Continuous monitoring of concrete bridges during construction and service as a tool for data-driven Bridge Health Monitoring

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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 behavior and makes accurate calibration of numerical models describing and predicting this possible behavior. Thus, project and construction can be optimized 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 behavior and consequently better planned and less expensive management. In this paper, a brief introduction to the monitoring process is firstly presented. Then, the importance of the monitoring of each period of a bridge's life is examined step by step, and illustrated with a relevant practical application examples.

1 INTRODUCTION

The 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.

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

2 BENEFITS OF 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 optimize 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 modeling. In these cases it is possible increase safety and to decrease managing costs 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 damaged 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 behavioral knowledge impossible: there are no two identical structures.
A good way to enlarge knowledge of structural performance is to monitor their behavior. 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. 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 behavior and to refine behavioral 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 in-

formation 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 behavior 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.

4 CONTINUOUS MONITORING OF BRIDGES

The importance and benefits of continuous 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 helps engineers to understand the real behavior 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; 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 prefabricated structures, sensors may be useful for quality control; Optimization 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 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 behavior of the structure and to compare it with theoretical estimates. Monitoring during this phase can be used to calibrate numerical models describing the behavior 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 subjected to degradation by ageing. Concrete cracks and creeps, steel oxidizes 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 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.

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 EXAMPLES OF CONTINUOUS MONITORING

5.1 *Buildings monitoring in Singapore*

Singapore is a cosmopolitan city-state often described as a gateway to Asia with a city landscape of tall buildings. The Housing and Development Board (HDB), as Singapore's public housing authority, has an impressive record of providing a high standard of public housing for Singaporeans through a comprehensive building program. As part of quality assurance of new HDB tall buildings, it was decided to perform long-term structural monitoring of a new building of a project at Punggol East Contract 26. This monitoring project is considered as a pilot project with two aims: to develop a monitoring strategy for column-supported structures such as buildings, and to collect data related to the behavior of this particular building providing rich information concerning their behavior and health conditions. The monitoring is to be performed during whole lifespan of the building, from construction to the in use. Thus, for the first time the sensors are used in a large-scale life cycle monitoring of high-rise buildings.

The Punggol EC26 project consists of six blocks founded on piles, and each block is a nineteen-storeys tall building, consisting of 6 Units and supported on more than 50 columns at ground level. The block called 166A has been selected for monitoring. A view of the building under construction is presented in Figure 1.

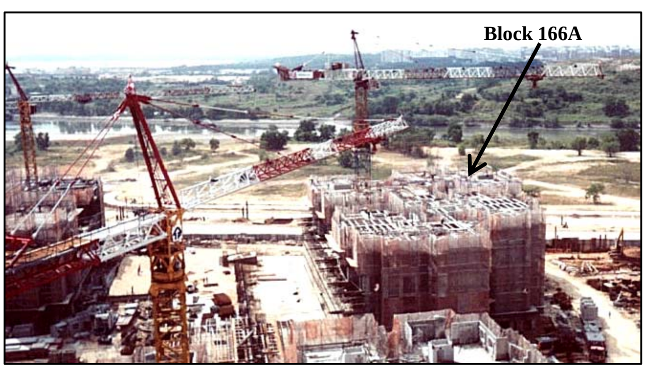

Figure 1. View to the Block 166A of Punggol EC26 project during construction

A good compromise with respect to budget and results has been to equip 10 ground columns (between 1st and 2nd floor) with SOFO deformation sensors. The ground columns have been selected being the most critical elements in the building while the number of sensors was adapted to the available budget.

The dominant load in each column is compressive normal force; therefore it is supposed that influence of bending to deformation can be neglected. Consequently single sensor per column, installed parallel to column axis, and not necessary in the center of gravity of the cross-section is estimated as sufficient for monitoring at local column level. The position of the sensor in column is schematically presented in Figure 2. The length of the sensors is determined with respect to the available height of the column (3.5 m) and on-site conditions, hence two-meters long sensors have been used.

In each column the sensor was attached on rebars before the pouring of concrete as represented in Figure 3. The sensor connector has been protected with a small connection box, which is also embedded in concrete. In this way neither the sensor cable nor the connector egresses from the column. The connection box is provided with a small opening allowing access to the sensor connector after the column is poured. Closed opening and connected sensor are presented in Figure 4.

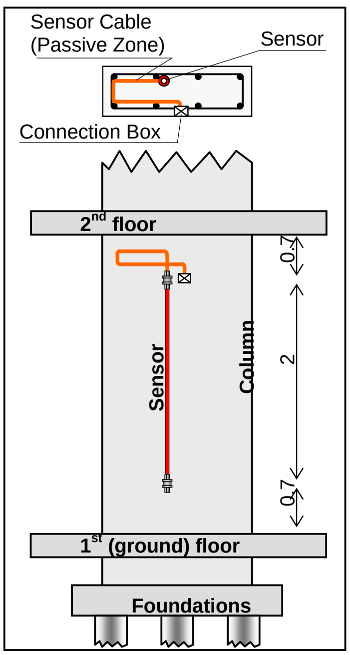

Figure 2. Sensor position in column

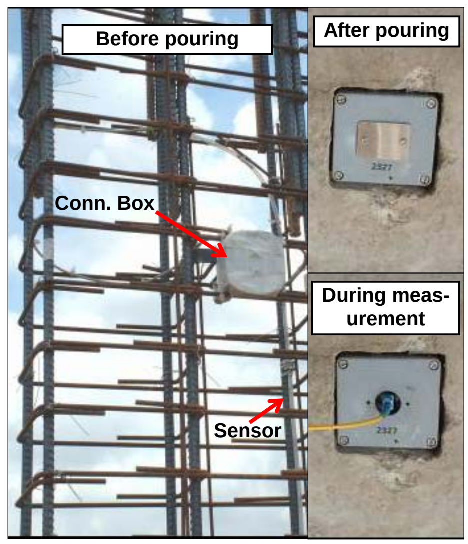

Figure 3. Sensor and connection box installed on a rebar cage, and connection box after the pouring of columns

At the time of writing, measurements performed over more than four years were collected. To decrease the costs of monitoring, only periodical readings have been performed, one campaign over all the sensors after a new storey was completed, and later periodically every few months. This periodical manner of collecting data is justified by the fact that no issue was detected during the construction phase or later.

The temperature in Singapore is ranged between 20°C and 30°C during the day or night and independently from the season. This fact along with the limited budget for monitoring leaded to decision to not monitor the temperature.

Full data analysis of the recorded results exceeds the topic of this paper. Therefore only themes important to present and highlight the performances of employed monitoring strategy are presented in this section.

Diagram presented in Figure 4 shows the time-dependent evolution of the average strain in columns monitored during more than four years.

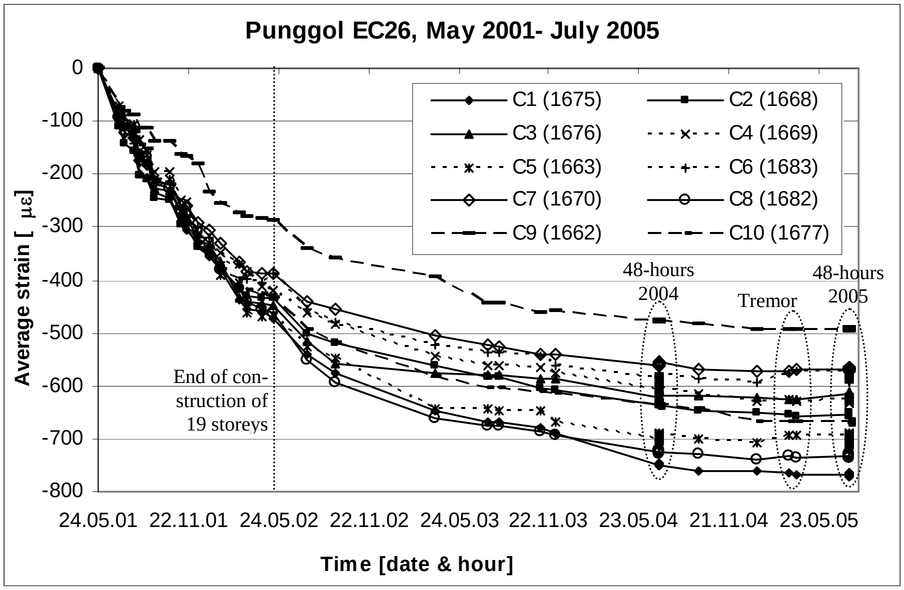

Figure 4. Evolution of total average strain in columns monitored by SOFO system

The following four particularly important periods are highlighted in Figure 6: (1) end of construction of 19 storey, (2) the first 48-hours continuous monitoring session performed in July 2004, (3) before and after tremor monitoring and (4) the second 48-hours continuous monitoring session performed in July 2005. All these periods as well as the full four-years monitoring record are analyzed more in details at local and global level in the cited reference (Glisic et al. 2005).

Such monitoring efforts have yielded results from the insights gained from enlarged knowledge concerning the real column behavior during construction and including the unexpected behavior of column C9 (lower deformations during construction) and Unit E which will help research into the accurate modeling of complex structures. Post-tremor analysis was performed after the March 2005 earthquake in neighboring Indonesia and confirmed no alteration of the structural behavior. The 48-hours sessions confirmed sound performance of the building in long-term and made possible post-tremor analysis.

The employed monitoring strategy and the selected SOFO monitoring system have successfully responded to the design criteria. The monitoring strategy has shown high performance in spite limitations imposed by design criteria (limited number equipped columns, lack of temperature measurement, lack of accurate shrinkage and creep coefficients, uncertainty concerning the real load during campaigns of measurement, etc.).

5.2 *Whole life bridge monitoring*

The Rio Puerco bridge is situated on national highway 40, near Albuquerque, New Mexico. It consists of three spans, with four girders in each span. Girders are precast prestressed I-beams, approximately 30 m long. They support a monolithic concrete deck cast on-site. The girders were fabricated in open-air plant. The workforms of four girders, with the rebar cages and strands, were aligned, the strands put in tension and the concrete was cast. The girders were then steam cured at temperature in range of 60°C to 90°C. Three days after the pouring, the strands were cut and prestressing force were introduced into the girders. Approximately three months later, the girders were transported on site and the deck was poured.

The main aim of the monitoring has been to evaluate prestress losses over the whole life of the bridge, including the early age of girders. For this purpose, four girders were equipped with SOFO sensors and thermocouples as shown in Figure 5. Each girder has contained 10 SOFO sensors and 6 thermocouples. This configuration of sensors allows monitoring of deformation and curvature, and the determination of thermal influences. Using appropriate algorithms it is possible to determinate prestress losses in girders. Only four girders are selected due to symmetry of the bridge. All sensors were installed before the pouring.

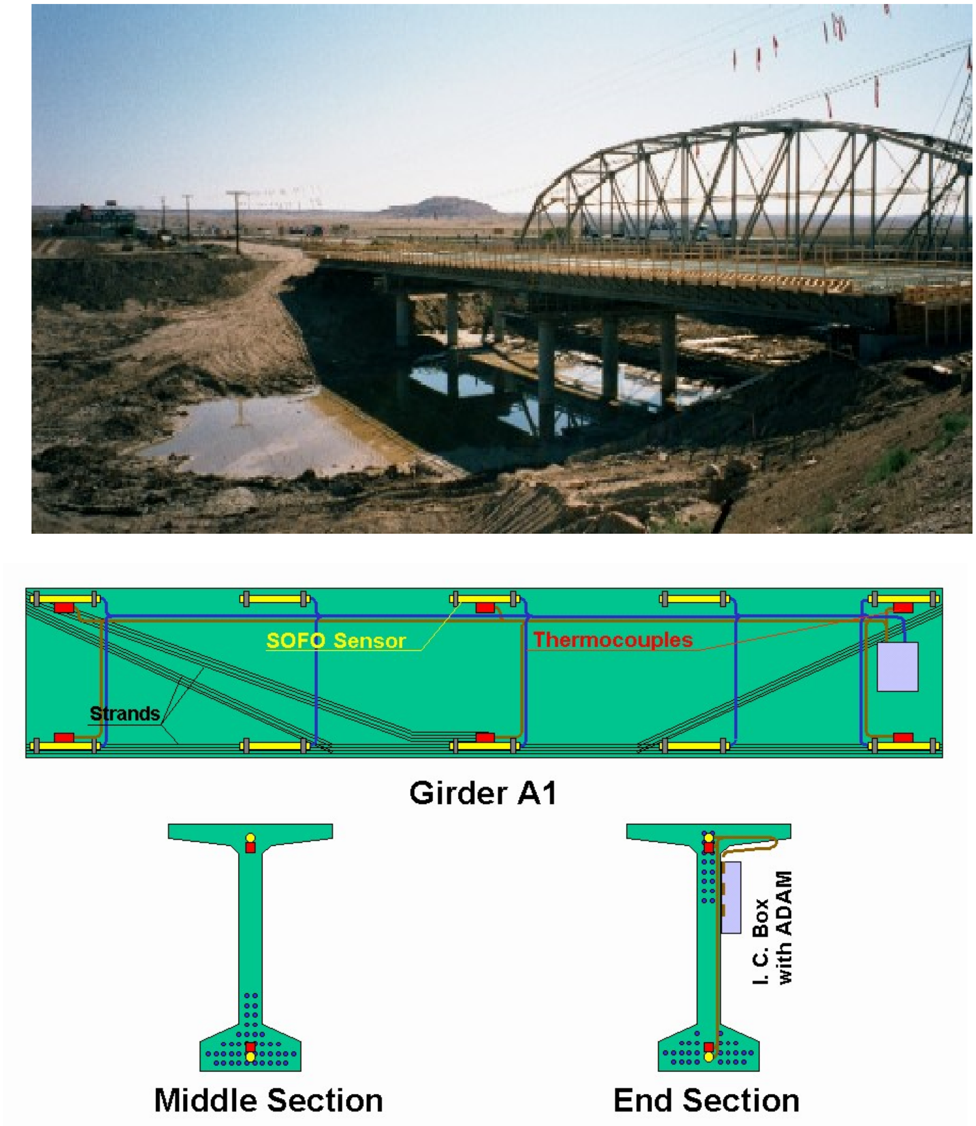

Figure 5. Rio Puerco Bridge view and sensor layout

Measurements started immediately after the pouring. In this way the early and very early age deformation were recorded during the first three days. The deformation is later recorded during the prestress phase, after each strand was cut. Thus, real initial strain state of girders was stored. Followed the period of continuous monitoring before transportation on-site, during transportation and during the pouring of the deck. In present, long-term monitoring is carried on. The results helped comparison with different theoretical models and confirmed very good condition of the bridge after construction as shown in figure 6..

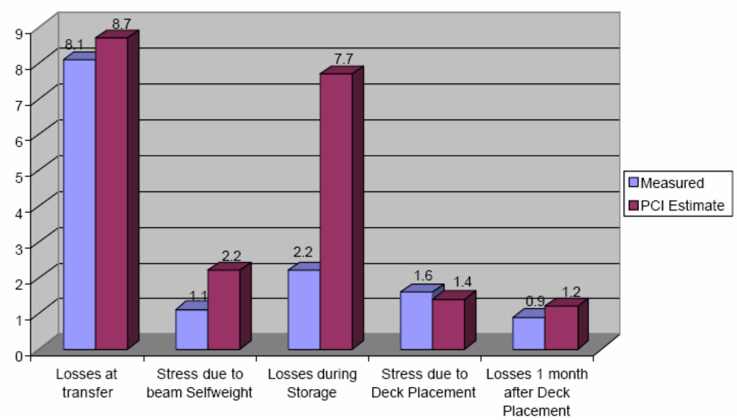

Figure 6. Rio Puerco Bridge: Figure 5. Rio Puerco Bridge view and sensor layout

6 CONCLUSIONS

Continuous monitoring allows the registering of relevant structural 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 behavior. 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 buildings in Singapore and a concrete bridge in New Mexico, USA.

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