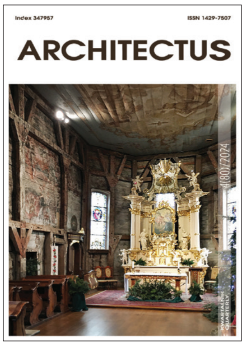

Architectus

2024
4(80)

DOI: 10.37190/arc240403

Piotr Marciniak*, Ireneusz Wyczałek, Zdzisław Pawlak*****

Methods for measuring and evaluating deformation in conservation work on wooden structures: an interdisciplinary case study of the parish church in Domachowo

Abstract

Wooden architecture is not widely represented in the Polish material heritage of culture. An interesting preserved wooden building is the parish church in Domachowo situated in the south part of the Greater Poland Voivodeship. As a result of numerous alterations and modernizations, it is currently a composite structure showing obvious signs of damage to the original geometry. For this reason, a project was initiated to measure the stability of a structure that has been exposed to extreme outdoor forces: mainly gusts of wind and uneven exposure to sunlight. The paper presents the outcomes of an interdisciplinary study on the stability of the structure of the church. The project required the implementation of two measurement methods: a static method at fixed intervals and a dynamic one with continuously recorded readings during the operation of variable loads.

The paper also describes the methodology of the implemented static-dynamic measurements and interprets the outcomes with a focus on the precision and stability of long-term readings of inertia sensors, and on the basic evaluation of the structure. The text also looks at the problem of organizing diagnostic procedures in the process of preparing work on a historic building.

The outcomes confirm that the combination of the two methods and the unconventional use of precision inclinometers for measuring wooden constructions opens new possibilities for the analysis of the structural deformation in wooden buildings in real-time and, for continuous monitoring of their technical condition. The dynamic-static method can also be used for analyzing structural displacements not only in wooden churches, but also in other historic buildings that are exposed to dynamic deformation. The research project and its outcomes have inspired wider reflection of the role of experimental research in diagnosing historic buildings.

Key words: displacement, heritage protection, wooden church, monitoring conditions of structures

Introduction

Polish sacral wooden architecture from the Middle Ages to the late 14th century is a considerably uncharted research area comprising a whole range of problems. These are related to the identification of carpentry techniques, structural systems, and architectural solutions, as well as details, decorations, and interior furnishings (Kornecki 1992, 8). In Poland, relatively few wooden historic buildings have survived. The Church of St. Michael the Archangel in Domachowo in the south of the Greater Poland Voivodeship, is an interesting example of a wooden church with a double-wall structure (Fig. 1). It is an oriented church of a complex architectural and structural form. Its central part is a single nave with a narrow, elongated chancel terminating in three sides to the east. The nave consists of two sections, both on a near square plan, with the west part slightly narrower than the east one. Adjoining the chancel to the north, is a sacristy set on a rectangular plan, as well as a rectangular chapel terminating in three sides to the south. A rectangular aisle terminating in a vestibule adjoins the south side of the nave. The entire building on its west

---

* ORCID: 0000-0002-4404-1184. Institute of Architecture and Heritage Protection, Poznan University of Technology, Poland, e-mail: piotr.marciniak@put.poznan.pl

** ORCID: 0000-0003-3963-8186. Faculty of Civil and Environmental Engineering and Architecture, Bydgoszcz University of Science and Technology, Poland.

*** ORCID: 0000-0003-2851-3433. Institute of Structural Analysis, Poznan University of Technology, Poland.

Fig. 1. Church of St Michael the Archangel in Domachowo
(photo by S. Milejski, source: SM Domachowo…)
Il. 1. Budynek kościoła św. Michała Archanioła w Domachowie
(fot. S. Milejski, źródło: SM Domachowo…)

side is complemented by a square tower with a porch on the ground floor, as well as two annexes on both sides (Różański et al. 2020, 177, 178).

During a conservation project between 2019 and 2020, the church's inner frame was uncovered to reveal the existence of paintings on the log structure (Fig. 2). The form and style of the paintings cast doubt on the previous dating of the church. The uncovered paintings, which also featured descriptions of the particular representations, were made on the log section with timber framing. In the beginning, the authors assumed that the additional framing was built simultaneously with the formwork during renovation in 1775 (Jankowski 2009, 193). The discovery led to an initial examination of both the structural systems. Among other things, it showed that the logs were connected at the quoins by half laps with mortice and tenon, which made it impossible to replace entire single logs. Additional random dendrochronological examination also showed that some of the logs in the chancel and roof framework dated from the 1360s (1368/1369), and some from the early 16th century (1502/1503) (Krąpiec 2020). None of these dates coincided with the dating proposed in the reference literature concerning the building to date (Różański et al. 2020). Later conservation and construction work commencing in the 1930s, designed by Lucjan Michałowski, contributed to the church's final architectural form (Tejszerska 2023). Currently the main load-bearing system is a wooden framework connected to oak log walls, which are preserved in the oldest part of the building, namely in the chancel and the nave (Fig. 3). All these considerations show that the church in Domachowo is a valuable example of historic wooden architecture in Poland and requires in-depth observation.

The results of geodetic measurements suggest a significant tilting of the structure of the church and its elements, both in the chancel and in the nave. The inclines are of different values, depending on direction. It can be assumed that the entire structure of the chancel tilts evenly towards the west by about 16 to 21 cm, and in the transverse direction the pillars of the north and south walls tilt towards the interior of the building. According to information from the 1920s concerning the condition of the structure, the building was already leaning to the west at the time. This is confirmed by, for example, windows that were installed under a different angle in relation to the pillars of the load-bearing structure. Moreover, the bases of the wooden columns were undercut with brick fillings (Różański et al. 2020). Conservation work launched in 2019 revealed a number of weakened points in the structure (mainly those mentioned above), as well as joints at the junction of the chancel and the nave carpentry, notches and nests left by removed elements, and a number of undercuts or cutouts. Observations also indicated that the structure was exposed to external factors, in particular strong wind (Fig. 4).

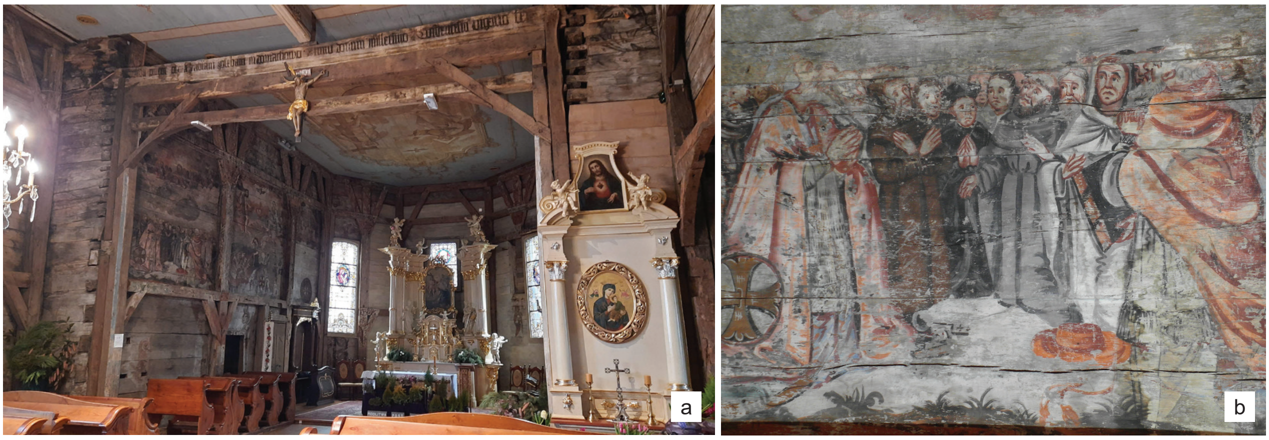

Fig. 2. Uncovered interior of the church with visible paintings on the wooden structure showing clear figural and ornamental themes:
a) view of the nave towards the chancel (photo by P. Marciniak),
b) figure detail of the paintings in the chancel (source: http://parafia-domachowo.pl/wp-content/uploads/2020/10/SAM_6014.jpg)

Il. 2. Odsłonięte wnętrze kościoła z widocznymi polichromiami na konstrukcji drewnianej, o czytelnych motywach figuralno-ornamentalnych:
a) widok z nawy w kierunku prezbiterium (fot. P. Marciniak),
b) fragment polichromii w prezbiterium (źródło: http://parafia-domachowo.pl/wp-content/uploads/2020/10/SAM_6014.jpg)

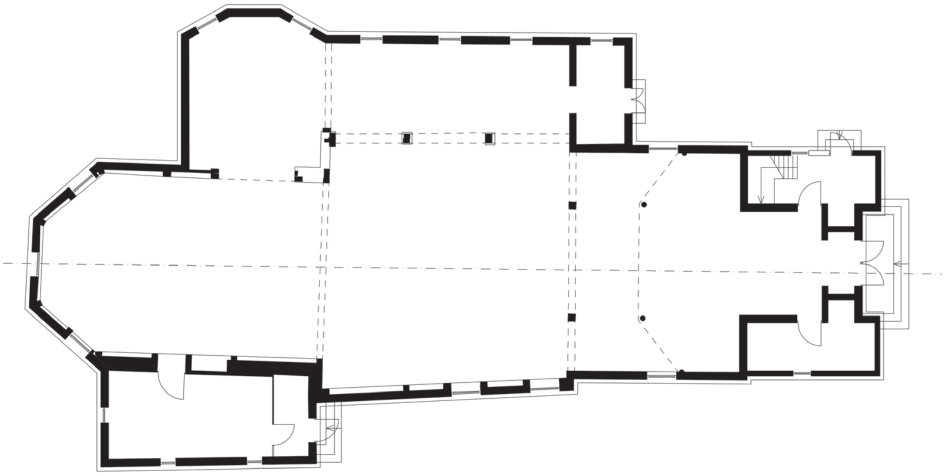

Fig. 3. Ground plan of the Church of St. Michael the Archangel in Domachowo (drawing by J. Jura, A. Rosa)

Il. 3. Rzut przyziemia kościoła św. Michała Archanioła w Domachowie (rys. J. Jura, A. Rosa)

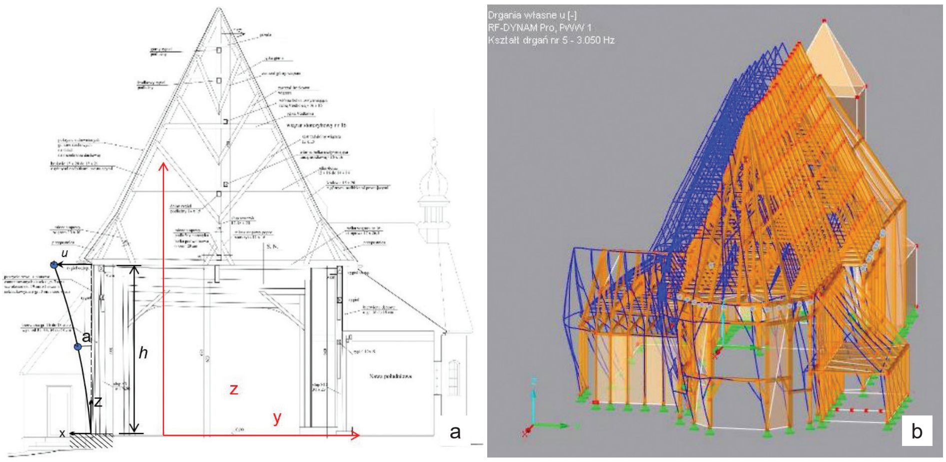

Fig. 4. Church of St. Michael the Archangel: a) diagram of existing inclinations (elaborated by P. Marciniak, b) digital model (elaborated by Z. Pawlak)

Il. 4. Kościół św. Michała Archanioła w Domachowie: a) odchylenia rzeczywiste – schemat (oprac. P. Marciniak) b) model cyfrowy (oprac. Z. Pawlak)

The main goal of the research project, inspired by the permanent deformation of the structure system, was to conduct measurements and analyze the deformation, in addition to diagnosing the actual condition of the building. Furthermore, the authors planned to analyze the structure based on a mathematical model, which made it possible to identify the weakest structural elements and, subsequently, to validate the numerical model used to conduct a comparative analysis, and to compare the geodetic measurements with a dynamic-static analysis of the structure (Pawlak et al. 2024).

The next objective of the project was to develop a method for diagnosing historic buildings of complex structure and problematic technical condition. An important element of the project was to determine the position of experimental architectural studies in a complex, interdisciplinary process related to the conservation and restoration of historic buildings. This may be of key importance for the proper organization of work, their sequence and ultimate schedule.

Current state of research

The research conducted in Domachowo falls within the broad range of research on the behavior of complex systems. Its origins are related to identifying damage in widely understood infrastructures: in aviation systems, and civil and mechanical engineering. The system is called Structural Health Monitoring (SHM) and is based on identifying and detecting damage and changes in materials or entire complex systems. The vast majority of recent SHM projects have aimed to identify damage in a broad scope of engineering structures (Farrar, Worden 2007). SHM is an automated process that combines precise data from networks of sensors with engineering information. The method is also important in preventive conservation and proper restoration of historic buildings. A significant feature of such systems is that they provide continuous monitoring of the observed structures with minimum interference into their authentic historic fabric (Clementi et al. 2021).

Current trends in the application of SHM in historic buildings include continuous unattended observation combined with modal analysis procedures using digital models. In recent years, there has been a large number of projects implementing the abovementioned methods to assess the behavior of historic constructions (Gopinath, Ramadoss 2021). In practice, SHM has been used for long-term assessments of wall structure behavior (Dal Cin, Russo 2019), for assessments of the general conservation of buildings (Kilic 2015), and for monitoring their condition (Lima et al. 2008). This has also included collecting data for comprehensive evaluations of the behavior of buildings, including monitoring their dynamic behavior

(Boscato et al. 2016; Anastasi, Lo Re and Ortolani 2009; Ye, Su and Han 2014; Lorenzoni et al. 2016). The vast majority of such measurements use integrated sensor systems that enable a comprehensive assessment of the observed parameters (Noel, Badway 2017).

During the structural assessment of the church in Domachowo, the authors decided to combine various methods. Usually, to assess the stability of buildings geodetic methods are applied, including precision tachymetry (Barsocchi et al. 2021). Such methods enable precise observations of displacements not only in engineering structures, but also in historic buildings (Gil et al. 2021; Petrovič et al. 2021). In order to increase the precision and frequency of measurements, the authors used hybrid solutions that combined tachymetry with a system of remote sensors installed on the building and in its vicinity.

Description of the research project

To fully diagnose the physical behavior of and to monitor the building, the authors used a combined measurement method featuring both static and dynamic measurements (tachymetry and inclinometers, respectively). Long-term studies were made monthly comprising three constituents related to two reference points that were considered stable. This was conducted using the tachymetric method. Short-term measurements used one of the typical monitoring techniques based on inertial tilt sensors (inclinometers). The authors called this combination the "Dynamic-Static Method" (DSM), which can be useful for analyses of both structural displacements of buildings, including wooden churches, and of other structures that are susceptible to dynamic deformation (Marciniak, Pawlak and Wyczałek 2023; Pawlak, Wyczałek and Marciniak 2023)[1].

The authors used a measurement grid containing six fixed measurement points and four bi-axial inclinometers. To control the accurateness of the static tachymetric measurements, they set an additional point, and to control the readings of the inclinometers, they installed two additional sensors. To assess both the dynamics and statics of the building at the examined points, they designed a diagram of complementary measurements using tilt sensors and a weather station. The thus collected data made it possible to evaluate the correlation of the tilt readings with the indications of wind gusts and the temperature on both sides of the church.

The static measurements were made using the tachymetric method with a 1-sceond Leica TCRP 1201+ and reflective foil targets. Based on the results of 15 double series of measurements, discrepancies between the series in the range of –1 mm to +1 mm were revealed, albeit the most common values were in the range of ±0.2 mm. This analysis illustrates the technical and accuracy capabilities of the tachymetric method in evaluating the stability of a structure exposed to periodic dynamic pressures. The obtained accuracy parameters are consistent with the results of similar measurements and guarantee accurate spatial resolution of the stability assessment of the studied structure. The actual results prove that specific features of wooden structures, even very old ones, do not undergo permanent deformation despite intensive pressures.

Dynamic monitoring requires continuous or quasi continuous monitoring of vibrations and inclinations or changes in other physical parameters. Earlier studies successfully used POSITAL FRABA ASG15 inclinometers with wire data transmission in the CANOPEN standard. In the discussed case, two such inclinometers were applied to verify the readings of a new set of wireless BWSENSING WF-WM400 inclinometers made using MEMS technology. Such sensors can be powered by solar energy or DC chargers. They can measure inclinations in very high frequency (up to 50 Hz) and then transmit the signals remotely via a Wi-Fi network.

In the basic version, four inclinometers powered from the power grid were installed on the site. The readings were collected synchronously every 2 seconds via a local Wi-Fi server, saved to disc and then remotely downloaded via the Internet. After an initial test, the authors set the frequency of recording the readings at every 10 seconds. Based on the analysis of the observations, the authors concluded that the records of inclinations in one point changed up to ±15 mm during intense winds in October 2021, taking into account the adjustments resulting from the absence of plastic transformations within the investigated structure (Fig. 5).

In order to compare the results of the inclination measurements with the weather conditions, the latter were recorded. To do so, a SENCOR 12500 Wi-Fi weather station was set up near the buildings. This comprised a base with a thermometer (inside the building) and a set of sensors: two thermometers, a barometer, an anemometer, and a rainfall meter. With access to the Weathercloud website, it was possible to remotely view the measurements of the station in a 10-minute cycle. The measured data was also collected within the same cycle. It was then remotely downloaded to a *.csv file and subsequently processed and analyzed using the authors' own methods and software. Afterwards, this data was compared to the inclinometer readings.

An important issue was to synchronize the data. Due to the available frequency of the data collected from the weather station, the authors assumed that all the readings would be processed into 10-minute cycles for further analysis. For the purpose of a joint examination of the results, the authors decided that the results of a single tachymetric reading would be grouped into one-month blocks that would include readings of the weather conditions, readings from the four WF/WM400 inclinometers and a maximum of two readings from the WGS15 control inclinometer for both axes.

The church in Domachowo was monitored for 24 months simultaneously with the wide-ranging conservation work inside the building. Some of the measurements were taken during a very quiet time in spring and summer, whereas some in winter when relatively strong gusts of wind had a significant impact on the characteristics of the readings. During the latter period, the authors obtained an interesting

---

[1] A detailed description of the research and its outcomes were presented at conferences and in publications which provided the basis for the present text (Marciniak, Pawlak and Wyczałek 2023; Pawlak, Wyczałek and Marciniak 2023; Wyczałek 2022).

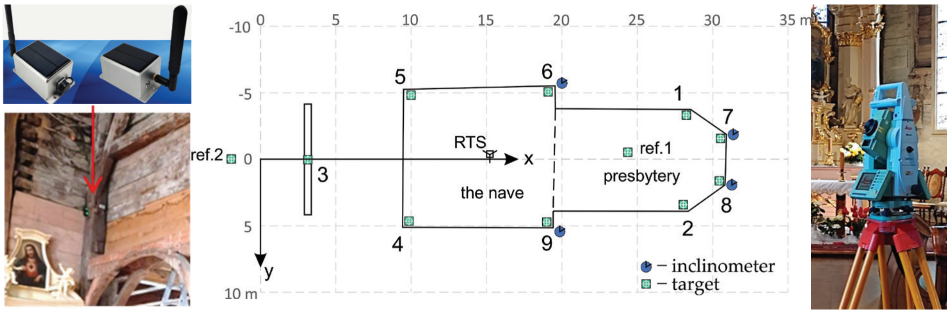

Fig. 5. Measurement diagram using a tachymeter and inclinometers (elaborated by I. Wyczałek)

Il. 5. Schemat pomiarowy wraz z wykorzystanym tachimetrem oraz inklinometrami (oprac. I. Wyczałek)

set of data which provided a point of departure for further assessment of the building's condition and the necessity to provide protection measures, as required. This disrupted the order of works, for which the monitoring of the structure was of key significance. Figure 6 shows changes in the displacements across and along the building (axis *Y* and axis *X*, respectively) determined from readings of inclinometers situated in the higher part of a pillar in the corner of the nave, at its junction with the chancel (Fig. 5, point 6).

Earlier experience in combining tachymeters with inclination sensors provided a solid basis for using this type of solution to measure displacements of the discussed building. The authors thus obtained an image of its response to significant wind pressure and heating from sunlight. Electronic tachymetry was used for static measurements, whereas using remote inclinometers provided an image of the building's sensitivity in various places to pressures caused by the weather, in particular by gusts of wind.

With regard to the research on the church in Domachowo, the authors reached the following conclusions:

– due to the considerable pressure of gusts of wind, in some places the uneven vibrations in the structure of the building reached ±20 mm; this made it possible to identify the most sensitive places for the numerical analysis and to take potential protective measures,

– there were no inclinations caused by changes in heating from sunlight,

– the results refer to a specific building, however everything points to the conclusion that the methods could, or even should, be implemented in other historic buildings or wooden constructions,

– thanks to the implementation of remote data transmission, proven in other monitoring applications, such research can be supervised on a remote basis, whilst the participation of a surveyor can be limited to several tachymetric measurements.

The monitoring of historic buildings that are susceptible to dynamic deformation is of particular importance. The aforementioned DSM can be useful for analyzing structural deformations not only in wooden churches, but also in other historic buildings that are exposed to this type of deformation during, for example, vibrations or minor earthquakes. DSM can also be used in particular applications of the Internet of Things and in transmitting data in real-time (Fig. 7).

Based on the results, it is possible to conclude that wooden constructions, even very old ones, are not susceptible to permanent deformation, despite intensive pressures. However, it is particularly important to monitor historic buildings that are exposed to dynamic deformations.

The numerical model of the structure confirmed the measurement results, in addition to identifying a considerable inclination within the structure of the church and its elements. The authors also conducted comparative analyses to investigate the impact of stiffening plates, namely floors, ceilings and wall cladding on the structure's static and dynamic response. The analyses showed that the structure of the building had insufficient lateral rigidity. The weakest element was the lateral system at the junction of the nave and the chancel (Fig. 8).

The junction was the point where the greatest lateral displacement occurred during windy weather, in both the numerical model and in the actual building. Especially weakened was the wall on the right side, where the rood beam connecting the opposite walls was broken. The authors also analyzed the impact of impairments in the structural elements, as well as the impact of the specific interconnections of post branches, on the behavior of the entire system. In addition, they conducted a dynamic analysis of the structure during both high and extreme climatic pressure (including strong gusts of wind). The objective of the dynamic analysis was to validate the calculation model and to determine if strong gusts of wind caused excess vibration in the building's specific elements. In a modal analysis of part of the structure the authors compared its dynamic parameters with and without the impairments in the nodes,

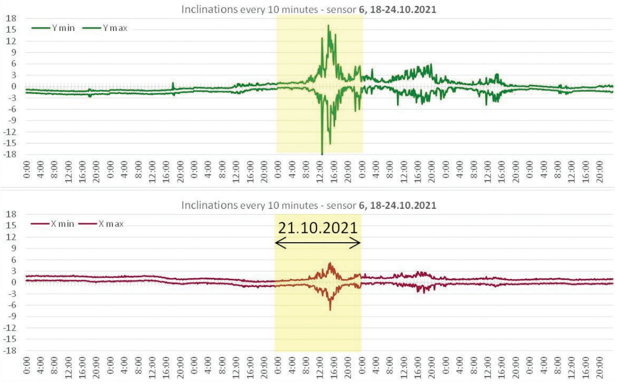

Fig. 6. Section of inclinometer readings with displacements of the wooden structure (18–24.10.2021) (elaborated by I. Wyczałek)

Il. 6. Wycinek odczytów z inklinometrów z widocznymi odchyleniami drewnianej konstrukcji (18–24.10.2021) (oprac. I. Wyczałek)

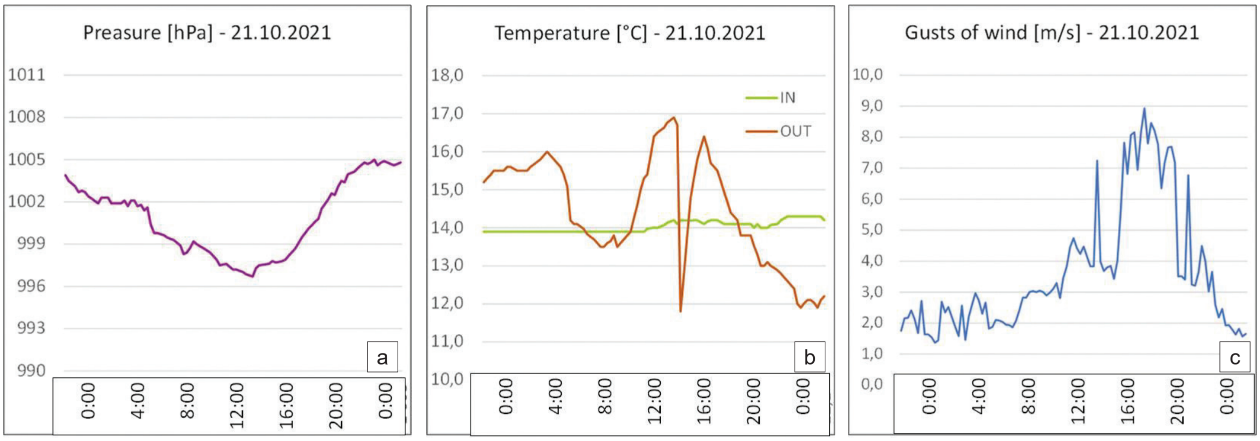

Fig. 7. Recording weather conditions and synchronization of data: parameters of weather station readings on 21 October 2021: a) pressure, b) air temperature and c) gusts of wind (elaborated by I. Wyczałek)

Il. 7. Rejestracja warunków pogodowych i synchronizacja danych – parametry z odczytów stacji pogodowej wykonanych 21.10.2021 r.: a) ciśnienie, b) temperatura powietrza, c) porywy wiatru (oprac. I. Wyczałek)

Fig. 8. View of transverse wall at the junction of the nave and the chancel:
a) numeric model o the structure – diagram (elaborated by Z. Pawlak),
b) view towards the interior of the chancel (photo by Z. Pawlak)

Il. 8. Ściana poprzeczna na styku nawy głównej z prezbiterium:
a) numeryczny model konstrukcji – schemat (oprac. Z. Pawlak),
b) widok do wnętrza prezbiterium (fot. Z. Pawlak)

in order to determine the degree of connection between the examined elements. This, however, is the subject of a separate publication (Pawlak et al. 2024).

Prospects and discussion

The unusual application of wireless inclinometers provided an image of the building's susceptibility to considerable force caused by weather conditions, mainly gusts of wind. The Dynamic-Static Method (DSM) can be useful not only for analyses of structural displacements in wooden churches, but also of other historic buildings that are sensitive to dynamic deformation (Marciniak, Pawlak and Wyczałek 2023). Using sensors that work in dispersed networks will make it possible to monitor the most valuable historic buildings threatened by external factors (e.g., weather, natural disasters, military conflicts, etc.). The developed measurement method of static and oscillating displacements of wooden structures can also be used in studies of many other types of buildings exposed to variable loads, including climatic and seismic pressures. Constant monitoring makes it possible to identify dangerous conditions or emergencies. As already noted, the method can be used in the practical application of the Internet of Things (IoT) and in real-time data transmission.

The research project and its outcomes have inspired further reflections on the role of experimental research in diagnosing historic buildings. The complex process of organizing conservation and restoration work, as well as the entire funding process, requires improvement in terms of both methods and planning. The scope of required documentation has already been developed by the conservation environment over many years of practical research and academic analyses (Tajchman 1995; Brykowska 2007).

Observations of many years ago concerning the coherence and logical organization of the working process on historic buildings have lost none of their relevance: *The conservation of a complex or single monument of historic architecture* […] *is and should always be a uniform process, constituting a whole: from the moment of diagnosis, through research, design and implementation, to the post-implementation documents* (Tajchman 1985, 157). Indeed, it is crucial to ensure a cohesive and logical conservation process, which arises from […] *the need to subject all the activities to the historic building, and thus to the main protection objective, which is the survival of earlier architectural work and to pass it on in its proper form to the next generations* (Tajchman 1985, 157).

The goals of managing a survey process of historic buildings are and will continue to vary, both from the point of view of identification (research) practice and implementation (business) practice. There is no precisely defined methodology of dealing with historic buildings, nor is there a standard for historic and conservation research. Such research should become the foundation of all studies and analyses of cultural property (Kwaśniewski 2019). For many years, researchers have advocated the development of cohesive standards for planning work on architectural heritage. Such voices result from the recommendations of major conservation documents and doctrine (Tajchman 2008).

The role of experimental research should be clearly specified. Apart from recognizing the obvious value of diagnostic procedures, they should also be properly programmed and set in a logical sequence. Based on earlier methodological recommendations (Tajchman 2008), it is possible to propose the organization of pre-project activities for historic buildings as in the table below (Table 1).

Naturally, the dynamics of changes arising from emerging discoveries may, to an extent, disrupt the process. Still, proper programming is key to achieving a final, positive outcome. In the case of historic buildings, it is crucial to plan pre-project work in order to ultimately design an optimal project in all its phases. Also important is the proper

Table 1. Pre-project work (elaborated by P. Marciniak)
Tabela 1. Prace przedprojektowe (oprac. P. Marciniak)

Scope of competence	**Scope of activities**	**Formal requirements**
Investor, architect/conservator	Initial identification of the building in situ – on-site inspections	–
Architect	Thorough measurement and drawing inventory, including details	–
Geologist	Geological ground survey (geotechnical opinion, as needed)	Regional conservator's approval
Archaeologist	Archaeological survey (as needed), including: – identification, documentation and securing of the archaeological site; – geological supervision during work	Regional conservator's approval
Architect	Comprehensive historic and architectural study with conclusions (as needed), including: – historic study (mandatory); – analysis of building techniques, including chronological stratification and valuation; **– diagnostic study of architectural elements;** identification of factors influencing technical conditions (humidity, temperature, salinity, biological hazards, other); conclusions and recommendations	Regional conservator's approval (connected with architectural research)
Structural engineer	– Evaluation of technical condition of the building (expert's opinion regarding structure) with conclusions (as needed), including: **– diagnostic study of structural elements;** – laboratory testing of strength of construction elements; – other testing in connection with architectural inspection	Regional conservator's approval (connected to architectural research)
Art conservator art historian	– Comprehensive conservation analysis of preservation of the historic material of the building with elements of interior furnishings, including: – identification of structure and technological properties (laboratory testing); – detailed conclusions and conservation recommendations for the entire building and its spatial arrangement	Regional conservator's approval
Architect/conservator structural engineer art conservator archaeologist art historian	Detailed conclusions and conservation recommendations (interdisciplinary study)	As arranged with regional conservator
Art conservator	Conservation work program taking into account previous diagnosis of technical condition and preservation of the historic building	–

organization of the funding process, which has a fundamental impact on costs and effectiveness. In the entire process, the primary role belongs to the architect/conservator, who should coordinate all the pre-project work and organize the work of the whole interdisciplinary team of experts. As shown in Table 1 above, some scopes of activities may overlap and this requires strict cooperation, in particular in the architect–conservator–structural engineer–art conservator team.

Conclusion

Contemporary conservation research on historic buildings, especially in the context of unusual situations, mixed-structure systems exposed to deformation, etc., requires an unconventional methodological approach that enables the use of experimental investigation methods. Developing a methodology of diagnostic procedures for structurally complex wooden historic buildings in a problematic technical state creates opportunities for fuller control of their physical condition. Combining real-time measurements with numerical analysis makes it possible to conduct appropriate conservation and restoration work (securing and strengthening, respectively), whilst preserving the most important architectural and aesthetical value of such buildings.

In the Polish legal system, there is a considerable shortage of standards for dealing with historic buildings during the preparation phase of projects, as well as during the development of relevant documentation. In this situation, it is also important to create a needs scenario to enable the use of experimental methods. Such methods may play a significant role in conservation practice providing full control of the preservation status of buildings.

Departing from established methodological models and designing surveys tailored to current conservation needs requires adapting methods to changing conditions. It also necessitates the cooperation of interdisciplinary teams led by suitably trained architects/conservators. Today, this is a significant shortcoming of the heritage protection system, which needs to be remedied. In some situations, extended diagnostic surveys should also become a mandatory practice.

Translated by
Marta Walkowiak

Acknowledgements
This research was funded by His Excellency Rector of the Poznań University of Technology, grant number: 0112/SIGR/0193. This support is gratefully acknowledged.

References

Anastasi, Giuseppe, Giuseppe Lo Re, and Marco Ortolani. “WSNs for Structural Health Monitoring of Historical Buildings.” In *2nd Conference on Human System Interactions. IEEE*, (May 2009): 574–9.

Boscato, Giosuè, Alessandra Dal Cin, Silvia Ientile, and Salvatore Russo. “Optimized procedures and strategies for the dynamic monitoring of historical structures.” *Journal of Civil Structural Health Monitoring* 6 (March 2016): 265–89. https://doi.org/10.1007/s13349-016-0164-9.

Barsocchi, Paolo, Gianni Bartoli, Michele Betti, Maria Girardi, Stefano Mammolito, Daniele Pellegrini, and Giacomo Zini. “Wireless sensor networks for continuous structural health monitoring of historic masonry towers.” *International Journal of Architectural Heritage* 15, no. 1 (2021): 22–44. https://doi.org/10.1080/15583058.2020.1719229.

Brykowska, Maria. “Dokumentacja naukowa niezbędna dla ochrony i konserwacji zabytków architektury.” *Roczniki Geomatyki* 5, no. 8 (2007): 115–28.

Clementi, Francesco, Antonio Formisano, Gabriele Milani, and Filippo Ubertini. “Structural health monitoring of architectural heritage: From the past to the future advances.” *International Journal of Architectural Heritage* 15, no. 1 (2021): 1–4. https://doi.org/10.1080/15583058.2021.1879499.

Dal Cin, Alessandra, and Salvatore Russo. “Evaluation of static and dynamic long term structural monitoring for monumental masonry structure.” *Journal of Civil Structural Health Monitoring* 9 (2019): 169–92. https://doi.org/10.1007/s13349-019-00324-z.

Farrar, Charles R., and Keith Worden. “An introduction to structural health monitoring.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, no. 365 (2007): 303–15. http://doi.org/10.1098/rsta.2006.1928.

Gil, Enrique, Ángeles Mas, Carlos Lerma, M Eugenia Torner, and Jose Vercher. “Non-destructive techniques methodologies for the detection of ancient structures under heritage buildings.” *International Journal of Architectural Heritage* 15, no. 10 (2021): 1457–73. https://doi.org/10.1080/15583058.2019.1700320.

Gopinath, Vinoth Kanna, and Ragi Ramadoss. “Review on structural health monitoring for restoration of heritage buildings.” *Materials Today: Proceedings* 43, p. 2 (2021): 1534–38. https://doi.org/10.1016/j.matpr.2020.09.318.

Jankowski, Aleksander. *Kościoły drewniane o zdwojonej konstrukcji ścian w Wielkopolsce*. Wydawnictwo Uniwersytetu Kazimierza Wielkiego, 2009.

Kilic, Gokhan. “Using advanced NDT for historic buildings: Towards an integrated multidisciplinary health assessment strategy.” *Journal of Cultural Heritage* 16, no. 4 (2015): 526–35. https://doi.org/10.1016/j.culher.2014.09.010.

Kornecki, Marian. ”Drewniana architektura sakralna w Polsce: zagadnienie typów i form regionalnych w rozwoju historycznym.” *Ochrona Zabytków* 45, no. 1–2(176–177) (1992): 7–39.

Krąpiec, Marek. *Wyniki analizy dendrochronologicznej prób drewna z kościoła pw. Michała Archanioła w Domachowie*. Kraków, 2020 [Manuscript in: Parafia pw. św. Michała Archanioła w Domachowie].

Kwaśniewski, Artur. “Why research – how to research. Comments on the methodology of contemporary historical and architectural studies and on their application in the adaptation of historic buildings.” *Architectus* 57, no. 1 (2019): 3–20. https://doi.org/10.37190/arc230110.

Lima, Hugo F., Romeu da Silva Vicente, Rogério N. Nogueira, Ilda Abe, Paulo Sérgio de Brito André, Catarina Fernandes, et al. “Structural health Monitoring of the church of santa casa da Misericórdia of Aveiro using FBG sensors.” *IEEE Sensors Journal* 8, no. 7 (2008): 1236–42. https://doi.org/10.1109/JSEN.2008.926177.

Lorenzoni, Filippo, Filippo Casarin, Mauro Caldon, Kleidi Islami, and Claudio Modena. “Uncertainty quantification in structural health monitoring: Applications on cultural heritage buildings." *Mechanical Systems and Signal Processing* 66–67 (2016): 268–81. https://doi.org/10.1016/j.ymssp.2015.04.032.

Marciniak, Piotr, Zdzisław Pawlak, and Ireneusz Wyczałek. "The Dynamic-Static Method (DSM) for Structural Displacement Analysis Using the Example of a Wooden Church in Domachowo (Poland)." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLVIII-M-2-2023 (2023): 1001–6. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1001-2023.

Noel, Adam, Abderrazak Abdaoui, Tarek M. Elfouly, Mohamed Hossam Ahmed, Ahmed A Badawy, and Mohamed S. Shehata. "Structural Health Monitoring Using Wireless Sensor Networks: A Comprehensive Survey." *IEEE Communications Surveys & Tutorials* 19 (2017): 1403–23. https://doi.org/10.1109/COMST.2017.2691551

Pawlak, Zdzisław M., Ireneusz Wyczałek, and Piotr Marciniak. "Two Complementary Approaches toward Geodetic Monitoring of a Historic Wooden Church to Inspect Its Static and Dynamic Behavior", *Sensors* 23, 8392 (2023). https://doi.org/10.3390/s23208392.

Pawlak, Zdzisław M., Piotr Marciniak, Ireneusz Wyczałek, and Martyna Żak-Sawiak. "Extended Monitoring as Support in Numerical Modelling of Complex Historical Timber Structure with Respect to its Weaknesses and Imperfections." *International Journal of Conservation Science* 15, no. 3 (2024): 1259–86. https://doi.org/10.36868/ijcs.2024.03.08.

Petrovič, Dušan, Dejan Grigillo, Mojca Kosmatin Fras, Tilen Urbančič, and Kozmus Trajkovski. "Geodetic Methods for Documenting and Modelling Cultural Heritage Objects." *International Journal of Architectural Heritage* 15, no. 6 (2021): 885–96. https://doi.org/10.1080/15583058.2019.1683779.

Różański, Artur, Tomasz Jurek, Piotr Marciniak, Patrycja Łobodzińska, and Urlich Schaaf. "Interdisciplinary Research on Wooden Architecture in Poland. A Case Study of the Wooden Church in Domachowo." *Archaeologia Historica Polona* 28 (2020): 175–97. https://doi.org/10.12775/AHP.2020.007.

SM Domachowo Kościół św. Michała Archanioła 2017 (8). ID 650491.jpg. Accessed December 15, 2024, at https://pl.wikipedia.org/wiki/Ko%C5%9Bci%C3%B3%C5%82_%C5%9Bw._Micha%C5%82a_Archanio%C5%82a_w_Domachowie#/media/Plik:SM_Domachowo_Ko%C5%9Bci%C3%B3%C5%82_%C5%9Bw_Micha%C5%82a_Archanio%C5%82a_2017_(8)_ID_650491.jpg.

Szymanowski, Przemysław. *Ekspertyza techniczna – I etap dotycząca stanu technicznego konstrukcji kościoła pw. św. Michała Archanioła w Domachowie*. Kościan, 2020 [Manuscript in: Parafia pw. św. Michała Archanioła w Domachowie].

Tajchman, Jan. "Badania i prace projektowe w zabytkach architektury w świetle ogólnej problematyki ochrony i konserwacji zabytków." *Ochrona Zabytków* 38, no. 3–4(150–151) (1985): 157–63.

Tajchman, Jan. "Konserwacja zabytków architektury – uwagi o metodzie." *Ochrona Zabytków* 48, no. 2(189) (1995): 150–9.

Tajchman, Jan. "W sprawie konieczności ustanowienia standardów wykonywania projektów dotyczących prac planowanych w zabytkach architektury." *Wiadomości Konserwatorskie*, no. 24 (2008): 17–45.

Tejszerska, Anna. "Przebudowa kościoła w Domachowie według projektu Lucjana Michałowskiego jako przykład działań konserwatorskich z okresu międzywojennego." *Wiadomości Konserwatorskie*, no. 74 (2023): 36–50.

Wyczałek, Ireneusz. "Volunteering for the future – Geospatial excellence for a better living." In FIG Congress 2022. Warsaw, 11–15 September 2022.

Ye, Xiao-Wei, You-Hua Su, and Jin-Ping Han. "Structural health monitoring of civil infrastructure using optical fiber sensing technology: A comprehensive review." The Scientific World Journal, 652329 (2014). https://doi.org/10.1155/2014/652329.

Streszczenie

Metody pomiaru i oceny deformacji konstrukcji drewnianych w praktyce konserwatorskiej. Interdyscyplinarne studium przypadku kościoła w Domachowie

Architektura drewniana nie jest szeroko reprezentowana w materialnym dziedzictwie kulturowym Polski. Jednym z interesujących zachowanych obiektów jest kościół parafialny w Domachowie położonym w południowej Wielkopolsce. W wyniku licznych przeróbek i modernizacji jest to obecnie konstrukcja złożona, wykazująca wyraźne oznaki uszkodzenia pierwotnej geometrii. Z tego powodu rozpoczęto projekt mający na celu pomiary stabilności konstrukcji narażonej na wpływ ekstremalnych czynników zewnętrznych: głównie podmuchów wiatru i nierównomiernego nasłonecznienia. W artykule przedstawiono wyniki interdyscyplinarnych badań stateczności konstrukcji tego kościoła. Realizacja projektu wymagała zastosowania dwóch metod pomiarowych: statycznej w ustalonych odstępach czasu oraz dynamicznej rejestrowanej na bieżąco podczas pracy zmiennych obciążeń.

Zaprezentowano również metodyki prowadzonych pomiarów statyczno-dynamicznych i zinterpretowano uzyskane wyniki, głównie w kontekście oceny dokładności, stabilności odczytów wieloletnich czujnikami inercyjnymi oraz podstawowej oceny konstrukcji. W tekście podjęto także problem organizacji badań diagnostycznych w procesie prac przygotowawczych dla zabytku.

Uzyskane wyniki stanowią dowód, że połączenie obu metod oraz niekonwencjonalne zastosowanie precyzyjnych inklinometrów do pomiarów konstrukcji drewnianych otwiera nowe możliwości analizy odkształceń konstrukcji w czasie rzeczywistym i bieżącego monitorowania stanu technicznego. Metoda dynamiczno-statyczna może być przydatna do analizy przemieszczeń konstrukcji nie tylko w kościołach drewnianych, ale także w innych obiektach zabytkowych podatnych na odkształcenia dynamiczne. Przeprowadzone badania i uzyskane wyniki stały się również przyczynkiem do szerszej refleksji dotyczącej ich roli i miejsca badań eksperymentalnych w rozpoznaniu zabytku.

Słowa kluczowe: przemieszczenia, ochrona zabytków, kościół drewniany, monitorowanie stanu konstrukcji