THE DYNAMIC-STATIC METHOD (DSM) FOR STRUCTURAL DISPLACEMENT ANALYSIS USING THE EXAMPLE OF A WOODEN CHURCH IN DOMACHOWO (POLAND) *

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ABSTRACT:

Medieval architecture in Poland is not widely represented in the tangible cultural heritage. A preserved structure with traces of medieval architecture is the parish church in Domachowo in southern Greater Poland (Wielkopolska). Due to numerous alterations and modernisations, it is now a complex structure showing clear signs of a damaged original geometry.
For this reason, a project was initiated to measure the stability of the structure, especially under the influence of extreme external factors: mainly gusts of wind and uneven sun illumination. The implementation of the project required using two methods of measurement: static, at fixed time intervals, and dynamic, recorded on an ongoing basis during the operation of variable loads. The outcomes consisting of a combination of both methods and the unconventional use of precise inclinometers for measuring wooden structures, opens up new possibilities for real-time analysis of structural deformations and ongoing monitoring of technical conditions.
The subject of this paper is to present the methodology of the conducted static-dynamic measurements (DSM) and the interpretation of their results, mainly in the context of assessing accuracy, stability of long-term readings with inertial sensors, and basic structural assessment.

1. INTRODUCTION

1.1 Historical background

In Poland, as in other countries of the northern part of Europe, there are few surviving examples of old wooden constructions. They did not survive the test of time as a result of numerous fires, wars or damage caused by reckless exploitation. St Michael’s Church in Domachowo, located in the southern part of Greater Poland (Wielkopolska) is an interesting example of a wooden church with a double log structure. (Fig.1.) During the conservation works carried out in recent years, the internal structure of the church was uncovered showing polychromes on a wooden structure. The form and style of these cast doubt on the dating of the church.
Formally, the building is dated to the 16th century, however the additional dendrochronological research shows that some of the structural elements in the presbytery and roof truss come from the second half of the 14th century (1369), and some from the early 16th century (1503), which may move back the original construction date of the church. This allows for a hypothesis that, at least within the presbytery, the church dates to an earlier time (Różański A., et al, 2020). This fact may place it among the oldest built cultural property item in Poland. Subsequent to several fires in the 17th and 18th centuries, the church was rebuilt and extended, some of the outbuildings were pulled down and new ones were built in their place. In its final shape, the building dates to the 1920s, when a side chapel was added to the nave, cutting through some of the walls that connect both aisles. A choir with a belfry was also added.

Figure 1. The wooden church in Domachowo (Poland).

* The main part of this paper was previously published in the FIG 2022 conference proceedings (Wyczałek et al, 2022). We have since refined this method based on new measurements. The results and conclusions are presented herein.

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Currently, the main load-bearing structure of the church is a half-timbered frame connected with oak log walls, which have been preserved in the oldest part, in the chancel and in the main nave.

1.1 Justification and research problem

Traces of alterations from the 1920s indicate that even then the body of the church leans towards the west. Among other things, this is evidenced by windows inserted at a certain angle in relation to the (non-vertical) columns of the load-bearing structure. Also, the damaged column bases were undercut by brick fillings. Restoration work undertaken in 2019 revealed a number of weakened places in the structure, mainly those mentioned above, as well as joints at the junction between the presbytery and the nave carpentry notches and nests left by removed, undercut or cut-out elements.
The results of geodetic measurements suggest a significant deviation in the structure of the church and its elements, both in the presbytery and in the main nave. The heels show a variable value, depending on direction. Generally, the entire structure of the presbytery leans evenly towards the west by about 16 to 21 cm, and in the transverse direction, the pillars of the northern and southern walls lean towards the interior of the building.
Atmospheric factors: wind and heat caused by changes in solar illumination, were identified as the main source of structural displacements.

2. METHODOLOGY AND ASSUMPTIONS

2.1 State of research and publications

Among other methods, the project involved precise tachymetry, used for determining the displacements of bridges (Yu at al., 2017; Omidalizarandi, 2018; Olaszek et al., 2020; Vurpillot, 2000) and other engineering structures (Pieraccini et al., 2004; Kromanis, 2021), as well as historic buildings (Gil, E. et al., 2021; Petrovič, D. et al., 2021). To increase the accuracy and frequency of the measurements, the authors used hybrid solutions combining tachymetry with methods based on other devices, including cameras (Charalampous et al, 2014), accelerometers and/or other sensors (Pieraccini et al., 2004; Omidalizarandi, 2018; Vurpillot et.al, 2000; Kromanis et al., 2021). They also applied inertial methods, which are used in analysing the vibrations of bridges under operational load (e.g. Olaszek et al., 2020), as well as towers, masts and other slender structures loaded by wind (e.g. Pehlivan and Bayata, 2016; Wyczałek et al, 2013), in addition to, for example, swing bridges during movement (Wyczałek et al, 2019). In historic buildings, these have been used to a limited extent within wireless sensor networks (Barsocchi, P. et al., 2021). The dynamic methods with inclinometers have not yet been used in analyses of wooden structures.

2.2 Methodology

This paper presents the use of combined measurement techniques for monitoring the building in question. The authors discussed the scope of the expected displacements, location of targets and sensors, and the method of measuring and processing the outcomes. These showed the location of the weak places in the structure and the type of displacements. Based on this knowledge, conclusions were formulated regarding monitoring principles that could be applied to other historical wooden buildings.
The authors called this the dynamic-static method (DSM), which can be useful not only in analyses of structural displacements in wooden churches, but also in other historical buildings that are susceptible to dynamic deformation (Wyczałek et al, 2022).
Long-term studies were carried out in a one-month cycle and included three components related to two reference points that were considered stable. The authors decided to perform this task using the tachymetric method. Short-term measurements involved one of the typical monitoring techniques, based on the use of inertial sensors (inclinometres).

3. MAIN RESEARCH ORGANISATION

3.1 Measurement grid

In order to obtain representative statistical data, the authors assumed 6 measurement points (sites 1, 2, 3, 4, 5 and 9) and four biaxial inclinometers (points 996-999). (Fig.2) To control the accurateness of static – tachymetric – measurements, an additional point 3a was established, and to control the readings of inclinometers, two more sensors were installed (991 and 992). To complete the verification and control system, two additional points were provided at the junction of segments 2 and 3 (sites 6 and 8) and one point on the beam supporting the choir (7).

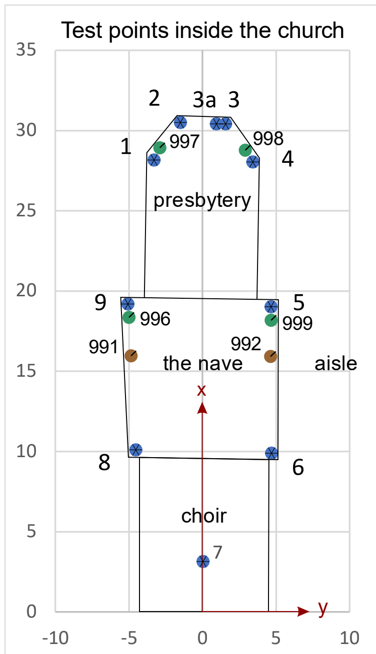

Figure 2. Distribution of test points - sites and inclinometers

In order to verify the hypothesis concerning the influence of atmospheric factors on the structure movement, the authors planned a calculation of correlation coefficients for two statistical representations: wind gusts and vibration values. Moreover, they checked the relationship between the static measurements and the displacement model based on the readings of the inclinometers.

3.2 Block diagram of measurements

For the purpose of assessing both the dynamics and statics of the building at the examined points, the authors developed a diagram of complementary measurements using TS (tilt sensors) and a weather station. The factors causing displacements which change the readings of the measuring devices were listed in the first block on the left; the second one showed the expected limit values of displacements at the ceiling level, and the third – the sensors used to carry out the measurements. (Fig.3.) The ‘calibration’ status was checked if the inclinometer readings changed by more than 1 mm compared to the tacheometric measurement. If an increasing trend of changes was found, a calibration adjustment was calculated, which was then taken into account for the adjustment of individual slope readings. This test was carried out separately for both axes of each of the inclinometers.

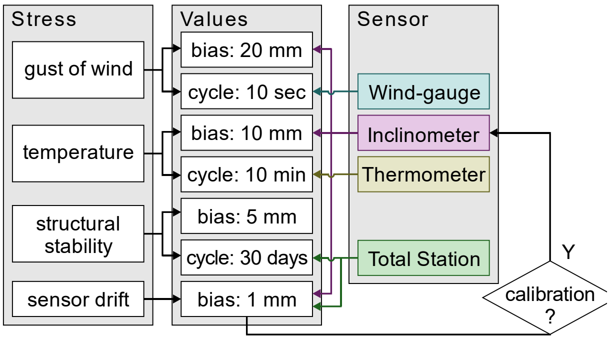

Figure 3. Block diagram of measurements

The data collected in this way allowed for the assessment of the correlation of the slope readings with the indications of wind gusts and the temperature on both sides of and inside the church.

3.3 Static monitoring

The basis of the static measurement is the tachymetric method, which was carried out with the use of a 1-second Leica TCRP 1201+ total station and targets in the form of reflective foil targets (Fig. 5). No prisms were used to ensure discretion of the measurement on an intensively operated object. The results of 15 double series of measurements showed discrepancies between the series in the range of −1 mm to +1 mm, with the most common values in the range of ± 0.2 mm.

The average variability of all displacement components between consecutive measurements was 0.4 to 0.6 mm, and compared to the initial state, only about 0.2 mm higher. Ultimately, the total detected inclinations did not exceed 1.5 mm in the ux direction (along the nave) and 3.6 mm in the uy direction. The longitudinal slope had a positive sign in the eastern part, and a negative sign in the western part, which indicates a parting of the structure. With regard to lateral movement, the greatest positive values were found in segment 1 (presbytery), while the central nave was stable. On the other hand, the magnitude of the vertical displacements was entirely within measurement errors, so there was no reason to conclude that the building had any settlements. The above analysis illustrates the technical and accuracy capabilities of the tachymetric method in assessing the stability of a structure subjected to periodic dynamic loads. The obtained accuracy parameters are consistent with the results of other similar measurements and guarantee proper spatial resolution of the stability assessment of the tested structure. The actual results confirm the special features of wooden structures, even very old ones, which, despite intense loads, do not undergo permanent deformation.

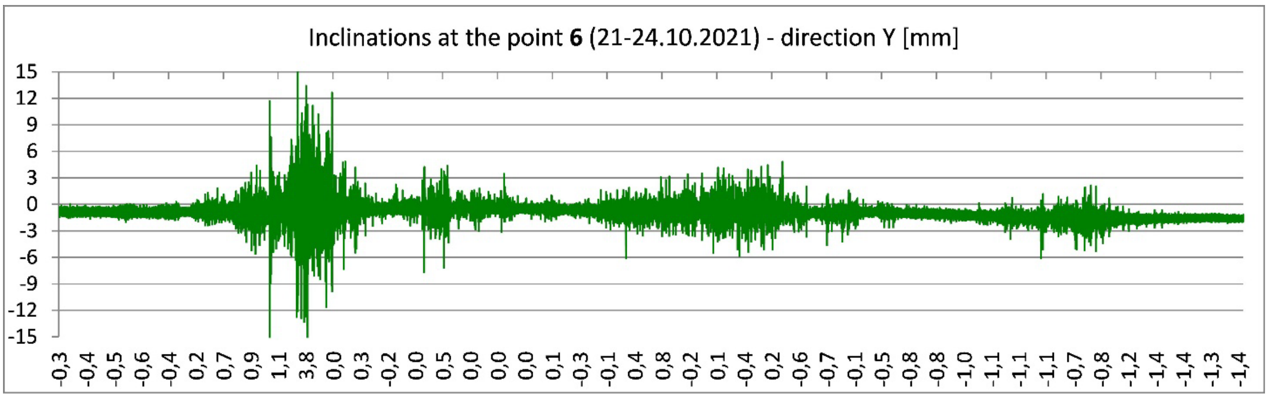

Figure 4. Selected diagram of structure vibration at point 996 in the 3-day recording period during strong winds: inclinations across the church, y axis direction

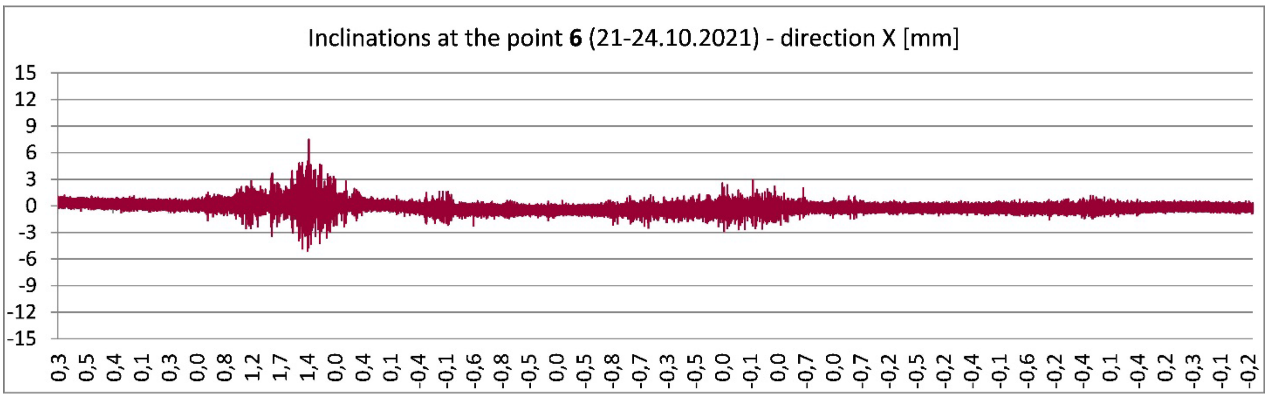

Figure 5. Selected diagram of structure vibration at point 996 in the 3-day recording period during strong winds: inclinations along the church, x direction.

3.4 Dynamic monitoring

Dynamic monitoring requires continuous or quasi-continuous measurement of vibration (period, amplitude), inclination (one or more angles) or changes in other physical parameters. Earlier studies (Wyczałek et al., 2013, 2019) successfully used the POSITAL FRABA ASG15 capacitive inclinometers with wire data transmission in the CANOPEN standard. Currently, two such inclinometers are used to verify the indications of a new set of BWSENSING WF-WM400 wireless precise inclinometers made in the MEMS technology. These in turn are characterized by a reading resolution of 0.001° and a declared precision of 0.005°, zero temperature drift 0.001° and an interaxial drift of 0.001° at work at 25° C. The sensors can be powered by solar energy or a 4.2 VDC charger. They can read inclinations with a very high frequency (up to 50 Hz) and then transmit the signals wirelessly using a WiFi network.
In the basic version, four inclinometers powered from the power grid were installed on the site. Readings were collected synchronously every 2 seconds via a local WiFi server and saved to disk, and then remotely downloaded via the Internet.
After the initial tests and analyses, the authors set the frequency of recording the readings at every 10 seconds.
The diagrams (Fig.4 and Fig.5) show the measurements of the inclinations at point 996 changed up to +/- 15 mm during strong winds on 21-24 October 2021, taking into account the adjustments resulting from the absence of plastic deformation of the structure under test (zero displacement of points measured with the complete station under set weather conditions: no wind, temperature 5–10 °C, poor sunlight).

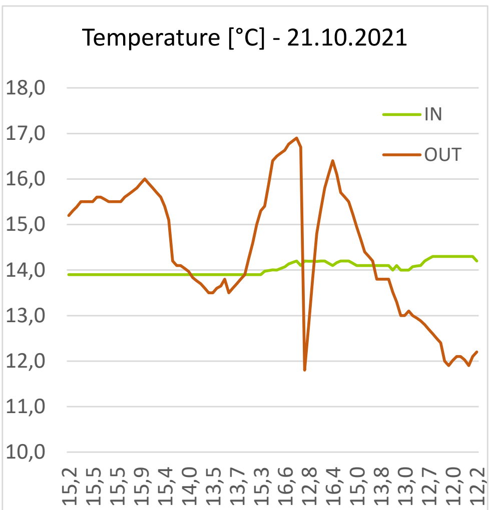

Figure 6. Readings of basic weather parameters on 21 October 2021, in turn: air temperature.

3.5 Recording weather conditions

In order to compare the results of inclination measurements with the atmospheric conditions, a SENCOR 12500 WiFi weather station was set up near the building (distance approx. 5 m, height approx. 5 m above the church floor), which included a base with a thermometer (inside the building) and a set of sensors: 2 thermometers (range −40 to + 60 °C, resolution 0.1 °C, precision 1 °C), (Fig.6) barometer (Fig.7), anemometer (range 0-50 m/s, resolution 0.1 m/s, precision 0.5 m/s) (Fig.8) and rainfall meter at the top of the lighting pole near the church. Thanks to the access to the Weathercloud website, it was possible to remotely view the station readings in a 10-minute cycle. Archival data was also collected in this cycle, which could be remotely downloaded in the form of a *.csv file, and then processed and analysed using own methods or software. This data was then used for comparison with the results of inclinometric measurements.

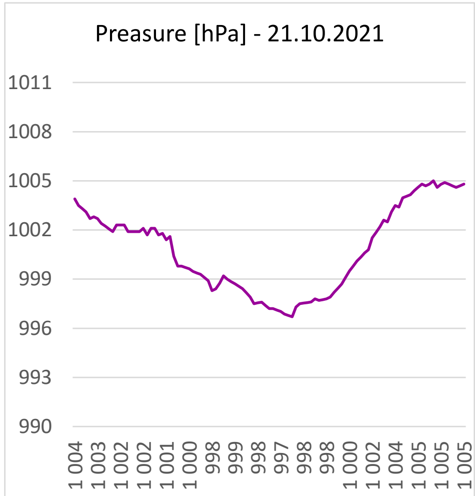

Figure 7. Readings of basic weather parameters on 21 October 2021, in turn: pressure.

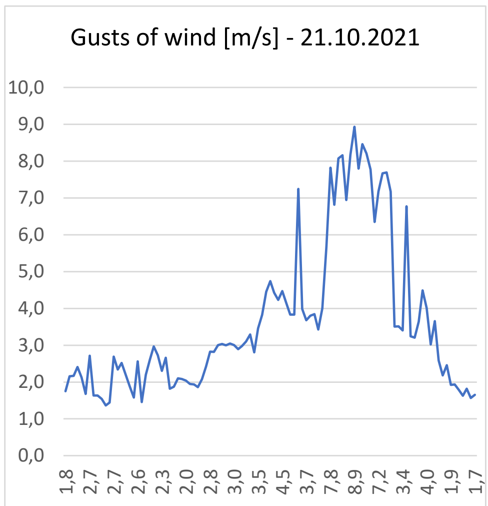

Figure 8. Readings of basic weather parameters on 21 October 2021, in turn: gusts of wind.

3.6 Synchronization of data

Due to the available frequency of data acquisition from the weather station, the authors assumed that all readings would be processed into 10-minute cycles for further analysis.
For the purpose of a joint study of the research results, it was assumed that the results of a single tachymetric measurement (2 full series converted into 3 displacement components) would be grouped into 1-month blocks, including: readings of atmospheric indicators, readings of 4 WF/WM400 inclinometers in two directions and maximum 2 WGS15 control inclinometer readings for both axes.

Up to the time of writing this paper, the research lasted 18 months, some of which were very calm, whilst the winter part of the study was characterized by considerably violent gusts of wind, which provided an interesting set of data constituting good starting material for the assessment of the building's condition.

4. SUMMARY AND CONCLUSIONS

Earlier experience with the combined use of a complete station and tilt sensors provided a solid basis for using such a solution to measure the displacements of the building discussed herein. Subsequently, an image of its response to the influence of significant wind pressures and heating under the influence of solar illumination was obtained on the one hand, and on the other, from the point of view of long-term stability (i.e. no permanent deformation) of the structure. Electronic tachymetry is a reliable method for static measurements, which, even with a 1-second, ensures sub-millimetre accuracy of the individual displacement components. It also guarantees a very high reproducibility of the results, which provided, during the one-year period of research, a reliable image of the building's condition as a function of time. The use of wireless inclinometers gave an image of the building's susceptibility, in various places, to significant forces caused by weather conditions, mainly gusts of wind. (Fig.9)
Based on the combination of both methods, during a quiet time it was possible to harmonise the readings by adjusting them mathematically.

5. PROSPECT AND DISCUSSION

With regard to the study of a specific wooden building presented herein, the authors found that due to the significant pressure of gusts of wind, the uneven vibrations in its structure reached ± 20 mm in some places, which allowed for the identification of the most sensitive places for numerical analysis and for taking possible protective measures. However, there were no inclinations due to changes in heating from sunlight. This impact will be analysed in more detail this summer. On the other hand, long-term measurements have, so far, shown the high stability of the structure.
The outcomes of the study refer to a specific building, however, the authors believe that these methods can and should be implemented in other old buildings or wooden constructions. Thanks to the implementation of remote data transmission techniques, proven in other monitoring applications, such surveys can be remotely supervised and the participation of the surveyor may be limited to taking tachymetric measurements several times.
For the purpose of evaluating the impact of external factors, the research was carried out to assess the displacements in a long-term perspective and short-term changes in displacements recorded in real time. Such a combined method was probably used for the first time for historic wooden structures.
The monitoring of historic buildings exposed to dynamic deformations is of particular importance. In this case the dynamic-static method (DSM) can be useful not only for analyses of the structural displacement of wooden churches, but also for other historical buildings that are susceptible to dynamic

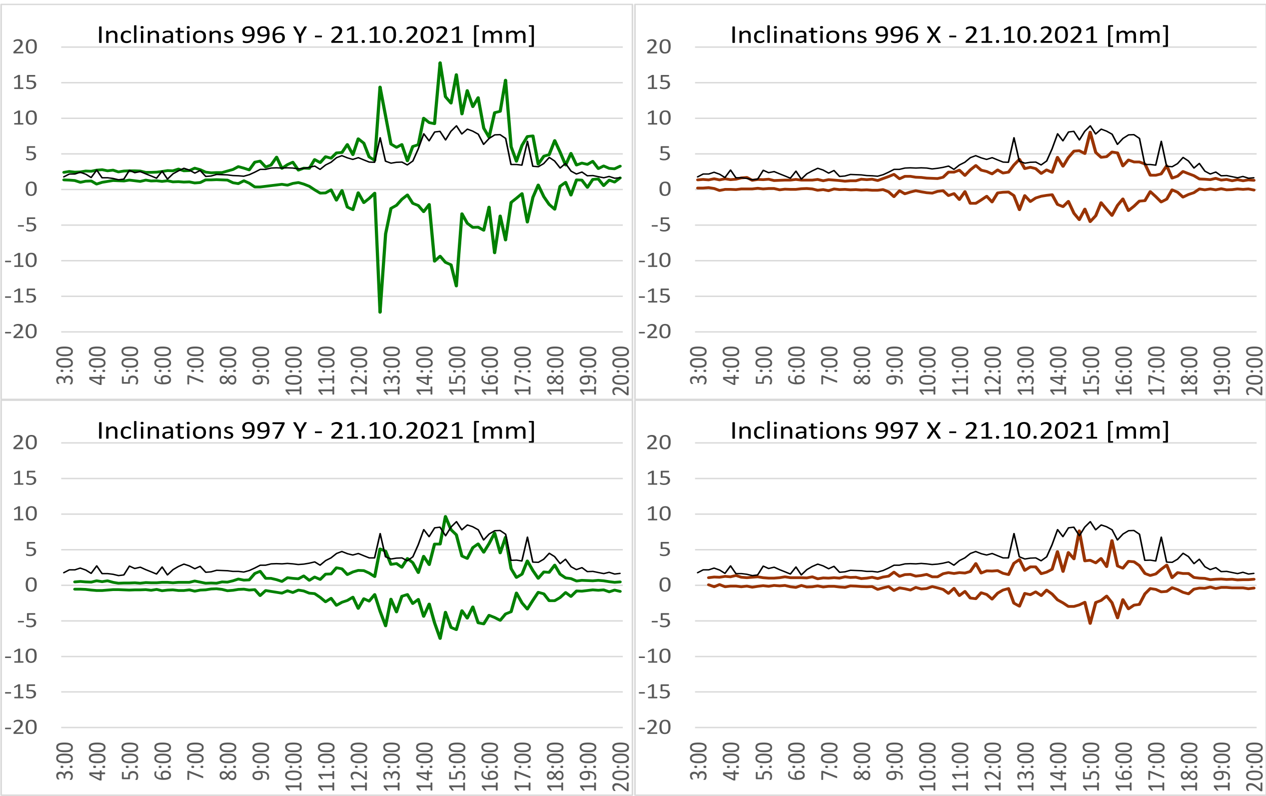

Figure 9. Readings of the maximum inclinations of the studied building in 4 places (sensors 996, 997, 998 and 999) at the ceiling level, corresponding to the readings from the weather station in Fig. 7; the thin black line indicates gusts of wind measured by the weather station

deformation, for example during vibrations or minor earthquakes. The method can also be incorporated into practical applications of the Internet of Things and real-time data transfer.

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