Static and dynamic measurements of the historic wooden church building in Domachowo

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Key words: wooden building, displacements, inertial sensors, total station

SUMMARY

Medieval architecture in Poland has not a large representation of material cultural heritage. At that time, building structures were largely made of wood, and these, in turn, did not survive the test of time as a result of numerous fires, war conflagrations or damage caused by reckless exploitation.
One of the preserved objects with traces of medieval architecture is the parish church in Domachowo in southern Wielkopolska. The architectural and historical research conducted in recent years indicates not only a change in the dating of the building but also a number of potential operational problems. Due to its numerous reconstructions and modernizations, it is now a complex structure with clear symptoms of the damaged original geometry. For this reason, a project was created to control the stability of the church structure, especially under the influence of extreme external factors – mainly wind gusts and uneven sun illumination. The implementation of the project required the simultaneous taking of two methods of measurement – static, at fixed time intervals, and dynamic, recorded on an ongoing basis during the operation of variable loads. Both types of measurements were made based on the experience of geodetic structural monitoring. For the purposes of static measurements, 9 reflective targets were installed, which were measured with the precision Total Station Leica TCRP 1201+ in relation to two fixed reference points. On the other hand, dynamic measurements were performed using two sets of inclinometers - two sensors POSITAL CANopen ASG15 and four WF-WM400 BWSENSING WiFi Wireless High-Speed High Accuracy Inclinometer Sensors. A CCL Electronics W100 weather station was also installed, allowing for ongoing monitoring of the external working conditions of the structure. The research conducted so far shows the stability of the church structure against long-term loads and at the same time relatively high vibrations and operation of the structure due to the pressure of violent gusts of wind – up to about ±18 mm at the ceiling level. The subject of this publication is the presentation of the methodology of the conducted static-dynamic tests and the interpretation of their results, mainly in the context of the assessment of accuracy, stability of long-term readings with inertial sensors, and basic structural and building assessment.

SUMMARY (optional summary in one other language in addition to English, e.g. your own language)

Budownictwo średniowieczne w Polsce nie stanowi licznej reprezentacji materialnego dziedzictwa kulturowego. Obiekty budowlane były wówczas w dużej mierze konstrukcjami drewnianymi, a te z kolei nie przetrwały próby czasu w wyniku licznych pożarów, pożogi wojennej czy zniszczeń spowodowanych lekkomyślną eksploatacją.
Jednym z zachowanych obiektów ze śladami średniowiecznej architektury jest kościół parafialny w Domachowie, w południowej Wielkopolsce. Prowadzone w ostatnich latach badania architektoniczno-historyczne wskazują nie tylko na zmianę datowania budynku, ale także na szereg potencjalnych problemów eksploatacyjnych. Dzięki licznym przebudowom i modernizacjom budynek kościoła jest obecnie konstrukcją złożoną, z wyraźnymi objawami uszkodzonej pierwotnej geometrii. Z tego powodu powstał projekt kontroli stateczności konstrukcji, zwłaszcza pod wpływem ekstremalnych czynników zewnętrznych – głównie podmuchów wiatru i nierównomiernego oświetlenia słonecznego. Realizacja projektu wymagała jednoczesnego użycia dwóch metod pomiarowych – statycznej, w stałych odstępach czasu oraz dynamicznej, rejestrowanej na bieżąco podczas oddziaływania zmiennych obciążeń. Oba rodzaje pomiarów wykonano w oparciu o doświadczenia monitoringu geodezyjnego. Na potrzeby pomiarów statycznych zainstalowano 9 odblaskowych celów, które są mierzone precyzyjnym tachimetrem Leica TCRP 1201+ w nawiązaniu do dwóch stałych punktów odniesienia. Pomiary dynamiczne są wykonywane przy użyciu dwóch zestawów inklinometrów – dwóch inklinometrów POSITAL CANopen ASG15 i czterech bezprzewodowych sensorów inklinometrycznych WF-WM400 BWSENSING WiFi o dużej prędkości i wysokiej dokładności. Zainstalowano również stację pogodową CCL Electronics W100, pozwalającą na bieżący monitoring zewnętrznych warunków pracy konstrukcji. Przeprowadzone dotychczas badania wskazują na stabilność konstrukcji kościoła wobec długotrwałych obciążeń, a przy tym stosunkowo duże drgania konstrukcji pod wpływem naporu gwałtownych podmuchów wiatru – do ok. ±18 mm na poziomie sufitu. Przedmiotem niniejszej publikacji jest przedstawienie metodyki przeprowadzonych badań statyczno-dynamicznych oraz interpretacja ich wyników, głównie w kontekście oceny dokładności i stabilności odczytów sensorów bezwładnościowych w długim przedziale czasu, a także oceny zachowania się konstrukcji w funkcji czasu oraz wskutek oddziaływania ekstremalnych obciążeń, zarejestrowanych podczas badań.

Static and dynamic measurements of the historic wooden church building in Domachowo

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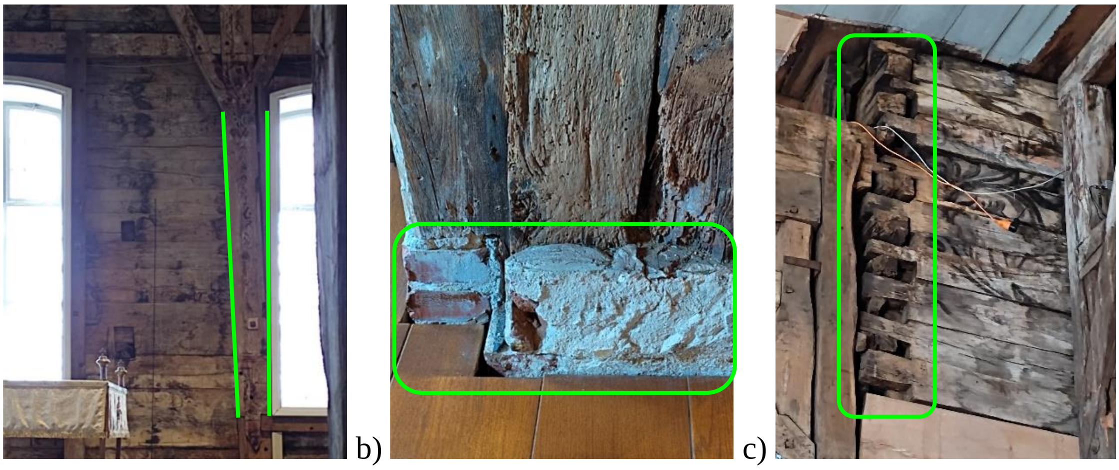
1. RESEARCH PROBLEM

In Poland, as in other countries of the northern part of Europe, not many monuments of the old wooden construction have survived – they did not survive the test of time as a result of numerous fires, war conflicts or damage caused by reckless exploitation. That is why the wooden building of the parish church in Domachowo, southern Wielkopolska, is a unique monument of cultural heritage. Formally, it is dated to the 16th century, however, it contains preserved fragments of timbered walls with paintings from the 14th century, which allows for a hypothesis that at least within the presbytery it comes from this distant time (Różański A., et al, 2020). This fact places it among the oldest construction monuments in Poland and Central Europe. As a result of 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. The final shape was given to the building in the 1920s (Fig. 1a), when a side chapel was added to the nave, cutting out some of the walls connecting both aisles (Fig. 1b). A choir with a belfry was also added. 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.

a)  b) 

Fig. 1. Church in Domachowo: a) external view from the NW side, b) view of the southern wall of the nave, partially resected for access to the side chapel.

Traces of reconstruction from the 1920s indicate that even then the body of the church was leaning 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 (Fig. 2a). Also, the damaged column bases were undercut by filling these places with bricks (Fig. 2b). Restoration work undertaken in 2019 revealed a number of weakened places in the structure, mainly those mentioned above, but also, inter alia, connections at the junction between the presbytery and the nave (fig. 2c), carpentry notches and nests after removed elements, or elements undercut or cut out. The above observations were the basis for an attempt to strengthen the structure, which was preceded by a diagnosis of the existing state, also taking into account displacement measurements.



a) b) c)

Fig. 2. Visible weaknesses in the structure of the church: a) the columns of the original frame structure significantly inclined towards the entrance (west), b) the brick base of the column, which was originally entirely wooden, c) weakened connections of the carcass structure

Atmospheric factors – wind operation and solar heating, resulting from changes in solar illumination – were identified as the main source of displacements of the church structure. The influence of changing groundwater level was also considered, but this factor was finally rejected. For the purposes of assessing the impact of external factors, a research program was planned, including the assessment of displacements in a long-term perspective and short-term changes in displacements recorded in real time. Long-term studies are carried out cyclically every month and include three components related to two reference points considered as stable. It was decided to perform this task using the tachymetric method. Short-term measurements are made of one of the typical monitoring techniques, based on the use of inertial sensors. In this regard, the experiences described in the literature on the subject were used and based on the author's own previous experiences.
Among others, precise tachymetry – the method based on measurement distances, directions and vertical angles – was used for determining the displacements of tunnels (Luo Y. et al., 2016; Zhou J. et al., 2020), bridges (Yu at al., 2017; Omidalizarandi et al., 2018; Olaszek et al., 2020; Vurpillot, 2000), dams (Woźniak, 2006; Zhou et al, 2021) 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). Accuracy analyzes, as well as own experience, show that this technique allows obtaining sub-millimeter accuracy (Luo Y. et al, 2016; Yu at al., 2017; Zhou et al, 2021), and in laboratory displacement measurements, accuracy even up to 0.1 mm (Woźniak, 2006; Kovačič et al, 2016). To increase the accuracy and frequency of measurements, hybrid solutions were used, combining tachymetry with methods using 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). Inertial methods were used in the analysis of vibrations of bridges under operational load (e.g. Olaszek et al., 2020), towers, masts and other slender structures loaded with wind (e.g. Pehlivan and Bayata, 2016; Wyczałek et al, 2013), as well as objects in motion, such as swing bridgesas (Wyczałek et al, 2019). In historic buildings, they were used to a limited extent, e.g. with the use of wireless sensor networks (Barsocchi, P. et al., 2021).
This paper presents the use of combined measurement techniques for monitoring the object mentioned above. The scope of expected displacements, the location of targets and sensors as well as the method of measuring and processing the results were discussed. The obtained results showed where the weak places of the tested structure are, what are the displacements and what is their correlation with the values of atmospheric factors affecting the tested object. It was found that the combination of the tilt measurement with the results of a (static) total station allows not only to calibrate the calculation algorithm but also to correct the drift of the inclinometers. Based on the experience gained, conclusions were formulated as to the monitoring principles that can be applied to other historical wooden buildings.

2. SELECTION OF MEASUREMENT PLACES, METHODS AND EQUIPMENT

2.1 The mathematical model

Based on the identified process of construction progress, four segments were distinguished on the tested structure (Fig. 3) and the condition of the connections between them was analyzed. It was found that:

1) a special character has the structure of the presbytery (segment 1, the oldest), which is a combination of a skeleton structure and logs; in relation to it, a hypothesis about the constancy of such a connection was formulated;
2) the weakest places were identified at the junction of the presbytery (segment 1) and the nave (segment 2); for them, a hypothesis about the instability of the connection was adopted.

It was assumed that the constancy of the structure is characterized by temporary displacements not greater than ±20 mm – the normal distribution N(0,20), and permanent displacements not exceeding ±5 mm – distribution N(0,5). Verification of the hypotheses about the instability of the indicated places of the structure should show that the movement of points in the given places is either negligibly small (hypothesis 1) or significantly large (hypothesis 2). Moreover, the results of the displacements of the remaining points should show their negligible values.

2.2 Measurement network

In order to obtain representative statistical data, 6 measurement points (marked sights numbered in Fig. 3a as 1, 2, 3, 4, 5 and 9) and four biaxial inclinometers (points numbered as 996-999) were assumed. To control the correctness of static – tachymetric – measurements an additional point 3a was established, and to control the indications of inclinometers, two more sensors were installed, 991 and 992. To complete the verification and control system, two additional

points were assumed at the meeting point of segments 2 and 3 (sights 6 and 8) and one point on the beam supporting the choir (7).
In order to verify the hypothesis about the influence of atmospheric factors on the structure movement, the calculation of correlation coefficients for two statistical representations – wind gusts and vibration values was planned. Moreover, the relationship between the static measurement results and the displacement model based on the indications of the inclinometers was checked.

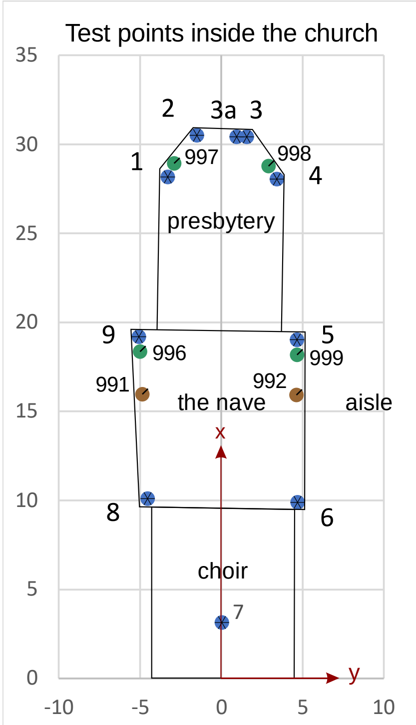


Fig. 3. Distribution of test points - sights and inclinometers - on the object (explanations in the text)

3. THE COURSE AND RESULTS OF MEASUREMENTS

2.3 Research flow chart

For the purpose of assessing both the dynamics and statics of the object at the examined points, a diagram of complementary measurements using TS, tilt sensors and the weather station was developed. It is presented graphically in Fig. 4. In the first block from the left, the factors causing displacements conducting a change in the readings of the measuring devices were listed; in the second one – the expected limit values of displacements at the ceiling level, in the third – the sensors used to carry out the measurements. The 'calibration' condition is checked if the inclinometer readings change more than 1 mm compared to the tacheometric measurement. If an increasing trend of changes is found, a calibration correction is calculated, which is taken into account for the correction of individual slope readings. This test is carried out separately for both axes of each of the inclinometers. The data collected in this way allows for the assessment of the correlation of the slope readings with the indications of wind gusts and the temperature on both sides outside and inside the church.

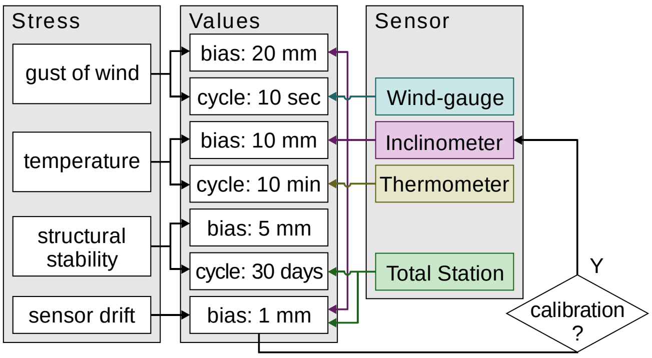


Fig. 4. Block diagram of the measurements: "bias" means the permissible values of displacement at the ceiling level, "cycle" defines the interval of data acquisition.

2.4 Static measurements

The basis of the static measurement is the tachymetric method – it 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. Based on previous experience, it was estimated that for distances up to 10 m and vertical angles up to 40°, all coordinates can be determined with the mean error of a single measurement ±1.0 mm and the error of the mean of 4 readings ±0.5 mm. 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 (Table 1). The sights are located 6.45−6.85 m above the floor level, while the ceiling rises to a height of just over 7 m. The height of 7.0 m is considered to be representative of the level for which the displacements are calculated. It was decided to control both the movement horizontally (ux, uy) and vertically (uz), but in order to avoid the results caused by subsidence of the foundations, as well as possible shrinkage and expansion of the structure, in addition, vertical displacements on the columns just above the floor are measured (points 11 and 12 in Fig. 3).

Fig.5. Leica TCRP 1201+ total station in the station in the center of the nave; on the left side, a reflective foil target – one of the points of reference.

Table 2 presents the results of measurements of displacements in ten consecutive months; values exceeding 2 mm are marked in red. The results presented in the table show that the average variability of all displacement components between consecutive measurements is 0.4 to 0.6 mm, and compared to the initial state – only about 0.2 mm higher. The exception is the average error in the transversal direction (uy), equal to 1.2 mm, which may suggest a certain tendency to tilt the body of the church to the sides. According to the '3σ' statistical rule, such accuracies allow to detect displacements along individual axes greater than 1.5 mm (and in one case – 3.5 mm). Ultimately, the total detected inclinations do not exceed 1.5 mm in the ux direction (along the nave) and 3.6 mm in the uy direction. The longitudinal slope has 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 are found in segment 1 (presbytery), while the central nave is stable. On the other hand, the magnitude of the vertical displacements is entirely within the measurement errors, so there is no reason to conclude that there are any object settlements.

Table 2. Components of displacements between the 'initial' and 'current' measurement (top) and between the 'previous' and 'current' measurement (bottom) determined by the tachymetric method.

pomiar_4		25.03.14:00	
delta_0–4			
0–4'1	0,0	-0,1	-0,3
0–4'2	-0,5	0,1	-0,5
0–4'3	-0,8	-0,2	-0,4
0–4'3a	-0,3	0,0	-0,7
0–4'4	0,2	-0,4	0,8
0–4'5	-0,4	-1,3	-1,6
0–4'6	-0,1	-1,5	-0,8
0–4'7	-0,1	-0,1	-1,1
0–4'8	-0,1	-0,9	-0,7
0–4'9	-0,8	-0,9	-0,8
średnio	*-0,3*	*-0,5*	*-0,6*
odch.std.	*0,3*	*0,6*	*0,6*
delta_2-4			
3–4'1	0,0	-0,1	-0,3
3–4'2	-0,5	0,1	-0,5
3–4'3	-0,8	-0,2	-0,4
3–4'3a	-0,3	0,0	-0,7
3–4'4	0,2	-0,4	0,8
3–4'5	-0,4	-1,3	-1,6
3–4'6	-0,1	-1,5	-0,8
3–4'7	-0,1	-0,1	-1,1
3–4'8	-0,1	-0,9	-0,7
3–4'9	-0,8	-0,9	-0,8
średnio	*-0,3*	*-0,5*	*-0,6*
odch.std.	*0,3*	*0,6*	*0,6*

pomiar_5		22.04.11:30	
delta_0–5			
0–5'1	-1,0	-0,2	-1,1
0–5'2	-1,5	0,2	-1,1
0–5'3	-1,8	-0,5	-0,9
0–5'3a	-1,2	-0,3	-1,1
0–5'4	-0,5	0,0	-0,4
0–5'5	-0,6	-1,4	-2,1
0–5'6	-0,4	-0,1	-1,4
0–5'7	-0,5	-0,2	-1,6
0–5'8	-1,2	-0,1	-0,8
0–5'9	-1,4	-0,9	-1,2
średnio	*-1,0*	*-0,4*	*-1,2*
odch.std.	*0,5*	*0,5*	*0,5*
delta_4-5			
4–5'1	-1,0	-0,1	-0,8
4–5'2	-1,0	0,1	-0,6
4–5'3	-1,0	-0,3	-0,5
4–5'3a	-0,9	-0,3	-0,4
4–5'4	-0,7	0,4	-1,2
4–5'5	-0,2	-0,1	-0,5
4–5'6	-0,3	1,4	-0,6
4–5'7	-0,4	-0,1	-0,5
4–5'8	-1,1	0,8	-0,1
4–5'9	-0,6	0,0	-0,4
średnio	*-0,7*	*0,2*	*-0,6*
odch.std.	*0,3*	*0,5*	*0,3*

pomiar_6		18.05.14:30	
delta_0–6			
0–6'1	-0,5	-0,3	0,0
0–6'2	-1,4	0,5	-0,8
0–6'3	-2,1	-0,1	-0,8
0–6'3a	-1,5	0,1	-1,0
0–6'4	-0,8	0,2	-0,6
0–6'5	-1,3	-1,7	-2,1
0–6'6	-0,8	-1,8	-1,6
0–6'7	-0,8	-1,2	-1,5
0–6'8	-0,4	-1,5	-1,1
0–6'9	-0,9	-1,0	-1,2
średnio	*-1,1*	*-0,7*	*-1,1*
odch.std.	*0,5*	*0,9*	*0,6*
delta_5-6			
5–6'1	0,5	-0,1	1,1
5–6'2	0,1	0,3	0,3
5–6'3	-0,3	0,4	0,1
5–6'3a	-0,3	0,4	0,1
5–6'4	-0,3	0,2	-0,2
5–6'5	-0,7	-0,3	0,0
5–6'6	-0,4	-1,7	-0,2
5–6'7	-0,3	-1,0	0,1
5–6'8	0,8	-1,4	-0,3
5–6'9	0,5	-0,1	0,0
średnio	*0,0*	*-0,3*	*0,1*
odch.std.	*0,5*	*0,8*	*0,4*

pomiar_7		19.06.11:00	
delta_0–7			
0–7'1	-0,6	-0,4	0,3
0–7'2	-1,8	0,3	-0,6
0–7'3	-1,1	-0,4	-0,1
0–7'3a	-1,0	0,0	-0,1
0–7'4	-0,8	-0,1	-0,1
0–7'5	-1,2	-2,4	-1,6
0–7'6	-1,0	-1,6	-1,0
0–7'7	0,2	-1,2	-1,4
0–7'8	0,1	-1,6	-1,1
0–7'9	-1,2	-1,8	-0,7
średnio	*-0,8*	*-0,9*	*-0,6*
odch.std.	*0,6*	*0,9*	*0,6*
delta_5-6			
6–7'1	-0,1	-0,1	0,3
6–7'2	-0,4	-0,2	0,2
6–7'3	1,0	-0,3	0,7
6–7'3a	0,5	-0,1	0,9
6–7'4	0,0	-0,3	0,5
6–7'5	0,1	-0,7	0,5
6–7'6	-0,2	0,2	0,6
6–7'7	1,0	0,0	0,1
6–7'8	0,5	-0,1	0,0
6–7'9	-0,3	-0,8	0,5
średnio	*0,2*	*-0,2*	*0,4*
odch.std.	*0,5*	*0,3*	*0,3*

pomiar_8		21.07.14:30	
delta_0–8			
0–8'1	-0,8	0,3	-0,2
0–8'2	-1,4	1,1	-0,3
0–8'3	-2,3	2,0	-1,8
0–8'3a	-1,4	0,6	-0,7
0–8'4	-1,7	0,4	-0,5
0–8'5	-1,4	-2,2	-1,1
0–8'6	-1,3	-2,3	-0,5
0–8'7	-0,1	-3,1	-1,3
0–8'8	0,1	-2,6	-0,9
0–8'9	1,5	-0,7	-0,2
średnio	*-0,9*	*-0,7*	*-0,8*
odch.std.	*1,1*	*1,8*	*0,5*
delta_7-8			
7–8'1	-0,2	0,7	-0,5
7–8'2	0,4	0,8	0,3
7–8'3	-1,2	2,4	-1,7
7–8'3a	-0,4	0,6	-0,6
7–8'4	-0,9	0,5	-0,4
7–8'5	-0,2	0,2	0,5
7–8'6	-0,3	-0,7	0,5
7–8'7	-0,3	-1,9	0,1
7–8'8	0,0	-1,0	0,2
7–8'9	2,7	1,1	0,5
średnio	*0,0*	*0,3*	*-0,1*
odch.std.	*1,1*	*1,2*	*0,7*

pomiar_9		27.08.11:00	
delta_0–9			
0–9'1	-0,4	-0,2	0,3
0–9'2	-2,0	0,5	-0,7
0–9'3	-2,3	1,0	-1,7
0–9'3a	-1,4	1,1	-0,7
0–9'4	-2,0	0,3	0,0
0–9'5	-1,5	-1,9	-0,6
0–9'6	-1,1	-1,4	-0,2
0–9'7	-0,7	-1,2	-0,3
0–9'8	-1,0	-1,5	0,0
0–9'9	-1,2	-0,9	-0,5
średnio	*-1,4*	*-0,4*	*-0,4*
odch.std.	*0,6*	*1,1*	*0,6*
delta_8-9			
8–9'1	0,4	-0,5	0,5
8–9'2	-0,6	-0,6	-0,4
8–9'3	0,0	-1,0	0,1
8–9'3a	0,0	0,5	0,0
8–9'4	-0,3	-0,1	0,5
8–9'5	-0,1	0,3	0,5
8–9'6	0,2	0,9	0,3
8–9'7	-0,6	1,9	1,0
8–9'8	-1,1	1,1	0,9
8–9'9	-2,7	-0,2	-0,3
średnio	*-0,5*	*0,2*	*0,3*
odch.std.	*0,9*	*0,9*	*0,5*

pomiar_10		25.09.10:30	
delta_0–10			
0–10'1	-0,7	0,2	0,6
0–10'2	-0,8	1,1	-0,1
0–10'3	-1,2	1,9	-1,2
0–10'3a	-0,5	0,8	-0,6
0–10'4	-1,3	0,8	0,5
0–10'5	-1,1	-1,2	-0,4
0–10'6	-0,7	-1,1	0,2
0–10'7	-0,7	-1,4	-0,2
0–10'8	-0,5	-1,2	0,8
0–10'9	-0,3	-0,4	-0,3
średnio	*-0,8*	*0,0*	*-0,1*
odch.std.	*0,3*	*1,2*	*0,6*
delta_9-10			
9–10'1	-0,3	0,4	0,3
9–10'2	1,2	0,6	0,6
9–10'3	1,1	0,9	0,5
9–10'3a	0,9	-0,3	0,1
9–10'4	0,7	0,5	0,5
9–10'5	0,4	0,7	0,2
9–10'6	0,4	0,3	0,4
9–10'7	0,0	-0,2	0,1
9–10'8	0,5	0,3	0,8
9–10'9	0,9	0,5	0,2
średnio	*0,6*	*0,4*	*0,4*
odch.std.	*0,5*	*0,4*	*0,2*

pomiar_11		27.10.21 10:3	
delta_0–11			
0–11'1	-0,1	0,3	0,8
0–11'2	-0,8	0,8	0,1
0–11'3	-1,6	2,2	-1,2
0–11'3a	-0,9	1,1	-0,1
0–11'4	-1,3	1,1	0,8
0–11'5	-1,0	-1,8	0,3
0–11'6	-1,1	-1,7	0,8
0–11'7	0,2	-1,5	0,7
0–11'8	-0,2	-2,5	1,0
0–11'9	0,0	-1,6	0,9
średnio	*-0,7*	*-0,4*	*0,4*
odch.std.	*0,6*	*1,6*	*0,7*
delta_9-10			
10–11'1	0,6	0,1	0,2
10–11'2	0,0	-0,3	0,2
10–11'3	-0,4	0,3	0,0
10–11'3a	-0,4	0,3	0,5
10–11'4	0,0	0,3	0,3
10–11'5	0,1	-0,6	0,7
10–11'6	-0,4	-0,6	0,6
10–11'7	0,9	-0,1	0,9
10–11'8	0,3	-1,3	0,2
10–11'9	0,3	-1,2	1,2
średnio	*0,1*	*-0,3*	*0,5*
odch.std.	*0,4*	*0,6*	*0,4*

pomiar 12		25.11.2021	
delta_0–12			
0–12'1	1,2	0,3	2,0
0–12'2	0,2	0,5	1,2
0–12'3	-0,2	1,6	-0,1
0–12'3a	0,7	0,4	0,8
0–12'4	-0,5	0,5	2,1
0–12'5	-0,8	-1,6	1,1
0–12'6	-1,4	-2,8	2,3
0–12'7	-0,3	-1,5	1,6
0–12'8	-0,2	-2,8	1,8
0–12'9	-0,2	-1,4	1,5
średnio	*-0,1*	*-0,7*	*1,4*
odch.std.	*0,7*	*1,5*	*0,7*
delta_9-10			
11–12'1	1,3	0,0	1,2
11–12'2	1,0	-0,3	1,1
11–12'3	1,4	-0,6	1,1
11–12'3a	1,6	-0,7	0,9
11–12'4	0,8	-0,6	1,3
11–12'5	0,2	0,2	0,8
11–12'6	-0,3	-1,1	1,5
11–12'7	-0,5	0,0	0,9
11–12'8	0,0	-0,3	0,8
11–12'9	-0,2	0,2	0,6
średnio	*0,5*	*-0,3*	*1,0*
odch.std.	*0,8*	*0,4*	*0,3*

pomiar 13 TS02		30.12.2021	
delta_0–13			
0–13'1	1,3	1,0	1,7
0–13'2	0,6	1,3	1,0
0–13'3	0,1	2,6	-0,3
0–13'3a	1,0	1,4	0,6
0–13'4	0,0	1,6	1,9
0–13'5	-0,4	-0,2	1,0
0–13'6	-1,5	-1,3	0,9
0–13'7	-0,7	-1,4	1,1
0–13'8	-0,8	-1,5	0,9
0–13'9	0,2	-0,4	0,7
średnio	*0,0*	*0,3*	*1,0*
odch.std.	*0,8*	*1,5*	*0,6*
delta_9-10			
12–13'1	0,1	0,7	-0,3
12–13'2	0,4	0,8	-0,2
12–13'3	0,3	1,0	-0,2
12–13'3a	0,3	1,0	-0,2
12–13'4	0,5	1,1	-0,1
12–13'5	0,4	1,4	-0,1
12–13'6	0,0	1,5	-1,4
12–13'7	-0,4	0,1	-0,5
12–13'8	-0,5	1,3	-0,8
12–13'9	0,4	1,0	-0,8
średnio	*0,1*	*1,0*	*-0,5*
odch.std.	*0,4*	*0,4*	*0,4*

pomiar_21		29.01.2022	
delta_0–21			
0–21'1	1,4	1,7	1,5
0–21'2	1,0	2,1	0,9
0–21'3	0,4	3,6	-0,5
0–21'3a	1,3	2,4	0,4
0–21'4	0,5	2,8	1,8
0–21'5	0,0	1,2	0,8
0–21'6	-1,5	0,2	-0,5
0–21'7	-1,1	-1,3	0,7
0–21'8	-1,3	-0,1	0,1
0–21'9	0,6	0,6	-0,2
średnio	*0,1*	*1,3*	*0,5*
odch.std.	*1,1*	*1,5*	*0,8*
przeciętnie	*0,7*	*1,2*	*0,6*
delta_9-10			
13–21'1	0,1	0,7	-0,2
13–21'2	0,4	0,8	-0,1
13–21'3	0,3	1,0	-0,2
13–21'3a	0,3	1,0	-0,2
13–21'4	0,5	1,2	-0,1
13–21'5	0,4	1,4	-0,2
13–21'6	0,0	1,5	-1,4
13–21'7	-0,4	0,1	-0,4
13–21'8	-0,6	1,4	-0,8
13–21'9	0,4	1,0	-0,8
średnio	*0,1*	*1,0*	*-0,5*
odch.std.	*0,4*	*0,4*	*0,4*
przeciętnie	*0,5*	*0,6*	*0,4*

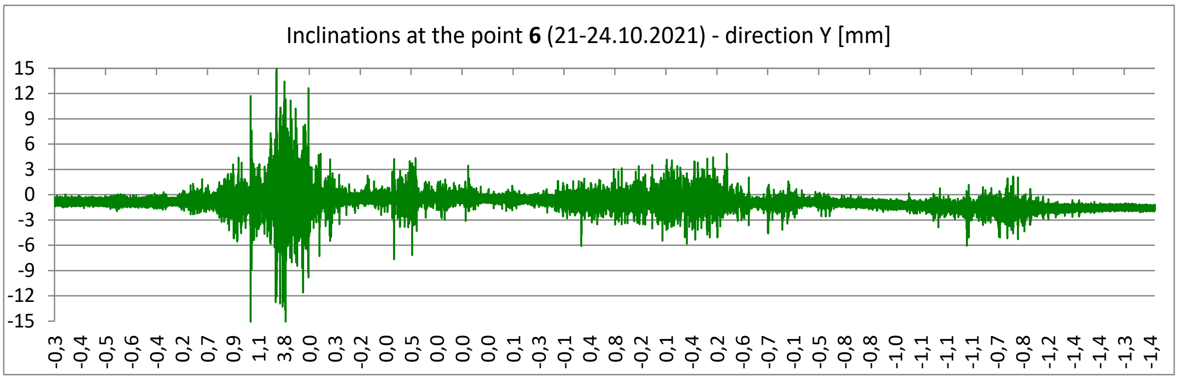
The above analysis illustrates the technical and accuracy capabilities of the tachymetric method in assessing the stability of a structure subjected to periodic dynamic loads. The obtained accuracy parameters are consistent with the results of other similar measurements and guarantee the appropriate spatial resolution of the stability assessment of the tested structure. The results themselves testify to the special features of wooden structures, even very old ones, which, despite intense loads, do not undergo permanent deformation.

2.5 Dynamic measurements

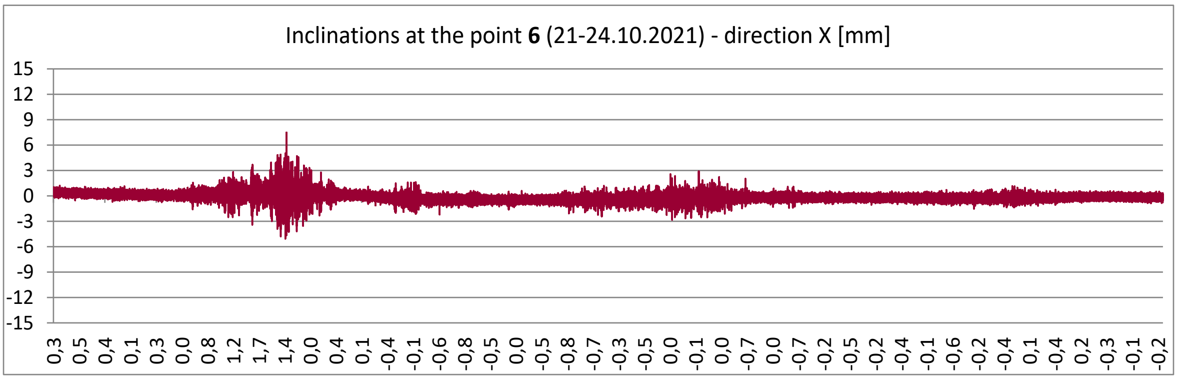
Dynamic monitoring require continuous or quasi-continuous measurement of vibration (period, amplitude), inclination (one or more angles) or changes in other physical parameters. Earlier studies (Wyczałek et al., 2013, 2019) successfully used the POSITAL FRABA ASG15 capacitive inclinometers with wire data transmission in the CANOPEN standard. Currently, two such inclinometers have been 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 power supply were installed on the site. Readings are 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 analyzes, the frequency of reading recordings every 10 seconds was established. The tilt readings were converted into transverse (horizontal) vibrations using a simple relationship, which assumes that the element is simply supported, hinged in the ground, and there is no internal resistance of the structure, i.e .:

$$u = h \cdot \tan(i)$$

where u is the value of the horizontal displacement at height h (h = 7 m), and i – the inclination angle of the column.
In this way, the values of the two components of the displacement – ux and uy – were obtained on the same level as the tachymetric targets. The planned determination was made that the conversion of slopes into displacements would be verified by the results of geodetic measurements. If, or until, these measurements show no motion, this fact shall be used to determine the drift velocity of the inclinometers.
The diagram (Fig. 6) shows the records of the inclinations at point 996 during strong winds on October 21–24, 2021, taking into account the corrections resulting from the absence of plastic deformation of the structure under test (zero displacement of points measured with the total station under set weather conditions – no wind, temperature 5–10 °C, poor sunlight).



a)



b)

Fig. 6. Selected diagram of structure vibration at point 996 in the 3-day recording period during strong winds: a) inclinations across the church, y axis direction, b) inclinations along the church, x direction. Angular values converted to horizontal displacements at a height of 7 m.

2.6 Registration of weather conditions

In order to compare the results of measurements of inclinations with the atmospheric conditions, a SENCOR 12500 WiFi weather station was set up near the object (distance approx. 5 m, height approx. 5 m above the church floor), which include 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), barometer, anemometer (range 0-50 m/s, resolution 0.1 m/s, precision 0.5 m/s) and rainfall meter, shown in the Figure 1a at the top of the lighting pole on the right side of the church. Thanks to the access to the Weathercloud website, it is possible to remotely view the station indications in a 10-minute cycle. Archival data is also collected in this cycle, which can be remotely downloaded in the form of a *.csv file, and then processed and analyzed using own methods or software. In practice, the data collected in the indications of atmospheric sensors was visualized in order to evaluate and size the interesting indications – temperature, as well as the direction and strength of the wind in gusts. The data is then used for comparison with the results of inclinometric measurements.

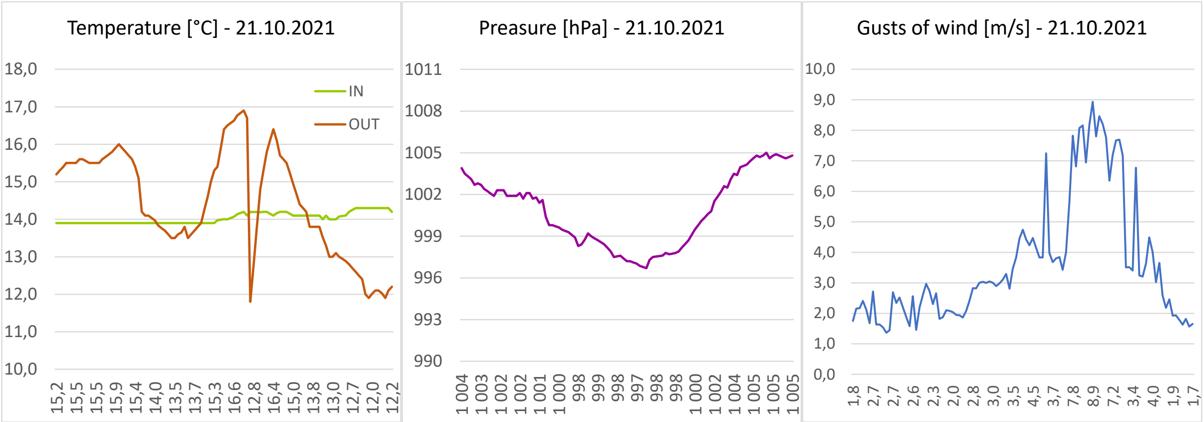


Fig. 7. Readings of basic weather parameters on October 21, 2021, in turn: air temperature and pressure as well as gusts of wind.

2.7 Synchronization of data

Due to the available frequency of data acquisition from the weather station, it has been assumed that all readings will be processed into 10-minute cycles for further analysis. This gives 144 readings per day, 1008 readings per week and an average of 4,400 readings per month.
For the purposes of the 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, i.e. internal temperature (T0), external temperature in the sunlit place (T1) and in the shaded place (T2), as well as the wind force and direction in gusts (WG – wind gust and WD – wind direction, respectively);
- readings of 4 WF/WM400 inclinometers in two directions: x – along the axis of the nave, y – across the nave, calculated in such a way that for each 10-minute 'reading' the minimum and maximum indications selected from among the pairs of readings recorded at that time;
- maximum 2 WGS15 control inclinometer readings for both axes in each 10-minute block of readings.

Until the time of writing this publication, the research lasted 10 months, some of which were very calm, and the winter part was characterized by quite violent gusts of wind – an interesting set of data was obtained, which constitute an appropriate starting material for the assessment of the condition of the facility. The set of maximum slope readings for the windy day 10/21/2021 is shown in Figure 8.

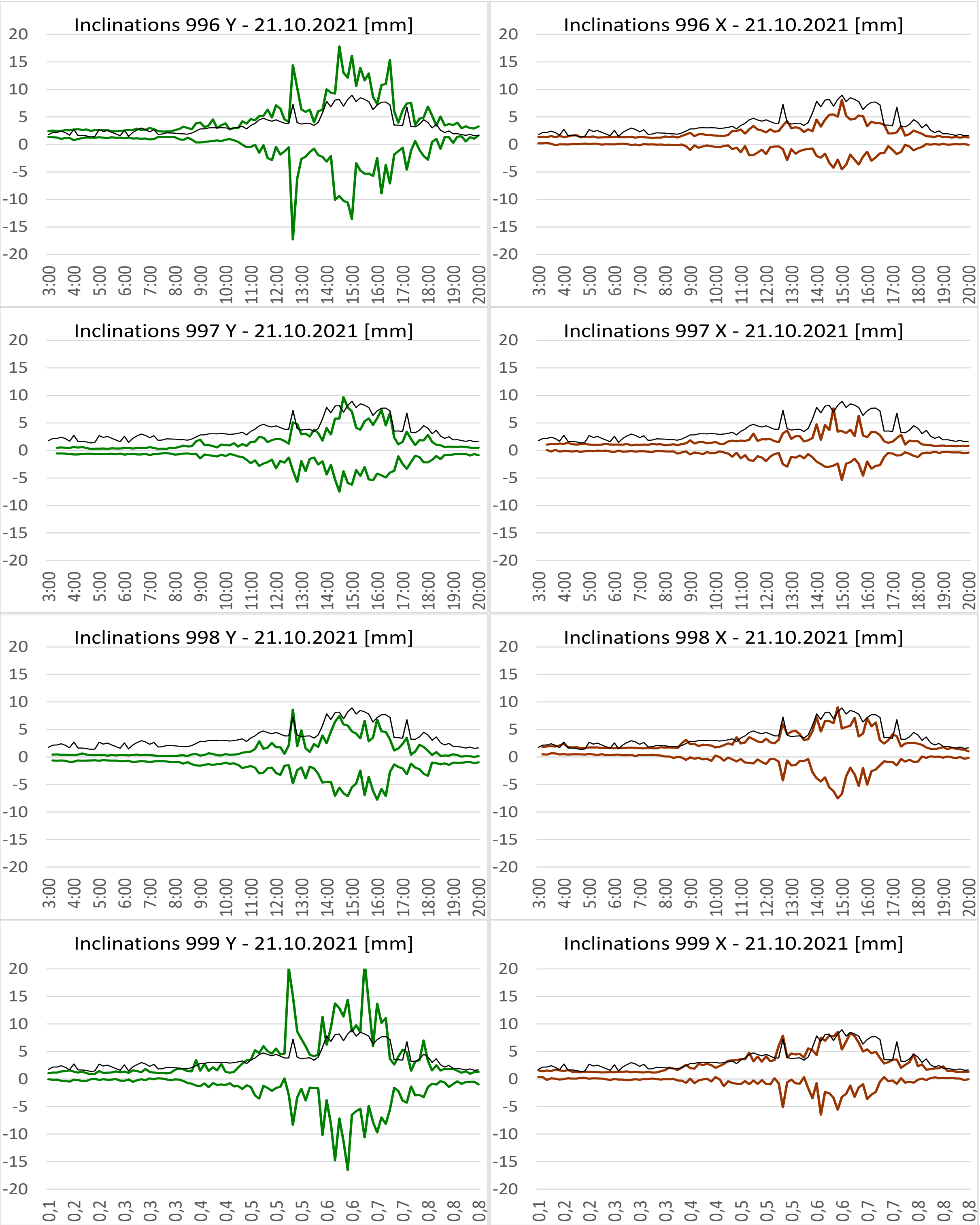


Fig. 8. Indications of the maximum inclinations of the tested object in 4 places (sensors 996, 997, 998 and 999) at the ceiling level, corresponding to the readings from the weather station in Fig. 7; thin black line indicates gusts of wind from weather station.

4. ANALYSIS OF THE RESULTS

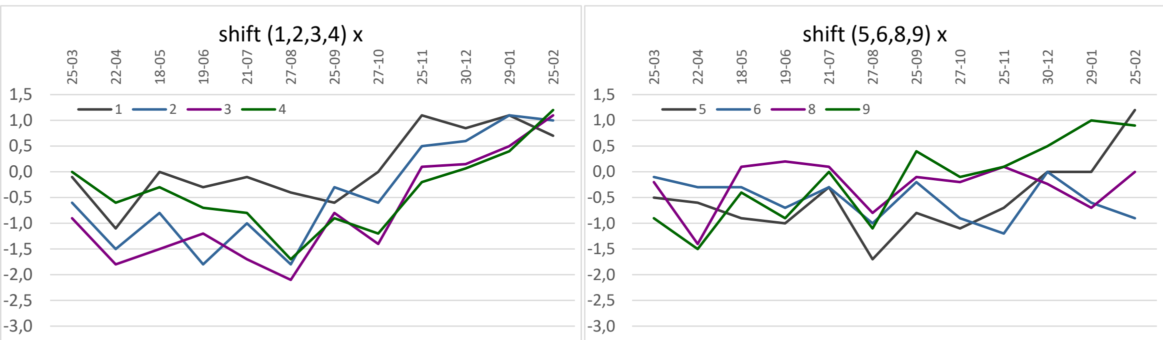
The results obtained from tachymetric and inclinometric measurements were assessed in terms of: 1) accuracy, 2) trend, 3) verification of the hypothesis of zero displacements.
The actual accuracy of the tachymetric measurement was verified on the basis of the differences between the displacements of points 3 and 3a, which, due to their location on the common beam, should show consistent displacement values in all directions. Based on the statistical evaluation of the differences in the relevant values, the following parameters were obtained:

– for changes between successive measurements: $m_{\Delta x} = 0.3$, $m_{\Delta y} = 0.8$, $m_{\Delta z} = 0.4$ mm,
– for changes in relation to the initial measurement: $m_{\Delta x} = 0.6$, $m_{\Delta y} = 1.0$, $m_{\Delta z} = 0.8$ mm,

which confirms the accuracy assumptions made for the tachymetric method.
On the other hand, the accuracy of the inclinometric measurement was assessed by comparing the results obtained based on the readings in the first test period, i.e. until October 2021, during which the measurements did not show any vibrations of the object due to wind pressure. The calculated mean inclinations recorded during tacheometric measurements are characterized by the following discrepancies:

- sensor 996: $u_{\Delta y} = -0.7 \pm 0.29$, $u_{\Delta x} = \ \ 0.5 \pm 0.33$ mm,
- sensor 997: $u_{\Delta y} = -0.8 \pm 0.23$, $u_{\Delta x} = -0.2 \pm 0.33$ mm,
- sensor 998: $u_{\Delta y} = -1.4 \pm 0.59$, $u_{\Delta x} = \ \ 1.3 \pm 0.33$ mm,
- sensor 999: $u_{\Delta y} = -1.5 \pm 1.03$, $u_{\Delta x} = \ \ 0.5 \pm 0{,}78$ mm.

These results prove that the sensors give results with an average error of approx. ± 0.4 mm, while the smaller mean deviations of points 996 and 997 indicate rather greater stability of the north wall than the instability of the sensors on the south side.
The above results show a relatively high agreement between the total station measurement and the indications of inclinometers in stable weather conditions (i.e. wind up to 4 m/s, variable insolation, air temperature 10–22 °C).
Due to the relatively numerous representation of the object (9 points), it was possible to separate two zones for mutual comparison: P – presbytery, N – main nave. In both zones there are 4 tacheometric points (excluding point 7 under the choir) and two inclination sensors.
The analysis of the 'static' displacement components for the entire research period is shown graphically in Figure 9.



a)

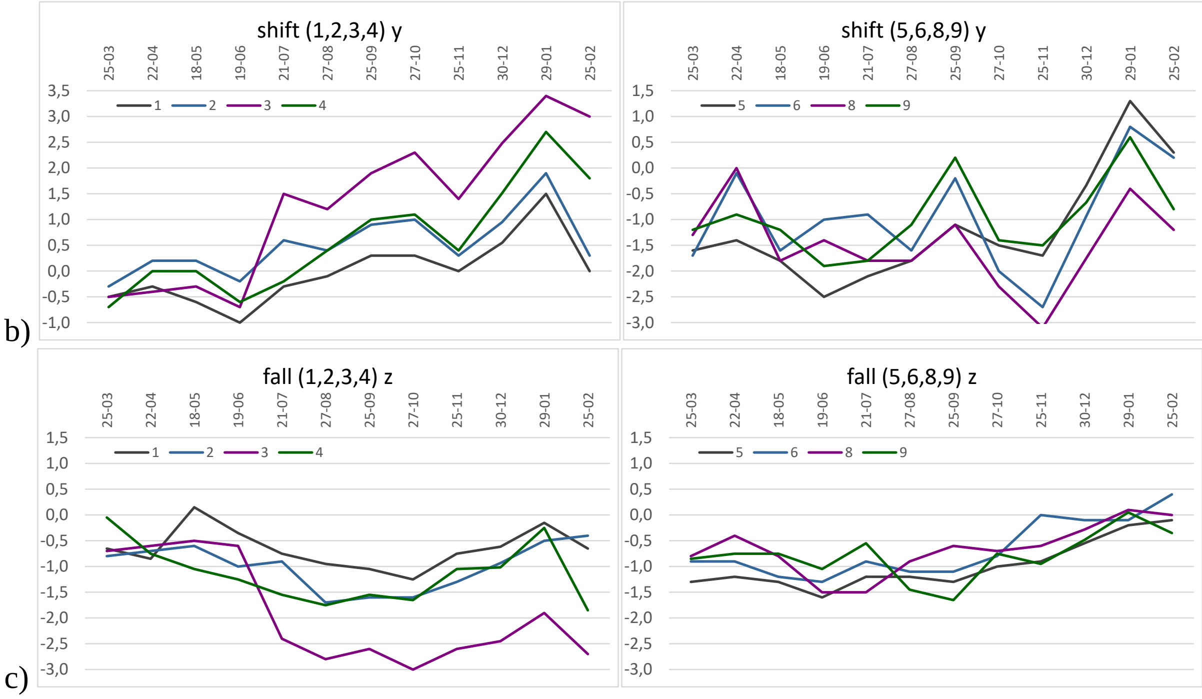


Fig. 7. Graphs of long-term displacements of points measured using the tachymetric method: a) movement in the x-axis direction, b) in the y-axis direction, c) settlement – points from the P section on the left, points from the N section on the right; each measurement with an average error of ± 1 mm.

The above statements show that the object undergoes slight horizontal displacements − up to 3.4 mm in point 3 and less than 1.5 mm in other points. Likewise, the settlements did not exceed −3 mm at point 3, and within the nave (zone N), the vertical displacements are within error ±1 mm. In further research

On the other hand, the indications of the inclinometers show fluctuations in the ceiling level reaching in point 5 (sensor 999) up to ±20 mm, however, in stabilized weather conditions, they do not exceed ±3 mm (with the scattering of successive readings in the series of ±1 mm). In order to assess the degree of compliance between the readings of the wind gusts and the indications of the inclinometers, the correlation coefficient was calculated for 1-day observations on October 21, 2021, when the sensors showed the occurrence of structure vibrations (u_y, u_x) due to wind pressure (wd). Results for $corr(wd, u_y)$ = 83−91% and corr $corr(wd, u_x)$ = 83−91% were obtained for all sensors, i.e. a relatively high agreement. This relationship will be the subject of further research (based on data from other windy days).

All the discussed results are case-specific, but interesting in terms of quality assessment. They show that the measurements carried out in this way allow to obtain the parameters for the assessment of the condition of the structure within the accuracy limits of ±1 mm for individual directions (axes) of displacements.

5. SUMMARY

Earlier experience with the combined use of a total station and tilt sensors provided a solid basis for using such a solution to measure the displacements of the object discussed here. Thanks to this, an image of its reaction 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 sure and reliable method of static measurements, which, even with a 1-second, 1-mm instrument – in these studies it was the Leica TCRP 1201+ – ensures sub-millimeter accuracy of the individual displacement components. It also guarantees a very high reproducibility of the results, thanks to which, for the one-year period of research, obtaining a reliable image of the object's condition as a function of time was ensured. The use of wireless inclinometers – in this case the WF/WM400 models from BW Sensing – gave an image of the object's susceptibility, in various places, to significant forces caused by weather conditions, mainly wind gusts. Thanks to the combination of both methods, in a quiet time, it was possible to harmonize the readings by correcting them mathematically.

The indications of inclinometers installed on a complex structure are very unstable and do not result only from the reaction to the action of rapidly changing external forces. This is a completely different behavior than in the case of flexible structures. The method of comparing selected, extreme indications in a 10-minute cycle gives a significantly better picture of the correlation between the exciting force and the response of the structure.

With regard to the study of a specific wooden object presented here, it was found that due to the significant pressure of wind gusts, non-uniform vibrations in its structure reach ± 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 solar heating. More precisely, this impact will be analyzed this summer. On the other hand, long-term measurements have so far shown high stability of the structure. According to the authors, long-term processes will be possible to evaluate by conducting cyclical – at least twice a year – tachymetric measurements of displacements.

The obtained results refer to a specific object, however, according to the authors, they can and even should be implemented in other old objects or wooden structures. Thanks to the implementation of remote data transmission techniques – proven in other monitoring applications – such surveys can be remotely supervised, and the participation of a surveyor may be limited to tachymetric measurements several times (twice a year).

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Ireneusz Wyczałek, Dr hab. Eng., Professor at the Poznań University of Technology, graduate of the Faculty of Geodesy and Cartography of the Warsaw University of Technology in the field of photogrammetry and cartography, obtained a PhD in technical sciences at the AGH University of Science and Technology in Kraków and a postdoctoral degree (habilitation) again at the Warsaw University of Technology. He specializes in the applications of various measurement methods in land- and engineering surveying. He lectures on surveying subjects at the Poznań University of Technology and at the Bydgoszcz University of Science and Technology. He has extensive scientific and practical experience in the use of geodetic measurements in construction and engineering. Author of expert opinions based on precise leveling, tachymetric and photogrammetric measurements and with the use of non-geodetic sensors.

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Piotr Marciniak is an architect, town planner and architecture historian. He studied architecture at the TU Poznań and was a research assistant at the Department of Architectural History there. He received his doctorate with a thesis on architecture of the Polish Roma people. He has lectured at universities in Poland, the USA, Cuba, and Georgia. He obtained his habilitation at the Warsaw University of Technology and title of professor. He received a research fellowship at the Herder-Institut für historische Ostmitteleuropaforschung-Institut der Leibniz-Gemeinschaft, Marburg. Since 2011, he has been a professor of architecture, architectural history and heritage protection at the Poznań University of Technology and head of the Department of History, Theory and Heritage Preservation. His research focus is on contemporary architecture in Poland and Central and Eastern Europe; conservation of the cultural and technological heritage; architecture of national and ethnic minorities; and architectural theory.

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