to the distance to an access node. There are several ways to set the power.

The first option is to program a priori location awareness. An obvious disadvantage of this approach is difficulties in maintenance and setting of such kind of systems - all distances have to be measured beforehand and all nodes programmed individually.

Another solution is to use systems of global positioning or means of triangulation to determine distances. However, this option requires additional expenses and modification of a sensor network; thus, appearing not worth-while.

One more option is the use of special chip that measures the link distance between two nodes based on signal delay (e.g. nanoLOC developed by Nanotron Technologies GmbH as well).

Finally, the network can function without distance awareness. Instead, a minimal output power can be set at a level sufficient for stable transmission (as shown in Fig. 11.2.3).

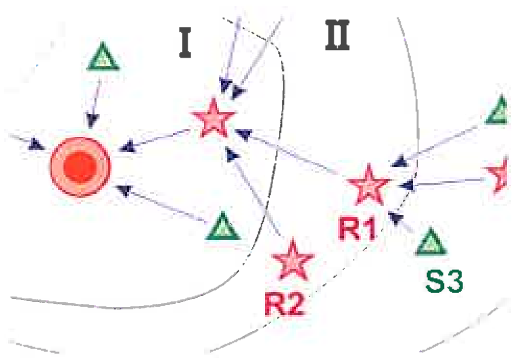


Figure 11.2.3. Router selection. Data collection.

Sensor node S3, located close enough to R1 and R2 routers, chooses R1 as the shortest way to the sink due to either a better signal from R1 or a possibility to save energy.

However (yet, excluding nanoLOC), a priori data is always based on a procedure of sending out a lot of test packets that reduces the efforts on energy savings gained during data transmission to nearby nodes. Besides, the ratio of maximal and minimal possible output power may be a bit bigger than 1; therefore, all complications caused by power increase to a node seem worthless. The latter perfectly describes nanoNET working in 2.4 GHz license-free ISM band with disturbances - current consumed by a node ranges from 55 to 78 MA, and a good radio connection, in our experience, is possible only when working values are close to maximal ones.

11.2.3.2 Low power supply

As it has already been stated before, in central data collection networks, nodes that are close to a sink have to transmit data frames more often and, consequently, consume more energy. For a more efficient wireless transmission, nodes may aggregate several packets into one to be transmitted further.

In figure 3, routers R1 and R2 in zone 2 each in its time either in TDMA or CSMA mode transmit packets to a router in zone 1. Often, only a dozen of bytes in each packet are useful data. In this case, a router in zone 1 can aggregate a number of packets into one and even add more data, for example, information on the senders of the packets.

11.2.3.3 A hidden node problem

Transmission without predetermined timing (not scheduled) causes a problem of a hidden node (fig. 11.2.4). A router may receive a signal from both S1 and S2; however, sensors are unaware of each other (a hidden node). A possible reason for it may be a particular location of nodes (as in fig. 11.2.4) or an obstacle. Since sensors are unaware of each other, they start data transmission simultaneously, and, as a result, a router does not receive any data neither from S1 nor from S2.

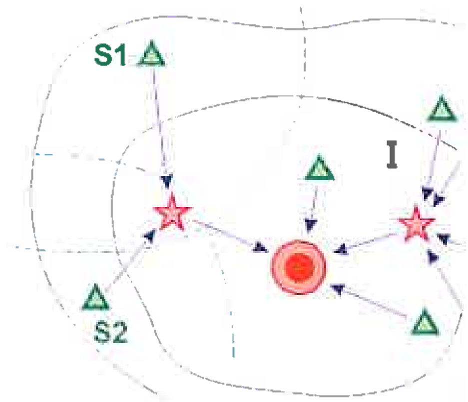


Figure 11.2.4. A hidden node problem.

CSMA/CA (Carrier Sensing Multiple Access with Collision Avoidance) modification of CSMA algorithm helps to overcome this problem. Prior to transmission (and if the carrier is idle), a node sends a request (RTS) to the destination point. If the destination node is idle, it responds as clear to send (CTS) and allows transmission. This example demonstrates that, although S1 does not sense S2, it will sense a node's response and suspend transmission. Still, CSMA modification and alike do not guarantee complete avoidance of collisions. For instance, S2 may send RTS packet to a node when the latter is receiving data from S1. In this case, data from S1 will be blocked and will have to be retransmitted, which is undesirable.

Let us look at the ways of carrier sensing. NanoNET nodes in case of CSMA [18] may sense the carrier in two ways: physically and logically. Moreover, physically, a node can evaluate the business of media basing either on an input signal level or on symbol detection technique (symbols are coded by Chirp Spread Spectrum Modulation – linear frequency modulation). In our experience, the use of input signal sensing only may be efficient only when noise is insignificant.

Logical algorithm - Network Allocation Vector (NAV) - works as follows: while sensing the medium if a node receives a packet, it determines the duration of transmission basing on special headers in the packet and sets up a corresponding decrementing timer. Next sensing will be initiated only when the timer reaches zero.

11.3 Some results from testing the network

In order to test the designed algorithm and to interpret correctly its results we needed to obtain the maximal available data transfer rate between the two nodes beforehand. So the new AVR embedded software based on the demo version supplied by Nanotron Technologies GmbH was created. One radio module sent the 1 or 128-byte packets as fast as possible; the other (remote node) acknowledged the reception.

The experiments with the developed software on the registration of the maximum data rates revealed the following results, presented in table 11.3.1.

The first four rows in the table correspond to the conditions in which the source side waits for the random period (CSMA/CA mode, 96 us in average for the first attempt) before the transmission, the second four rows - to the mode when the transfer starts just after the end of the inter frame gap. The numbers in the last column do not include the time of the next frame preparation spent by the external MCU and conform to the maximum reachable data rates.

The calculation of maximal number of transmitted frames per second and corresponding effective data rate was done on the basis of analysis (assembled code) of low level functions responsible for transmission and information on frame data formats.

The registered data rates of 530 kb/s and 840 kb/s are close to the calculated above values (524 kb/s and 831 kb/s) and are inside the error limits. The uncertainty of these experiments was rather low (less than 1%) because the distance between the two nodes (the transmitter and the receiver) was only few meters and the radio communication was very reliable, so noises and radio signals from the other sources did not influence the transmission. In the real environment the percentage of the successfully transmitted packets is less than 100% and depends on many factors including the distance between the source and destination nodes.

It should also be mentioned that the use of CSMA without the collision avoidance algorithm is not recommended in nets with more than two active nodes.

Table 11.3.1. The number of transmitted frames per second and the effective data rates depending on the frame length, bit rate and the transmission Mode.

Mode	Frame contains payload of		Bit rate		Number of transmitted frames per second / effective data rate	
	1 byte	128 bytes	1 Mb/s	2 Mb/s	demonstrated	maximal
SPI@4MHz / MCU@8MHz, CSMA/CA "truncated" mode with collision avoidance	+		+		1141 / 8.9 kb/s	1656 / 12.9 kb/s
	+			+	1420 / 11 kb/s	2500 / 19.5 kb/s
		+	+		530 / 530 kb/s	617 / 617 kb/s
		+		+	840 / 840 kb/s	1101 / 1101 kb/s
SPI@4MHz / MCU@8MHz, CSMA "truncated" mode without collision avoidance	+		+		1300 / 10.2 kb/s	1969 / 15.4 kb/s
	+			+	1511 / 11.8 kb/s	3289 / 25,7 kb/s
		+	+		560 / 560 kb/s	656 / 656 kb/s
		+		+	918 / 918 kb/s	1232 / 1232 kb/s

The routing algorithm described in this paper was tested in real environment. The installation for checking one of its variants based on link quality measurements is presented at figure 11.3.1. In order to simulate the conditions of low signals and establish routing between zones all nanoNET modules were used without antennas. Besides the radio signal strength was limited to the lowest possible value by writing the corresponding bits in transceiver register.

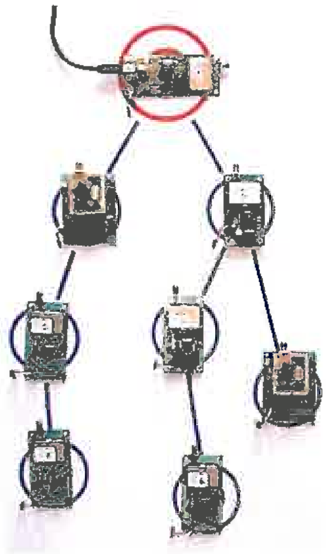


Figure 11.3.1. Implementation of routing algorithm based on link quality feature.

The node in the upper circle was the sink node and was connected to a computer through USB interface.

The carried out experiment showed the stability of established network and proved self-adjustment. If a node has been moved somewhere within the existing tree (the initial radio linkages are shown by solid lines between circles), it automatically reconfigured.

11.4 The new wireless network for real time measurements

The theory has been put to practice in several field applications and proven to work reliably. Fig 11.4.1 shows a typical implementation of this kind of network:

The wireless radio network is used to collect the measurement data from the field, the router is filtering and packaging the data and transmitting it further on to the internet server where it is stored on the database. This database can be accessed everywhere so the system is very good when the information must be distributed for condition monitoring or for research purposes.

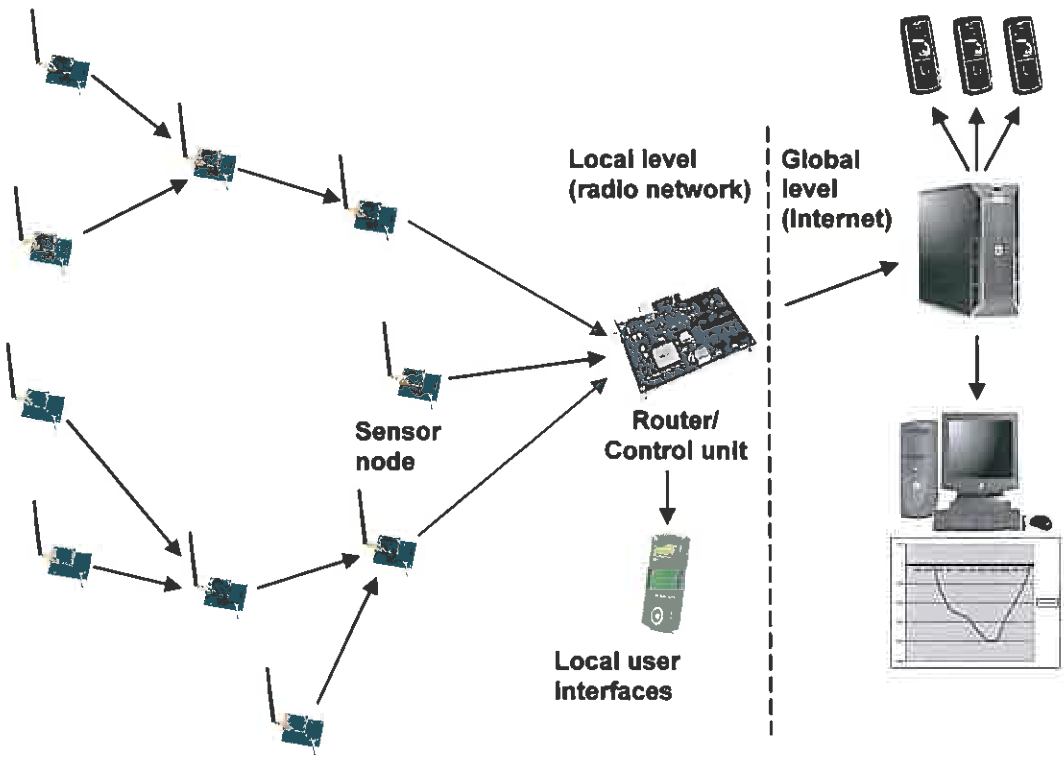


Figure 11.4.1. Wireless real time network with internet connection.

11.5 Real time monitoring of large objects

VTT has developed a special wireless application for the condition monitoring of large objects (for instance bridges, pipelines, windmills). This sensor network consisting of central processing node and wireless (or wired) sensor nodes. Strain gauges are used for measuring loading and tension of static structures. Accelerometers are used for vibration analysis and spectral analysis for measuring ball bearings and motors′. Acoustic emission measurement is applied for diagnosis of structural fatigue or ruptures. The principle of the network is shown in Fig 11.5.1.

- Distributed sensor network that allows phase accurate real time measurement from multiple points
  - New possibilities for monitoring of large structures
  - The measurement range can be extended to several hundred meters by adding more base stations to the synchronized sensor network
- Extremely accurate synchronization between measurement nodes
  - ~10 ns for base stations and wired sensors (IEEE 1588)
  - ~1 µs for wireless sensor nodes (nanoNET).

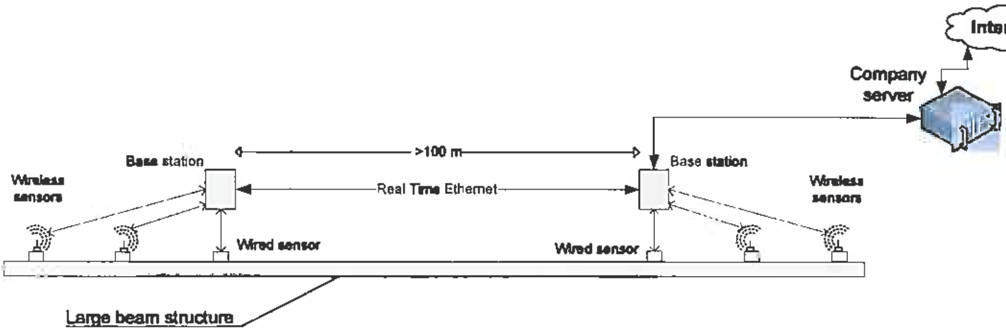


Figure 11.5.1. Wireless monitoring of large objects.

12 Monitoring and bridge management

12.1 Monitoring and bridge owners aspects

12.1.1 General

Finnish Road Administration (Finnra) represented owner's side and experience in SIMO-project. Finnra is the largest bridge owner in Finland, having about 14 500 bridges in general road network under its management.

Bridge monitoring could be a new tool for bridge management. Until now special inspections and also other special studies have been used to collect more advanced information from environmental conditions, bridge condition and bridge structural behaviour. That detailed information has been used for repair design and calculations for example to clarify the need for strengthening. The measurements, as bridge loading tests, have been one-off tests, no permanent monitoring has been used before SIMO-project.

Typical for Finnish bridges is their relative small size. The mid length of bridges is about 25 m and the amount of large bridges, which are easily to be seen as potential monitored bridges, is quite small. Also the probabilities of extreme environmental loading events are on low level - there are no considerable earthquakes and the risk of heavy winds is low.

12.1.2 Needs for road bridge monitoring in Finland

In Finland there are practically no needs for large monitoring systems which are used often in large-scale bridges. However, there are clear needs for monitoring due to other reasons, as:

- The conditions of Finnish climate, as low temperature, large temperature variation and using of de-icing salts, have to be taken into account in special areas such as in concrete deterioration.
- Traffic loading have quite high share of total loading because the bridges have short spans and the permissible vehicle weights are high. Vehicle weights and amounts have also increased much during the last decades.

- The average age of the bridge stock is rapidly increasing. During 1960's and 1970's the amounts of yearly built bridges were high. Now those bridges are in general repairing age.
- The quality of bridge construction has clear influence on bridge deterioration. Often in special inspections there have been found failures which could have been notified and repaired already during construction by modern measurements.

The Finnish conditions have special features which can be studied either with single-bridge level or general measurements.

In single-bridge monitoring special sensors in critical details can be used to gather information from deterioration and parameters influencing to that. The condition development of the structure, which is visually often impossible to see, is possible to be followed by a set of sensors.

In more general type of monitoring the studying method could be to collect data from different kind of environmental conditions and for different kind of materials and structures. Those can be used to formulate different environmental stress categories or verify general degradation models. Now this general condition work has been made with the aid of special inspection data of Reference Bridge -group of bridge stock. In the future partly these reference bridges could be monitored permanently.

Traffic loads from normal traffic have increased rapidly from 1960's until now. The permissible total weights of normal heavy vehicles were less than half of modern 7 - 8 axle 60 t trailer trucks. The amounts of heavy vehicles have multiplied. Also the needs for special heavy transportations have increased. The design loads of road bridges reached their present level in the beginning of 1970's. During 1970's also the fatigue design for steel road bridges was taken into use. For these reasons the information from real traffic loads and their influence on bridge structures is very important. Especially the bridges designed and built before 1970's are critical in road network concerning their load-carrying capacity and fatigue resistance.

Monitoring of bridges during construction can give all-round information about conditions and progress of work compared to plans. Monitoring and different kind of measurements as those of temperature, moisture and displacement can give help in quality control. In many cases the same monitoring system can give also important information from the bridge during the normal operation.

12.1.3 Future bridge monitoring system of Finnra

The above mentioned needs for the monitoring could be fulfilled by the systems having the next features:

- Monitoring critical bridges in road network
- Ensuring the safety of bridges in "end-use"
- Collecting general data from material degradation
- Collecting data from heavy vehicle weights (Bridge-WIM).

In the Finnish road network there are critical bridges concerning both their load-carrying capacity and bad condition. Some permanent monitoring systems could be installed especially to bridges which have low load-carrying capacity for heavy transportations to get measurement results from bridge real behaviour and condition development. Some larger steel bridges need also fatigue history measurement for better estimation of their remaining fatigue life.

Bridge monitoring is in many cases good way to ensure the safety of bridge in "end-use", when the long-term safety of the bridge is suspected and the rebuilding or larger repair of the bridge is planned. Often the rebuilding or repair can be moved forward and the schedule of it can be optimized when enough measurement data from the bridge and its condition development is attained. Measurement can be either permanent monitoring or just smaller periodic measurements.

Collected data from material degradation is used to verify degradation models, which are used in predicting condition development in bridge management. Some monitoring systems could be installed to bridges of Reference Bridges -group. Influence of different environmental conditions has to be analyzed.

Collecting data from heavy vehicle weights could also be one important task for future monitoring. With modern B-WIM systems bridges can be used as weighers for axle, bogie and total weights of vehicles. This information is not up-to-date in Finland at the moment. Adequate accurate weight information can be produced both with movable and permanent systems.

Bridge contractors, both in new building and maintenance, will hopefully wake up to see also the advantages of bridge measurements and monitoring. Finnish Road Administration has already some long-term bridge maintenance contracts where the contractor can optimize the repairing methods and schedule. In new building risk management and quality control could also be carried out partly with new kind of measurements.

Before new monitoring systems can be built in Finland in full scale some further work have still to be done:

- Some more experience is still needed from different kind of bridges and cases to further optimize different kind of monitoring systems and to see better the real advantages of the systems.
- Investment costs for permanent monitoring are still quite high. Economical benefit is, however, important for the owner and estimation methods for it could need some further studies.
- How the management of bridge monitoring and monitoring data will be arranged. If a larger system with many instrumented bridges will be built, a centralized system and certain quality requirements for the measurements are needed.
- Enough resources have to be directed to build up the systems when they are needed and economically justified.

12.2 Monitoring results and usage in bridge management

This chapter of SIMO end report depicts past and ongoing experiences of Ramboll in the field of bridge monitoring. Many of the Ramboll monitoring experiences have been published in various contexts on different forums (e.g. /1 - 4/), but still it is good to compile some of the experiences in this SIMO end report. In addition, some predictions (not revolutionary, though) about the possible future role of monitoring in bridge management are given.

12.2.1 Monitoring as part of durability and performance assessment

In principle, every change that happens on the bridge or to the bridge can be monitored, but that would not be economically feasible. Monitoring forms one part of the data acquisition in bridge management and inevitably its share will increase in the future, but visual inspections and on-site and laboratory tests will long remain an essential part of bridge management. Figure 12.2.1 describes the process flow on general level. The general process shown in the picture hardly changes a lot, but in time the questions in the flowchart boxes get more and more accurate answers and consequently the decision-making in bridge management becomes more straightforward and transparent.

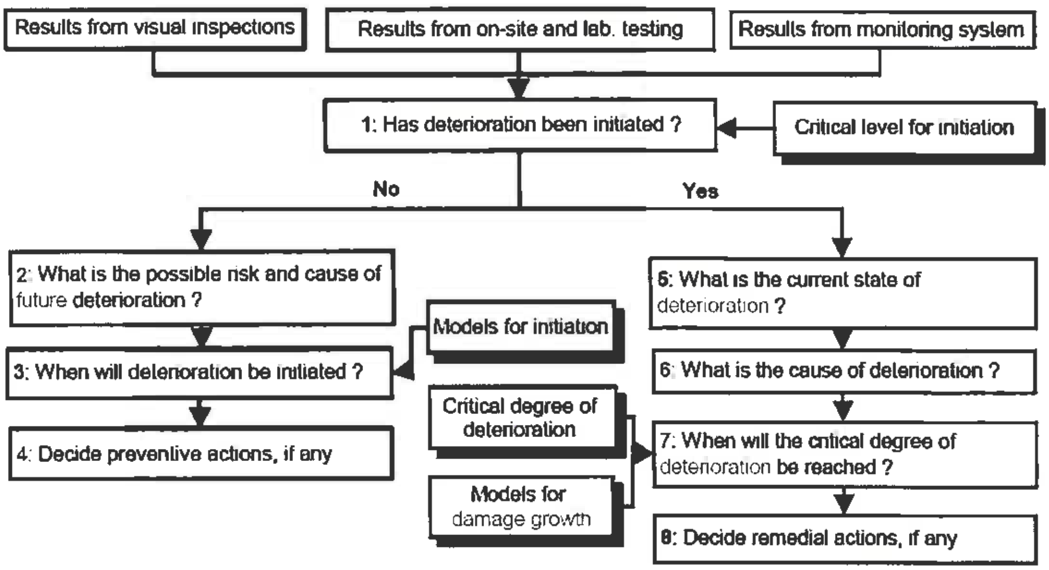


Figure 12.2.1. General process for durability assessment and performance management.

Monitoring has been applied to bridges during years, and in many scales and compositions. When linking countries with huge bridges, the cost of even very highly sophisticated monitoring system is not critical, but when dealing with existing small and medium size bridges, the cost is a factor that is very carefully studied. The benefit expected from monitoring must be clear before the system is mounted on a bridge.

12.2.2 Ramboll's experiences about bridge monitoring in Denmark

In Denmark bridge monitoring has been used in various cases:

- Monitoring for verification of the effect of repairs

  - o Drying out after replacement of waterproofing or surface treatment
  - o Corrosion potentials after partial replacement of chloride contaminated concrete (in some cases it is very expensive to remove all contaminated concrete)
  - o Strengthening (deflections etc.).

- Monitoring of new structures - initiation of reinforcement corrosion
  - o The sensor determines the initiation of corrosion at different depths due to chloride penetration
  - o The time for initiation of corrosion on the actual reinforcement can be estimated
  - o Optimum time for preventive actions can be determined.

- Monitoring of traffic by using web-cam
  - o Control of traffic.

Monitored deterioration mechanisms cover the most important mechanisms that trouble all concrete bridge owners: chloride initiated corrosion, carbonation initiated corrosion, freeze-thaw damage, alkali-silica reaction and mechanical damage (structural performance). These mechanisms have been monitored through key material parameters, such as temperature, moisture, chloride content, pH, corrosion risk/initiation time and key mechanical parameters like strain, deflection and vibration.

In Ramboll's Danish experiences there are three main circumstances, when monitoring should be considered. These are:

1) difficult access
2) repair costly or impossible
3) reference for a wider set.

Number one in the above list refers to situations, when a problematic area or detail in the bridge has been discovered, but it is difficult to access for example due to heavy traffic or difficult location (height, under water, etc.).

Number two refers to situations when for example carbonated or chloride contaminated concrete should be replaced with new concrete, but the replacement work has been estimated to be very costly or otherwise problematic, and thus another repair method, usually cathodic protection is introduced. In Denmark this approach has been used successfully for example in high stressed (local) areas like behind post-tensioned anchors. But because of the high structural importance of the local area monitoring has been applied to control the cathodic protection. In Figure 12.2.2 the system set-up on-site is presented.

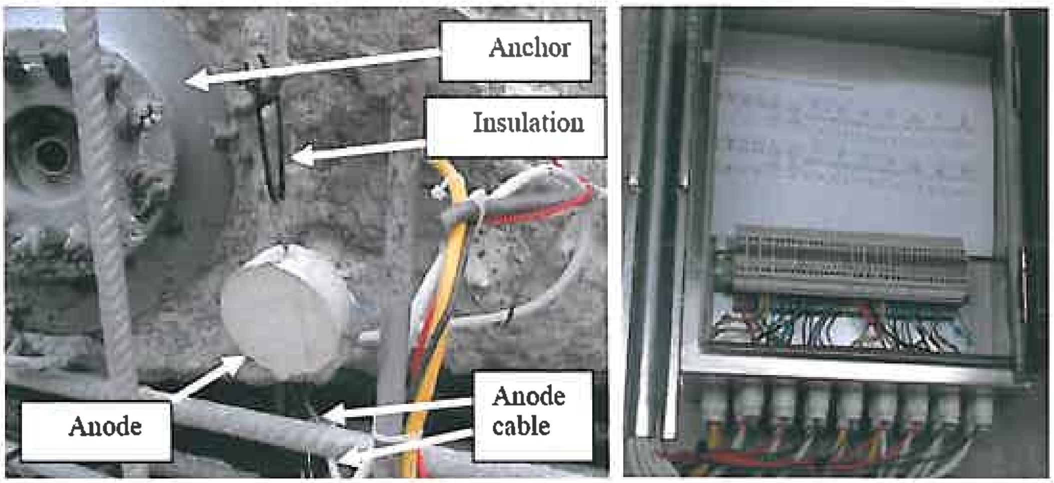


Figure 12.2.2. Cathodic protection with monitoring.

Number three is already a step further in the bridge management decision-making process: the idea is to use the monitored bridge as a reference for same kind of bridges in same kind of loading environment (traffic, climate, de-icing salt). It is expected that this kind of reference bridge idea works best for highway or motorway sections that have been constructed in the past, say during 1960's or 1970's. A lot of same kinds of bridges were built in a short time to cross the motorway, and if some durability or performance problems are encountered nowadays in one of those bridges, it can be estimated that the same problems are prone to appear in the other (similar) bridges on that motorway too. Consequently, the first counteractions and their rough timings can be drafted for the whole bridge stock on that motorway section even before special inspections.

12.2.3 SensoByg - a Danish counterpart to SIMO project

The most recent research step in the field of monitoring in Denmark is so called SensoByg. SensoByg is an acronym for a project and a consortium consisting of six R&D performers and over ten industrial partners, with the main objective to develop and demonstrate the advantages of monitoring systems based on integrated, wireless sensor technology and intelligent support systems for decision-making. The 4 M€ project started in March 2007 and will end in 2010.

The main focus of SensoByg will be the monitoring of moisture, because moisture governs the durability of concrete and it controls the risk of corrosion. In bridges the main reason for repair of superstructure is the leaking waterproofing membrane, so SensoByg is expected to bring valuable knowledge and experience to bridge management sector. In Figure 12.2.3 a placement of a wireless (with extra supplementary battery pack) sensor in a road bridge during summer 2007 is presented. A total of five sensors were placed in the water run-off line of the bridge deck, where experiences show the highest risk of detecting water leaks.

Figure 12.2.3. Battery pack on the left and the sensor on the right (left picture). The row of sensors is visible before installation of waterproofing membrane and asphalt (right picture). The battery pack and sensor are covered with 6mm thick teflon protection plate to protect them from open flames during the installation of the bituminous waterproofing membrane.

SensoByg is intending to go further than SIMO project when it comes to the decision-making part of bridge management process. The follow-up and comparison of the results of both SIMO and SensoByg projects can generate pragmatic information about the possibilities of bridge monitoring. As pilot projects with different monitoring set-ups is increasing and data retrieval is becoming more and more reliable, the next big and difficult step is to analyse thoroughly how monitoring should be used in bridge management. Clear guidelines are missing worldwide.

12.2.4 Monitoring as routine part of bridge management

The biggest "hype" in the field of structural health monitoring is over (after having reigned during half a decade in the beginning of new millennium), as no instant payoffs were gathered in spite of the wildest visions. During the last years there has been a quiet return to the patient and somewhat slow development work, including basic research, product development, experiments, pilot projects, small advances, drawbacks, etc.

With the current knowledge it is impossible to predict exactly when the monitoring of small and medium size bridges will be a routine part of bridge management, but the increase of monitoring seems inevitable, for various reasons:

- labour costs are increasing all over the world (including also developing countries) and different device costs are decreasing
- bridges are getting older and their number is increasing
- bridge management models are changing in many countries (e.g. orderer-producer models), and objective, real-time data of bridges is wanted
- in developed countries there is a clear shift from new infrastructure investments to infrastructure upkeep and maintenance
- bridge management systems are spreading also to the developing countries and with the increased awareness of ICT possibilities there may arise urge to jump directly to the next generation of bridge management systems.

While the above mentioned trends advance slowly but steadily, Ramboll experiences from the past two decades concerning bridge monitoring can be concluded in the following "theses" or findings (which are well in line with other published experiences today).

Monitoring reduces costs and thus enhances the possibility to become routine action in bridge management, if by using monitoring

- repair, strengthening or replacement of a structure can be postponed (a more accurate prediction of the condition of the structure allows for a less conservative rehabilitation strategy)
- the extent of repair or strengthening can be reduced
- the monitored structure or part of it provides information for many structures
- less expensive approaches can be used (monitoring may verify the performance of the selected approach e.g. drying out of concrete or cathodic protection).

Monitoring (once installed and working as planned) has advantages such as

- information can be obtained with less traffic interference and less access costs
- more reliable information is acquired on the development of deterioration and performance
- early warnings of damages and safety risks are received

but still there are many drawbacks which should be overcome. These include for example following:

- long term performance of sensors is not well documented (nor guaranteed)
- monitoring system may be costly to install and difficult to maintain
- limitations in the number of sensors makes it difficult to get a true picture of the condition of the entire structure.

To the question whether monitoring should be used or not in bridge management or whether it will ever be a routine action in bridge management of ordinary bridges, the cautious answer is "conditional yes", with the following conditions to be fulfilled:

- a careful comparison of costs and benefits of monitoring compared to the traditional approaches will be made
- monitoring will be combined with inspections (visual, NDT, laboratory analyses) and/or evaluations (e.g. of deformations etc.)
- relevant specific questions will be answered (the use of monitoring results must be specified before the monitoring system is designed)
- open, but realistic and patient attitude must be maintained.

Good results can be expected when optimal balance is found between different assessment methods. Solid bridge engineering expertise is needed to decide (case by case), which assessment methods to use and in which extend. One possible combination is presented in Figure 12.2.4.

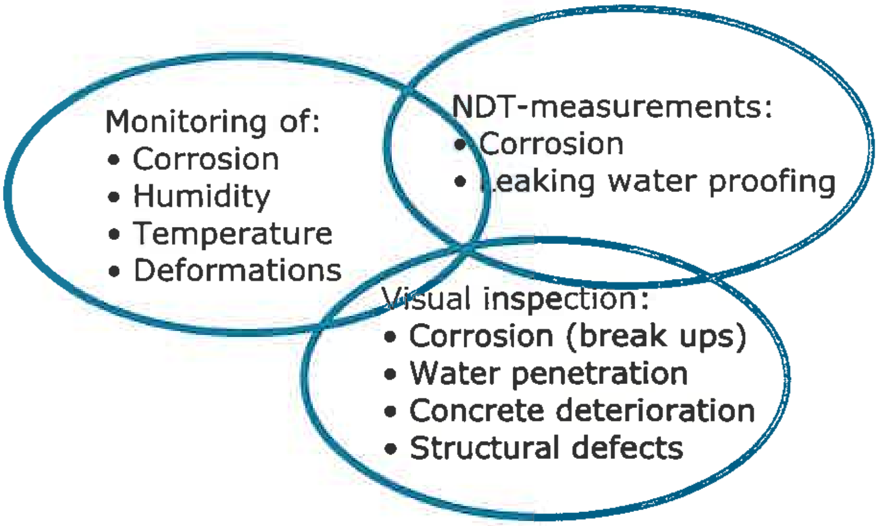


Figure 12.2.4 Combination of different methodologies used in an assessment of a deteriorating concrete bridge (The Skovdiget West Bridge in Denmark), with objective to gain life extension and avoid repair costs.

References

1. C. V. Nielsen; H. E. Sorensen; A. Knudsen; P. H. Moller; P. Lundhus. *Applications of Wireless Sensors in Concrete Structures*. IABSE Conference "Information and Communication Technology (ICT) for Bridges, Buildings and Construction Practice" in Helsinki, Finland, June 4 - 6, 2008.

2. *Bro 13-0-021, Skovdiget vest - Monitering, afsluttende undersøgelser.* Vejdirektoratet. Maj 2008. (in Danish)

3. de la Motte, Morten. *Rambølls experience with monitoring in general & SMART monitoring*. Bridge management and Materials Technology. Ramboll 2007.

4. *SMART STRUCTURES - Integrated Monitoring Systems for Durability Assessment of Concrete Structures*. Brite-Euram III Contract No. BRPR-CT98-0751. Project Report, September 2002.

12.3 Monitoring, inspections and bridge maintenance

There are a great number of bridge monitoring devices and techniques applicable for detecting various phenomena in different structures. Experiments with these systems have shown promising results. A great amount of data has been produced from phenomena than cannot be detected visually or with other traditional non-destructive methods. Despite the good experiences, monitoring systems and data have had only a limited use in bridge management at the network level. The question is how to use this new technology to get the maximum benefit for the bridge owner? Is it possible to increase the knowledge and improve the quality of critical decisions in a way that it would lead to significant improvements in the management of the whole bridge network? These are still open questions and there are number of challenges to overcome before the monitoring systems and techniques can be fully utilised in bridge management.

In the following the role and use of bridge monitoring systems in bridge management is discussed and compared with the information produced by the current bridge inspection system used in Finnish Road Administration (FINNRA).

FINNRA has about 14 300 bridges. The current bridge health monitoring is based on periodic visual inspections and targeted special inspections (Figure 12.3.1). Periodic visual inspections give a broad overview to the current status and condition of the bridges. Most importantly, the visual inspections provide a systematic framework to assess and compare the condition of a large number of different bridges. An inspection manual and inspection instructions have been developed gradually over the past years and they have been tailored to meet the different aspects of various structures. A considerable amount of information and knowledge of the behaviour of the structures have been built-in in the system. As the inspections are relatively cheap they enable a fairly large coverage. Every year about 2 700 visual inspections are made to the bridges of FINNRA. The annual cost is about 500 000 €, which is roughly 1% of the total annual rehabilitation budget.

Information from the visual inspections is used widely e.g. in present condition state estimation, strategy formulation, bridge management policy formulation, performance management and maintenance planning and programming. Although the periodic inspections give a good overall picture of the condition of the bridges, the information is not precise. The visual inspections are based on subjective evaluation and there is large variation in the condition estimates and particularly in the cost estimates. The information is not sufficient and detailed enough for the work planning and the selection of working methods.

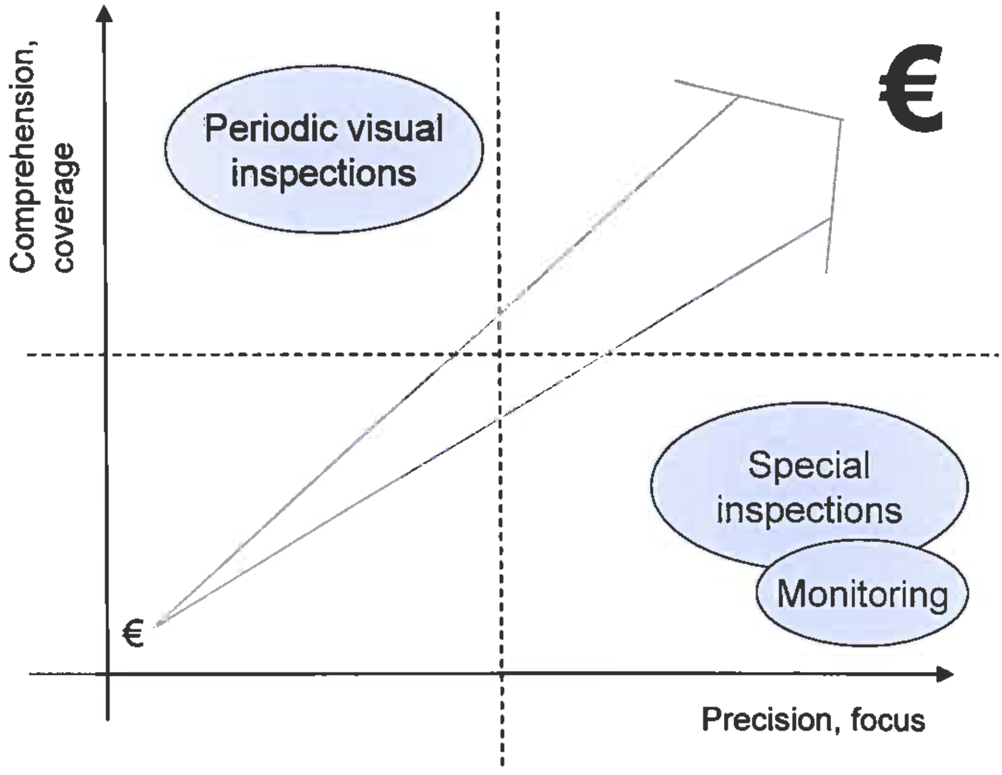


Figure 12.3.1. Bridge health monitoring systems.

In special inspections visual condition estimates are complemented with several tests and samples which give detailed and objective information on the structural health and condition of the bridge. This information is readily suitable for work planning, selection of working methods, cost estimation and estimation and calibration of deterioration models. However, detailed testing, special arrangements and accessories such as cranes and boats increase the price of the inspections. The number of special inspections varies from year to year and is typically less than 100. Still, the annual total cost of special inspections is about the same magnitude as in the periodic visual inspections. Clearly, the special inspections need to be carefully planned and targeted to a limited amount of bridges.

Monitoring is used to get focused, precise information typically only on few condition parameters, but over a long time period or periodically over shorter time periods. Monitoring systems have several advantages. Continuous measurements and observations over a longer time period give a more detailed, reliable and precise information on the behaviour of structures and materials than single tests. The sensors are often installed already in the construction phase or during a reconstruction enabling observations of the structures which would otherwise be inaccessible without expensive destructive methods. Continuous monitoring enables also early warnings of structural damages and safety risks. Finally, once the monitoring system has been installed information can be acquired easily and with relatively low costs.

The downside is that the monitoring systems and the installation of the systems are still quite expensive when compared with the special inspections. Moreover, the sensors and monitoring systems are often tied to a given bridge, the installation and setup of the systems takes time and in most cases, the installation is sensible only during the construction or reconstruction phase. Consequently, majority of the monitoring systems are suitable only to a limited target group and require time and detailed planning.

Monitoring techniques provide valuable information and new possibilities both for bridge level analysis and decision-making and bridge management at the network and programming levels. At the bridge level, particularly promising application areas are:

1) Large bridges and complex structures where the set up and maintenance costs of the monitoring systems can be easily justified with high potential savings in bridge maintenance and more detailed planning and accurate timing of the rehabilitation actions. Monitoring provides also new possibilities for quality assurance of new bridges and the reconstruction work.
2) Constructions with difficult access and which cannot be observed without high expenses (e.g. critical underwater structures).
3) New, rare and complex structures and materials with no or little prior experience.
4) Bridges in end use. Monitoring systems can be used to ensure safety and to optimise the timing of the rebuilding.
5) Bridges with low load-carrying capacity, especially in heavy transportation network.

Since bridge monitoring systems and special inspections are expensive they are not readily applicable to the management of the large bridge network. However, these systems can be used to increase the knowledge of the behaviour of different structures and then utilised at the network level by

1) developing new materials and reconstruction methods,
2) adjusting the life time estimates of the current structures and helping to avoid unnecessary and heavy reconstructions,
3) improving the utilisation of the existing bridges e.g. by upgrading the load bearing capacity and axle load restrictions,
4) creating new and calibrating the existing deteriorating models,
5) improving the instructions of periodical visual instructions and the cost estimates.

Despite the great potential of the bridge monitoring, only few devices have been installed in the bridges of FINNRA. There are number of reasons for this, such as:

1) Bridge monitoring is a relatively new concept. There are a large number of different systems available and new technology is developed continuously. There is not that much experience on large scale use and long time performance of these systems. Most importantly, there is only little knowledge on how this information should be used and utilised at the network level.
2) Deterioration of bridges is relatively slow. The time span of an interesting phenomenon from the early stages to the critical point is likely to take several years. In some cases, a monitoring system installed today is expected to give valid, relevant, reliable information up to 10 or 20 years, or even more. Setting up such systems requires careful planning and long-time commitment. Ensuring maintenance and post processing of the information from the devices for a long time period is not straightforward. Fast development of IT, monitoring systems and sensors as well as possible compatibility requirements with the Bridge Register makes this task even more difficult.
3) Large scale use of monitoring systems requires well organised data storage, post processing and management. Modification of the current Bridge Register or development and maintenance of a new system for the monitoring data is likely to be very expensive.
4) There is no established practice on
    a. Who is responsible for the use and maintenance of the monitoring devices?
    b. Who is responsible for the data collection, processing and management?
    c. Who owns the data, where the data is stored, what kind of data is stored?
    d. How the data is utilised and what kind of information is stored in the Bridge Register?

To exploit better monitoring methods and devices, the first step would be to add the information on the monitored bridges, monitoring devices, suppliers and manufacturers of the monitoring systems to the Bridge Register of FINNRA. If this information is not available to the potential users, the use of the monitoring data from a number of different devices and bridges is likely to be limited.

Whether or not the monitoring results or summaries of the monitoring results should be added to the Bridge Register is a more complicated question. The Bridge Register already includes the test results from the special instructions. Similar results and summaries could be easily added from the monitoring systems. However, the utilisation of the results requires clear instructions on how these results should be used and interpreted. Furthermore, to enable comparisons between the bridges, the results should follow a standard format and the measures and indexes used should be commensurate. More sophisticated tools for analysing monitoring data are likely to be too expensive to be implemented and included in the Bridge Register.

Decreasing prices of monitoring systems opens new possibilities to monitor also small, ordinary bridges. As the number of monitored bridges increases, the instructions, coordination and commonly agreed standards become more and more important. Large scale use of monitoring systems requires clear instructions on:

- how the monitoring systems are used,
- what kind of variables and structures are monitored,
- how the results are processed, summarised and interpreted,
- how the quality of the monitoring results is managed.

To address these questions, close co-operation between bridge designers, constructors, monitoring systems providers, consultants and owner is needed. Also the role of different parties needs to be discussed and clarified. For example, should the recommendations on the use of a bridge monitoring system be made by the designers already in the designing phase?

To achieve the highest possible impact at the network level, a strong coordination on bridges and phenomena to be monitored, analysed and reported is needed. The monitoring systems should have a well defined problem setting with a strong linkage to network level bridge management addressing the critical aspects of bridge maintenance. At the bridge level, the best combination of inspections and monitoring systems requires cases by case judgements with profound bridge engineering knowledge and expertise of monitoring systems and techniques.

13 Recommendations of bridge monitoring sensors, measurements and data collection

The SIMO project has been concentrated on the long-term monitoring and testing of sensors and device. The purpose was not to search sensors, which could be used in monitoring. All the sensors tested in the project have been available by the dealers and it was not intended to develop new type of sensors. Also the measuring device has been provided from dealers, but in some cases the measuring devices have been earlier developed by the project partners company.

The main purpose in the project was to test sensors and measuring device for a quite long time and it is also intended to continue the testing after the project. In the next phase of research the monitored bridges are intended to connect to bridge management system in Finland.

13.1 Sensors

There are tens of sensors available for monitoring, but in this project only some quite common sensors have been used. The sensors have been installed on 5 bridges. The most common sensors, which can be used for a long-term monitoring are as follows:

- Deflection or movement transducers can be used to measure the deflection of the bridge or the deflection of the bridge component. The sensors used in the project can be mechanical deflection transducers, laser sensors, theodolites and photogrammetric methods. The laser sensors are quite popular, because the deflection can me measured without mechanical rod, but on the other hand fog or snow fall may prevent measurements. Also the sudden change of temperature in the air may reflect the laser beam and give unreliable results. The deflection of the bridge can be used to estimate the overall condition of the bridge and also the total weight of the heavy vehicle crossing the bridge. Mechanical deflection transducers can be used to measure the relative movements of the bridge components or the sag of the bridge bearing. Long-term deflection monitoring values can tell about the decreasing rigidity of the concrete bridge.

- Force transducers are used to measure forces between bridge components or supporting forces due to heavy crossing vehicles. The self weight of the bridge is quite high and therefore the normal transducers cannot be installed under bridge bearings. Usually strain gauges are also used to measure forces.

- Accelerometers are installed to measure the natural frequency of the bridge. In many research reports the accelerometers have been used to detect the failure in some components of the bridge. Theoretically modal analysis and FE (Finite Element) calculations can be used to detect the exact failure point in the bridge, but in reality the environmental conditions and non-rigid connections have effect on natural frequencies and possible failure point is difficult to specify. The accelerometers are very sensitive to high frequencies, which sometimes hide the important low frequencies. The first natural frequency of some type of bridges (e.g. suspension bridges) is quite low and therefore accelerometers sensitive to low frequencies have to be selected. The accuracy of the low frequency accelerometers is not high enough to measure (static) deflections induced by heavy traffics. The vibration of the bridge can also be measured by other sensors e.g. deflection and force transducers. The damping of the bridge can also be calculated using acceleration-time series. Natural frequency values are needed when developing the physical model (e.g. FE model) of the bridge.

- The most common sensor used to measure forces and small deflections (strains) is strain gauge. The gauge is usually glued or welded on steel surface of steel beams (steel bridge) or reinforcements inside the concrete (concrete bridge or deck of the bridge). The strain gauge is measuring the strain of steel induced by external forces or change of temperature. If the change of temperature does not cause stresses the effect on temperature has to be eliminated. Usually the temperature change is quite slow and strains caused by the traffics can be measured without temperature correction. If strain gages are intended to use for long-terming strain measurements further research is needed due to creeping of clue or gauge. The strain gauges are used by connecting gauges to Wheetstone bridge to have sensitive enough. If only one gauge is used the others gauges have to be substituted with resistances.

- Optical fibres are also used to measure temperatures, strains and moisture of the structure. Optical fibre is quite cheap but measuring device is more expensive than device used for voltage measurements. The advantage of the optical fibres is the capability to measure from many points using only one fibre including Braggs gratings. Mostly the fibres are installed inside the structure e.g. inside the concrete near reinforcements. Also fibres are sensitive for changes in temperature and therefore the temperature measurements are included in all measurements. The fibre optics is usually used for slow (static) measurements due to measuring device data collection speed. The measuring frequency is depended on the amount of Bragg gratings on a fibre.

- Humidity sensors are used to measure humidity inside the structure and they are needed to estimate and calculate the corrosion speed of reinforcements and also the deterioration of the concrete or steel components. The condition of the water protection layer is important to know, but there is not available cheap sensors, which will show water leaking everywhere on a bridge deck. Optical fibres can be used to detect water leaking, but they should be installed over the whole deck of the bridge.
- Corrosion sensors are mostly based on current measurements inside the concrete. In paragraph 7.2 is presented the anode-ladder sensor, which is quite common type of corrosion sensors. The corrosion speed inside the concrete is depended of the climate conditions and humidity, which is changing a lot day after day. Therefore the continuous and permanent measurements are needed to have reliable results. Also the corrosion may change in different points of the bridge reinforcements, but the critical points in the bridge are difficult to detect using only a few measuring points.
- The climate conditions are measured using weather stations or separate sensors. Nowadays in every country e.g. in Finland there is already comprehensive weather stations network, but if local weather information is needed near the bridge, the separate weather station has to be installed. In Finland the weather information is collected by Finnish Meteorological Institute and also FINNRA is collecting information using weather stations situated on the main roads.
- Thermometers are commonly used to detect the temperature of the bridge or components of the bridge. The temperature can be measured using thermocouples, PT100 thermometers or also optical fibres can be used.
- Wireless sensor has been developed in recent times and seems to be a very important possibility in the monitoring in the future. Today the main problems which have to be solved are the lifetime of battery and the range of connection. The microcircuits in wireless sensors have been developed to perform simplified tasks with low energy. They are also capable to 'sleep' to save energy during measurements. Also they are developed to transfer data to base station directly or via other sensors generating thus the smart sensors network. The communication distance between sensors or base stations is limited to 100 m outside due to limited radio transmission power.

Usually sensors are working quite reliable, because they are tested to withstand severe conditions. The life age of sensors may be up to 10 or 20 years. If the sensors have been installed on the surface of the bridge they can be replaced quite easy, but if they are situated inside the structure and has been installed during building the reliability of sensors is very important.

13.2 Measuring equipments

Most of the sensors used in bridge monitoring have been designed using voltage or currency output and which can be measured e.g. by pc and data acquisition card. Nowadays also some models of measuring cards are able to supply directly accelerometers without any extra amplifier. On the other hand strain gauges are only working with strain gauge amplifier, which must be included in monitoring equipments. Some sensors e.g. weather stations are supporting digital output and therefore cannot be measured by normal data acquisition card.

The normal pc is not suitable for long-term monitoring, because it should work in very severe conditions like temperature and humidity change and sometimes in strong vibrations without service. Rolling hard drive and fun are not designed to work for a long time in a very severe conditions and especially hard drive is sensitive for vibration and impacts. However there are available industrial pc computers which have been designed without hard disk and fun, but also the operating system should be stable to work for a long time without fatal errors. Pc and operating system like Windows is not reliable enough and must be booted at least once in a day or once in a week. Unfortunately the pc is not capable to measure anything during booting. Concerning the programming, pc is easy to program for monitoring when graphical programming languages are used.

The second possibility for monitoring device is to use (micro) logger for monitoring. The logger has been tested to run in very severe conditions (e.g. -40 °C … + 50 °C) and is also designed to work for a long time. The logger is using individual programming language, which is not quite easy to use. On the other hand the measuring program is running quite reliable and data can be copied to laboratory e.g. width modem. Logger is also suitable for short period measurements, because it can be battery operated. The maximum battery life may be from one week to 2 month depending on the sensors and battery capacity.

The third possibility is to use programmable automation controller (PAC). PAC is a compact controller that combines the features and capabilities of a PC-based control system with that of a typical programmable logic controller (PLC). A PAC thus provides not only the reliability of a PLC, but also the task flexibility and computing power of a PC. PACs are most often used in industrial settings for process control, data acquisition, equipment monitoring, machine vision, and motion control. Additionally, because they function and communicate over popular network interface protocols like TCP/IP, OLE for process control (OPC) and SMTP.

When selecting the measuring device it should keep in mind the device should work reliable for a long time, but also be easy to repair or replace with same or other type of equipment. This means, the monitoring and measuring program should be exactly documented. It is possible and obvious the measuring device model has changed or even out of manufacturing during long-term monitoring.

13.3 Data transfer and data saving

The measured data can be saved on the hard drive of measuring device, but in long-term monitoring the data has to be transferred to laboratory, which can be done using ADSL (Asymmetric Digital Subscriber Line) if wired phone connection is available or using wireless GSM (Global System for Mobile Communications) modem. It is recommended the data is analyzed in measuring device to minimise the amount of transferred data. Only if the data processing is not completed or the measuring frequency is low (e.g. 0.1 Hz), the whole data can be copied to server via ADSL or GSM.

The data should be saved systematically to database in server for further analyzing. In the future the monitoring, design model, information model and service life model have to be connected to work together and for creating an effective bridge management tool.

13.4 Post processing of data

In long-term monitoring the post processing of data is very important task, because the advantage of monitoring can only be showed by building efficient tools and programs for data processing. In a rare occasion the pure measured results are needed to estimate the condition of the bridge or structure. Therefore the usage of measured data have to be considered carefully when selecting sensors and measuring devices for monitoring. The following simplified methods can be selected to process the data

- To reduce the amount of data, maximum and minimum values of the fixed period are gathered and showed (e.g. maximum and minimum values/minute or day).
- The trend of average or extreme values are calculated and shown.
- The number of exceeding of thresholds is calculated and classified (statistics).
- Exceeding of critical action limit is saved and send to control room or to authorities (alarms).
- The measured values or critical values are used to calculate the capacity of the structure or component of the structure.

Traditionally the processed data has been given by paper reports, but nowadays the electrical and statistical reporting is recommended.

13.5 Bridge monitoring and bridge maintenance

Monitoring of bridges can be seen as part of the infra maintenance system (*Fig. 13.5.1*). In the future probably all the infra structures will be included into the same software platform and can be administrated using simplified programs and tools.

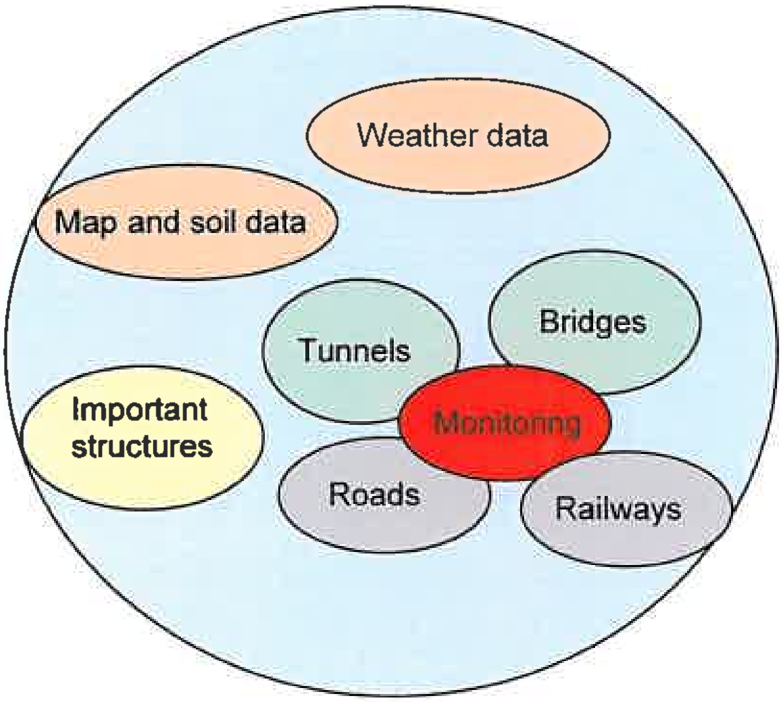


Fig. 13.5.1. Monitoring and infra maintenance.

Monitoring of bridges can be utilised in many ways in maintenance of bridges and safe usage e.g. with following ways:

- To control the quality of the bridge after building, preparing or rehabilitation.
- To send an alarm to authorities or control room after traffic accident, fire, explosion or unexpected natural phenomena.
- To monitor the bridge against terrorism or illegal usage.
- To monitor and guide heavy or unexpected lorries or carriages.
- To gather continuously reliable information and data of the bridge structures and also inside the structure for maintenance.
- To give valuable information for designers of the behaviour of the bridge.
- To gather information of the heavy vehicles going over the bridge, e.g. types, weights, axel loads and speeds.

13.6 Recommendations to start monitoring of bridges as a part of bridge maintenance system

The monitoring device, sensors and data analyzing is developing all the time, but at the moment much research and resources are available for the infra monitoring. On the other hand, long-term monitoring will give the results after many years and therefore it should be started to day or in a near future. The principles, advantages and usages to begin the bridge monitoring are as follows:

- To start monitoring will also start the data collection which will be valuable when needed in the future.
- The good and reliable enough monitoring sensors and measuring device are already available and can be installed in bridges.

- Monitoring devices can also be used for alarm and emergency purposes and also to control the quality of the work or materials.
- The monitoring should be included as a part of the bridge building process. Some sensors e.g. strain gauges in reinforcements and optical fibres have to be installed before concrete casting. Power supply if possible and cable gutters have to be included in design process. If monitoring is included in design process, instrumentation is easier and cheaper to implement.
- All bridges are not wise to monitor, only bridges with long span, new type or bridges belonging to common type can be monitored. Also bridges having unknown failures or defects can be researched be sensors to find out reasons for odd behaviour.
- The administration of infra structures have already began. The administration of bridges including monitoring is one important section which has to develop within infra administration.
- The analysing methods and life cycle models have to be researched and developed to utilize better monitoring results.

In Finland there are nowadays over 14 000 bridges, most of them are quite short concrete bridges. In order to have a comprehensive bridge monitoring ensemble, total 5 to 10 different types of bridges have to be monitored in a year, which means total 50 to 100 monitored bridges after 10 years.

14 Conclusions

In SIMO project five different kind of bridges has been monitored to test sensors and monitoring device in a long-term monitoring. The sensors and measuring device have been working quite well, but still maintenance visits are needed to guarantee continuous operation. It is recommended that the monitoring will be continued also in the future to have more data and more information of the long-term behaviour and reliability. In the project only common types of sensors have been tested, but in the future more information is needed for other type of sensors. Bridge monitoring can be performed easily by PC, but the reliability is not very good due to rotating components and operating system. The common and reliable programmable measuring device is needed to guarantee long-term monitoring of bridges. Wireless sensors are developing very fast, but still the low battery age and short radio waves range is a problem, and therefore the usage is now only for short-term monitoring. The long-term monitoring can also include control and classification monitoring for traffic and if needed automatic monitoring and video pictures interpretation can be used in emergency cases and to send alarms to authorities. The monitoring sensors can also be used to control the quality of the work and materials in the bridge and also to develop strength and life-cycle models to be more reliable.

Bridge monitoring and infra (also bridge) administration can operate together and therefore the scenario has to keep in mind, when monitoring decisions will be made in the future.

Co-operation also international between companies and research institutes is needed when developing monitoring equipments and software due to different skills concerning the whole monitoring area.

15 Summary

The report is the final report of SIMO (Monitoring of bridges) TEKES (Finish Funding Agency for Technology and Innovation) project composed by VTT and also other project partners.

The report describes common sensors and monitoring device which have been installed and used in five selected road bridges in Finland. The monitored bridges have been, Kirjalansalmi suspenson bridge in Parainen, Boxby concrete bridge in Sipoo, Hännilänsalmi suspension bridge in Viitasaari, Jylhänranta concrete bridge in Pulkkila and Siikajoki bridge in Revonlahti. The sensors used for monitoring have been deflection transducers, laser sensors, accelerometers, strain gauges, thermometers, humidity sensors, optical fibres, corrosion sensors and weather stations. Most of the measuring devices and sensors have been obtained from normal shop, only some measuring sensors and measuring device have been developed before the project beginning. The aim was also to test wireless connections and data transfer to laboratory. The measured data have been verified to physical models e.g. FE (Finite Element) and life cycle models in order to develop and improve existing models.

The sensors and measuring device have been working quite well for one or two years. Most of measured data could have been copied to laboratory using ADSL or GSM modems. In most cases the copied data have been afterwards analyzed in laboratory, but also in some cases analyzing have performed also on site using running programs in measuring device. Monitoring device in Kirjalansalmi suspension bridge have been connected to network using ADSL modem and all the data could be copied to laboratory and also triggering values can be included to send alarm messages. In Boxby bridge the temperature, humidity and weather conditions are measure to estimate the deterioration of the concrete and also to make quality control after restoration. In other bridges measurements have been performed to research the conditions of the bridge or to develop the strength model of the bridge. The benefit of measured and analyzed data have been estimated in maintenance work of the bridges.

During the project it has been found, there are nowadays available reliable sensors with adequate reliable and measuring device, which could be installed in bridges to start accumulation of data. The data can be transferred to laboratory via ADSL or GSM modems for further analyzing. The monitored data can been used for alarm sending, to control weights of heavy vehicles and the quality of restoration. Also the data can be verified to results of strength model.

Further monitoring and analyzing is needed to find out the reliability of monitoring device and sensors and to connect all the measured data and analyzed data to bridge information model, quality model, life cycle model, strength model and design model.

References

1. Background document D5.2.S1, Guidelines for monitoring of steel bridges, Sustainable Bridges.

2. A. Miyamoto, X. Zhou, X. Shao. Lifetime engineering of civil infrastructure, part 2. Yamaguchi University, November 2007.

3. A. Miyamoto, S. Hamada, S.H: Lee. Lifetime engineering of civil infrastructure, part 3. Yamaguchi University, November 2008.

4. N R Buenfield & all. Intelligent monitoring of concrete structures. Ciria. London 2008.

5. IABSE Conference. Information and Communication Technology (ICT) for Bridges, Buildings and Consruction Practice. Helsinki 2008.