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From Digital Surveying to Heritage Analysis on the Example of a Baroque Church: A Proposal for Structural Strengthening and Monitoring

Od cyfrowej inwentaryzacji do analizy dziedzictwa na przykładzie barokowego kościoła – propozycja wzmocnienia konstrukcji i monitoringu

Keywords: masonry, church, Baroque, laser scanning, orthophotogrammetry, analysis, strengthening, monitoring

Słowa kluczowe: mury, kościół, barok, skanowanie laserowe, ortofotogrametria, analiza, wzmacnianie, monitoring

Introduction

The methods used to survey and analyze the state of preservation, and also to monitor geometry in historical structures, include many technologies. In recent decades, new tools have emerged, including: 3D scanners, rapid prototyping, spherical and infrared photography, photographs taken from unmanned aerial vehicles (UAV), expanded virtual reality and computer rendering in many dimensions. These technologies give us almost unlimited possibilities of their use when working with cultural heritage sites and buildings. For a long time ICOMOS,[1] or, for example, ICOMOS/CIPA, as well as Waldhäusl and Ogleby,[2] discussed the need for appropriate information on heritage structures. The current development of data collection often leads to an overwhelming amount of information about objects (e.g. 3D point clouds, databases), the quality of which varies. Therefore, modern technologies that have changed the possibilities of surveying and documenting cultural heritage structures should be used reasonably and by trained specialists. Although the development of measuring equipment (cameras, lenses, laser scanners of various types, used on static or

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mobile platforms, on the ground or from the air) and software have provided the means to digitally collect data, their storage, extraction and dissemination must be realized intentionally and prudentially. It should be remembered that GPS (Global Positioning System), coupled with tacheometers and laser scanners, also providing the possibility of geo-referencing GIS (Geographic Information Systems), are only computer systems for storing, extracting, visualizing, distributing, and analyzing three-dimensional data. These systems, combined with powerful CAD/CAM and production tools, can be used to create 2D and 3D surveys that are needed in further analysis and diagnosis.[3] The final decision as to the shape of the documentation resulting from the survey, as in the case of cultural heritage management, should still be carried out by an architect—a constructor—a restorer, a prepared, educated person, armed with new technologies.

History, architecture and structure of the church

Our paper presents the possibilities of applying innovative technologies to surveying, modeling and analyzing the structural condition of a historical monument—a Baroque church located in Southern Poland—and is an extension and summary of a study presented partly by Bednarz et al.[4]

It is worth adding that the state of preservation of architectural monuments, including historic churches, town halls, and residential buildings, is important in terms of the technology in which they were erected (wood, brick), in the section it is necessary to act in the field of asset protection. It should be assessed that the current control of bans should be carried out in the case of materials covered by statutory protection, e.g. by entering into the register of monuments. Activities related to the surveying and analysis of a building's structural behavior must also precede all renovation procedures to be carried out on the building and its adaptation and reuse.[5]

The church under study was the first property of the Society of Jesus in Silesia. Numerous sources[6] reported that construction started in 1688 and finished in 1692. The church's entrance portal was added later, in 1695. The designer of the church was Andreo Quadro from Milan, who modeled its layout on the Il Gesù Church in Rome (frequent in the case of religious buildings of the Society of Jesus). The church was founded by bishop Karol Ferdynand Waza and bishop Franciszek Ludwik von Neuberg.[7] The church was built as oriented, slightly rotated towards the north, with a basilica plan featuring galleries. The basement level is elevated in relation to the ground level.

The church has one underground floor, covering the entire contour of the church, which contains the crypts. The sacristy, which is a two-story building, was added on the northeastern side. Passage to the sacristy is possible through the side chapel of the presbytery. The southeastern corner of the church is connected with the neighboring buildings. The frontal facade was created in a symmetrical arrangement with two towers. The entrance is located axially, and covered with a decorative portico. The central nave with the presbytery is covered by a gable roof finished (in the apse zone) with the form of half a cone. The side facades are covered with separate pitched roofs. The church is roofed with metal sheets. The dominant element of the interior of the church is its wide middle nave that smoothly connects with the presbytery, which ends in an apse. Above the main entrance is a gallery for a choir with organs. The nave is vaulted by a barrel vault with lunettes. The chancel in the front part is vaulted with a cross vault. The vault of the apse has the form of three interconnected lunettes separated by radially placed ribs (middle telescope without a window opening). A massive cornice that cuts off the vaulting zone is a distinctive interior element. On both sides of the nave there are three chapels, which open towards the nave with arcaded passages. Similar chapels are located on the sides of the presbytery (one per side). Between the arcades there are double pilasters which, together with double buttresses within the vault, create a rhythmic, transverse division of the interior. The system is supplemented by arcades on the level of side galleries. The interior of the church is well-lit, the windows are located within the scope of the lunettes at the level of the vault, with additional windows at the height of the gallery and in each of the chapels in the basement area. Vaults at the level of the gallery and in the chapels have the form of cross vaults with wide, flattened ribs, which constitute a decorative element.[8]

The building has a solid structure, the wall thickness ranges (in the above-grade zone) between 0.8 m and even 1.5 m. The wall on which the naves are supported has an average thickness of 1.2 m. Within the presbytery and the apse, the wall is thicker. Changing the wall thickness is probably a consequence of the lack of side parts of the building in this section (chapels with galleries are not present within the apse). Chapels and side galleries are separated by walls perpendicular to the partitions encircling the nave. These walls act as elements that stiffen the structure. The thickness of the perpendicular walls is about 1.5 m. These walls are elevated above the vaults of the gallery, where they are chamfered in accordance with the shape of the roof. They completely disappear just above the nave's point of support. These transverse walls constitute massive buttresses for the structure of the nave and take over the struts from the main vault. The location of the buttresses is not accidental, they are located in the axes of double pilasters and buttresses. The only openings in the buttresses are passages on the galleries and technical openings at the level of the attic (above the galleries).

The most intense element of the church's construction is the vault, which is the focus of this study. The vault in question can be divided into four zones. The first, largest part, is the vault of the nave. As mentioned above, it is a barrel vault divided into spans by means of double butts. Within each span there are two telescopes located opposite each other. In total, there are three spans within the nave. The radius of the arch of the vault is about 7.05 m, the height is about 6.75 m. The lunettes descend slightly outwards. On the basis of the measurements, a roof outer layer thickness of 0.25 m was assumed, butts with a thickness of about 0.47 m. Additional reinforcements of the above-mentioned vault were observed, occurring only in the dorsal part, the rib running along the top of the vault, and transverse ribs in the telescope axes, forking and circling telescopes on the sides. The second zone is the cross vault located in front of the presbytery (on the axis of the last side chapels). Here, too, a slight descent of the ridge of the arches towards the window openings was visible. There are no visible ribs within the vault. The thickness of the vault's shell was assumed as above. The area of the apse with a rather unusual form of the vault can be regarded as the third zone. The inner surface is a part of an ellipsoid, within which radially orientated ribs (reminiscent of the form of the hearth) have been located. Between the ribs there are three lunettes with a complicated form of arches. In the plane of the curved outer wall, they take a form similar to lunettes in the rest of the building (a rectangle finished with half of the ellipse). This shape blends seamlessly with the arcuate edges of the oblique ribs. At the same time, the system of an outwards descending backbone is preserved. The apse pattern, like the entire vault, is symmetrical. Side lunettes (with windows) have a similar shape to each other. However, it is different from the central lunette. This is due to the fact that the center of the ellipsoid falls in the space between the buttresses separating the cross vault from the apse. Therefore, the last buttress "cuts" a part of the ellipsoid, thus affecting the shape of the apex side arches. The last, fourth zone that can be distinguished within the vault in question is the vault above the southern apse (choir). It has a relatively simple form. It consists of a single-span barrel vault with two lunettes without windows.

All the zones mentioned above are separated by transverse buttresses. Arches separating the apse from the rest of the presbytery have a form similar to the buttress within the nave vault. The difference appears only in the way they are arranged in relation to each other, within the nave of the pair of buttresses they have a symmetrical system, while in the presbytery, the ribs that separate the apse have a cascading form (rising towards the apse).

Due to the many years of neglect caused by the lack of sufficient funds, many structural elements (perimeter walls, vaults) and finishing (especially facades) of the church require immediate renovation and conservation intervention. In order to perform conservation and renovation works on a monument of this class, its technical state of preservation should be assessed first. Due to the wide range of planned works, it was first necessary to carry out a structural and conservation expertise, perform a detailed survey of the site (including a 3D building survey), perform structural analysis and prepare a conservation program and a construction and conservation design of the church's renovation.

Survey of the church's structure and damage

In order to perform an accurate structural survey of the church, it was decided to perform a 3D laser scan and compare this survey with an ortophoto model and DSM (Dense Stereo Matching) model. Both methods allow for the automatic reconstruction of a 3D model from photographs. The reconstruction process consists of a number of steps. The first step is the detection and description of local features (binding points) and their description in all photos by algorithms[9] used for this process. The next step is the automatic matching of the points identified in the images, their automatic orientation in 3D space by means of a photogrammetric spatial notch and the elimination of distortion from the photographs based on the parameters calculated from automatic alignment. The last step is the automatic concentration of point clouds with automatic photogrammetric procedures from images without distortion.

For the proper display of the object, the photos should not be taken from one place, while the camera positions should move evenly around the objects, while maintaining appropriate coverage of the photos. It gives the possibility of performing the correct photogrammetric indentation.

A laser scanner was used to acquire the point cloud, which reached a range of up to 130 m and accuracy of the distance measurement of ± 2 mm. The scanning range is 360° horizontally and 305° vertically. During the measurement, seventeen scans were made and over 230.6 million points were obtained inside and outside the measured building (Fig. 1). The process of combining scans was carried out in the scanning software,[10] to which 20 cm reference balls were used, and then their combination was improved via a "cloud to cloud" algorithm.

Photographs for orthophotogrammetry and DSM were made with a hand camera with a 50 mm solid support at resolution (4928 x 3264 pixels) and a 4K camera mounted on a DJI Phantom 4 UAV with a gimbal, with a resolution of 4000 x 3000 pixels and a large plant. Over 500 photos were collected inside and outside the building. The process of image data processing to the point cloud was carried out using AgiSoft software.[11] The result of processing were two independent models. The entire process of acquiring photographic material and comparison of the models were thoroughly presented by Bednarz et al.[12]

Currently, the church is in an unsuitable technical condition, which means that it was observed to be damaged to a degree that may endanger safety of use (Fig. 2). There were also signs of corrosion in the roofing area. Similarly, in the interior of the church, traces of moisture in the walls as well as cracks that indicate

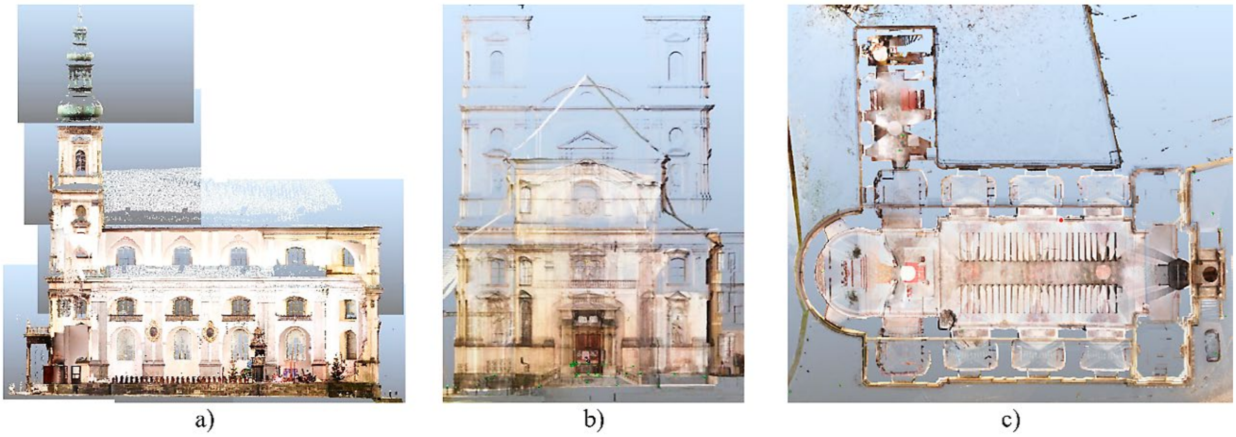

Fig. 1. 3D scans of the church: longitudinal section (a), cross-section (b), plan (c).

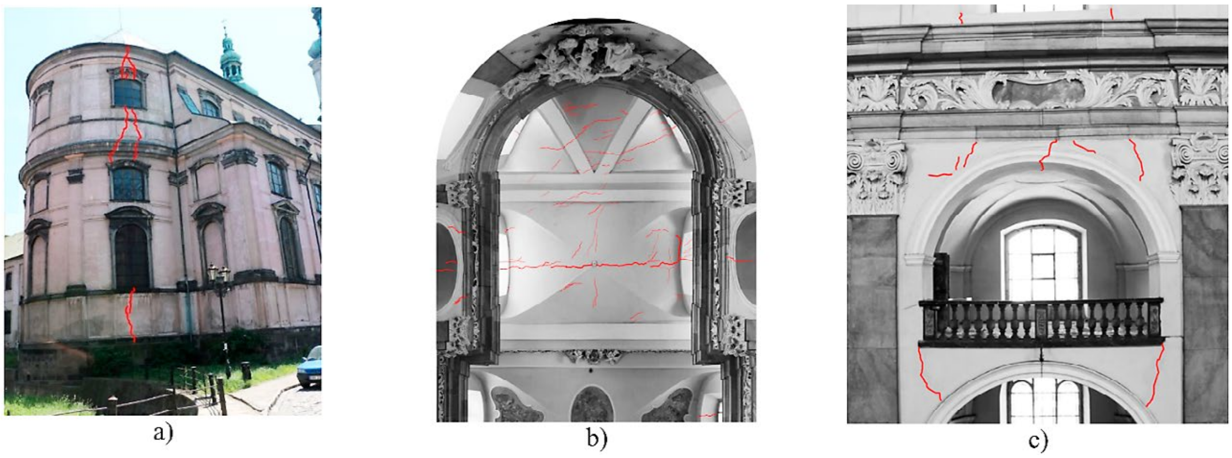

Fig. 2. Church damage: outside (a), inside (b), inside (c); photo by Ł. Bednarz.

irregularities in the behaviour of the structural system were visible.

To verify the survey's results, control points were selected on the structural elements of the building in the model. Analysis of the control points demonstrated that the back part of the model was deformed (displaced). This might have been a consequence of the subsidence of the footing.

Material testing

The material factors for the design and numerical model were implemented on the basis of results of laboratory experiments (Fig. 3), non-destructive and quasi-non-destructive tests and study described by Bednarz et al.[13] and were also compared with results obtained from the author's own study.[14] Among the quasi-non-destructive material tests, the CoDiT (Compact Diagnostic Test) method proposed by Skłodowski,[15] which utilises small-diameter micro-core material (typically 5 to 12 mm) to obtain as much data as possible, such as material density, ultrasonic wave propagation velocity, strength etc. can be very helpful.

Example results of measurements of absorptivity and porosity have been reported in Table 1, while the results of compressive strength measurements have been collected in Table 2.

The object placed under analysis was a masonry specimen. The wall was found to consist of an anisotropic material consisting of two basic elements: small-sized ceramic elements (bricks and/or stones) and the mortar that connects them.

Considering the available computational possibilities and their level of complexity, it was not possible to analyze larger structures or their parts taking while into account the allocation of material to the mentioned elements. Therefore, it was presumed that when analyzing bigger elements or complete structures, the material can be treated as isotropic with homogenized elastic properties. When wall parameters are determined as an isotropic material, it is necessary to perform a homogenization process to determine the outcome parameters from the component parameters and the relationships between them. One of the basic parameter necessary for calculations is the Young's modulus.

Results of the numerical analysis

Calculations were performed in ABAQUS/Standard software.[16] On the basis of the documentation of the church, a finite element model (FEM) was prepared.

Fig. 3. Bricks in a material strength testing machine – determining strength through compression (a–c),brick porosity (d); photo by Ł. Bednarz.

The calculations were conducted considering a linear material model for the masonry elements of the structure. However, geometrical nonlinearity was considered. For the FEM, the following material parameters were presumed: E=5500 MPa (Young's modulus), ν=0.167 (Poisson's ratio), ρ=1800 kg/m^3 (density) from material tests (Fig. 3a–c). In the 3D FE model, only the parts of the church that constitute the primary structural system were taken into consideration. The masonry walls as well as the masonry vaults were discretized using quadratic tetrahedral elements of type C3D10. The total number of finite elements was equal to 391250 and the total number of nodes was equal to 625585. The resulting FEM of the church has been shown in Figure 5a. For the foundations where subsidence was not observed (blue color, see Fig. 4b) the boundary conditions were used as defined displacements in three directions: U1=0, U2=0, U3=0. For the foundations where the settlement occurred (red color, see Fig. 4b), the displacement boundary conditions were taken as follows: U1=0, U3=0 (the boundary condition in Y-direction was unlocked). In Figures 5, 6 and 7, the results of the numerical simulations are presented.

The analysis led to the observation changes in the method of operating the system depending on the area of support. Based on the simulations of the overall

Sample number	**Weight of the sample soaked in water**	**Weight of the sample on a hydrostatic balance**	**Weight of the sample after drying at 105 °C**	**Water absorption**	**Porosity**
	m_n	m_{wh}	m_s	n_w	p_o
	[g]	[g]	[g]	[%]	[%]
1_1	48,943	31,652	42,835	14,3	35,3
1_2	43,655	28,665	38,522	13,3	34,2
2_1	10,338	6,695	8,958	15,4	37,9
2_2	60,231	36,650	52,200	15,4	34,1
3_1	6,525	3,986	5,525	18,1	39,4
3_2	26,585	15,251	22,654	17,4	34,7

Table 1. Results of measurements of absorptivity and porosity. Samples are numbered according to scheme x_y, where: x – brick number, y – sample number from brick x.

Sample number	**The upper area of the sample**	**The bottom area of the sample**	**The average area of the sample**	**Destructive force**	**Compressive strength**
	A_u	A_b	A_a	P	f_k
	[mm^2]	[mm^2]	[mm^2]	[N]	[N/mm^2] = [MPa]
1	16035	16173	16104	71000	4,41
2	17660	17700	17680	91000	5,15
3	15985	15985	15990	196000	12,26
4	14390	14590	14490	119000	8,21
5	16096	16112	16104	125000	7,76
6	16334	16434	16384	108000	6,59

Table 2. Results of compressive strength measurements.

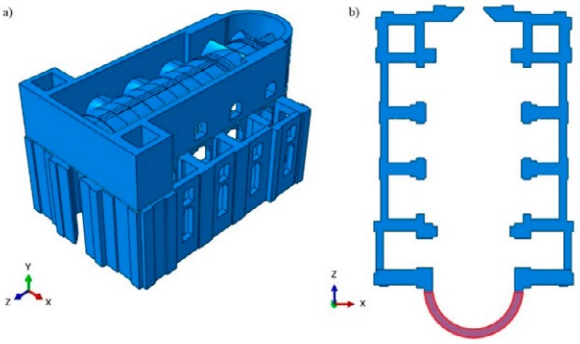

Fig. 4. View of entire finite element model of the church (a) and the view of the foundations of the structure (b).

model, it can be noticed that the greatest stress values were concentrated within the transverse axis located at the point of origin of the perimeter wall support. The increase in stresses within the walls was directed towards nearby window openings.

The FEM analysis confirmed the actual behavior of the church, existing markings in which stresses concentrated along the transverse axis of the cross vault and had their continuation on the side walls. This means that the subsidence zone most probably includes the entire apse along with the first pair of buttresses and reaches to the window lines at the cross vault. The main subsidence zone was found to be concentrated in the apse zone.

The analysis presented here does not provide a final picture of the actual stresses in the building structure. It indicates only the process to be used—determining

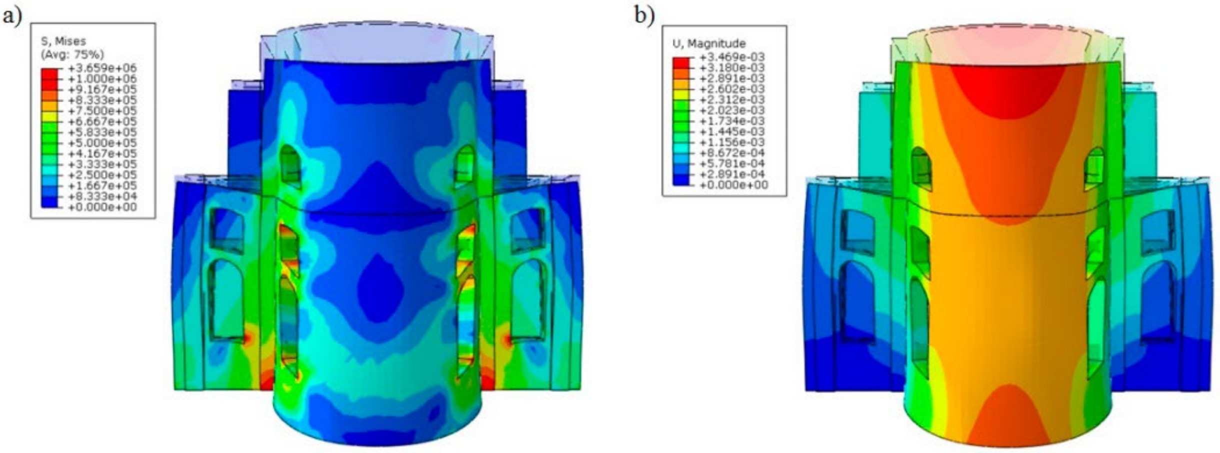

Fig. 5. Results of the numerical investigations (Y–X view): von Mises Stress (a) and displacements (b).

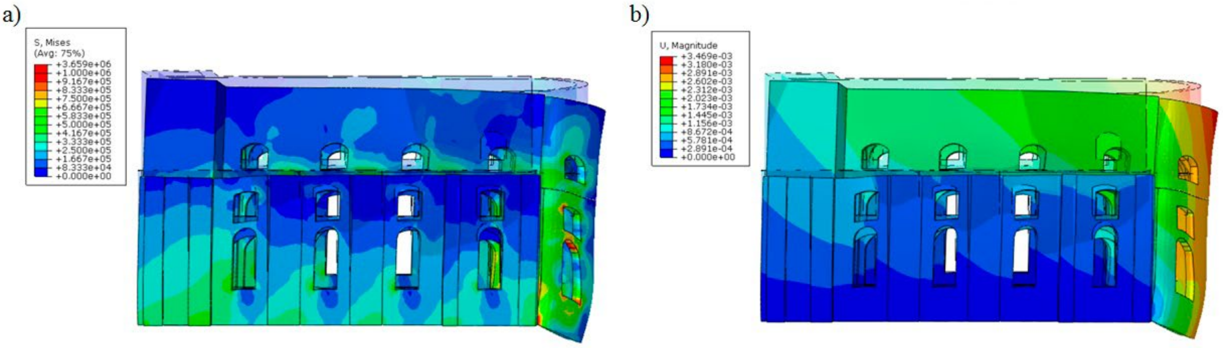

Fig. 6. Results of the numerical investigations (Y–Z view): von Mises Stress (a) and displacements (b).

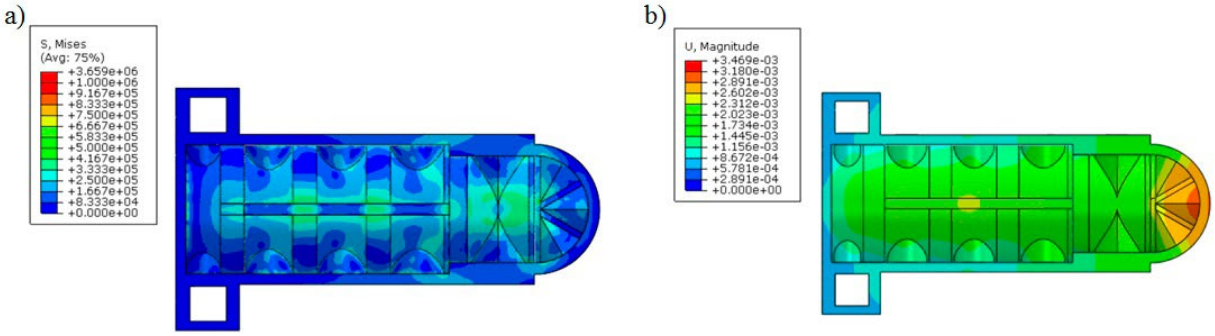

Fig. 7. The results of the numerical investigations (X–Z view): von Mises Stress (a) and displacements (b).

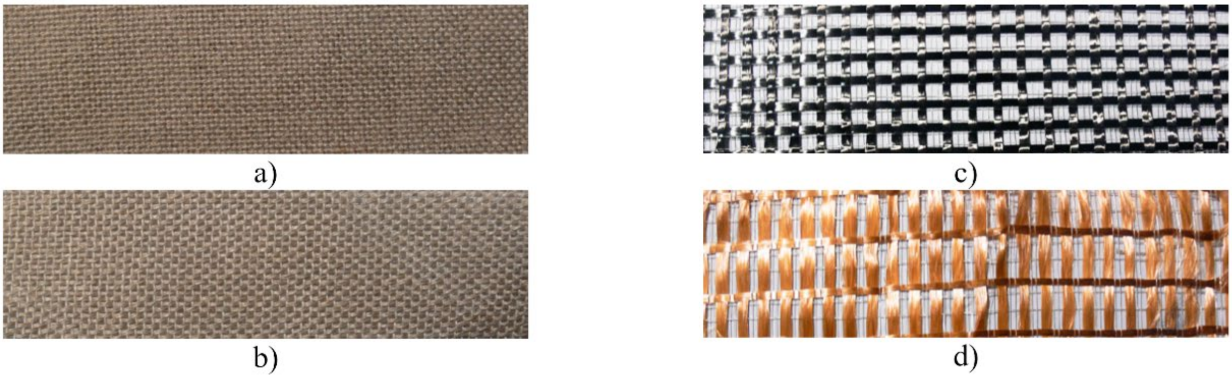

Fig. 8. Linen fabric (a), hemp fabric (b), C-FRCM carbon fiber mesh (c), PBO-FRCM (zylon) fiber mesh (d); photo by Ł. Bednarz.

the next stages of the analysis of this type of structure and drawing attention to the areas subject to the greatest stress, which may require intervention. The use of many variants (different loads, displacement and support changes) enabled simulation of the static behavior of the church and identification of the most strenuous parts and comparison of this image with reality. The number and quality of the modelled variants used, combined with a critical look at the probability of their actual occurrence in the structural system may provide additional information about the scope of planned conservation work with regard to maintenance and possible reinforcement of the building.

Strengthening methodology

The results obtained from numerical analyses can be used to make decisions regarding repair work and strengthening interventions in heritage buildings. In this regard, interest has been growing in new technologies and methods which can be used in restoration of public-owned buildings. One of the tasks that contemporary engineers specializing in structural reinforcement have to face more and more frequently relates to maintaining building structures in serviceable condition, which have been partially or significantly destroyed. Current trends in structural reinforcement involve the application of innovative methods of repairing and stabilizing structures. In this respect, composite materials represent one of the most recent scientific advancements.

Conventional reinforcement methods, such as shotcrete or additionally reinforced concrete or steel structures, result in increasing the load-bearing capacity and rigidity of the structure. They can also cause irreversible changes to the aesthetics of the building. When a significant increase of the load-bearing capacity of the structure is necessary, composite materials can be used as an alternative solution to conventional methods of reinforcing existing buildings. The mechanical parameters of fibers used in composite material reinforcement systems reduce tensile and bending stresses in the original structure, while at the same time allowing for increased loading of the structural element. Tests have demonstrated that fiber-based composite materials can be applied successfully to repair existing steel, masonry, timber and reinforced concrete structures and to appropriately safeguard them.

Historically, organic fibers have been used in reinforcement interventions. In recent years, there have been renewed attempts to make use of biological—bio-composite materials, such as jute, linen (fig.8a), hemp (fig. 8b) or broom in strengthening heritage buildings.

Tensile strength is the overriding factor to be taken into account in the selection of an appropriate reinforcement system. For this reason, fibrous FRP (Fiber Reinforced Polymer) composite materials with a polymer (thermoplastic and thermosetting resins) warp or with a mineral FRCM (Fiber Reinforced Cementitious Matrix) warp, reinforced with carbon, basalt, graphite, glass, boron, aramid fibers or steel, are of crucial importance. FRCM (Fiber Reinforced Cementitious Matrix) systems are an alternative solution to the FRP systems. They comprise a fiber mesh (e.g. C–FRCM mesh made of carbon fiber (Fig. 8c) or PBO–FRCM mesh made of PBO (polyparaphenylene-benzobisoxazole) (zylon) fiber (Fig. 8d)) in a mineral warp without epoxy resins. Attempts to generate FEM models of composite strengthening systems for heritage structures have been undertaken by numerous scholars.[17]

The numerical analysis can help in the formulation of a proposal for the building strengthening. The character of the building and its historical value called for the techniques which would allow the least possible intervention in the historical tissue of the building. This was the reason for opting for the C-FRCM or PBO–FRCM system, which consists of a mesh embedded in a mineral matrix. This solution could be used to reinforce the vaults (Fig. 9) and masonry walls. The mesh has to be applied to appropriately prepared wall and vault surfaces. This requires also adequate access and work space. It is recommended that the mesh application be preceded by injecting cracks as well as the precise removal of old plaster on the walls and drying uncovered and damp bricks.

Calculations made by the authors indicate that the strengthening applied can reduce dangerous tensile stress in the majority of the walls and vaults, locally changing also its impact. This complies with the char-

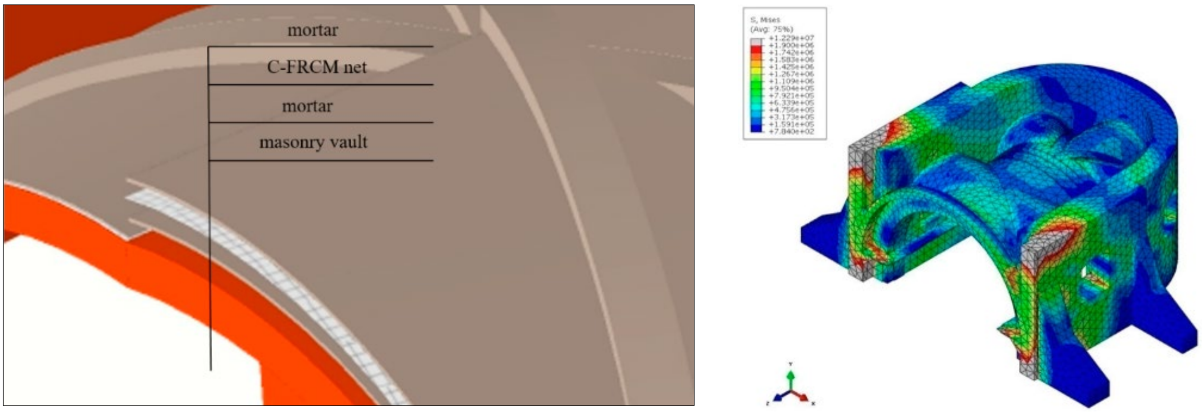

Fig. 9. Vault strengthening model adopted in the calculation (left) and presbytery model after vaults strengthening (von Mises Stress) (right).

acter of the strengthening behavior and is in line with the recommendations of its manufacturer, who emphasizes that the idea behind strengthening using the carbon mesh involves reducing tensile stress by distributing it over a larger area, thereby dispersing localized tensile stress concentrations.

Structural monitoring

Monitoring refers to a system of methods and techniques used to measure the condition of a structure. Monitoring activities can be classified according to a variety of criteria, e.g. the goal of the monitoring, the type of measurements (static, dynamic), the nature of testing (destructive, quasi-destructive or non-destructive), time of monitoring, etc. The best results can be obtained using a hybrid system comprising techniques for the assessment of static or dynamic behavior of the structure over time, enabling tracking of changes in the geometry of the structure (which can occur also as a result of delayed phenomena) and non-destructive tests of building materials.

The example presented in the paper is focused on the idea of monitoring the building's geometry. Of course, it is possible to use sensors installed on the building that measure vibrations, crack openings, deflection, etc., but this method is very expensive and requires the analysis of large amounts of data. This approach shows only changes at specific measured reference points, not global changes.

Ongoing monitoring of the building was recommended as there was a lack of earlier detailed data on changes to the geometry of the building, as well as to the displacements and cracking of its structural elements. The digital documentation generated represents a valuable tool for the preservation of heritage buildings. Models generated on the basis of this documentation have been used to assess the condition of structures and to identify factors contributing to their destruction. It is possible to detect displacements and the propagation of cracking of 3D elements by repeating 3D scanning and superimposing successive images upon each other. This technique is an effective tool for monitoring the condition of a structure, without physically accessing the structural elements of the building. Thanks to its millimeter precision, such technology can be also applied to register surface degradation of, e.g., brick or stone masonry surfaces.[18]

Probably the most effective way to describe the behavior of the building structure is a monitoring based on a periodic registration of cracks, displacements, and the surveying of reference points or surfaces by means of 3D scanners or orthophotography.

Conclusions

The paper presents a simple and a fast methodology of surveying, analyzing, strengthening and monitoring an existing historic building. The acquired digital data were used to develop a digital model and a detailed analysis of the behavior of the structure. Based on the finite element method (FEM), a properly calibrated material model showed the areas that were found to require reinforcement. It has also been shown that the periodic comparison of a building structure's geometry with the use of point clouds can be used as a method of monitoring the geometry of a building with good approximation and in a non-invasive way that includes the monitoring of cracks and damage. It is a very precise method, which does not generate significant costs and is not overly time-consuming. The data thus obtained provide accurate and reliable geometric data that can be used in FEM analysis. The use of different load patterns and the resulting stress distributions can be compared to the actual state of the structure. They may indicate a significant impact of external load or ground changes on the building structure, especially on arches and vaults.

The presented procedure does not always provide a full picture of the actual behavior of the building. It only indicates the probability of processes that can be prevented in advance. The most effective way to describe the behavior of the building structure is very well described in the literature and cited: digital modeling and monitoring based on the periodic registration of cracks, displacements, the surveying of reference points and increasingly popular periodic geometric monitoring using point clouds supported by a wide range of specialists.

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Abstract

The paper presents digital surveying (orthophotogrammetry, 3D laser scanning), modeling, static numerical analysis and a proposal of reinforcement and SHM (structural health monitoring) of a historic Baroque church. The authors describe a comprehensive analysis of the structural condition of the building, including: a survey of the building using photographs taken manually and via UAV flyover to perform orthophotogrammetry, and a laser scanner to create a 3D point cloud. Destructive and non-destructive material testing and structural calculations were performed. The scope of the analysis presented provided insight into the state of preservation of the church and helped in making the right decision on further action—in construction and conservation. The paper also proposes a methodology for strengthening and structural health monitoring for this type of historical buildings.

Streszczenie

Artykuł przedstawia cyfrową inwentaryzację (przy wykorzystaniu ortofogrametrii i skaningu laserowego 3D), modelowanie, numeryczną analizę statyczną i propozycję wzmocnienia i monitoringu stanu konstrukcyjnego (SHM) zabytkowego kościoła barokowego. Przedstawiono kompleksową analizę stanu konstrukcyjnego budynku, która obejmowała: inwentaryzację obiektu przy użyciu fotografii wykonanych ręcznie i poprzez nalot dronem, przy wykorzystaniu ortofotogrametrii oraz skanera laserowego, aby otrzymać trójwymiarową chmurę punktów. Przeprowadzono też inwazyjne i nieinwazyjne badania materiałowe oraz obliczenia konstrukcyjne. Analizy dostarczyły wiedzy na temat stanu zachowania kościoła i pomogły podjąć odpowiednią decyzję w zakresie działań budowlanych i konserwatorskich. Artykuł zawiera również propozycję metodologii wzmacniania i monitorowania stanu budynków zabytkowych tego typu.