BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 65 (69), Numărul 1, 2019
Secţia
CONSTRUCŢII. ARHITECTURĂ

STRUCTURAL BEHAVIOR OF A HYBRID STEEL-CONCRETE BRIDGE
EXPERIMENTAL SET-UP

BY

MARIA-CRISTINA SCUTARU*, NICOLAE ŢĂRANU, CRISTIAN-CLAUDIU COMISU, GHEOGHIŢĂ BOACĂ, ADRIAN IANOŞ and MIHAI STAŞCOV

Technical University “Gh. Asachi” of Iasi,
Faculty of Civil Engineering and Building Services,

Received: January 28, 2019
Accepted for publication: February 27, 2019

Abstract. The use of modern systems for constant bridge monitoring has known a surprising evolution in recent years, being implemented in case of numerous operating structures. It was born in response to the administrators’ need to know the technical state of the bridges belonging to their subordinate network at any time and to distribute the limited budget available for the maintenance works as efficiently as possible. With the help of a Structural Health Monitoring (SHM) system, degradations are discovered as early as possible, in most of cases in the beginning stages of their development, when the cost of remediation is minimum. This paper presents the steps followed in the experimental program that aims to determine the degradation state of a mixed steel-concrete structure based on the analysis of data from a monitoring system installed on it. It is part of a comprehensive research program at the Faculty of Civil Engineering and Building Services at the ”Gheorghe Asachi” Technical University of Iaşi.

Keywords: bridge; Structural Health Monitoring; maintenance; monitoring; sensors.

---

*Corresponding author: *e-mail:* scutaru.mya@gmail.com

1. Introduction

Bridges have been designed and constructed since ancient times to ensure the continuity of a communication path when encountering an obstacle, while allowing the free space necessary for the continuation of the obstacle (STAS 5262, 1992). These engineering works establish new economic relations between various areas, substantially contributing to the economic development through the faster and easier transport of goods and people.

Today, most of the road infrastructure is already built; therefore, the main challenge is its maintenance. Most of the time, this challenge proves to be even more costly than the replacement of the entire structure. Although bridges are of great importance to society, bridge managers are faced with insufficient funds for all repair works needed to keep structures up to performance standards on a regular basis. That is why, together with researchers in the field, they have constantly tried to develop new cost-effective methods of both construction and maintenance works to improve structural sustainability as much as possible.

To facilitate the assessment and monitoring of structures, bridge researchers have developed new technologies that continuously monitor structures and identify the presence and extent of various types of degradation from the early stages of their development. Based on the information provided by the SHM devices and technologies, the responsible staff can take the most appropriate decisions regarding the intervention works at the right time.

The main objective of this paper is to present the preparatory stages of the experimental program regarding the implementation of an automated, efficient system for monitoring a mixed steel-concrete structure and determining its viability.

2. Literature Review

Modern concepts specifically designed to optimize maintenance and intervention programs on bridges have been extensively investigated over time. In recent years, researchers have focused particularly on optimizing the funds needed for bridge maintenance, using various methods to predict the evolution of degradation (Orcesi & Frangopol, 2011).

In the literature currently available worldwide, the processes and technologies forming the automatic bridge monitoring methodology are combined under the name of Structural Health Monitoring (SHM).

The use of SHM systems has accelerated in a relatively short period of time. The most important objective of these systems is to ensure the early identification of the occurrence and evolution of defects and degradations in order to intervene as soon as possible to remedy them and prevent the evolution of the damages that may affect the traffic safety (Bota *et al.*, 2014). Based on the analysis of the data captured from the structure, these programs establish its ability to meet the needs of the administrator, both presently and for a future period of time.

Over time, the concept of SHM has received various definitions, some of them presented below.

The main definition states that the SHM represents the process of implementing a defect identification strategy. Initially, these technologies were used in the aerospace and mechanical industries (Worden *et al.*, 2015; Yang & Soh, 2009; Farrar & Worden, 2007). It is only in the last decades that construction engineers found it appropriate to build and implement similar systems to identify degradation and track their evolution (Farrar & Worden, 2007).

Karbhari (2009) provides a brief overview of the evolution of the SHM concepts. Originally defined as a conventional inspection process represented by classic visual inspections, the concept has evolved to refer to monitoring inspections based on the collection of different sets of data including acoustic data to determine the possible changes in structural characteristics due to the occurrence of degradation (Klikowicz *et al.*, 2016).

The first example could be the Taiwan-made steel-concrete composite bridge that ensures the continuity of the road to the Caohu River. The bridge has a total length of 476 m, with four openings of different lengths (93 m + 145 m + 145 m + 93 m), the width of the bridge being 25.8 m (Fig. 1 *a*). The superstructure underwent an extensive rehabilitation process at the end of which it was decided it needed monitoring. Therefore, various in-situ tests were conducted before the assessment of the non-degraded structure stage of the bridge. The implemented SHM system includes 4 types of sensors (strain gauge, LVDTs, inclinometers and temperature strains) mounted in the most important points of the third opening. In this way, the structure manager knows the technical state of the structure at any time (Sung *et al.*, 2016).

a *b*

Fig. 1 – *a* – Caohu Bridge (Taiwan) (Sung *et al.*, 2016); *b* – Agigea Bridge (Romania).

In our country, one of the most representative examples of structure that benefited from the implementation of a SHM system is the Agigea Bridge, which connects Constanța city and Vama Veche (Fig. 1 *b*). This bridge is the first cable structure in Romania, with a total length of 267 m, spread over four spans (40.5 m + 40.5 m + 162.5 m + 23.5 m). The monitoring system consists of eight pairs of voltage sensors in four characteristic sections. The sensors were located at the bottom of the metal beams, in contact with the lower sole, to monitor the technical state of the structure (Mihalache *et al*., 2017; Romanescu, 2014).

3. The Şcheia Bridge Description

The bridge under investigation, built in 1958, it has been in operation for about 61 years. The structure ensures the continuity over the Siret River of the road connecting Iaşi, the largest area of development of Moldova, with the capital Bucharest and the rest of the country. The bridge is passed on by long and heavy vehicles on a daily basis.

In a longitudinal section, the Şcheia bridge has four spans with variable lengths (50.35 m + 60.00 m + 60.00 m + 50.35 m), resulting in a superstructure of 220.70 m and a total length of 236.40 m (Fig. 2). From a constructive point of view, it is a mixed steel-concrete structure with a static stack of continuous beam. In order to ensure the inherent deformations during construction and operation without affecting the bridge safety, 23 expansion joints were provided, two of which were the main ones, on the two abutments, and 21 in the concrete slab (Scutaru *et al.*, 2018).

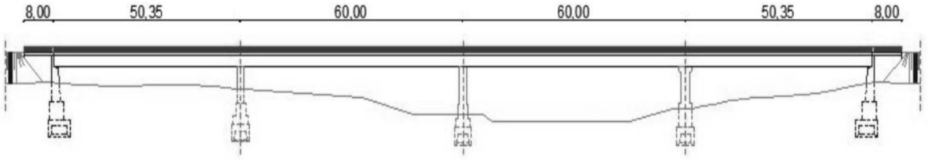


Fig. 2 – Side view of the Şcheia Bridge.

Due to the specificity of the national road with two lanes and a reinforced moor, the structure has two lanes in opposite direction. The cross section (Fig. 3) reveals its 7.44 m width, including two sidewalks of 0.83 m each. In the current context of design requirements, the structure has important functional deficiencies; there is no grilled pedestrian protection and the differentiation between the carriageway and sidewalk is achieved by raising the latter. The overall width of the superstructure is 9.52 m, measured between the inner sides of the parapet. The height of a ridge is 10.55 m, being known as the lowest water level considered for a period of 10 to 30 years, depending on the importance of the structure.

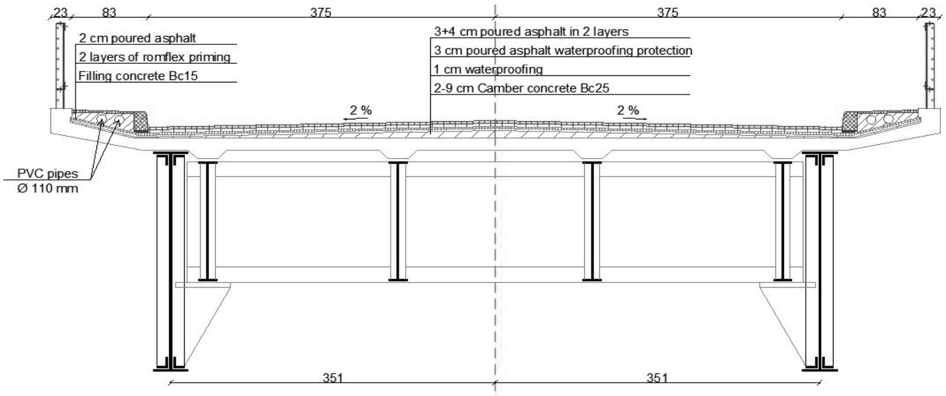


Fig. 3 – The bridge cross section.

The superstructure of the bridge is made of two solid steel girders, continuously adjacent to the supports, and a reinforced concrete slab on top. Between the two girders there are four balks. The distribution of loads between the girders, balks and maintaining of these elements in the correct position are achieved by the struts. One of the interesting features of this structure is the lack of connectors between the flanges of the girders and the concrete slab. The main girders have a constant height of 2.40 m, being arranged at an interax distance of 7.00 m. At the bottom of the steel structure, there are horizontal bracings (Fig. 4).

Fig. 4 – View of the bracing system.

Since the beginning of its operation in 1958, the most recent interventional works were carried out in 2002, when extensive rehabilitation works were performed, especially on the infrastructures that had suffered severe degradation. However, in 2015 the administrator commissioned the most recent regular maintenance works on the structure. Taking these issues into account, a technical expertise was carried out by an authorized expert in 2018 and the documentation required to start the most extensive structure repairs is currently being prepared.

4. Construction Materials Properties

In the documents owned by the bridge administrator, the National Company for Road Infrastructure Administration (C.N.A.I.R) in Romania, the Regional Directorate of Roads and Bridges (D.R.D.P.) in Iaşi, it is specified that the metal structure was received by the Romanian State in 1956–1957 as war compensation from Russia for the damage caused by its army in World War II. It is also mentioned that these metal beams are refurbished as they were initially used for a provisional bridge in the former Soviet Union.

As no extensive works have been carried out so far, the value of the mechanical characteristics, the type of materials used and the position of the reinforcements are not known exactly. It should be noted that, because the site is difficult to access, no non-destructive tests could be carried out on the structure. That is why the documents currently attached to the Building Book, along with the standards and norms in force at the time of the bridge construction were consulted.

The research team made a brief estimate based on all available data on the building materials used. The main structural elements of the bridge, the metal beams, were found to be made of OL52 steel, the equivalent of Euronorme steel S355. The name recently given to the material shows that the value of the yield limit is 355 N/mm^2. At the time when the bridge was built, the balks, struts and vertical bracings were made of OL37 steel, the equivalent of S235 steel in the new normative, with a yield limit of 235 N/mm^2.

Another main element of the framing system of the Şcheia Bridge is the reinforced concrete slab. The degradations that the bridges show prove that no massive intervention works have been done since the construction phase. As mentioned above, the component parts of the bridge could not be investigated; therefore, they were estimated exactly like in the case of the metal beams. The plate was considered to be made of a C40/50 class concrete, most commonly used in the construction of these types of components of mixed steel-concrete bridges in the 1950s. The steel reinforcement used could be OB37, with diameters between 5 and 12 mm, the layout mode resulting from the resistance calculations.

Although not part of the resistance element, the materials from which the Şcheia Bridge path is made have a significant impact on the structure, passing the loads from the vehicles to the concrete slab and then to the metal beams. When encountering various path degradations, the vehicles engaged in crossing the structure generate a series of vibrations with a strong dynamic impact on the structure: the existing degradations of the entire structure increase and new ones are produced. As a result of periodic maintenance works in 2015, the path of the analysed bridge was replaced, along with the expansion joints. The structure of the new pathway consists of two layers of cast asphalt, the 3 cm thick wear layer and the 4 cm bonding layer. To prevent water from penetrating into the concrete slab and degrading this element to destruction, a special waterproofing for bridges of 1 cm thick was laid and protected by a 3 cm thick asphalt concrete layer. In order to ensure the transversal slopes necessary for the smooth running of the traffic, a layer of concrete type Bc25 of variable thickness, 2 cm to 9 cm, is placed between the concrete net and the waterproofing.

5. Instruments Used to Monitor the Structure

In order to model and determine the Şcheia Bridge mode of operation, the research team analysed the data obtained by numerically modelling the structure in a special program based on the Finite Element Method. This facility determined the type, number and location of data capture sensors. The equipment currently available belongs to the Department of Communications and Foundations, Faculty of Civil Engineering and Building Services in Iaşi.

The main features of the monitoring chain components are presented below. Due to the parameters of the framing system and the available tools, 2 types of accelerometers in 3 characteristic sections were installed. It was decided that the monitoring chain was made up of 2 accelerometers produced by Brüel & Kjær and 1 accelerometer from PCB Piezotronics. These devices are among the best performing in their segment, being used to instrument a wide range of bridge structures around the world.

5.1. Brüel & Kjær Uniaxial Accelerometer

The uniaxial accelerometer Brüel & Kjær used in the structure monitoring is of the 4507 B 001 type, which is an extremely reliable tool for bridge monitoring, especially in the case of mixed steel-concrete structures. According to the datasheet (2012), it has the following general characteristics:

- increased resistance due to the hermetic housing made of titanium and the integrated connector of the same material;
- easy installation irrespective of the structure type and the material from which it is made, the attachment being achieved through clips;
- low sensitivity to electromagnetic field disturbances;
- low weight;
- high mounting and tri-axial design;
- excellent response to low frequency recording;
- hermetic connection.

4507 B 001 accelerometers (Fig. 5) are designed and developed specifically for use in monitoring structures in difficult environments. With a minimalist but compact and robust design, it also has high measurement sensitivity, an extremely important feature when it comes to capturing data on modal parameters of bridges or constructions in general.

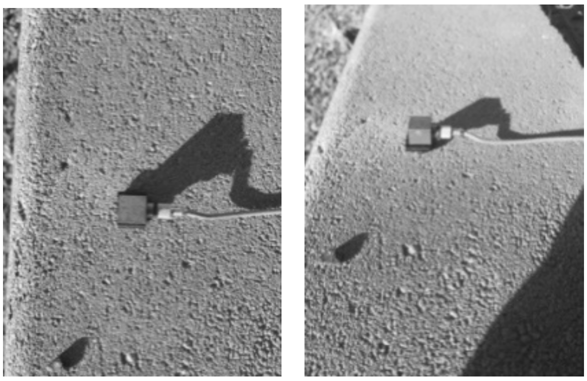


Fig. 5 – 4507 B 001 type uniaxial accelerometer from Brüel & Kjær.

The instruments covered by this subchapter have a mounting surface at the base of the device. It has a threaded hole on the right side, being used to connect the cable responsible for transmitting data to the deck. In order to ease the mounting of the sensors and their attachment to the monitored structures, the designers of the manufacturing company have developed special clips, greatly facilitating the installation process, making it more flexible.

5.2. PCB Piezotronics Uniaxial Accelerometer

The uniaxial accelerometer produced by PCB Piezotronics used in this application is 628F01 type. This type of sensor was chosen because it has general features similar to those found in the Brüel & Kjær accelerometers.

This accelerometer is built entirely of quartz to provide increased strength and stability. In this way, the sensor offers excellent durability in the event of extreme disturbances and disturbing factors, supporting low frequencies and ensuring measurements in the event of high frequencies.

The uniaxial accelerometer shown (Fig. 6) requires a DC power source to operate, the current being provided by the Controller Module. This sensor has a mounting surface disposed at the bottom of the unit, attaching it to the monitored element by means of a wax film. At the top, the data transmission cable is attached, thus linking to the Controller Module.

Fig. 6 – Uniaxial accelerometer of PCB Piezotronics 628F01 type.

5.3. Controller Module from Brüel & Kjær

The modern monitoring system created and installed on the □cheia Bridge has an extremely important hardware component responsible for processing the data and transmitting it to the computer or storage unit. This unit, called Controller Module, was supplied by the German manufacturer Brüel & Kjær.

This controller is the Faculty’s facility, being part of a data acquisition and processing system called PULSE 3560-B-140. Due to its features, the devise automatically synchronizes and transmits measurements from the structure. The device shown (Fig. 7) comprises 6 front-end outputs (5 input channels and 1 output), being one of the most performing units in its segment.

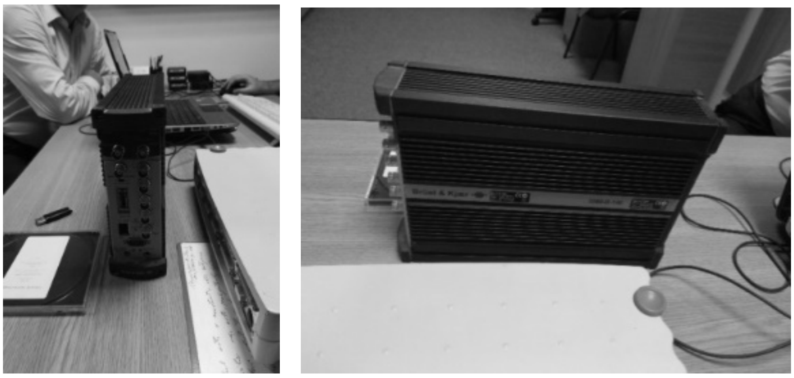


Fig. 7 – Brüel & Kjær Controller Module.

The main features of the Controller Module are:

- robust and compact housing, perfect for daily use, especially under severe conditions
- it is powered by both batteries and direct current and can be used for up to 5 hours
- easy synchronization with other devices of this type
- silent operation up to 35°C

One of the most important features of the Controller Module is the dynamic module. The dynamic module automatically compensates for the recorded data, also benefiting from the possibility of real-time alert, once it is found that the structure's characteristics exceed the thresholds set by the installation of the monitoring system and notify the administrator as soon as possible.

6. Experimental Procedure

As we specified, the Şcheia Bridge was monitored through 3 sensors, 2 of the 4507 B 001 type from Brüel & Kjær and 1 of the 628 F 01 type from Piezotronics, installed on the bridge stemming. This approach was chosen because the stemming zone is much easier to access, not endangering the integrity of devices that could be affected by heavy vehicles engaged in crossing the structure. On the other hand, the sensors have not been installed on the surface of the steel beams, the area being difficult to access due to the high elevation height.

Due to the specificity of the structure, its analysis in terms of the degradation encountered and the areas where these degradations are present, it was decided to mount the sensors on the second span. It has a light of 60,00 m, being representative of the entire structure. In the following, both the exact locations of installation, together with the fastening procedure, and the loads used to determine the modal characteristics of the structure, will be presented.

6.1. Instrumentation Mode

The sensors presented above were installed in three characteristic sections, as follows:

- the first unit from Brüel & Kjær of 4507 B 001 type was mounted in the central section of the monitored opening (Fig. 8 *a*);
- the second unit from Brüel & Kjær was installed at 1/3 of the opening, on the left side of the central section, at a degraded expansion joint, being picked up by the administrator with a metal place (Fig. 8 *b*, *c*);
- the third unit, the PCB Piezotronics type 628 F 01 was mounted at 1/3 of the opening, on the right side of the central section (Fig. 8 *d*).

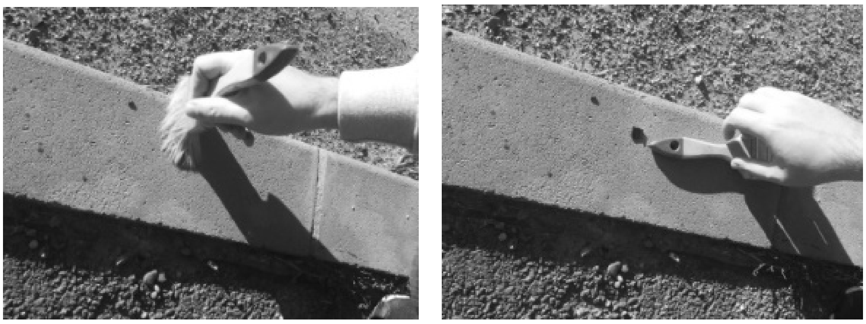

a *b* *c* *d*

Fig. 8 – Sensors locations.

After identifying the exact location of the sensors and the front of the stemming zone on the right side of the structure (being the most required section due to the heavy traffic in transit to Iaşi and the finding of the more pronounced degradation in this section), the installation surface was cleaned of impurities (Fig. 9 *a*). Dust removal was done with a brush by vigorously removing the dust and particles on the surface of the stemming to achieve the best adhesion between the adhesive and the contact surface.

The next step is to apply the adhesive to the surface of the stemming and to attach the special clips in all three sections (Fig. 9 *b*). The third stage is the arrangement of the accelerometers and their connection to the data processing device.

The last step in structuring instrumentation, perhaps most important step, is the start of the Controller Module (Fig. 10) and the data acquisition program, thus giving the start of the records.



a *b*

Fig. 9 – *a* – Cleaning the surface; *b* – Layout of the clips.

Fig. 10 – Starting the Controller Module.

6.2. Loads Used

For the greatest applicability of the determining of degradation method promoted within the research program developed by the Faculty of Civil Engineering and Building Structures from Iaşi, it was decided that the measurements should take place under traffic. In this way, the exact conditions of the administrator were simulated, disturbing traffic as little as possible, being one of the most important roads in the administration of D.R.D.P. Iaşi.

Recordings under traffic highlight the passing of heavy vehicles (Fig. 11) that produce excessive vibration of the structure in operation. These vibrations reveal the degradation state, in the case of the Şcheia Bridge, resulting in the first analysed of the data a rather advanced state of degradation. At the same time, it is pointed out the degradations caused primarily by the lack of cooperation between the steel girders and the concrete slab, the most important defect of the structure, the lack of the maintenance works execution or their faulty execution.

Fig. 11 – Heavy vehicles crossing the bridge.

7. Conclusions

This paper provides a brief description of the steps taken by the research team to design and prepare a modern bridge monitoring system that was used on the structure operation. The case study highlights the benefits that this modern approach can bring to administrators and society in general if it is implemented in as many structures as possible.

The article is part of a complex research program regarding the implementation of modern systems for tracking the behaviour of bridges in time. One such system is SHM, implemented within the structures that ensure the continuity of roads in Romania. The program is developed within the Faculty of Civil Engineering and Building Services at ”Gheorghe Asachi” Technical University in Iaşi.

REFERENCES

Bota A., Imai K., Kashima S., *International Issues on Extimation of Load Carrying Capacity of Bridges Based on Damage and Deficiency*, Al XIV-lea Congres Național de Drumuri şi Poduri, Cluj-Napoca, Romania, 2014.

Farrar C.R., Worden K., *An Introduction to Structural Health Monitoring*, Philosophical Transactions of The Royal Society A., **365**, 303-315 (2007).

Karbhari V. M., *Introduction: Structural Health Monitoring – a Means to Optimal Design in the Future*, In V. M. Karbhari, F. Ansari (Ed), Structural health monitoring of civil infrastructure systems (p. xv - xxiv), Cambridge: CRC Press, Cornwall, UK, 2009.

Klikowicz P., Salamak M., Poprawa G., *Structural Health Monitoring of Urban Structures*, Procedia Engineering, **161**, 958-962 (2016).

Mihalache A.I., Pantea I.A., Leahu C.G., *Monitoring of Bridge Over the Danube-Black Sea Canal at Agigea*, Journal of Young Scientist, **V**, 63-66 (2017).

Orcesi A. D., Frangopol D. M., *Optimization of Bridge Maintenance Strategies Based on Structural Health Monitoring Information*, Structural Safety, **33**, 26-41 (2011).

Romanescu C., *Non-Destructive Testing and Inspection System for Health Monitoring of Road Bridges*, Presentation CESTRIN – Bridge Department, 11.07.2014.

Scutaru M.C., Comisu C.C., Țăranu N., Boacă G., *Răspunsul structural la acțiunea dinamică a unui pod cu structură mixtă oțel-beton*, 15th Congress of Roads and Bridges, Iaşi, Romania, 2018.

Sung Y.C., Lin T.K., Chiu Y.T., Chang K.C., Chen K.L., Chang C.C., *A Bridge Safety Monitoring System for Prestressed Composite Box-Girder Bridges with Corrugated Steel Webs Based on in-situ Loading Experiments and a Long-Term Monitoring Database*, Engineering Structures, **126,** 571-585 (2016).

Worden K., Cross E.J., Dervilis N., Papatheou E., Antoniadou I., *Structural Health Monitoring from Structures to System-of-Systems*, International Federation of Automatic Control Papers OnLine, 48–21, 001–017, 2015.

Yang Y.W., Soh C.K., *Piezoelectric Impedance Transducers for Structural Health Monitoring of Civil Infrastructure Systems*, In Karbhari V.M., Ansari F. (Ed), Structural health monitoring of civil infrastructure systems (p. 43 – 71), Cambridge: CRC Press, Cornwall, UK, 2009.

* * * Product Datasheet for CCLD Accelerometer Type 4507 B 001, Brüel & Kjær, 2012.

* * * *STAS 3221 – 86 Poduri de şosea. Convoaie tip şi clase de încărcare*, Institutul Român de Standardizare, 1986.

COMPORTAMENTUL ÎN EXPLOATARE A UNUI POD CU STRUCTURĂ MIXTĂ OȚEL-BETON

Organizarea programului experimental

(Rezumat)

Utilizarea sistemelor moderne de monitorizare continuă a podurilor a cunoscut o evoluție suprinzătoare în ultimii ani, fiind implementate în cazul tot mai multor structuri aflate în exploatare. Această evoluție a apărut ca răspuns la nevoia administratorilor de a cunoaşte în orice moment starea tehnică a podurilor de pe rețeaua din subordine şi de a distribui cât mai eficient bugetul limitat disponibil întreținerii aceste rețele. Cu ajutorul sistemelor automate de monitorizare de tipul Structural Health Monitoring (SHM), degradările sunt descoperite încă de la primele etape ale dezvoltării lor, costurile remedierii fiind minime. Lucrarea de față prezintă paşii realizați în pregătirea programului experimental ce are ca obiectiv determinarea stării de degradare a unei structuri mixte oțel-beton pe baza analizării datelor provenite de la un sistem de monitorizare instalat pe aceasta. Prezenta lucrare face parte dintr-un amplu program de cercetare desfăşurat în cadrul Facultății de Construcții şi Instalații de la Universitatea Tehnică ”Gheorghe Asachi” din Iaşi.