Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 161 (2016) 958 – 962

Procedia Engineering

www.elsevier.com/locate/procedia

World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium 2016, WMCAUS 2016

Structural Health Monitoring of Urban Structures

Piotr Klikowicz[a],*, Marek Salamak[a], Grzegorz Poprawa[a]

[a]*Silesian University of Technology, Gliwice, Poland*

Abstract

The paper presents review of structures with Structural Health Monitoring System (SHM). The most interesting examples of structures are discussed with regard to sensors, the most common reasons of installation SHM and benefits. The example of monitoring system of urban bridge in Gliwice city is described.

Peer-review under responsibility of the organizing committee of WMCAUS 2016

Keywords: structural health monitoring system; SHM; bridges; maintenance;

1. Introduction

Structural Health Monitoring (SHM) is a measuring system created for continuous monitoring of structure's technical condition. SHM allows, by monitoring and analysing the measured physical quantities, to check the assumptions made at the design stage. It can also be used for structure management and optimisation of maintenance works which results in the extension of life cycle and more efficient use of funds for renovations. Setting appropriate alarm thresholds in SHM application leads to minimise the possibility of damage and thus increase the structure and its user’s safety. With the development of electronics in the 70s of the twentieth century, SHM was mainly developed in the offshore field, where it was used on offshore platforms (Farrar and Worden, 2013). In the 80s, first bridges and buildings were already monitored. Currently, we are seeing a popularization of SHM thanks to the continuous electronics miniaturization and optimization of digital image processing algorithms. They are particularly important in the case of key urban infrastructure such as bridges, tunnels, public buildings, high-rise buildings, stadiums, etc.

---

* Corresponding author. Tel.: + 48 506 175 545.
E-mail address: piotr.klikowicz@polsl.pl

Peer-review under responsibility of the organizing committee of WMCAUS 2016
doi:10.1016/j.proeng.2016.08.833

Monitoring systems can be divided into warning, scientific and mixed systems, which combine two first systems. The monitoring of the largest and most important urban buildings are usually mixed installations, which are the basis for data acquisition about structures and materials.

2. Warning systems

The systems warning about poor technical condition became popular in Poland after the tragic crash of the exhibition hall in Katowice in 2006 (Fig. 3) when 65 people were killed and 170 were injured [1].

Fig. 1. Exhibition hall in Katowice after catastrophe, [10].

It was the most tragic occurrence of this kind in Polish history. The commission investigating the causes of the disaster found that the hall had collapsed due to the snow overload on the roof. Fatal design mistakes and improper maintenance of the facility were also among the causes. Shortly after monitoring of public utilities was required in Polish law. Public utilities in this case are: sports and entertainment arenas, shopping centres, stadiums, etc.

There are several companies carrying out monitoring of flat roofs, offering systems with various degrees of sophistication. From measuring single physical quantities to complex installations connected with algorithm used to assess the behaviour of the whole structure. Notwithstanding the need to ensure safety administrators often choose to install more advanced monitoring systems encouraged by the possibility to minimise expenses for snow removal from the roof. The applications included with this type of monitoring usually contains some pre-determined levels of information about structure's effort, e.g. normal operation, snow removal, failure warning.

Deflection or deformation of selected elements are usually measured. In installations for commercial purpose the appropriate number of sensors and their location on the roof are important. A good solution improving the reliability of the installation is to double sensors in the particular measuring points. Installation should be preceded by a thorough analysis of the structure, and after the installation, calibration and verification are necessary by applying appropriate mass and conducting a trial measurement (test load).

3. Monitoring as the source of information about structure

Bridges were one of the first structures equipped with the continuous monitoring systems. On the largest bridges which are usually treated as a prototype or are of particular importance systems with warning and scientific functions are most frequently installed. The example is the Akashi Kaikyo Bridge completed in 1998. It is a bridge with the largest main span in the world. Besides a length record, the object has an unusual design with dampers placed in the pylons. It was built in extremely difficult terrain exposed to the influence of seismic and typhoons actions. One of the earthquakes from 1995 when the bridge was still under construction caused the displacement of terrain and elongation of the bridge by 1 meter in relation to the original length. More than 50 sensors were installed on the bridge and these included: accelerometers, anemometers, displacement sensors and thermistors. By using the monitoring, the functioning of the structure was checked in extremely adverse conditions such as typhoon (T. Miyataa, et a, 2002).

On a few bridges in Poland a monitoring system which combined the warning function with the possibility to deepen knowledge was installed. One of the bridges is Redzinski bridge in Wroclaw and bridges over the Vistula River in Kwidzyn and Pulawy. There are 222 sensors installed on Redzinski bridge, which is a record in Poland. Installation allows to measure: deck vibrations, pylon and suspension cables, forces in the cables and deformations in selected points of the structure [7]. The bridge in Kwidzyn is in turn one of the largest extradosed bridges in Europe. Deformation of box superstructure, span deflections and horizontal movement of pylon are measured [8].

The bridge in Pulawy is a through arch structure. It was opened in 2008. Its span in the axes of supports is 212 m long. The bridge monitoring consists of three subsystems: weather, visual and structural. A sophisticated observation system of weather conditions is installed on the object where except common sensors measuring temperature, wind speed and direction, were also sensors recognizing the type of precipitation and surface condition. These sensors are connected to variable message signs transmitting information to drivers. The structure is observed by 68 deformation sensors, 30 accelerometers and 10 inclinometers. In total 186 parameters are measured in the arch and deck [11]. With the use of measurement data thermal interaction analysis was performed on the structure. The gathered data reveals that extreme temperature values measured in a steel arch structure ranged from -25 ºC do +55 ºC. Moreover, large differences between the measured values of temperature between the arch and the hangers were noticed.

4. Monitoring of the bridge in Gliwice as a source of information about the measurement methods

An interesting example of structure monitoring is the installation on the bridge in Gliwice. The tested object is an overpass over the Klodnica River with the flood area. The total length of the object is more than half a kilometer. It consists of 12 spans: two external 36 m and 10 internal 48 m. Under each roadway separate structures were designed with a two girder in cross section and structural height of 2.4 m (Fig 2).

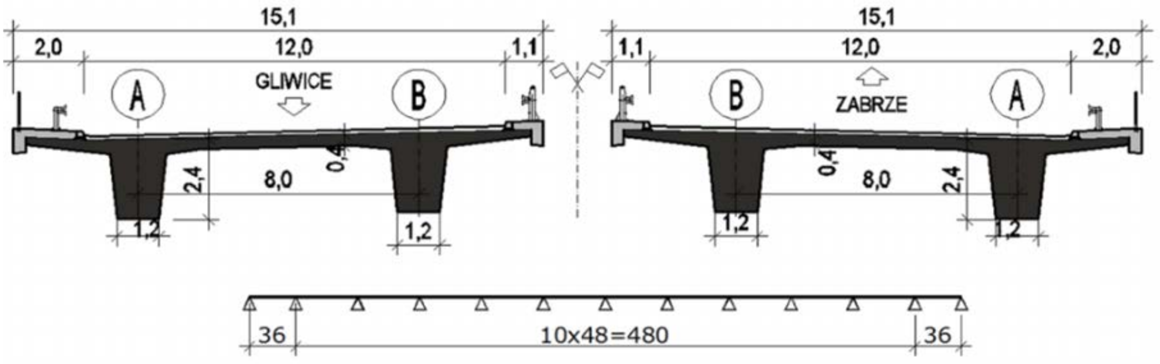

Fig. 2. Cross-section and static scheme of the bridge in Gliwice.

In contrast to previously described bridges this monitoring system is rather the scientific installation used to verify different methods of measurement and sensors in field conditions. The warning function might be adding by appropriate software when it would be needed. It is used to: determine internal forces acting parallel to the axis of the girder, measure changes in the elastic modulus over time, temperature distribution in the cross section of girder, control support reactions in terms of weak foundations and verify innovative measuring system of acoustic type. Coda Wave Interferometry (CWI) is the measurement method which involves the analysis of acoustic signal differences in the segment analysing physical changes in the tested medium (Klikowicz and Salamak, 2015). CWI Sensors were installed over the length of 4 meters in the middle of the last span. Each of the eight sensors can be both a transmitter and a signal receiver (Fig 3). Such arrangement allows the localization and identification of velocity changes of acoustic wave propagation within the field limited by sensors. In the future the results of ultrasound tests will be compared with results obtained with the use of other techniques (extensometers and string strain sensors).

The remaining part of the measurement system in span contains several string Geokon strain sensors and thermistors (Fig. 4). These sensors are connected in three logical subsystems. The first of them (shown in Fig. 3 as Sk) consists of three string extensometers placed in the separating casing made of polystyrene reinforced with polyvinyl chloride. The casing with sensors was filled with concrete and placed in the axis of the girder in the compression zone when concreting the superstructure (Fig. 4b).

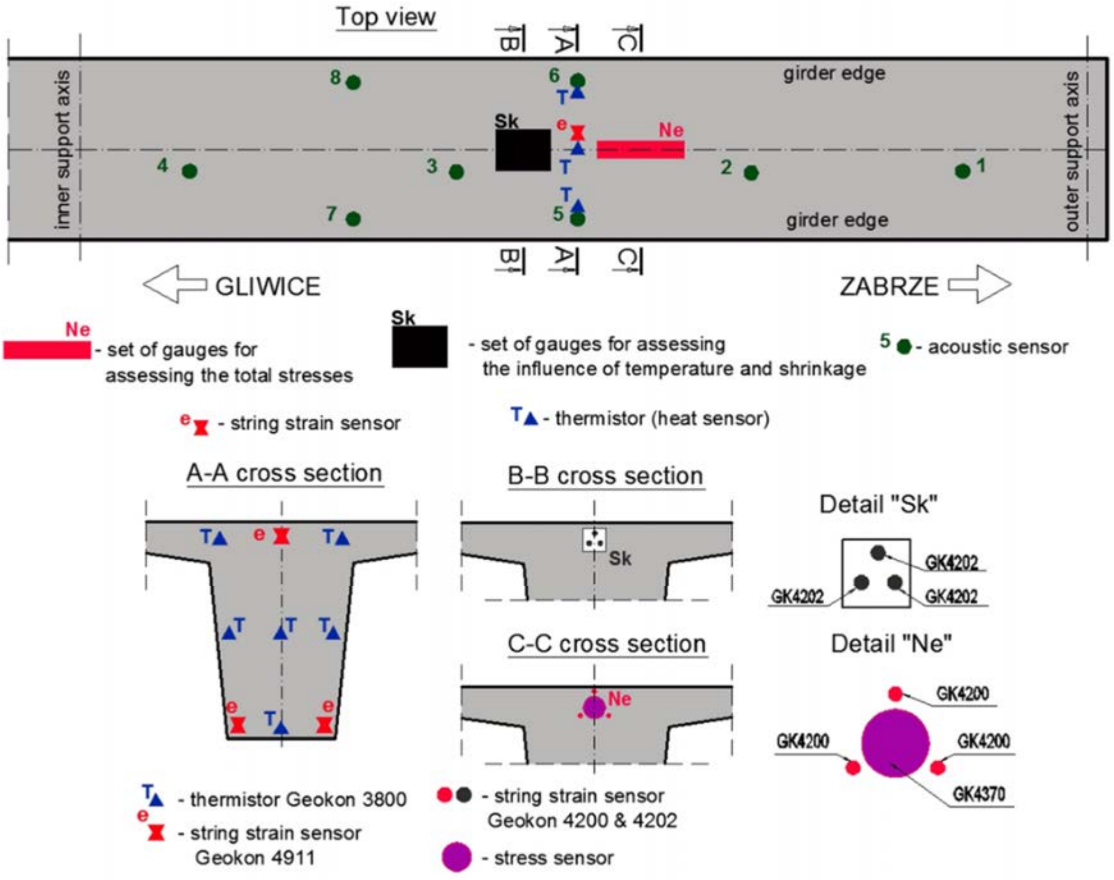

Fig. 3. Diagram of measuring system installed on the bridge in Gliwice.

Due to the isolation from external influences, shrinkage and thermal strains can be read from the sensors. Another part of the measurement installation (shown in Fig 3 as Ne) is designated to determine constitutive compounds and changes in elastic modulus during the exploitation of the structure. It consists of three string strain sensors integrated with stress sensor (Fig. 4a). The modulus of elasticity is not the same at each point of the structure, it also changes over time. Knowing the appropriate value of the elastic modulus is required to calculate stresses in the structure which are determined from Hooke's law by multiplying the measured strain by elastic modulus of elasticity.

Fig. 4. Diagram of a measuring system installed on the bridge in Gliwice.

The installation is supplemented by three strain sensors connected with reinforcement of the main girder and temperature sensors located in such a way to determine its distribution in the cross-section of the girder (Fig. 3). In addition, using other components of the system, modulus of elasticity, shrinkage and thermal deformations can be determined. The temperature is measured over the entire height of the girder in ten points. All this gives a lot of information about the state of stresses in this cross-section and can be a point of reference for new measurement method in SHM - Coda Wave Interferometry.

Independent system are the sensors installed in bearing pads. Three string strain sensors are installed in each of them. The sensors are situated vertically at equal distances from the axis of load in plan. The installation is the last stage of research on identifying alternative ways to determine support reactions (Klikowicz and Salamak, 2014).

5. Conclusion

Technical monitoring systems of the structure realise a continuous measurement of discrete physical quantities (displacements, deformations, temperature, wind speed), allowing determination of variables of the structure condition - e.g. deformations, stresses, deflections, radii of curvature, temperature field distribution, creep process recording, etc. The interdisciplinary character of SHM systems requires a specialised dedicated approach in their design, manufacturing and operation; typical installations of SHM systems are carried out on new buildings, less on those that already have a long history of operation. Construction of SHM system depends on the anticipated type of found damages, used materials and phenomena used in the detection method. Presented in the paper system monitoring the changes of selected physical quantities of urban bridge is a testing ground which will be used to select optimal measurement methods and validation of signal processing algorithms, and in particular, in quantification monitoring information value.

References

[1] Barcik W., Sieńko R., Biliszczuk J., 2011. System monitorowania konstrukcji mostu rędzińskiego we Wrocławiu. Wrocławskie Dni Mostowe - Aktualne realizacje mostowe. The monitoring system of the bridge Redzinski in Wroclaw. Wroclaw Days Bridge - Current projects bridge 24-25 November 2011 Wrocław, (in Polish).
[2] Bednarski Ł., Sieńko R. 2013. Z monitoringiem bezpieczniej. More safety with monitoring. Inżynier Budownictwa, 10/2013, p. 104-108, (in Polish).
[3] Biliszczuk J., Barcik W., Sieńko R. 2009. System monitorowania mostu w Puławach. Mosty 4/2009, p. 12-17
[4] Klikowicz P. Salamak M. 2014. Indirect determination of support reactions in concrete bridge elements., 10th CCC Congress, Liberec 2014, p. 101-105.
[5] Klikowicz P. Salamak M. Lazinski P. 2015. New methods for monitoring and diagnosis of concrete bridges - coda wave technology. 11th CCC Congress, Heinburg 2015.
[6] Miyataa T., Yamadaa H., Katsuchia H., Kitagawab M., 2002. Full-scale measurement of Akashi–Kaikyo Bridge during typhoon. Journal of Wind Engineering and Industrial Aerodynamics 90 (2002) p.1517–1527.
[7] Onysyk H. 2012. Analiza zmian temperatury stalowej konstrukcji mostu przez rzekę Wisłę w Puławach, Analysis of changes in the temperature of the steel structure of the bridge over the Vistula River in Pulawy, Drogi i mosty 1/2012 p.36-55, (in Polish).
[8] Żółtowski K. 2015. Monitoring konstrukcji mostu podwieszonego i extradosed, Monitoring the construction of suspension bridge and extradosed. Wybrane zagadnienia. Mosty 6/2015 p.34-38, (in Polish).
[9] www.geokon.com, (access 02/2016).
[10] www.dziennikzachodni.pl, (access 02/2016).