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DEVELOPMENT OF PERFORMANT TECHNOLOGIES FOR BRIDGE MONITORING

BY

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Abstract. The development and the implementation of a Structural Health Monitoring (SHM) system is a key aspect in assuring and evaluating various bridge structures for their capacity to serve their intended purpose. With a SHM system help, degradations can be identified even at an early stage of their development and the bridge administration can take the optimum decision for the structure.

Due to the budget limitation, it is essential to determine the most appropriate strategy in order to minimize the cost of intervention works and to maintain the structure in optimal condition for exploitation. If the degradations are not identified early, and continue to expand, they will reach a point in impaired smooth running of traffic, and would even compromise the structure. This paper presents some essential features related to the evolution of Structural Health Monitoring (SHM) technology for bridge structures.

Keywords: degradations identification; monitoring methods; SHM components; sensors.

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1. Introduction

Structural Health Monitoring (SHM) represents a relatively new technology to investigate the degradation state of a structure. The main objective for implementing this type of systems is that the administrations need to maintain bridge structures in optimal operating conditions.

The first studies and experimental programs regarding the degradation state of bridges started in the early 1950 (Farquharson & Vincent, 1954). After these studies, an increasing awareness on the deterioration issues of bridges has been recorded. In our country, the transportation infrastructure is rapidly developing and the existing once ages. The evaluation and the monitoring of the technical condition of bridges are essential issues for maintaining a high level of traffic quality. In order to solve these issues, researchers have developed a new technology that can continuously monitor the structure and identify different types of degradation. Based on this technology, the administration can take the most suitable decision to repair the degradations, even in their early stages.

The main aim of this paper is to present some essential features related to the SHM technologies and to the specialised devices and sensors that have been and are currently used for the evaluation of bridges technical condition.

2. The Concept of Structural Health Monitoring

The SHM techniques consist in the implementation of various strategies for identification and intervention in case of structural degradations (Farrar & Worden, 2007). The SHM systems have been used mainly in aerospace and mechanical engineering and, in recent decades, had begun to be implemented in civil engineering field.

Karbhari (2009) stated that several ways of defining the concept of SHM have existed over time. Firstly, it was defined as a conventional process of investigation, consisting mainly in visual inspections. With the evolution of technology, the process has expanded and it so that, the inspections are nowadays based on the collection of various data sets, including: acoustic data and features changes in structure with the onset of degradation (Housner *et al.*, 1997; Klikowicz *et al.*, 2016). More recent, the concept was defined as an embodiment of systems that enable detection of abnormalities in the structural response by combining non-destructive testing and structural features (Klikowicz *et al.*, 2016).

Also, the term SHM has been increasingly used to describe a series of new systems implemented to existing structures. These systems are designed to continuously assist and inform the managers and the operators about the degradation state of the structure, the variation of the load magnitudes and the possibility and the probability of sudden changes in the degradation state (Brownjohn, 2007).

Other authors (Housner *et al*., 1997; Farrar & Worden, 2007; Orcesi & Frangopol, 2011) have defined SHM technologies for structures as non-destructive methods used *in-situ*, that are responsible for the investigation of their degradation state. These methods were developed in order to provide the necessary data for easy and accessible identification of the possible changes in the structural characteristics. The latter may indicate the nature of the defects, their development and, in some particular cases, the emergency level.

The SHM systems can be implemented in various ways depending on the type of the structure (Brownjohn, 2007). However, all applications have a set of common components that can be observed at different levels. These components include: sensors, units for data storage and transmission and database management systems. Based on the data collected by these units, specific models for the investigation of the structural response can be developed. These models have a unique set of features, generally referred as "learning from the past experience" which enables the system to offer predictions on the evolution of the degradation level. The scheme of a typical SHM system is depicted in Fig. 1.

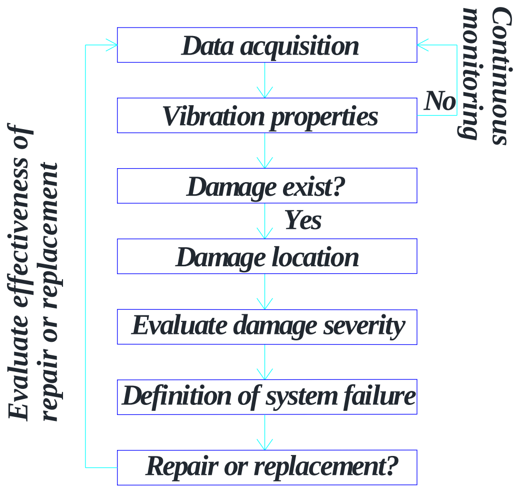

Fig. 1 − Structural scheme of a SHM system (Karhbari and Lee, 2009).

3. The State of Degradation

According to the definition formulated by Farrar and Worden (2007), degradation can be defined as a distinctive change that may affect the structural response. Thus, the concept of degradation is not significant without the existence of a comparison between two different stages of the system. The first stage is represented by the initial phase, without degradation, while the second stage is the current state of the structure. The authors (Farrar & Worden, 2007), considered that the definition of degradation is limited by the changes in material properties that may occur at the elements extremities and on the connectivity systems. Only these changes can severely influence the structural response.

The term degradation does not involve total loss of system functionality. It generally referred only to the fact that the system is not fully operational, in an optimum manner, to meet current standards. If it is no intervention in time to limit the evolution of degradations, the limit of acceptability may be exceeded. The latter is generally referred as *the transfer point*, and once it is reached, the whole structural system will be affected.

Degradations can gradually accumulate in significant time periods, such as the accumulation of fatigue or degradations by corrosion. However, the degradation effects usually occur in short periods of time, as a result of various events in the life of the structure, like accidents or crossing structure by a military convoy.

Catbas (2009) defined the state of degradation as a result of the total amount of defects and degradations that affect the strength and the stability of structures. This state of structural degradation can be continuously monitored through a number of different tests and through various experimental programs.

The state of degradation, as defined above, may be also analysed, using the dynamic identification methods. The latter consist in the investigation of several parameters, such as: natural frequencies, modal shapes and damping factors. For each type of parameters, the variation is graphically depicted and the graph patterns and the peak values are analysed (Marques *et al*., 2014; Bedon & Morassi, 2014; Farahani & Penumadu, 2016).

4. Structural Health Monitoring (SHM) System

Karbhari (2009) states that all structures deteriorate in time due to a wide spectrum of causes, most of them being related to severe environmental conditions. By using a SHM system the bridge administrator has access to the variation in time of the parameters that characterize the degradation state. Based on these parameters, the most appropriate strategy of intervention is chosen and applied. In order to select a specific type of intervention, it is necessary to examine the current condition of the bridge structure, and to assess its remaining period/life. This is in contrast to most of the actual situations when funds are allocated several years after the degradation was found.

Another important feature of the SHM systems is that they give close predictions on the evolution of the degradation state. In some particular cases, the SHM system may provide warnings in real time to bridge administrators about the development of a major structural deterioration or on the emergency level.

The damage assessment for bridge structures is often performed only by simple visual inspections (Collins *et al*., 2014). According to norms (AND 522-2006; AND 504-2007), the visual inspections are performed every year for the bridges that are located on the national roads. The visual investigation is concluded by the assessment of an index called technical condition index (I_{ST}). With this index help, the bridge is placed into a technical class. The latter is used by bridge engineers to recommend the type of intervention works for the structure. However, the visual examination does not provide an effective way of determining the structure degradation. It is therefore necessary to develop a system for permanent bridge monitoring, but, at the same time, to ensure accuracy of results and an update of the data used to evaluate the structural integrity.

5. Integrated Monitoring of the State of Degradation

According to Brownjohn (2007), the measurements that cover a bridge monitoring program depend on the structure type, the risk to which it is subjected and the location. Based on the type and the average values of the monitoring parameters, the bridge engineers can give reliable predictions on the remaining life of the structure. The scheme of application of a SHM system, as proposed by Karbhari and Lee (2009) is presented in Fig. 2.

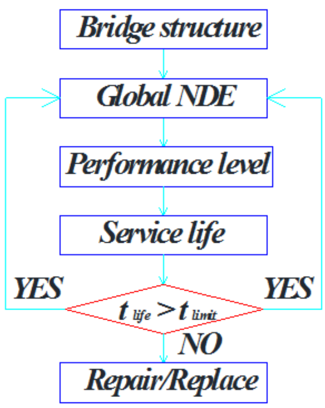

Fig. 2 – Flow chart of SHM (Karbhari & Lee, 2009).

The SHM system of bridges may be organized in four different stages: operational assess, data acquisition, normalization and elimination of any possible interferences, feature extraction and condensation of information and developing statistical approach required for characterization data discriminatory (Farrar & Worden, 2007; Worden *et al*., 2015).

5.1. Operational Assessment

The first stage of a SHM system is generally termed as the operational assessment. In this stage, the bridge administration establishes the type and the characteristics of the structural monitoring process, along with the list of tools used to carry it out. Also, the first stage is responsible for finding the response to four questions that are related to the estimation of the degradation capacity:

- What is the economic justification and/or the safety of life related to the introduction of a SHM system?
- How is defined and identified the degradation system and what are the main causes of damage occurrence?
- What are the operational and the environmental conditions of the structure?
- What are the operational and the environmental limitations for data acquisition and transfer?

5.2. Data Acquisition, Normalization and Elimination of Any Possible Interference

The second stage of the SHM systems may be divided into three different sub-stages: data acquisition, data normalization and eliminating any possible interference. The first sub-stage consists in selecting the input loads method, the type, the number and the location of sensors. Also, at this stage, the bridge engineers establish the necessary hardware components for the data acquisition, storage and transmission to the central server.

Data acquisition, the main tool for characterization of the degradation state, is achieved by using various techniques of dynamic identification. One of the most utilized methods is the vibration technique. The main advantage of this technique is represented by the relatively minimal number of sensors that need to be installed on structure (Farahani & Penumadu, 2016).

Data normalization is an important sub-stage of SHM system since the data recordings can be performed in various conditions. Data normalization is defined as the separation and the elimination of disturbances in the recorded data by comparison with existing databases. The interferences that may occur in data acquisition are caused by the variation of operational and environmental conditions (Farrar & Worden, 2007).

Cleaning the data set of possible interferences is the process through which all data are accumulated and sorted out in order to be further transmitted to the central server.

The process of data acquisition, normalization and elimination of interference should not be static. The information gained in this stage can be used as model for future selection processes, for the development of the statistical models and for the improvement of the data acquisition process.

5.3. Feature Extraction and Condensation of Information

This stage is represented by the identification of the data that are used to compare the most important two stages of the structure: the undamaged and the damaged one. Due to the high data volume, it is essential to implement a condensation process data. This process enables the speedy transmission of large amounts of data between the monitored structure and the central server.

Some of the most used feature extraction methods have been studied and discussed by Farrar and Worden (2007). The first method consists in the correlation between the measured quantities of the structural damages and the first observation of defects on the structure, preferably in the undamaged stage.

The second method is used when the engineers do not have access to the initial stage of the structure. Thus, they can use a specific program that applies the engineering flaws that are similar to ones expected to appear to the analyzed structure in a normal operation. The program can predict the values and the evolution of the most important system response quantities. In addition, it can be used to validate the diagnostic measurements and to decide if that features are sensitive enough to distinguish between undamaged and damaged systems.

The third method is usually referred as *damage accumulation testing*. In this test, the structural components are degraded using realistic loading conditions, such as fatigue testing or temperature cycling.

The SHM systems provide large sets of data related to the structure characteristics. Thus, the data condensation is an important process of the integrated monitoring of bridge structure. This stage is necessary, because all feature sets obtained over the structure lifetime needs to be compared with older sets. Moreover, all data need to be condensed to occupy little space in the server memory.

5.4. Development of the Necessary Statistical Data for Characterization Discriminatory

In the last stage of a SHM system, the collected data are statistically divided in series, based on specific features, such as: the type of the structure, the degradation characteristics and the degradation degree. The development of a statistical model is based on the implementation of several algorithms that are dealing with the extraction of the characteristics necessary to quantify the technical condition.

6. Components of a SHM System for Monitoring the Technical Condition of Bridges

The SHM systems work by collecting data from the sensors installed on the structure (at the points indicated in the project tracking), continuously or periodically and transmitting them to a common storage through a dedicated network (Karbhari, 2009).

According to Catbas (2009), a comprehensive SHM system requires recognition and integration of various components, necessary to its embodiment (Fig. 3). The main part of a monitoring system is represented by the components that are aiming to identify the structural degradations and to assess the structural performance. This is a fundamental element of the system, based on which the technology and the equipment necessary to remedy the damages are selected.

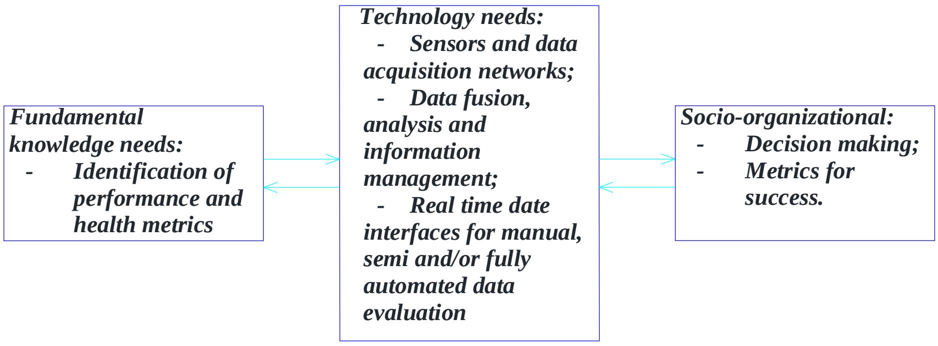

Fig. 3 – Main components of a complete SHM (Catbas, 2009).

The embodiment of a SHM system is the same to any type of structure, and the only components that may vary are the specialized sensors. Each type of sensor is capable to collect and transmit a limited number of measurements. The sensors are selected based on the type of the structure, the degradation state and the type of the parameters to be analyzed. According to Yu *et al*. (2013), a SHM system of high performance is composed of sensors (*i.e.* front-end circuit sensor), a central processing unit, a communication circuit (which can be wired or wireless) and an alarm system.

A SHM system usually consists of three main elements: a measuring instrument, a unit for data reading and a storing unit (Collins *et al*., 2014). Depending on the type and the complexity of the monitoring program, a single unit may be utilized for both, measuring and data reading. These particular units are able to perform the conversion of the measured signals taking into account the variation paterns and the peak values.

6.1. Types of Sensors Used in SHM Systems

McNeill (2009) stated that the embodiment of any SHM system is mainly based on the type of the parameters that are to be analyzed. Based on the latter, the corresponding type of sensors is selected. The sensors may be divided in several categories according to their properties. The main category is referring to the type of the input signal and it includes: voltage, acceleration, temperature and displacement sensors. The sensors are also categorized by their materials properties and by the measurement technology.

6.1.1. *Piezoelectric Sensors*

Due to the increasing interest of bridge administrators for electromagnetic impedance (EMI) technology, the piezoelectric sensors have witnessed a rapid development and expansion of their use. EMI technology uses small sensors, made of lead zirconated titanium (PZT) that are disposed on the existing structures or on newly constructed ones (Yang & Soh, 2009). PZT sensor technology is based on the fact that any change in the monitored impedance will be caused by changes in the structure mechanics. By measuring these changes and comparing them with specific values, the SHM system can give predictions on any structural changes.

A special type of piezoelectric sensors, which are often used for structural assessment, is represented by special receptors called piezoelectric sensors acoustic emission (AE). The use of such sensors is based on the idea that the appearance and the development of degradations is accompanied by the release of short bursts of acoustic energy, known as acoustic emissions (Yapar *et al*., 2015). This release of energy causes stress waves traveling through the structure that are detected by the AE piezoelectric sensors.

6.1.2. *Wireless Sensors (WS)*

Swarts and Lynch (2009) stated that a SHM system should be able to detect the occurrence of degradation and to locate it with considerable accuracy. Thus, a dense sensors network should be installed on the structure, which in some cases may lead to high financial costs.

The wireless sensors, along with their processing systems are suitable for monitoring applications, especially when the query data are done automatically. Wireless sensor networks (WSNs) integrate elements from various technologies, such as: wireless communications, sensors, computer, modern networks, IT (Liu *et al*., 2014). Wireless systems use the same type of sensors as wired systems, but they are continuously transmitting the signal through the network without storing any data.

An important advantage of the wireless systems is represented by the speed of installation and dismantle of the sensors network. Also, the wireless sensors can be used in emergencies cases, when it is essential to know the state of viability of the structure in short time intervals.

The main drawback of the WS systems is the financial cost of this sensors network. Thus, several experimental programs (Liu *et al*., 2014) have been developed in order to optimize the sensors network and to reduce the system power.

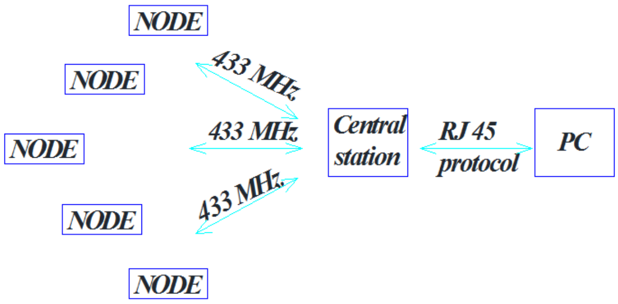

Fig. 4 – System structure for a SHM wireless system (Liu *et al*., 2014).

6.1.3. *Magnetoelastic Stress Sensors*

In case of cable stayed and suspension bridges, the SHM systems include Magnetoelastic stress sensors, also known as vibration sensors (Wang, 2009). These sensors are used to measure the resonant frequency of the output signal of the monitored member. The generated frequency signal is transmitted well over the bridge cables without suffering significant interferences.

According to Wang (2009), Magnetoelastic sensors (EM) are the most suitable transducers that can be used to analyze the stress variation along the pre-stressed reinforcements and the bridge cables. The sensors can be installed in two ways: either embedded in concrete structures, or attached *in-situ* to bridge cables.

6.1.4. *Fibre Optic Sensors*

The fibre optic sensors (FOS) are increasingly used in SHM systems developed for structures made of fibre reinforced polymer (FRP) composite elements (Ansari, 2009; Dilena, 2015). FOS (Fig. 5) send pulses through fibre cables at regular intervals and measure the time the signal returns to source. The data are recorded by calibrating the intensity of the FOS with the micro and macro bending of the fibre cables. When the cross sections of a cable change, time change may occur in the return signal. This change may be related to the structure parameters with which it is linked (Collins *et al*., 2014).

The FOS are used in SHM systems due to their unique set of characteristics, including: small sizes (diameters of 250 microns) and adaptable geometries. Also, the FOS are neutral to electric and electromagnetic interferences. The FOS are remote-sensing elements, which means that they are easily installed and dismantled (Ansari, 2009).

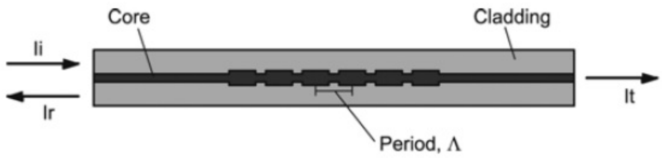

Fig. 5 – Schematic diagram of the functional principle of FOS sensors (Rodigues *et al*., 2010).

Other significant advantages of using FOS in SHM systems, include (Brownjohn, 2007):

a) high accuracy and sensitivity even after a large number of measurements;

b) immunity to magnetic interference;

c) versatility in application;

d) stability of the material properties;

e) operability in aggressive environmental conditions.

6.1.5. *Optical Detection Sensors*

The optical detection sensors (ODS) are able to collect data, to take images and to detect degradations without being in physical contact with the structure (Shinozuka & Mansouri, 2009). The SHM systems based on ODS consists in: optical telescope, image capturing unit, detection unit and data recording system.

The ODS were developed as part of remote sensing technologies (RST). The latter includes the equipment, the hardware and the software tools used for monitoring structure based on image processing. The RST are used for monitoring structures located in highly populated urban areas, in order to detect the occurrence of possible changes after natural or artificial disaster (Shinozuka & Mansouri, 2009).

6.1.6. *GPS (The Global Possition System)*

In some cases, the SHM systems can be developed using GPS technology. The latter may be used as an alternative to the data capture system if there exist the risk of building interferences. The data recorded by GPS systems depend only on the time of transmission of the radio waves from satellite to receiver (Brownjohn, 2007).

According to Brownjohn (2007), the SHM-GPS system consists in: a base station antenna, a GPS logger, a rover antenna and another logger. The base station and the GPS antenna are placed in a fixed location in the close vicinity of the structure, while the rover antenna and the logger are mounted on the structure. The GPS measurements, also referred as real-time kinematic measurement provides accurate date about structure position with tolerances of 1 cm at rates up to 10 Hz.

7. Conclusions

A review of the latest progress related to SHM system for bridge structures was presented and discussed in this paper. The SHM systems were classified and analysed based on the equipment and the sensors that are currently used for the monitoring and evaluation of bridges technical condition.

Various publications related to integrate monitoring of bridges degradation state were presented and summarized in paragraph form. For each program, the parametric studies, the results and the conclusions were highlighted.

Based on the experimental programs presented in this paper, it can be concluded that SHM system of bridges can provide quantitative information for both structural safety evaluation and maintenance purposes. In addition, the SHM systems have been found to be a very useful tool in reducing the number of inspections, and eventually to their elimination.

This paper represents the first step of a complex research program regarding SHM systems of bridges under development at The Faculty of Civil Engineering and Building Services Iaşi.

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DEZVOLTAREA TEHNOLOGIILOR PERFORMANTE PENTRU MONITORIZAREA PODURILOR

(Rezumat)

Dezvoltarea şi implementarea unui sistem Structual Health Monitoring (SHM) este un factor cheie în asigurarea şi evaluarea diferitelor structuri de poduri în scopul verificării capacităţii lor de a servi cerinţelor de siguranţă a traficului. Cu ajutorul unui

sistem SHM, degradările pot fi identificare chiar şi într-un stadiu incipient al dezvoltării lor, iar administratorii podurilor pot lua decizii optime de intervenție pentru structura analizată pe baza acestor informații.

Datorită limitărilor bugetare, o bună monitorizare a stării de degradare este esențială pentru determinarea celei mai potrivite strategii de a minimiza costul lucrărilor de intervenție, precum şi pentru menținerea structurii în condiții optime de exploatare. În cazul în care degradările nu sunt identificate în timp util, şi continuă să se extindă, acestea vor ajunge la un punct în care vor afecta buna desfăşurare a traficului şi chiar vor duce la compromiterea structurii. Lucrarea prezintă câteva caracteristici esențiale legate de tehnologia SHM de monitorizare a stării tehnice a unei structuri de poduri.