WIRELESS SENSOR NETWORK SYSTEMS FOR STRUCTURAL HEALTH MONITORING OF BUILDING STRUCTURES

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Keywords: structural health monitoring, wireless system, lightweight roof structures, hybrid monitoring system.

Abstract. Wireless structural monitoring systems have been of interest in structural engineering for the last several decades with regard to ensure structures safety and serviceability. In the last decade, structural sensing network technologies became superior monitoring solutions because of low installation cost, fast communication time and efficient online assessment capability that can be further enhanced by a dedicated numerical simulation support. This paper presents WiSeNe^{MONIT}, the wireless system of continuous structural monitoring designed primarily for buildings of typical structural load bearing systems made of steel roofs as well as steel or reinforced concrete roof supporting structures.

1. Introduction

Building failures occur because of many factors that can be grouped into design, execution and exploitation reasons. Errors in design and execution are usually related to the adoption of wrong static schemes, incorrect solutions for joints or connections, or inherited structural defects and faulty fabrication procedures. In the latter cause, failures are sudden and Structural Health Monitoring systems (SHM systems) are not able to give sufficient time for an early warning of forthcoming disastrous events. The study of important factors affecting the structural performance and/or being a potential source of structural failures/collapses has been conducted and aspects related to structural health monitoring activities in Poland have been presented in [1].

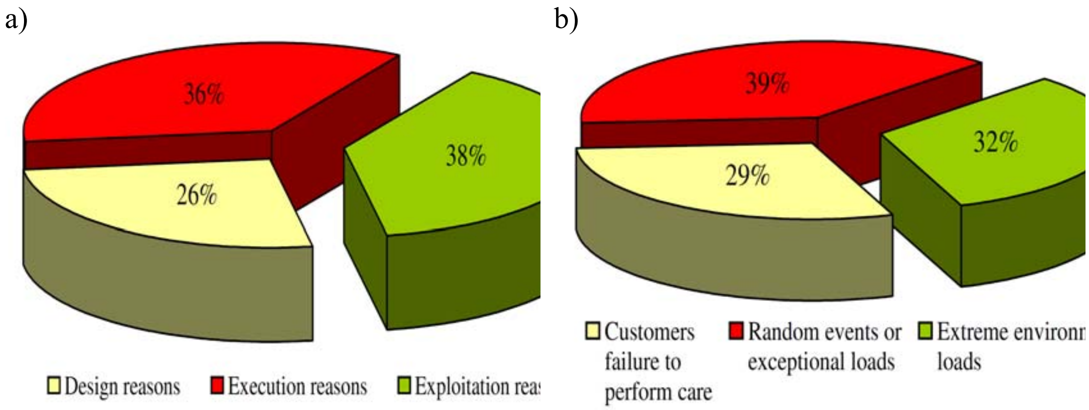

Fig. 1. Factors responsible for building failures: a - general classification, b – classification of exploitation reasons [1]

Fig. 1a shows the statistics of building catastrophic events in Poland. Survey of building collapses in Poland proves that failure cases are in the most related to exploitation reasons during service. In such cases, the application of monitoring systems is a very efficient tool ensuring their intended safe exploitation conditions. Fig. 1b gives the statistics of failures related to exploitation reasons. The statistics gives clear indication that the SHM system could be an effective tool for checking online the magnitude and character of actions on buildings and related structural responses. Therefore the technology might be regarded the most appropriate tool for improving the structure robustness and avoiding catastrophic events.

2. Climatic actions and structural failures

Climatic actions such as related to temperature change, rain, wind and snow are all factors affecting the behaviour of civil engineering structures. The latter of the above mentioned factors is normally recognized in the design process by providing in the calculations the statistical data for peak values of the snow accumulation on ground over the winter season, and transforming it to the roof level. In colder regions, the design snow load represents snow deposited by multiple snow events. The above procedure may also be applied in more moderate climates. In between snow events, roofs may have a reduced snow depth due to either wind scour or by melting as a result of temperature oscillating around zero Celsius degrees. Such events, although reducing snow layer, may result in a heavier snow load due to the snow density increase. Therefore, the weight of accumulated snow/ice, not the depth, becomes critical in assessing the roof's vulnerability to failure.
In the last decade there was a number of collapses of buildings related to unusual climatic conditions. Such cases include in Poland a series of tragic collapses of large-span flat roofs due to snow load or in case of flexible roof covering - ponding from a heavy rainfall. This included the collapses of roofs of Katowice International Fair in 2006 (Fig. 2a - 65 losses of human life and more than 170 injured) and the storehouse of electronic supplementary parts near Warsaw in 2009 (Fig. 2b - large economic consequences).

a) b)

Fig. 2. Collapses due to extreme climatic loads: a - extreme snow loading, b - extreme rain water ponding of membrane covering [1]

3. Building regulations

Nowadays, because of climate change and application of more economic and lightweight structures, a necessity for SHM systems to be implemented for the safety assessment of a certain class of civil engineering structures is fully accepted and even not being debated or questioned. An increase of extreme weather events in Poland that is a principal climatic factor responsible for some spectacular building failures involving human life and substantial economic losses, has been the main reason for amendments introduced to building law regulations in respect to the technical conditions of buildings. The new regulations require that public buildings designated for presence of a number of people, such as concert halls, sport halls, exhibition and trade fair halls, train and bus station halls, or similar, should be equipped, depending upon particular requirements, with permanent monitoring system enabling the structural safety control through such parameters as displacements, strains and stresses of structural elements. This official statement and new wireless technologies related to data acquisition and data transmission give way in Poland for the development of wireless monitoring systems to be developed.

4. Exemplary wireless SHM systems

Wireless structural monitoring systems have been of interest in structural engineering for the last several decades with regard to ensure structures safety and serviceability. In the last decade, structural sensing network technologies became superior monitoring solutions because of low installation cost, fast communication time and efficient online assessment capability that can be further enhanced by a dedicated numerical simulation support.

Wireless monitoring systems has already been proposed for practical applications. The system of Wireless Intelligent Sensor and Actuator Network (WISAN) proposed in [2] is able to perform in an inexpensive way data acquisition for the tasks of structural health monitoring. Based on this solution, a fully autonomous SHM system for bridges proposed in [3] is ambient-energy-powered and minimally dependent upon the human involvement.

Wireless sensors and wireless sensor networks are so promising to the structural engineering profession that it has begun to consider them as a very attractive substitute for traditional monitoring systems. In Poland, the concept of wireless monitoring system for building serviceability purposes (snow removal necessity) has recently been developed and implemented in practice under the trade mark of WiSeNe [4] (an abbreviation referred to the Wireless Sensor Network). The typical scheme of the system is shown in Fig. 3. The safety assessment and alerts or other service state condition messages are based on recording the structural deflections of representative number of nodal points. Measurements are predicted and archived online in a fully automatic manner. Measuring devices are mounted directly to main structural elements in a way that does not affect their performance and their anticorrosive film layers, and without any transmitting or supplying wires. The only system component requiring the mains supply is the central unit managing the operations of system modules integrated in one online system.

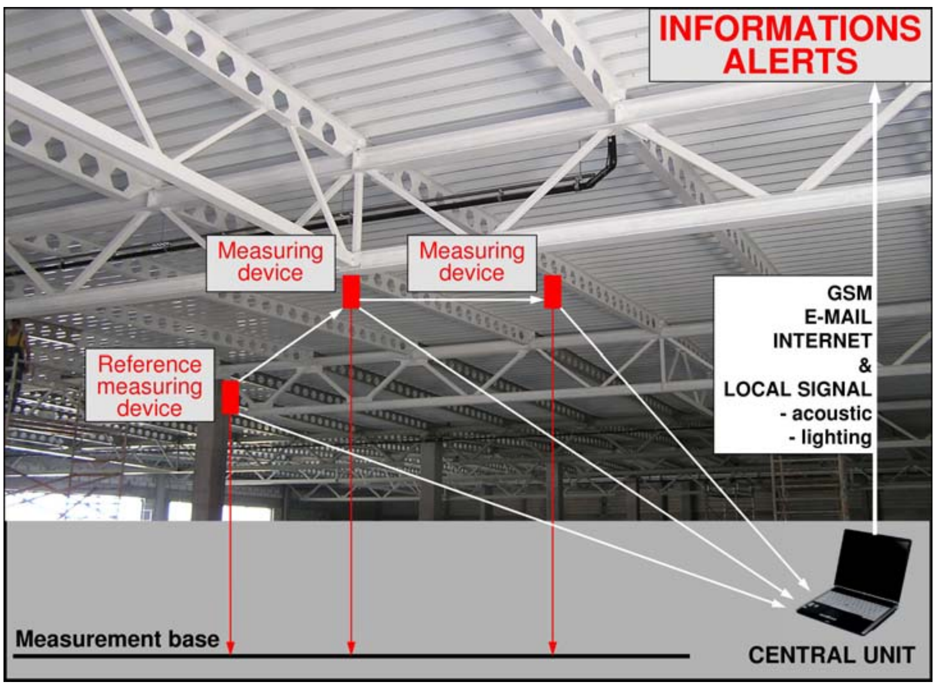

Fig. 3. Scheme of the WiSeNe monitoring system

The main components of the WiSeNe monitoring system are shown in Fig. 4. They are the long-life battery supplied measuring unit (Fig. 4a) and the power supplied central unit (Fig. 4b). Fig. 5 shows the scale effect of the measuring unit with reference to the structural element it is mounted to.

a) b)

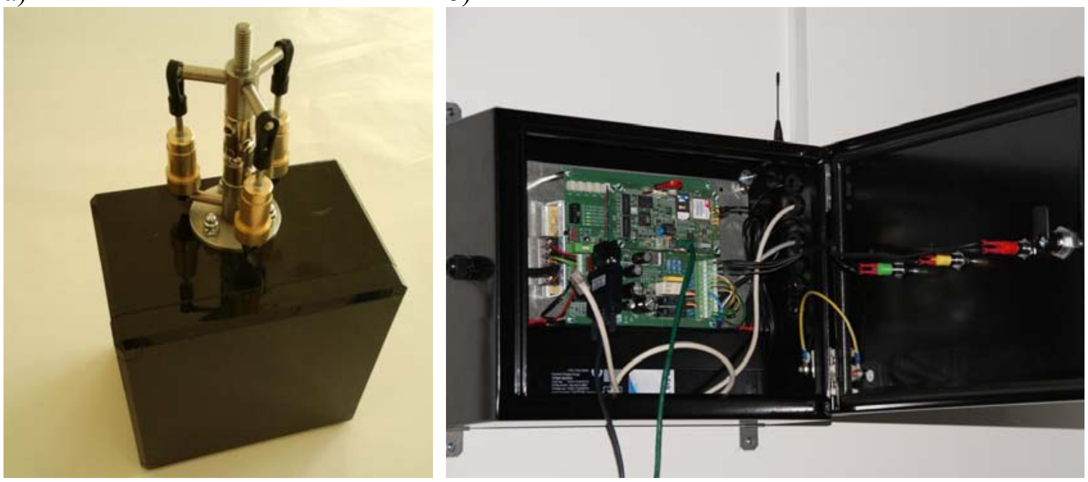

Fig. 4. Two main components of the WiSeNe monitoring system

Fig. 5. Measuring unit mounted to the structural element

The example of measurement results for an industrial building is shown in Fig. 6. It gives an idea about the graphical output obtained for the displacement measurements recorded during the winter period 2010/11 with an addition of the explicit marking of four threshold values for end-user display statements corresponding to the system built-in assessment criteria chosen as an important indication of the serviceability/safety state levels of the monitored structure. These levels for large-span roof single-storey structures are set as follows:

- State level L1: by default as a value corresponding to approximately 30% of the failure load.
- State level L2: by default as a value corresponding to approximately 50% of the failure load.

- State level L3: by default as a value corresponding to approximately 70% of the failure load.
- State level L4: by default as a value corresponding to approximately 95% of the failure load.

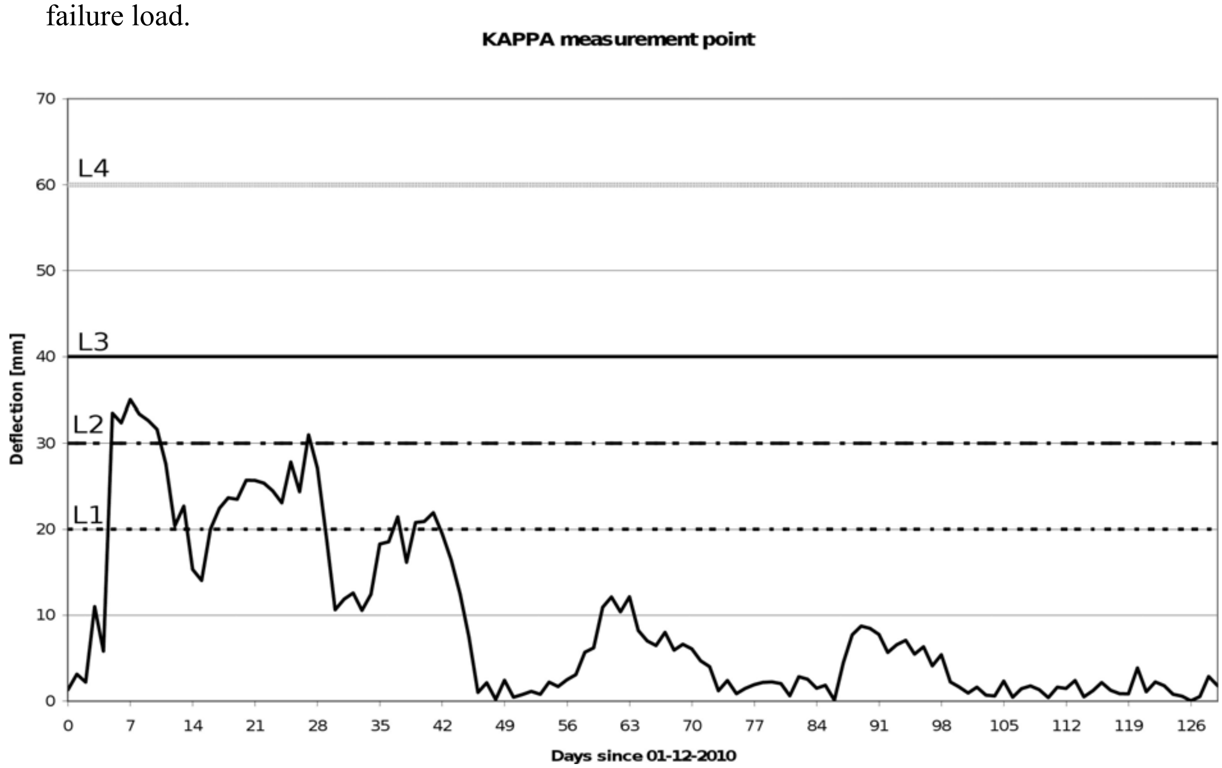

Fig. 6. Example of measured displacements for an industrial building

The four threshold levels L1-L4 correspond to a "summer" service conditions (quasi-permanent combination of actions), a "winter" service conditions (frequent combination of actions), an "expected winter" service conditions (characteristic combination of actions), and finally a "exceptional winter" service conditions (close-to-ultimate combination of actions). They are directly related to the five reaction levels given in Table 1.

Table 1. Reaction levels corresponding to the four threshold levels of structure health state

Threshold displacement value „a"	RUR (Resistance Utilization Ratio) level	Reaction related activity	System state reaction	Sampling frequency	Type of announcement to end-user
a $\leq$ L1	First	-	Normal	T	None
L1 < a $\leq$ L2	Second	-	Higher normal	T/2	Information
L2 < a $\leq$ L3	Third	Inspection	Higher	T/4	Warning alert
L3 < a $\leq$ L4	Fourth	Intervention	Highest	T/8	Intervention alert
a > L4	Fifth	Evacuation	-	T/8	Evacuation alert

It is important to note that the sampling interval time *T* (see the fifth column of Table 1) at which all the displacements controlling the actual state of the structure are recorded is not of a constant value but is implemented in the system as a variable value being dependent upon the reaching of the threshold values of the displacement by representative points of the structure nodes. The base value *T* is being set in accordance with the consultation with the structural engineer/designer and the owner/user of the building subjected to SHS activity.
It is not a surprise that the displacement of a representative point varies during the winter time. It is because of the change of snow layer deposition on the roof and the presence of additional variable load components that may act on the structure. It is important to note that the value of recorded displacement depends also upon the temperature change of structural elements with reference to the execution temperature. Temperature is not a parameter measured in the system WiSeNe and included as the parameter influencing the criteria driving the reaction related activities to be undertaken. The temperature effect on the resistance assessment criteria is less important for structures that are fully isolated from the impact of external climatic conditions, and for structural systems exposed to external climatic conditions but being statically determinate. Hyperstatic structures are more sensitive even for a narrow change of temperature and therefore the temperature should be in general included as a vital parameter to be measured and evaluated in the SHM system.

5. Proposed SHM wireless sensor network system WiSeNe^{MONIT}

The concept of WiSeNe system described in the previous section is being further extended within the MONIT project to account primarily for the safety assessment and to maintain the feature related to the rationalization of maintenance procedures. It is a low-cost wireless sensing system that is designed for large-scale applications in typical building structures [5]. The safety assessment and alerts or other service state condition messages are based on recording not only the displacements but also the temperature changes in representative number of elements. Laboratory and field tests are now underway to validate the performance of the system prototype for measuring static response of lightweight steel large-roof structures. System WiSeNe^{MONIT} is shown schematically in Fig. 7. It consists of two main subsystems, namely on-line that is the original WiSeNe system extended for the temperature effect, and off-line that makes the system to be an engineered product supported by a numerical module. The on-line subsystem is responsible entirely for recording, storing and evaluating the structural deflections of representative number of nodal points and the temperature changes in representative number of elements.

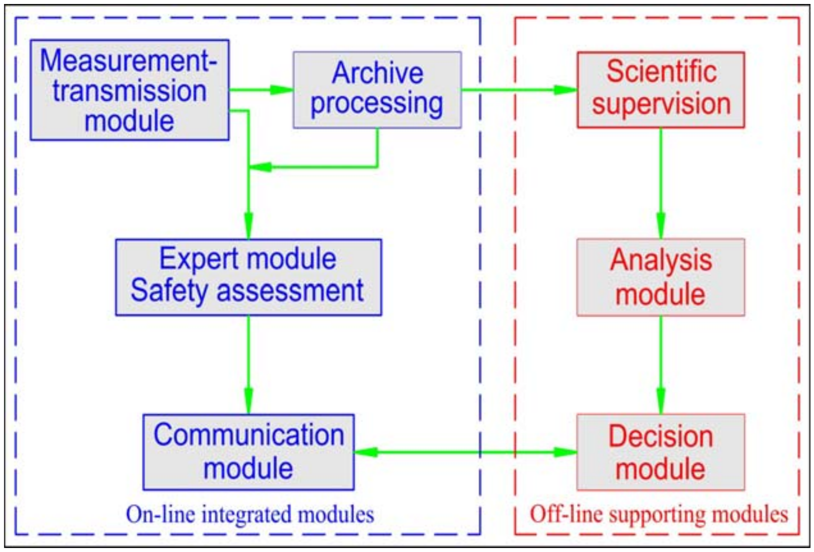

Fig. 7. General data flow diagram of WiSeNe^{MONIT}

The crucial component of the WiSeNe^{MONIT} monitoring system is the external analysis module (off-line subsystem). The off-line subsystem provides additional information about the loading conditions and strain/stress states in all the structural elements, taking into account the actual state of displacements and verifies the system criteria based on built-in threshold values of displacements. It utilizes information about the displacement and temperature sent automatically via Internet by the on-line subsystem. Using it as an input for calibration of the numerical model of topology and element connectivity as accurate as required for the monitored structure, the off-line subsystem carries out the complete structural analysis to conform with the displacements of input data in order to find the strain/stress fields in all structural elements corresponding to the actual combination of actions. The subsystem is activated as frequently as is required from the safety/serviceability point of view but not rare than the attainment by displacements corresponding to the subsequent threshold levels implemented in the on-line subsystem. It allows obtaining a continuous record of strain/stress states in structural elements. After reaching the third threshold level, the frequency of numerical analysis is doubled in order to accurately monitor the performance of the structure in order to make decision for the intervention activities on the basis of the full knowledge about the RUR level in critical structural members and joints.

Complete information about the capacity utilization level of structural elements allows for more precise estimation of the safety level and, as a result, stipulates more rational decision to be undertaken for prevention/intervention activities, such as snow removal from the roof or clearance of the drainage installation. Detailed knowledge of the internal forces gotten from the off-line module and as well as of the RUR levels in the most stressed volume of structural elements enable for the optimal planning and implementation of required intervention activities, such as sequence of the snow removal from the roof or on the extreme side - an appropriate scenario for the evacuation of building.

External off-line subsystem has additional advantages, namely allows for the identification of the weakest structural elements and critical joints, verifying the design project with regard to its relevance to the reality, i.e. the structure that has been completed and allowed for service. Structural analysis of the real system subjected to monitoring provides information for the evaluation of optimal number and distribution of measurement units, and in general – better consistency in the data produced by the on-line subsystem. In turn, it may be a source of more realistic evaluation of threshold values for displacements needed for the more accurate predictions outputted by the on-line subsystem.

6. Concluding remarks

Wireless sensor network systems of technical monitoring of structural safety and serviceability are very efficient solutions for rationalization of safety prediction and establishment of maintenance procedures with regard to low-rise buildings of typical lightweight structural systems. In this case, there is no need for advanced measurement methods and measuring equipment with high power consumption.
The system WiSeNe^{MONIT} presented above, developed for typical single-storey buildings of steel lightweight roof structures, has many advantages, namely: no wire network, easy and fast assembly, safety for structural elements with regard to possible damage to both the element and protection materials and relatively low cost of entire erection and maintenance of the system. It allows for easy extension or adoptions to new requirements, like change in the placement of measuring units or additional installation of measuring units. External module of off-line subsystem allows for obtaining reliable information about the parameters that are more difficult for the direct and reliable measurement by wireless sensors. Parameters obtained from the off-line subsystem fulfil the requirement of current building regulations with regard to the necessity of monitoring strain/stress fields of structural elements besides those related to structural displacements.
Wireless monitoring system in the developed configuration enables therefore for monitoring exercise based on complete information provided by two subsystems:
- On-line subsystem with a limited number of points for direct displacement measurement.
- Off-line subsystem with unlimited number of information about indirect measurement of strain/stress states and capacity utilization ratios of structural members and joints.

System modules are responsible for the analysis of measurement results and on the basis of this analysis the system generates appropriate messages, providing the owner/user (service manager) with the actual state of structural safety level. The frequency of structural performance condition sampling is dependent upon the most important factors affecting the building safety and serviceability conditions, such as the year season and accompanied climatic actions on the structure, including the temperature of structural elements. The monitoring on-line subsystem automatically adjusts the sampling frequency to the changing external conditions, optimizing the power consumption and limiting the exchange number of internal power supply sources, therefore minimizing the maintenance costs and ensuring a sustainable reliability level of the system.

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