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# Implementation of the Structural Health Monitoring systems for bridges

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## Summary

*In recent decades, the use of Structural Health Monitoring (SHM) systems for monitoring the degradation states of new or existing bridges has seen an accelerated development. This is primarily due to the need of the administrators to have access to a wider range of information directly from the structure to facilitate decision-making on the necessity and urgency of maintenance work. SHM systems are also an important tool for design engineers to track the behaviour both during the execution and in the exploitation of new materials or innovative designs.*

*As time passes, construction materials and, by implication, bridges age and are subjected to various types of degradations that lead to structural and traffic damages, sometimes quite significant. By implementing a SHM system and monitoring data from it, degradations are identified from the very early stages of their development, when the cost of remediation and the damage of the entire construction are much lower. The efficiency of using these types of systems, maintenance and repairs done as quickly as possible ultimately develops into an increase of the structure lifetime, resulting in significant material benefits that can be oriented toward the investment sector. Additionally, administrators may use the information provided by the SHM systems to better manage the limited budget and resources available, which makes it more efficient to allocate funds to keep the entire road network in optimal viability.*

*In the present paper, the authors deliver a brief presentation of the applicability of the monitoring systems, both of new structures and those already in operation, along with the aims and benefits of implementing such systems. Finally, the article briefly presents three examples of structures benefiting from tracking time behaviour through SHM systems.*

Keywords: Structural Health Monitoring (SHM), bridges, maintenance, monitoring, durability, service life.

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## 1. INTRODUCTION

Since the beginning of the last century, researchers in the fields of dynamics, bridge construction and maintenance have developed various systems responsible for tracking the behaviour of structures over time. These systems have been reunited as Structural Health Monitoring (SHM), developing a new direction of research with an impressive evolution speed, especially in the second half of the last century. This is mainly due to technological progress in the field of construction and informatics, but also to the increasing interest of bridge managers to keep them at optimal performance levels for as long as possible, using the limited funds available. Another explanation for this interest is the aging of bridges already in operation, which in time leads to the exponential increase of the necessary funds both for inspecting the structure and following the evolution of the various degradations considered to be dangerous and for the execution of the maintenance and repair work.

The increasing use of SHM systems, has brought considerable improvement in knowledge of dynamics bridge structure, causes of degradation processes, speed, mode of development and the degree to which such degradation affects or will affect structural safety [11]. The use of SHMs leads to the discovery of degradations from the early stages of their development, thus greatly facilitating the remediation process and lowering its cost.

One of the main goals of using SHM systems is providing the specialists in road and bridge administrations with access to as much up-to-date information on the current state of the bridges [7]. Based on the information from the structure, the work required to be executed and the associated cost, are determined. Also, in the ideal case where multiple structures within the same administrator's responsibility are permanently monitored, the most efficient prioritization of the works to be executed within the following period can easily be achieved within the limits of the available budget.

In this article, the authors present the benefits of implementing SHM-type systems. In Chapter 4 there are three examples of structures that benefit from continuous monitoring of technical state through modern monitoring systems.

## 2. APPLICATION OF SHM SYSTEMS

When deciding to install a SHM system, designing it takes into account a number of factors such as the geometry of the deformations, the physical and chemical properties of the materials used to build the structure, the internal forces and the tensions located in its critical areas. The scheme of a SHM system is shown in Figure 1.

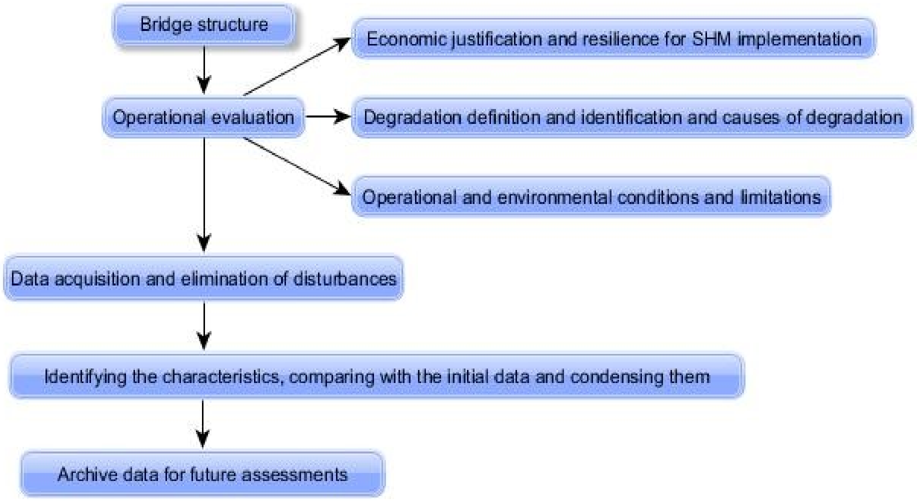


Figure 1. Scheme for applying a SHM system

The information required for good predictions on the future behaviour of the analysed structure can be collected by measuring and tracking the evolution of loads to which the structure is subjected, its response to loads, structural changes due to degradations and maintenance and repair work carried out over time. In the subchapters below, the objectives of the SHM systems implementation both for new structures and those already in operation are presented.

### *2.1 Application of SHM systems to new or under construction structures*

The implementation of systems and technologies for monitoring new or under construction bridges has as main objective the capture and storage of data necessary to effectively determine the intrinsic forces developed within the structure and the causes of the various defects caused by them. Over the last few years, more and more designers have decided to implement such systems in the case of the structures responsible for supporting an important communication route or which has an innovative design. This approach aims to determine any changes in structural parameters and to verify the technological processes that are part of the construction and assembly works.

The benefits of using SHM systems from the construction phase of the structure are highlighted especially in the actions to prevent the occurrence of bridge geometry defects. These defects are caused by the poor assembly of structural elements, sensors or instruments responsible for monitoring the environment. Monitoring aims at early detection of any events that, by their development, could lead to degradation of the analysed structure. One of the most important advantages is the use of the data provided by SHM systems in the risk management programs at the construction stage of the structure. These risks are due to the vulnerability of the bridge to the occurrence of accidents or calamities.

The design of the monitoring, data acquisition, processing and storage systems occurs simultaneously with the realisation of the technical project of the newly built structure, making it an integrated part. Design engineers and those in administration institutions prefer such an approach because of the higher implementation speed and the fact that the system can be programmatically activated from the time the structure is executed. This need arises as a result of the desire to validate assumptions supported in the design calculations with regard to the forces, reactions and displacements to which the structure is subjected during constructive processes. At the same time, once the system identifies the modification of certain parameters and the corresponding alarm signals are transmitted to the people in charge, the corrective measures required can be taken very quickly. Thus, the use of the SHM system provides the possibility to control and mitigate any possible design and construction errors which, if found at an advanced stage of the structure, would lead to significant delays and increased work cost [3].

### *2.2 Application of SHM systems to structures in operation*

Nowadays, most of the road infrastructure is already built, the main challenge being to maintain it in optimal operating conditions. Due to the limited budget funds made available to administrators for the maintenance of the entire road network, both they and the designers and builders were forced to research and develop new methods to reduce construction and maintenance costs while increasing the durability of the structure. The execution of such maintenance works sometimes requires funds higher than those required for the complete replacement of the respective superstructure or the entire bridge [7].

Liu et al. [9] considers that the structure of a bridge under exploitation and subjected to permanent loads, utilities and environmental factors will suffer degradation which, if not intervened in due course, will lead to a decrease in the technical status index resulting in damage to the safety and the sustainability of the structure. In order to prevent these inconveniences, it is recommended to perform periodic non-destructive tests or implement a SHM system, both during construction and especially in operation. These tests and SHM systems are designed to control the degradation appearance and development and to ensure a high degree of social, economic and scientific safety.

Over time, due to aging and excessive exploitation, bridge structures suffer more and more degradations. Administrators choose to deploy a SHM-based system on an existing structure to determine the occurrence of degradation processes and to make a more accurate estimate of their evolution. These estimates are the most useful tools used for budget planning to support the maintenance of the medium to long-term road network. Another very important benefit of SHM systems deployed to operating structures is used by researchers to understand the causes that lead to different types of degradations [3].

## 3. THE PURPOSE OF IMPLEMENTING A SHM SYSTEM

SHM structure monitoring systems are mostly used to obtain the necessary information to identify the various structural parameters used to determine the occurrence of degradations and the planning of the maintenance and repair work. At the same time, the data thus collected can also be used to improve design rules and diagnose the pre- and post-hazard structure. Therefore, SHM systems are considered to be the most efficient tool for determining structural characteristics and assessing the technical value of the bridge [4.

Hann [6] asserts that the purpose of tracking the behaviour of bridges over time and, implicitly, the use of SHM systems spring from the need to know the evolution of structure performances and data necessary for the proper assessment of its exploitation capability. Studying the data thus collected, specialist engineers can draw up a list of recommended intervention measures to be taken to maintain or restore the monitored structure.

Bridge administrators consider that other benefits of using SHM systems are their capability of estimating the remaining life of the structure, ensuring an accurate cost-benefit assessment and analysing the life cycle of the structure [4].

The main objectives of the SHM monitoring systems are [6,8]:

- Validating the parameters and assumptions made by the designer during the design process, bringing considerable benefits to the improvement of technical standards and design codes;
- Detecting the occurrence of any abnormalities occurring in the loads, the response of the structure to those loads and the degradations from their incipient phase in order to ensure structural safety and traffic;
- Providing real-time data needed to evaluate the structure’s safety degree as quickly as possible;
- Providing the necessary information to plan and prioritize inspections, maintenance, repair and rehabilitation;
- Monitoring the execution of repair and reconstruction works to assess their effectiveness;
- Obtaining the data to be used later in research projects.

The advantages of installing a SHM system on any type of structure are [5]:

- Reduced interference from traffic measurements;
- Reduced spending for access by authorized persons responsible for monitoring the structure;
- Much easier tracking of hard-to-reach bridge elements;
- Easy prediction of degradation evolution;
- Providing data needed to take early remedial measures for early-stage degradation;
- Providing the necessary information for defining maintenance and repair planning strategies taking into account the current level of degradation and its evolution;
- Evaluating the efficiency of repair work;
- Documenting decisions on carrying out inspections and special tests.

The implementation of a SHM system is done after analysing the needs of the respective structure, in order to determine precisely the type of parameters to be monitored. They depend on the type of structure, building materials and the environment. In the literature [15], the monitored physical parameters fall into the following four categories:

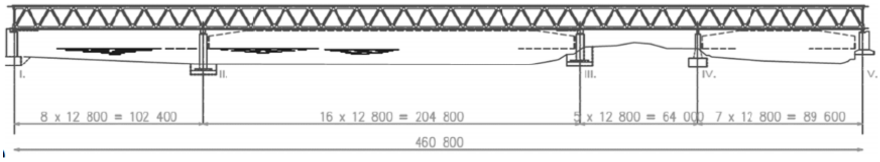
- Parameters related to loads;
- Parameters related to the characteristics of the structure (static and dynamic characteristics);
- Parameters related to structure response (cable forces, fatigue accumulation, etc.);
- Environmental parameters (wind, temperature, humidity, earthquake, etc.).

## 4. EXAMPLES OF STRUCTURES MONITORED USING SHM SYSTEMS

### *4.1. The Port Bridge (Bratislava - Slovakia)[2]*

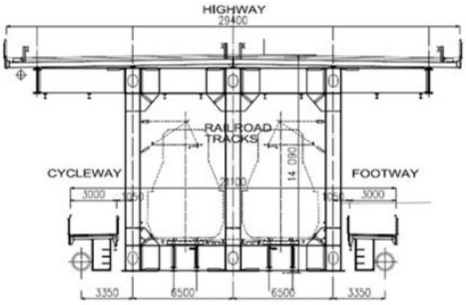
### *4.1.1. The bridge structure*

The Port Bridge is located in Bratislava Harbour, the capital of Slovakia. The structure serves the D1 motorway, ensuring the Danube crossing and being a combined bridge, rail and road. From a constructive point of view, the bridge has a total length of 460.80 m, with a continuous beam with 4 openings (102.40 m + 204.80 m + 64.00 m + 89.60 m) (Figures 2a and 2b).



a. Longitudinal section

b. Northern longitudinal view



c. Cross section

Figure 2. The Port Bridge [2]

The construction of the bridge took 8 years, and it was open to traffic in 1985. In the cross section (Figure 2c) there are three meal beams with a height of 11.70 m, with an interax distance of 6.50 m. At the upper part of the beams, there is a deck with a mixed steel-concrete structure, serving the two ways of the motorway. At the bottom, there are 2 railway lines between the main beams and 2 pedestrian walkways in the console.

At the time of designing, taking into account the current and perspective port capacity, specialist engineers took into account a structure capacity of 50.000

vehicles per day. Due to the accelerated pace of development of the area, the creation of new economic routes and the fact that the structure is the most used in Slovakia, the number of vehicles engaged in crossing the bridge in 24 hours doubled compared to the estimated one.

### *4.1.2. Modelling the bridge structure using the Finite Element Method and analysing the results*

Ároch et al. [2] modelled the bridge structure as an integral part of the research project. This modelling was carried out using the ANSYS program with bar and plate elements, to calculate the natural frequencies and vibration modes of the structure. To take into account the loads that the bridge is subjected to by traffic, different mobile charges were applied. The structure of The Port Bridge modelled in the ANSYS program can be seen in Figure 3.

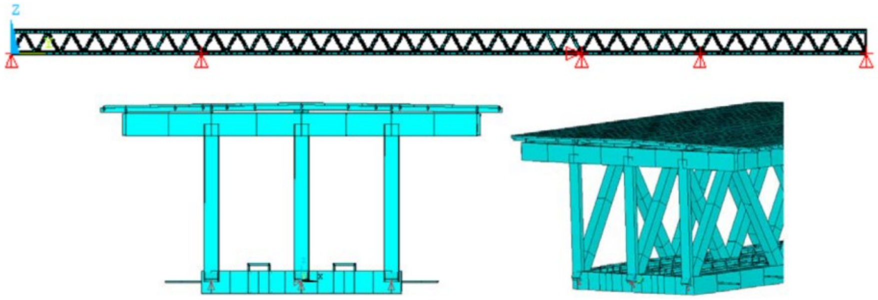


Figure 3. The Port Bridge – Modelling within the ANSYS program[2]

### *4.1.3. Performing in-situ measurements and comparing results with those obtained using the ANSYS program*

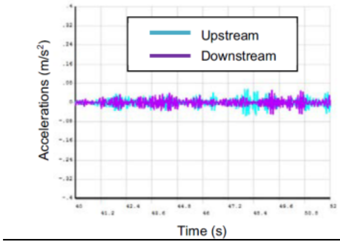
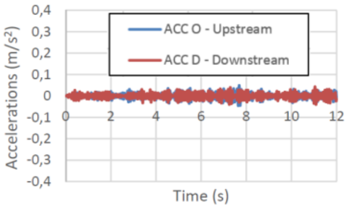
For the purpose of an accurate in-situ analysis of the structure, the researchers [14] decided to install 12 NI 9074 accelerometers, 8 NI 9144 accelerometers, 8 NI 7064 accelerometers, 2 Wi-Fi antennas on the bridge .and a data storage device near the bridge.

Once the SHM type monitoring system was located, the biggest problem identified was the synchronization between the vehicle type engaged in crossing the structure and the data from the sensors installed on it. For this purpose, a camera was placed next to a tablet. Thus, correlations were made between the measurements and the captured images (the vehicles) with a tolerance of 0.2 m. Through the system so designed, the accuracy of the vehicle localization is ±5m at the 460.80 m of the structure.

In their article, the authorsÁroch et al. [2] provide data on a comparison of the vertical acceleration results calculated for maximum structure opening of 204.80 m and the valued corresponding to the point considered on the actual structure. In Table 1 below, it can be seen that the peak acceleration value in both cases is 0.06

ms$^{-2}$. In the next step, a similar comparison of the frequency data was made, concluding that the results from the numerical analysis are similar to the in-situ measurements.

Table 1 Comparison of vertical accelerations at the base of the structure measured over time 40 – 52 s [2]

| Accelerațiile calculate | Accelerațiile măsurate |
|---|---|
|  |  |

### *4.2. Sydney Harbour Bridge (Sydney - Australia)[1]*

Alamdari et al. [1](2017) present the instrumentation of the famous Sydney Harbour Bridge superstructure. For this structure, a unique SHM – type monitoring system was used to track the behaviour of more than 400 substructures. This system has been in use since 2014.

#### *4.2.1. The bridge structure*

The Sydney Harbour Bridge (Figure 4) supports the continuity of Australia’s most important communication metropolis route, connecting the northern part of the city to its center.

In the cross section, there are two metal arches supporting the loads from traffic on 6 lanes for vehicles, 4 lines for public transportation and 2 sidewalks (Figure 5). Trafficking on an ordinary day reaches several tens of thousands of vehicles.

Following the traffic study conducted by Alamdari et al. [1], the team of researchers considered the second vehicle band, on the eastern side of the structure, to be the most exploited. From a constructive point of view, the selected strip consists of 2 layers of asphalt laid on the surface of the concrete slab in cooperation with the metal structure.

Figure 4. Sydney Harbour Bridge[16]

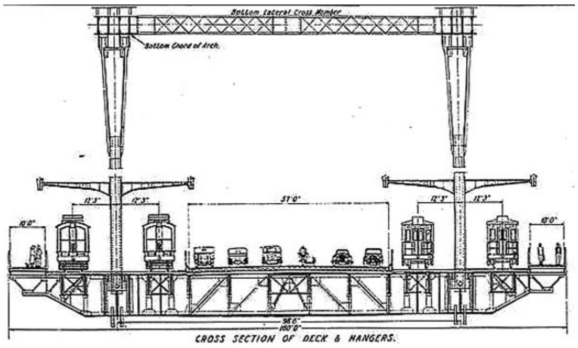


Figure 5. The Sydney Harbour Bridge– Cross section [17]

The bridge steel structure is made of small arcs, with 800 such arches being arranged over a distance of 1.2 km (Figure 6). This layout makes the items difficult to access and, consequently, inspect. However, according to the Australian standards, the entire structure of the bridge is inspected twice a year.

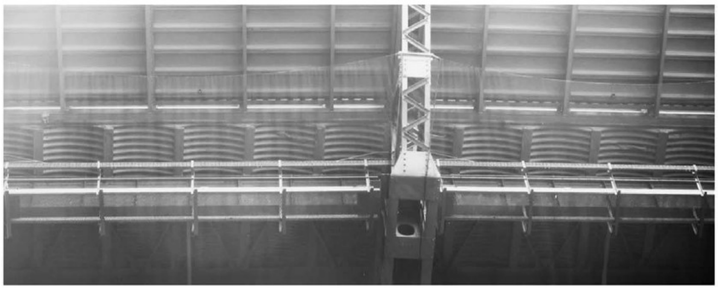


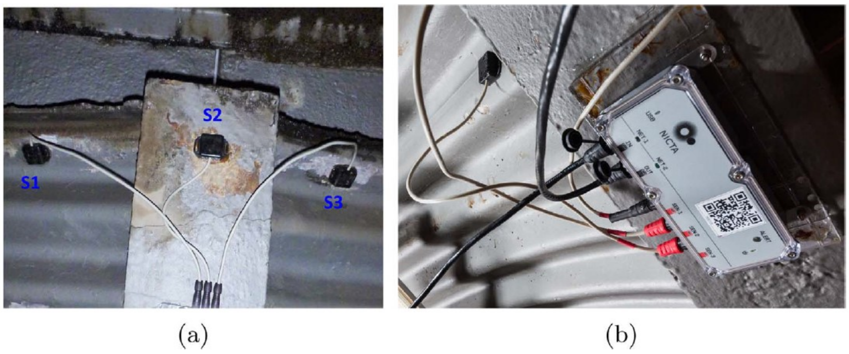
Figure 6. The Sydney Harbour Bridge – Series of 9 arcs supporting the analysed band [1]

Alamdari et al. [1] developed and implemented a SHM-type system to continuously monitor the 800 arches. When the system detects any abnormality in the recorded data, it automatically alerts the structure managers and staff in charge through a phone application. A visual inspection of the structure is made in the shortest possible time, and any degradation found resolved. The main advantage of this SHM system is the low degree of traffic damage.

The built-in SHM system includes data capture units (sensors), information transport media (in this case, cables) and a unit for their analysis and storage. This last component can provide all the relevant information on the degradation state of each component arc, along with recommendations on the required work to be done to remedy them [13].

### *4.2.2. Data acquisition systems*

Each arc of the 800 monitored was equipped with three tri-axial accelerometers of the MEMS type, as can be seen in Figure 7. These three sensors were disposed at the most requested arc points, one at the top and the other 2 on each side of this sensor. Continuous uses of the 2.400 accelerometers produce about 1 TB of information per day, excessive volume for processing the entire amount. In order to minimize this disadvantage, the researchers decided to allocate a calculation node for each arc to filter process and analyse the data thus collected and to transmit to the centre server only those data considered important for the structure [13].



(a) (b)

Figure 7. Sydney Harbor Bridge – a. Positioning of the three triaxial accelerometers for a monitoring arc, b. Arc calculation node [1]

Typically, data collection for the analysed bridge consists of two main phases: the data production phase and the collection phase. In the information production phase, the sensors capture different data, processing them directly into the node. Then, a brief list of information on the degradation state of the monitored structure is produced. In the second described step, the data collected is stored in the computation node, transmitting it to the central database at precise time intervals.

Researchers Alamdari et al [1] proposed the use of Spectrum Moments to measure structural response accelerations. These moments are composed of Power Spectral Density (PSD), which contains the most important data about structure characteristics. Additionally, PSD can characterize spectral or temporal signals, resulting in timely detection of any anomalies occurring within the signal. PSD is capable of quantifying the energy level of the signal by using sufficient bandwidth to avoid causing a lack of important information and producing a limited number of vibration modes.

### *4.2.3. Case studies on the structure*

In order to demonstrate the effectiveness of the modern system of monitoring the degradation state of the structure, the authors of the reference paper, Alamdari et al. [1], carried out five case studies on the proposed bridge.

The first four case studies have been channelled into monitoring those arcs affected by degradation developments. Each study involved the instrumentation of a relatively small number of arches, mainly due to the large data volume. For the good conduct of the study, the exact causes of these degradations have been identified by visual inspection prior to the beginning of data capture. This research approach is very effective in tracking the evolution of degradation discovered during the latest visual inspection of the bridge.

The fifth case study, the most complex, demonstrates that the proposed approach can also be used to identify a degraded arc without a visual inspection to indicate what element is affected. Thus, 85 arcs were monitored for a period of 22 days in July 2015. Based on the data captured, the arcs were grouped according to their behaviour, anomalies were analysed and the cause of their occurrence was determined. This approach studies the possibility of monitoring the entire structure and determining the occurrence and evolution of degradation.

## *4.3. Agigea Bridge (Agigea - Romania)*

### *4.3.1. The bridge structure*

In our country, one of the most conclusive examples of bridge degradation monitoring systems is the Agigea Bridge (Figure 8). It is located on the DN 39 national road at km 8+988, near Agigea town, ensuring the traffic on the Danube – Black Sea canal. The bridge under consideration provides one of the most important connections between Constanţa and Vama Veche.

Figure 8. Agigea Bridge

From the point of view of the static scheme, the Agigea Bridge has an asymmetrical structure, with a pillar located on the left side of the canal, towards Constanța. This bridge is the first cable structure in Romania with a total length of 267.00 m, and consisting of 4 openings (2x40.50 m + 162.50 m + 23.50 m). One of the most important features is that the superstructure is composed of two type I beams, continuous in the support, with a 15 cm opening [10,12].

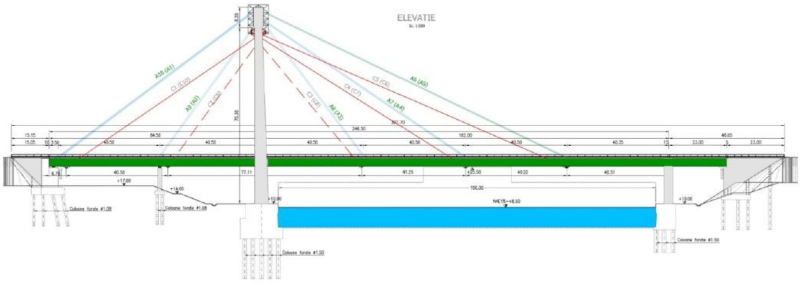


Figure 9. The Agigea Bridge scheme [10]

*4.3.2. The structure instrumentation*

The monitoring system developed and implemented on the Agigea Bridge consists of 8 pairs of tension sensors in four characteristic sections, as can be seen in Figure 10. The sensors have been installed at the bottom of the metal beams, in direct contact with the lower side. The main purpose of this SHM system is to monitor the technical state of the analysed structure. The devices used are complemented by an alarm system, which is responsible for alerting administrators and traffic participants when thresholds are exceeded by degradation and structural safety is jeopardized [12].

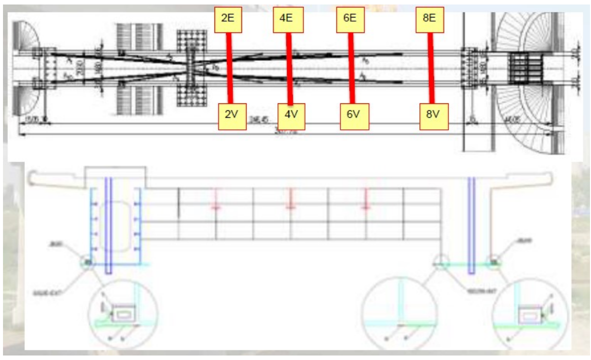


Figure 10. Location of stress sensors located on the Agigea bridge [12]

## 5. CONCLUSIONS

The development of SHM degradation monitoring systems is a real challenge for both bridge management engineers and those who are in charge of designing new structures and rehabilitation works.

The implementation and use of integrated SHM monitoring systems lead, over time, to improving the knowledge of the structural mechanisms behaviour, the interaction between these mechanisms, the whole structure, the way of development and the degradation causes. These systems help to make and justify the best decisions regarding the timing of the intervention work and the extent of their expansion. At the same time, information from SHM systems helps to achieve budget planning. The funds available are channelled to the concrete needs of the road network, the necessary intervention work being done in a timely manner, thus preventing the development of degradation and serious damage to the safety of the structure.

Over time, the implementation of the systems under consideration leads to lower costs for inspections and the execution of maintenance, repair and rehabilitation works and the delays in traffic due to these works.

The paper is part of a complex research program, developed within the Faculty of Civil Engineering and Building Services – ”Gheorghe Asachi” Technical University in Iaşi. This study focuses on the development of bridges monitoring methodologies, combined under the name of SHM (Structural Health Monitoring).

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