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STRUCTURAL HEALTH MONITORING OF CONSTRUCTION

Jakub Niedoba

Brno University of Technology, Faculty of Civil Engineering, Veveří 331/95, 602 00 Brno, Czech Republic
correspondence: Jakub.niedoba@vutbr.cz

Abstract. The paper is concerned with the possibilities of long-term monitoring of constructions using modern wireless sensors and systems. There are currently many constructions under long-term monitoring performed by modern sensors. The monitoring enables an assessment of the current health of the construction or it can be used to recalculate and adjust the BMI models and subsequently evaluate the static and dynamic resistance of the construction. The sensors and systems installed enable the detection of hidden defects or newly emerging failures and damage. Using the results obtained from the monitoring of the construction, it is possible to predict and carry out a timely repair or maintenance of the construction, which will ultimately decrease the financial and time-related costs, ensure greater safety and prolong its lifetime and resistance.

Keywords: Structural health monitoring, wireless sensors, bridge monitoring, diagnostics of engineering structures, box girder bridge.

1. Introduction

Many new structures that are important and help to fulfil the fundamental functions of a state are constructed every day all over the world. From the perspective of building construction, the fundamental functions mainly include provision of infrastructure, ensuring safety, or securing the basic necessities of life. The category of important constructions includes, for example, skyscrapers, dams, bridges, military structures etc. If their operation becomes restricted or an accident happens, there may occur not only threat to life and loss of property but also, for example, a significant and long-term infrastructure deterioration, irreversible environmental damage or lowering of the living standard.

Structural health monitoring – SHM enables continual monitoring of the mechanical-physical properties of structures, subsequent evaluation of their health and determination of damage. A simplified diagram of SHM is shown in Figure 1 [1]. SHM of constructions is defined as continual monitoring and analysis of a selected construction [2]. The monitoring is performed using measuring sensors, which are fitted to the structure or in its close proximity. The sensors monitor the mechanical-physical and geometric properties, and climatic changes in the vicinity focusing on changes over time. The goal of SHM is an evaluation of the health of the structure based on the data obtained. Subsequently, the data can be used to identify the location, extent, size, and seriousness of the defect or failure.

In the past, SHM was used as a detection system in astronautics and aviation [1]. It contributed to a significant improvement in safety in these fields and also to a better understanding of the behaviour of materials under both typical and exceptional load conditions. The information obtained could be used

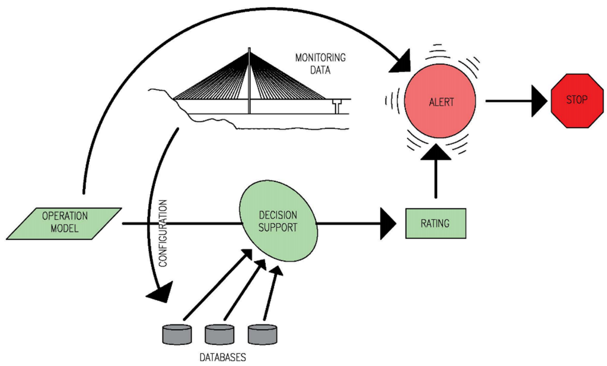

Figure 1. Diagram of SHM [1].

to design better structural details, more functional, more economical and safer models etc. Identification of damage through SHM usually involves the following steps [3]:

- detection of damage to the structure,
- damage localisation,
- damage identification,
- examination of the seriousness of the damage,
- prediction of the lifetime of the structure.

SHM involves many different processes, the most important of which are data sensing and transmission, data multiplexing, data processing and interpretation, description of changes occurring in the structure and materials, changes to the virtual model of the structure based on the current state. Using the information obtained and BIM software, it is possible to devise a plan for maintenance, reassess the static action of the construction and propose a solution to the situation or temporarily restrict the operation of the construction [4].

Damage to the structure is detected through the physical phenomena occurring on the structure. The sensor reacts to the physical phenomena by generating electrical, optical or other waves, which are further transmitted to a datalogger and sent to a database. In the database, multiplexing takes place and the data are sorted and selected using specialized software. The software goes through all the data, which is multiplexed and compared, and a new database with the needed results is created. The results can be further processed and evaluated by a subsystem or manually. The processing method is usually selected based on the frame rate of the signal and the assumed amount of the data. The subsystems largely use various algorithms or the deep learning method. In most cases, the data are then converted to graphical output which is located at a web interface, where everyone has their own user access. In the case of extensive or important constructions, the data can be further passed on to various organizations which use them for health and property protection, improvement of the traffic infrastructure capacity, enabling faster arrival of the emergency services etc.

2. Wireless systems

Generally, a system of regular visual inspections is used. The purpose of the visual inspections is an assessment of the health and detection of defects and damage to the construction. The visual inspections are very intuitive and provide direct information about the construction. However, a disadvantage is that they only provide information based on the visual surface condition of the structure. New bridge constructions are often built from modern materials. They are often segmented and robust; therefore, although the inspections are conducted by qualified experts with long experience and valid authorization [5], they may be insufficient for an overall assessment of the health. Also, in order for an expert to conduct an inspection, they should be able to get close to the construction being checked. Therefore, regular maintenance of the access roads should be carried out. However, especially with old constructions, it is missing or they are not maintained at all. The assessment of the construction health can be affected by a subjective interpretation of the results by the inspector. For the reasons mentioned above, a wrong determination of the current health can be made due to hidden defects which cannot be revealed by a visual inspection [6]. Early notification of a failure or defect of the construction is necessary for satisfying the standards and the internal regulations of the organizations ensuring the functionality of the construction, following the professional methodologies for ensuring the safety of the construction, or ensuring the protection of human lives and property.

Modern monitoring systems can be used as an alternative for inspection of constructions. The standard monitoring systems include sensors, cables and an evaluation system. The cabling is usually used as a communicator between the datalogger and the sensor, and for the supply of electrical power. A disadvantage of the standard systems is the cabling leading to each sensor. In important and large constructions, hundreds of sensors are commonly used. Establishing a robust cable network is demanding and time-consuming. For example, for the Tsing Ma Bridge in Honkong [7], 350 sensors were used on one bridge construction. Building an extensive cable network is demanding, time-consuming and expensive. The cables also have to be secured against damage caused by the weather such as rain, wind, sun, or even vandalism. Furthermore, access must be provided for the staff who will be installing the whole system.

In order to make the monitoring easier and to lower the costs, wireless sensors started to be used. These sensors do not require cabling. They are powered directly by their batteries and, in most cases, they contain solar panels, which charge the batteries and, thus, prolong the lifetime of the sensor. The data are transferred from the sensor to the database through wireless communication systems. The advantage of their use is significant time-saving in the entire project, from proposal to implementation. The installation of the sensors is much easier, as it is not necessary to access all the parts of the construction, only the parts where the sensors will be located. Moreover, it is not necessary to place on the construction any other additional elements protecting the cabling. The standard lifetime of the sensor batteries is around 2 years, which can be affected by the battery capacity, the number of sensing elements in one sensor and the frame rate of the sensors.

With the costs related to the computing and communication technologies decreasing, the costs of wireless sensors decrease as well. This fact has positively affected many areas in which the sensors are commonly used nowadays. Application of wireless sensors has been proposed, in many cases, in order to lower the costs and the manual effort needed for their installation. In the construction industry, wireless sensors started to be applied in 1998, when Straser and Kiremidjian [8] first proposed a solution using radio sensors placed on the construction in order to lower the total costs of establishing a monitoring system. Many researchers then started to be interested in the possibilities of using wireless technologies. The researchers‘ efforts resulted in the invention of a low-cost wireless technology, which is now used in the construction industry for monitoring the health of a construction.

3. Practical application of the sensors

The wireless sensors used for the measurement are shown in Figure 2. The sensors contain inclinometer, accelerometer, temperature and humidity sensor. The measurement accuracy of the sensors is shown in Table 1. The data transfer from the sensor to the database is realised through LoRaWan and NBIoT communication. This communication is better for the sensors than the GSM or LTE networks, which do not reach as far as the valley at the foot of the dam or the bridge chambers and underground underpasses [9]. The frame rate of the sensors can be set individually; the standard is 2.7–3.0 mHz. For long-term monitoring of a bridge overhead road, the frame rate was set to 2.7 mHz (once in 360 s). The sensors also record data when an unexpected situation occurs. The sensors are powered by the LiSoCL2 batteries and their lifetime primarily depends on the frame rate. The lifetime of sensors on bridge constructions is around 1 year. Then, the battery must be quickly replaced.

Figure 2. Wireless sensor.

Sensor type	Accuracy
Inclinometer	0.001°
Accelerometer	0.001 g
Temperature	0.01°
Humidity	0.01 %

Table 1. Accuracy of the wireless sensor.

4. The construction measured

From research and explorations, an overhead road with long-term static problems was selected as the construction to be measured. The road connects the Czech Republic and Slovakia, it is part of the D2 motorway and spans the Morava river and the II/425 road. The overhead road comprises two bridge units (left and right). Each bridge unit consists of 16 simple span bridge constructions on the Czech side. On the border line, over the Morava river, there is a continuous box girder bridge with 3 spans bridging the Morava river. The continuous box girder bridge is shown in Figure 3. On the Slovak side, the overhead road continues with 4 typical simple span constructions. In total, the overhead road comprises 20 simple span units with a length of 35.5 m and a continuous box girder construction with a length of 40.0, 80.0 and 49.1 m (a total of 169.12 m). The II/425 road passes under the 8th span (counted in the direction of stationing, i.e., away from Brno). The total length of the overhead road is 879 m and the width is 13.45 m. The bridge was built in 1980 and it is straight, with the skew angle of 0°.

Figure 3. View of a box girder bridge against the direction of stationing (view in the direction of Brno).

The supporting structure of simple span units comprises 9 prefabricated prestressed DPS girders with the axis distance of 1 500 mm which are joined in the transverse direction with a reinforced concrete slab with a thickness of 200 mm. The bridge construction spanning the Morava river is a single-box bridge with a closed rectangular profile. The width of the chamber is 6 550 mm and its height is variable from 1 300 to 3 500 mm. The thickness of the vertical walls is 200–700 mm; the thickness of the lower plate is 150–650 mm and that of the top plate is 220 mm. The upper, passable part of the bridge is widened on both sides using 3 300 mm cantilever. The box girder was originally prestressed with 24 tendons Pz of 7 mm. In 1991, it was reconstructed and 4 pieces of external tendons were added. All the spans of the supporting structure are placed on pot bearings.

The profile grade of the motorway in the overhead road section is directed in the crest vertical curve of R = 22 000 m. The cross slope of the right motorway bridge is one-sided, descending to the right outer side with a gradient of 2.0 %.

In the experiment, wireless sensors were fitted to the border overhead road. The sensors were placed on the right border box girder bridge. In total, the construction was fitted with 2×3D accelerometer, 2×3D tilt sensor, 2× temperature sensor and 2× humidity sensor. The sensors were fitted to the walls in the central span of the box girder bridge closer to the Czech Republic. The location of the sensors is shown in Figure 4. As the structure has long-term static problems and failures occur both in the supporting structure and in the substructure, it was decided that an extensive diagnostic of the bridge overhead road would be performed. The diagnostic is focused on the material properties of the structure, detection of failures, checking the condition of the concrete repair with additional concrete cover, and checking the prestressed and load-bearing reinforcement. It is planned to monitor the structure for 5 years and regularly compare the condition of the supporting structure with the previous data and with a model of the structure which will be made based on the data obtained from the extensive diagnostic.

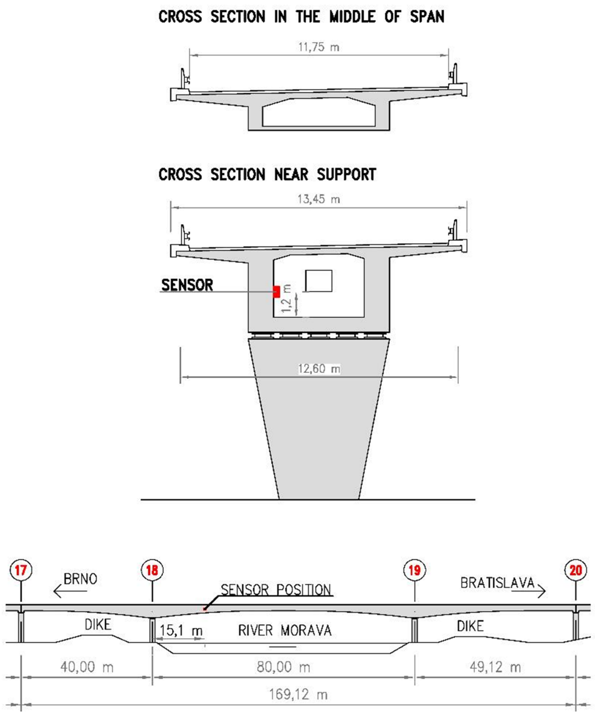

Figure 4. Longitudinal and cross section of the bridge.

5. Results of the structural monitoring

The structure has been monitored since 26th April, 2022. At the same time, an extensive diagnostic has been performed of the overhead road using both destructive and non-destructive tests. As part of the diagnostic, core bores were taken (by [10]). An evaluation was made of the hardness and strength of the concrete using the Schmidt hardness tester (by [10]). Carbonation was evaluated (by [11]), the cohesion of the concrete was determined (by [12]), and the condition of the prestressing reinforcement and the position of the reinforcement were checked (by [13]).

In the first six month of the monitoring, the functioning of the mechanical connections between the sensors and the structure was checked as well as the functioning of the sensors on the structure. Figure 5 shows the temperature and humidity in the chamber. The data show that, even during the summer months, the chamber is excessively humid and a considerable leakage into the structure occurs. Figure 6 shows that on 1st June, 26th June and 16th July excessive leakage occurred. This corresponds with the records from the meteorological station located in the adjacent town, see [14]. The meteorological data show that, on 1st June, 25th June and 15th July, there were heavy rains. The most significant change in humidity, recorded on 26th June (from 90.8 to 98.1 %), occurred after all-day rain with the rainfall being 32.7 mm/day. The leakage into the bridge chamber was also confirmed by the preliminary diagnostic results and the main inspection of the structure (see the photo of the bridge chamber in Figure 7). The long-term humidity in the bridge chamber in the summer months (June and July), when the average temperature of the surrounding environment is 25.6 °C, is 96.2 %.

The tilt of the structure along all the axes is very stable. Since the sensing takes place once every 6 minutes, the dynamic traffic load cannot be sensed. Vertical lines showing incorrect measurement can be detected in the recorded data. These errors were probably caused by signal drop-outs of the sending device. The data can be used to determine a change in the longitudinal tilt of the box girder bridge caused by the temperature. At a temperature of 15 °C the tilt of the chamber was -0.179°. At the highest temperature recorded, 30 °C, the tilt of the chamber was -0.216°. The difference between the angles can be used to determine a change in the deflexion in the middle of the longest bridge span. The deflexion changed by approximately 25.8 mm.

The acceleration of the structure is also stable. A change in the acceleration occurred during local renewal of the abrasive layer carried out at night-time between 1st July and 2nd July. This renewal caused a change in the acceleration along all the axes. The change in the acceleration was recorded by both sensors at the same time. This change was apparent for the entire time of the repair, i.e., over 8 hours. When the road was being repaired, no significant change in the tilt of the structure occurred, probably due to the fact that the extent of the repair was small.

6. Conclusion

SHM of a bridge overhead road on the border crossing confirmed leakage into the structure due to nonfunctional waterproofing. The monitoring also provided preliminary results related to the health of the structure and also the average acceleration and deflexion of the structure. The initial monitoring checked the functioning of the sensors and the initial data obtained were used to determine the limit values of acceleration and tilt, at which irreversible damage to the structure might occur. The limit values will be further compared with a model and then entered in online evaluation software. When the limits are exceeded, the evaluation software will immediately inform the construction manager. This warning system will be used for ensuring the safety of the bridge overhead road, an early warning, and an urgent inspection of the structure. Based on the inspection, a decision will be made whether critical damage really occurred and an immediate repair is necessary, or whether the

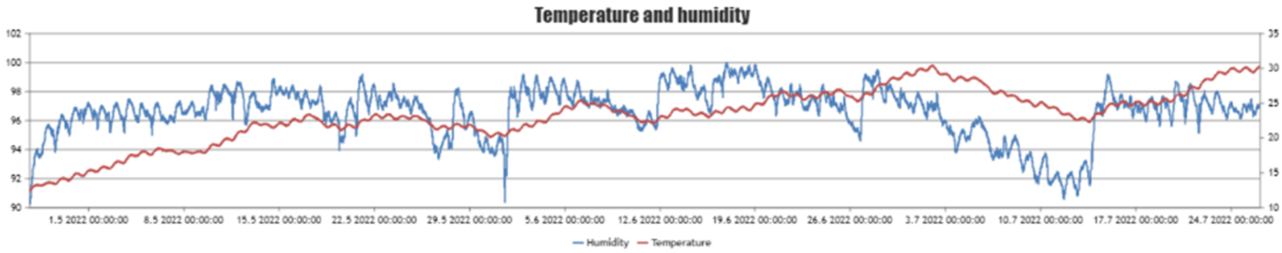

Figure 5. Temperature and humidity.

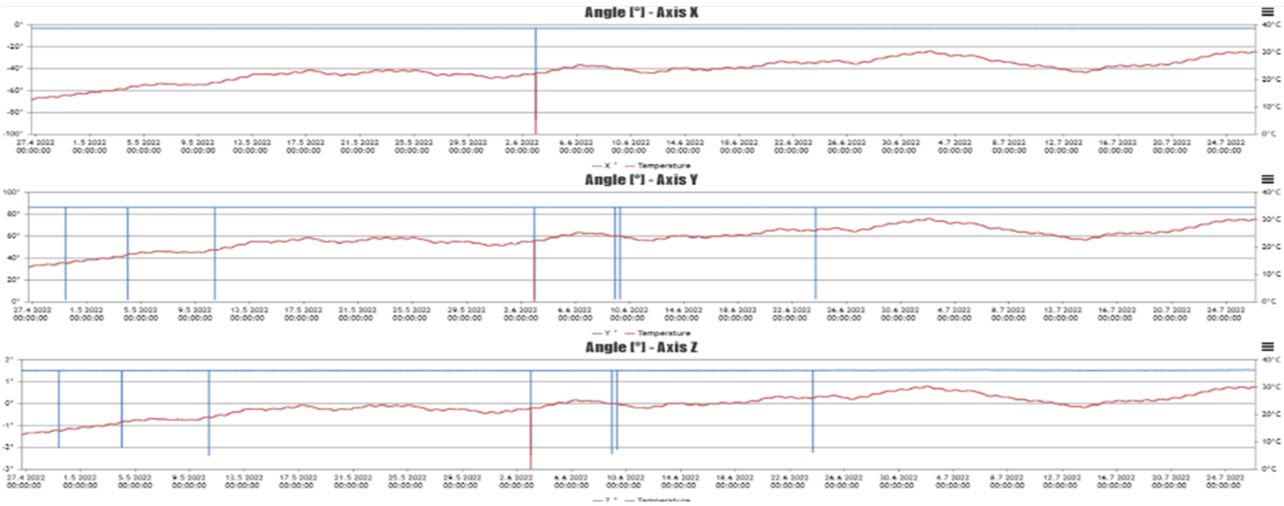

Figure 6. Raw data from tilt sensor.

(a). (b).

Figure 7. On the left – a view of a sensor placed on the wall of a box girder; on the right – a view of the top plate of a box girder, where leakage and urban dripstone occur.

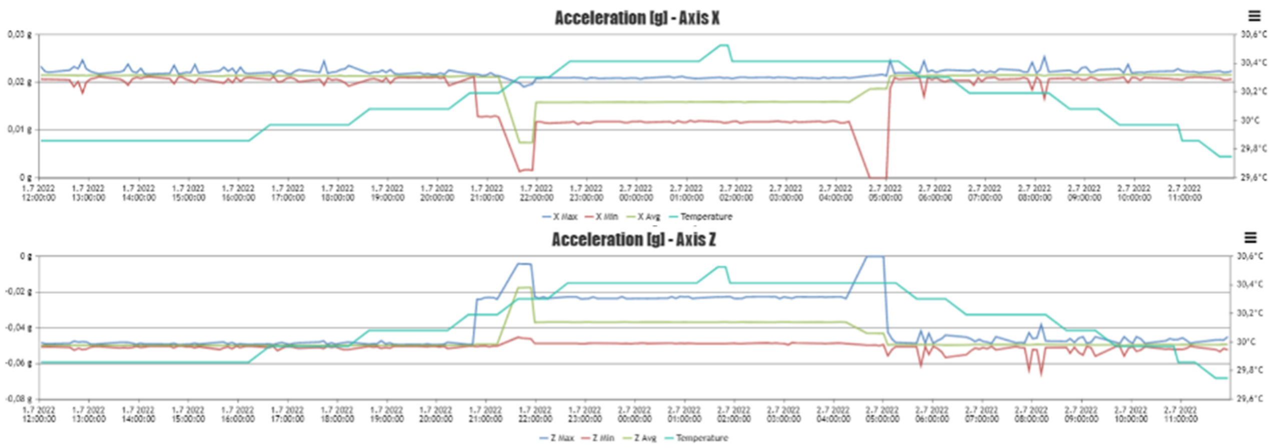

Figure 8. Record of the acceleration during the repair of the road.

defect is less serious and its repair can be postponed until the next renovation planned.

The preliminary results from SHM clearly show that the sensors sense real changes in the health of the construction. Based on the results, it was suggested to the construction manager that an immediate replacement was necessary of the full-surface waterproofing of the top plate and of the passable asphalt layers of the construction. Based on the recommendation, the manager decided to plan extensive road reconstruction and full-surface waterproofing. During the reconstruction, it will be possible to use SHM to monitor changes in the acceleration of the structure, as there will be a considerable change in the actual weight of the structure. It is a full surface reconstruction of the road, where a change in the tilt of the structure is expected. The data from the planned reconstruction will be further compared with the data from the reconstruction that took place on 1st and 2nd July shown in Figure 8 and with a model which is being prepared. The project includes a plan for excessive crossing over the box girder bridge. During the crossing, the frame rate of all the sensors will be temporarily changed to 5 Hz in order to record in detail the changes in the structure caused by the crossing. It is also planned to fit additional sensors (potentiometers) to the construction for the time of the crossing. Based on the data obtained from the sensors, the relationship between the tilt and the deflexion of the structure will be specified.

The data from SHM can be used to immediately check the structural health and thus ensure safety and sustainability. The advantage is that the data are collected and interpreted continually. Therefore, if some damage to the construction occurs, SHM will evaluate the condition of the structure and contact the experts responsible for the safety of the structure. Based on SHM and the decision made by the expert, the risk resulting from the current condition of the construction is assessed and, thus, the safety and usability of the structure is ensured.

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