TITLE PAGE

Submission date: 31.07.2002

Word count: 7488

Structural Monitoring of Concrete Bridges during Whole Lifespan

Dr. Branko Glisic, Solutions & Services Manager, SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland, Phone: +41 91 610 18 00, Fax: +41 91 610 18 00, e-mail: glisic@smartec.ch

Dr. Daniele Inaudi, CTO, SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland, Phone: +41 91 610 18 00, Fax: +41 91 610 18 00, e-mail: inaudi@smartec.ch

ABSTRACT

Abstract. Bridges are omnipresent in every society and they affect its human, social, ecological, economical, cultural and aesthetic aspects. This is why a durable and safe usage of bridges is an imperative goal of structural management. Measurement and monitoring have an essential role in structural management. The benefits of the information obtained by monitoring are apparent in several domains. First, it helps to improve and enlarge the knowledge concerning structural behaviour and makes accurate calibration of numerical models describing and predicting this possible behaviour. Thus, project and construction can be optimised in structural and economical aspects. Second, permanent monitoring can give early indications of structural malfunction. In this way, safety measures can be considered in time, and intervention on the structure can be performed immediately and with minimal economic losses. The lifespan of a bridge starts with construction. Followed by testing of the bridge and most importantly the service period. During service, the structure may be refurbished, strengthened or enlarged, according to necessities. Finally, at the end of usage, the bridge can be dismantled. Monitoring during each period of the bridge lifespan is important and can give rich information allowing a better understanding of structural behaviour and consequently better planned and less expensive management. In this paper, a first brief introduction to the monitoring process is presented. Then, the importance of the monitoring of each period of a bridge's life is examined step by step, and illustrated in an on-site example. Experience using a monitoring system designed for lifespan monitoring of concrete bridges is presented in this work.

Structural Monitoring of Concrete Bridges during Whole Lifespan

Dr. Branko Glisic, Solutions & Services Manager, SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland, Phone: +41 91 610 18 00, Fax: +41 91 610 18 00, e-mail: glisic@smartec.ch
Dr. Daniele Inaudi, CTO, SMARTEC SA, Via Pobiette 11, 6928 Manno, Switzerland, Phone: +41 91 610 18 00, Fax: +41 91 610 18 00, e-mail: inaudi@smartec.ch

Abstract. Bridges are omnipresent in every society and they affect its human, social, ecological, economical, cultural and aesthetic aspects. This is why a durable and safe usage of bridges is an imperative goal of structural management. Measurement and monitoring have an essential role in structural management. The benefits of the information obtained by monitoring are apparent in several domains. First, it helps to improve and enlarge the knowledge concerning structural behaviour and makes accurate calibration of numerical models describing and predicting this possible behaviour. Thus, project and construction can be optimised in structural and economical aspects. Second, permanent monitoring can give early indications of structural malfunction. In this way, safety measures can be considered in time, and intervention on the structure can be performed immediately and with minimal economic losses. The lifespan of a bridge starts with construction. Followed by testing of the bridge and most importantly the service period. During service, the structure may be refurbished, strengthened or enlarged, according to necessities. Finally, at the end of usage, the bridge can be dismantled. Monitoring during each period of the bridge lifespan is important and can give rich information allowing a better understanding of structural behaviour and consequently better planned and less expensive management. In this paper, a first brief introduction to the monitoring process is presented. Then, the importance of the monitoring of each period of a bridge's life is examined step by step, and illustrated in an on-site example. Experience using a monitoring system designed for lifespan monitoring of concrete bridges is presented in this work.

INTRODUCTION

Civil structures are omnipresent in every society, regardless of culture, religion, geographical location and economical development. It is difficult to imagine a society without buildings, roads, rails, bridges, tunnels, dams and power plants. Structures affect human, social, ecological, economical, cultural and aesthetic aspects of societies and associated activities contribute considerably to the gross internal product. Therefore good design, quality construction as well as durable and safe usage of civil structures are goals of structural engineering.

The most safe and durable structures are usually structures that are well managed. Measurement and monitoring often have essential roles in management activities. The data resulting from the monitoring program is used to optimise the operation, maintenance, repair and replacing of the structure based on reliable and objective data. Detection of ongoing damage can be used to detect deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

Many structures are in much better condition than expected. In these cases, monitoring allows to increase the safety margins without any intervention on the structure. Taking advantage of better material properties, over-design and synergetic effects, it is possible to extend the lifetime or load-bearing capacity of structures. A small investment at the beginning of a project can lead to considerable savings by eliminating or reducing over-designed structural elements.

Malfunctioning of civil structures often has serious consequences. The most serious is an accident involving human victims. Even when there is no loss of life, populations suffer if the infrastructure is partially or completely out of service. Collapse of certain structures, such as nuclear power plants, may provoke serious ecological pollution. The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by the costs of reconstruction while the indirect impact involves losses in the other branches of the economy. Fully collapse of historical monuments, such as old stone bridges and cathedrals, represent an irretrievable cultural loss for society.

Learning how a structure performs in real or laboratory conditions will help to design better structures for the future. This can lead to cheaper, safer and more durable structures with increased reliability and performance. Structural diversity due to factors such as geographical region, environmental influences, soil properties, loads etc.

makes absolute behavioural knowledge impossible: there are not two identical structures. Structural monitoring represents a good way to enlarge knowledge of structural performance.

In this paper, first an introduction to the monitoring process and concept of structural monitoring of concrete structures is presented. It includes notion of structural monitoring, presentation of principal components of the monitoring systems and monitoring assessment. In the second part of paper, particularities of monitoring during each stage of a concrete bridge life, from the pouring to the use, are presented and illustrated by examples performed on-site using the monitoring system called SOFO.

STRUCTURAL MONITORING PROCESS

The monitoring process consists of the following activities:

1. Selection of the monitoring strategy
    a. Identification of parameters to be monitored
    b. Monitoring assessment and schedule
    c. Selection of monitoring system or systems
    d. Selection of sensor topology and network
2. Installation and maintenance of monitoring system
3. Collecting and storage of data
4. Data postprocessing (visualization, interpretation and analysis)

These activities are briefly presented in this section.

Selection of monitoring strategy 1: monitoring parameters, monitoring assessment and schedule

Monitoring (or auscultation) of structures involves recording of time dependent parameters during certain periods. To start a monitoring project, it is important to define the goal of the monitoring i.e. to identify the parameters to be monitored, monitoring assessment and schedule. Monitored parameters can be physical, mechanical, chemical or other, and are usually present in each point of the structure. These parameters have to be properly selected in a way that they reflect the structural behavior. Each structure has its own particularities and consequently its own selection of parameters for monitoring.

There are different approaches to assess the structure and we can classify them in three basic categories: static monitoring, dynamic monitoring, and system identification and modal analysis, and these categories can be combined. Each category is characterised by advantages and challenges and which one (or ones) will be used depends mainly on the structural behaviour and the goals of the monitoring.

Each category can be performed during short and long periods, permanently (continuously) or periodically. The schedule and pace of monitoring depends on how fast the monitored parameters change in time. For some applications, periodical monitoring gives satisfactory results, but information which is not registered between two inspections is lost forever. Only continuous monitoring during the whole lifespan of the structure can register its history, help to understand its real behaviour and fully exploit the monitoring. The investment in the maintenance of the structure, using periodical inspections as a mean of control, can exceed the cost of a new structure.

Selection of monitoring strategy 2: monitoring systems and structural monitoring

The totality of means used for monitoring is called monitoring system. The main components of a monitoring system are sensors, carriers of information, reading unit, interfaces and data managing subsystems. The aim of the sensor is to detect the magnitude of the monitored parameter and to transform it to transportable information (e.g. optical of electrical information). The carrier leads the information from the sensor to the reading unit, which decodes the information and retrieves the magnitude of the monitored parameter. The measurement is visualised and presented to the operator by a user interface. Finally, the data managing subsystem is necessary to control and manage the data obtained from monitoring. The components of a monitoring system can be separated or differently combined (e.g. sensor and carrier can make one device). An example of a monitoring system and its components, in case of the system called SOFO, is presented in Figure 1.

Generally, the sensors can be discrete or distributed. Discrete sensors can have short or long gage. Discrete sensors detect the observed parameter only at the location where it is installed, while the distributed sensor detects the observed parameter in several locations of the structure. SOFO, Bragg-grating and Brillouin scattering based sensors are examples of discrete long-gage, discrete short-gage and distributed sensors. Selection of type of sensor depends on level on which the structure is to be monitored.

Monitored parameters can genrally be observed at material, structural or both material and structural level. Main difference between material and structural monitoring is in used monitoring strategy and monitoring system: material monitoring provides information related to material behaviour, but poor information concerning the structural behaviour; structural monitoring provides information related to structural behaviour. The difference between the material and structural monitoring is highlighted in Figure 2.

In Figure 2, the strain monitoring of a bended concrete beam using four discrete short-gage sensors (g_{1t}, g_{1b}, g_{2t} and g_{2b}) and two long-gage sensors (s_t and s_b) is presented (1). All sensors placed in the top of the beam (g_{1t}, g_{2t} and s_t) measure the same value, while the bottom sensors (g_{1b}, g_{2b} and s_b) measure different values, due to the crack openings. Short-gage sensors (g_{1b} and g_{2b}) are highly influenced by crack presence and they provide information related only to their locations in the beam. The long-gage sensor (s_b) measures an average value of the strain combined with the crack openings, which is related to the structural behaviour. E.g. it is possible to determine structural behaviour of the beam by calculating its curvature as ratio between measurement difference and distance between sensors (2). There is no simple technique that allows determination of structural behaviour using results obtained from short-gage sensors. Hence, for the monitoring strategy presented in Figure 2, long-gage sensors allow monitoring at structural level, while the short-gage sensors allow monitoring on material level. This is why in this paper we will concentrate on long-gage sensors.

Selection of monitoring strategy 3: selection of sensor topology and sensor network for structural monitoring

Long-gage sensors can be combined in different topologies and networks, depending on geometry and type of structure to be monitored, allowing monitoring and determination of important structural parameters such as average strains and curvatures in beams, slabs and shells, average shear strain, deformed shape and displacement, crack occurring and quantification as well as indirect damage detection.

To perform a monitoring at a structural level it is necessary to cover the structure, or a part of it with sensors. For this purpose the structure is firstly divided into cells (see Figure 1). Each cell contains a combination of sensors appropriate to monitor parameters describing the cell's behavior. Knowing the behavior of each cell, it is possible to retrieve the behavior of the entire structure. The combination of sensors installed in a single cell is called sensor topology in this paper. Totality of sensors is called sensor network.

Sensor topology in each cell is appropriated to the parameter which is representative for this cell (e.g. strain, curvature, etc.). Sensor network can contain cells with different topologies. The most used are the simple topopgy, the parallel topology and the crossed topology (3).

Simple topology consists of single sensor installed by preference in a direction of principal strain. It is mainly used for monitoring linear structural elements (beams), which are subject to axial compression or traction combined with longitudinal shear stresses and dead load (see Figure 3), e.g. piles or columns. In these cases no bending occurs and the strain is constant over the cross-section of the beam. Thus, the sensor can be installed regardless to the position in the cross section, and provide information directly related to the structural behavior of the monitored elements. An example of a cell equipped with simple topology subject to normal stresses (σ_i), longitudinal shear stresses (friction τ_i) and dead load (g_i), is presented in Figure 3. If several cells containing simple topology are enchained and fully cover the monitored element, then distribution of strain along the element as well as relative displacement in direction of element can be retrieved. The relative displacement is obtained as integral of strain. In addition, if the Young modulus and thermal expansion coefficient of construction material are known, and time dependent strain (shrinkage and creep) can be estimated, then the distribution of normal forces can be qualitatively determined. We note that simple topology can also be used in cases when the strain field in monitored element is complex, and principal strain is not in direction of the sensor. The sensor will provide information (measure) the average strain in the direction of its gage-length, but no direct conclusions concerning the structural behavior of monitoring element can be carried out.

Parallel topology consists of two parallel sensors with equal gage lengths installed at different levels of structural element cross-section. Direction of sensors corresponds by preference to the directions of normal strain lines. Parallel topology is schematically presented in Figure 2. The parallel topology is used for the monitoring of parts of the structure which is subject to bending: the sensors installed at different levels in cross-section will measure different values of average strain allowing monitoring of average curvature in the cell. The average curvature is calculated assuming that the Bernoulli hypothesis (2) is satisfied. If the monitored part of the structure contains representative number of cells equipped with parallel topology (e.g. for beams the minimum number is three) then the average curvature can be monitored in each cell, and consequently the distribution of curvature over entire monitored part of structure can be retrieved. Deformed shape of the monitored part of the structure is obtained by double integration (2) of curvature. If, in addition, two characteristics related to absolute displacement are monitored (e.g. displacements in two points or one displacement and one rotation) and these characteristics are used as boundary conditions for double integration, then it is possible to determinate absolute displacement perpendicular to direction of sensors. Since the curvature is directly proportional to bending moment, the distribution of curvature helps to qualitatively determinate distribution of bending moments. If Young modulus, moment of inertia and thermal expansion coefficient are known, and time dependent deformations can be estimated, then the distribution of bending moment can be quantified. If the ultimate strain in concrete is known, then from geometrical proportion and position of neutral axis it is possible to determine depth of cracks as well as sum of their openings in each cell.

Crossed topology consists of two crossed sensors installed with a pre-defined angle with respect to direction of normal strain lines. The aim of this topology is to detect and quantify shear strain. The angles of sensors are by preference identical by value, but different by sign. However, it is possible to use sensors with different angles. The algorithm allowing retrieving of shear strain depends on angles of both sensors, their gage-length and strain field in the equipped cell. Since the measurements of the sensors are influenced by normal strain too, it is recommended to set the crossing point at a neutral line. In such a way the influences of normal strain will be annulled. An example of crossed topology for sensor angles of $+\alpha_{s,i}$ and $-\alpha_{s,i}$, and the crossing point set onto the neutral line is presented in Figure 3.

Installation of monitoring system

The installation of the monitoring system is a delicate phase. Therefore it must be planned in details considering seriously on-site conditions and notably the structural component assembling activities, sequences and schedules. Main principles and issues met during the installation are briefly cited in this subsection.

The components of the monitoring system can be embedded into the fresh concrete or installed on the structure surface using fastenings, clamps or gluing. In both cases the installation of the monitoring system can annihilate the structure (e.g. embedded sensors reduce area of the cross-section, to set the connection boxes or extension cables on surface it is necessary to drill the holes and to install fastenings, etc.). Therefore, it is important to ensure that, from the structural and aestetichal point of view it is possible to install the system, and that the presence of the monitoring system as well as the installation works will not decrease the performance of the structure.

The installation takes time, and if it is to be performed during the construction of the structure, it may delay the works. Components of monitoring system that are to be installed by embedding can only be safely installed during a short period between the rebars completion and pouring of concrete. Hence, the schedule of installation of the monitoring system has to be carfully planed taking into account the schedule of works, time necessary for the system installation, but in the same time it has to be flexible in order to adapt to work schedule changes that are frequent in building sites.

When installed, the monitoring system has to be protected, notably if monitoring is performed during the construction of the structure. The protection has to prevent accidental damage during the construction but also to ensure the longevity of the system. Thus, all external influences, periodical or permanent, such as vandalism, rodents (or other animals), wind, rain, sun etc. has to be taken into account when designing the protection for the monitoring system.

Collecting and storage of data

The monitoring data can be collected manually or automatically, on-site or remotely, with or withour human intervention, periodically or continuously. These options can be combined in different way, e.g. for example during the test of the bridge it is necessary to perform measurements automatically, on-site, with human intrvention and periodically (after each load step). For long-term in use monitoring the maximal performance is automatic, remote (from the office), continuous collecting of data without human intervention.

Data can be stored in form of reports, tables, diagrams etc. on different types of supports such as electronic files (on hard disc, CD, etc.) or hard versions (printed on paper). The manner of storage of data has to ensure that data will not be lost and that a prompt access to any selected data is possible (e.g. one can be interested to access only data from one group of sensors and during a selected period of monitoring).

The softwares that manage the collecting and storage of data are to be a part of the monitoring system. Otherwise, the data management can be difficult, demanding and expensive.

Data postporcessing

Data postprocessing consists of interpretation, visualization and analysis. Collected data is in fact huge amount of numbers (dates and magnitudes of monitoring parameters), and has to be transfomed to usefull information concerning the structural beavior. This transformation depends on monitoring strategy and algorithms that are used to interpret and analyse the data. It can be performed manually, semi-automatically or automatically.

Manual data postprocessing understands manual export and analysis of data. It is practical in cases where the amount of data is limited. Semi-automatic postprocessing cosisists of manual export of data and automatic analysis using the softwares. It is applicable in cases where the data analysis is to performed only periodically. Finaly automatic postprocessing is the most convenient, since it can be performed rapidly and indepndent of data amount or frequency of analysis.

The data postprocessing has to be planned along with selection of monitoring strategy and appropriate algorithms and tools compatible with the choosen monitoring system have to be selected.

WHOLE LIFESPAN MONITORING OF BRIDGES

The importance of whole lifespan monitoring is highlighted in this section (4).

Monitoring during construction of a new bridge

Construction is a very delicate phase in the life of structures. For concrete structures, material properties change through ageing. It is important to know whether or not the required values are achieved and maintained. Defects (e.g. premature cracking) that arise during construction may have serious consequences on structural performance. Monitoring data help engineers to understand the real behaviour of the structure and this leads to better estimates the real performance and allow more appropriate remedial actions.

Important information obtained through the monitoring during construction includes the following: Estimation of hardening time of concrete in order to estimate when shrinkage stresses begin to be generated; Deformation measurements during early age of concrete in order to estimate self-stressing and risk of premature cracking; When structures are constructed in successive phases, measurement can help to improve the composition of concrete when necessary. In case of pre-fabricated structures, sensors may be useful for quality control; Optimisation between two successive phases of pouring due to evaluation of cure in previous phases; For prestressed structure, deformation monitoring of cables helps to adjust prestressing forces and determine the relaxation; Monitoring of foundation settlement helps to understand the origins of built-in stresses; Damage caused by unusual loads such as thunderstorm or earthquakes during construction may influence the ultimate performance of structures; Optimal regulation of structural position during erection; Knowledge improvement and recalibration of models.

The installation of a monitoring system during the construction phases allows monitoring to be carried out during the whole life of the structure. Since most structures have to be inspected several times during service, the best way to decrease the costs of monitoring and inspection is to install the monitoring system from the beginning.

Monitoring after refurbishing, strengthening or enlargement of bridge

Material degradation and/or damage are often the reasons for refurbishing existing structures. Also, new functional requirements for the bridge (e.g. enlarging) lead to requirements for strengthening. If strengthening elements are made of new concrete, a good interaction of new concrete with the existing structure has to be assured. Early age deformation of new concrete creates built-in stresses and bad cohesion causes delamination of the new concrete, thereby erasing the beneficial effects of the repair or strengthening efforts.

Since new concrete elements observed separately represent new structures, the reasons for monitoring them are the same as for new structures, presented in the previous subsection. The determination of the success of refurbishment or strengthening is an additional justification.

Monitoring during testing of bridge

Bridges have to be tested before service for safety reasons. At this stage, the required performance levels of structures have to be reached. Typical monitored parameters (such as deformation, strain, displacement, rotation of section and cracks opening) are measured. Tests are performed in order to understand the real behaviour of the structure and to compare it with theoretical predictions. Monitoring during this phase can be used to calibrate numerical models describing the behaviour of structures.

Monitoring during service of bridge

The service phase is the most important period in the life of a structure. During this phase, construction materials are subject to degradation by ageing. Concrete cracks and creeps, steel oxidises and may crack due to fatigue loading. The degradation of materials is caused by mechanical (loads higher then theoretically assumed) and physico-chemical factors (corrosion of steel, penetration of salts and chlorides in concrete, freezing of concrete etc.). As a consequence of material degradation, the capacity, durability and safety of structure decrease.

Monitoring during service provides information on structural behaviour under predicted loads, and also registers the effects of unpredicted overloading. Data obtained by monitoring are useful for damage detection, evaluation of safety and determination of the residual capacity of structures. Early damage detection is particularly important because it leads to appropriate and timely interventions. If the damage is not detected, it continues to propagate and the structure no longer guarantees required performance levels. Late detection of damage results in either very elevated refurbishment costs (5) or, in some cases, the structure has to be closed and dismantled. In seismic areas the importance of monitoring is most critical.

Subsequent auscultation of a structure that has not been monitored during its construction can serve as a basis for understanding the present and for predicting the future structural behaviour. This is discussed next.

Monitoring during dismantling of bridge

When the structure does no longer respond to the required performances and the costs of reparation or strengthening are excessively high, the ultimate life-span of the structure is attained and the structure should be dismantled. Monitoring helps to dismantle structures safely and successfully.

EXAMPLE OF WHOLE LIFESPAN STRUCTURAL MONITORING

Example of a whole lifespan monitoring is presented in this section. The example contains the most important results obtained after the enlargement of an existing bridge, named Versoix Bridge, in Switzerland. Since the monitoring is performed on both new and old concrete elements, and the aim is to illustrate in a best way the topic of this paper with a real application, this example is selected and presented even if the monitoring was not performed literally over the whole lifespan.

Monitoring system - SOFO

The monitoring system SOFO (French acronym for Surveillance d’Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers) is used in presented example. It is based on low-coherence interferometry in optical fiber sensors (6). It consists of long-gage sensors, a reading unit and data acquisition and analysis software.

Typical sensor gage-length ranges from 250 mm to 10 m. The resolution (minimal detectable change of optical signal translated in measured deformation) reaches 2 µm independently of the gage length and accuracy of measurement is 0.2% of the measured value (linear correlation between the optical signal and the deformation). The dynamic range of the sensors is 0.5% in compression and 1.0% in elongation, and single measurement typically takes 6 to 10 seconds.

The SOFO system was developed in early 1990’s and since 1995 it has been commercialized and applied to the monitoring of a wide range of civil structures, such as geotechnical structures, bridges, dams, residential and industrial buildings, just to name a few (7). The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 5 years, making it ideal for both short- and long-term monitoring. Being designed for direct embedding in concrete, the sensors allow easy installation; require no calibration and feature high survival rate (better than 95% for concrete embedding). The long gage-length makes them more reliable and accurate than traditional strain sensors, averaging the strain over long bases and not being influenced by local defects in material (e.g. cracks and air pockets). More information on the SOFO system and its applications can be found in the references (7). The components of the system are presented in Figure 1.

Description of Versoix Bridge

The North and South Versoix bridges are two parallel twin bridges (8). Each one supports two lanes of the Swiss national highway A9 between Geneva and Lausanne. In order to support a third traffic lane and a new emergency lane, the exterior beams were widened and the overhangs extended (see Figure 4).

Because of the added weight and pre-stressing, as well as the differential shrinkage between new and old concrete, the bridge bends (both horizontally and vertically) and twists during the construction phases. In order to increase the knowledge on the bridge behaviour and performance and to optimise the concrete mix, the engineer decided to monitor strain, displacement and temperature over whole lifespan of the bridge.

The sensors were surface mounted onto the existing (old) part of the bridge and embedded into the fresh concrete of the new part of the bridge. Eight sensors per cross-section were installed as shown in Figure 5, and total of 12 sections is equipped as shown in the same figure. The sensors are connected to reading unit by means of intermediate connection boxes and multifibre extension cables. The central measurement point with the reading unit is situated near the abutment.

Monitoring during and after enlargement

The main concern during the construction was to ensure good interaction between old and new concrete. In order to control the interaction, two sensors are installed side-by-side in new and old concrete (see Figure 5). Monitoring performed during more than two months after the pouring showed that both sensors measured the same deformation, i.e. the deformation imposed by new concrete (expansion and contraction due to hydration process as well as the shrinkage) was transferred to the existing concrete with no delamination. Therefore, the interaction between the old and new concrete is estimated as a very good (Figure 6). In addition horizontal deflection due to unequal heat on left and right side of the cross-section and different pouring times is detected (see Figure 8).

Monitoring during enlargement works helped to optimize concrete mix design. The pouring was performed in several stages using the same, specially designed workforms. After the first pouring stage, an important shrinkage was observed, which was not in accordance with predicted models. Hence, the concrete mix design was optimized for the next stages.

Monitoring during testing of bridge

During a load test, performed in Mai 1998 after the end of construction works, the vertical displacement of the bridge was also monitored using the same fibre optic sensors. Figure 7 shows an example of the measurement taken during the load test of the bridge. Values obtained with SOFO sensors are calculated using double integration of curvature. Measurements were also performed using dial gages (invar wires installed and measured by IBAP-EPFL under the bridge) and are presented in the same figure. Results of test confirmed the design performances of enlarged bridge.

Monitoring during service of bridge

Long-term monitoring of the Vesoix Bridge continues. Monthly quasi-static measurements are performed in order to monitor strain and displacement evolution of the bridge. Five years strain evolution of a cross-section is presented in Figure 8. After the cross-section is bended horizontally due to unequal heat and different time of concrete pouring, all sensors measure approximately same deformation confirming that the cross-section is not exposed to unexpected bending due to damage or delamination. Thus the traffic is not reduced and safety margin is maintained.

In Figure 9 diagrams of strain obtained by measurements (sensor A11) are compared with the models (Strain – calc. Shrinkage + temperature) and very good accordance is observed confirming good design and realisation of the bridge. The evolution of shrinkage is not finished but it is stabilised (see Figure 9). The seasonal temperature variation, influenced behaviour of the bridge and can also be seen in Figure 8.

CONCLUSIONS

Structural monitoring is defined as such type of monitoring that allows conclusions concerning global, structural behaviour of the structure and not local, material behaviour. Since the concrete is non-homogeneous material, containing inclusions (aggregate) and discontinuities (cracks) it is recommended long-gage sensors to be used for its structural monitoring. Since the concrete is subject to dramatic dimensional and structural changes during hydration process, it is recommended the sensors be embedded and start monitoring with very early age.

It is demonstrated that long-gage sensors offer large possibilities since they provide measurement that is not influenced by local material defects. Moreover, they are able to monitor defects such as cracks in reinforced concrete. The averaged value obtained by long-gage sensors is fully in accordance with philosophy of reinforced concrete where the cracked concrete is considered as homogenous material at macro-level.

It is not enough to use appropriate equipment for monitoring, but it is also necessary to employ good monitoring strategy. What topology of sensor will be used for monitoring depends on type of the structure and of expected loads. Good monitoring strategy can provide excellent results with relatively limited budget.

The whole lifespan monitoring comprehends continuous or periodical registering of parameters including all phases of the structure life. The benefits of whole lifespan monitoring of bridges are presented in this paper. They reflect through better planned and less costly structural management, increase of safety and improvement of knowledge concerning real structural behaviour. The whole lifespan monitoring calls for sophisticated monitoring systems, which performances satisfy safety, technological, economical and esthetical aspects, being easy to use, fast to install, durable, reliable, stable, independent of human intervention and insensitive to external influences.

The advantages of whole lifespan structural monitoring during different periods of the structure life are presented and illustrated by results obtained using the SOFO system. Real on-site example carried out using SOFO monitoring system installed onto the Versoix Bridge in Switzerland. The following benefits are gathered from this particular project:

- Evaluation of interaction between the new and existing concrete;
- Optimization of concrete mix design;
- Evaluation of load bearing performance and comparisons with predicted design;
- Evaluation of long-term deformation and its influence to degradation of bridge performance (no degradation over 5 years).
- Safety margin maintained as a consequence of monitoring.
- No need to stop the traffic in order to evaluate current performance.

The presented benefits fully justify the whole lifespan monitoring concept.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. Samuel Vurpillot, Dr. Pascal Kronenberg and personnel of IMAC-EPFL for collaboration, technical support and interest in new technologies.

REFERENCES

1. Glisic B., Inaudi D., Long-gage fiber optic sensors for global structural monitoring, First International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures, ISIS Canada, September 19-20, 2002, Winnipeg, Manitoba, Canada
2. Vurpillot S., Analyse automatisée des systèmes de mesure de déformation pour l'auscultation des structures, Ph.D. Thesis N° 1982, EPFL, Lausanne, Switzerland (1999)
3. Inaudi D., Glisic B., Long-gage sensor topologies for structural monitoring,The first fib Congress on Concrete Structures in the 21st Century, October 13-19, 2002, Osaka, Japan
4. Glisic B., Inaudi D., Vurpillot S., Whole lifespan monitoring of concrete bridges, IABMAS'02, First International Conference on Bridge Maintenance, Safety and Management, July 14-16, 2002, Barcelona, Spain
5. Frangopol D. M., Estes A. C., Augusti G., Ciampoli M., Optimal bridge management based on lifetime reliability and life-cycle cost, Short course on the Safety of Existing Bridges, ICOM&MCS, pp 112-120, EPFL, Lausanne, Switzerland (1998)
6. Inaudi D., Fiber Optic Sensor Network for the Monitoring of Civil Structures, Ph.D. Thesis N°1612, EPFL, Lausanne, Switzerland, 1997.
7. www.smartec.ch
8. Inaudi D., Vurpillot S., Glisic B., Kronenberg P., LLoret S., Long-term Monitoring of a Concrete Bridge with 100+ Fiber Optic Long-gage Sensors, SPIE's International Symposium on Nondestructive Evaluation Techniques for Aging Infrastructure & Manufacturing, Vol. 3587, Pages 50-59, March 3-5, 1999, Newport Beach, USA

FIGURE CAPTIONS

Figure 1: Typical application and components of the SOFO monitoring system, with network consisting of cells equipped with parallel topology

Figure 2: Parallel topology used for structural monitoring and difference between long-gage structural monitoring and short-gage local material monitoring

Figure 3: Simple and crossed topology

Figure 4: View to Versoix Bridge before enlargement

Figure 5: Position of sensors in cross-section , and sensor network along the bridge

Figure 6: Old-new concrete interaction monitoring

Figure 7: Monitoring during the load test

Figure 8: Versoix bridge five-years strain evolution

Figure 9: Uncoupling of shrinkage and temperature

LIST OF FIGURES

Figure 1: Typical application and components of the SOFO monitoring system, with network consisting of cells equipped with parallel topology

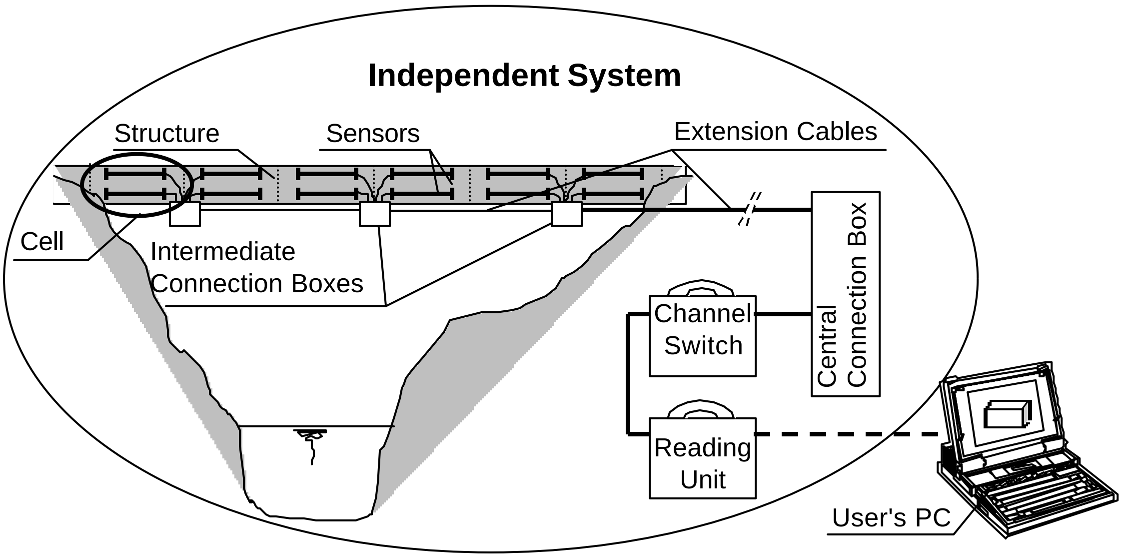

Figure 2: Parallel topology used for structural monitoring and difference between long-gage structural monitoring and short-gage local material monitoring

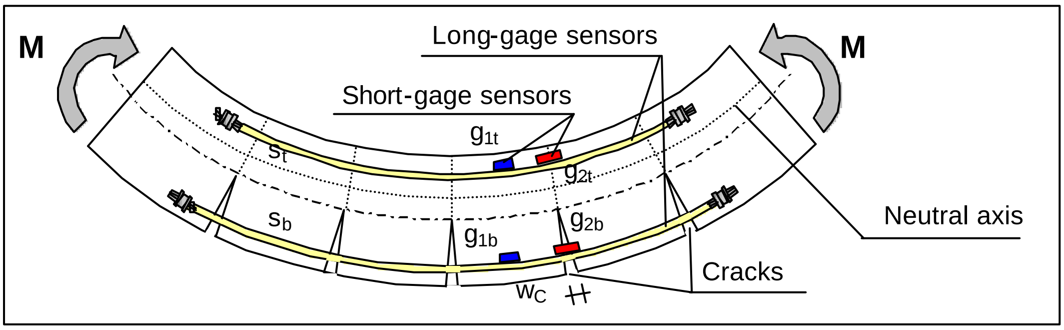

Figure 3: Simple and crossed topology

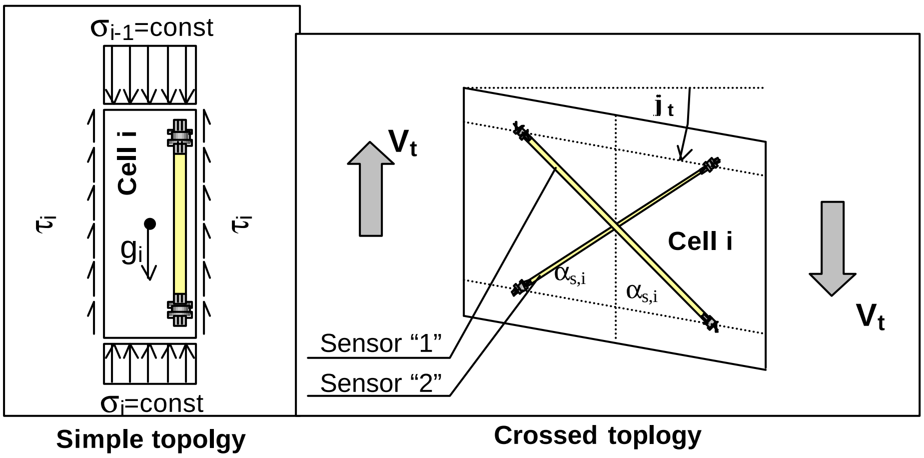

Figure 4: View to Versoix Bridge before enlargement

Figure 5: Position of sensors in cross-section , and sensor network along the bridge

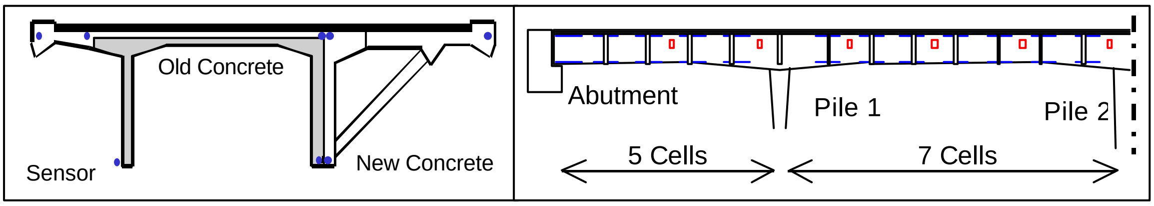

Figure 6: Old-new concrete interaction monitoring

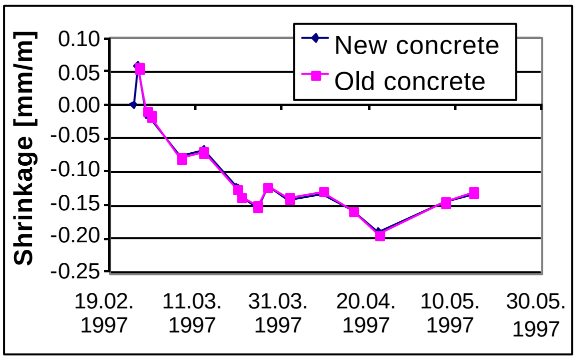

Figure 7: Monitoring during the load test

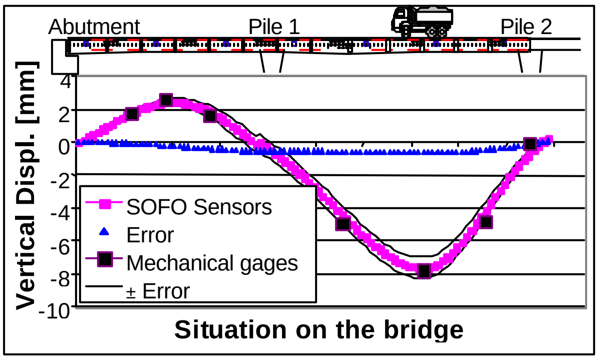

Figure 8: Versoix bridge five-years strain evolution

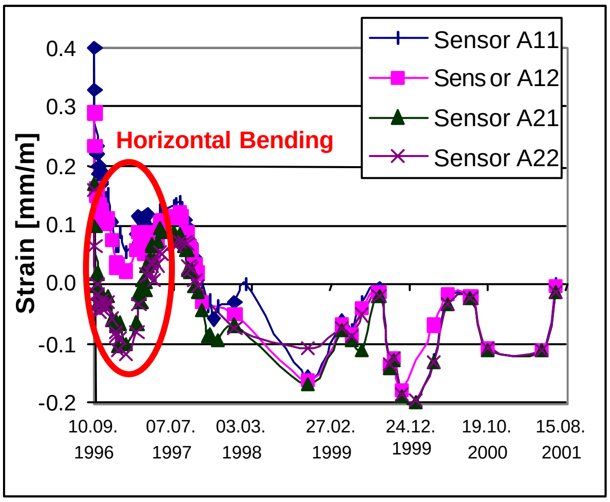

Figure 9: Uncoupling of shrinkage and temperature