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Wireless Network Node to Monitor Stress in Steel Structures

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***Abstract*—The article presents a wireless measuring node operating in a system monitoring stress in steel structures. Stress sensor is a foil strain gauge, working in a half-bridge circuit. The presented node is based on the microcontroller Atmeg 8, and the data transmission modem used 433 MHz band. The use of 22-bit ADC allows for measurement of the stresses at 4 u-strain resolution. The article discussed the structure of the node, installation problems in the actual real projects and the results of laboratory tests. Based on the research it can be concluded that the measuring node can be used to monitor the load caused by residual snow on the steel roofs.**

***Index Terms*—Strain measurement; mass measurement wireless sensor networks; sensor systems and applications.**

I. INTRODUCTION

Measurements of stresses in materials rarely are used solely to determine internal stress or elongation. Most often they are used to measure the values which indirectly cause the stress. These values are: strength, mass, pressure, torque. Based on the elastic element and strain sensor, it is possible to create the measuring system for measuring the above values. Depending on occurring conditions, to measure stress used can be: optical systems which use the properties of optical fiber [1], [2], semiconductor strain gauges [3] and MEMS gauges [4] (which offer a high sensitivity), strain gauge rosettes (to measure the multi-axis deformation) [5] and, most widely used, metal foil, or wire strain gauges.

In industrial applications, the measurement of stress is used to determine the strength of the tested elements in the typical operating conditions. This is in the case of wired system measuring deformation of railways during the passage of trains, presented in [6]. While in [7] is presented a system based on strain gauges which measures the stress in the toothed gear of gearbox.

In medical applications, the stresses are measured mainly in order to diagnose or assess the suitability of new materials for implants. A wireless system for monitoring stress of hip implants is presented in [8], wherein strain gauges are attached directly to the implant in a patient's body, while electrodes are led out to the skin surface to the measuring node that reports the main controller data via a radio link 180 MHz. Whereas, in [9] presented a wireless system using a rosette strain gauge to monitor the bone-tissue maintenance.

In building construction, the measurements of stress and forces are carried out mainly in the moment of the release of such the building for use, as in the case of load of bridges, stairs or walkways. It can be noted that the continuous monitoring of certain parts deformations of the buildings construction can bring significant economic and utility benefits. Permanent monitoring is mainly used when developing new building materials and checking their parameters, or to improve the safety of the building use. An example of such the measurements can be system presented in [10], which measures the stresses occurring in the newly designed concrete structures. The system is based on an integrated nickel-concrete sensor to measure internal stress. [11] illustrates a wireless system for monitoring stress of PVC plates used in the hall construction. In this system the measuring nodes transmit information about stress of walls and roofs of the monitored hall. Data transfer took place in two stages, first from the measuring system to the network gateway using an interface IEEE 802.15.4, and then to the server via the GSM/GPRS network. Nodes using metal strain gauges. The article [12] presents a system that uses an optical sensor based on the fiber Bragg grating (FBG) for measuring stresses and displacements of rocks in excavations and mining sidewalks. A similar method is applied to the simultaneous measurement of stress and temperature of the wire rope in [13]. Systems using optical sensors offer many measuring capabilities, but are very complex and the creation of autonomous nodes operating in the territorial dispersion is very difficult and costly.

A very interesting example of a miniature measuring node is a node of the total dimensions equal to 1cm^3 presented in [14]. This node works in a universal system to measure stress where the measurement data are wire-transmitted, it complicates the use of a node in the distributed systems. Wired system to monitoring construction of building based on the metallic strain gauge is presented on the paper [15]. In the article [16] presented a comprehensive system for monitoring the condition of a building's roof. The structure tensions were measured used optical fiber. In addition, atmospheric parameters such as temperature and wind velocity, and relative displacement of roof elements were

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measured. This system was used to monitor the railway station in Bern.

Our article presents a wireless node to measure stresses in the steel structure using folic strain gauge. This node works in the system of monitoring of stresses in building construction based on steel frame. The main task of the system is to monitor the stresses of roofs caused by residual snow or extreme winds, measurement of the weight of snow and possibly alerting users about exceeding the permissible loads.

II. MONITORING THE SNOW LOAD

The problem of the load of building structures by snow depends on the geographic region of the building. In countries and regions where there is a heavy snowfall and weather conditions are conducive to creating and retention of snow cover on building constructions, there are regulations and building standards which minimize the probability of the occurrence of disasters caused by the above factors. In central and eastern Europe this problem is important. In Poland there are building standards [17] based on statistical indicators defining the exposure of snow in every region of the country. On the basis of these data structures of roofs are designed. In addition, the construction law imposes an obligation on the owner of property for systematic removal of snow from the roof in case of exceeding the critical thickness of the snow cover. Despite this, construction disasters sometimes occur. According to data from the General Office of Building [18], in 2014 in Poland occurred 57 construction disasters which was caused by residual snow on roofs of buildings and strong winds (in 2006 it was 113 [19]). The reasons for this are several, the most important of them are:

- Non-compliance with the construction law - ignoring the need to make regular inspection and removal of snow from roofs;
- Use of inappropriate materials for load-bearing roof structures, characterized by lower flexural strength than assumed in the project;
- Lack of sufficient knowledge about the change of snow mass due to atmospheric changes. (Average density of different types snow according to [20], [21] is presented on Table I);
- Abnormal weather conditions, taking into account the statistics, in Poland within 50 years occurred four years in which the average value of the snow load was exceeded;
- Inaccurate or difficult to used methods of measuring the mass of residual snow.

TABLE I. DENSITY OF SNOW DEPENDING ON SNOW TYPES.

Type of snow	**Average density of the snow cover [kg/m^3]**
Powder snow in low temperature	10–30
Fresh snow	50–70
Humid fresh snow	100–200
Settled snow (some hours after fall)	200–300
Old snow (some weeks after fall)	350–400
Firn (one year old snow)	400–800
Glacier, ice	850–900

Due to the construction possibilities of buildings with flat roof, like: warehouses, large-surface stores, halls, hangars - used are mainly steel roofs based on truss support frame and cover with a pleated sheet. In view of the relatively flat surface of roofs, the slope of the roof surface changes in the range of 11 to 33 degrees. There are favourable conditions for deposition of snow layers, since the angle of the roof slope is insufficient to spontaneous snow slide. The result is the rapid collection and long retention of snow mounds on the building. This may be the cause of exceeding the permissible roof load. This leads to the collapse of roof trusses, destruction of roof cover and often the whole building. The method for preventing such incidents is an adequate monitoring the thickness of snow cover. There are several methods to estimate the mass of snow lying on the roof. They are briefly described below [22]:

- Snowstake – measuring the thickness of the snow takes place by means of a calibrated rod which is in each case inserted into the snow cover.
- Stationary snowstake – the measurement is carried out in the same manner as before except that the indicator is permanently mounted on a special platform on the roof.
- Ultrasonic snowstake – the measurement is done by ultrasonic measuring the distance from the ultrasound head, placed on the known height, to the snow cover. A drawback of these solutions is the ability to measure only the thickness of the snow cover, so that it is impossible to clearly determine the mass of lying snow.
- Snow gauge – a device which measure the density of the snow on the basis of a sample with a given area or volume. Electronic snow gauges in addition to the snow density can calculate the mass of snow scaled per unit area [kg/m^2]. The problem with these devices is the need to sample the snow for the cover.
- Snow weight – measuring the mass of snow is made simply by placing a digital weight with a known area on the roof. This solution does not require sampling and gives immediate result of load calibrated in [kg/m^2]. Nevertheless, the accurate of the indications can be significantly reduced by freezing the lower layers of the snow what prevent deformation of the scale pan.

There are also used systems combining these techniques to make the best measure of weight and mass of snow.

III. STRAIN GAUGE SYSTEM TO MEASURE THE LOAD OF SNOW

Built by the authors a strain gauge system is a universal system for monitoring stresses and expansion in structures using skeletal steel frame. Nevertheless, it was designed for use as a system monitoring the load of metal roofs. The system structure is shown in Fig. 1.

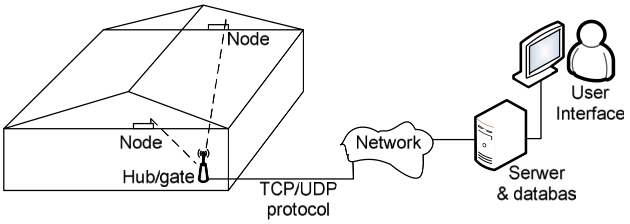
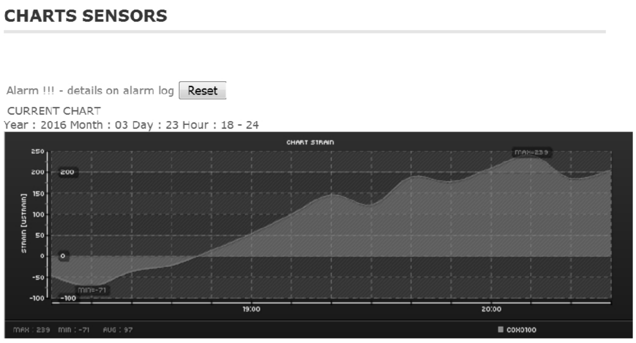


Fig. 1. Bloc structure of system for monitoring stresses and expansion in steel structures.

The method of measurement of the roof snow load proposed by the authors is different from the above. It is based on measuring the deformation/strain of the support elements of the roof. Based on these measurements and knowledge of the construction parameters (dimensions of a truss, dimensions of individual spans) and roof materials (type of steel used, Young's modulus) current stress are calculated. The system automatically compares the measured stress with an acceptable provided in the project. In the future the system will have the function of calculating the weight of snow per unit area, and the resultant weight of the snow for the entire roof.


CHARTS SENSORS

Alarm !!! - details on alarm log

CURRENT CHART
Year : 2016 Month : 03 Day : 23 Hour : 18 - 24

MAX : 239 MIN : -71 AVG : 97

Fig. 2. User window – part of the website user interface.

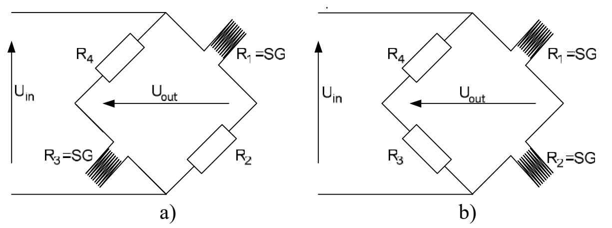
An element performing the measurement is a node installed in the measuring location. The data wirelessly reach the network hub which is designed to receive data from all measuring nodes and send it to the main system controller. For this purpose, a TCP/UDP protocol is used. Hub is also the gate to the TCP network. The main controller is a server and a database. The main task of the server is receiving information from the hubs, archiving of results, their processing and presentation for the user in the form of dynamic websites. Server can collect data from one or more hubs, this allows for monitoring one or more building via one system. The user of the system in the window of observation has the current view of stress distribution in the selected node, he may also view the history of measurements and select the number of nodes from which he wants to observe the measurements. In the case of register, the alarm caused by exceeding allowable stress values, the user receives immediate information in the main window. Detailed information on all alarms are shown in the alarm window. An example view of the user's window is given in Fig. 2.

IV. WIRELESS MEASURING NODE OF STRAIN GAUGE NETWORK

A. Construction of the Measuring Node

The node is a component of the system which performs the measurement signal acquisition. It is installed on the roof structural element whose deformation is measured. Measuring sensor is a foil strain gauge. The basic measuring circuit of the metal strain gauge is a Wheatstone bridge. After analysis of the cases, it was decided to use half-bridge circuit with two active strain gauges, or half-bridge differential circuit, as shown in the Fig. 3.

In the measuring node the Wheatstone bridge works as an unbalance bridge and is treated as a converter of change the resistance to voltage [23], [24].



a) b)

Fig. 3. Strain gauge location in Wheatstone bridge circuit: (a) half-bridge circuit; (b) differential half-bridge circuit.

If $R_1 = R_2 = R_3 = R_4$ and $\Delta R << R$ the output voltage from the half-bridge circuit can be represented by (1)

$$U_{out} = \frac{U_{in}}{2}\left(\frac{\Delta R}{R+\dfrac{\Delta R}{R}}\right) \approx \frac{U_{in}}{2}\left(\frac{\Delta R}{R}\right). \qquad (1)$$

Taking into account the two active strain gauges, the measuring sensitivity of the circuit increases twice in comparison to quarter-bridge. This is very important because real measurements of the strain (ε) are at a few µstrain. Where 1 µstrain is the strain producing a deformation of one part per million.

The strain gauges used in the system are the foil strain gauges made of constantan having a strain gauge constant K = 2.15, and base resistance R = 120 Ω.

The signal from the bridge system is applied to 22-bit analog-to-digital converter MCP3551 which allows sampling voltage with a frequency of 12 samples per second. The actual measurements are made with a frequency of 1 in 20 seconds. The resolution is limited to 20 bits. Connection between sensors and ADC is presented on Fig. 4.

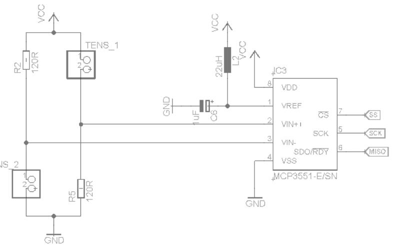


Fig. 4. Electrical wiring diagram of the half-bridge circuit with analog to digital converter MCP3551.

The signal converted to a digital value goes to micro-controller ATmega 8 through the SPI interface. In the controller the measured value is checked with an alarm threshold and if the threshold is not exceeded, the next measurement is performed. If the alert threshold is exceeded, the information is sent to a network hub. The task of the controller is also suitable format of measurement data to send (assigning identifiers and timestamps) and service of transmissions.

The measurement data are sent to the network hub with the RFM12B chip. It is an integrated transceiver operating in the ISM band, using a frequency of 433 MHz. This transceiver allows for the transmission of data with bandwidth to 115 kbps. In a chip with integrated antenna the communication is possible over a distance of 150 m–200 m which let to monitor the buildings within an area of

10000 m^2 (assuming unfavourable marginal position of the hub). This distance can be achieved with the maximum permissible transmit power +5 dBm (3 mW) and a reduced throughput to 1.2 kbps. In the described node baud rate is set to 19.2 kbps while the transmission power on 1 dBm – it allowed for communication range of up to 30 m. The actual node is shown in Fig. 5.

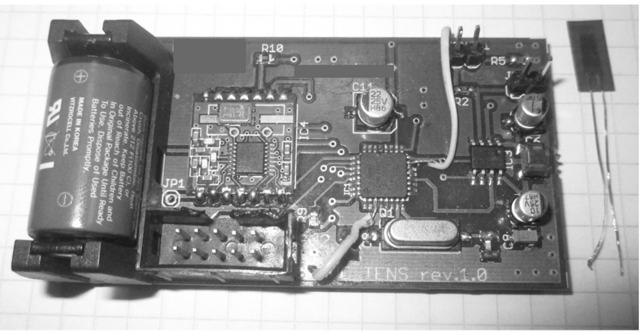


Fig. 5. Measuring node for strain monitoring system and used strain gauge.

The micro-controller, ADC converter and communication modem are selected for low demand for electricity according to the methods of optimization described in [25]. The node during normal operation consumes an average of 1.2 mW. The power source under test conditions is the battery with capacity 1200 mAh which allows for 41 days of continuous work on the assumption of sending data every 10 minutes. Ultimately, the current capacity of the battery will be increased. the measuring node has been made on a bilateral PCB plate with dimensions 74 mm × 40 mm.

B. Computational Simulations and Tests

The node must be installed on an element whose deformation is measured. This is dictated mainly by minimizing distortions induced in the lines connecting the node with the strain gauge. Due to the relatively low weight, the node will be glued to a metal element of roof, similarly like the strain gauges. If a node is mounted on a roof bolt, used will be half-bridge differential system, if on a purlin used will be half-bridge system. This situation is illustrated on the Fig. 6.

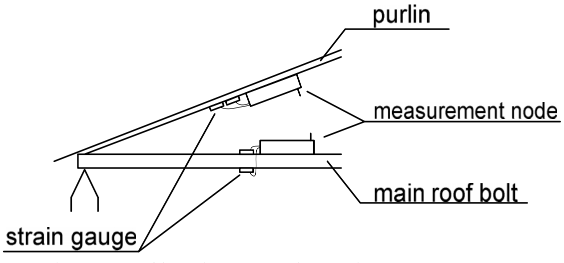


Fig. 6. Various type of location measuring node.

Below will be presented computational simulation allows validate the adopted solution. Roof deflection closed by snow is schematically presented on Fig. 7. In accordance with the building standards [26], deflection f of a support element (bolt) with the length l cannot exceed $l/250$. Assuming the length of the base bolt is l = 10 m, the deflection f_{max} = 0.04 m.

At the maximum deflection the length of the bolt will increase and will amount l_{max} = 10.00032 m, which is equal to the strain ε = 32 μstrain.

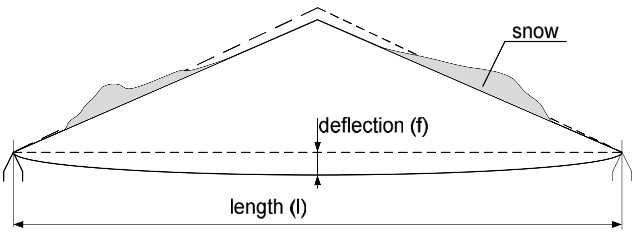


Fig. 7. Resizing the roof under load. Dash line – size without load, solid line – size under load of snow.

Measurement resolution of the half-bridge circuit $\Delta R_{\min}$ of the node can be calculated based on the voltage of the half-bridge circuit and the parameters of the ADC is shown in (2). Where the Q is the resolution of ADC and full scale output voltage is the same as input voltage, $U_{in} = U_{FSO}$ = 3.3 V

$$\Delta R_{\min} = \frac{Q \times 2 \times R}{U_{in}} = \frac{\left(\frac{U_{FSO}}{2^{20}}\right) \times 2 \times R}{U_{in}}. \tag{2}$$

In order to determine the minimum tension that can be measured by the node, the value calculated in (2) should be substituted into (3)

$$\varepsilon_{\min} = \frac{\Delta R_{\min}}{R \times K}. \tag{3}$$

After substituting the data for the node, we get information that minimal elongation which can be measured by node is 0.44 μstrain (theoretically). Comparing it with the stress and the maximum elongation, we see that the system offers 72 levels of resolution, translating it to a relative error we will get 1.38 %. It is an error which includes just the resolution and parameters of measurement tools used here. It does not include a random error caused by electromagnetic interference or improperly installed sensors (no misalignment, incorrect glue).

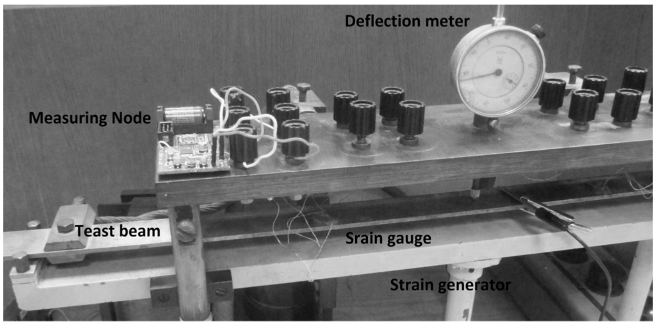


Fig. 8. Measuring node during the test.

The measuring node has been tested in laboratory conditions, what is presented on Fig. 8.

During the laboratory studies, comparative tests were performed. They compared the results of measurements taken by the constructed node and a professional strain bridge NI 9237 made by National Instrument (in both cases, used the foil strain gauge with a base resistance of 120 Ω and K = 2.15). During the tests, the devices measured the stress of the steel beam with a thickness of 3 mm. The deformation of the test beam was created by a static stress generator. The measurement results are presented in Fig. 9. The measurements made by the NI 9237 bridge have better linearity and lower noise (at 1 µstrain). The measurements made by the built node have a much more variation in values (4 µstrain – which is denoted by the error bar value on Fig. 9). This measurement resolution is acceptable to measure the typical values of deformation occurring in roofs (0 µstrain–32 µstrain), but disruptions and an electromagnetic noise on the analog signal are a big problem and will be investigated by authors.

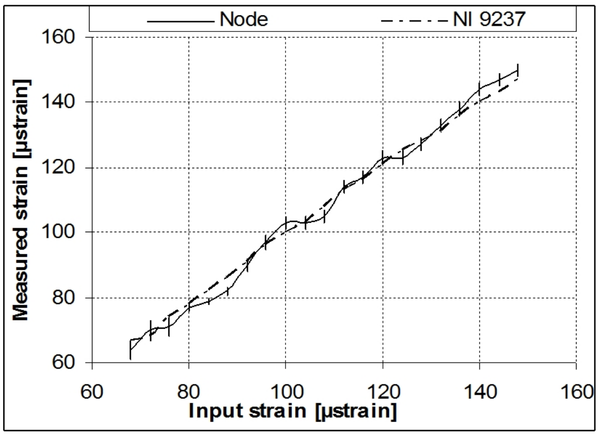


Fig. 9. Comparison result of measurements from constructed node and NI 9237 strain bridge.

Use of the half-bridge differential circuit pre-eliminates the problem of temperature influence on the measurement results. It should be noted that for the used strain gauges made of constantan the coefficient of resistance changes as a function of temperature α = 0.00002 [1/°C]. Assuming a change in temperature by 10 °C], we get a strain gauge resistance change ΔR = 0,0012 Ω. This change in resistance is tantamount to the structure strain ε = 46 µstrain. Thus, the temperature compensation is required. In the differential system, the compensation of temperature error can be best illustrated by (4), which binds the output voltage with the resistance change of all the arms. In the case of temperature change, there will be an additional change in the resistance ΔR_T which will be eliminated by placing active strain gauges in neighbouring arms of the bridge. Element numeration is in accordance with Fig. 2(b).

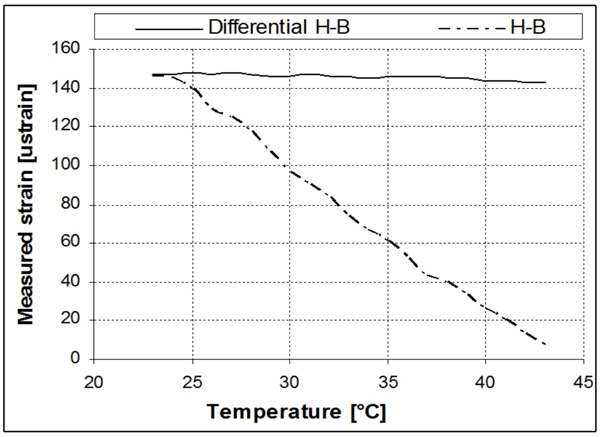


Fig. 10. Impact of temperature change on strain measurement.

$$U_{out} = sU_{in}\left(\frac{\Delta R_1 + \Delta R_T}{R_1} - \frac{\Delta R_2 + \Delta R_T}{R_2} + \frac{0}{R_3} + \frac{0}{R_4}\right), \quad (4)$$

where s is the sensitivity of the half-bridge circuit. On Fig. 10 the impact of temperature change of the working environment on the measurement results is presented. During the test, strain of beam was constant and temperature increased from 23 °C to 43 °C. The graphs show that the temperature error of the differential half-bridge circuit is e_{DHB} = 0,2 [µstrain/°C], while the error of the half-bridge circuit is e_{HB} = 7 [µstrain/°C]. This can be concluding that in real conditions only the differential circuit can be applied. It is possible to use the half-bridge circuit (it is easier to install), but then it becomes necessary to measure temperature and to make adjustments on data processing. But according to [27], even using additional temperature sensor can be complicated, to eliminate temperature error from result of strain measurement. The problem of temperature influence during strain measurement is important, and will be investigated by authors.

The communication between the node and the network hub has been verified. Maximum span of communication was 40 m on free space and 30 m inside the building. It is possible to increase the range to 90 m by increasing the transmit power of the modem. However, it is connected with the increase in energy demand which is not beneficial because it would shorten the working of the node on battery power.

V. CONCLUSIONS

Presented in the article the wireless node to measure the stress, is predisposed to work in the system monitoring snow load of steel roofs. Component selection shows that the system is able to measure stress at few µstrain, with the time resolution at the level of seconds. These parameters allow to use the system to monitor the dynamic stress caused by, for example, sudden wind or strong rain. Such conditions, combined with the residual snow, are causing many construction disasters. The threats caused by these conditions cannot be detected by methods and systems based on measuring the density or the mass of snow. The proposed system introduces an improvement monitoring of the buildings state and thus it improves the safety of persons inside.

Currently, all components of the system (measuring node, system gate, master server and user interface) have been built and tested. The measuring node has been tested in laboratory conditions. The reached measurement resolution (4 µstrain) predispose the node for to operation in the monitoring system for loading of steel roofs. It was tested that the range of used radio modems can communicate of the system gate with the nodes located within 30 m.

The authors are currently working on two issue allowing to increase the functionality of the node and hence the whole system:

– Construction of an energy-efficient node – the first step is to change the node controller on the MSP430 series microcontroller and to change the radio interface to the standard IEEE 802.15.4;

– Increasing the resolution of the measurement through the development of systems conditioning and filtering the signals entering the input of the ADC transducer.

After completion of laboratory work the implementation the system in a real object (a steel warehouse) is planned.

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