IJARSCT
ISSN: 2581-9429
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Volume 5, Issue 8, May 2025
Impact Factor: 7.67

Structural Health Monitoring (SHM) of Sustainable Civil Infrastructure

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Abstract: *Although structural health monitoring is one of the most popular study areas in structural engineering, at least in the civil sector, practical applications are still lagging behind. Since practical applications still face challenges in becoming a normal practice in civil engineering, the purpose of the paper is to summarize the major research accomplishments on the topic and discuss the causes. The safety of monitored structures in comparison to traditional non-monitored ones is also examined, along with current design methodologies and structural health monitoring concepts.*

Keywords: Structural health monitoring, degradation and obsolescence, maintenance strategies, periodic monitoring, complexity

I. INTRODUCTION

Since its inception, the study of structural behavior has accompanied theoretical advancements in structural mechanics (Benvenuto 1991), offering fundamental insights into physical phenomena and confirming computational processes. But over the past 20 years, this field has also taken on new functions and has steadily evolved into the fundamental instrument for addressing the so-called time-dependent safety problem (Mori and Ellingwood 1993) in the practice of civil engineering.

The transition from basic experimental observation to structural health monitoring has been fueled by two factors: first, the impact of modern construction materials' deterioration and functional obsolescence on infrastructure economics; and second, the availability of innovative, affordable, and long-lasting hardware/software tools to perform complex data acquisition and signal processing tasks. In fact, Structural Health Monitoring (SHM) is simply the fusion of conventional experimental and theoretical structural mechanics, information and communications technologies, electronics, and material science.

To derive specific integrated design approaches, applications of this discipline can result in the definition of monitored structures, a class of structures whose characteristics in terms of safety and reliability indices should be considered differently from traditional structures, where safety relies solely on passive resistance. Additionally, a crucial first step in creative structural engineering is the incorporation of monitoring system principles into structural design, which opens the door to the creation of intelligent adaptive structural systems.

Reviewing the major research findings on SHM and discussing the reasons why practical applications still struggle to establish themselves as standard practice in civil engineering are the goals of this paper.

II. MATERIALS DEGRADATION AND OBSOLESCENCE

Most infrastructure in wealthy nations was constructed shortly after World War II employing structural systems made of steel, reinforced concrete, composite, or pre-stressed concrete. Across the globe, these methods continue to be the most widely utilized construction approaches. In infrastructure management, material obsolescence and degradation are a major concern not just because infrastructure stocks are so old, but also because they pose a difficulty from a certain angle, as in recently developed nations. The economic value of the infrastructure assets is reduced as a result of the physical and mechanical characteristics of these building materials deteriorating over time at a comparatively rapid rate.

DOI: 10.48175/IJARSCT-26949

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For instance, according to recent research, corrosion may have an annual economic impact of three to four GDP points worldwide.

Reinforcing steel corrosion brought on by chloride ion intrusion into concrete is the primary source of structural member deterioration in concrete structures, which are by far the most prevalent, most widespread, and most consequential. Alkali-silica interaction, freeze-thaw assault, corrosion caused by carbonation, and internal and external chemical attack are other less frequent reasons why concrete deteriorates. The corrosion potential for the steel bars is caused by concrete degradation, particularly chloride ion ingress and concrete carbonation. However, the actual corrosion development and the rate of the process are also influenced by the temperature and moisture content of the surrounding concrete, making the phenomenon extremely 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 idea of obsolescence is more closely linked to the changing needs of infrastructure users, such as commercial speed, traffic volumes, vehicle size and weight, etc. (for transportation infrastructures). However, low maintenance costs brought on by deterioration can also result in obsolescence. While the evaluation of obsolescence is based on complicated considerations that include direct, indirect, and social costs for decommissioning and replacement, the decision-making process that goes along with it is based on quantitatively estimable criteria derived from direct and indirect observations

III. 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

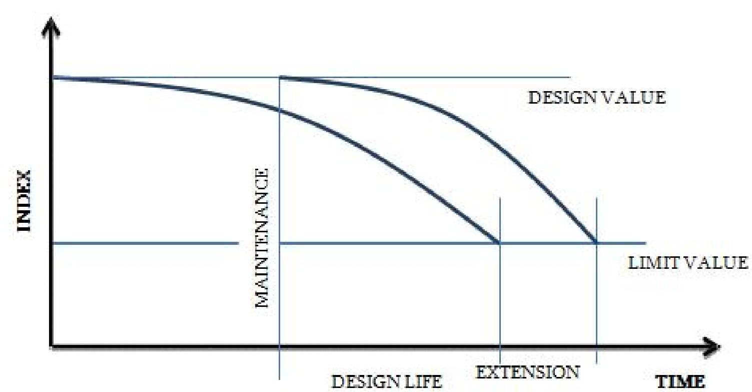

Figure 1. Typical lifetime function and the effect of maintenance

In the context of lifecycle cost optimization, the works of Frangopol and Liu and Miyamoto et al. are noteworthy among the authors who introduced the usage of lifespan functions. A more recent evaluation of the strategy, carried out as part of the European project IRIS is demonstrating that the method is a useful and efficient instrument for managing built facilities.

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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.

Because all of the process's quantities are inherently uncertain, the process can be expressed in probabilistic terms because their determination can be dependent on statistical knowledge bases. Notably, the entire process might be constructed in a backward processing manner, which would also entail redetermining the safety coefficients that will be utilized.

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) can be regarded as a tool for performing this task.

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.

The performance of traditional inspections at predetermined intervals is required by standards and laws pertaining to infrastructure safety; SHM systems cannot legally circumvent this need.

It is still not well known how reliable it is to determine the structural states from the SHM data, despite the fact that a large number of damage identification algorithms have been presented and confirmed in the literature.

Redundancies are required for sensor installation and maintenance throughout operations because, despite the availability of highly dependable, robust, and stable sensor technologies on the market today, sensory systems always exhibit certain failures.

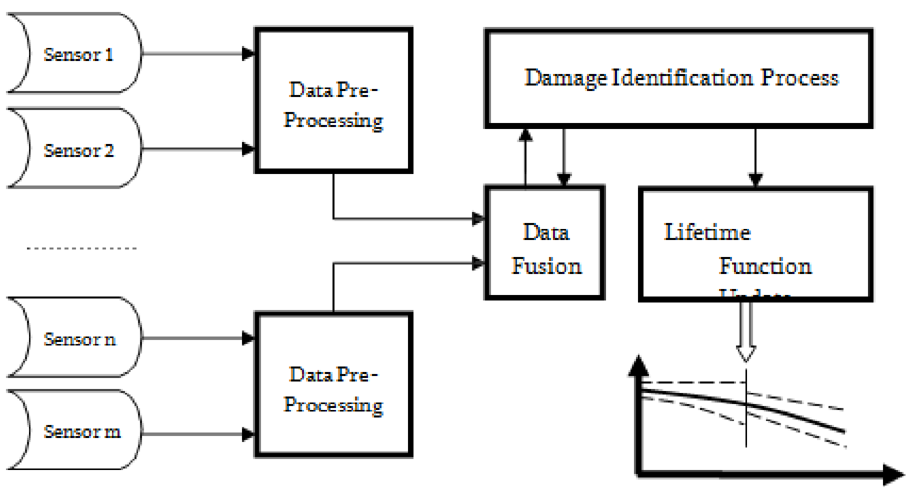

Figure 2. Lifetime functions update via SHM.

Electronics (computers, data loggers, etc.) have a shorter operational life than any other system component and a significantly shorter operational life than the structure; as a result, electronic components will need to be replaced frequently.

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Engineers in infrastructure owners' organizations are hesitant to rely on SHM since there is currently insufficient dissemination of education on SHM systems and global infrastructure monitoring techniques in civil engineering university programs.

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,) have pointed out such situation and traced research needs for possibly overcoming the above difficulties in the diffusion of SHM technologies.

IV. MONITORING SYSTEMS

In recent years, a great deal of research and experience on monitoring systems has been made public, yet some problems still exist. Here are some unanswered questions along with a succinct overview of the research findings.

Permanent versus periodic monitoring

Permanent monitoring refers to a system of observation that is permanently established and kept operational on the structure, usually from the beginning of construction. This method is the most comprehensive approach to SHM since it lets you get continuous time-series of data that include environmental parameters, load characteristics, structural response parameters (both static and dynamic), and other variables that are crucial for managing the deterioration processes of materials.

Permanent monitoring systems have a conceptual benefit in that the time-series of data may be processed in a variety of ways, such as online and multi-stage processing, revealing features that may also show unanticipated structural tendencies. It is possible to fully describe events such as earthquakes, shocks, storms, etc., which enables a thorough assessment of the phenomena and the associated structural response.

In addition to evaluating the state of the particular structure being studied, this is crucial for characterizing occurrences that are not consistently described in design codes and have a low likelihood of happening. It is also possible to process data online, which enables real-time alarms and warnings. Rain-flow counts can be applied to stress time-histories to offer online assessments of residual fatigue life and accumulated damage. A dedicated organization and sophisticated architectures for data transmission, management, and permanent storage are necessary for permanent monitoring systems because of their high cost, meticulous design requirements, and massive data output.

An suitable sensory system is temporarily installed on the structure and data is collected for a brief period of time (a few hours to a few weeks) in order to perform periodic monitoring. Every measurement campaign undergoes feature extraction, and the temporal histories of the campaigns' distinctive features are used to ascertain the structure's health status.

There are various benefits to routine monitoring. Initially, periodic monitoring may be seen as a non-destructive assessment technique that is more complex than traditional ones but conceptually aligned with them, making it easier for infrastructure owners to understand. The second is that the number of structures to be monitored determines how much the instrumentation system will cost to acquire and maintain. Data administration is easier than in the prior instance, but there is no discernible difference in the damage identification techniques that can be used.

The main drawbacks are that sensor typologies are inevitably limited, which means that some phenomena cannot be recorded. Of course, unintentional events that happen between campaigns cannot be recorded either, even though their effects on the structure could be disclosed.

It's unclear whether one strategy is better than the other in infrastructure management practice. It should be emphasized that periodic monitoring is better suited for SHM applications on big structure stocks that contain repetitive simple schemes, whereas permanent monitoring is generally recommended for large complex structures. The primary features of the two strategies are compiled in Table 1.

DOI: 10.48175/IJARSCT-26949

	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

Table 1. Characteristics of permanent versus periodic monitoring

Diagnostic and Prognostic Algorithms

One of the most prevalent topics in SHM research is the creation of diagnostic or damage diagnosis algorithms. In order to identify damage, a process that can evaluate monitoring data and ascertain the incidence, location, and severity of damage is intended. Numerous journal and conference publications have suggested a wide range of these methods. Analyzing computer-simulated data, benchmark studies, and small-scale laboratory tests is typically how their efficacy is demonstrated. Damage identification on actual structures subjected to intentionally caused damages is covered in very few articles. Typically, dynamic response measurements are taken both before and after the structure has been subjected to a known amount of damage. As far as the author is aware, there are instances in the literature where behavioral abnormalities in relation to the predictions made by design models have been found, but no instance where algorithms of this kind have shown an increase in damage in actual constructions. The author believes that the creation of diagnostic algorithms has matured significantly, and that a thorough review paper will be highly beneficial in identifying the needs for further study as well as in distributing them to possible practical users.

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) but further research is still needed. A synthetic categorization of the algorithms can be found in (Del Grosso).

The computational complexity of the different algorithms is also very different and the influence of environmental conditions encountered in real cases is largely influencing 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.

Two classifications can be distinguished in terms of prognostic algorithms, or algorithms that can determine how long a structure will last. Material deterioration models and finite element structural models are used in a first class. These models optimize the static or dynamic parameters to capture the evolution of the structural circumstances and the actual structural response. There are heuristic models in the other class. Using the updated lifetime functions to forecast the predicted life is a straightforward and highly useful method. Although this method avoids the computational complexity of the first class of methods, it nonetheless offers valuable.

V. GUIDELINES AND STANDARDS

To present, only a small number of standards and guidelines have been published. ISO 14963:2003, "Mechanical Vibration and Shock: Guidelines for Dynamic Test and Investigation on Bridges and Viaducts," and ISO 18649:2004, "Mechanical Vibrations – Evaluation of measurement results from dynamic tests and investigations on bridges," are the only recognized international standards. The use of dynamic measurements to carry out periodic SHM functions on bridges is covered by these standards. Additional guidelines that cover the topic of SHM and monitoring system design more broadly have been published by research organizations such as ISIS Canada (ISIS Manual n. 2-Guides for Structural Health Monitoring) or created as part of global research initiatives like the European SAMCO and IRIS.

Within the IRIS framework, CEN WG 63 has developed a proposal for standards pertaining to the usage of lifespan functions .Recently, Russia released an intriguing standard called GOST P 53778 2010 Building and Structures – Technical inspections and monitoring rules. In general, structural and geotechnical inspection and monitoring during service life are covered this standard, which is required in the Russian Federation. Various authorities across the world have established rules for the inspection and management of different kinds of infrastructures, but they don't specifically address the problems with structural health monitoring as they are explained here.

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.

The suitability of such safety considerations is therefore called into question when the structure has a persistent monitoring system that provides information on its structural conditions and permits actions to be made to keep 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.

VI. CONCLUSIONS AND DIRECTIONS OF FUTURE RESEARCH

The primary research and application accomplishments in SHM technologies have been compiled in this publication. There are still a number of unresolved issues that might be investigated further. The first and most significant concern is about the safety coefficients that should be used in the design of monitored structures, aside from the necessity for standardization, which was already covered in the previous paragraph. This pertains to both the construction of new structures and the renovation of existing ones, as the monitoring system's presence might reinterpret the probabilistic modeling of design uncertainties.

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DOI: 10.48175/IJARSCT-26949