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Experimental Validation of Damage Detection Algorithms for Static Response Data

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ABSTRACT: Prestressed concrete structures are subjected to several degradation processes during their service life. Damages may remain undetected by visual inspections and an appropriate intervention program is difficult to schedule without the support of an integrated monitoring system.

The Authors proposed a non model-based analysis of long-term monitoring data, based on signal processing techniques for data analysis, including Correlation Analysis and Proper Orthogonal Decomposition. The reliability of the proposed damage detection procedures has been first tested on a set of computer simulated responses.

The results from the numerical simulation have been used to design an experimental program; two laboratory prestressed concrete beams exposed to environmental conditions and subjected to a static dead load have been used. The beams have been instrumented with fibre optic deformation and temperature sensors installed as in the computer simulation. Measured time histories of the undamaged and damaged states have been processed using the proposed damage detection algorithms.

1 INTRODUCTION

In the last years the development of non-destructive testing methods for new and existing reinforced concrete structures has been recognized as an important tool to reduce maintenance costs allowing a rational approach to the assessment of repair options, scheduling of inspection and maintenance programs. The presence of any defects like cracks or corrosion on a concrete structure is usually a symptom of damage. Causes can be from various natures: mechanical, physical, chemicals or due to concrete shrinkage during setting. For example, pre-stressed structures are subjected to temporary overloads and stress losses due to corrosion or rupture of tendons. These alterations can cause cracks, which may close when the structure has to support only its own weight. In addition, reinforced and pre-stressed concrete structures vary largely for geometry and boundary conditions.

As an alternative to the conventional local inspection methods, usually limited to particular classes of structures or damages, global vibration-based methods have been widely developed over the years, in particular using changes in the dynamic response, but the topic is still barely tackled (Wenzel & Pickler, 2005). The basic principle of the cited methods is to point out

changes in the dynamic properties of the structure and to use them for assessing the degree of damage due to degradation processes as cracking, steel corrosion or pre-stressing tendons ruptures. In addition, the methods usually require a finite element model of the monitored structure to detect damage. In some cases, these methods cannot be effectively used, especially when changes in the dynamic properties due to damage are smaller than changes due to environmental effects, when cracks close under the action of the pre-stressed force or when the structure is particularly complex to be modelled. For the monitoring of bridges, actual and future trends are the use of vibration signals under ambient, unknown excitation due to wind or traffic (output-only data), and the use of very large arrays of sensors (Deraemaeker et al., 2008). Basically, vibration characteristics can be implemented either in the frequency domain or in the time domain. Alternative to frequency domain methods and as a time domain approach, the coefficients of the autoregressive (AR) models fitted to the measured response time histories of a structure have been recently chosen as damage sensitive features (Wang & Ong, 2008).

As a valid alternative to the proposed vibration analysis in damage identification, the Authors present herein a non-model-based procedure by using long-term deformation time histories. The aim of the proposed method regards both the instrumentation and the data analysis phase. The used deformation sensors can be easily installed on each type of structure and the monitoring can be also performed during the usual working activities. Although obtaining data from monitoring may be easy and fast, the phase of data processing from static measurements is usually complex and expensive in terms of time and resources (Sohn et al., 2000). Structural models in particular can be difficult to create and may not accurately reflect real behavior. For these reasons, a statistical procedure able to discover anomalous behavior in data measured by deformation sensors, without using finite element models, is presented in this paper.

2 COMPUTER SIMULATION

In the previous papers, the reliability of the damage detection procedures proposed by the Authors (Lanata & Del Grosso, 2006) has been tested on a set of long-term simulated responses using reinforced concrete beams subjected to static environmental loads and instrumented with fiber optic extensometers. The proposed methods, based on Proper Orthogonal Decomposition (POD) and other signal processing techniques, have been thoroughly verified by several simulated damage scenarios on statically determined and undetermined concrete beams. The long-term structural responses under thermal loads have been generated for eight years using four measurements in a day; in this case damage detection is possible after at least one year from the beginning of the monitoring. Considering the difficulty to perform laboratory tests on real structures for such a long period, another numerical study has been developed to consider a short-term monitoring experiment as good as the long-term one. A second simulation only 3-months long has shown that the daily cycle can be compared to the yearly cycle when at least two measurements are performed every hour. In this case damage could be identified after a few days of measurements. This last simulation have proved that the proposed non-model-based damage detection algorithms could be successfully applied also to a short period monitoring performed in laboratory.

Due to these latter results, an experimental program has been carried out by the Authors in cooperation with other European research groups. The laboratory tests had been performing in order to obtain a long-term static monitoring on pre-stressed concrete beams exposed to environmental conditions and instrumented with fiber optic deformation sensors. The research program aims to study the real behavior of prestressed concrete structures due to environmental variations. In addition, data interpretation is dedicated to find a relationship between measured static structural response and features related to degradation.

3 LABORATORY TESTS

The tests had been carrying out on two pre-stressed concrete beams, available at Autostrade per l'Italia Laboratory in Romagnano Sesia, Italy. The beams' monitoring could be used to understand the structural response of the specimens to environmental parameters and to test the ability of proposed data processing algorithms in identifying the insurgence of damage. The experimental tests are being performed with the cooperation of Ecole Politechnique Fédérale de Lausanne (EPFL) and SMARTEC, Switzerland.

3.1 Geometrical and material properties

The tested specimens, cast in 1992, are post-tensioned concrete beams of 8 m in length with a rectangular cross section (0.25 large and 0.40 height). Each beam has a post-tensioned inclined cable formed by two standard tendons of 0.6" diameter and 4 additional reinforcing bars at the corner of the section (10 mm diameter). Shear reinforcement consists of 8 mm diameter stirrups spaced at 250 mm in the central section and at 150 mm near the supports. The geometric characteristics of the beams are shown in Fig. 1.

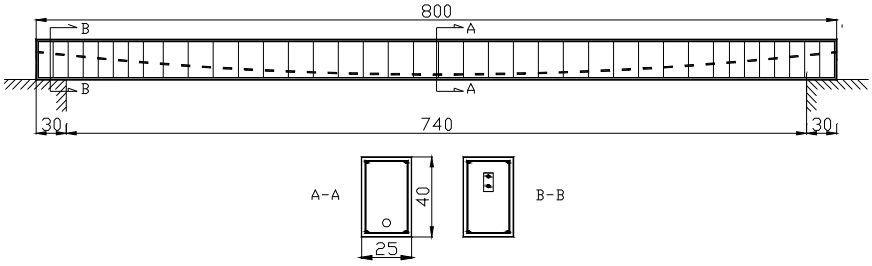

Figure 1. Geometrical properties of the specimen.

Each tendon was post-tensioned, giving an initial force of 130 kN, and anchored to the end of the beam. A dead load was added on the beams in order to reduce the effect of the initial pretension force. Details on the material properties can be found in Lanata & Mercalli (2008).

From the available design data, a bending moment of about 50 kNm has been assessed for the cracks opening in the central section of the beam. The only weight of each beam gives a bending moment of about 15 kNm. It was decided to add a dead load on the beams in order to increase the bending moment up to 25 kNm. This last value has been considered satisfactory by taking into account the following considerations. First of all 50 kNm is a theoretical value corresponding to the transition between State I and State II and it has been decided not to reach this limit; the stress losses of tendons have not been considered in the computation. Finally the tested specimens have different damages in the ducts: one beam has diffused and pitting corrosion of tendons locally introduced since the beginning and the other beam has filling defects of the duct. As a consequence, the rate of the initial pretension force cannot be exactly computed.

3.2 Experimental program and setup

In order to recreate the simulation setting used for the numerical benchmark, the laboratory beams have been located outside and exposed to environmental conditions. The environmental conditions are related to the geographic position of Autostrade per l'Italia laboratory located on the hills close to the Alps in the North of Italy. Temperature reaches +40°C in summer and -15°C with snow during winter. Moisture is influenced by rainy springs and autumns. The beams are exposed to wide temperature variations due to night/day cycles such as to the effect

of sun exposition. The thermal gradients between the upper and the lower surfaces of the beam will induce deformations to be measured.

The system installation has been completed on April, 16th and 17th, when the beams were simply supported without any added dead loads. The sensors instrumentation has been supplied by SMARTEC and the acquisition system has been supplied by EPFL. The first beam (called Beam A) has been instrumented with four fiber optic deformation sensors SOFO (Inaudi & Glisic, 2002) at the lower surface and four fiber optic deformation sensors at the upper surface; the second beam (Beam B) has been instrumented with only four fiber optic deformation sensors at the lower surface. Each sensor has an active length of 1 m. Six thermocouples have been glued on the upper and lower beams surfaces to measure temperature changes. The sensors location for the specimen instrumented with eight sensors (Beam A) is shown in Fig. 2. The four sensors on the lower surface of the Beam B have the same disposition. Four measurements per hour have been scheduled. The dead load has been put on the beams on May, 8th and this has to be considered as the reference condition (Fig. 3).

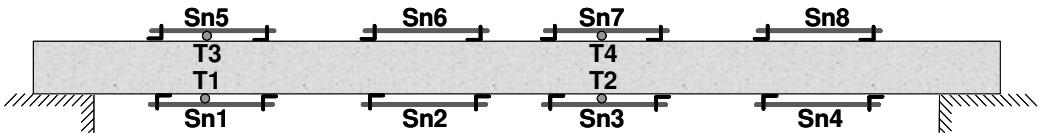

Figure 2. Sensors location on the Beam A (Sn: SOFO sensor; T: thermocouple).

Figure 3. View of the beams after the placement of the dead load.

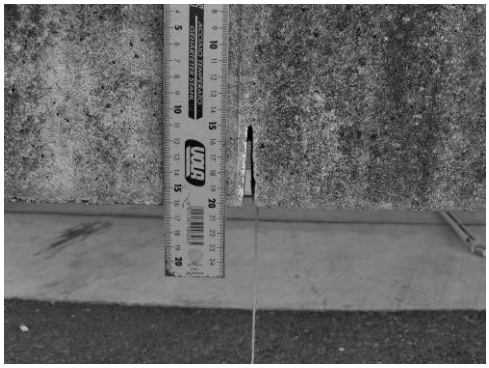

Figure 4. View of the current size of the cut in the middle section of the Beam A.

The structural response of the beams in the reference condition has been measured for about 40 days, as the computer simulation had shown the stabilization of the parameters extracted by POD after about one month from the start of the measurements. The first damage has been introduced on June, 18th. A cut of 1 cm in depth was produced using a saw in the middle section

of the beam instrumented with 8 sensors. The cut was deepened on June, 23rd, until the reinforcing bars were reached (about 3 cm in depth). A third level of damage was created on July, 9th. The previous cut was deepened again by cutting also the lower reinforcing bars (about 5 cm in depth, Fig. 4).

4 DATA INTERPRETATION

In the first phase of the monitoring, the reference state and the behavior under changing conditions like temperature and other environmental effects have been observed. The time histories from measurements of sensors elongation show a good correlation with temperature and the daily cycles are detectable and related to the elongation measurements (Fig. 5).

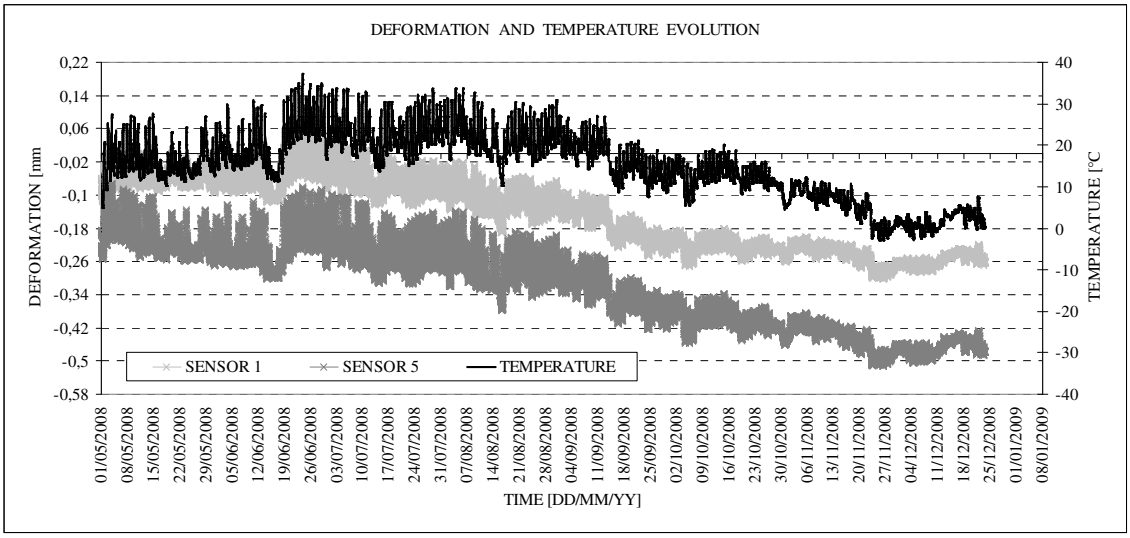

Figure 5. Example of temperature and elongation time histories for a sensor on the lower surface (Sensor 1) and a sensor on the upper surface (Sensor 5) of the Beam A.

Some considerations can be done by observing the complete time histories. Obviously, temperature gradients are much more significant during the summer and also show strong variations between consecutive days during the spring. The gradients are significantly smoother in the autumn, starting from the middle of September. The same trend is shown by the time series of the elongation measurements.

A simple correlation analysis has been performed to find the relationship between the following sensors. The correlation plots allow to retrieve some important results.

- Sensors with the same expected response in elongation (bottom) or contraction (top) for each beam. Deformation sensors with the same expected response show a very good correlation in time (Fig. 6).
- Sensors on Beam A and sensors on Beam B in the same position (bottom). The relationship is quite good also between sensors installed on different beams (Fig. 7).
- Temperature sensors on the top and temperature sensors on the bottom. The correlation between the temperature sensors in all the positions is constant in time and no differences in their behavior appear between temperature measured on the upper surface and temperature measured on the lower surface of the beam.
- Sensors on the top and sensors on the bottom of the Beam A. Correlations between deformation sensors on the top and on the bottom of the Beam A show a different trend and the correlation becomes stronger only in the last period of observation (Fig. 8).

- Deformation sensors and temperature sensors. In all cases no constant correlation exists between deformation sensor and their relative temperature sensor (Fig. 9). The index doesn't show a stable value during the whole monitoring period.

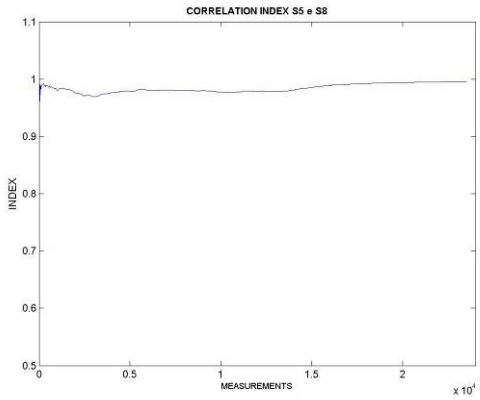

Figure 6. Example of correlation index between sensors on the top of the Beam A (Sensor 5 and Sensor 6).

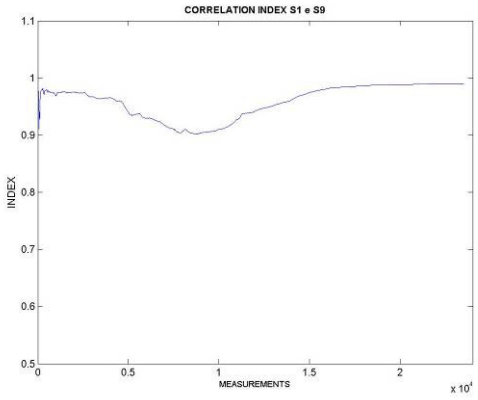

Figure 7. Correlation index between Sensor 1 on the bottom of the Beam A and Sensor 9 on the bottom of the Beam B.

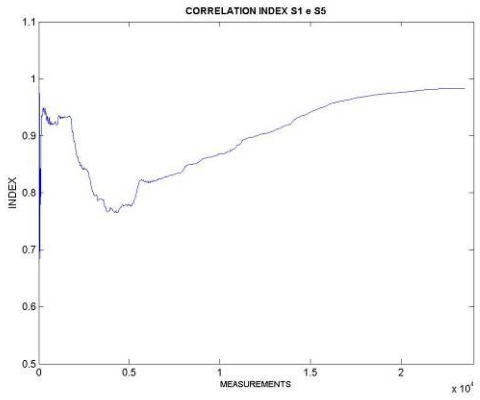

Figure 8. Correlation index between Sensor 1 on the bottom and Sensor 5 on the top of the Beam A.

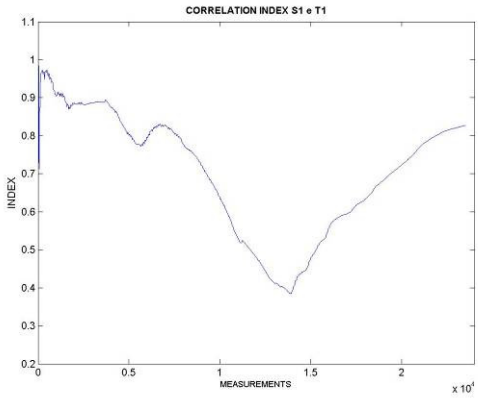

Figure 9. Correlation index between Sensor 1 and Temperature 1 on the bottom of the Beam A.

The correlation analysis has put into evidence that temperature has a fundamental role in the deformation of the beam, but other related environmental effects influence the relationship between sensors and measured deformations as well. As a matter of fact, the variations of the elongation measurements are greater during the spring and the summer, when sensors on the upper surface of the beam are probably subjected to significant effects due to the direct sunlight exposition. During the autumn, when the sun has a lower power, the correlation between sensors on the bottom and sensors on the top becomes stronger. In the same period, the relationship between deformation sensors and temperature sensors has a slope inversion. As a conclusion, deformation measurements seem to be strongly dependent from temperature gradient; the correlation between elongation and temperature measurements is expected to be different within different temperature ranges. A pre-processing should be performed on deformation data in order to remove the dependency from temperature ranges related to other environmental effects.

Usually all the damage detection algorithms based on statistical signal processing need stable features to be compared with the damaged situation. The performed experimental tests have shown that it could be possible to obtain stable features from real data, only when the

temperature gradients are within a certain range of variation or when the elongation measurements are filtered adequately within each temperature range. For high gradients, the influence of other 'non linear' environmental effects causes a change in the measured response. When the temperature variations are high, the parameters extracted from the measurements seem not to be stable in time and therefore not reliable without some pre-processing analysis.

5 DAMAGE IDENTIFICATION

The data measured between the load positioning and the introduction of the first cut were initially supposed to represent the undamaged situation to be compared with the damaged ones.

Data processing of the 8-month long time series has been performed with the algorithm tested on the simulated time histories to detect damages (Proper Orthogonal Decomposition). The eigenvalues and the orthogonal eigenvectors are calculated from the covariance matrix of the sensors using all previous measurements. The variations of the extracted eigenvectors show a shift related to the load positioning (visible for all the sensors) but they seem not to be correlated with the damage introduction (Fig. 10 and Fig. 11). Time series have been also filtered with different filters in order to remove the temperature trend, but also this analysis has revealed as uselessness. Probably the application of different filters within each temperature range could be satisfactory but it is not been addressed in this study. Also other statistical analysis algorithms have failed in the damage detection. The correlation between sensors on the damaged beam and sensors on the undamaged beam has shown to be apparently the same for the damaged and undamaged beams.

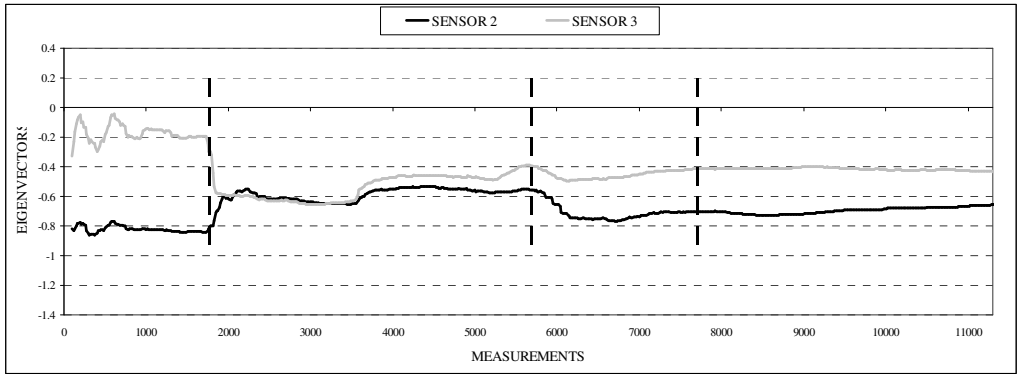

Figure 10. Zoom on eigenvectors variation during the period of damages realization. Dotted lines indicate the put of the dead load and the two main levels of artificial damage.

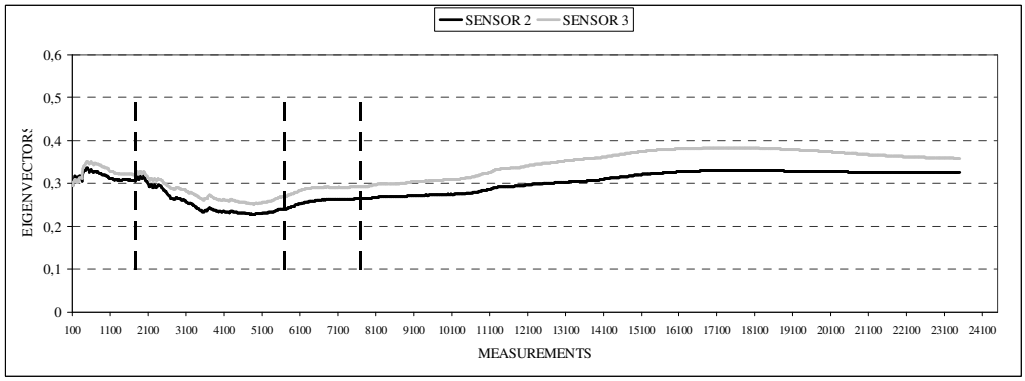

Figure 11. Example of eigenvectors variation during the whole monitoring period.

6 DISCUSSION AND CONCLUSIONS

This first level of analysis has put into evidence some interesting considerations that during a preliminary analysis were interpreted as failings of the applied algorithms of damage detection. Starting from the analysis of the POD results, it could be concluded that the damage introduction remains undetected for the second level of damage, while a false positive indication of damage could be retrieved in the period between the dead load positioning and the first level of damage (Fig. 10). Also the identification of the first level of damage is not so clear, because the eigenvectors increase a little before the damage introduction.

Theoretically, simulations had shown that the daily cycle could be compared to the yearly cycle and good results could be obtained if the daily cycles are regular. In particular, the signal stabilization already appeared one month after the monitoring starting for the simulated cases. However, by observing the eigenvalues of the Proper Orthogonal Decomposition and the correlation indices, it seems that the signals reach a stabilization after about 6 months from the test starting (Fig. 11). This is probably due to the strong variations of the temperature related to the geographic position of Autostrade per l'Italia laboratory. The thermal gradients between the upper and the lower surfaces of the beam induce strong deformations to be measured and 'strange' daily cycles. This should be the reason why the damage information are hidden into the threshold of the temperature changes. Probably damages were performed too early when the reference period was not long enough.

In addition, correlation analysis has shown that there is an indirect effect probably related to sun exposition that changes the relations between sensors. This 'non linear' effect should be deeper investigated and removed from the time series with a pre-processing analysis.

The other focus issue is the removal of the variability due to the environment when the yearly cycle has not been completed yet. The removal of the environmental variations has not been addressed in the present study.

The experimental tests have proved that in real situation associated with high thermal gradients, at least one year of monitoring is necessary before a damage detection procedure can be successfully applied, probably without any pre-processing analysis.

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