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STRUCTURAL HEALTH MONITORING AND INFRASTRUCTURE AUTOMATION

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ABSTRACT

Structural Health Monitoring is nowadays one of the preferred research topics in structural engineering disciplines but practical applications are still behind, at least in civil engineering. The paper is aimed at arguing about the reasons because practical applications still encounter difficulties in becoming a standard practice in civil engineering and about the capabilities of SHM not yet exploited. One of the reasons resides in the low economical appeal that the installation of SHM systems frequently have, at least in the short term. Consequently, the main focus of the paper, in order to overcome such disadvantage, is put on the lack of integration of SHM system with building and infrastructure automation systems. The characteristics of these systems will be briefly reviewed and the added value of performing integrated functions will be pointed out. Indeed, modern asset management in building and infrastructure is becoming a very complex technological field as the need for minimization of energy consumption, reduction of CO2 emissions, minimization of operational costs an maximization of the availability during maintenance is becoming the more and more important. Integration of monitoring systems providing information supported decision capabilities will pave the way to the realization of smart asset management systems for infrastructure. The paper will also present an approach for establishing a roadmap towards such goal.

KEYWORDS

Structural health monitoring, infrastructure automation, energy management, security management.

INTRODUCTION

In developed countries, the greater percentage of infrastructures has been built after World War II using steel, reinforced or pre-stressed concrete and composite structural systems. These techniques also form the basis of modern structural engineering and still are the most commonly used construction systems worldwide.
However, materials degradation and obsolescence represent a key issue in infrastructure management not only where infrastructure stocks are so old but also where, as in recently developed countries, they represent a problem in perspective. Indeed, degradation of the physical and mechanical properties of these construction materials develops with time at a relatively significant speed, thus causing a loss in the economic value of the infrastructure assets. Recent studies have found that the global economic consequences of corrosion may be evaluated to reach 3 to 4 GDP points per year (Schmitt et al. 2009).
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 at all levels on maintenance strategies and maintenance cost optimization. For example, according to the European White Paper on Transport (European Commission 2011) modernization of the European infrastructure system able to improve safety, security and sustainability of transport is considered a key issue for the future of the Union.
Goals have been envisioned for the period 2020-2030 concerning inter-modality, efficiency in transport of goods and passengers and looking at a very significant reduction of casualties occurring during transport. These goals cannot be achieved without a profound innovation in the construction sector as well as in infrastructure management techniques. Referring to the documents prepared by the European Construction Technology Platform (ECTP 2005), the following research fields have been individuated:

- Modeling the performance of the infrastructure,
- Monitoring the performance of the network,
- Improving the performance of the infrastructure: materials and construction techniques,
- Enhanced management.

With particular focus on risk management, the ECTP Strategic Research Agenda indicates the objectives represented in Figure 1.

12. Risk Assessment definition of a common EU regulatory framework on security and institutional continuity

CIS	–Monitoring and Alert Systems for Civil Infrastructures (Landslides, Avalanches, Flood, Earthquake –Full protection –Implementation of standards
Route/ network	–Evaluation of risk and risk prioritisation –Mitigation of risk –Retrofit –Monitoring (ICT systems) –Procedures –Their application to networks
Component/ struct. element	–Development of an Instrument for Risk and Safety quantification –Improvement of structural design to resist natural hazards –Evaluation of the performance of the single components of a structure, design criteria, retrofit techniques and materials –Development of standards
Sub component	–Knowledge

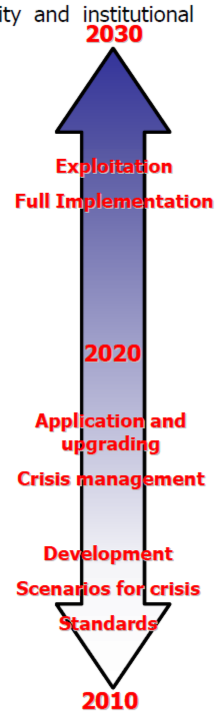

Figure 1. Security against manmade hazards and risks (from ECTP Strategic Research Agenda - Focus area Networks)

As indicated, the focus of innovation covers a much wider scope than Structural Health Monitoring alone, diffusing the idea that the infrastructure of the future will become a system much more complex that will integrate many different components, ranging from innovative materials to ICT and management modules.
The present paper is aimed at discussing the role that Structural Health Monitoring (SHM) techniques may play in the achievement of the above goals and how a broader approach to infrastructure automation may help SHM to spread as a standard practice. The discussion will be preceded by a short summary of SHM techniques and by a review of the capabilities and limitations offered by current SHM practice.

SHM PRACTICES AND TECHNOLOGIES

General Discussion

In the last fifteen to twenty years, structural health monitoring of civil structures has been the subject of intensive developments both from the scientific and the practical points of view. In particular, structural health monitoring of bridges, port structures and dams has received specific attention (Glisič & Inaudi 2007, Wenzel 2009, Del Grosso et al. 2008, 2010).

Observation of the behavior of real structures is an 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 & Ellingwood 1993) in civil engineering practice.

The transformation from simple experimental observation to Structural Health Monitoring has been driven by two technological breakthroughs: the availability of sensors that can be permanently installed on or embedded into a structure and theoretically function for its entire life, and the availability of hardware/software devices able to manage large and complex sensory networks acquiring data, analyzing them, and providing information on the structural conditions and on their expected evolution.
Different monitoring approaches have been developed and extensively tested in the field:

- periodic monitoring, consisting in performing monitoring campaigns at fixed time intervals;

- permanent monitoring, consisting in continuous measurements of the structural response;
- dynamic monitoring, consisting in the measurement of the dynamic structural response,
- static monitoring, consisting in the measurement of the static response, and
- combined monitoring, in which the different approaches are combined together.

In addition, measuring of external load parameters and environmental conditions has been proven to be particularly important in taking under control materials degradation phenomena.
This has however resulted in complex instrumentation systems, also difficult to be efficiently designed and expensive to be installed and maintained. The issue of system maintenance is particularly critical, because if the sensor technology can be considered nowadays reliable enough for the purpose of practical implementation of SHM systems, electronic hardware components are characterized by a short (commercial) life, thus obliging the structure owners to a relatively frequent refurbishment of permanently installed SHM systems.

A very large variety of data interpretation tools, both model-based and non-model-based, have also been developed and applied in practice. However, the issue of the reliability of damage identification (as concerning probability of false conclusions on the presence and location of damage) with respect to minimum detectable damage size, time after damage needed for detection, etc., is still an open question (Del Grosso & Lanata 2012).
Due to the above considerations, despite of the very large scientific developments on the subject and of the theoretically proven effectiveness of SHM techniques in infrastructure management, the use of SHM is still far from becoming a standard practice.

In the following subparagraphs, a brief review of current practices and technologies is presented.

Sensory Systems

Several innovative sensor technologies have been developed and diffused on the market in the recent years. As concerning contact sensing, fiber optics and MEMs based sensor platforms are amongst the technologies that have induced the most significant impact on the diffusion of SHM procedures.
Currently available fiber optic sensors (FOS) are able to measure a very large variety of parameters useful for understanding the phenomena relevant to assess the condition of civil structures. Durability, stability and robustness of these sensors have proven to be superior than conventional instrumentation and suitable for long-term permanent monitoring; in addition, they can be easily embedded into structural members, especially in concrete members, and cables. Current experience has demonstrated that FOS have been able to work for nearly 15 or 20 years without maintenance and rates of malfunctioning with proper installation are usually less than 10%. Optical connectors between sensors and transmission lines have however shown to be the most critical issue.

MEMs based sensors and sensor platforms are also able to measure most of the relevant parameters, with however some limitations. Table 1 shows a comparison of the parameters that can be measured with the two technologies, according to currently available products.

It has to be noted that MEMs based sensors are generally less expensive than FOS sensors, and less expensive than traditional electro-mechanical instruments, but their durability and robustness are not yet extensively experienced in practice. MEMs sensors contain electronic components, therefore they need an autonomous power supply (battery) or they need to be equipped with energy harvesting devices.

Table 1. FOS and MEMs sensory systems

Parameter	FOS	MEMs
Temperature	X	X
Humidity	X	-
PH/Chemicals	X	-
Loads/Pressures	X	-
Displacements/Rotations	X	X
Accelerations	X	X
Strains	X	X

In the measurement of strains, FOS can be packaged to measure local strains or the average strains over bases ranging from a few centimeters to several meters, thus being more suitable for application on large and massive

structures. Recent developments in FOS technology have introduced quasi-distributed and distributed sensing systems for temperature and/or strains (static), able to provide closely spaced measurements from a few millimeters to 1 m, in this latter case up to sensor lengths of many kilometers (Glisič & Inaudi 2007).
Distributed FOS systems have been successfully used in the monitoring of bridges, dams and pipelines (Inaudi & Glisič 2005). When used for the monitoring of strains, the sensing optical cable shall undergo the same deformations as the structural material; generally the cable is glued onto the surface of the structure and up to now there is no clear evidence of the long-term behavior of adhesives.
MEMs based platforms can be integrated with microcomputers to provide local data processing capabilities (intelligent sensing) for the sensors integrated within the platform or placed in the vicinity and connected to them (Figure 2).

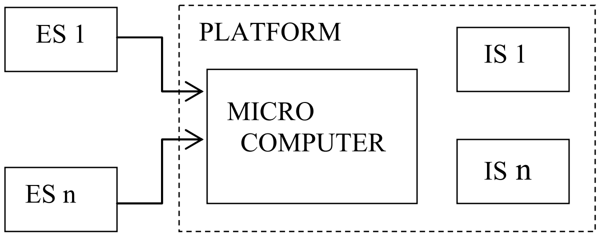

Figure 2. Intelligent sensor platform scheme. IS: integrated sensors; ES: external sensors

For displacement measurements, other types of contact sensors are also available. For example, GPS antennas represent a well-established technology and have been effectively used to measure static and dynamic (low frequency) displacements of structures (Fuggini 2009).
Non-contact (remote) sensing techniques have been used since a very long time for the measurement of displacements (and strains) in structures. Recent developments in laser and radar technologies as well as in image processing in geodesy, topography, medicine and other fields such as homeland security, have rendered many techniques a valid alternative for field application to civil structures (FIG/SIAG 2011). A recent study (Vaghefi et al 2012) has evaluated 12 potential remote sensing technologies, already commercially available, for structural and non-structural condition assessment of highway bridges.

Data Transmission and Acquisition Systems

For large structures, this is the most complicated and expensive component of the system and also the potential source of malfunctions and maintenance costs, depending on the technologies used and on the relative combination of signal transmission and data acquisition/transmission.
For MEMs based sensing, the basic transformation from signals to binary data takes place in the platform and data transmission can be accomplished through wires, fiber optic cables or in wireless mode according to different transmission protocols. This is a substantial difference with respect to traditional instrumentation, where the electrical signals need to be transferred over long distances, thus requiring complex conditioning and electrical protection of the cables.

Depending on the different transmission protocols, the main limitation resides in the distance between the transmitting platform and the receiving device. For example, data transmission via Ethernet, USB and wireless protocols is in practice limited to a few tens of meters, while transmission via fiber optic cables or the use of standard telecommunication protocols has no such limitation. Another issue is the power intensity required for data transmission, that is also different depending on the protocol as it is different the location of the power source, i.e. either in both the transmitter and the receiver or in the receiving devices only (Ethernet, USB).
When using FOS, problems are different because sensor interrogation shall be performed with light and decoding of the light signals to produce binary data shall be accomplished by dedicated hardware/software devices, more expensive than conventional data loggers.

On the other hand, transmission of light signals through optical cables is free from electro-magnetic disturbances and does not require signal conditioning. Consequently, light signals can be transmitted over consistent lengths, up to several hundred meters or even kilometers and optic cables only need mechanical protection. Data acquisition modules are usually limited in terms of number of controlled sensors and external junction boxes and optical switching devices are usually required for complex instrumentation systems, thus increasing the risk of malfunctions in the optical connections. In addition, placement of optical cables is more complex than electrical cables due to limitations in bending. However, systems comprising several hundreds of sensors have been realized, showing very good performance in time.

In distributed optical sensing systems, the distinction between sensing elements and transmission lines is overcame, because the optical cable is the sensing element and the transmission line at the same time, but decoding is more complex and the devices more expensive.

Real-world applications usually mix FOS, MEMs based sensors and traditional sensors, thus requiring complex architectures of the data transmission and acquisition systems, such as the one depicted in Figure 3.
Economic implications of system installation may be different in permanent and in periodic monitoring. In particular, periodic monitoring eventually only requires permanent installation of the sensors and interrogation lines, but data acquisition can be performed periodically and data manipulation can be performed offline. Permanent monitoring requires instead complete system installation.

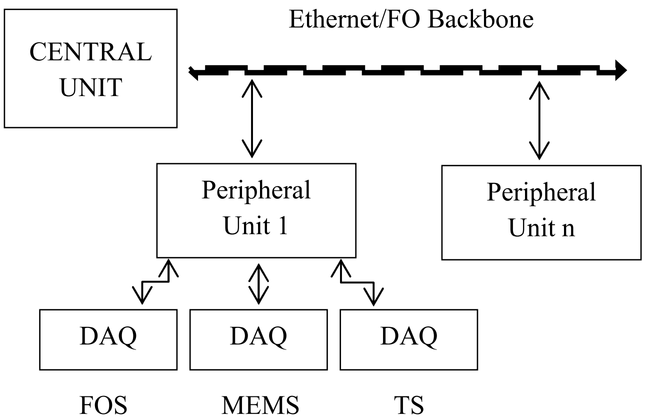

Figure 3. Typical system architecture. FOS: fiber optic sensors, MEMS: MEMs based sensors, TS: traditional sensors.

The issue of selecting between permanent and periodic monitoring is discussed in the next subparagraph.

Permanent vs Periodic Monitoring

Permanent monitoring, especially when installed at the construction stage, 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 assess the structural conditions.

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 management and permanent storage.

Periodic monitoring is performed by temporarily connecting DAQs to a permanently installed sensory system or 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 at least part of the instrumentation system is distributed on the number of structures to be monitored; monitoring can also be outsourced by paying some extra cost of installation for every campaign. There is no significant difference in the damage identification algorithms that can be applied with respect to the previous case, but data management is simpler.

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 2 summarizes the main characteristics and potential of the two approaches.

Table 2. Permanent vs. 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

Damage Identification Algorithms

A large variety of damage identification algorithms have been proposed in hundreds of journal and conference papers. Their effectiveness has been 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:

- length of the reference period,
- minimum detectable damage for given signal to noise ratios,
- time of observation after damage needed for detection,
- capability of locating damage,
- capability of determining the intensity of damage,
- capability of identifying multiple damages occurring at different locations, and
- 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 approaches to successive stages of processing.

It is noted that simple algorithms can be easily implemented in smart sensing systems (MEMs platforms or Peripheral Units) to provide quick on-line detection of anomalies. At least, data validation and detection of sensor malfunctions can be performed at the local level, routing clean data only over the transmission system components.

To the aim of the present discussion, the issue of the economic value of the information gathered from the damage identification (or condition assessment) process should be specifically addressed.
A first consideration concerns the relationship between the structural condition observed at a given time and the usual procedures adopted by infrastructure owners for maintenance optimization. These procedures, standardized in some countries, are based on condition indices derived from visual inspection and conventional non-destructive tests. Rating of condition indices allows maintenance planning.
Heuristic relationships between the information gathered from SHM and conventional condition indices can be for example established. A second consideration concerns the use of numerical models. This aspect may be of particular interest because it is one of the possible research developments that could increase the added value of SHM.

Numerical Twins

Numerical models able to represent the real structural behavior during the lifetime of the structure are sometimes called numerical twins, as they are (or should be) the exact copy of the real structure in numerical terms.

Structural system identification and finite element model updating is a known field in structural dynamics. System identification from dynamic measurements is in particular well known and several software packages are available to extract eigenvalues and eigenmodes, like for example in MATLAB.
Modifying the parameters of a finite element model in order to reproduce in a dynamic analysis the same eigenvalues and eigenmodes extracted from the measurements is also an affordable task, that can be performed by several approaches. In practice, FE model updating is a numerical technique used to minimize the differences between the dynamic response of the real structure and the FE model. Special purpose optimization routines and sensitivity analyses (Barthorpe 2011) can in general be used; an effective and practical tool is for example described in (Mordini & Wenzel 2007). Updated models can be very useful in damage identification as their results can help interpreting anomalies in SHM data streams.

Constructing numerical twins is however more complex than just dynamic finite element model updating because all the relevant phenomena should be appropriately represented in the model, including material degradation and environmental effects. Stochastic finite element techniques and/or other types of stochastic modeling may be available for that purpose but it can be affirmed that the research on the subject is as its early stage.

The availability of efficient procedures to construct and maintain exhaustive numerical models (twins) will definitely improve the reliability of damage identification and residual life prediction processes.

Economical Considerations

Depending on the characteristics of the monitoring system (e.g: permanent or periodic, extension, etc.) and on structural and environmental complexity, the initial cost of a monitoring system can be estimated to be approximately 0.5 to 1% of the structure's cost. This cost generally includes system design, procurement, installation and field testing of all system components, and the basic software. The incidence of the initial cost of the SHM system may not be considered very significant but an annual cost for system maintenance and data interpretation shall be considered as well, contributing to the life-cycle cost of the system.
Reasoning about system economics means to compare the life-cycle cost with expected benefits. During early developments of SHM technologies, infrastructure owners have in many cases considered favorably the installation of monitoring systems, mainly because of the relatively small incidence of system installation cost and of the expectations on potential results. In some cases, installation of SHM systems has been pushed by the consequences of reported structural failures, in other cases by the uncertainties related to the safety of existing infrastructure, or by the realization of innovative structural solutions, etc. In many cases, perception of the potential benefits was understood, but sometimes it was not very clear and decisions have been dictated by research interests.

Nowadays, the effects of the financial crisis on world economy and the fact that SHM methodologies in civil engineering can be considered to have reached a good level of maturity, the issue of cost/benefit analysis should be faced explicitly.

Benefits do not come from the data but from the transformation of data into information and into knowledge. This process is accomplished by the diagnostic and prognostic features of the SHM approach. Substantial savings can be obtained if the SHM system is a specialized part of a more complex infrastructure management system (IMS), thus rendering applications of SHM even more attractive.
This issue is addressed in the next paragraph.

INTEGRATING SHM IN INFRASTRUCTURE MANAGEMENT SYSTEMS

The previous discussion has pointed out that SHM practices and technologies involve integration of many different fields of engineering, from material science to structural mechanics. ICT is however playing a paramount role and most of the times represents the major investments, both in the hardware and the software components in technology developments and practical implementations.
Widening the approach from single structures to networks, as in highways and railways, it is evident that significant economic and technological advantages may be obtained by integrating the different systems present in the network.

However, as indicated in Figure 1, besides safety of structural components, other aspects have become key issues in infrastructure technology. Among them, users' safety and environmental sustainability are the most important, but also jobsite safety during construction and maintenance operations has been an important subject for research and innovation.

An interesting review of some of these new developments can be found for example in (Siskos and Sambrakos 2004).

In the recent years, many of such developments have been already transformed into practical applications, like automated toll collection systems, vehicle speed and weight control, traffic control, messaging systems, etc. In many instances, the relevant parameters are collected by means of sensing equipment that can also be of valuable interest for SHM applications, like for example weight-in-motion sensors, closed circuit cameras, airborne and space-borne sensing, etc.
Another technology that has been already exploited in practice is related to energy management and control. This is particularly important in railways, but in many highways side spaces have been equipped with large energy harvesting equipment (solar panels), with the final scope of rendering the infrastructure autonomous from the energy point of view. Sophisticated energy management systems have also been developed for large networks.

In this view, transportation infrastructures are transforming from typical civil engineering systems to more complex systems in which the communication and information components are taking a more and more important role.

The above finding suggests to consider SHM systems as an integrated subcomponent of more complex infrastructure monitoring systems performing different tasks, as indicated in Figure 4.

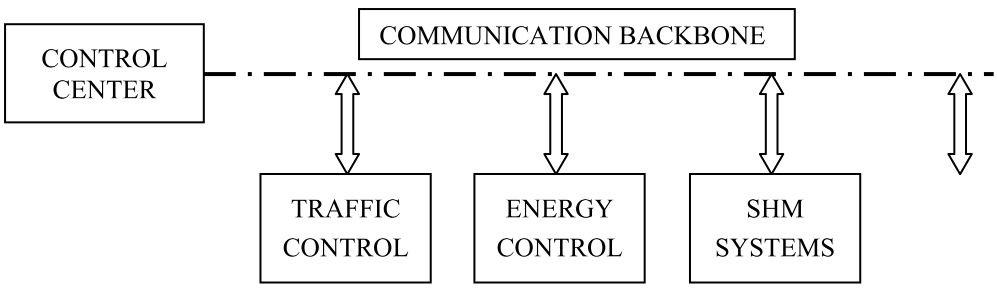

Figure 4. Integrating SHM in Infrastructure Management Systems

This approach may overcome some of the disadvantages that the technique of Structural Health Monitoring still encounters in becoming a common practice in infrastructure management. In particular, installation, operational and maintenance costs are amongst these disadvantages.
Very often, the cost of the communication systems connecting the sensors to data loggers and data processing units exceeds the cost of the sensory system itself. In addition, the cost of maintaining an on-line control center is usually not considered to be justified with respect to the expected benefits, at least in the short term. Integration of SHM in a global infrastructure monitoring system may largely reduce these costs and also pave the way to the development of global infrastructure performance modeling.
The development of global infrastructure performance models based on monitoring data, including the evolution of structural conditions, is indeed considered a very valuable tool for a better and safer infrastructure management approach.

Defining a Roadmap

Up to now, the development of the different management systems has proceeded independently from one system to the other, reaching a consistent maturity in several ones. A global approach to safer and more sustainable infrastructures however calls for integration.

To move towards such integration, a roadmap should be defined. It is worth noting that the issue of breaking the barriers among the different engineering disciplines that concur in the different systems developments has to be faced first, establishing a common language and background.
Involvement of infrastructure owners and system providers in the definition of goals will also help scientists and engineers to set up strategic research lines.

It is believed that establishing appropriate forums for exchange of information, discussions and elaboration of proposals will be very useful.
The activity of associations like ISHMII can be regarded as an important component in the definition and implementation of such roadmap.

New Research Topics

Combining SHM supported infrastructure integrity management with global infrastructure and asset management techniques is however suggesting new topics for research and development. It is worth mentioning that these topics, among many others, may be grouped in two levels.

On a lower level, issues like managing large and geographically distributed data communication networks supporting different kind of sensing equipment and merging different kinds of data into hierarchical data bases properly supporting engineering decisions represent a challenge to ICT people and also require a new holistic approach to infrastructure management strategies.
On the upper level, risk-based infrastructure performance modeling needs to cope with the interaction among different aspects and management strategies.

To give an example, modeling of the interaction between the decision of performing maintenance or rehabilitation works and users' safety and cost of transportation in road and railway networks is an issue that has already been pointed out. Some studies have shown that the costs due to the loss of performance and risk of accidents during this kind works may largely overcome the cost of the works themselves.

Development of complex decision models in integrated infrastructure management systems is therefore a very important issue not yet fully considered in infrastructure engineering research.

CONCLUSIONS

This paper has presented a discussion on the current technologies and applications in Structural Health Monitoring, highlighting the characteristics that, on the one side, render the practical implementations very beneficial to ensure safety and security of infrastructures but, on the other side, pose the problem of the real cost/benefit ratio.

It has been proposed that integration of SHM systems into a broader infrastructure management approach will be very fruitful for further developments and practical applications of this technology.

A few suggestions for defining a roadmap towards such integration and for developing new research topics have also been given.

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