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WHOLE LIFESPAN MONITORING OF CONCRETE BRIDGES

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Abstract. *Civil structures are omnipresent in every society, regardless of culture, religion, geographical location and economical development. They affect human, social, ecological, economical, cultural and aesthetic aspects of societies. Therefore, no only good design and quality construction, but also a durable and safe exploitation of civil structures are imperative goals of structural engineering. The most safe and durable structures are usually those that are well managed. Measurement and monitoring have an essential role in structural management. In this paper, the importance and the benefits of monitoring during the whole lifespan of concrete bridges are presented.*

The lifespan of a concrete bridge starts with construction – pouring of concrete. Follow curing of concrete, 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 exploitation, 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, the importance of monitoring of each period of a concrete bridge's life is examined step by step, and illustrated an on-site example.

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 behaviour possible. Thus, project and construction can be optimised in structural and economical aspects. Second, permanent monitoring can give early indications of structural malfunctioning. In this way, safety measures can be considered in time, and intervention on the structure can be performed immediately and with minimal economic looses.

Experiences using a monitoring system designed for lifespan monitoring of concrete bridges is presented in this work.

1 INTRODUCTION

Monitoring (or auscultation) of structures involves recording of time dependent parameters during certain periods. These parameters are related to the construction material (concrete, steel, timber, etc.) and to the structure itself. In both cases they can be physical, mechanical or chemical.

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In the next paragraphs we will explain generally and through examples, importance and benefits of monitoring performed during each phase of the structure life.

2 WHY MONITORING

Monitoring is usually carried out in order to achieve one or several goals. They are presented and discussed in this section.

Structural Management: The most safe and durable structures are usually those that are well managed. Measurement and monitoring have an essential role in structural management.

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 conditions 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.

A few structures might present deficiencies, which cannot be identified by visual inspection or modelling. In these cases it is possible increase safety and to decrease managing costs[1] by taking actions before it is too late. Repair will be cheaper and will cause less disruption to the use of the structure if it is done in time. Monitoring can also reduce insurance costs.

The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by 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.

Increase of safety: 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 infrastructure is partially or completely out of service. Collapse of certain structures, such as nuclear power plants, may provoke serious ecological pollution.

Having permanent and reliable monitoring data from a structure, can help to guarantee the safety of the structure and its users.

Knowledge improvement: 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 no two identical structures.

A good way to enlarge knowledge of structural performance is to monitor their behaviour. That's why monitoring during the complete lives of structures, from construction to the end of service, is of interest from the theoretical point of view as well as from the point of view of structure management. Theories need to be tested, and an excellent method to test theories describing the civil structures is monitoring[2]. For structures built of unusual materials (e.g. roofs composed of thin plastic membranes or tensegrity structures) monitoring is an effective way to comprehend the real behaviour and to refine behavioural theories.

3 MONITORING ASSESSMENT

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 structural behaviour and goals of 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 parameter changes in time. For some applications, periodical monitoring gives satisfactory results, but information 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 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[1, 3].

4 WHOLE LIFESPAN MONITORING OF BRIDGES

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

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 of real performance and more appropriate remedial actions.

Important information obtained through monitoring during construction includes the following: Estimation of hardening time of concrete in order to estimate when shrinkage stresses begin to be generated[4]; Deformation measurements during early age of concrete in order to estimate self-stressing and risk of premature cracking[3]; 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[6]; 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[7]; Knowledge improvement and recalibration of models[8].

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[9], 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[10]. Also, new functional requirements for the bridge (e.g. enlarging) lead to requirements for strengthening[11]. 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 previous subsection. The determination of the success of refurbishment or strengthening is an additional justification[11].

Monitoring during testing of bridge: Bridges have to be tested before service for safety reasons[11]. 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 estimates[12]. Monitoring during this phase can be used to calibrate numerical models describing the behaviour of structures[8].

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 subjected 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[11], 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[1] 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 of present and for prediction of future structural behaviour[12]. 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.

5 EXAMPLE OF WHOLE LIFESPAN MONITORING

The North and South Versoix bridges are two parallel twin bridges[11]. Each one supported 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 1).

Figure 1: View to Versoix Bridge before enlargement

Figure 2: SOFO system reading unit

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 decide to monitor strain, displacement and temperature over whole lifespan of the bridge. The SOFO monitoring system[14, 15] (see Figure 2), based on low-coherence interferometry in the optical fibres[15], was selected for this purpose, since its performances meet the requirements for whole lifespan monitoring.

The sensors ware 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 3, and total of 12 sections is equipped as shown in Figure 4. 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 and is shown in Figure 2.

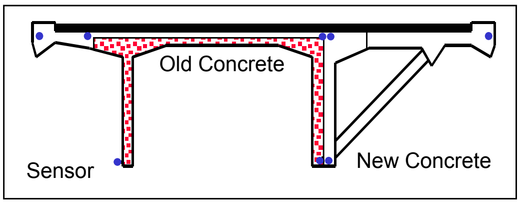

Figure 3: Position of sensors in cross-section

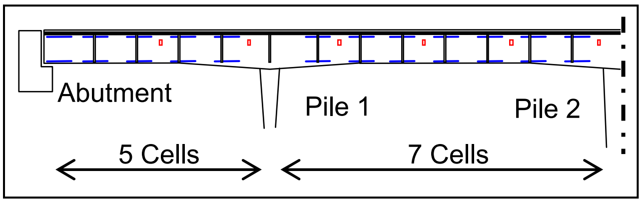

Figure 4: Longitudinal position of sensors

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, the sensors are installed side-by-side in new and old concrete (see Figure 2). Monitoring performed during more than two months after the pouring shown that both sensors measured the same deformation and thus the interaction between the old and new concrete is estimated as a very good. 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 7). An example of measurements is presented in Figure 5.

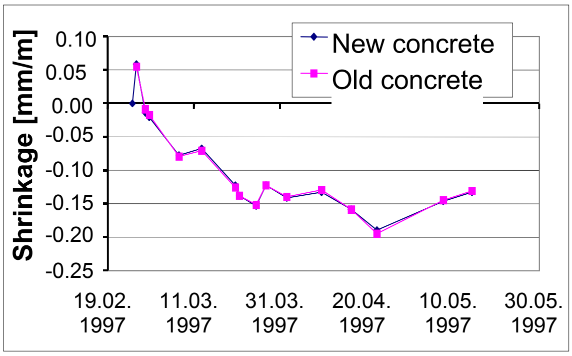

Figure 5: Old-new concrete interaction monitoring

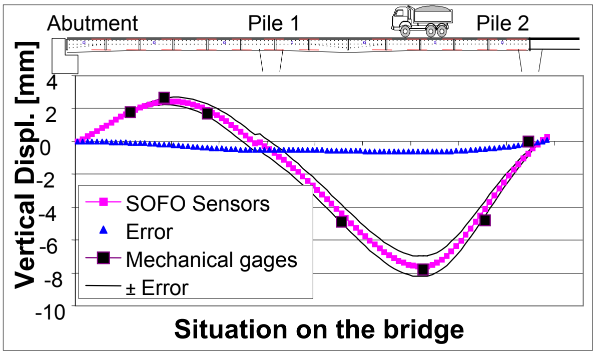

Figure 6: Monitoring during the load test

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 6 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[16]. 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 7. After the cross-section is bended horizontally due to unequal heat and different time of concrete pouring, all sensors measures approximately same deformation confirming that the cross-section is not exposed to unexpected bending due to damage or delamination.

In Figure 8 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 8). The seasonal temperature variation influenced behaviour of the bridge and can also be seen in Figure 8.

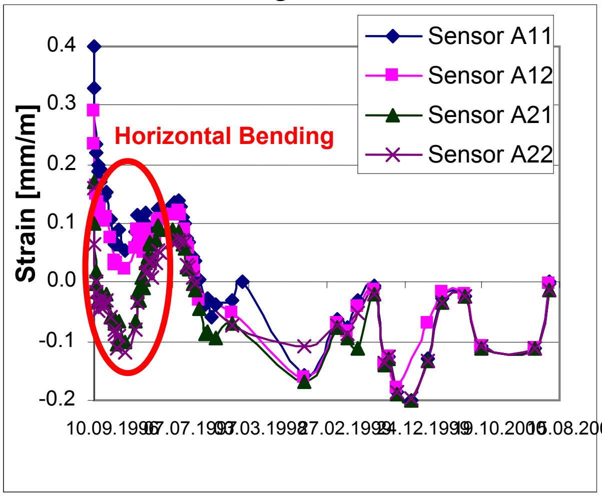

Figure 7: Versoix bridge five-years strain evolution

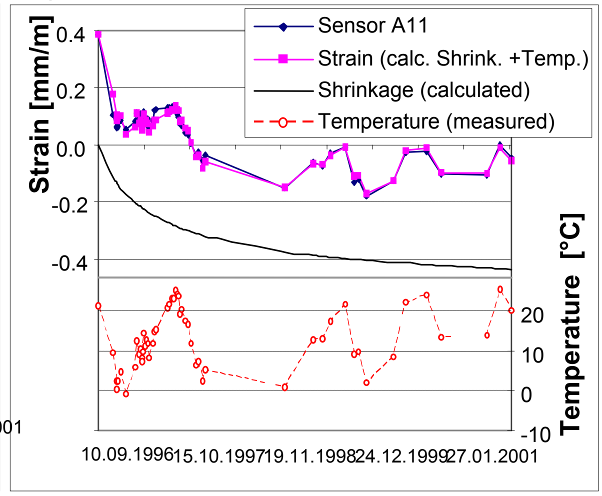

Figure 8: Uncoupling of shrinkage and temperature

6 CONCLUSIONS

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 from human intervention and insensitive to external influences.

The advantages of whole lifespan monitoring are illustrated by real on-site example, carried out using SOFO monitoring system installed onto the Versoix Bridge in Switzerland. The benefits gathered the each phase of the bridge's life are presented and they fully justify The whole lifespan monitoring concept.

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