ON THE RELIABILITY OF SMART MONITORED STRUCTURES

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ABSTRACT :

In the last years, since the idea of integrating monitoring and control systems into civil structures has been proposed, many significant advancements have been produced in sensor technology, data fusion and data interpretation algorithms. However, despite of these advancements, only a limited number of applications of on-line structural health monitoring systems has been realized in practice. The paper analyzes the situation by summarizing the characteristics of some of the applications performed on special structures and discusses the issue of creating a procedural framework that can stimulate the diffusion of SHM techniques even in more conventional structures. The leading idea of the approach is to explicitly link SHM techniques to a structural reliability measure and then to design codes.

KEYWORDS: Structural Health Monitoring, Structural Reliability, Design Codes

1. INTRODUCTION

For a number of reasons, condition assessment for existing structures has received considerable attention in the last years both in engineering research and in common engineering practice. Among these reasons: the need for performing extensive refitting for use and structural rehabilitation of existing buildings and infrastructure, the need of assessing the safety and residual life of structures that have expired their design life or that have suffered damages due to ageing, accidents and natural events, such as earthquakes or extreme weather conditions and, last but not least, the need of optimizing maintenance strategies of building and infrastructure stocks (Aktan et al., 1996). In addition, the evolution of design codes from a prescriptive to a performance-based format conceptually requires new structures to be conceived within a complete life-cycle framework, in which a periodical evaluation of the fulfillment of the performance targets becomes an intrinsic requirement (Aktan et al., 2007).

The development of Structural Health Monitoring tools that has taken place in the last 15 to 20 years has provided a valuable support to structural condition assessment, integrating the more conventional programs of visual inspections and non-destructive testing with the deployment of long-term on-line instrumental monitoring systems. In particular, the evolution of sensing technologies and data acquisition systems has been impressive and a great research effort has also been dedicated to data analysis and interpretation algorithms, although in this latter field a number of problems still remain open (Del Grosso and Lanata, 2008).

A number of important practical applications of structural health monitoring have also been performed on real structures, mainly on bridges and other special structures, as for example reported in recent conferences (Chang, 2007), (Koh and Frangopol, 2008). Basically, condition assessment via structural health monitoring procedures can be performed according to two different approaches: the first approach is based on the measurement of the dynamic response of the structure to service loads and ambient vibrations, while the second approach is based on the measurement of the static response of the structure to ambient loads, namely temperature variations. In both cases model-based identification and statistical signal processing techniques have been proven to be able to detect anomalies in the response parameters that can be associated to structural changes, like damage or degradation of the structural materials and components and in some instances complete damage identification has also been proven possible.

Nevertheless, the acceptance of structural health monitoring techniques as a standard tool for assessing the actual structural conditions and reducing uncertainties in a performance-based life-cycle design approach is still a matter of discussion and further research is needed before it will spread in engineering practice. There are still many unresolved problems to study, but the main issue is concerning the uncertainties residing in the logic process that can be constructed to determine the actual structural reliability from the monitoring data. The sources of uncertainty that are involved in this process are related to:

- the type, number and location of sensors with respect to the location of the structural change;
- the sensitivity of the measured parameters with respect to the intensity of the change;
- the measurement errors;
- the dependability of the data transmission and storage systems;
- the ability of the data processing algorithms in identifying the changes with an acceptable level of confidence;
- the availability of a reasoning paradigm for updating with an acceptable level of confidence a structural reliability measure on the basis of the identified changes.

The adoption of SHM techniques as standard tools for structural reliability assessment in building and infrastructure codes will only become effective once the above uncertainties will be fully characterized. Some recent studies have considered some aspects of the above issues either on the basis of field experiments or on the basis of computer models. To mention a few: Marsh and Frangopol (2007) have determined the necessary number and position of sensors in order to optimize cost and reliability level in a corrosion monitoring study; Nayeri at al. (2007) have shown that identification parameters determined by means of natural excitation techniques in conjunction with the eigensystem realization algorithm can effectively track the changes induced in a building during retrofitting works; Catbas et al. (2007) have discussed the limitations in the structural identification procedures due to the various sources of complexity always present in large civil structures; Frangopol et al. (2008) present the determination of the actual reliability index against yielding and fatigue of a truss bridge based on a statistical processing of the strain monitoring data collected on critical members; Hosser et al. (2008) have presented a similar approach for the determination of the reliability index of prestressed concrete beams in which monitoring data are used to derive the actual probability distributions of the leading parameters in reliability calculations.

In the present paper, a further discussion on the relationships between structural safety and monitoring processes is presented, based on a review of the experiences gathered in the last years and an attempt is made to provide a conceptual framework for the future research on the subject.

2. REVIEW OF RECENT MONITORING EXPERIENCES

Designing, installing and operating a long-term monitoring system is a quite complex task that in many instances presents drawbacks that may affect the usefulness of the system or require special treatment of the measurement data. In the following, some considerations will be drawn based on the experience gathered during recently performed monitoring programs or monitoring experiments, with the aim of addressing the issue of the reliability of monitoring systems.

In the reported field experiences, that only cover a part of the activity performed in the past years, mostly fiber optic long-base deformation and rotation sensors of the SOFO family (Inaudi, 2000) have been used, together with conventional sensors for temperature measurements. The permanent data logging system was therefore composed by the SOFO reading unit and optical switch, equipped with a bridge able to include the reading of conventional electrical sensors. In the majority of the reported cases the monitoring systems were intended to perform on-line long-term static monitoring. In some cases, dynamic deformation time histories have also been recorded using a temporarily attached dynamic SOFO reading unit. Dynamic measurements have also been repeated with conventional accelerometers

2.1. Monitoring of harbor piers

An extensive monitoring project is being conducted in the Port of Genoa in the framework of a cooperative research program between the Port Authority of Genoa and the Department of Civil, Environmental and Architectural Engineering of the University of Genoa (Del Grosso et al., 2002). At the moment, the project comprises the monitoring of three piers and of a part of the breakwater, subjected to retrofitting interventions.

The first completed realization of the global project has been the long-term monitoring program of the San Giorgio pier (Del Grosso et al., 2008 a). The San Giorgio pier is used for coal import and it has been recently subjected to a retrofitting program. The facility has been built in the 1920s and the vertical walls delimiting the quays are made of heavy concrete blocks; more recently, a further section has been added to the pier in order to increase berthing space and actually the pier measures 400 metres in length. The evolution of bulk ships involved also the need of increasing the water depth in the adjacent basin and dredging activities were programmed to increase the actual water depth from 11 m to 14 m. The planned works have required strengthening of the wall. The structure has been underpinned with jet-grouting columns up to the depth of 18 m, and the blocks have been connected by means of vertical steel rods. Stability has been improved with permanent active tendons installed along the entire length of the pier (Figure 1).

The east quay wall of the San Giorgio pier has been equipped in 1999 with an array of 72 SOFO fibre optic linear deformation sensors (67 of them effectively installed and functioning), in order to detect possible distress caused by the dredging activity. The sensors are located in a service tunnel along the top blocks, in such a way to have 3 sensors in 24 measuring sections (Figure 1). All the sensors have an active length of 10 metres. The sensors have been positioned in triplets for a set of measuring sections, in order to derive the curvatures in the vertical and in the horizontal planes. The optical fibres are routed from the sensors to the measurement system located in a close-by building. Measurements are stored into a relational database that can be remotely accessed for processing through the data network of the Port Authority.

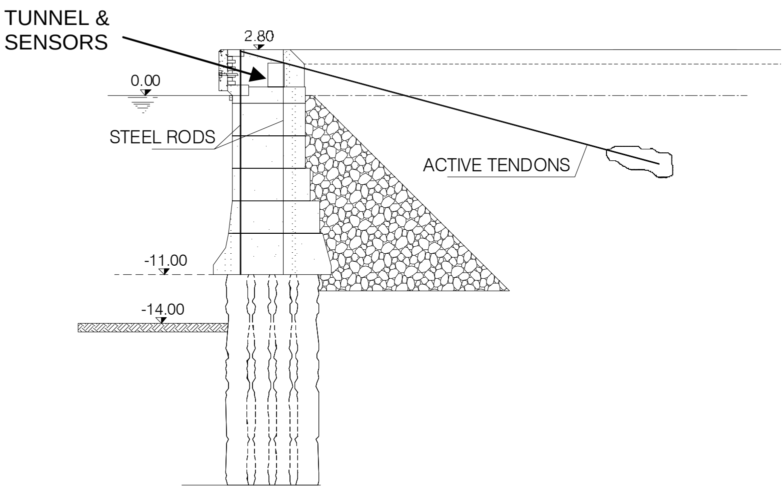

Figure 1 San Giorgio Pier – East wall cross section and location of sensors

The system has been functioning for five years with some interruptions due to maintenance and repositioning of the reading unit. As reported above, the installation of some of the sensors revealed very difficult and they were not put in place. A few other sensors or connecting cables have been damaged during operation of the terminal and the reading of others has become unreliable because of the presence of coal dust in the optical connections. The system is actually switched off, needing extensive maintenance interventions.

Data analysis and interpretation has been performed by means of statistical correlation algorithms. Movements of the sensors in absence of perturbations of the equilibrium of the wall were almost perfectly correlated to external temperature variations (Figure 2). Cross-correlation between couples of sensors have allowed disclosure of mechanical damage or malfunctioning of the sensors due to dust. Evidence of movements of the wall during dredging operations has also been disclosed (Figure 3). In both cases, the correlation index becomes stable only after some months of readings.

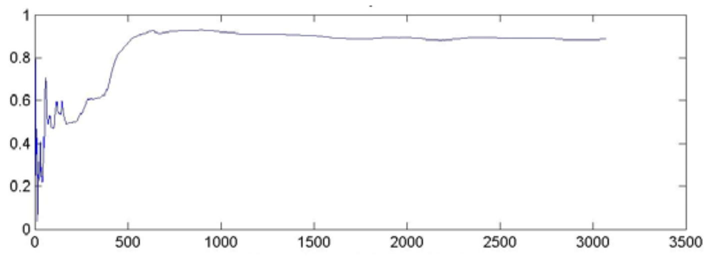

Figure 2 Correlation index between external temperature and sensor data versus time

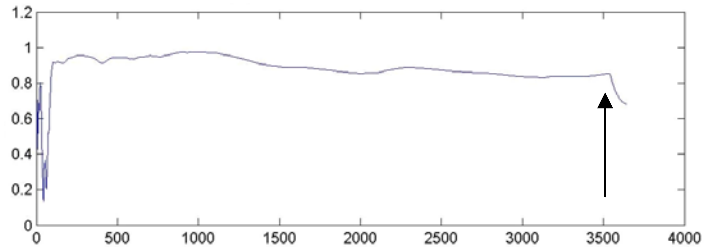

Figure 3 Correlation index between two sensors versus time
The arrow indicates dredging operations

2.2. Monitoring of bridges

A monitoring system has been installed during construction of a cable stayed bridge overpassing a canal in the Port of Venice (Del Grosso et al., 2006) in order to verify some design assumption and to provide on-line structural health monitoring during service life. The cable-stayed bridge is formed by a composite steel and reinforced concrete beam, continuous over two spans of 105 m and 126 m in length, respectively. The bridge axis is a circular segment of 175 m radius. The deck on each of the two spans is supported by 9 cables attached to a reinforced concrete pylon nearly 80 m high. A realistic rendering of the bridge is reported in Figure 4.

Figure 4 – Rendering of the cable-stayed bridge

The monitoring system comprises 48 linear SOFO deformation sensors, 4 SOFO compatible fiber optic inclinometers and 24 temperature sensors placed on the two spans. In addition, each cable is equipped with a specially packaged SOFO sensor while 12 SOFO sensors and 6 thermocouples have been embedded in the structure of the pylon during concreting. An anemometer has also been placed on the top of the mast. All the signals are routed to a control room placed in the basement of the mast. The permanent static acquisition system is linked to a standard telephone line for remote operation and control. A dynamic reading unit can be temporarily attached to system. The number and position of the sensors have been optimized in order to allow the static reconstruction of the deformed shapes as well as the dynamic identification of the vibration modes.

The installation of a SOFO sensor in the pylon revealed some difficulties because the length of the sensors was greater than the length of the pouring courses. Density of re-bars also complicated the installation. Installation of the sensors on the steel girders took place after the complete mounting of the steel part of the deck and in parallel with the spinning of the stay cables. A typical installation set up of the sensors on a lateral girder is shown in Figure 5. For clamping the sensors on the surface, steel reference plates have been previously welded on the girder web.

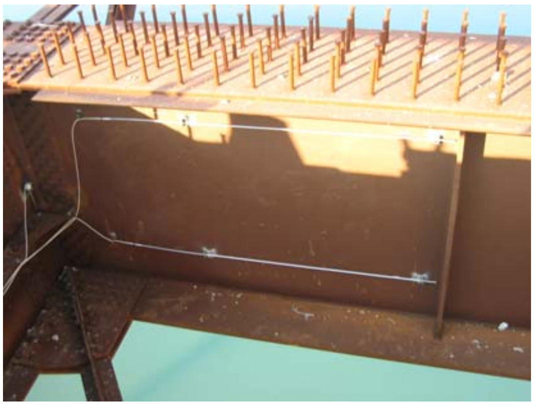

Figure 5 Positioning of the SOFO sensors on the girder web

Installation of the sensors in the cables required the definition of a special procedure for the final cable tensioning and protection. One sensor was damaged during the mounting of the casing. Data analysis and interpretation has taken place in two steps: during and at the end of the construction phase and during the final proof-load testing. During this latter phase dynamic measurements have also been performed with the SOFO sensors and repeated with conventional accelerometers. From the static measurements, the deformed shapes of the structure during the various steps of cable tensioning and position of the proof-loads have been derived and successfully compared with conventional topographic displacement measurements. System identification and tuning of a finite element model of the bridge have been performed for both fiber optics and accelerometer readings, showing a very good agreement between the two.

2.3. Monitoring of sample r.c. beams

A set of algorithms for the identification of damage from continuous static monitoring data using the Proper Orthogonal Decomposition and the Wavelet Packet Decomposition has been developed and tested using synthetic data (Del Grosso and Lanata, 2006, 2008). A validation of the algorithms using sample reinforced prestressed concrete beams is actually under way in the framework of a cooperative research between the Department and Autostrade per l'Italia S.p.A. on the monitoring of corrosion effects in bridges (Del Grosso et al., 2008 b).

Based on synthetic data series, the algorithms have been able to detect, localize and in some instances quantify the intensity of damages simulated by reducing the stiffness properties of some elements of the finite element model represented in Figure 6 according to different damage scenarios.

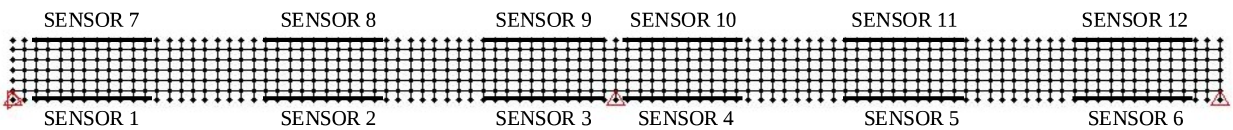

Figure 6 Beam simulation model and location of the virtual sensors

Long-base sensors analogous to the SOFO type have been simulated by appropriately processing the displacements of their end points. The model has been subjected to synthetically generated temperature time histories and probability distributions of temperature scatters from seasonal averages, simulating a five-years long observation; white-noise probability distributions have also been used to simulate measurement errors. Simulation of damage has suddenly been introduced after a number of readings roughly representing a three-years time.

All the damage detection algorithms require an initial period of observation to become stable and the reliability of damage detection has resulted to be dependent on the position of damage with respect to the position of the sensors. Nonetheless, the algorithms have shown to be sensitive even to small damages, of the order of a 50% stiffness reduction on a single element, as shown in Figure 7.

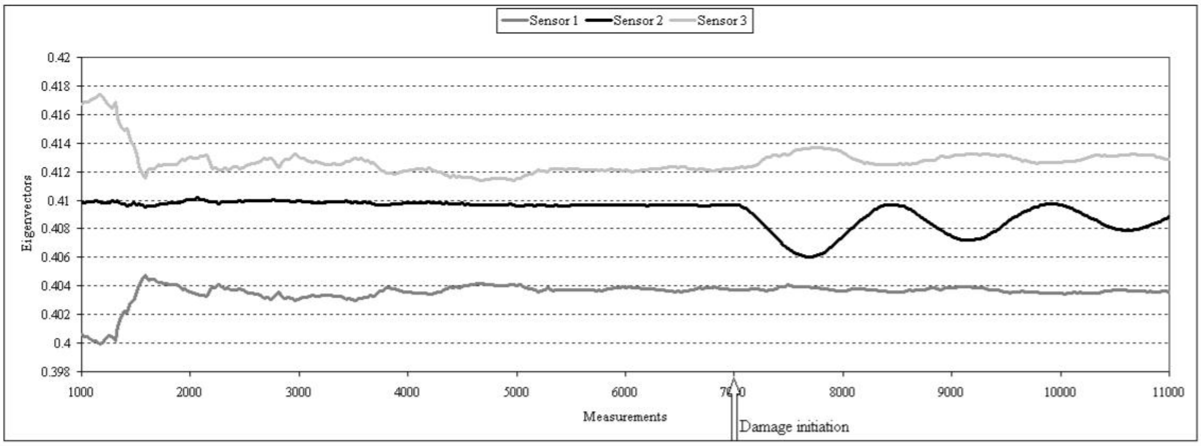

Figure 7 POD eigenvectors for 1 element stiffness reduction of 50% inside sensor 2 base length

The sensitivity and stability of the algorithms can be improved and localization and quantification of damage can be obtained by further processing of the data, as described in the mentioned references. Dynamic monitoring has also been simulated using white-noise processes to represent ambient vibrations.

Dynamic monitoring has also been simulated on a set of r.c. beam models subjected to known states of corrosion in the reinforcing bars (Del Grosso et al., 2008 b). Correspondence between synthetic and real data has been quite difficult to obtain as experimental measurements were highly dependent on boundary conditions.

2.4. Final remarks

The case studies presented in the previous sections allow tracing some remarks, especially referable to the static monitoring approach. As a first comment, it has to be observed that in designing a monitoring system a loss of sensors has to be accounted for; this lead to the conclusion that in order to be reliable a monitoring system should be easy to maintain or at least have some degree of redundancy. The number and position of sensors is a key issue in reliable damage identification procedures but, on the other hand, it will greatly influence the cost of the monitoring system. It is not yet clear from present experience if damage identification can also be obtained from global response parameters (e.g.: curvatures or deformed shapes in beams) in the same way in which it can be obtained directly from sensor readings.

Damage identification algorithms from static monitoring have proven to be sufficiently dependable using simulated data. However, no clear evidence of the reliability of the proposed algorithms coming from the laboratory or from the field is presently available nor it can be found in the literature. The use of dynamic monitoring is more common and more extensively studied but still, there is very little evidence that dynamic measurements and system identification procedures are really able to detect the small changes in structural materials or components that may lead to a timely identification of structural defects.

3. RELIABILITY OF MONITORED STRUCTURES

Coming back to the original point, can we say that a monitored structure is more reliable than a conventional one? How can we represent this in mathematical terms, in such a way that the structural health monitoring paradigm can be implemented into design codes?

Looking at the above questions from the point of view of the conventional limit-state approach, the target reliability of a structure is ensured by appropriate values of partial safety factors that are applied to characteristic values of loads and resistances. These safety factors take into account such many unknowns as the real probability distributions of loads and resistances and the effects of the simplifications made in design calculations. There can be no doubt that a better knowledge of the real probability distributions of the design parameters and of the behavior of the constructed system could result in more realistic determinations of the characteristic values with a consequent reduction of the safety factors (or an extension of the design life), but this would need a formalization of the complete process.

For example, Hosser et al. (2008) have recently proposed a procedural framework for the reliability assessment of prestressed concrete beams, based on the updating of probabilistic models as a function of the measured data; similar procedures are already applied for the residual life evaluation of existing offshore platforms, as described in API codes of practice.

However, based on the previous discussions, it appears that providing a formalized procedure for general classes of structures to derive probabilistic models of structural health monitoring information from current experiences represents an open subject for future research. The use of these models at the design stage of a structure that is intended to be monitored from the start of its life-cycle is also an issue to be investigated further.

It is also possible to look at the above questions from the viewpoint of a performance-based design. Up to know the capabilities offered by a performance-based approach in construction design are not fully understood by the engineering community and only in very limited cases this approach has been implemented into building codes (Aktan et al., 2007). Once a set of performance targets has been defined for a certain structure, monitoring becomes essential in order to demonstrate that these performance targets are met all over the life-cycle of the structure. In principle, to ensure structural safety, the quantitative evaluation of a reliability index by means of probability models may not be needed explicitly and non probabilistic representations of the uncertainties involved in the health monitoring process could also be employed, thus opening the way for the application of non-classical algorithms.

4. CONCLUSIONS

In the paper, the relationship between structural health monitoring and structural reliability is discussed from the point of view of assessing the safety level of an existing structure and of designing a new structure for being monitored. The uncertainties associated with the monitoring process have also been discussed in the light of recent structural health monitoring experiences both in the field and in the laboratory and of recent studies.

Future lines of research have also been envisaged.

REFERENCES

Aktan, A. E. et al. (1996). Condition assessment for bridge management. *Journal of Infrastructure Systems* **2:3,** 108-117.

Aktan, A.E., Ellingwood B.R. and Kehoe B. (2007). Performance-Based engineering of constructed systems. *Journal of Structural Engineering* **133:3**, 311-323.

Catbas, F.N. et al. (2007). Limitations in structural identification of large constructed structures. *Journal of Structural Engineering* **133:8**, 1051-1066.

Chang F.-K. (2007). Structural Health Monitoring: Proc. 3rd Int. Conf. on SHMII, Vancouver, Canada.

Del Grosso A., Lanata F., Pieracci A. and Brunetti G. (2002). Structural Monitoring Project in the Port of Genoa. *Proceedings of the 3rd World Conference on Structural Control*, Como, Italy.

Del Grosso, A., Inaudi D., Posenato D. and Torre A. (2006). Experiences in Data Analisys and Interpretation from Continuous Static Monitoring of Bridges. *Proceedings of the 4th WCSCM*, San Diego, (on CD-ROM).

Del Grosso A. and Lanata F. (2006). Damage detection and localization for continuous static monitoring of structures using a Proper Orthogonal Decomposition (POD) of signals. *Smart Materials and Strucures*, **15**, 1811-1829.

Del Grosso, A., Lanata F., Pieracci A., Brunetti G. and D. Inaudi (2008 a). Health Monitoring of old structures in the Port of Genoa. *Proceedings MEDACHS'08*, Lisbon.

Del Grosso, A., Lanata F., Pardi L. and Mercalli A. (2008 b). Health monitoring for corrosion detection in reinforced concrete bridges. In Koh and Frangopol (2008), 329-330 (text on CD-ROM).

Del Grosso, A. and Lanata F. (2008). A critical review of recent advances in monitoring data analysis and interpretation for civil structures. 4th European Conference on Structural Control, St. Petersburg, Russia.

Frangopol D.M., Strauss A. and Kim S. (2008) Bridge reliability assessment based on monitoring. *Journal of Bridge Engineering*, **13:3**, 258-270.

Hosser, D., Klinzmann C. and Schnetgöke R. (2008). A framework for reliability-based system assessment based on structural health monitoring. *Structure and Infrastructure Engineering*, **4:4**, 271-285.

Inaudi D. (2000). Application of fibre optic sensors to structural monitoring. *Trends in Optical Nondestructive Testing and Inspection*, Elsevier, 459-472.

Koh, H.M. and Frangopol D.M. (2008). Bridge Maintenance, Safety, Management, Health Monitoring and Informatics. Proceedings of the 4th IABMAS Conference. CRC Press/Balkema, Leiden, The Netherlands.

Marsh, P.S. and Frangopol D.M. (2007). Lifetime multi-objective optimization of cost and spacing of corrosion rate sensors embedded in a deteriorating reinforced concrete bridge deck. *Journal of Structural Engineering* **133:6**, 777-787.

Nayeri, R.D., Masri S.F. and Chassiakos A.G. (2007). Application of structural health monitoring techniques to track structural changes in a retrofitted building based on ambient vibrations. *Journal of Engineering Mechanics* **133:12**, 1311-1325.