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# Structural Health Monitoring: research and practice

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ABSTRACT: Structural Health Monitoring is one of the preferred research topics in structural engineering but practical applications are still behind, at least in the civil sector. The paper is aimed at reviewing the main research achievements on the subject and to argue about the reasons because practical applications still encounter difficulties in becoming a standard practice in civil engineering. Structural health monitoring concepts and current design approaches are also discussed with consideration of the safety of monitored structures versus conventional non-monitored ones. Existing standards on structural monitoring and the need for the development of new standards integrating design, maintenance and management of constructed facilities are addressed.

## 1 INTRODUCTION

Observation of structural behavior is a very old discipline that has accompanied theoretical developments in structural mechanics since its origins (Benvenuto 1991), providing basic knowledge of physical phenomena and verification of computational procedures. However, in the last twenty years this discipline has also taken different roles, gradually becoming the basic tool for facing the so-called *time-dependent safety problem* ( Mori and Ellingwood 1993) in civil engineering practice.

The shift from simple experimental observation to Structural Health Monitoring has been driven by two factors: on the one hand, by the consequences led by degradation of modern construction materials and functional obsolescence onto infrastructure economics and, on the other hand, by the availability of cheap, effective and durable innovative instrumentation and hardware/software tools to accomplish complex data acquisition and signal processing functions. Structural Health Monitoring (SHM) is indeed just the combination of traditional experimental/theoretical structural mechanics, electronics, material science, and information and communications technologies. Applications of this discipline can lead to the definition of *monitored structures*, a class of structures the characteristics of which in terms of safety and reliability indices should be considered differently from traditional structures, where safety relies on passive resistance only, in order to derive specific integrated design approaches (Del Grosso 2008 ).

In addition, the integration of monitoring system concepts in structural design is an essential step in innovative structural engineering, paving the way to the development of smart adaptive structural systems.

This paper is aimed at reviewing the main research achievements on the SHM subject and to argue about the reasons because practical applications still encounter difficulties in becoming a standard practice in civil engineering.

## 2 MATERIALS DEGRADATION AND OBSOLESCENCE

In developed countries, the greater percentage of infrastructures have been built just after World War II using steel, reinforced, composite or pre-stressed concrete structural systems. These techniques still are the most commonly used construction systems worldwide. Materials degradation and obsolescence are a key issue in infrastructure management not only where infrastructure stocks are so old (Aktan et al. 2007) but also where, as in recently developed countries, they represent a problem in perspective. Indeed, the physical and mechanical properties of these construction materials tend to degrade with time at a relatively significant speed, thus causing a loss in the economic value of the infrastructure assets. For example, recent studies have stated that the global economic consequences of corrosion may be evaluated to reach 3 to 4 GDP points per year (Schmitt et al. 2009).

Considering concrete structures, which are largely the most diffused ones, the most common and serious in terms of consequences, cause of deterioration in structural 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. Concrete degradation and especially chloride ion ingress and concrete carbonation is responsible for creating a corrosion potential for the steel bars, but the actual development of corrosion and the rate of the process are also dependent on temperature and moisture content in the surrounding concrete (Dangla and Dridi 2009), thus rendering the phenomenon very complex. Besides corrosion, fatigue is also an important cause of degradation in steel structures subjected to moving loads or vibrations. In bridges, degradation of joints and supports because of fatigue, corrosion and ageing is also an important issue influencing management strategies and costs.

Corrosion and material degradation cause a decrease in the resisting section of members and fasteners which in turn results in a degradation of resistance and stiffness of the whole structural system. Detection of the presence and progress of the phenomena can be made by direct monitoring of the electrochemical driving parameters or, indirectly, by analyzing the changes with time of the structural response (Del Grosso et al. 2008, 2011).

The concept of obsolescence is more related to the evolution of the needs of infrastructure users, for example (for transportation infrastructures) in terms of commercial speed, traffic volumes, size and weight of vehicles etc., but obsolescence can also be produced by the unfavorable levels of maintenance costs induced by degradation. Evaluation of obsolescence results from complex considerations involving direct, indirect and social costs for decommissioning and substitution, but the corresponding decision making process is based on parameters that can be quantitatively estimated from direct and indirect observations.

## 3 MAINTENANCE STRATEGIES AND COST OPTIMIZATION

Due to the large economic effort needed to keep the existing and future infrastructure systems in efficient and safe conditions, in the recent years several studies and practical applications have been performed on maintenance strategies and maintenance cost optimization.

The approach that has recently received considerable attention and that is considered the most attractive for practical applications is based on the use of *lifetime functions*. A lifetime function

(Figure 1) represents the decay in time of a performance index that may eventually represent the reliability index or a more complex weighted sum of several indicators.

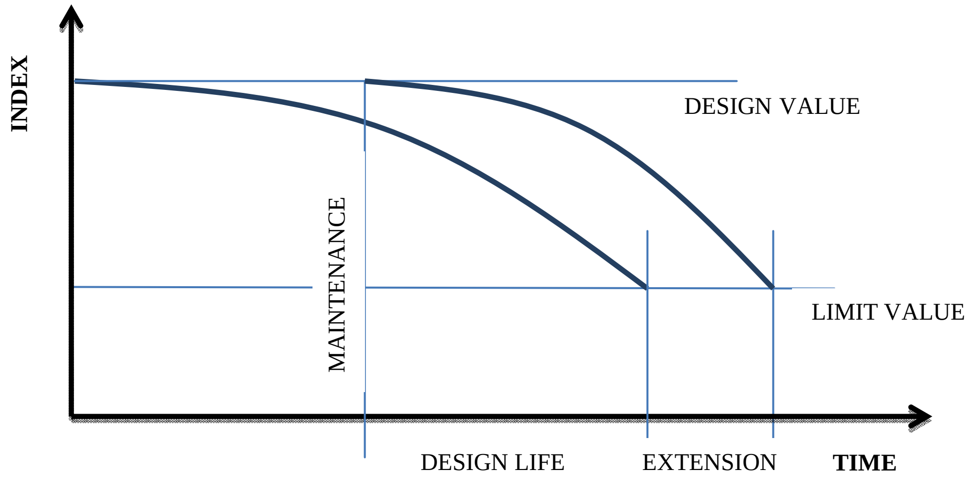


Figure 1. Typical lifetime function and the effect of maintenance.

The use of lifetime functions has been introduced by several Authors; among them it is worth mentioning the works by Miyamoto et al. (2001) and by Frangopol and Liu (2006) in the context of lifecycle cost optimization. A more recent review of the approach, performed in the framework of the European project IRIS (Wenzel et al. 2011) is leading the method to represent an effective and practical tool for managing constructed facilities.

In synthesis, it is a-priori assumed that the decay of the performance index, originally at the design value, is such that the limit acceptable value is reached at the end of the design life and that the lifetime curve is represented by a simple exponential expression. At any time during the life of the facility, a maintenance intervention should be able to improve the index and, at the limit, recover the design value of the index itself extending the expected operational life. Preventive and condition based maintenance can both be considered within the process. Maintenance can be repeated several times and the operational life can in principle be extended as long as economically feasible. The above formulation allows to establish a life-cycle cost optimization process based on heuristics and knowledge-based rules.

All quantities involved in the process are however uncertain in nature; their determination can be based on statistical knowledge bases and therefore the process can be formulated in probabilistic terms. It is noted that the whole procedure could be developed in some backward processing, involving also a re-determination of the safety coefficients to be used at the design stage.

Assessment of the actual structural conditions allows the a-priori lifetime curve to be periodically updated with the effect of reducing the uncertainties involved in the process and transforming the approach in a really effective infrastructure management tool. Structural Health Monitoring ( Del Grosso and Lanata 2011) can be regarded as a tool for performing this task (Figure 2).

In current infrastructure management the use of SHM is not however a common practice. Although in many special cases, like long-span bridges and super-tall buildings, SHM systems have been efficiently implemented and used for maintenance planning, most of the infrastructure management applications (e.g.: highway and railway bridges) are still based on traditional observations (visual inspection and standard NDE). There are many reasons for that. The following is a tentative list of those reasons.

- Standards and regulations concerning infrastructure safety impose performance of traditional inspections at fixed time intervals; this obligation cannot be legally avoided using SHM systems.
- Although a consistent number of damage identification algorithms have been proposed and validated in the literature, the reliability of the determination of the structural conditions from the SHM data is still to be widely experienced.
- Although very reliable, durable and stable sensors technologies are nowadays available on the market, the sensory systems always show some malfunctions; this needs redundancies at sensor installation and maintenance during operations.
- The operational life of electronics (data loggers, computers, etc.) is shorter than that of any other system components and much shorter than the operational life of the structure; this will require frequent substitutions of electronic components.
- Education on SHM systems and global infrastructure monitoring approaches is still not enough diffused in civil engineering university programs; consequently, engineers in infrastructure owners organizations are reluctant to rely on SHM.

In synthesis, the economic and technical advantage of using SHM systems in infrastructure management is still questioned by potential users. Recent discussions held at an academic workshop (6th IASCM International Workshop on Structural Control and Health Monitoring, Sydney, 2012) have pointed out such situation and traced research needs for possibly overcoming the above difficulties in the diffusion of SHM technologies.

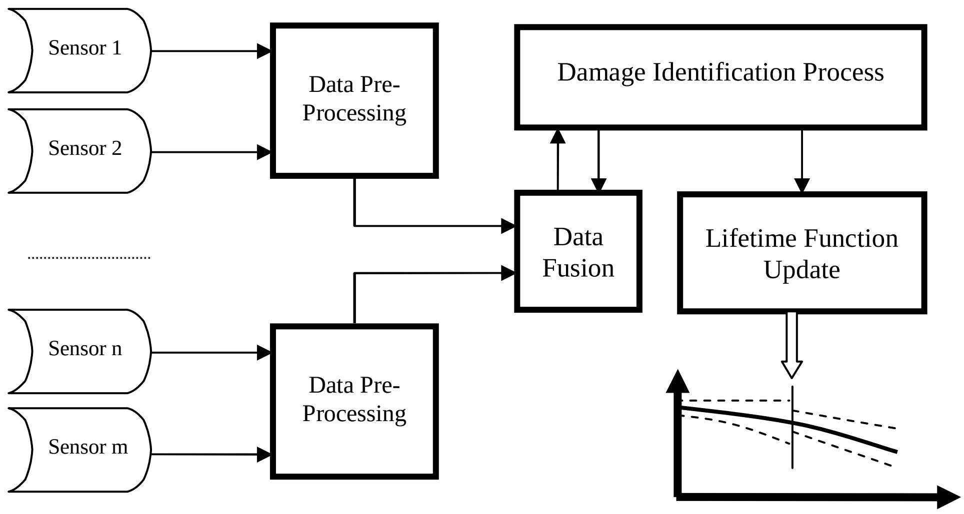


Figure 2. Lifetime functions update via SHM.

## 4 MONITORING SYSTEMS

A very large amount of studies and experiences on monitoring systems have been made available in the recent years but some issues still remain open. A brief summary of research results and some open questions are presented here.

### *4.1 Permanent versus periodic monitoring*

By permanent monitoring it is intended a monitoring system that is permanently installed and maintained in operation on the structure, typically from the construction stage. This is the most complete approach to SHM, allowing to obtain continuous time-series of data comprising structural response parameters (static and dynamic), environmental parameters, load characteristics, and other quantities important to the control of materials degradation processes.

The conceptual advantage of permanent monitoring systems is that the time-series of data can be processed in many different ways, including on-line and multi-stage processing, disclosing features that may also reveal unexpected structural behaviors. Events like earthquakes, shocks, storms etc. can be completely described allowing a comprehensive evaluation of the phenomena and of the corresponding structural response.

This is important not only for assessing the conditions of the single structure under study but also for characterizing events that have a low probability of occurrence and that are not consistently modeled in design codes. In addition, data processing can be performed on-line allowing warnings and alarms to be raised in real-time. Rain-flow counts can be performed on stress time-histories to provide on-line evaluations of the accumulated damage and of the residual fatigue life. The disadvantage of permanent monitoring systems is that they are relatively expensive, they need to be designed very carefully and they produce a very large amount of data, thus requiring a dedicated organization and complex architectures for data transmission, management and permanent storage.

Periodic monitoring is performed by temporarily installing an appropriate sensory system on the structure and gathering data for a short time (from a few hours to a few weeks). Feature extraction is performed for every measurement campaign and the health conditions of the structure are determined from the time-histories of the characteristic features of the campaigns.

Periodic monitoring presents several advantages. First of all, periodic monitoring may be considered a non-destructive evaluation tool more sophisticated than traditional ones but conceptually consistent with them, and therefore more easy to be understood by infrastructure owners. Secondly, the cost of acquisition and maintenance of the instrumentation system is distributed on the number of structures to be monitored. There is no significant difference in the damage identification algorithms that can be applied but data management is simpler than in the previous case.

The main disadvantages reside in the fact that the sensor typologies are necessarily limited and consequently some phenomena cannot be recorded and, of course, accidental events occurring between subsequent campaigns cannot be recorded as well, although their effects inducing damages in the structure could be disclosed.

In infrastructure management practice, there is no clear understanding on whether one approach is superior to the other. It can be noted that, in general, permanent monitoring is to be preferred for large complex structures, while periodic monitoring is more suitable for SHM applications on large structure stocks comprising repetitive simple schemes. Table 1summarizes the main characteristics of the two approaches.

Table 1. Characteristics of permanent versus periodic monitoring

| | **Permanent Monitoring** | **Periodic Monitoring** |
|---|---|---|
| **Sensor types** | Extended | Restricted |
| **Data management** | Complex | Simple |
| **Accidental events** | Recorded | Not recorded |
| **Damage identification** | On-line | Off-line |
| **Warnings & Alarms** | Real-time | Deferred |
| **Fatigue life evaluation** | Direct | Indirect |
| **Installation costs** | High | Low |
| **Operational costs** | High | Low |

### *4.2 Diagnostic and Prognostic Algorithms*

The development of damage identification or diagnostic algorithms is a very common topic in SHM research. For damage identification it is intended a procedure able to analyze the monitoring data and determine occurrence, location and intensity of damage. Hundreds of journal and conference papers have proposed a large variety of such procedures. Their effectiveness is usually proven by analyzing computer simulated data, benchmark studies and small scale laboratory experiments. Relatively few papers are reporting about damage identification on real structures subjected to artificially induced damages, normally using measurements of dynamic response before and after a known damage level has been induced in the structure. In the Author's knowledge, there is no case reported in the literature where algorithms of this type have revealed insurgence of damage in real structures but cases are reported where behavioral anomalies with respect to predictions given by design models have been detected. In the Author's opinion, the development of diagnostic algorithms has reached a substantial maturity and the preparation of a comprehensive review paper will be very fruitful for disseminating them to potential practical users and identifying the needs for future research.

All algorithms need a period of observation in which the structural health conditions can be considered unchanged (reference period). The effectiveness of a diagnostic algorithm can be measured in terms of: a) length of the reference period, b) minimum detectable damage for given signal to noise ratios, c) time of observation after damage needed for detection, d) capability of locating damage, e) capability of determining the intensity of damage, f) capability of identifying multiple damages occurring at different locations, and g) reliability. This latter aspect has been recently investigated (Del Grosso and Lanata 2012) but further research is still needed. A synthetic categorization of the algorithms can be found in (Del Grosso 2012).

The computational complexity of the different algorithms is also very different and the influence of environmental conditions encountered in real cases is largely influencing their effectiveness. In practical applications, SHM operators privilege the use of the most simple of them, consisting in frequency analysis, various types of correlation and simple predictive models, leaving the more complex to successive stages of processing. It is noted that simple algorithms can be easily implemented in smart sensing systems to provide quick on-line detection of anomalies.

As concerning prognostic algorithms, i.e. algorithms able to estimate the remaining life of the structure, they can be grouped in two classes. A first class makes use of finite element structural models that include material degradation models. In these models the static or dynamic parameters are optimized in order to reflect the real structural response and the evolution of the structural conditions. The other class comprises heuristic models. A simplified and very practical approach is to use the updated lifetime functions to predict the expected life. This approach avoids the computational complexity of the first class of methods but provides very useful information to support engineering decisions.

## 5 GUIDELINES AND STANDARDS

A limited number of guidelines and standards has been released to date. The only official international standards are the ISO 14963:2003 – Mechanical Vibration and shock – Guidelines for dynamic test and investigations on bridges and viaducts and the ISO 18649:2004 – Mechanical vibrations – Evaluation of measurement results from dynamic tests and investigations on bridges. These standards refer to the use of dynamic measurements to perform periodic SHM functions on bridges. Other guidelines, more widely addressing the issue of SHM and the design of monitoring systems have been published by research organizations like ISIS Canada (ISIS Manual n. 2 – Guidelines for structural health monitoring) or have been produced in the framework of international research projects like the European SAMCO and IRIS. In the IRIS framework, a proposal for standards covering the use of lifetime functions has been elaborated by CEN WG 63.

An interesting standard has been recently issued in Russia (GOST P 53778 2010 Building and Structures – Technical inspections and monitoring regulations). This standard is mandatory in the Russian Federation and broadly addresses structural and geotechnical inspection and monitoring during service life.

Rules for inspection and management of various types of infrastructures have been issued by several agencies in the world, but they do not expressly address issues related to structural health monitoring as described in this context.

It is however recognized that the lack of international standards and regulations on buildings and structures considering the use of SHM represents an obstacle to the diffusion of the applications. The need for working on this subject is therefore pointed out.

A particular aspect that still need to be investigated from the theoretical standpoint in view of impacting on design standards is related to the reliability of monitored structures versus non-monitored ones. In conventional structural design codes according to the European limit state format or the American LRFD, characteristic values of loads and resistance of materials are deduced from standard probability distributions and, in addition, safety verifications are performed by applying appropriate safety factors to characteristic values, to reflect the uncertainties involved in the process.

A question now arises regarding the appropriateness of those safety factors when uncertainties are reduced by the presence of a permanent monitoring system on the structure providing information on the structural conditions and allowing interventions to be made for keeping the probability of failure below the acceptable limits. To date there is no study, in the Author's knowledge, addressing this question in a systemic way. It is envisaged that the backward use of the lifecycle functions could provide a useful approach.

## 6 CONCLUSIONS AND DIRECTIONS OF FUTURE RESEARCH

The paper has summarized the main research and applications achievements in SHM technologies. Several open problems still remain unsolved and may be the subject of future research. Apart from standardization needs, as already mentioned in the previous paragraph, the first and probably most important issue is related to the safety coefficients that should be adopted in the design of monitored structures. This relates to refurbishment design of existing structures as well as to the design of new structures, whereby the presence of the monitoring system can redefine the probabilistic modeling of design uncertainties. A second issue is related to the use of updated behavioral models (FE models) that constantly reflect the state and the evolution of structural conditions. Reliable techniques to construct and use these models, sometimes referred to as "numerical twins" of the real structure, still have to be developed and experienced.

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