Raszczuk and Karolak *Herit Sci* (2021) 9:43
https://doi.org/10.1186/s40494-021-00516-1

Heritage Science

RESEARCH ARTICLE

Correlation between the cracking pattern of historical structure and soil properties: the case of the church in Kożuchów

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Abstract

The paper presents a diagnosis of damage to heritage structures based on the case of the historic church in Kożuchów. The Church of the Purification of the Blessed Virgin Mary dates back to the thirteenth century and is an important sacral building in south-west Poland. Renovation and strengthening works have been conducted in recent years with the goal of structurally stabilizing the heritage building. The paper includes a short history of the building, as well as a review of contemporary diagnostic methods used in heritage buildings with emphasis on the methods used in the diagnosis of the discussed object. Correct diagnosis of the heritage building is the key to selecting an optimal design solution for supporting and strengthening the building structure. Pre-design analysis was based on a geotechnical assessment of ground conditions, identifying cracking patterns of walls and vaults, preparing a digital model using Heritage—Building Information Modeling technology and performing structural analysis. The main cause of cracking of the walls and vaults of the church is related to uneven subsidence and localized stability loss of the building's foundations, resulting from differentiated soil and water conditions beneath the building. Based on the research and analysis, final conclusions and proposals for strengthening the structure were presented, including jet-grouting columns, tie rods and Fibre Reinforced Cementitious Matrix systems.

Keywords: Historical buildings, Diagnosis of historical structures, Diagnostic methods, Cracking pattern analysis, Geotechnical investigation, Strengthening

Introduction

Various causes of damage of heritage buildings

Historical structures are important elements of culture and a source of knowledge for shaping social consciousness. Increased degradation of heritage buildings, which has been observed in recent years, demands development of effective diagnostic methods as a basis for selecting the most appropriate conservation interventions to strengthen the historical structures. Problems relating to securing stability of historical structures are of growing interest to researchers and engineers (i.a. in [1]).

Heritage buildings were built dozens or hundreds of years ago. They were built over long periods of time. Over the years, they experienced damage and breakdown, and were as a result subjected to repairs. These interventions impacted also the static status of the structure, often curtailing degradation processes. But at the same time, this prevented a return to the original state of the structure in later years.

Where documentation is incomplete, which is very common with historical structures, restoration to the original state is difficult and most often impossible. In addition, documented historical structures are characterized by high material heterogeneity [1, 2]. In consequence, determining mechanical parameters in different places may be difficult. This relates to, for example the foundations. For this reason, every historical building

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requires its own individualized methodology for diagnosis and selection of interventions [3]. Despite this, the recognizing of the common features relating to identifying the causes of damage and the most significant threats is possible. The main causes of damage and significant threats faced by historical structures are as follows:

- subsidence of the ground substrate (e.g. in the case of the Leaning Tower in Pisa [4], the cathedral in Mexico City [5], or the Church of St. John in Gdansk [6]),
- errors in design and implementation of construction solutions during the building process (e.g. expansion of the Church of St. John in Gdansk involved placing the building on foundations designed for a much smaller structure [6]),
- additional, unforeseen loading (incl. fires, explosions, seismic movements etc.),
- reduction of material strength resulting from degradation caused by external environmental conditions (e.g. impact of water, wind, frost, temperature changes, pollution etc.).

All of these causes may affect the technical state of structural elements or entire building structures of historical objects. Consequently, they can lead to a dangerous threat to the safety of the structure, what is even more adverse as the issue often refers to historic buildings that should be protected by all means. This paper focus on the correlation between cracking pattern on masonry structure and heterogenous soil conditions.

Geometrical survey and H-BIM modeling as a basis for diagnostic activities

Rapid development and proliferation of new diagnostic technologies for historical buildings means that they can be applied in building maintenance and use, as well as during design and implementation of conservation interventions. Diagnostics based on modern methods allows for material identification and restoration of the internal structure of individual elements, which is extremely important when documentation is lacking for existing structures. Based on diagnostic test results, it may be possible to plan appropriately and carry out conservation and strengthening interventions in historical buildings [7].

Non-destructive testing methods are the most important among the available modern diagnostic methods for historic buildings [2, 3], due to the fact that they offer the maximum protection of the historic substance resulting from their character. The most commonly used testing methods include: visual assessment [8], geotechnical investigations [5, 6, 9], geometrical survey and H-BIM [10–16], core sampling [17, 18], ultrasound testing [19–24], geo-radar (GPR) testing [25–30], operational modal analysis (OMA) [31–34]. One of the most important phases in the diagnostic process is the selection of the appropriate methods for investigation including pros and cons for each of them.

A listing of the testing methods used in case of church Kożuchów with characteristic, advantages and disadvantages is presented in Table 1.

Due to the complex nature of non-destructive testing like core sampling, GPR scanning, ultrasonic investigations and difficulties in interpreting the resulting data, these tests may sometimes result in unsatisfactory results. This may be the result of applying an incorrect test method or a lack of precision. Visual assessment appears to be one of the easiest methods to apply. The conclusion is that the best results can be obtained by applying several methods, allowing for verification of results. Modern monitoring systems combined with advanced computer analysis have been deployed in many important historic buildings, including St. Mark's Basilica in Venice [35], city cathedrals in Florence [36], Padua

Table 1 Diagnostic methods used in the case study

Method	Method characteristics	Advantages/disadvantages
Visual assessment	Assessment of external surfaces and cracking patterns	+ Low cost + Does not require specialized equipment − Results are qualitative
Geotechnical investigations	Geological cores	+ Assessment of differentiated subsidence rates of building foundations − High costs, especially with respect to deep bore holes
Geometrical survey including H-BIM	Interactive model built by the use of the historical architectural and construction documentation, photogrammetric techniques, laser scanning, and other data obtained from the physical analysis of the building	+ The possibility to understand, analyze, document, advertise and virtually reconstruct the whole structure + Enables also energy simulations, time, and cost calculations, and other functions that may improve the way to manage the maintenance and restoration processes − Complex and time consuming method

and Mexico [37], and towers [38]. In turn, in the case of e.g. the Milan Cathedral, the dynamic assessment was applied [33]. Proper assessment and identification of the problem allows for diagnostics and appropriate intervention. Currently, the problem of damage diagnosis is often treated too generally. Researchers and designers use integrated methods to assess the safety or hazard status of a structure, especially when it comes to historically significant buildings [39–43]. When visual assessment suggests that the cause of damage to a structure (cracks) is in the ground substrate, the case may require to carry out geotechnical tests to verify the foundation conditions of the building. The H-BIM (Heritage BIM) is an innovative concept, increasingly applied by researchers and engineers in the recent years [10]. It consists in creating a three-dimensional model of an existing historical or historic object in an appropriate degree of detail. The model applies not only to architecture, but also to the building structure. H-BIM is a complex method allowing to obtain a detailed building and structure models with its history documented In principle, in the first step, the H-BIM library is created by the use of technologies laser scanning, photogrammetry, and other data obtained from the physical analysis and historical architectural documentation and manuscripts [14]. Particularly, the use of historical data for modelling the H-BIM library components introduces the possibility to elaborate the details stored behind the surface of the parametric objects, in regard to their material, structural elements, historical or cultural characteristics and also conservation status and maintenance program [15, 16]. What it more, is the opportunity to enter temporal parametric data that represent the incidents occurring through the life cycle of the building [44]. In the third step, that is parametric modeling in 3-D, the integrated point cloud is segmented, according to the rules and historical patterns, in order to identify objects to be modeled. What is worth emphasizing, is the fact that thanks to H-BIM, it is possible, not only to conduct the complex analysis of the heritage structure, but also to understand issues related to materials and construction techniques, as well as to help in the conservation, management, renovation or reconstruction processes of heritage buildings, including those that no longer exist or are not well documented [10].

Cracking of masonry structure in relation to soil properties

Cracking of walls is often a consequence of uneven ground subsidence (differential soil settlement) [45], especially when there are heterogeneous soil conditions. Uneven soil subsidence results in uneven settlement of building foundations. The most common causes of subsidence are [46]:

- ground movements caused by differing soil structure underneath the building foundations and by differing physical and mechanical soil parameters,
- building structures on ground of low load bearing character, e.g. clay or organic,
- inadequate compaction (or lack of it) of soil during the construction work or faulty foundation work,
- decrease of groundwater level, causing in consequence changes in the volume and strength of the supporting ground substrate,
- changes in environmental conditions, changes in humidity caused by cyclical weather conditions (rain, frost, drought, etc.), causing changes in soil structure and its mechanical properties,
- growing vegetation drawing water from the ground and natural soil degradation processes,
- vibrations and ground movement associated with nearby earthworks, traffic or natural seismic phenomena.

The problem of soil and foundation subsidence is a complex engineering issue [47], especially in the case of historic or heritage buildings, built tens or hundreds of years ago, often upon soil that is heterogeneous, possesses poor loading capabilities and is poorly compacted.

As a result of uneven subsidence, tensile stresses are created in the building structure, causing cracking of walls and degradation of the structure as a whole [43]. Analysis of the cracking pattern should provide a basis for assessing structural safety [48] and for planning reinforcements or repairs. Many authors conclude that analysis of wall cracking patterns and determination of cause may be a good method for assessing threats to structural safety, e.g. in relation to historic towers [49]. In Fig. 1 typical wall cracking patterns associated with foundation subsidence as determined in [50–52].

Introduction summary and objectives of the research

The appearance of cracking patterns and their morphology has been the subject of many research papers describing damage in masonry structures (inter alia [39, 53–56]). At this point, what is worth noting is the fact, that the most common cause of masonry damage is movements of ground substrate, which is the case in 60–70% damage incidents [46]. In recent times, heritage building collapses have occurred in Poland, the causes of which can be attributed indirectly to soil and water conditions. One such example was the collapse of the church tower in Otyń in 2012 [9]. The most recent spectacular building failure was the collapse of columns and vaults in the Castle of the Pomeranian Princes in Szczecin.

The main goal of the conducted diagnostic works and structural analysis of the historic building is to prevent

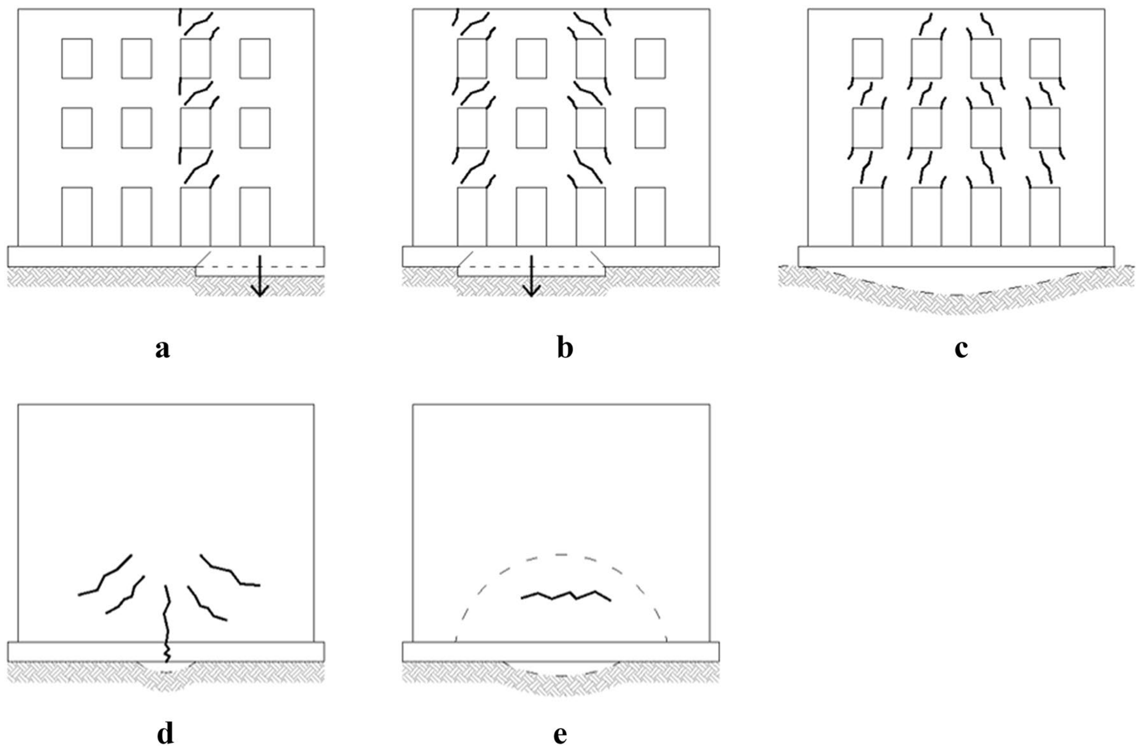

Fig. 1 Images of typical cracking patterns arising from irregular subsidence of building foundations: **a** subsidence of the corner of a building, **b** small scale subsidence of the central part of foundations, **c** large scale subsidence of the central part of foundations, **d** localized subsidence of a foundation in the case of weak foundations, **e** localized subsidence of foundations in the case of strong foundations (own drawing in accordance with [50–52])

further damage and, in the extreme cases, to prevent a construction disaster. In the case of objects with numerous masonry cracks, one of the probable causes are changes in physical and mechanical soil properties. Proper analysis of the structure is possible if, for diagnostics purposes, appropriate geometrical survey is conducted in order to recreate the technical documentation of the building. The implementation of the model in H-BIM technology allows to perform 3-D analysis of the structure. Only the combination of many diagnostic methods enables the correct assessment of the technical condition of the structure along with the selection of the optimal strengthening methods.

Moreover, the aim of the paper is to demonstrate the correlation between the image of historic object damages and groundwater conditions.

Methods

Case study—church in Kożuchów: architectural characteristic and historical description

Kożuchów is one of the oldest towns in Lower Silesia (the first records date back to 1273 [57]). The medieval town was located at the crossroads of trade routes. Consequently, it quickly grew in importance and architectural sophistication. Significant fragments of fortification walls, a castle and the parish church of the Purification of the Blessed Virgin Mary, so named in the mid-thirteenth century, have survived to this day [58–60]. The present corpus of the church is the result of several construction phases. The early Gothic church had a two-part corpus, consisting of a nave and presbytery. The building was damaged in the great fire of 1339, which destroyed most of the buildings in Kożuchów. Most probably only the stone walls survived. The church was rebuilt between 1340 and 1369. In the fourteenth century, a high tower was added to the north. At the beginning of the fifteenth century, extension work was carried out. This involved widening of the nave by 12.5 m. The side walls, pillars and gable walls were also demolished. New masonry side walls were built. A porch was added on the west side and the nave was extended to the south and connected to the chancel through space made by breaking through the arcades in the wall. In the second half of the fifteenth century, the church was enlarged with addition of another three chapels and a porch to the southern nave. Over the centuries the church was damaged by fire several more times (1488, 1554, 1637, 1764). Interventions were needed to repair the vaults (1554) and to rebuild the roofing (1764). In the first reconstruction, the roof of the church was rebuilt as a gable roof over the main body, and a gable and pulpit roof over the sacristy and chapels. The church was covered with three parallel roof covers, one for each nave. The tower was covered with a helmet in the form of an octagonal broken pyramid. The war damage suffered by Kożuchów in 1945 spared the church. At its core, the building is a late Gothic structure with added Renaissance elements (the vaults of the nave and the presbytery) and Baroque elements (the Ogrójcowa chapel, the helmet of the tower).

Research methodology

Analysis of the resulting cracks may be an indication of uneven foundation subsidence, which in turn may indicate heterogeneous ground conditions upon which the building rests. The lithographic structure may comprise many layers and may be characterized by differing physical and mechanical parameters. The issue described above concerns the situation in many historic objects built centuries ago in medieval towns, where soil layers accumulated in succeeding years. Due to the fact, that design cross-sections of analyzed historic buildings (cathedrals, palaces) were of considerable size, the situation is more than likely that they extended over a diversity of soil and water conditions. For this reason, analysis of the cracking pattern of a heritage structure, usually requires geological surveying at points surrounding the historic building in order to ascertain a full picture of the geotechnical status of the underlying substrate. The key challenge lies in locating the bore holes and in determining the depth of the boreholes which can extend to tens of meters.

The most appropriate procedural algorithm for selecting design solutions for the repair and strengthening of a historic building must be based on a wider assessment of the structure of the building and its technical condition. A multi-level correlation of available data enables solving technical issues as a basis for selecting appropriate structural solutions. In the first step the H-BIM model preparation is needed. Then the identification of cracking pattern and geotechnical investigation were carried out. Finally the structural analysis was performed and strengthening solutions were designed the procedure used in the case of the church in Kożuchów is presented in Fig. 2.

Results and discussion

Geometrical survey and H-BIM model

The contemporary devices and software allow to prepare 3-D model of historical object in H-BIM technology, aiming to carry out—in the next step—an appropriate numerical simulations and structural analysis. In case of the church in Kożuchów, tachometric technique was used to determine the global localization of each point for the vaults, arches and walls (Fig. 3). The measure procedure was carried out from outside and from inside.

After the preliminary visual inspections, the range of geometrical survey was defined. All of the points were uploaded to the H-BIM software (Autodesk Revit) using additional software (Autodesk ReCap), that allows this transfer. Figure 4 presents an axonometric view of the church building.

Based on the visual inspections and preliminary analysis of the cracking pattern a hypothesis was formulated concerning the influence of soil and water conditions on the uneven settlement of the building structure, and in consequence on structural cracking. The cracking pattern indicates that it occurs something

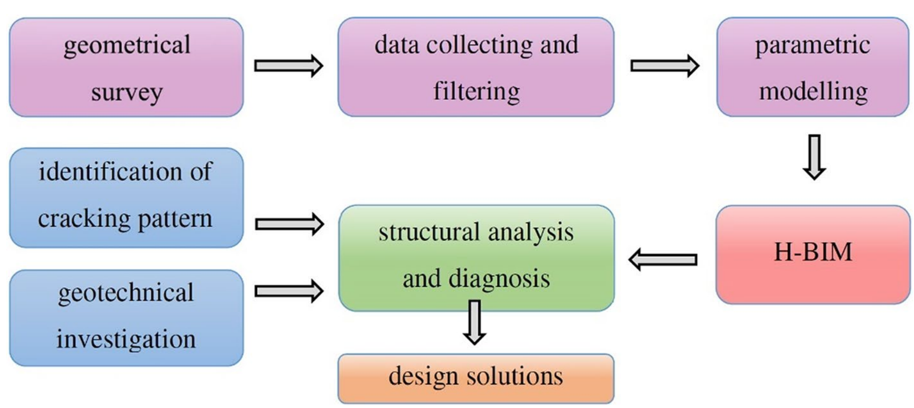

Fig. 2 Flow chart of the methodology used in the church in Kożuchów

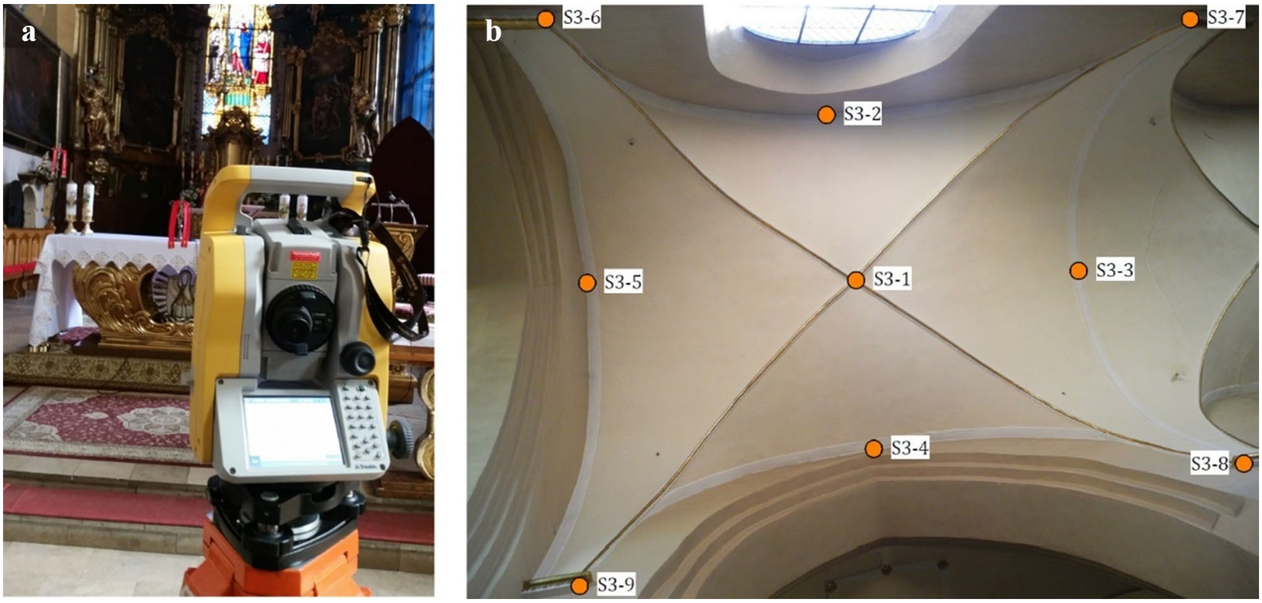

Fig. 3 Geometrical survey in the church: **a** measurement device, **b** points definition for laser scanner measurement

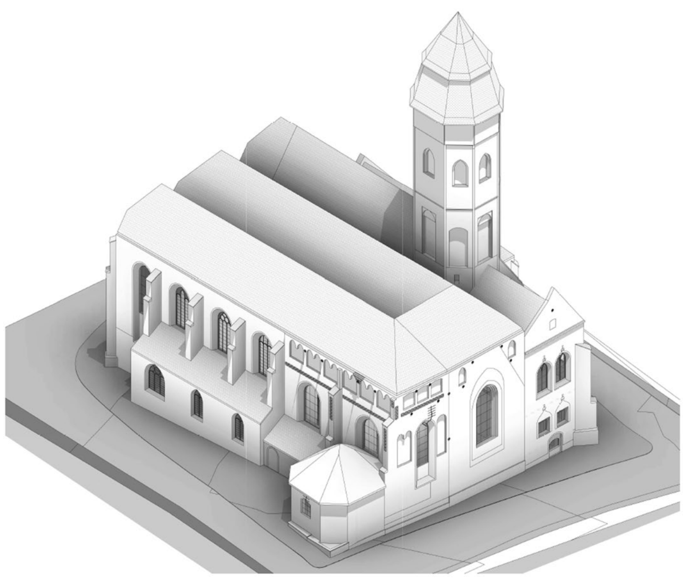

Fig. 4 View of the digital model of the church in Kożuchów prepared in Revit

separate from cracking of the vaults resulting from the gable wall displacement in external direction. The cracking pattern points to global deformation of the gable wall, which leans out into Kościelna Street. The horizontal displacement of the gable wall has been confirmed through tacheometric testing (Fig. 5).

Geotechnical investigation of the ground substrate

Investigation of the cracking pattern and assessment of the displacement of the gable wall, prompted formulation of the hypothesis that damage had been caused by variations in soil and water conditions. Geotechnical tests were carried to test the hypothesis based on boreholes in the ground in conjunction with core sampling of

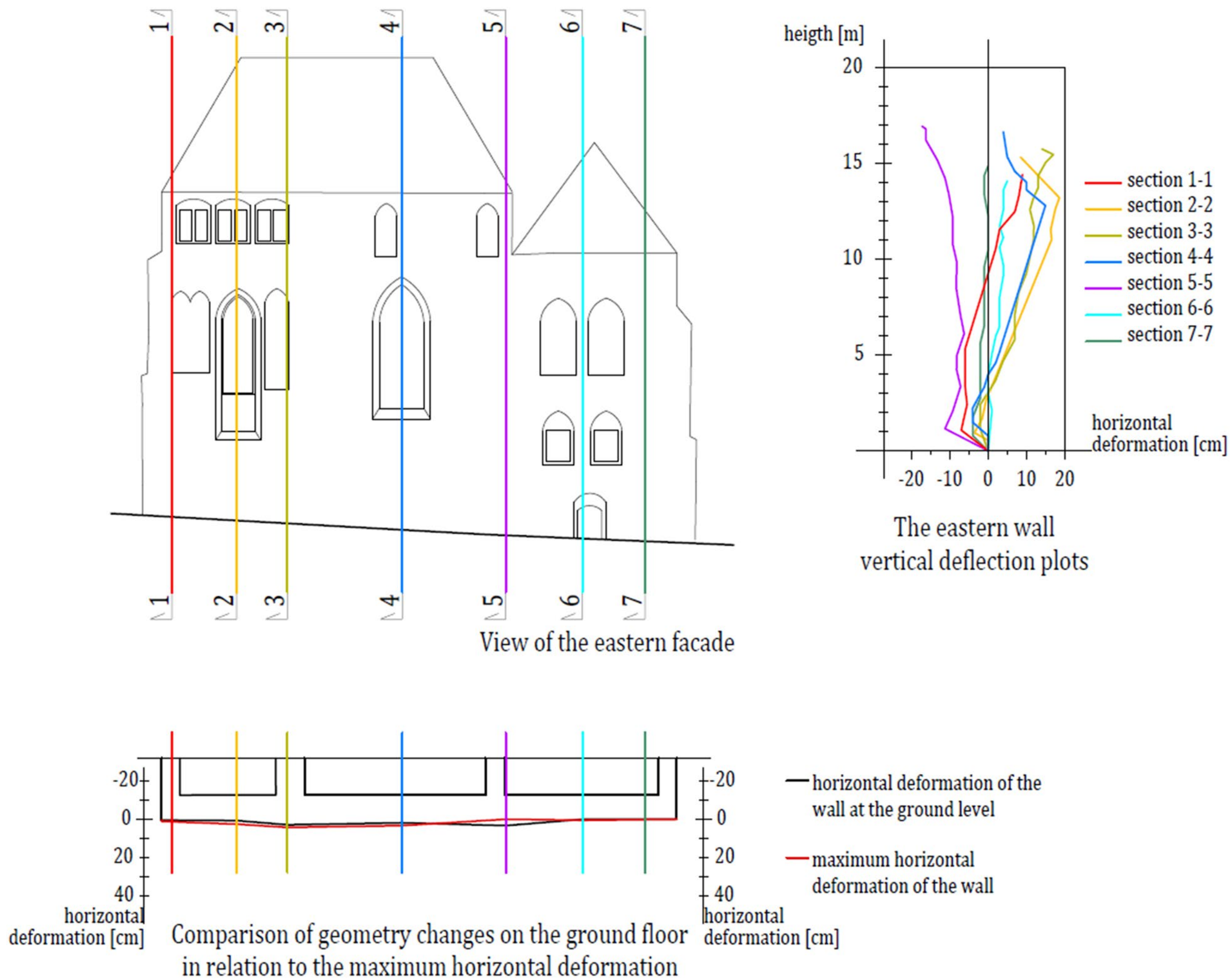

Fig. 5 Assessing displacement of the gable wall into Kościelna Street

the foundation walls [61]. Six geological boreholes were drilled to a depth of about 4 to 12 m below ground level (total depth of approx. 50 running metres) and 5 core samples were taken from the foundation wall in the east, where damage was greatest. The locations of the boreholes and core samples from the foundation wall are presented in Fig. 6.

A dry drilling method without pipe casing was used for preparing the geological boreholes. During the testing process, macroscopic description of soils (type, admixtures, layers, colour, moisture content) was recorded on an ongoing basis and samples were collected for laboratory testing, ensuring that the natural moisture content or natural granulation was assured. Soil samples were taken to enable laboratory analysis to determine the physical–mechanical parameters of the ground substrate (on average, 3 or 4 samples were taken from each borehole). Laboratory testing involved a sieve analysis of the collected loose soil samples, whereas the condition of compacted soils was determined by testing the consistency limit and determining the moisture content.

The results of geological borehole and laboratory testing served to separate out geo-technical layers in the ground substrate, and so, to determine geological and engineering conditions. The ground conditions supporting building foundations were also determined. In all, 7 geo-technical soil layers were separated out in terms of their physical–mechanical properties (degree of plasticity and compaction), (Table 2).

Geological surveying identified the soil-types appearing in the area of the building's foundations. A subsurface earthworks layer was identified (which includes uncontrolled deposits of clay, sand and brick rubble) and also deeper layers of indigenous compacted soils (including mainly sandy clays, phyllosilicate clays and fine clays) and non-compacted soils (sands). The

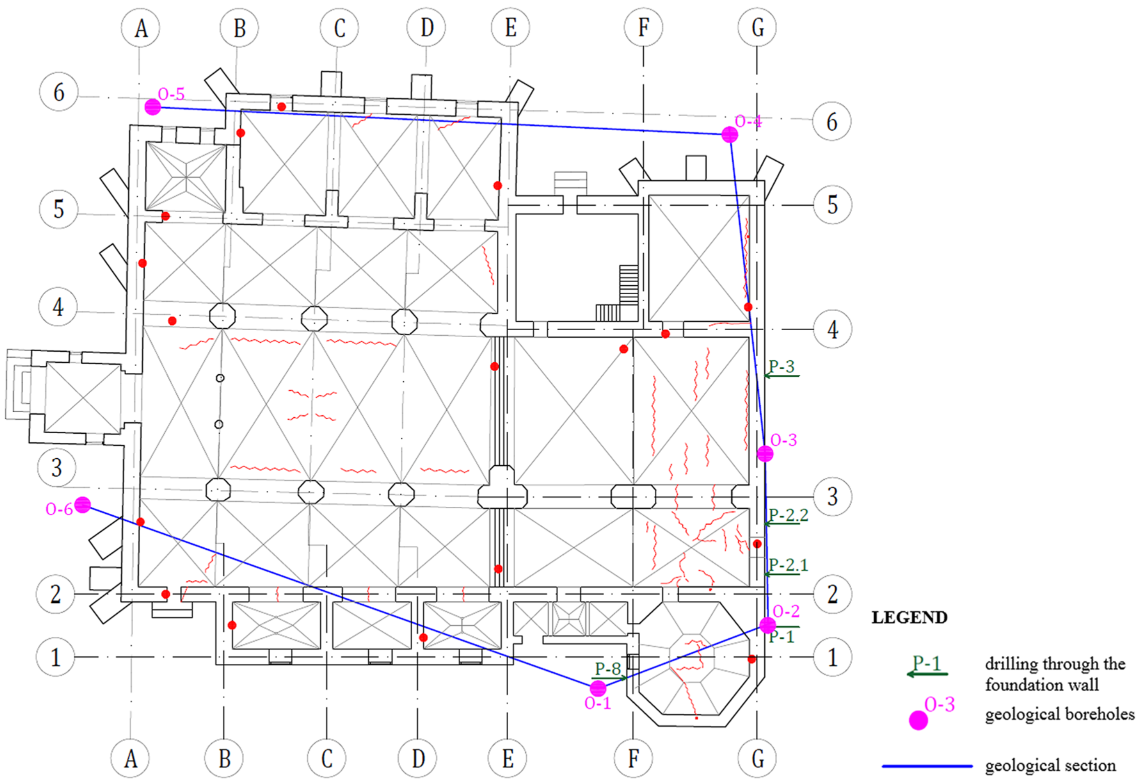

Fig. 6 Ground-level plan of the church (with vaults) showing locations of geological sections, geological boreholes (O), drillings through the foundation walls (P)

Table 2 Listing of ground substrate geo-technical layer properties

Symbol	Description	Density index (ID) for noncohesive soils/liquidity index (IL) for cohesive soils
I	Uncontrolled anthropogenic soils (brick rubble, clay, sand), appearing in a plastic state	IL = 0.50
IIa	Fine grain, moist sand appearing in semi-compacted state	ID = 0.45
IIb	Medium grain sands, coarse, moist sand, appearing in a semi-compacted state	ID = 0.40
IIIa	Hydrated sand-gravel, appearing in a semi-compacted state	ID = 0.50
B1	Phyllosilicate clays, sandy clays, dust with phyllosilicate sand layers, moist, appearing in a plastic state	IL = 0.43
B2	Phyllosilicate clays, sandy loams, dust with phyllosilicate sand layers, moist, appearing in a hard-plastic state	IL = 0.18
D	clays, sandy clays, silts, wet, damp, appearing in a compacted or semi-compacted state	IL < 0.00

research also accurately determined the morphology and hydrography of the ground substrate. The depth of the ground water table was determined to be located 4.50–5.80 m below ground level and 7.80 m below ground level (in the O-3 geological borehole). Groundwater resources change under the influence of precipitation, evaporation and may be subject to seasonal fluctuations of ± 1.0 m. The diversity of ground layers appearing in the geological borehole locations indicates complex ground conditions underlying the foundations of the building (Fig. 7).

The analysis the influence of soil and water conditions on the building foundation is possible on the basis of geological cross-sections obtained for different directions in relation to the ground-level floor plan of the building (Fig. 8).

As a result of the core samples (vertical relative to the wall), the condition of the building's foundation was

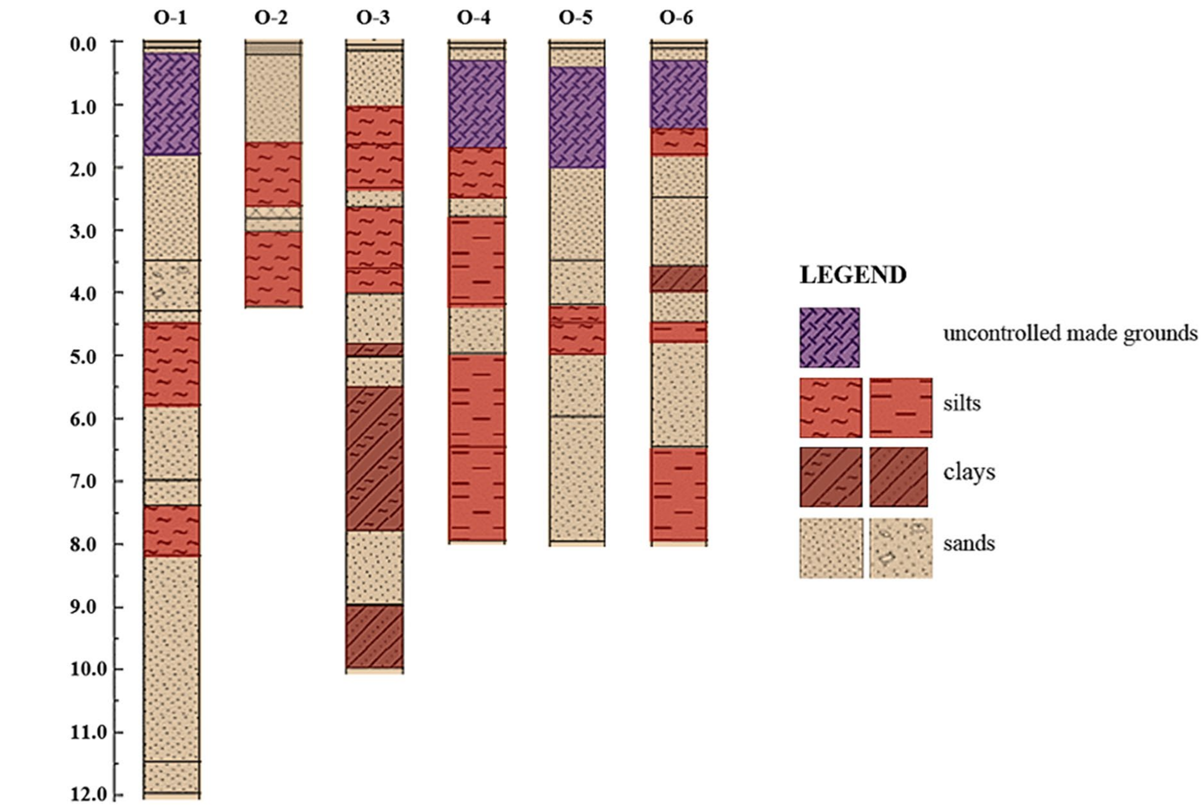

Fig. 7 Soil characteristics in specified geological boreholes

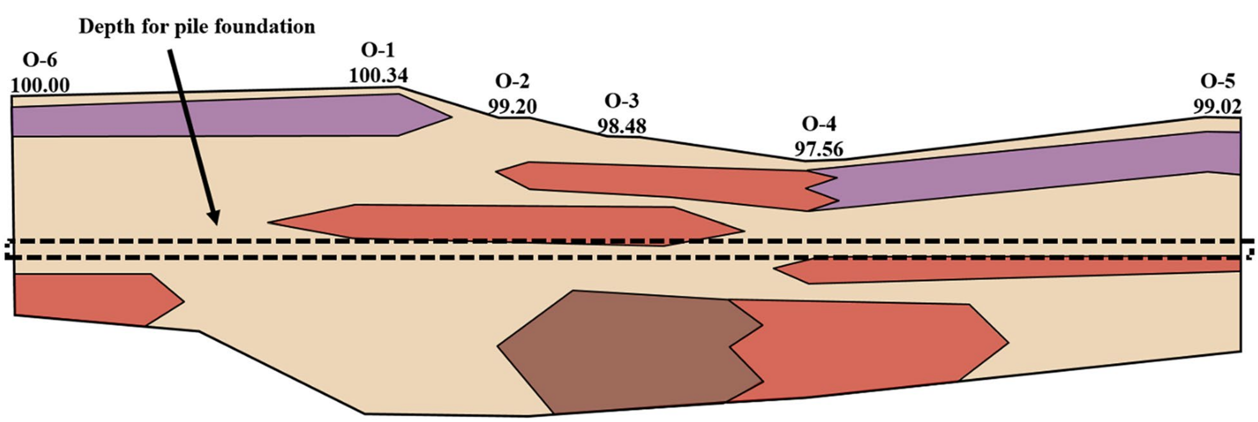

Fig. 8 Schematic geological section

determined for the eastern wall area. The church structure was built on stone foundations placed at a depth of 0.60 to 0.70 m below ground level. The south-eastern chapel was built at a depth ranging from 2.10 to 1.40 m below ground level. The frost depth for the village of Kożuchów is 0.80 m, which means that part of the foundations on the eastern side do not meet minimum requirements. Existing foundations are set partly in substrate subject to displacement (fine grained dust and phyllosilicate clays), and sensitive to freezing and ground water level changes. In the event of even slight water absorption, they can plasticize rapidly under even a small load and reduce their load-bearing capacity. The foundation wall of the church on the east side and the chapel is built with pebbles, sandstone and brick on clay and lime mortar. The content of clay in the mortar determines the mechanical properties of the wall (especially the modulus of elasticity) are variable for different moisture levels. Taking into account the cracking pattern on the walls and vaults of the building and soil substrate that is sensitive to ground water level changes beneath the foundations, it can be concluded that the foundations have sustained a loss of stability (related to both rotation and displacement) in the eastern wall of the church and the chapel in the south-eastern part of the building. These foundations are displacing in both horizontal (outside) and vertical (settling) directions.

It was determined that the observed damage (cracking) was caused by uneven horizontal and vertical movements of the foundations arising from variations in geological substrate. The cracking has been caused by: foundations that are too shallow, periodic fluctuations in water level in weak load-bearing soils and soil loosening due to excavation.

It was necessary to strengthen the foundations of the church in the eastern part and in the south-eastern chapel to avert the threat of building collapse.

Analysis of cracking patterns of walls and vaults

Observation of numerous cracks on the walls and vaults of the church prompted structural assessment of the building. The cracks were inventoried and presented on floorplans of the church. Cracking on the vault surfaces and vertical cracks in the walls were noted. Special attention was paid to the numerous longitudinal cracks in the eastern part of the heritage building (Fig. 9).

Cracking appeared on both walls and vaults mainly in the eastern part of the building, but also in the main nave. The most significant crack was identified in the inter-nave arch in axis 3, between axes F and G. In this case, the damage to the arch also manifested itself by shifting a wall fragment in a vertical direction. The crack size measured approx. 15–20 mm, posing a serious threat to structural safety. The direct cause of the crack and the formation of a hinge in the interval arch in axis 3 was the significant vertical load of the structure in the area of the roof truss above the arch. Measured from the church floor, the height of the nave at its highest point is 11.52 m. The vaults are supported by external walls (southern and eastern), by the rood arch in the E axis and by the pillar located at the intersection of axes 3 and F. Examples of the cracking are shown in the photographs in Fig. 10.

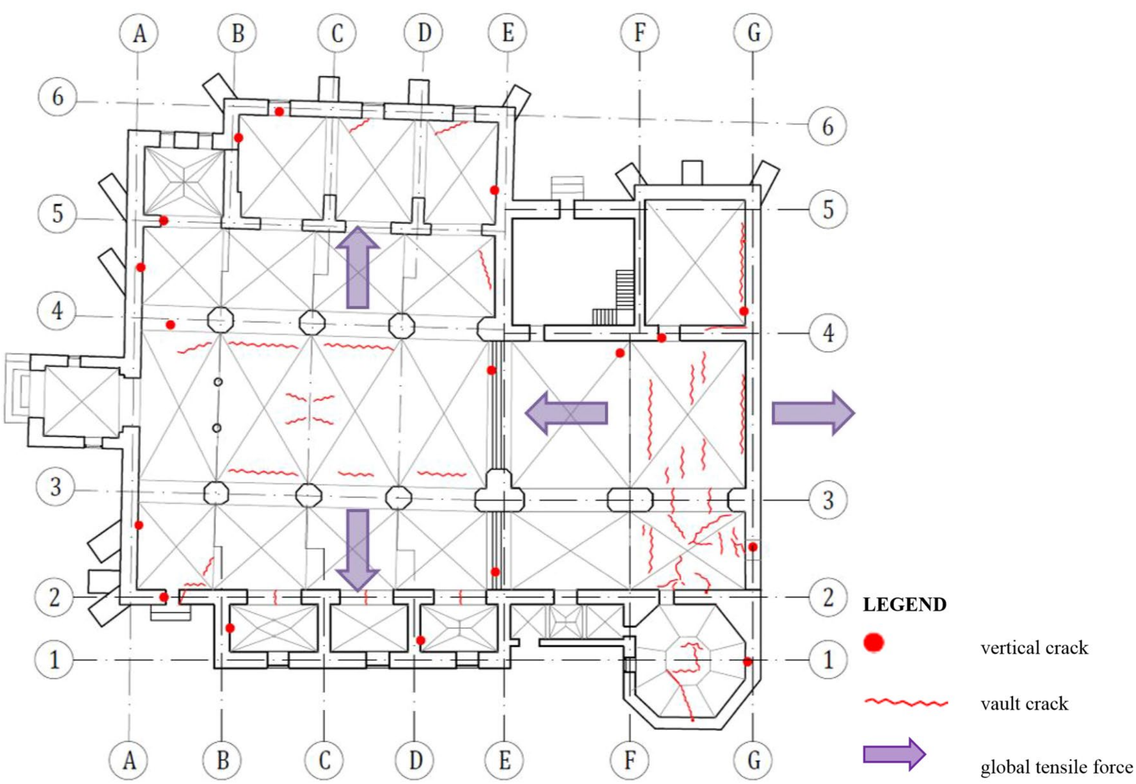

Fig. 9 Church plan including cracks appearing on the walls and vaults

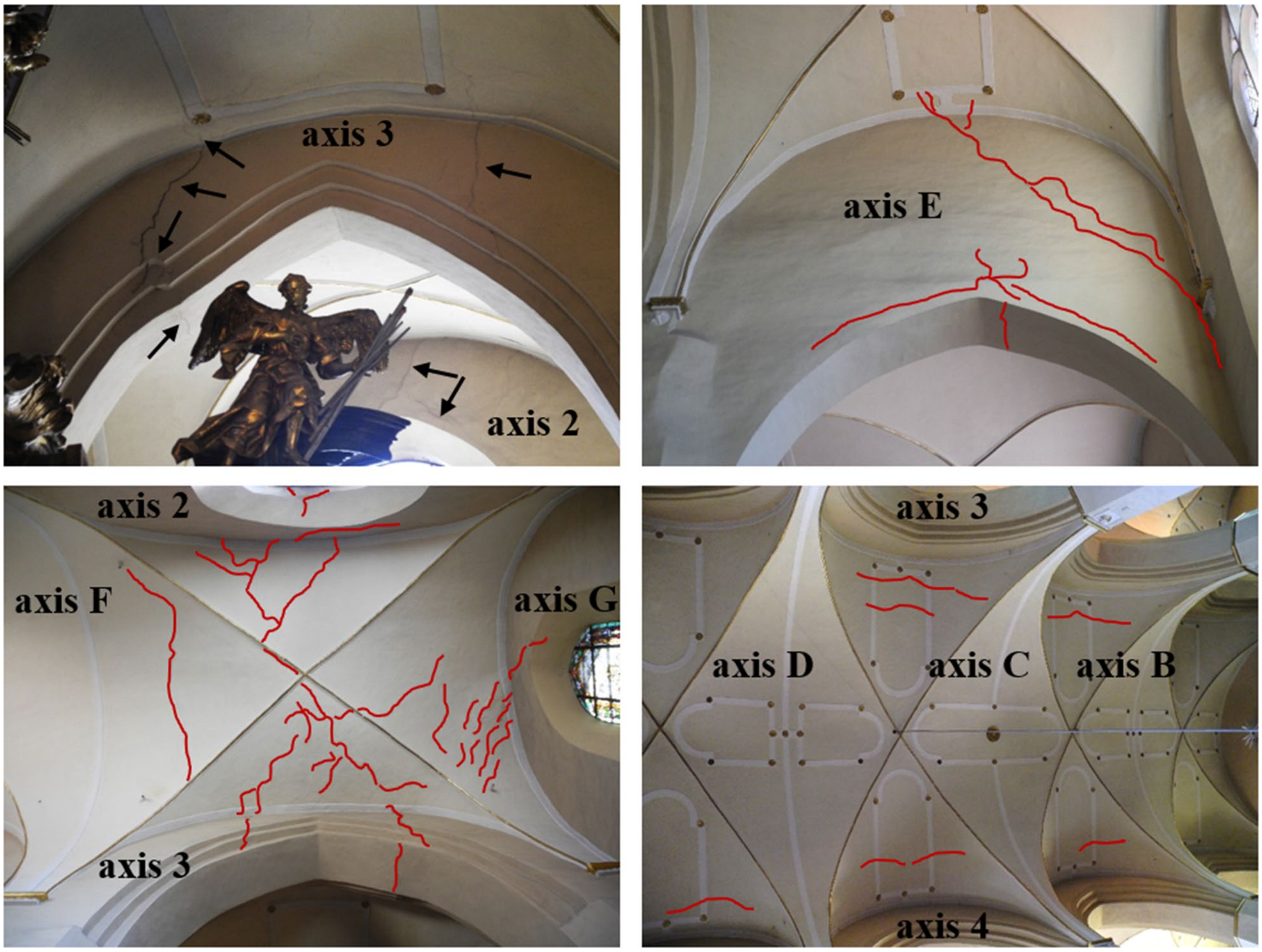

Fig. 10 Examples of cracks appearing on walls and vaults of the church

Cracking penetrating the entire thickness of the cross-section was observed in the area of the southern nave and the adjoining chapels. The cracking is concentrated especially in the area of the keystones of the window lintel arches in the upper part of the southern facade. Diagonal cracking was observed in the rood arch, which separates the southern nave from its extension towards the presbytery. Moreover, a deformation (twisting) of the rood arch from the vertical plane was observed. With a maximum height of 13.95 m, the main nave consists of 4 bays covered by cross vaults. Cracking was observed in line with the direction of compressive stress.

In the eastern part of the building, the cracking pattern of vaults indicates the occurrence of tensile stress along the external wall of the building. A typical vault cracking pattern resulting from exceeding tensile capacity in specific places in relation to the situation in the church in Kożuchów is presented in Fig. 11.

The analysis of the influence of the load from the roof into church walls

During the diagnosis process, the influence of the load from the roof into church walls was checked. For this purpose, the 3-D roof data were uploaded from H-BIM model to structural software (Fig. 12). Various live load (wind) cases were considered to determine the predicted vertical reaction on the external walls.

As a result of structural analysis, the values for reactions from the roof to the wall was determined (Fig. 13).

It was estimated that the internal stresses in the walls caused by horizontal forces from the roof are on the low level and do not have crucial meaning for the cracking appearance in the vaults, but there was a need to add tie rod to ensure the stability of high top walls.

Structural strengthening of the church

The scope of strengthening work focused on the eastern part of the church foundations and the chapel

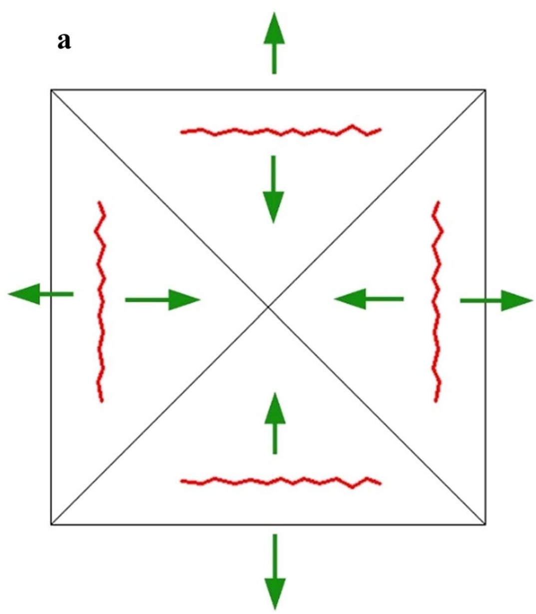

Fig. 11 Cracking patterns for cross-vaults: **a** typical, **b** vaults in the eastern part of the church in Kożuchów

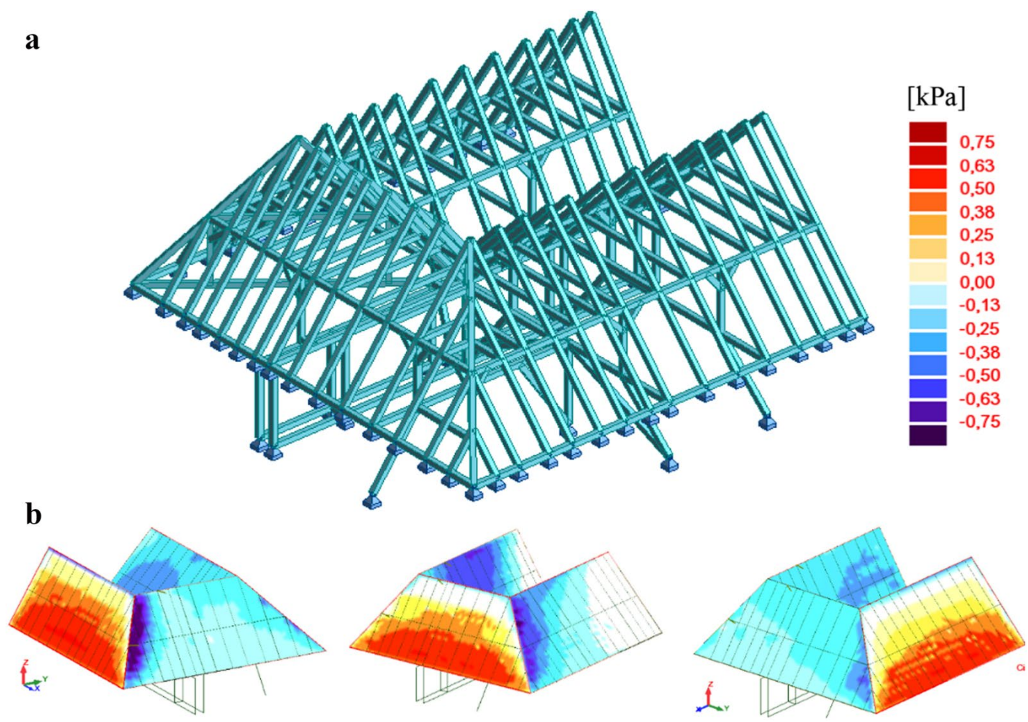

Fig. 12 3-D numerical model for structural analysis of the roof: **a** static scheme, **b** various live load cases (wind)

foundations in the south-east side (Fig. 14). The intervention that was made in this case, should have preventive aims and ensure a passive counteracting for the settlements. Otherwise, such a deep intervention may cause some unexpected reaction for the global structural behaviour in the future. The strenghtening project was prepared on the basis of results of structural analysis.

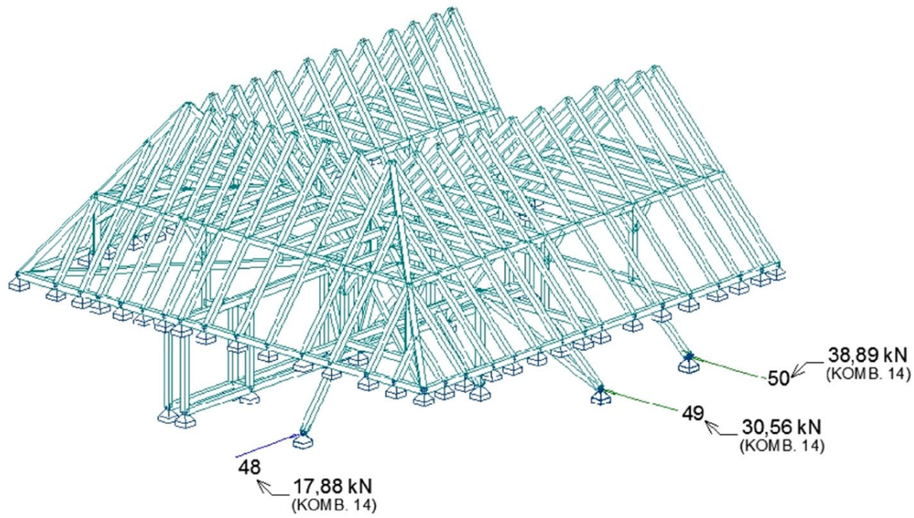

Fig. 13 The values of reaction forces from the roof which act on the external walls

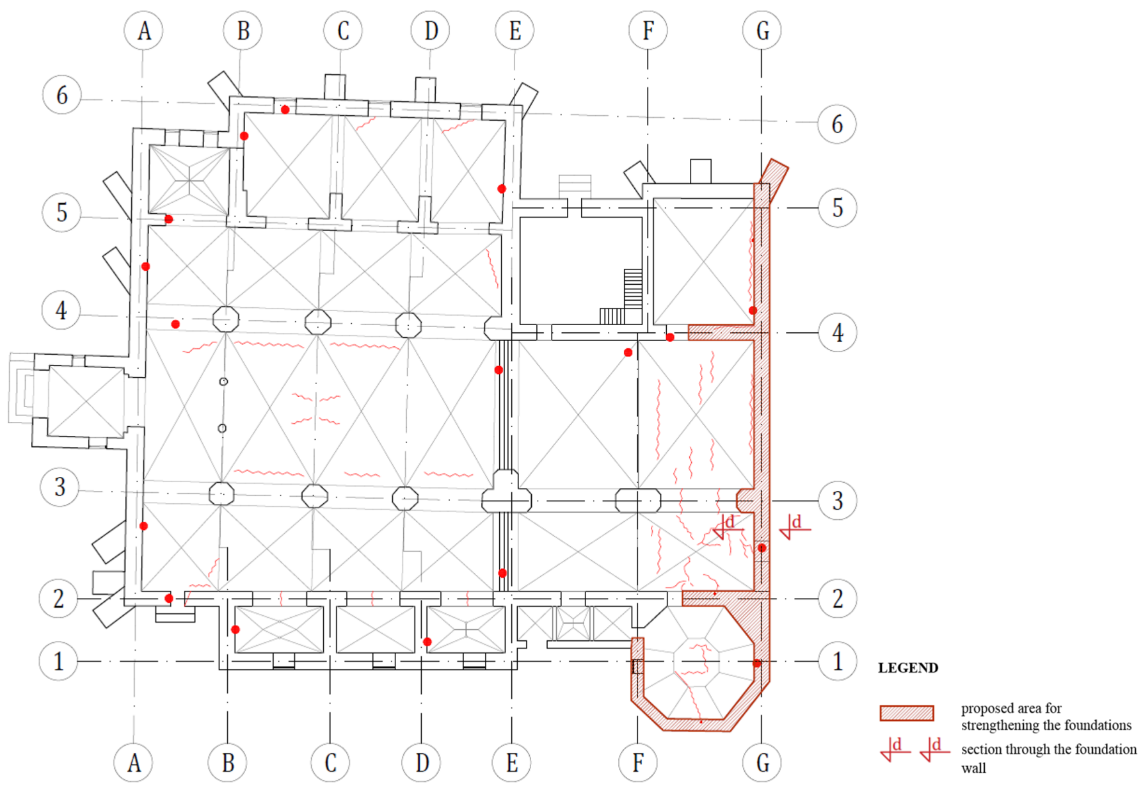

Fig. 14 Plan of the church (with reference to the vaults) showing the foundation area proposed for strengthening

When it comes to strengthening existing historic buildings built using traditional technologies, non-vibrating technologies and technologies that are insensitive to changing ground water levels should be considered [61]. In the case of the church in Kożuchów, the strengthening measures applied involved constructing cement and ground columns using jet—grouting technology. Reinforcement involved replacing low-load bearing soils with a concrete substrate of a strength of 3.0 to 7.0 MPa. Figure 15 shows models of the church, indicating a design

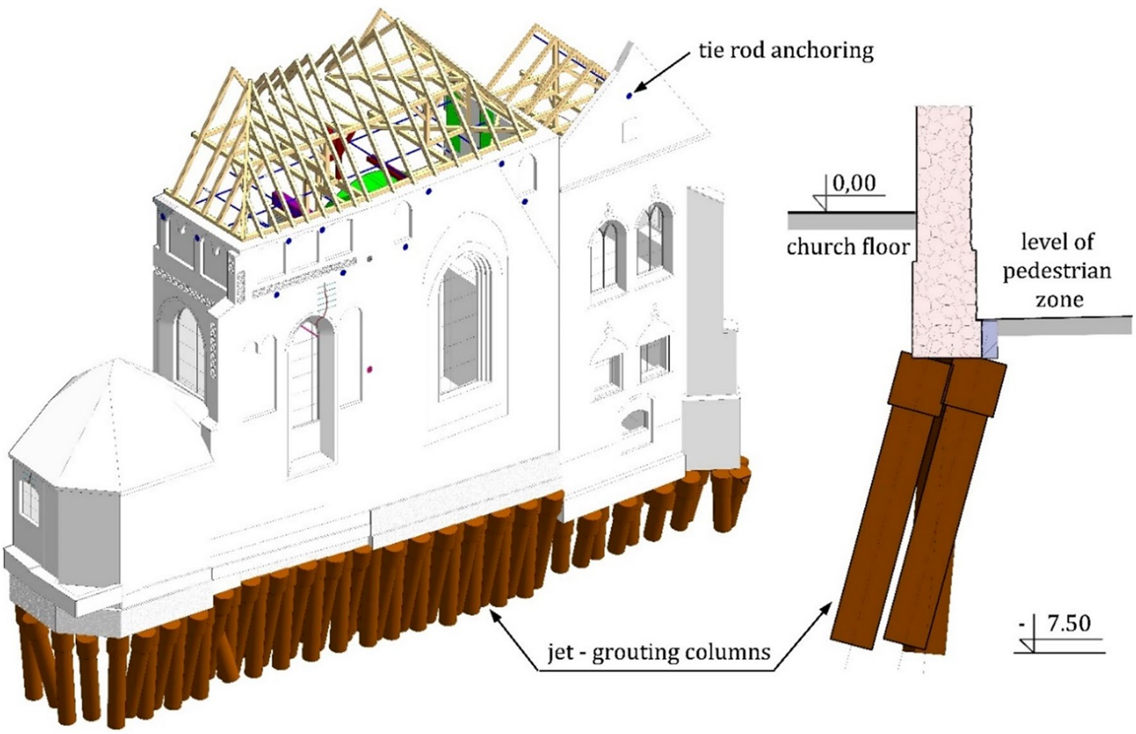

Fig. 15 Axonometric view of the church showing design for strengthening with jet-grouting columns and zones for tie-rod anchoring (left). Diagonal cross-section through the foundation zone (right)

for reinforcement of the foundations based on using piles.

First, tie rods were introduced in order to stabilize the structure and take over the forces from the roof, and then the vaults should be strengthened due to damage occurring in them. In addition, the strengthening of the upper sections of the building through introducing

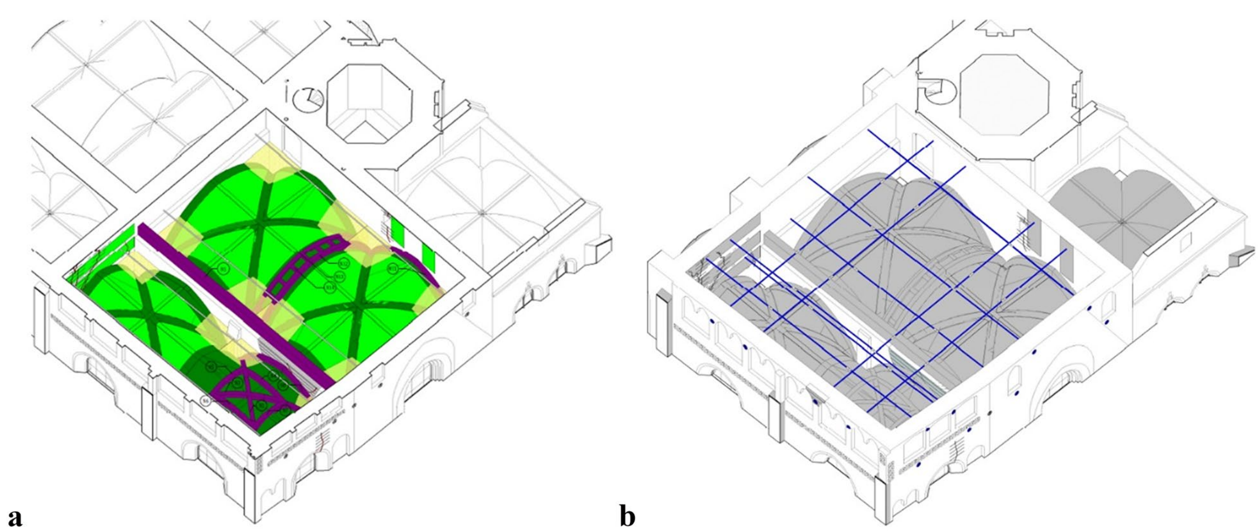

Fig. 16 Axonometry of the vaults with strengthening introduced in the form of: **a** C-FRCM carbon fibre nets (marked green), **b** 40 mm diameter tie rods (marked blue)

steel cables and strengthening the vaults on the roof side using FRCM technology was necessary (Fig. 16).

Conclusions

1. H-BIM method is an advanced approach that allows to obtain detailed building and structural model and gives the opportunity to conduct a global analysis of the technical state and state of stresses. It is strongly recommended to prepare the H-BIM model for heritage objects before any structural interventions, especially in the case where the building structure is complex. Furthermore, the contemporary H-BIM models allow to collect information about the previous and current interventions in one digital file, what should be the principle in contemporary design processes.
2. Based on the structural roof analysis, it was estimated that the internal stresses in the walls caused by horizontal forces from the roof are on the low level and do not have significant meaning for the cracking pattern in the vaults, however, there was a need to add tie rods to ensure the stability of high top walls.
3. Geotechnical research conducted at large scale (especially geological boreholes drilled to considerable depths), enabled the determination of soil properties in the area of the building's foundations, and as a consequence, indication of the causes of cracking of the church structure.
4. The main cause of cracking of the walls and vaults of the church was related to uneven subsidence and localized stability loss of the building's foundations, resulting from differentiated soil properties beneath the building.
5. Every historical building requires its own individualized approach for diagnosis and selection of design interventions.
6. Based on diagnostic results including modern techniques, it may be possible to plan appropriately and conduct conservation and strengthening interventions in historical buildings.

Acknowledgements
Not applicable.

Authors' contributions
Conceptualization: KR; analysis: AK, KR; resources and data: AK, KR; writing—original draft preparation: AK, KR; writing—review and editing: AK, KR; supervision: KR. All authors have agreed to the published version of the manuscript. All authors read and approved the final manuscript.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare no conflict of interest.

Received: 4 November 2020 Accepted: 31 March 2021
Published online: 13 April 2021

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