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INCLINOMETER METHOD OF DISPLACEMENT MEASUREMENTS AS AN ALTERNATIVE TO OPTICAL MEASUREMENTS IN STRUCTURAL HEALTH MONITORING - ON SITE TESTS

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The paper presents a method of structural monitoring with the use of angular and linear displacement measurements performed using inclinometer and laser measuring devices. The focus is mainly on the inclinometer measurement method, which is a solution free from the basic disadvantages of optical methods, such as sensitivity to any type of visibility restrictions, pollution or influence of weather conditions. Testing of this method was carried out in practical application in an wireless monitoring system, installed in a large-area industrial building. The measurement results performed using the inclinometers were compared with simultaneous measurements of linear displacements performed with the use of proven methods based on laser rangefinders. The research and analysis show that the method of measuring angular displacements using the inclinometers with MEMS sensors of appropriate quality is a very good, better than typical optical methods, solution of structural monitoring systems that allows to obtain accurate and reliable results.

Keywords: structural health monitoring, monitoring of deflections and rotations, inclinometer, wireless structural monitoring, low-cost monitoring system

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1. INTRODUCTION

Structural health monitoring is one of the tools used to improve the safety of structures. As such tool it must be characterized by an appropriate level of reliability and credibility. Large-area buildings with lightweight structures and flat roofs, such as warehouses, commercial buildings, industrial and exhibition halls, are particularly exposed to failures and collapses. They are characterized by a significant share of variable loads in total actions, which makes the structures of these buildings particularly sensitive to extreme climatic actions. At the same time, there are observed a common tendency to use increasingly economical and unconventional structure solutions, which, combined with intensifying weather anomalies, such as heavy snowfall, heavy rains or hurricane winds, intensifies this sensitivity. These issues were discussed, among others in [2, 3, 4].

In this context, structural health monitoring, which makes it possible to monitor the behaviour of the structure under the influence of changing loads, and thus to take appropriate preventive actions in the event of exceeding safe levels of these loads, is of particular importance. The most important part of any monitoring system is the measuring devices directly responsible for monitoring the behaviour of individual structural elements. In practical applications, there is a large variety of monitored quantities, and their selection depends on the needs arising from the type and significance of the structure and the existing actions [3-7, 9-11]. For typical structure solutions, which are most often used in the above-mentioned large-area facilities, displacement measurements are the most useful [3-5, 9, 10]. The displacements reflect well the behaviour of most structures under load, and at the same time are relatively simple in measurements and interpretation. The most common displacement measurement methods used in monitoring systems have been described in many publications, e.g. [1, 3, 4, 7, 9, 10].

This paper concerns the use of inclinometers to measure angular displacements as an alternative to commonly used linear displacements measured with optical methods and presents research that is a continuation of the tests described in the paper [8]. The operating principle of the inclinometer means that the inclinometer measurement method is free from the basic disadvantages of optical methods, such as sensitivity to any type of visibility restrictions, pollution or influence of weather conditions. The concept of using inclinometer method of displacement measurements, laboratory investigations of inclinometer sensors and the method of compensating their temperature drift are described in [8]. MEMS (Micro-Electro-Mechanical System) sensor used in these tests is characterized by a absolute measurement resolution of even 0.0004° and the temperature stability better than 0.0005°, which means that the measurement error can be less than 0.001°.

This paper presents on site tests of the developed inclinometer device in practical application in an wireless monitoring system, installed in a large-area industrial building. The results of angular measurements were compared with simultaneous measurements of linear (vertical) displacements performed with the use of proven methods with laser rangefinders. The research show that the method of measuring angular displacements using MEMS sensors of appropriate quality is a very good, better than typical optical methods, solution of structural monitoring systems, that allows to obtain accurate and reliable results.

2. ON SITE TESTS

Practical testing of the measurement method and developed inclinometer measuring devices was carried out in an industrial building with a steel structure in which both enclosed spaces, not exposed to below zero temperatures and other environmental influences, as well as open spaces, exposed to atmospheric environment can be distinguished. The structure of the hall with dimensions of 120x360 m is composed of steel, single-span truss purlins with a span of 18 m and lattice girders with a span of 15 m, based on reinforced concrete columns fixed in foundations. The structure scheme and examples of the monitored trusses with the location of measuring devices, both inclinometer (marked: I) and laser measuring devices (marked: L), is shown in Fig. 1 and Fig. 2. In the open parts of the building, both inclinometer and laser devices (for comparison purposes) were installed, and in the enclosed parts only laser devices were used.

The complete inclinometer device consists of the Inclinometer Measuring Device (IUP) and the Inclinometer Module (MI), connected by cable - Fig. 3. The task of the Inclinometer Measuring Device is to manage the Inclinometer Module, ensure cooperation and wireless communication with the rest of the system components and power supply, both for IUP and MI. The main element of the Inclinometer Module is the inclinometer sensors SCA103T made in MEMS technology. Examples of inclinometer attachments to the girder and purlin are shown in Fig. 4.

In general, inclinometer devices were fixed at one end of girders or purlins. In order to check the possible effects resulting from the lack of full symmetry of load and structural response to such actions, additional inclinometers were used for one of the girders - one (W4-IB) next to the main sensor (W4-I), opposite the girder chord and the other (W4-IA) at the opposite end of the girder.

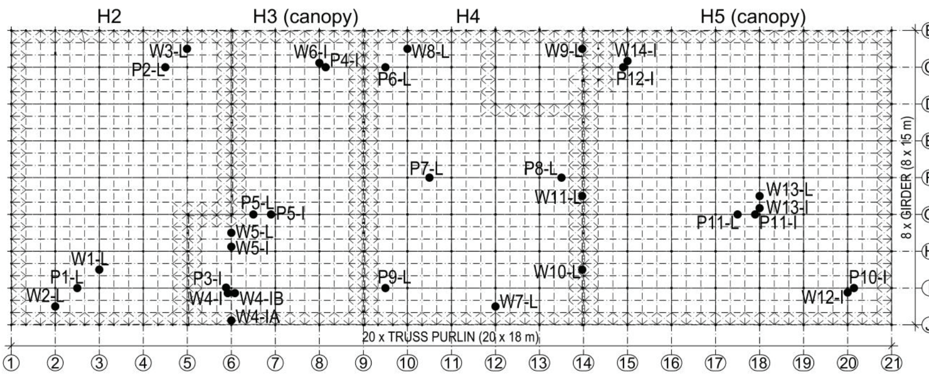


Fig. 1. Arrangement of measuring devices in the facility (Device markings: L - laser rangefinder, I - inclinometer)

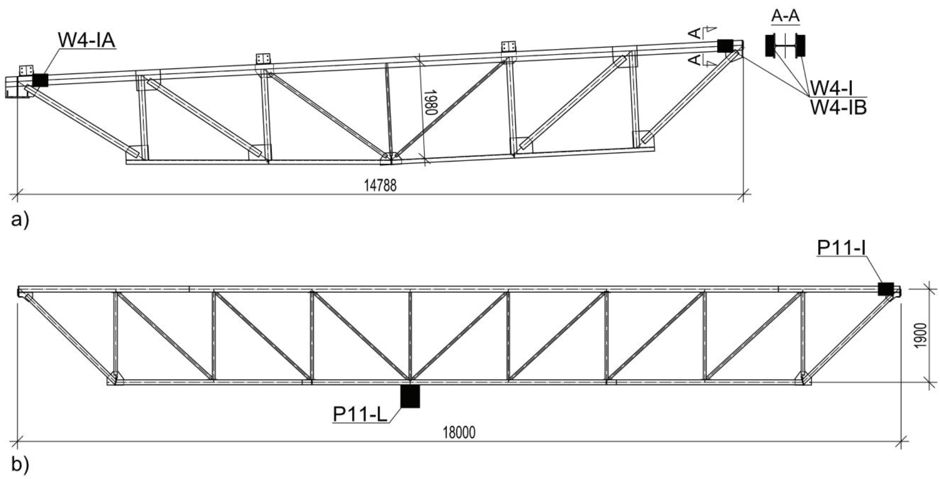


Fig. 2. Example of the monitored girder (a) and truss purlin (b)

In addition to measuring devices (inclinometers and rangefinders), the installed system also includes Retransmitters used for communication between system components, Access Devices for communication of measuring devices with the Central Unit which manages the entire system. All devices installed on the structure are powered by four AA batteries, and the only device of the system that requires power from the power grid is the Central Unit, which in the event of a power failure is powered from the built-in UPS. Communication between devices installed on structure, as well as communication with the Central Unit is carried out wirelessly in the IEE-802.15.4 standard, in the 2.4 GHz band.

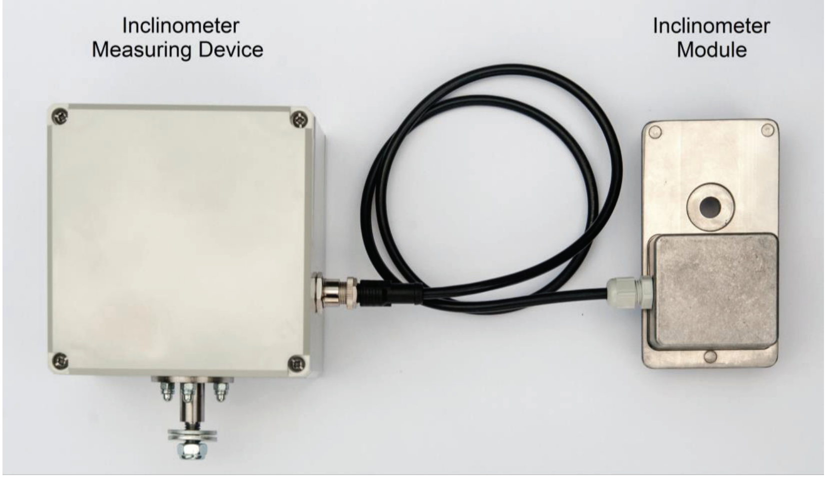
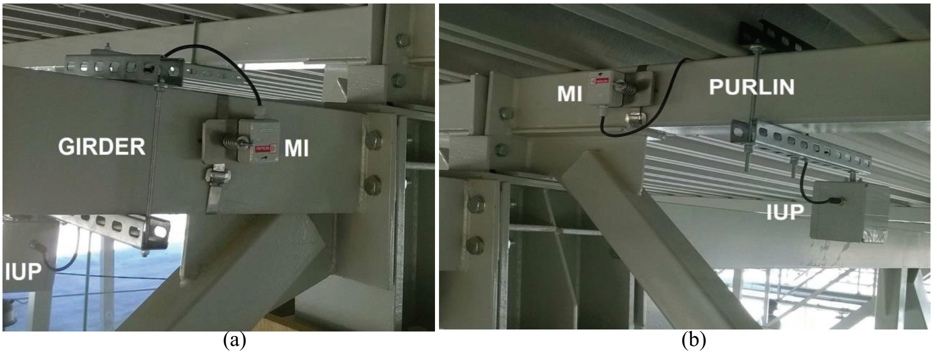


Fig. 3. Complete inclinometer device

Communication with the system takes place via a website, and the Central Unit is responsible for it. The system cyclically, at programmed intervals, automatically adapted to changing load conditions, collects and analyses information on changes in rotation angles and vertical displacements of representative structural elements caused by loads, e.g. snow or rainwater. On the basis of these data, the Central Unit generates messages about the changes of the measured values being a measure of load changes and indirectly the bearing capacity utilization of the structure.



(a) (b)

Fig. 4. Examples of inclinometer devices (IUP and MI) attachment to the girder (a) and truss purlin (b)

Table 1. Permissible and threshold values of deflections and rotation angles for measuring devices

Measuring Device L-Laser I-Inclinometer	Localization	Permissible value	Threshold value [mm] or [°]			
		Deflection [mm] Rotation angle [°]	L1	L2	L3	L4
P1-L	H2	18 mm	5 mm	9 mm	13 mm	18 mm
P2-L	H2	18 mm	6 mm	10 mm	14 mm	18 mm
W1-L	H2	13 mm	0 mm	5 mm	9 mm	13 mm
W2-L	H2	12 mm	4 mm	0 mm	8 mm	12 mm
W3-L	H2	12 mm	0 mm	4 mm	8 mm	12 mm
P5-L	H3 (canopy)	14 mm	4 mm	7 mm	11 mm	14 mm
W5-L	H3 (canopy)	11 mm	0 mm	6 mm	7 mm	11 mm
W4-I-A	H3 (canopy)	0.117°	0.035°	0.059°	0.088°	0.117°
W4-I-B	H3 (canopy)	0.128°	0.038°	0.064°	0.096°	0.128°
P3-I	H3 (canopy)	0.212°	0.064°	0.106°	0.148°	0.212°
P4-I	H3 (canopy)	0.218°	0.065°	0.109°	0.153°	0.218°
P5-I	H3 (canopy)	0.212°	0.064°	0.106°	0.148°	0.212°
W4-I	H3 (canopy)	0.128°	0.038°	0.064°	0.090°	0.128°
W5-I	H3 (canopy)	0.118°	0.035°	0.059°	0.083°	0.118°
W6-I	H3 (canopy)	0.128°	0.038°	0.064°	0.090°	0.128°
P6-L	H4	18 mm	6 mm	10 mm	14 mm	18 mm
P7-L	H4	18 mm	6 mm	10 mm	14 mm	18 mm
P8-L	H4	22 mm	7 mm	11 mm	15 mm	22 mm
P9-L	H4	18 mm	6 mm	10 mm	14 mm	18 mm
W7-L	H4	16 mm	4 mm	9 mm	12 mm	16 mm
W8-L	H4	14 mm	4 mm	7 mm	0 mm	14 mm
W9-L	H4	29 mm	9 mm	15 mm	20 mm	29 mm
W10-L	H4	23 mm	7 mm	12 mm	16 mm	23 mm
W11-L	H4	15 mm	4 mm	8 mm	11 mm	15 mm
P11-L	H5 (canopy)	16 mm	0 mm	7 mm	12 mm	16 mm
W11-L	H5 (canopy)	10 mm	0 mm	5 mm	0 mm	10 mm
P10-I	H5 (canopy)	0.228°	0.068°	0.114°	0.160°	0.228°
P11-I	H5 (canopy)	0.228°	0.068°	0.114°	0.160°	0.228°
P12-I	H5 (canopy)	0.163°	0.049°	0.082°	0.114°	0.163°
W12-I	H5 (canopy)	0.130°	0.039°	0.065°	0.091°	0.130°
W13-I	H5 (canopy)	0.120°	0.036°	0.060°	0.084°	0.120°
W14-I	H5 (canopy)	0.088°	0.026°	0.044°	0.062°	0.088°

The main task of the system is to monitor behavior of the structure under the influence of changing loads and warning about exceeding of successive levels (threshold values) of the rotation angles and vertical displacement of structural elements in the sensor installation locations. On this basis, the ratio of load carrying capacity utilization of monitored structure elements and the type of generated message are determined - from information (exceeding threshold L1) to alarm (exceeding threshold L4). For each measurement point the permissible value of the rotation angle (φ_{perm}) or displacement (w_{perm}) from variable loads and four threshold values (from L1 to L4) are defined, typically 30%, 50%, 70% and 100% of the permissible value - Table 1.

At small values of permissible displacements, due to the measurement accuracy, the number of thresholds is limited to 2 or 3. Permissible values of the rotation angle vary in the analysed system in the range 0.088° to 0.228°, and permissible linear displacements within the range from 10 mm to 29 mm.

3. DISCUSSION OF RESEARCH RESULTS

The system was installed in the facility before the winter period of 2017/2018, and this paper presents, for the sake of clarity, an analysis of the measurement results registered in the period one month, when non-negligible snowfall occurred – January 2018 has been chosen. The main objective of the research was to test a new method of displacement monitoring, namely, the measurement of rotation angles using the inclinometer devices described in the paper [8]. Fig. 5 presents the results of the rotation angle measurements of the upper chord of the truss purlins in the open part of the building.

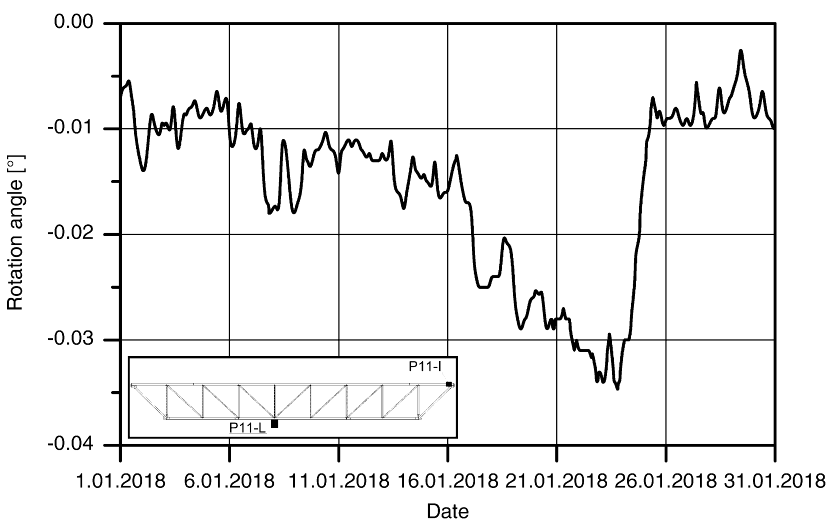


Fig. 5. The measurement results of rotation angle at P11-I

The graph shows a clear rotation angle in the period from 16 to 24 January 2018, caused by snowfall, whose history is shown in Fig. 6. The graph of snow load was developed on the basis of data available in the resources of the Institute of Meteorology and Water Management, which has a network of meteorological stations and provides the measurement results performed at these stations. The results were taken from the station located closest to the facility where the monitoring system was installed, confronting them with data from other neighboring meteorological stations. According to the standards, the snow load on roofs is reduced by the shape coefficient of the roof, which in this case is 0.8. This in turn means that it can be assumed that the snow load of the monitored roof was not greater than 80% of the load recorded by the meteorological station.

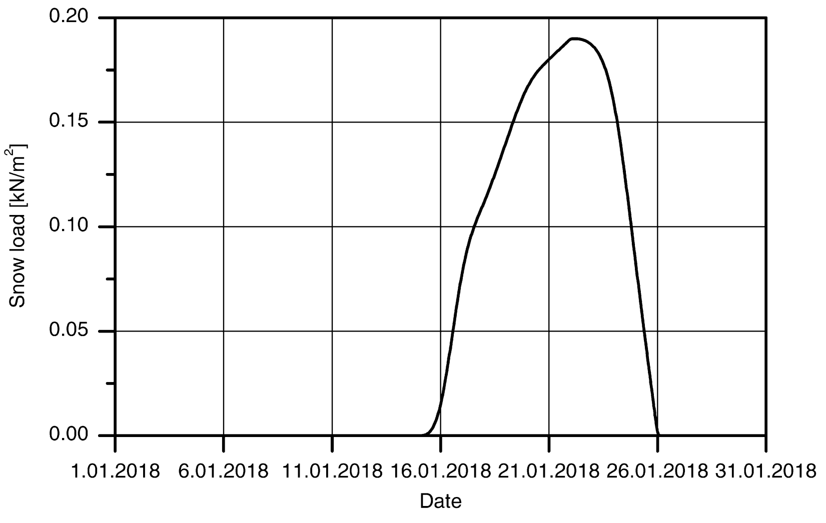


Fig. 6. Snow load in the analysed period

Installation of inclinometer devices on the structure of an open building exposed to outside temperature causes the need to take into account the influence of this temperature on the measurement results. Fig. 7 shows a graph of outside temperature changes developed using the measurement results taken from one of the meteorological stations. The analysis of data presented in Fig. 5, Fig. 6 and Fig. 7 shows that in the period from the beginning of snowfall on January 16 to January 21, the snow fall amounted to about 0.16 kN/m^2 (so the roof load did not exceed 0.8 · 0.16 kN/m^2 = 0.13 kN/m^2), and the rotation angle at point P11-I at this time was 0.018° and was significantly lower than the value of the first threshold L1, which is 0.068° for this measuring point.

It should be noted a slight increase in the rotation angle in the period from 16 to 17 January despite of snowfall (Fig. 5, 6) - this was caused by increase in temperature (Fig. 7). Then, during the snowfall, the temperature was practically constant, which is important as changes of temperature causes significant changes of the measured rotation angle. It is clearly visible in the first days of January, when temperature drop of about 8°C caused change of the angle by about 0.009°.

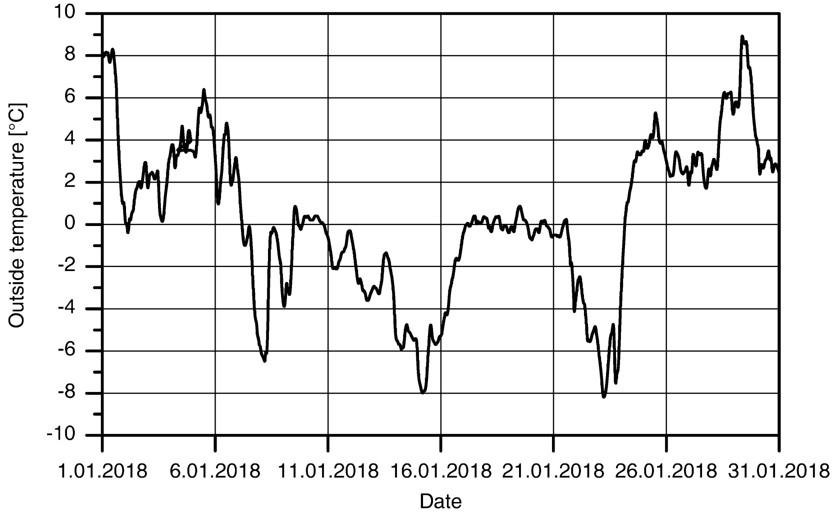


Fig. 7. Outside temperature changes

For the purpose of comparison on the same purlin, measurements of deflections in the middle of its span were also performed - Fig. 8. The analysis of these measurement results shows that in the above mentioned period from January 16 to January 21, the deflection was about 2 mm and, as in the case of measurements of the rotation angle, did not exceed the value of the first active threshold (L2) at P11-L equal to 7 mm.

When measuring linear deflections using laser distance meters, the measurement accuracy is on the order of 1 mm, which means that the result at the level of 2 mm is subject to a significant error. The results of deflections measurements depend on temperature changes, similarly as in the case of rotation angles measurements, however, due to the lower accuracy than in the case of angle measurements, this relationship is less visible.

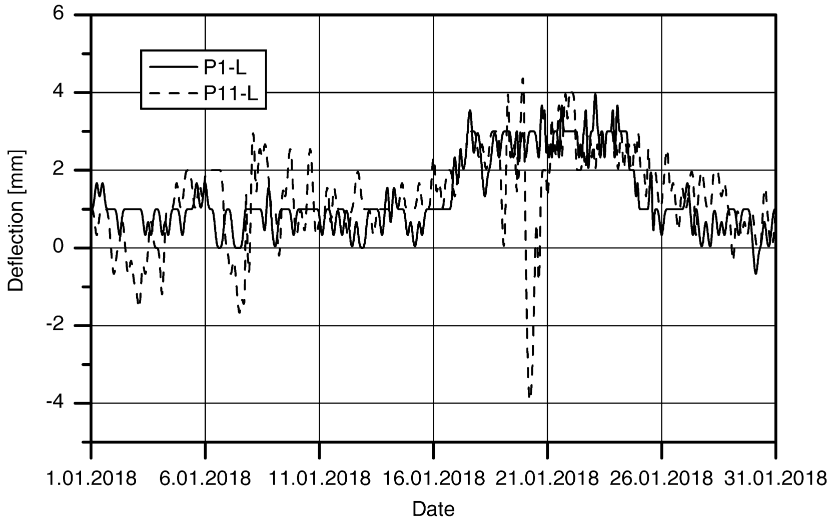


Fig. 8. The measurement results of the deflection at points P11-L and P1-L

The Fig.8 also shows the deflection graph of the purlin located in the enclosed part of the building - point P1-L. Comparison of the graphs confirms the influence of temperature changes on the measured deflections - in the enclosed part of the building, where temperature was kept constant, thermal changes in the structure were negligible, while in the open part, the changes are visible. With the measurement accuracy, which is possible to obtain in the used rangefinders, the displacement values resulting from temperature fluctuations are not as clear as with inclinometers, but they are not negligible.

Similarly to the purlins, laser devices and inclinometer devices were also installed on lattice girders. Considering the main objective of the system testing and small deflection values, resulting from small snow loads, the analysis of the measurement results was reduced in this case to the results of rotation angle measurements. Fig. 9 presents a graph of the rotation angles measured by inclinometer devices installed on one of the girders located in the open part of the building.

The purpose of studying the behavior of this girder has been extended by testing the symmetry of this behavior both in relation to the center of the span and to the center plane of the girder. Therefore, three inclinometer devices were installed - two at one end, placed on the opposite flanges of the upper chord (W4-I and W4-IB), and one at the other end of the girder (W4-IA), as shown in Fig. 2 and Fig. 4. The analysis of the graphs shows that the readings of sensors installed at one end of the girder (W4-I and W4-IB) are similar, but reading of the device installed in point W4-IB is about 25% higher than the device's indications in point W4-I. This indicates a lack of full symmetry of the girder behavior relative to its own longitudinal axis, which results, inter alia, from torsion the girder. Also, from the comparison of the rotation angles graphs recorded by the devices installed at the opposite ends of the girder, there is some asymmetry resulting from the lack of full symmetry of the girder structure, such as girder inclination and various spans of outermost intervals, as well as the lack of uniformity of snow load.

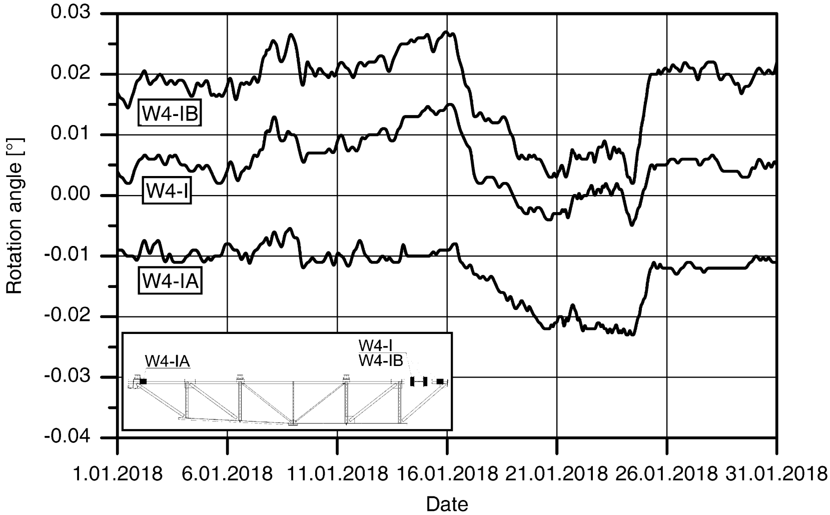


Fig. 9. The measurement results of the rotation angle at W4-I, W4-IA, W4-IB

In the period of snowfall described in reference to the purlins, i.e. from 16 to 21 January 2018, the maximum value of the rotation angles occurred at point W4-IB and equated to 0.024°, wherein in January 16-17 we also observe the effect of temperature - faster angle change. Similarly to the measurement of purlin angles, we can observe here a clear dependence of these changes on temperature, but it has the opposite direction than at the purlins, i.e. lowering the outside temperature leads to a change of angle in the opposite direction than the snow load. This behavior results from a different one than the purlins, the girder support scheme on the column and another solution of connections between the girders. Purlins are connected to each other with a certain eccentricity (see Fig. 4b), which in the situation of temperature changes leads to local bending of the upper purlin chord, to which inclinometers are fixed, in the opposite direction than the bending of the whole purlin.

On the other hand, in the case of girders, the connection between them is realized as axial (Fig. 4a), so there are no local deviations of the shape of deformations at the ends and under the influence of temperature the upper chord bend along the entire length in the same direction. The range of the rotation angles under the influence of temperature is comparable to that occurring in purlins - with temperature change of 8°C observed at the beginning of January (Fig. 7), the rotation angle is, depending on the device, from 0.004° to 0.007°.

The observed rotation angles due to temperature changes, both at the purlins and at the girders, are in the range of about 0.01° for every 10°C. This means that for the maximum possible temperature variations around ±30°C, we have to take into account the rotation angles up to ±0.03°, which in some cases is close to the value of the first threshold L1 - Table 1, so it is not negligible. In the case of installation of inclinometer devices on external structures exposed to the atmospheric conditions, temperature influence on the results of angular measurement should be taken into account by introducing appropriate correction of angular measurement results or selecting such places in the structure that are not sensitive to this effect.

The analysis of the measurement results for both purlins and girders shows that the tested method of monitoring of the structure deformation by measuring the rotation angles in characteristic places is a good alternative and supplementation of the method based on laser displacement measurements. It is characterized by a very good, better than with laser devices, measurement accuracy (Fig. 5, 8, 9), which allows to measure even very small changes in angles (even 0.001°), and thus, allows to monitor small changes in loads. An angle measurement resolution of 0.0001° (0.0018mm/m) and repeatability of ± 0.0005° (± 0.009mm/m) can be even achieved. In the case of the analysed structure elements, both purlins and girders, the smallest measurement unit corresponded to a roof load lower than 0.01 kN/m^2, which means that inclinometer sensors allow to "notice" a load change of less than 1 kg/m^2. Such a high accuracy of the discussed measurement method, in addition to an indisputable, beneficial effect on the effectiveness of the monitoring system, is also associated with some difficulties in the application of the system, resulting from temperature influence on the behavior of the structure. Sensors react even to very small changes in temperature of the structure, which somewhat hampers evaluation of the results and is particularly noticeable with small load ranges in external applications, when the rotation angles caused by thermal fluctuations are in the same order as angles caused by loads.

4. CONCLUSIONS

The purpose of the work described in this paper was to test the method of monitoring displacements of structure based on measurements of rotation angles with inclinometers. In contrast to optical measuring methods, inclinometers use gravity as a reference, so they are not limited by visibility conditions, which is particularly important in monitoring systems exposed to low temperatures or high humidity as well as high atmospheric pollution. The use of MEMS sensors in inclinometers, after applying the offset temperature drift correction procedure, allow to obtain high measurement accuracy at an acceptable price and low energy demand. Energy efficiency, apart from being in line with current ecological trends, makes devices inexpensive to operate, especially in wireless systems. In contrast to optical measurement methods requiring regular battery replacement and maintenance to ensure adequate cleanliness of the optics, inclinometers are practically maintenance-free, and in the case of wireless systems only battery replacement once for a few years is needed. Discussed method, based on the measurement of rotation angles using inclinometers with MEMS sensor, can therefore be a good alternative and supplement to optical methods using, for example, laser rangefinders.

The conducted research showed very good metrological properties of used MEMS sensor and its usefulness in the measurement method being developed. The device is characterized by a very good measurement resolution, by an order of magnitude better than with typical laser rangefinders. This allows to precisely monitor the load changes, even at the level of 0.01 kN/m^2, which is a much better result than required for this type of monitoring systems. The practical use of such high resolution, however, requires the proper approach to system design in specific applications as well as the correct interpretation of the measurement results in the context of taking into account thermal influences. In the era of current methods of design and structural analysis, this is obviously not an issue that would limit the application of this method in practice.

The research carried out so far confirms that the measurement of rotation angles using inclinometers with MEMS sensors is a good solution, better than traditional optical methods, for monitoring of structures. Further research should concern mainly the application of the described method in various structural systems, in terms of developing a methodology for determining optimal monitoring sites, allowing to obtain reliable and representative results under different load patterns and thermal influences.

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LIST OF FIGURES AND TABLES:

INKLINOMETRYCZNA METODA POMIARU PRZEMIESZCZEŃ W MONITORINGU KONSTRUKCJI JAKO ALTERNATYWA DLA OPTYCZNYCH METOD POMIAROWYCH - BADANIA NA KONSTRUKCJI

Słowa kluczowe: *monitoring konstrukcji, monitoring ugięć i kątów obrotu, inklinometr, bezprzewodowy monitoring konstrukcji, niskokosztowy system monitoringu*

STRESZCZENIE

W artykule przedstawiono badania "In-situ" metody monitorowania przemieszczeń konstrukcji, bazującej na pomiarach kątów obrotu realizowanych przy pomocy inklinometrów. Badania przeprowadzono w obiekcie produkcyjnym o stalowej konstrukcji nośnej, w którym występują zarówno przestrzenie zamknięte, nie narażone na ujemne temperatury i inne wpływy środowiskowe, jak i przestrzenie otwarte o charakterze wiat, narażone na bezpośrednie działanie środowiska atmosferycznego. Konstrukcję hali stanowi układ stalowych, jednoprzęsłowych płatwi kratowych o rozpiętości 18 m i dźwigarów kratownicowych o rozpiętości osiowej równej 15 m, opartych na słupach żelbetowych utwierdzonych w fundamentach. W obiekcie zainstalowano zarówno czujniki inklinometryczne jak i dalmierze laserowe, przy czym w artykule skupiono się na pomiarach kątów obrotu realizowanych przy pomocy czujników inklinometrycznych, a wyniki pomiarów ugięć były analizowane jedynie w celach porównawczych.

Zainstalowany system monitoringu był w pełni automatyczny, z bezprzewodową komunikacją i zasilaniem wszystkich urządzeń za wyjątkiem zarządzającej całością jednostki centralnej, która wymagała zasilania z sieci elektrycznej. Komunikacja z systemem odbywała się poprzez stronę WWW. Zadaniem systemu było monitorowanie zachowania się konstrukcji pod wpływem zmieniających się obciążeń i sygnalizowanie przekraczania kolejnych poziomów (wartości progowych) kątów obrotu i ugięć elementów konstrukcji, określonych w miejscach instalacji czujników. Generalnie zdefiniowane zostały cztery wartości progowe, odpowiadające 30%, 50%, 70% i 100% wartości obciążenia zmiennego, przy czym w przypadku bardzo małych poszczególnych wartości progowych ograniczano ich liczbę do 2 lub 3.

Przeprowadzone badania wykazały bardzo dobre właściwości metrologiczne zastosowanego w inklinometrach czujnika typu MEMS i jego przydatność w opracowywanej metodzie pomiarowej. Urządzenie charakteryzuje się wysoką rozdzielczością pomiaru, o rząd wielkości lepszą niż w przypadku typowych dalmierzy laserowych. Pozwala to monitorować zmiany obciążenia nawet rzędu 0,01 kN/m^2, co jest wynikiem znacznie lepszym niż wymagany w

systemach monitoringu. Praktyczne wykorzystanie tak wysokiej rozdzielczości wymaga jednak odpowiedniego zaprojektowania systemu i prawidłowej interpretacji wyników pomiarów z uwzględnieniem wpływów termicznych. Dotychczasowe badania potwierdziły, że pomiar kątów obrotu za pomocą inklinometrów MEMS jest dobrym rozwiązaniem do monitorowania konstrukcji. W przeciwieństwie do optycznych metod pomiarowych, inklinometry wykorzystują grawitację jako referencję, nie są więc ograniczane warunkami widoczności, co jest szczególnie ważne w instalacjach narażonych na niskie temperatury, wysoką wilgotność oraz duże zanieczyszczenie atmosfery. Czujniki typu MEMS, po zastosowaniu procedury korekcji temperaturowych zmian przesunięcia zera, pozwalają uzyskać wysoką dokładność pomiarów przy akceptowalnej cenie i niskim zapotrzebowaniu na energię. Energooszczędność, poza tym, że wpisuje się w aktualne tendencje proekologiczne, sprawia, iż urządzenia są tanie w eksploatacji, szczególnie w systemach bezprzewodowych. W przeciwieństwie do rozwiązań optycznych wymagających regularnej wymiany baterii i konserwacji w celu zapewnienia odpowiedniej czystości optyki, inklinometry są praktycznie bezobsługowe, a w przypadku systemów bezprzewodowych konieczna jest jedynie wymiana baterii raz na kilka lat.

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