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DEVELOPMENT OF BRIDGE STRUCTURAL HELTH MONITORING

BY

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Abstract. Some essential issues about new technologies for monitoring bridge structures are presented in this paper. Those technologies have been brought together under the Structural Health Monitoring (SHM) name. As time passes, older structures suffer degradations that affect the structural safety and the traffic. With a system of this type, degradations are identified at the earliest stages of their occurrence and the remediation costs required are much lower. Another reason of SHM implementation is the interest of administrators to maintain the structures into optimal conditions for the traffic safety, but at the same time, to fit into their budgets. Because of the technology needs for implementation, SHM is a relatively new field, the first documented attempt to monitor a bridge dating from 1937. The advantages of using this type of system, and also some examples of structures that have benefited from these features are presented in this paper.

Keywords: Structural Health Monitoring; bridge; maintenance; durability; service life.

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1. Introduction

Bridge Structural Health Monitoring (SHM) is a topic of great interest for many researchers in the construction and maintenance of structures, especially for road infrastructure managers. This interest can be explained by the desire of companies responsible for managing the road network to maintain structures at a safe level using the available budget. Those structures must allow traffic to be carried out in optimal conditions. Another explanation for the interest in SHM systems is the aging of the existing road network. This fact leads to the exponential growth of necessary costs for inspecting, maintenance and repairs of the structures. Once implemented such a system, degradations are detected at an early stage, being easier to repair and at lower costs.

Inaudi (2009) stated that the main objective of implementing a SHM system is the administration desire to provide as much information as possible about the structure current condition. These observations are based on the appearance and the evolution of degradations on new structures or on the existing ones. Karbhari and Lee (2009) stated that the use of SHM systems provide the equipment necessary to assess the technical condition of a structure at any time of its life.

SHM systems can be used to discover and solve the deficiencies of visual inspections and to complete data from them. Lately, in more developed countries, managers of important bridges have chosen to implement monitoring systems to evaluate the condition of the structures. This solution may lead to the disappearance of visual inspections.

Döhler *et al.* (2014) said that the main objective of the research in this field is to develop or improve existing automated monitoring methodologies. They are used for an effective identification of degradations and for handling those risks involving with the operation of dynamic systems.

Simeng *et al.* (2016) stated that the assessment of the structure degradations is very important both economically and for safety reasons. This is because structures, including bridges, must be operational for long periods, despite live loads, the environmental impact and the potential for accumulation of degradations.

Several systems for permanent monitoring the structures state of degradation have been developed to solve the problems presented in recent years by experts in the field.

Those systems were called *SHM systems*. The functional scheme of a SHM system implementation is presented in Fig. 1.

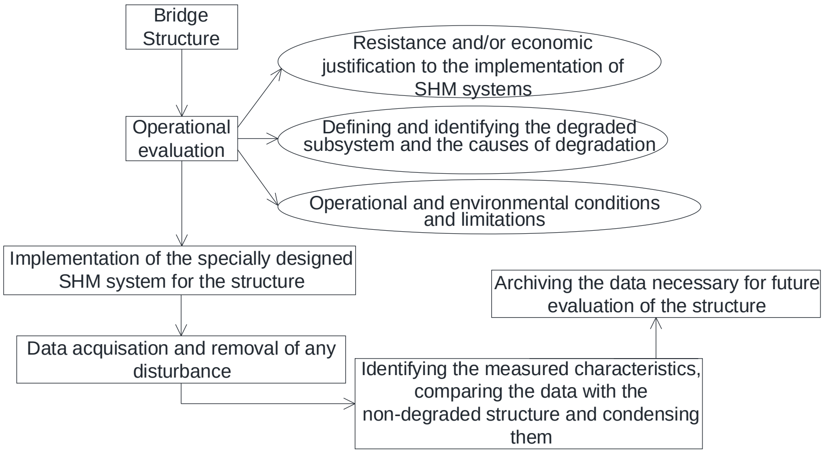

Fig. 1 – Applying scheme of a SHM system.

2. Monitoring Systems Development for the Bridge Structures

2.1. The History of Research and Development of SHM Systems

Brownjohn (2007) presents a brief history about the development of SHM systems used for different types of constructions. Thus, he states that the most important development of SHM systems has its origin in major construction projects such as dams, large span cable-stayed bridges, and in offshore extraction platforms of oil or gas. The author believes that it is almost impossible to determine the first form of a SHM system. In the second half of the twenties century, registration and interpretation of changes in the physical parameters of the structures began to be researched and used in determining the degradation state. Those systems have experienced a high development in a relatively short time because of the evolution of electronic devices, computer acquisition and data storage capabilities.

The first programs for bridges monitoring were designed and implemented to improve the knowledge of the structure behavior and to calibrate the test-structure-response model. The first documented attempt to monitor a bridge was carried out by Carder in 1937. He created a program developed to measure different parameters during the construction of the Golden Gate Bridge and the Bay Bridge in San Francisco. The main objective was to investigate the dynamic behavior of structures and the consequences of a possible earthquakes (Brownjohn, 2007).

According to the same author, in 1954, University of Washington described the first monitoring of a bridge, namely Tacoma Narrows Bridge. Its life was relatively short, its structure collapsing due to instability caused by the wind. The importance of this work is quite high because almost all monitoring processes of large span suspension bridges made after the publication of this paper examined the possibility of instability due to the wind effect.

One of the most utilized methods to assess the structural damage is the method based on vibrations study of bridges and buildings structures. This method has been used since 1980s. The modal properties and the quantities derived from these properties were the first features analyzed for degradations identification. In addition, in time, the researchers have studied environmental and operational conditions of structures. They concluded that those parameters had an unfavorable impact on structures (Farrar & Worden, 2007).

Some studies of the pioneering period of monitoring bridge structures proposed a new technique to identify the progressive cracks in the structural members. This technique was applied at that time (1981) on a bridge with three spans subjected to fatigue. Other more recent studies, have focused on modal parameters change. Thus, the quantification of changes represents the degradation identification method. The conclusion of those research works was the fact that the identification of higher modes of vibration is necessary for identifying reliable damage of the structure. It is possible that the first mode of vibration not to provide useful information about the presence of damages (Alamdari *et al.*, 2017).

In recent decades, permanent monitoring programs of bridges have been frequently used for new structures or for the existing ones in countries such as Japan, USA, Australia or European countries.

Many of the existing studies are based on short-term monitoring, but more recent studies have focused their attention on the application of SHM systems for the structures in service, recording data for a long periods of time. These systems use different types of sensors for monitoring the variables and responses of the structure, highlighting the need for statistical data analysis for long periods of time to assess and quantify the uncertainties (Alamdari *et al.*, 2017).

The latest researches have focused their attention on the optimization of conventional monitoring bridges with small opening, especially in Europe. This is due to the large number of such structures in use and their importance. For this type of bridges, the overall response of the structure is more sensitive to the possible occurrences of defects. In those cases, the visual inspection is difficult to be performed and SHM systems represent a very useful tool for administrators.

In recent years, some researchers have developed an approach based on indirect measurements. They found that changes in the bridge structure causes changes in interaction between vehicle and bridge. Thus, they determine the state of structure degradation based on the processing of data collected by the sensors mounted on a vehicle that is crossing the structure (Alamdari *et al.*, 2017).

Some studies have developed new implementation of SHM systems. Initially, these systems were designed to diagnose the degradation state of existing bridges. With evolution of time, SHM systems were implemented in the design stage, especially for bridges with large openings (*e.g*. Shanghai Chongming Crossing which has central opening of 1.200 m or Messina Strait Bridge with central span of 3.300 m). Another trend is the synchronization of the implementation of SHM processes with the bridge construction. Thus, certain types of sensors (e.g. sensors used to determine the occurrence of corrosion or fiber optic sensors) can be mounted on the structure during the construction stage. Some developments in technology have enabled the utilization of sensors capable of monitoring the integrity, sustainability and security of the structure (Ko & Ni, 2005).

2.2. Application of SHM Systems on New Structures or on Those under Construction

Catbas (2009), states that the main objective of the SHM systems application on structures in the construction phase, is the need to accumulate data about the forces inherent of the system and possible distortions due to tensions arising at this stage. Many structures built in recent years incorporate monitoring systems specially designed to determinate any possible modification in the building materials parameters or to verify the accuracy of the construction works. Monitoring at this stage is especially needed for large structures, with a special design. This type of monitoring demonstrates its effectiveness, especially in installation errors and/or environmental monitoring aimed at preventing any degradation of it. SHM systems are useful tools for risk management that may arise during the construction phase, when the framing system is structurally incomplete. In that stage, the system is vulnerable to accidents or disasters.

The design of monitoring and data acquisition systems used during the construction phase or that will be installed on the new structure is performed before or through the bridge conception. It is preferable to integrate the SHM system design directly into the technical project. This is because those systems can perform assumptions validation made by the designer during the calculations in terms of forces and reactions of the bridge structure. If in this stage, the monitoring system indicates the need of changes to certain parameters, the necessary measures it can be quickly taken to remedy them and to control the risk of the structure to undergo some deformations or defects. In addition, designing the structure control system can serve as a tool for controlling and mitigation potential design and execution errors. This can lead to the significant delays if problems are discovered in the construction phase (Catbas, 2009).

2.3. Application of SHM Systems on Existing Structures

Bridges are designed to cross obstacles, to achieve new economic relations and contribute to the possibility of more rapid goods and people movements. However, due to limited budgets of administrators, designers' engineers and builders are trying to develop new ways to reduce costs as much as possible and, at the same time, to increase sustainability. Today, in almost all countries where the largest part of the road infrastructure is already built, a major challenge is to manage network maintenance and to make it work smoothly and safely. Sometimes this challenge is even more costly than replacing the whole structure (Inaudi, 2009).

Liu *et al*. (2014) present the idea that a bridge in operation subjected to live load and environmental conditions will suffer degradation and erosion. This will result in variation of the degradation index of the structure, its safety and sustainability. Therefore, the authors recommend regular tests both during bridge construction and in operation to control the structure and ensure a high level of safety in social, economic and scientific terms. To assess the state of structure degradation is necessary to carry out a dynamic test, which is considered the most effective method used in this case.

In time, structures are subject to aging, they becoming more and more degraded. Given this, a SHM system can be implemented to identify degradation processes, to forecast their development and for a better understanding of their causes. Data from the implemented systems are used to make decisions about structural safety, maintenance schedule, repair or rehabilitation or, in extreme cases, the structure demolition. For bridges, SHM systems are mounted for solving problems related to performance, changes in geometry, displacements, vibration, damage or visible signs of aging. For structures that have exceeded the projected lifespan, monitoring is used to identify degradation developments (Catbas, 2009).

The authors Yu *et al*. (2013) present a system for monitoring the structures loadbearing capacities during their lifetime. The experimental results showed the degradations produced by the structure by passing a vehicle that exceeds 100% the maximum allowable load. Thus, it was found that the single passage of this type of vehicle on a bridge with asphaltic bitumen pavement is equivalent with 256 passes of one with the legal weight. In the case of concrete pavement, the passage of the same vehicle is equivalent to 65.500 passes of a standard vehicle. Because avoiding these exceedances axle load is impossible to be achieved by the administrator, it requires ongoing assessment of structures to prevent their collapse and to take early remedial measures.

2.4. The Motivation of Developing SHM Systems

All industries want to identify defects and damages to their products in the shortest possible time. This identification requires implementation of specific forms of SHM, motivated by the economic impact on the structure safety. Until SHM systems implementation, there were no other methods other than visual inspections to assess the safety of the structure after an event. Thus, SHM has proven to be a reliable tool that leads to minimizing uncertainty related to the events. With this instrument, the material damages are reduced. The use of the appropriate devices leads to the extension of the predicted lifetime for the monitored structure due to timely interventions on early-stage of degradation (Farrar & Worden, 2007).

SHM systems are designed specially to help structural administrators. This system is an important tool used in evaluation programs to the degradation of bridge structures, along with visual inspection. Administration engineers need access to a wide range of knowledge about the integrity and safety of a transport network, the hole structural system or even a single element of that system. Data should be able to be collected and accessed in real time to assess not only the derelict structures, but also to specify when necessary preventive measures need to be taken. Thus, there has been a need for an efficient method of collecting data from a structure or network in exploitation and their processing to assess the key performances of the structure such as reliability, sustainability and serviceability (Karbhari, 2009).

Brownjohn (2007) present several cases where SHM system implementation is necessary:

a) modification of an existing structure;

b) structures that may be affected by external works;

c) structures during demolition;

d) significant possibilities of the structure movements over time or materials degradation;

e) extracting information through the structure feedback (this information is used to improve future projects based on experience);

f) assessment of damages caused by fatigue;

g) monitoring the innovative systems behave;

h) assessing structural integrity because of a natural disaster or accident;

i) decreased costs necessary for construction and increased maintenance needs;

j) implementing the concept of performance-based design.

3. Benefits of SHM Systems Implementation

Karbhari (2009) presents some advantages of using SHM systems and several stages of development through which they have passed over time. Thus, these systems have become an important tool used by their managers for bridges monitoring. In that article, the author makes a comparison between a structure and a patient. In the early stages of this branch development, systems could only say that the “patient” is ill. With the development of technologies, the SHM system has managed to find the “disease” location, to state the reasons for its occurrence and the effects of disease incapacity.

The basic steps of a SHM system (Fig. 1) are data acquisition, transmission of data to a central computer, query and making decisions based on comparison of datasets accumulated over time. For this reason, SHM is an essential decision-making system based on concrete information from the main structure. It is composed mainly of sensors and databases and, like any system, it has many critical elements. Another advantage of the SHM system is represented by the fact that traditional inspection leads to significant losses, especially for road users. Those losses can be translated into delivery delays of goods and services, but also in long waiting times in traffic.

SHM systems can be effectively used to provide objective data of the structure for management and decision-making that are necessary to implement the optimal maintenance scenario. This scenario considers both the needs and the costs to achieve those works. SHM systems can be designed to obtain data on global structural properties. With the implementation of this system, it can be designed and fitted a local monitoring system to determine the performance of the metric and how they have evolved under the possible degradation (Catbas, 2009).

With the implementation of SHM systems, the data collected from different structures can be used to gain a better understanding of the structure response, mechanisms of occurrence and evolution of degradation. Those are very important information for designing other structures.

In his article, Inaudi (2009) presents many benefits of SHM systems. He said that those benefits depend on the specific application of the system. Thus, the most important advantages mentioned by the author are presented below:

1° *Monitoring results in reducing the uncertainties* – The structure administrators must deal with many uncertainties, such as the actual condition of the materials, the actions to which the structure is subjected or the system age. These uncertainties should be considered in the decision phase to keep the structure safe. Monitoring systems are a useful tool in making decisions taking into account all data provided by the structure and lead to a considerable reduction of uncertainties. Applying these systems also leads to lower costs to ensure the structure due to the decrease of the risk.

2º *Monitoring reveals faults and degradations in real time and increase the safety of the structure* – Some problems cannot be identified through visual inspections or numerical modelling. These problems can become very dangerous for the structure if they are not resolved on time. If the necessary decisions are not taken in time to remedy or prevent defects or degradations, they can even lead to the collapse of the structure or the affected element. It is well known that repair is much cheaper than total replacement of the structure or element, and causing less disturbance of the road users, when it is done at the right time. Consequently, continuous monitoring of the structure and unlimited access to the resulting data have led to a considerable improvement in the safety of the structure and its users.

3º *The discovery of the structure hidden resources through monitoring* – Due to safety margins provided by the designer and existing in construction materials, structures are sometimes better than expected. In these cases, monitoring leads to an increase in safety margins, even without the intervention work being done. This fact can lead to reducing the costs necessary to repair and replacement of the affected elements.

4º *Monitoring leads to enhancing knowledge of structure* – Gaining knowledge of the structures behaviour under real conditions improve the future design concepts. This will lead to the development of safer and more sustainable structures, increasing the performance of the entire infrastructure. Although it is an important investment in project implementation, it leads to cost saving by optimizing design and discovery of defects and degradations at an early stage.

5º *Long-term quality assurance*– The structure of the monitoring system ensures the continuous flow of data, contributing to the qualitative assessment of the construction during the execution phase, during the operation and the maintenance or repairs execution. This eliminates hidden costs related to the poor works quality. Researchers have shown that most defects and degradations occur during the construction period. However, many defects will only be discovered after many years. In that stage, the repair costs are higher and the structure is no longer under warranty.

6º *Structural monitoring helps bridge management* – Monitoring data is used to perform on-demand maintenance, to optimize maintenance works, repair or replace of degraded structural elements. The monitoring can be integrated in the management structures to increase the decisions quality through access to reliable and impartial information. The main benefit at this stage is the ability of administrators to perform maintenance and reconstruction work when needed. Another advantage is the planning of necessary funds based on actual data from the source.

Comisu (2008a) provided an economical estimate that shows that the integrated monitoring system implementation offers the following benefits:

a) reduce the necessary costs from carrying out inspections and maintenance by 25%;

b) reduced costs resulting from traffic with 30% that occurs due to the decreasing number of inspection points;

c) 10% reduction of the total lifecycle costs of the structure by applying the remaining lifetime predictors;

d) assisting operators responsible during the decision-making process necessary to intervene in the earliest stages of degradation development for keeping the structure in optimal conditions.

The first disadvantage, and the most important, of SHM implementation established by Karbhari (2009) is that the transition to maintenance based on unplanned works resulting from changes in computational systems is quite expensive. Implementing such a system, although effective, requires high costs due to the components multitude and their high performance.

4. Application of SHM Systems

Over time, more and more bridge managers in developed countries have chosen to implement this type of monitoring system due to the many advantages they offer. Thus, the iconic structures of these countries were initially monitored, after which the implementation of these systems extended to the usual structures.

Since bridges in operation are of different construction dimensions and are built using a variety of materials, many bridge structures already built can become candidates for monitoring using SHM. Several old bridges have historical significance and their preservation becomes more important than optimizing functional values (Inaudi, 2009).

For this work four structures monitored using SHM system were chosen as examples:

i) The above mentioned author (Inaudi, 2009) presents a series of bridges that are successfully monitored through SHM technology.

ii) The first example of this work is the I-35W Bridge St. Anthony Falls Bridge (USA, Fig. 2). Due to failure of old structure in 2007, the administrators decided to install a complete monitoring system on the new structure to avoid another tragedy, but especially to increase public confidence in the new one. The primary objective of SHM system was to support construction processes, to register the structural behavior of the bridge and to contribute to an intelligent transport and security system. Monitoring instruments recorded static and dynamic parameters in essential points of the structure. This bridge can be considered one of the first "smart" bridges in the USA.

Fig. 2 – I-35W St. Anthony Falls Bridge (USA) (https://www.gti-usa.net/Saint-Anthony-Falls-Replacement-Bridge.shtml).

Habel (2009) describes one of the first challenges in SHM projects in Europe, namely monitoring the performance of the Great Belt Link Bridge (Storebælt Bridge, Denmark, Fig. 3) built between 1989 and 1998. Due to the environment and aggressive concentrations of chloride contained in seawater, concrete durability had monitored continuously using 446 specialized corrosion monitoring sensors.

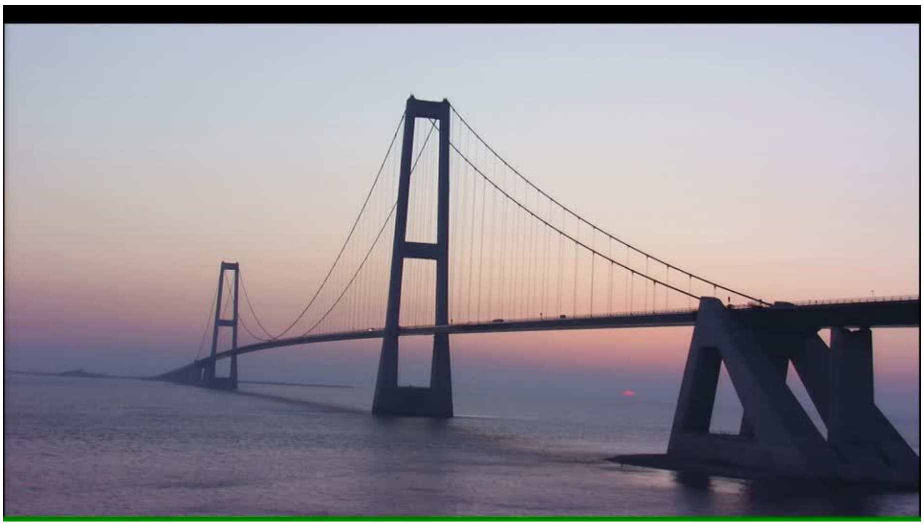

Fig. 3 – Great Belt Link (Storebælt Bridge) (http://footage.framepool.com/en/bin/426741,great+belt+bridge,great+belt,denmark/).

Another example is the bridge Ali Çetinkaya (Turkey, Fig. 4) located in Bafra, Samsun on Kızılırmak River. The total length of the bridge is 250 m, with 7 spans consisting of 7 arcs. Each span has 36 m and the height of an arch is 6.20 m. The bridge is the longest bridge built with Bowstring technology in Turkey. The dynamic characteristics of the structure have been identified by ambient vibration measurements while the structural response to seismic actions was recorded via 11 uniaxial accelerometers located on the vertical and transverse directions. The measurements were conducted for 6 minutes using environmental loads (Türker & Bayraktar, 2014).

Fig. 4 – Ali Çetinkaya Bridge (https://www.researchgate.net/figure/265415594_fig1_Fig-1-Views-from-Ali-Cetinkaya-Bridge)

In our country, an example of a structure that benefited from the implementation of a performance monitoring system is the Agigea Bridge Romania, (Fig. 5). It is located on the national road DN 39, near Agigea, linking Constanta and Vama Veche. The bridge is the first cable-stayed structure in Romania. The total length of the bridge is 267 m ($2\times40.5\,\text{m}+162.5\,\text{m}+23.5\,\text{m}$). The rehabilitation works were finalized in August 2015, when administrators decided to install a degradation monitoring system due to the importance of the structure. The monitoring system consists of 8 strain gauges placed in pairs in 4 characteristic section (Fig. 6). The sensors are installed at the bottom of the steel girder web, the main purpose of which is to monitor the stress state of the analysed structure. The SHM system is also completed by an alarm system, which is responsible for alerting administrators and users to the extent of certain degradation and threshold levels, which endangers trafficking in optimum conditions. (Romanescu, 2014).

Fig. 5 – Agigea Bridge (http://www.puterea.ro/).

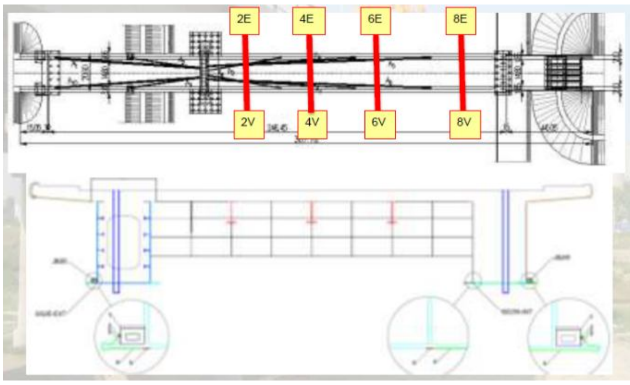

Fig. 6 – The location of the strain gauges in the Agigea Bridge (Romanescu, 2014).

5. Conclusions

This paper offers a review about important data for SHM technology. Thus, it was presented a brief overview of the system's history and the benefits of its development, both in design and construction phases as well as in the structures in operation.

SHM systems have been used in recent years mainly to implement and verify new technologies for the construction of some parts of the structure. Another application is the data collection. Those data are necessary for diagnosis and prognosis of the structural technical state evolution. This system can be an important aid to structural managers, especially when the desired budget planning is based on the concrete needs of the road network and for making the best decisions on structures that require repair works. SHM is a useful tool because it leads to the decrease, until the visual inspections are eliminated, providing more accurate data than these.

This work represents one of the first steps 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 SISTEMELOR DE MONITORIZARE A STĂRII DE DEGRADARE A PODURILOR

(Rezumat)

Sunt prezentate unele aspecte esenţiale privind noile tehnologii de monitorizare a structurilor de poduri. Aceste tehnologii au fost reunite de către specialişti sub denumirea de Structural Health Monitoring (SHM). Odată cu trecerea timpului, structurile aflate în exploatare suferă degradări care conduc atât la afectarea siguranţei structurale, cât şi a traficului. Cu ajutorului unui sistem de acest tip, degradările sunt identificate încă din primele etape ale dezvoltării lor, costurile de remediere necesare fiind mult mai mici. Un alt motiv al implementării sistemelor SHM este reprezentat de interesul administratorilor de a menţine structurile în condiţii optime de exploatare pentru siguranţa traficului, încadrându-se în acelaşi timp în bugetele avute la dispoziţie. Datorită necesităţilor tehnologie, SHM este un domeniu relativ nou, prima încercare

documentată de monitorizare a unei structuri datând din anul 1937. În acest articol sunt prezentate avantajele utilizării acestui tip de sistem de monitorizare, precum şi câteva exemple de structuri care au beneficiat de-a lungul timpului de caracteristicile sale.