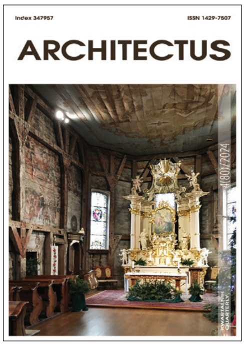

Architectus

2024
4(80)

DOI: 10.37190/arc240405

Łukasz Bednarz*, Alicja Hoyenski, Gabriela Wojciechowska*****

Research and structural conservation of historic vaults

Abstract

This paper focuses on issues concerning the research and conservation of historic vaults with particular emphasis on condition analysis. Traditional and modern methods of strengthening vaults are presented, including techniques using composite materials such as: FRP (Fiber Reinforced Polymer), FRCM (Fiber Reinforced Cementitious Matrix).

The process of assessing the condition of the vault using various methods, e.g., visual inspection, laser scanning, non-destructive NDT, is discussed. The paper presents an example of the use of carbon mesh to reinforce a vault in a historic building – highlighting the need for diagnostic monitoring after repair work. The use of the HBIM (Historic Building Information Modelling) model to accurately represent the geometry and structural analysis of the vault is described. The numerical model was created using the finite element method (FEM).

Effective conservation of historic vaults requires a harmonious combination of traditional methods and modern technologies. It has been shown that the correct identification of structural problems and the adoption of appropriate conservation strategies are key to preserving architectural heritage and ensuring its integrity for future generations. In addition, the importance of continuous diagnostic monitoring of the vault after repair enabling ongoing assessment of the effectiveness of the methods used and early detection of possible structural problems was highlighted.

Key words: composite materials, historic vaults, flexible joints, HBIM models

Introduction

As one of the most responsible structures, historic vaults can lose their strength and aesthetic qualities when exposed to adverse factors. Often, for reasons such as degradation of materials changes in loads, altered water and soil relations or the need to adapt to modern safety standards require strengthening measures. The conservation of vaults often requires a combination of structural and architectural conservation techniques. Reinforcements must be planned and carried out with respect for the historical, scientific and architectural values of these elements. The design and selection of strengthening materials should result from a thorough assessment of the technical condition, load analysis and stress distribution. The most common methods of stabilising the technical condition and reinforcing vaults include the use of tie-beam systems, glued-in steel bars or sheets, injection and the increasingly popular composite materials in the form of meshes, rods, cords, mats and tapes of FRP (Fiber Reinforced Polymers) or FRCM (Fiber Reinforced Cementitious Matrix) and polymeric prone joints (Jasieńko, Łodygowski, and Rapp 2006; Kwiecień 2013; Bednarz 2021). Reinforcing the vaults with these high-strength and flexible construction materials ensures increased stability and durability of the vaults.

The article presents the different types of reinforcement used in the conservation of historic vaults, including traditional, modern and mixed methods, as well as an example of the implementation of reinforcement from Silesia using carbon nets, maintaining the authenticity and durability of historic vaults.

Technical condition assessment of the vault

Before a strengthening and maintenance method is chosen, a survey should be carried out to determine the condition of the vault. This process involves several steps and

* ORCID: 0000-0002-1245-6027. Faculty of Civil Engineering, Wrocław University of Science and Technology, Poland.

** ORCID: 0000-0003-1684-1579. Faculty of Architecture, Wrocław University of Science and Technology, Poland.

*** ORCID: 0000-0001-7041-5373. Faculty of Architecture, Wrocław University of Science and Technology, Poland, e-mail: gabriela.wojciechowska@pwr.edu.pl

Fig. 1. Visual inspection of a failing vault using a drone (photo by G. Wojciechowska)

Il. 1. Inspekcja wizualna sklepienia w stanie awarii przy użyciu drona (fot. G. Wojciechowska)

uses various methods to gain a thorough understanding of the current condition of the structure and to identify potential problems.

The visual inspection (Fig. 1) is the first step in assessing the technical condition of the vault. It allows the initial identification of damage such as cracks, scratches, material loss, dampness or deformation. Based on these observations, it can be determined which areas require more detailed examination.

The condition assessment should include the production of drawing (metric) documentation, in which structural damage, e.g., existing scratches and material loss, is marked. The documentation should include detailed architectural drawings (Łużyniecka 2022), photographs, possibly photogrammetric studies and/or 3D laser scanning to create digital models of the structure. These models may include geometric data augmented with metadata on material parameters, architectural characteristics and the transformation of the building – if HBIM (Historic Building Information Modelling) documentation is developed or used off-the-shelf.

It must be remembered that a correct assessment of the state of preservation and the cause of damage results not only from a thorough inventory and modelling, but also from a knowledge of the history of transformations to which the building has been subjected over the centuries.

This is followed, if possible, by material tests, including strength tests, e.g., compressive and peel strength, chemical and physical analyses, material composition. Particularly non-destructive methods (Non Destructive Test – NDT) appear to be very useful at this stage of the procedure.

Based on the results, a suitable model should be selected for the calculation (static or dynamic) (Scacco et al. 2020). In vaults of brick, stone, concrete or mixed construction, a structural analysis is recommended. Because the geometry of vaults is difficult to capture in traditional computational models, FEM (Finite Element Method) models are helpful in this respect. The use of FEM allows a detailed analysis of the elements under the influence of the loads acting on them (existing and designed). FE models are valuable tools for the analysis and design of structural reinforcement using different types of materials. These models use numerical methods to simulate the behaviour of the structure and assess the effectiveness of the reinforcement used. They also allow the simulation of different loading variations and potential failures such as cracking, delamination or overstressing.

Types of reinforcement for historic vaults

Reinforcing historic vaults is a process that requires both knowledge of building technology and a deep understanding of the static working of these structures and knowledge of conservation doctrine. Different methods are used to ensure the durability and stability of these structures: traditional, modern or mixed. The type of reinforcement chosen depends, among other things, on the technical condition of the vault and the extent of the conservation work that may be required, depending, for example, on the artistic and architectural qualities of the vault.

Traditional methods of reinforcing historic vaults

Traditional reinforcement techniques have been tested for hundreds of years, proving their effectiveness and durability. However, traditional materials may not provide sufficient strength to withstand dynamic forces in areas exposed to vibrations from, for example, road or rail traffic. Traditional reinforcement methods may not meet the requirements of current building standards for load-bearing capacity and safety, especially for structures requiring additional reinforcement due to new loads

Steel tie rods

Tie-beams can be used in a variety of vault types and are tailored to the specific structural needs of a particular building. They usually connect opposing vault headers, thereby reducing strutting forces in the supports. In this way, they prevent the vault from spreading laterally, which could compromise the integrity of the entire structure. The introduction of tie beams into the vault neutralises these forces. This maintains stability and extends the life of historic buildings. Anchoring elements must be properly matched to the wall material to ensure adequate adhesion and strength of the connection. Once the ends of the tie bars are fixed in the walls, the bars are tensioned using special tensioning devices. This process involves gradually increasing the tension in the bars until a suitable level of vault stabilisation is achieved. Steel tie rods are exposed to corrosion and therefore need to be protected from the elements. Various methods of protection are used, e.g., galvanising, painting with anti-corrosive paints, application of protective coatings. The installation of tie-beams is relatively non-invasive (usually the tie-beams have a small cross-section and do not obscure the vault), which is important for historic buildings where the preservation of the original building fabric is a priority.

Injections

Injections are the process of introducing special injection materials into cracks and fissures in masonry to strengthen the structure from within. Injection materials include epoxy resins, cements, mineral mixtures and other specialised substances to improve the cohesion and load-bearing capacity of the vault. Injections are primarily used to address micro-spaces and cracks that can weaken the vault structure. The process begins with a thorough analysis of the condition of the structure, identifying the damage and determining the areas requiring intervention. Pressurised injection materials are then injected into the designated areas and all cracks and cavities are carefully filled. One of the key decisions concerns the selection of the appropriate material. Epoxy resins are characterised by their high mechanical strength and excellent adhesion to the substrate – this makes them ideal for reinforcing highly stressed structures. Cements and mineral mixtures, on the other hand, are more compatible with historic building materials, which is important in terms of preserving the authenticity of the historic substance.

The injection process usually uses special injection pumps that allow precise dosing of the material and control of the injection pressure. Monitoring and controlling the effectiveness of the injection is also an important step, where non-destructive methods, such as ultrasound, are often used. With these techniques, it is possible to accurately determine the degree of gap filling and assess the effectiveness of the reinforcement.

The injection method contributes to the strength of the constituent materials, improves the load-bearing capacity of the structure, and effectively seals and protects against moisture and aggressive gases that can penetrate the masonry. The process of regenerating masonry vaults using injection is very delicate and requires a series of carefully selected preliminary measures. The selection of the injectant components and the adaptation of the consistency to the specific needs of the case are crucial.

Reinforcing historic vaults using injection has many advantages. First and foremost, it is relatively non-invasive, effectively reinforcing while preserving the original character of the monument. In addition, injections can be used in conjunction with other strengthening methods, such as glued-in steel bars or composite mesh, so that comprehensive stabilisation of the structure can be achieved.

Bonded steel bars or sheets

The technique of inserting steel bars or plates involves introducing steel elements into the construction of vaults to carry additional loads and improve the integrity of the building. The strengthening process begins with a thorough analysis of the technical condition of the vault and the identification of the areas that need strengthening. Once these areas have been determined, appropriate cuts or holes are made in the structure into which the steel bars or plates will be inserted. The steel elements are then thoroughly cleaned and protected against corrosion. When steel bars are pasted in, the elements are placed in specially prepared channels that can be made in the vault. The bars are then fixed with special epoxy or cement adhesives to ensure their permanent bond to the structure. These adhesives are characterised by high strength and excellent adhesion to a variety of building materials, which guarantees the effectiveness of the reinforcement. As with the bars, the pasting of the steel sheets consists of placing them in prepared notches in the vault. These plates are usually pasted on the surface of the vault or in its cross-section – depending on the specific construction and reinforcement needs. The process requires precise surface preparation, as well as the right choice of adhesives. This method allows for a significant increase in the strength of the structure, but due to the extent of the work it does not allow for rapid reinforcement, which is crucial when the structure needs to be secured quickly.

Modern methods of reinforcing historic vaults

Modern reinforcement techniques use composite materials and technologies that minimally interfere with the original structure of monuments. Modern composite materials are lightweight and have high tensile strength, making them suitable for increasing the load-bearing capacity of vaults without significant additional weight. They are also flexible, allowing them to accommodate possible "movements" and deformations of the vault. This is particularly important for structures located both in areas with increased seismic activity and in historic city centres with increased vehicular traffic. These materials are corrosion-resistant, ensuring long-term durability and minimising the risk of deterioration over time. Reinforcing historic structures with innovative composite materials follows conservation principles – it is minimally invasive and reversible (with proper design and execution).

Among the most common modern strengthening methods are surface reinforcement with composite materials and polymeric flexible joints.

Surface reinforcement using composite materials (FRP/FRCM)

Surface reinforcements using composite materials can be in the form of meshes, rods, cords, mats, tapes and sections of FRP or FRCM systems. Thanks to their high strength and low weight, they effectively reinforce structures while minimising interference with the historic fabric. FRCM systems use reinforcing fibres (carbon, glass, basalt, aramid, PBO (e.g., polyparaphenylene benzobisoxazoles) as the fixing matrix; the mineral compositions have relatively good vapour permeability and do not block moisture migration in the form of water vapour, which is very important when there are, for example, frescoes on the vaults, on the side of their palisade, which require structural intervention. It is important to remember to analyse in detail the method of application and the type of composites used. Improper use, disregarding the laws of statics and building physics, can be associated with the destruction of an object of considerable architectural and cultural value.

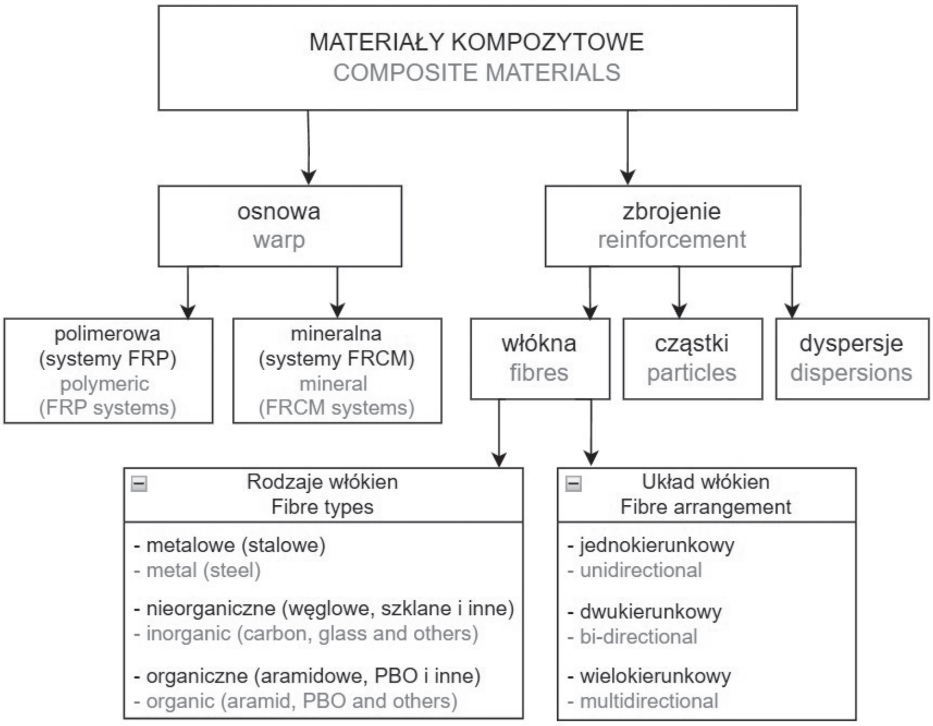

Fig. 2. Composite materials (elaborated by Ł. Bednarz)

Il. 2. Materiały kompozytowe (oprac. Ł. Bednarz)

Fig. 3. Vault during installation of carbon mesh composite reinforcement (photo by Ł. Bednarz)

Il. 3. Sklepienie w trakcie układania zbrojenia kompozytowego z siatek węglowych (fot. Ł. Bednarz)

Fig. 4. Vault after reinforcement (photo by Ł. Bednarz)

Il. 4. Sklepienie po wykonaniu wzmocnienia (fot. Ł. Bednarz)

Numerous studies have shown (Valluzzi, Tinazzi, and Modena 2002; Oliveira, Basilio, and Lourenço 2010; Carozzi, Milani, and Poggi 2014; Lignola et al. 2017) that this type of reinforcement is suitable for the repair of structures, including masonry, as it provides them with an adequate level of safety, especially when these are subjected to asymmetric loads.

The term composite material refers to a material that is constructed from at least two different components, with their combination occurring at the macroscopic level. In most composite materials, two phases are distinguished: a matrix (matrix), which acts as a binder, and a dispersed phase (reinforcement) (Fig. 2). The properties of the composite depend on the properties of the two phases, their proportions in the total volume of the composite, how the dispersed phase is distributed in the matrix and its geometrical features. Depending on the type of dispersed phase, composite materials are divided into particle-reinforced, dispersion-reinforced and fibre-reinforced.

Fibre-reinforced composites, which are very often used to reinforce masonry structures, use various fibres as load-bearing elements (Figs. 3, 4). The matrix not only binds the fibres together, but also distributes external loads between the fibres and protects them from external influences.

FRP fibre-reinforced composites in polymer matrixes (thermoplastic and thermosetting resins) and FRCM in mineral matrixes are characterised by very good technical performance, as well as relatively simple production methods and moderate costs. These characteristics make them extremely effective for practical use – while providing excellent mechanical strength with minimal dead weight.

Glass fibres are the oldest and cheapest fibres used to reinforce composites. A major disadvantage of the resin matrix composite reinforcement system is the poor fire resistance of the bonding – the adhesive, where already at

60°C the shimmering process starts and the linear and form deformability increases.

FRCM systems use an inorganic mortar consisting of a hydraulic binder and additives – chemically, physically and mechanically compatible with the substrate, especially brick masonry. FRCM systems offer several important advantages, including: heat resistance, applicability to damp substrates, ease of application on uneven substrates, and applicability over a wide temperature range from +5°C to +40°C.

Polymeric flexible joints

Polymeric flexible joints are used to connect and reinforce damaged or weakened vault components to both ensure structural stability and maintain historic integrity (Kwiecień 2013). In this method, susceptible polyurethanes are used to strengthen masonry structures – primarily through injections that create flexible joints that can transmit and dissipate significant amounts of deformation energy. The pliable polyurethanes are used in two main roles: as flexible joints for filling cracks in masonry (PolyUrethane Flexible Joints – PUFJ) and as an adhesive layer and matrix in composite joints (Fibre Reinforced Polyurethane – FRPU).

In laboratory tests, flexible polyurethane joints were shown to significantly increase the load-bearing capacity of masonry structures compared to traditional repair methods such as cement mortars or rigid epoxy resins. In four-point bending tests, polyurethane joints outperformed the traditional ones because they did not damage the repaired bricks. This is crucial in the conservation of historic masonry – as preserving the original material is a priority.

Vulnerable polyurethanes used as adhesives to reinforce masonry using FRPU composites reduce the stress concentrations typical of rigid layers made of mineral mortars or epoxy resins. As a result, shear stresses are more evenly distributed, protecting composite fibres and brittle masonry substrates from localised damage that can lead to rapid peeling and reduced joint effectiveness. As a result, the use of polyurethanes increases the load-bearing capacity of the reinforcement and protects historic substrates from damage.

The two main applications of susceptible polyurethanes in FRPUs are – the use of ready-made composite laminates (with fibres embedded in an epoxy matrix) bonded to a weak substrate with a susceptible polyurethane adhesive, and the use of highly deformable polyurethanes as a matrix for the composite fibres. In the first case, the composite laminates transfer loads more uniformly and reduce the risk of local damage. In the second, the flexible polyurethane matrix evens out the curvature of the fibres – thus enabling loads to be transferred evenly over a greater number of fibres, increasing the strength of the composite and reducing shear stresses in the substrate.

The use of a susceptible polyurethane matrix in FRPU technology not only distributes stresses over all the fibres in the cross-section, but also acts as an elastic adhesive layer and increases the ability of masonry structures to withstand dynamic loads and uneven settlements. This is particularly important for historic buildings, where maintaining structural integrity is crucial to their longevity and safety.

Mixed methods

Reinforcing historic vaults often requires mixed methods, which combine a variety of techniques to ensure optimal stabilisation and preserve the authenticity of the structure. Mixed methods combine traditional and modern technologies to achieve optimum results in the conservation process. In some cases, especially when vaults are severely damaged, a combination of traditional techniques (e.g., steel bar pasting) and modern composite materials is used. This approach allows for optimal strengthening of critical areas of the vault, while maintaining the structural integrity and aesthetic appearance of the historic building. Another example is the use of tie-beams with composite meshes.

Diagnostic monitoring

Once the vaults have been reinforced, systematic diagnostic monitoring of the vaults is necessary (Bednarz 2021; 2023; Bednarz et al. 2021) to ensure that the reinforcement is effective and that there are no signs of further damage or material degradation. This enables and early response to potential problems, and ensures the long-term preservation of historic vaults.

The diagnostic monitoring of historic buildings itself, associated with what is known as Structural Health Monitoring (SHM), is the process of observing and analysing the condition of a building in real time. It is one of the tools of diagnostics in its broadest sense, alongside materials testing and structural analysis – extremely helpful in the early detection of structural defects or damage posing potential safety risks to people and the structure itself.

The purpose of diagnostic monitoring is to continuously measure key geometrical, mechanical and physical parameters of a structure or its components that change over time. This provides knowledge of a given situation by identifying the mechanisms of change at an early stage. Thus, diagnostic monitoring is intended to facilitate the implementation of appropriate preventive and corrective measures in historic structures.

Example of implementation of reinforcement with carbon mesh

Using the example of research carried out on the vaulting of a church in Silesia, it is possible to illustrate how the methods described in this article can be used to assess the technical condition and select an appropriate method of structural conservation of the vaulting (Fig. 5). The lunette vaulted church was built in the 18th century. The vaults of the church can be divided into two zones. Zone one, which is the largest part, is the vaulting of the nave. It is a cradle vault divided into bays by porticos located on the dorsal side of the vault. Within each bay there are two lunettes located opposite each other. There are a total of five bays within the nave. The radius of the vault arch is approximately 3.45 m, the arrow approximately 3.33 m. The lunettes with a ridge descending towards the outside. Based on the measurements, the thickness of the vault shell was assumed to be approximately 0.12 m, the ridged ridges to be approximately 0.30 m thick and from approximately 0.47 m to approximately 0.60 m wide. Additional reinforcements of the vault in question (two steel ties) are present between the 1st and 2nd and 2nd and 3rd bays on the side of the rainbow arch under the vault arches fixed at a height of approximately 6.50 m above the floor. The area of the chancel and apse can be considered as the second zone. The chancel has a cross vault. The thickness of the vault shell was assumed to be about 0.12 m, with ridge gourds about 0.30 m thick and about 0.25 m wide. The semi-circular apse of the presbytery is covered by a vaulted ceiling with three radial lunettes in a complex form of arches. The layout of the apse, like that of the entire vault, is symmetrical (Fig. 6). The above-mentioned areas are separated from each other by a rainbow arch. The support of the vault in question is provided by the perimeter walls of the nave and chancel.

Fig. 5. Laser scanning point cloud (elaborated by G. Wojciechowska)

Il. 5. Chmura punktów ze skaningu laserowego (oprac. G. Wojciechowska)

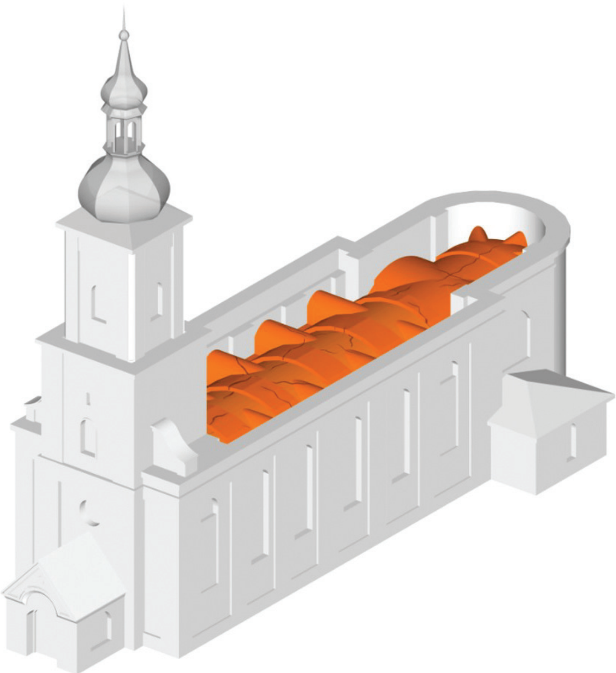

Fig. 6. HBIM model – simplified model of the body of the church and detailed model of the vault (elaborated by A. Hoyenski)

Il. 6. Model HBIM – uproszczony model bryły kościoła i szczegółowy model sklepienia (oprac. A. Hoyenski)

The most worrying damage in the analysed building is the cracks mainly concentrated in the zone of the vaults and the external walls of the nave. The main axis along which cracks and fissures appear is the axis of the nave and the lines running transversely to the axis of the nave, passing through the central part of the vault. They cover almost the entire surface of the vault. These cracks have their continuation on the side walls and near the window openings (damage to the lintels is visible). A similar situation is present in the chancel and apse area. There, too, numerous cracks and scratches are visible (Fig. 7). No major damage was found in the axis of the apse.

The outstanding scratch is a crack running across the rainbow arch, which is a continuation of the damage to the nave vault in the main axis of the church.

The previously described scratches have varying degrees of opening. The largest cracks are found in the connection between the vaults and the external walls (they can be up to several centimetres wide on the dorsal side of the vaults). Numerous cracks of considerable opening also occur on the external walls of the body and the tower. Some of the wall scratches are also visible on the outside of the building.

The arrangement of the described scratches indicates the occurrence of tensile forces within the vaults and the walls supporting them. The direction of these forces is mainly directed across the axis of the church. The probable cause of this situation is the location of the church on a small escarpment cut off from the road by a retaining wall excessively irrigated periodically by water from surface run-off from the adjacent cemetery and traffic of heavy agricultural machinery.

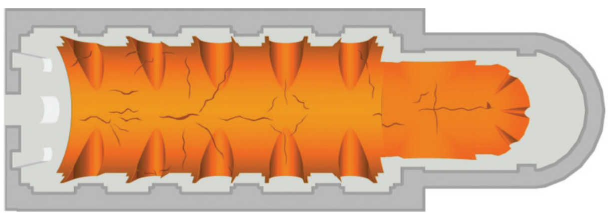

Fig. 7. View of the vault from below – damage inventory (elaborated by A. Hoyenski)

Il. 7. Widok sklepienia od dołu – inwentaryzacja uszkodzeń (oprac. A. Hoyenski)

Description of the study

To accurately represent the geometry of the vault, laser scanning was used. It provided precise data on the shape and dimensions of the vault and enabled a detailed digital representation to be created. Figure 5 shows the data in the form of a point cloud – from this a detailed 3D model of the vault was created (Figs. 6, 7).

Model HBIM

Historic Building Information Modelling (HBIM) is a tool that allows the integration of collected data into a single digital model. In the case of the church in question, the HBIM model included data from laser scanning (vault geometry) and non-destructive testing (material data). Due to the specific nature of the task, the vault model was made at a higher level of detail than the exterior walls of the church (Fig. 6). The model was the basis for simulations of the behaviour of the structure under different loads in numerical analysis software.

Numerical model based on the finite element method (FEM)

The analysis of masonry structure performance and calculations are very complex issues. This is due to the two-material structure of the masonry, which consists of bricks joined by a thin layer of mortar. This composite structure leads to anisotropy and non-linear material behaviour. In engineering practice, simplified calculation methods based on long-term experimental studies conducted on real or simplified models of masonry are often used (Magenes, Calvi 1997; Hendry 2001).

However, when a precise analysis of both the material itself and the structure made of it is needed, this approach proves insufficient. This is particularly the case when analysing historic and historical buildings. When renovating and reinforcing these structures, which usually have a complex static system and high dead weight, it is necessary to use more advanced calculation methods. In such cases, the finite element method (FEM) is very helpful.

The calculations carried out using FEM allowed a detailed analysis of the mechanical properties of the vault. The numerical model was created using a homogenised material model, the parameters of which were determined, among other things, on the basis of laboratory tests. The finite element method provided simulation of the stress and strain distribution under various loading scenarios. This made it possible to identify the weakest points in the structure and predict potential failure locations.

Choice of amplification method

Due to the extensive damage to the vaults, with cracks on the dorsal side reaching up to several centimetres in opening width, and the scratching of the external walls, it was necessary to reinforce the object at the level of the vaults. In this case, the decision was made to use steel ties to stiffen the longitudinal and transverse system of the building. Within the vaults, injections were designed as well as reinforcement and consolidation of the dorsal surface with C-FRCM (Carbon Fiber Reinforced Cementitious Matrix).This state-of-the-art reinforcement method ensures adequate load-bearing capacity, durability and minimal interference with the original historic structure.

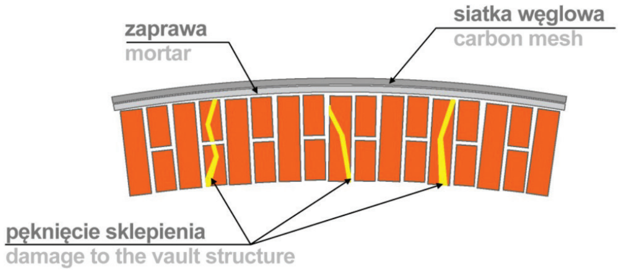

Fig. 8. Diagram of vault repair using carbon mesh (elaborated by A. Hoyenski)

Il. 8. Schemat naprawy sklepienia przy użyciu siatki węglowej (oprac. A. Hoyenski)

Reinforcement of the vaults with carbon nets according to the C-FRCM system was carried out over the entire scratch area in a single layer on the dorsal side (Fig. 8). Larger cavities and irregularities in the vaults were filled with the system's levelling mortar. An approximately 3 mm thick system-specific fixing mortar was applied to the moistened substrate. The carbon mesh was immediately blended in and covered with a second layer of the approximately 3 mm thick system fixing mortar. The mesh was laid from armpit to armpit of the vault and from rib to rib, extending the mesh over the ribs and over the walls to a height of min. 20 cm.

Once the reinforcements were in place, anchoring of the carbon mesh reinforcements to the walls was carried out using rolled-up strips of mesh (min. 40 × 60 cm in size) fixed in the openings in the walls in an arrangement determined during the work. Holes 30–36 in diameter and at least 25 cm deep were filled with an epoxy compound after thorough cleaning and blowing out with compressed air, and then a coiled carbon mesh was placed in them. The parts of the mesh protruding from the wall were blended into the 3 mm thick fixing system mortar. A similar procedure was carried out on the vaults and dorsal ribs by using anchor spacing every min. 1.5 m (for linear joints) and 1 pc. / 1.5 m^2 (for surface connections).

Diagnostic monitoring

Once the repair work was completed, it was recommended that a diagnostic monitoring system be implemented that included the installation of meters to monitor key parameters of the structure, i.e., scratches, deviation from vertical, temperature and humidity inside and outside. The monitoring data should be analysed on a regular basis, allowing an ongoing assessment of the effectiveness of the repairs and a rapid response to any problems.

Summary

The investigation and conservation of historic vaults is a complex process requiring an interdisciplinary approach combining traditional repair techniques with modern methods of analysis and strengthening. The assessment of the technical condition of a historic vault is non-simple and multi-stage. It requires the use of various research methods. Visual inspection, photogrammetry, laser scanning, non-destructive testing, HBIM modelling and numerical modelling using FEM collectively allow precise diagnosis and effective strengthening of historic buildings to ensure their durability and safety.

The paper presents a variety of strengthening techniques, including traditional methods such as the use of tie-beams, injection, and the pasting of steel bars or plates, as well as modern approaches using composite materials.

It also highlights the advantages of mixed methods combining traditional and modern techniques to enable a more comprehensive approach to the conservation of historic structures. Special attention was given to innovative solutions (such as the use of susceptible polyurethanes in FRPU systems and C-FRCM composites) and their effectiveness in repairing damaged masonry structures.

The practical application of the methods described is illustrated on the example of a study of the vaults of a church in Silesia. Thanks to a comprehensive assessment of the technical condition and the use of carbon nets to reinforce the vault, the durability and safety of the structure was achieved with minimal interference with its original character.

Once a historic vault has been repaired, it is essential to implement systematic diagnostic monitoring to enable long-term evaluation of the effectiveness of the maintenance work carried out and early detection of any problems. Diagnostic monitoring is a key element of a preventive maintenance strategy.

In conclusion, it can be assumed that effective conservation of historic vaults requires a harmonious combination of traditional methods and modern technologies. An interdisciplinary approach taking into account the latest developments in materials engineering and digital technology is essential in preserving cultural and architectural heritage for future generations.

Translated by
Łukasz Bednarz,
Alicja Hoyenski,
Gabriela Wojciechowska

References

Bednarz, Łukasz. *Monitoring diagnostyczny obiektów historycznych*. Oficyna Wydawnicza ATUT – Wrocławskie Wydawnictwo Oświatowe, 2023.

Bednarz, Łukasz. "Wybrane materiały stosowane w renowacji zabytkowych murów." *Inżynier Budownictwa* 5 (2021): 57–60.

Bednarz, Łukasz, Dariusz Bajno, Zygmunt Matkowski, Izabela Skrzypczak, and Agnieszka Leśniak. "Elements of pathway for quick and reliable health monitoring of concrete behavior in cable post-tensioned concrete girders." *Materials* 14, no. 6 (2021): 1–29. https://doi.org/10.3390/ma14061503.

Carozzi, Giulia, Gabriele Milani, and Carlo Poggi. "Mechanical properties and numerical modeling of Fabric Reinforced Cementitious Matrix (FRCM) systems for strengthening of masonry structures." *Composite Structures* 107 (2014): 711–725. https://doi.org/10.1016/j.compstruct.2013.08.026.

Hendry, Arnold William. "Masonry walls: materials and construction." *Construction and Building Materials* 15, no. 8 (2001), 323–330. https://doi.org/10.1016/S0950-0618(01)00019-8.

Jasieńko, Jerzy, Tomasz Łodygowski, and Piotr Rapp. *Naprawa, konserwacja i wzmacnianie zabytkowych konstrukcji ceglanych*. Dolnośląskie Wydawnictwo Edukacyjne, 2006.

Kwiecień, Arkadiusz. *Polimerowe złącza podatne w konstrukcjach murowych i betonowych.* Wydawnictwo PK, 2013.

Lignola, Gian Piero, Carmelo Caggegi, Francesca Ceroni et al. "Performance assessment of basalt FRCM for retrofit applications on masonry." *Composites. Part B: Engineering* 128 (2017): 1–18. https://doi.org/10.1016/j.compositesb.2017.05.003.

Łużyniecka, Ewa. "The use of 2D vector studies as an architectural research stage in the era of digital spatial models." *Architectus* 71, no. 3 (2022): 79–86. https://doi.org/10.37190.

Magenes, Guido, and Gian Michele Calvi. "In-plane seismic response of brick masonry walls." *Earthquake Engineering & Structural Dynamics* 26, no. 11 (1997): 1091–1112. https://doi.org/10.1002/(SICI)1096-9845(199711)26:11<1091::AID-EQE693>3.0.CO;2-6.

Oliveira, Daniel V., Ismael Basilio, and Paulo Brandão Lourenço. "Experimental behavior of FRP strengthened masonry arches." *Journal of Composites for Construction* 14, no. 3 (2010): 312–322. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000086.

Scacco, Jacopo, Bahmi Ghiassi, Gabriele Milani, and Paulo B. Lourenço. "A fast modeling approach for numerical analysis of unreinforced and FRCM reinforced masonry walls under out-of-plane loading." *Composites Part B: Engineering* 180 (2020): 107553. https://doi.org/10.1016/j.compositesb.2019.107553.

Valluzzi, Maria Rosa, Davide Tinazzi, and Carlo Modena. "Shear behavior of masonry panels strengthened by FRP laminates." *Construction and Building Materials* 16, no. 7 (2002): 409–416. https://doi.org/10.1016/S0950-0618(02)00043-0.

Streszczenie

Badania i konserwacja konstrukcyjna sklepień historycznych

W artykule skupiono się na zagadnieniach dotyczących badań i konserwacji sklepień historycznych ze szczególnym uwzględnieniem analizy stanu technicznego. Przedstawiono tradycyjne oraz nowoczesne metody wzmacniania sklepień, w tym techniki wykorzystujące materiały kompozytowe, takie jak FRP (Fiber Reinforced Polymer) i FRCM (Fiber Reinforced Cementitious Matrix).

Omówiono proces oceny stanu technicznego sklepienia, wykorzystując metody takie jak inspekcja wizualna, skaning laserowy oraz nieniszczące badania NDT (non-destructive testing). W artykule przedstawiono przykład zastosowania siatek węglowych do wzmocnienia sklepienia w historycznym obiekcie, podkreślając konieczność monitoringu diagnostycznego po przeprowadzeniu prac naprawczych. Opisano zastosowanie modelu HBIM (Historic Building Information Modelling) do precyzyjnego odwzorowania geometrii i analizy konstrukcyjnej sklepienia. Model numeryczny został utworzony przy użyciu metody elementów skończonych (MES).

Efektywna konserwacja sklepień historycznych wymaga harmonijnego połączenia tradycyjnych metod z nowoczesnymi technologiami. Wykazano, że właściwa identyfikacja problemów konstrukcyjnych oraz zastosowanie odpowiednich strategii konserwatorskich są kluczowe dla zachowania dziedzictwa architektonicznego i zapewnienia jego integralności na przyszłe pokolenia. Ponadto podkreślono znaczenie ciągłego monitoringu diagnostycznego sklepienia po naprawie, co pozwala na bieżącą ocenę skuteczności zastosowanych metod oraz wczesne wykrywanie ewentualnych problemów strukturalnych.

Słowa kluczowe: materiały kompozytowe, sklepienia historyczne, złącza podatne, modele HBIM