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SHM of Ageing Reinforced Concrete Structures

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ABSTRACT: The issue of early detection of material degradation and reduction of load carrying capacity of ageing reinforced concrete structures through SHM techniques is addressed in the paper. The use of innovative sensing devices and data analysis and interpretation techniques is briefly discussed. Examples of real-world applications, laboratory testing and numerical simulations are also presented.

1 INTRODUCTION

Reinforced Concrete (R.C.) is perhaps the most diffused modern construction method worldwide. Indeed, advances in materials technology have nowadays rendered this construction technique competitive with steel structures even for high-rise buildings and medium to long-span bridges. However, in the last 20 to 30 years the issue of durability of R.C. structures has been dramatically posed: ageing resulting from phenomena like concrete degradation and corrosion of re-bars and tendons have been recognized to be able of severely affecting aesthetics and resistance of structures. Many structures, initially supposed to be rehabilitated or retrofitted after 50 years of usage, are now in need of significant intervention, even though they are still far from their estimated lifetime limits. This will require an important economical effort that could be reduced or even avoided by using durable concrete materials and life-cycle evaluation of concrete structures in design and retrofit phases.

Very extensive studies have been therefore dedicated to this issue, including basic studies on material behavior, optimal mix-design, development of innovative components, and life-cycle engineering approaches. Among these latter studies, considerable attention has been given to retrofitting techniques and to the optimal planning of maintenance interventions. As a part of the related developments, Structural Health Monitoring (SHM) by means of permanently installed instrumentation systems has gained increasing importance as it has been proven to be a very promising tool for keeping under control the evolution of ageing phenomena in newly constructed as well as in retrofitted structures.

In the present work, after reviewing the most relevant phenomena connected with the ageing of R.C. structures, some of the most effective techniques that can be used in SHM for the particular case are discussed, showing some of their capabilities and limitations. The problem of early detection of degradation phenomena is especially addressed.

2 AGEING OF R.C. STRUCTURES

2.1 Deterioration phenomena

Concrete may deteriorate due to inadequate design and construction practices, lack of maintenance, or because an inadequate concrete was specified. Anyway, it is the interaction between the concrete and the environment that determines the possible deterioration mechanisms. The most common and in terms of consequences most serious cause of deterioration in structural concrete members is due to corrosion of reinforcing steel induced by chloride ion ingress into concrete. Other less common causes of deterioration in concrete are carbonation induced corrosion, freeze-thaw attack, alkali-silica reaction, and external and internal chemical attack.

The corrosion process is complex and generally, its main effect is a reduced strength of the structural element studied and therefore a reduction of the structural reliability. The basic electrochemical process of corrosion takes place due to the formation of anodes and cathodes. The first ones develop where the passive layer is destroyed and the steel is dissolved. These processes are due to the presence of a certain amount of non-combined chlorides in concrete; they destroy the passive layer and also participate in the reaction that locally causes the steel dissolution (pit corrosion). The cathodes develop where hydroxide ions are formed due to the combination of oxygen, water and the electrons coming from the anode. As a conclusion, the corrosion in steel needs the combination of humidity and oxygen, in order to take place.

In reinforced concrete members the presence of an alkaline environment with PH>11.5 provides additional protection to steel, as regards corrosion. In fact, the concrete alkalinity creates a natural protective layer around the steel reinforcement, called passive layer. Concrete is also a permeable material, into which aggressive agents diffuse and reach the reinforcing steel, causing its depassivation and corrosion, as far as water and oxygen are available. Heterogeneities in the surface of the steel, such as differences in grain structure and composition, and local differences in the electrolyte, due to the heterogeneous nature of concrete, cause a region of the bar to act as an anode and another region to act as a cathode, so that the whole process of corrosion can easily begin.

2.2 Normative references

Design procedures regarding concrete structures required by the present codes and standards are predominantly based on strength principles and limit state formulation. The durability aspect is a natural extension of the classical resistance verification where deterioration effects are normally neglected. This classic prescriptive nature of codes results in a lack of insight into deterioration consequences and this means that, at the structural design stage, there is an absence of clear understanding of the actual in-service durability performance of a structure. This is acceptable for structures of minor importance, but not for the important ones exposed to aggressive actions. Alternatively, most of the existing national and international codes have recently started to introduce the use of the criterion of durability based on the analysis of service life.

The conceptual basis of such an approach is to ensure that the required performance is maintained throughout the intended life of the structure along with the optimization of the incurred lifetime costs. Details of the approach can be for example found in the work by Narasimhan et al. (2009). In other words, a performance code describes a level of accepted performance to which the assembly or construction must conform without specifically outlining how materials are to be assembled. Material composition has to be tested and its results analysed. Furthermore, some of the results have to be included in mathematical models in order to perform a lifetime estimation regarding the type of action – chlorides, as for example described by Baroghel-Bouny et al. (2009) or carbonation, as described by Thiery et al. (2006).

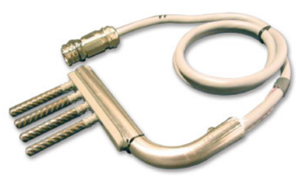
At the present time, the accepted model for the deterioration of structures is Tuutti's model (1982). As a function of time, this model clearly distinguishes an initiation time followed by a propagation time. The initiation time refers to the penetration of the aggressive agents into the concrete cover, while the propagation time is related to the evolution of different forms of deterioration after corrosion takes place. The sum of the initiation and propagation periods results in the service life period of the structure. The extent of both these periods depends on the environmental exposure of the structure or its members.

3 SHM APPROACHES AND SENSING DEVICES

Monitoring of the evolution with time of the governing parameters and of their effect plays therefore a paramount role in the assessment of the actual conditions of an ageing R.C. structure. Modern instrumentation allows continuous recording of humidity and electrochemical parameters at selected locations in the structural members as well as continuous or periodical recording of the static and/or dynamic responses of the structures. In the following subparagraphs, some of the recently marketed sensing devices will be briefly described.

3.1 Corrosion sensors

Figures 1a, b and c depict some sensing devices that can be effectively used in the monitoring of corrosion phenomena.


a


b


c

Figure 1 – Corrosion Sensors (Senscore™)

The sensing device in Figure 1a is composed by 4 mild steel rebars that are anchored to a stainless steel support. The rebars are placed in the concrete at different depths, usually starting from just below the surface of the concrete cover and including the depth at which the structural rebars are placed. The sensor allows the measurement of the corrosion current at the different depths, thus giving indications about the presence of corrosion and about its rate at different depths. The sensor in Figure 1 b is aimed at measuring the concrete resistivity (inversely linked to the humidity) and temperature at different depths in the concrete; it is composed by 4 stainless steel rebars and can be placed in the same way as the corrosion sensor. The placement in combination of the two sensor types gives a more complete picture of the conditions influencing the corrosion initiation and progression in a R.C. structure. The sensors in Figure 1a and in Figure 1b are designed for installation in new structures or during retrofitting works comprising the substitution of the concrete cover. The sensor in Figure 1 c, suitable for use in existing structures before or after repair or maintenance, combines the two functions. It is composed by a cylindrical element containing mild steel elements for measuring the corrosion current at different depths and stainless steel rings for measuring the concrete resistivity (moisture content). Two temperature sensors also complement this information.

3.2 Deformation sensors

The data obtained from the above described corrosion sensors are able to provide local information on the corrosion phenomena but they don't give any direct indication about the effects of corrosion on the global characteristics of the structural member. To provide this further information, measurements of the response of the structure in terms of static and/or dynamic deformations are needed. Recent experiences have shown that the most suited deformation sensor technology for permanent installation in R.C. members is fiber optics.

The advantages of fiber optic sensors over traditional ones are well known and there exist a great variety of fiber optic sensors for structural monitoring. For more detailed information, the works by Udd (1991,1995) and by Inaudi (1997) are referenced. Figure 2 illustrates the four main types of fiber optic sensors. *Point sensors* have a single measurement point at the end of the fiber optic connection cable, similarly to most electrical sensors. *Multiplexed sensors* allow the measurement at multiple points along a single fiber line. *Long-base sensors* integrate the measurement over a long measurement base. They are also known as long-gage sensors. *Distributed sensors* are able to sense at any point along a single fiber line, typically every meter over many kilometers of length.

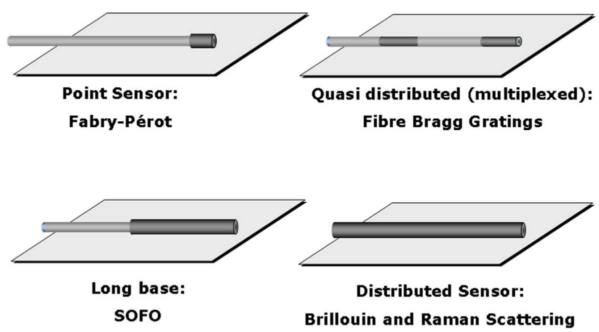


Figure 2: Fiber Optic Sensor Types

The most diffused in applications to R.C. structures are the sensors based on the Fiber Bragg Grating (FBG) and the SOFO™ sensors. They can be attached on the surface of an existing structure or they can be installed on the rebars prior to concrete pouring, so that they can remain in operation for the entire life of the structure. Both can be suitable for static and for dynamic readings. FBG sensors can also be packaged in long-base solutions, include temperature compensation and provide temperature measurements. SOFO sensors are intrinsically temperature-compensated.

Distributed sensors provide static only temperature and/or strain measurements; they can also be installed inside the structural member or glued at its surface. Details of the principles governing the functioning of distributed fiber optic sensors can be found in the book by Glišić and Inaudi (2007). The advantage of distributed sensing is that the influence of sensor positioning with respect to the location of potential damage is greatly reduced. In addition, as described in a paper by Glišić et al. (2009), distributed sensing can reveal the formation and evolution of cracks.

4 DAMAGE IDENTIFICATION TOOLS

The measured structural parameters are usually used to construct a mechanical model that is later updated using monitoring data. The mechanical model can be used for: a) reliability analysis and/or b) damage identification. Recently, the integration of the reliability analysis with the long-term SHM has been attempted by Frangopol et al. (2008) and improved by including the uncertainty propagation in the assessment process by Law and Li (2010). Furthermore, the mechanical model is very useful also to extract the structural features (static or dynamic) that are sensitive to damage or material degradation.

A recent work by Lanata (2010) has put into evidence that theoretical and lab knowledge needs to be transferred to real structures in order to control static or dynamic parameters during in-service conditions. In particular, as noted by Lanata and Schoefs (2010), for large structural systems interacting with their environment, safety and operability of the system depend on phenomena involving not only structural behaviour, but also coupled structure-environment responses.

In particular, the automatic detection of damages from continuous static monitoring is still a challenge. Scientifically, the most successful methods are not yet identified, even though a great number of signal processing algorithms like discrete wavelet analysis, wavelet packet transform and autoregressive analysis have been investigated. However, these methodologies may be prone to a harmful affect in case of using data with outliers. Among many other methods, Robust Regression Analysis (RRA) has been proposed and applied by Lanata and Schoefs (2010). Posenato et al. (2008) proposed a methodology based on Moving Principal Component Analysis (MPCA); a comparative study with other signal processing algorithms has shown that for quasi-static monitoring of structures, the proposed methodology performs better than other methods, also in case of noise, outliers, data missing and databases with different sensors types.

5 EXAMPLES OF CONTINUOUS MONITORING

To exemplify sensor placement, typical data and real-world problems related to data interpretation for early detection of structural degradation in reinforced concrete members, a few cases are reported in the following.

5.1 Buildings monitoring in Singapore

The Housing and Development Board (HDB) of Singapore, as part of quality assurance of new tall buildings, decided to perform long-term structural monitoring of a new building of a project at Punggol East Contract 26 (Figure 3). The monitoring was performed during the whole lifespan of the building, from construction to the in use.

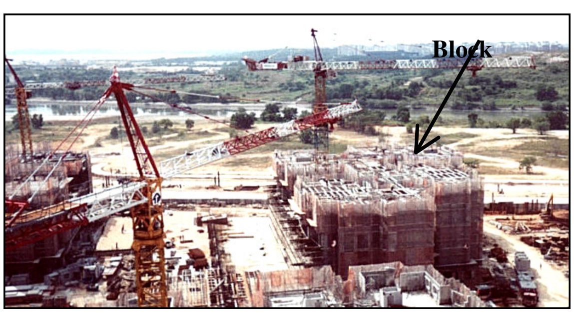


Figure 3 – View of the building during construction.

The project consists of six blocks founded on piles, and each block is a nineteen-store tall building, consisting of 6 Units and supported on more than 50 columns at ground level. One block has been selected for monitoring. Ten ground columns have been equipped with SOFO deformation sensors. In each column the sensor was attached on rebars before the pouring of concrete. Measurements were taken at selected times and a few sessions of continuous monitoring were also performed. All these periods as well as the full four-years monitoring record are analyzed more in details at local and global level in a paper by Glišić et al. (2005). The measured strains have been successfully compared with the values predicted by design.

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 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.

Measurements started immediately after 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 had been 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.

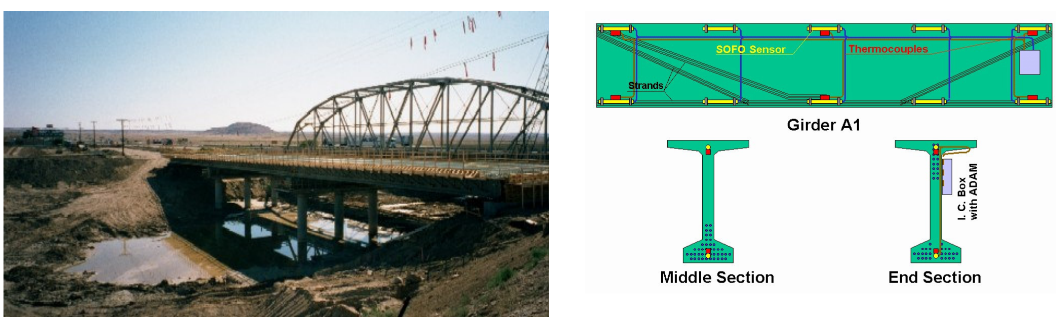


Figure 4. Rio Puerco Bridge view and sensor layout

5.3 *Laboratory testing*

Open air laboratory testing was performed from April 2008 to June 2010 on two prestressed concrete beam specimens equipped with SOFO deformation sensors, one of which was subjected to artificially induced damages. Strain and temperature data have been continuously recorded for the whole period of observation. Dynamic measurement campaign is presently under study, while preliminary analyses of the strain and temperature time-series have been presented in the papers by Lanata (2010) and Del Grosso et al. (2010). Figure 5 represents the characteristics of the beam specimens and sensor placement for the beam subjected to damages; the other beam was equipped with a lower number of sensors and kept intact for reference. After a few weeks of reference readings, the specimens were subjected to a ballast load inducing tensile stresses in the beams approximately equal to one half of the compression due to prestressing.

Preliminary processing of the data performed by means of correlation analyses and Proper Orthogonal Decomposition (POD) has revealed that the external temperature variations as well as insulation and humidity play a great influence on the capability of detecting the presence of damage.

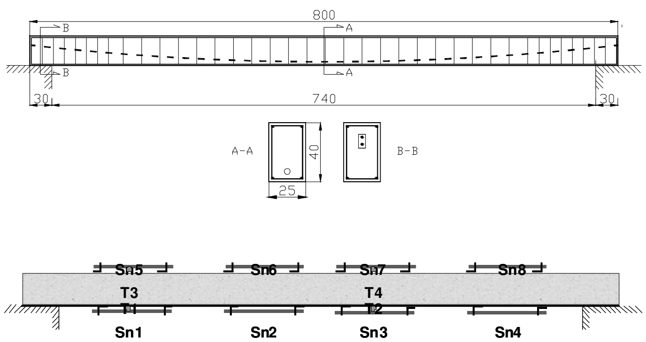


Figure 5. Specimen characteristics and sensor locations

Data preprocessing in order to filter the environmental effects has also been performed showing that the capability of damage detection can be significantly increased. It has to be noted that application of the algorithms to numerically simulated data sets obtained by finite element models reproducing the conditions of the experiment but not including the effects of direct solar radiation and humidity variations has resulted in efficient detection of the modification of the static response even due to very limited intensities of damage.

Figure 6 illustrates the comparison between the plots of the strain versus temperature variations at a significant location, as obtained from the raw data and from the numerical simulations. The simulation did cover the application of the ballast load, causing a shift in the strain-temperature trends. The plots underline the scattering of the readings that is caused by the real environmental conditions.

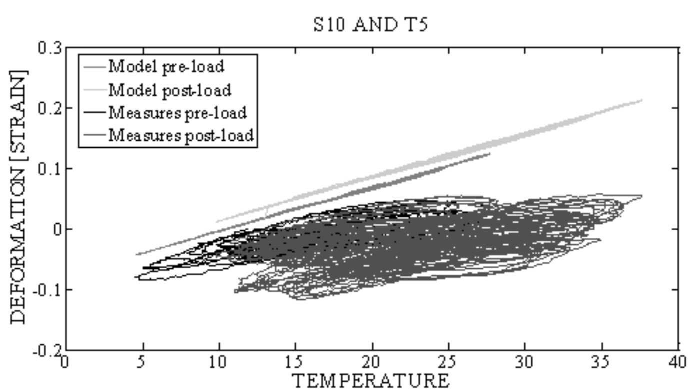


Figure 6 – Comparison between numerically simulated and measured strains. Strain vs. temperature plots.

6 CONCLUSIONS

The paper has discussed the problems related to the use of structural health monitoring techniques in the assessment of the ageing conditions of reinforced concrete structures. The main phenomena causing degradation with time of R.C. structural members have been briefly characterized and the instrumentation systems more suitable for their direct and indirect monitoring have been presented together with a very short review of the available interpretation algorithms. Some case studies have also been presented showing the capabilities offered by fiber optic deformation sensors in the monitoring of the response of real structures. However, the experimental study summarized in the last paragraph has shown that the assessment of structural degradation as due to early corrosion phenomena is very difficult and false indications may arise from the influence of environmental conditions. It is noted that further long term field experimentation is needed in order to develop and validate reliable algorithms for damage identification. Merging of data from corrosion and deformation sensors should also be investigated through practical applications.

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