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STRUCTURAL ANALYSIS, CONSERVATION PRINCIPLES AND MONITORING APPLIED TO AN EVANGELICAL CHURCH IN ŻELISZÓW (POLAND)

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Abstract. *Żeliszów (German: Giersdorf) is a village located in south-western Poland (120 km from Wroclaw, 160 km from Dresden). According to many, the evangelical church was designed by the famous German architect Carl Gotthard Langhans in 1796. The church was built in classicistic style in accordance with an elliptical floor plan with exterior masonry walls and a timber construction comprising oval galleries covered with a wooden vault. A neo-gothic tower was added in 1872. The building has been abandoned since 1945. This means that aside from the need for conservation intervention to improve the technical condition of the building, it is also necessary to adapt the church to new uses. The goal of the research reported in this paper was to evaluate the degradation and deformation of the building structure using HDS 3D laser scanning, coupled with destructive, non-destructive and quasi non-destructive testing of the timber structure, brick and stone masonry walls and damp.. The poor technical condition of the church is the result of long-term degradation, natural ageing processes of construction materials and damage to the roof cover which caused excessive damp in the building structure. HDS 3D scanning uncovered deflection of masonry walls and numerous deformations of the timber construction, but indicated that there was no serious damage to major structural elements such as pillars and rafters. Regular laser scanning was proposed as a quick and non-invasive method for monitoring changes in the building structure. Conservation interventions aimed at strengthening the building structure were recommended on the basis of visual inspection, HDS 3D laser scanning and results obtained from testing of the building structure.*

1 INTRODUCTION

The evangelical church in Żeliszów was built in 1796 - 1797. According to many, the church was designed by the famous German architect Carl Gotthard Langhans, who designed the Brandenburg Gate in Berlin and numerous evangelical churches in Silesia built with galleries based on an oval floor plan. When compared to other Langhan projects, the church in Żeliszów is distinguished by its oval floor plan for exterior masonry walls and the timber construction of galleries.

Figure 1: Church interior (around. 1927).

Figure 2: Condition of the church in Żeliszów (2012).

The first important church repairs were carried out in 1835. The roof cover was changed in 1840. The current roof cover made of fish scale-laid plain tiles dates from 1928. The neo-gothic tower was built in 1872. Renovation work in the years 1927-1928 included inter alia, a change of the roof cover. The building has not been used since 1945. It was closed until 1956. The current condition of this valuable heritage building is the result of degradation over the course of many years.

Aside from the technical condition and required conservation interventions, there is also the challenge of adapting the church to new uses. In this regard, historical and social conditions must be taken into account. Before 1945, Żeliszów village was part of the German Province of Lower Silesia and the church belonged to the Evangelical Parish of Giersdorf.

After 1945, number of protestants in the area decreased considerably. As Żeliszów has also a Catholic church dating from the 14th century, which is used by Catholic parish, there has not been a need for using the abandoned evangelical church for religious purposes. The task of finding a new use for the church building must also deal with the problem that there is little interest and support on the part of the local community.

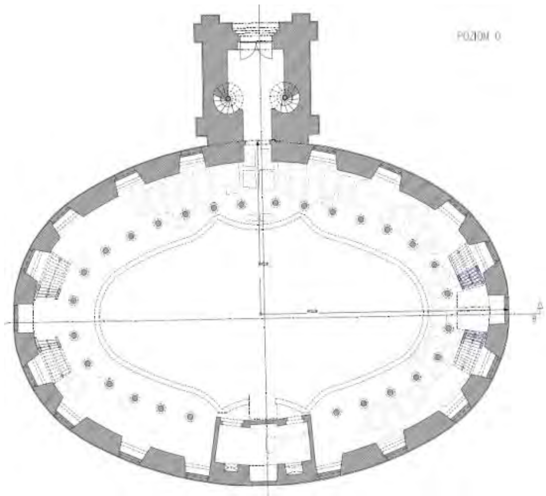

Figure 3: Floor plan of the church.

Figure 4: Church interior (2012).

2 LASER SCANNING

An HDS 3D spatial scanner was used to monitor and inventory the structure of the church interior. An inventory and spatial model were developed based on the three-dimensional laser scans, drawings accessed in archives and field on site measurements. The spatial scanning method enabled analysis of the structural arrangements and precise measurement of the elements making up the rafter framing, which were not possible to carry out in a traditional way due to the degraded condition of the building [1], [2]. The research established inter alia the detail of the deformation of the dome, displacement and deformations of structural elements and the degree of inclination of external walls, as well as location and extent of cracks. The building inventory along with photographic documentation and testing of building materials provided the basis for analysing the stability of the structure and assessing the degree of damage.

Figure 5: Picture from the 3D scan [3], [4].

Figure 6: Spatial model of the church.

3 MATERIALS ASSESSMENT

Non-destructive testing (inter alia by means of a resistograph) of selected wood elements and destructive compression testing in the laboratory to determine the strength of bricks were used to assess the degree of damage of structural elements [5], [6], [7], [8].

Resistograph testing is used to determine the state of wood tissue in structural elements. Testing was carried out using an IML RESI F-400S resistograph. The method is based on measuring resistance to drilling, which is recorded as a graph as drilling into the element proceeds. Drilling was carried out using a thin and flexible drill bit 3 mm in diameter. Results of the testing are presented as graphs showing the relationship between the amplitude of resistance and drilling depth for each monitoring point. One of the results obtained from a measuring point is presented in Fig. 7.

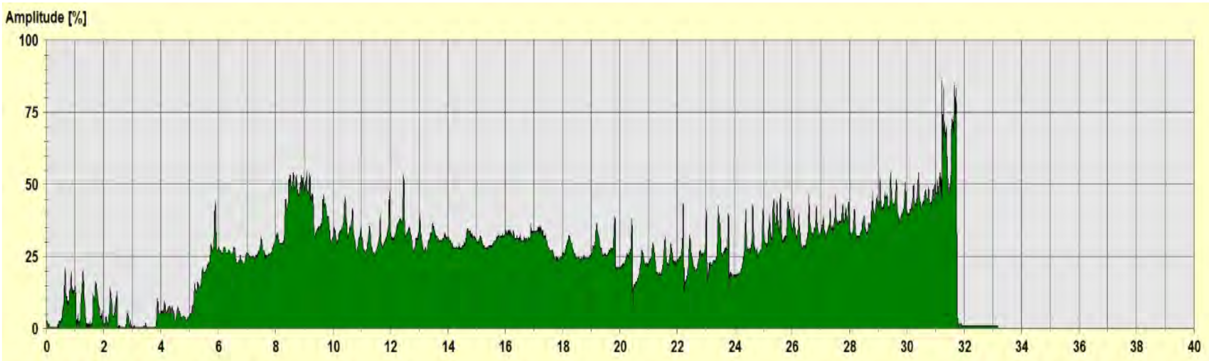

Figure 7: Results of resistograph testing for a gallery pillar.

Using a drill resistance measurement device is a means for localising defects and structural damage in wooden elements without affecting their properties, which is especially significant in heritage buildings [9, [10]. Moreover, it provides a way for assessing the depth at which wood is damaged in transverse cross-section of a timber element and for assessing the condition of wood in support areas [11].

The test results obtained show that the largest damage is in the surface layers of the wood. The average amplitude of drilling resistance for most of the measurements is in the region of 25-30%. The parameters of the wood tested can be qualified as healthy of average durability. Values of less than 25% in sections longer than 1 cm (reduced durability parameters) were found in elements, which were exposed to atmospheric impacts due to damage of roof cover. Damp elements were found to have been attacked by moulds, which contributed significantly to their damage.

The most unfavourable test result for wood damage in the cross-section of the surface layer was used for the purposes of calculating structural stability – a reduction was assumed of 30% in the dimensions of the cross-section when compared to initial parameters.

Tests of the compression strength of bricks were carried out in the laboratory of the Building Institute of Wroclaw Technical University using a Tecnotest compression-testing device. Bricks obtained from the interior of the church were tested (sample no. 1 – floor, no 2 – cornice, no. 3 – lintel). Samples were sliced cut to a size and the surface for compression testing was smoothed with lime cement. Compression testing was initiated after seven days of sample preparation. The results obtained are presented in Tab. 1. The differences in results for sample no. 2 and sample no. 3 may be the result of differing atmospheric impacts. Damage to roof flashing resulted in soaking of the bricks over many years (no. 2), which affects their mechanical properties.

Tab. 1. Test results of brick strength

Sample no	1	2	3
Construction period	Beginning of the 20th century	End of the 18th century	End of the 18th century
Destructive force [kN]	254.00	251.20	515.00
Strength [MPa]	15.62	13.00	22.80

Figure 8: Samples prepared for compression strength testing.

Figure 9: Compression strength testing.

The lowest compression test result for the brick – approx. 13 MPa was used for the purposes of calculating the compression strength of the wall, on the basis of which the compression strength of the wall as a whole was estimated at 1.5 – 1.8 MPa.

4 ANALYSIS OF STRUCTURAL STABILITY

The masonry walls of the church were built with full bricks and local sandstone and were plastered. The two-level wooden galleries are supported by wooden pillars, and together constitute the support for the rafter framing. That is why they are treated as one supporting structure for the purposes of calculating structural stability.

The double collar beam roof rafters with a wooden cradle is doubly reduced to form a king post truss. The king post is fixed to the ridge and collar tie (single section). Every second truss is a main one, with jack rafters supported by the wall and the pillars.

The frame of the king post consists of a cross beam, strengthened with braces in the form of St. Andrew crosses. In the area of the rafter, main trusses are concentrated longitudinally with braces in the form of St. Andrew's crosses. The dome is plastered with lime plaster.

There is considerable damage to the structure caused by damp in places where the roof cover is damaged. Many years of moisture penetrating the structural elements and exposing them directly to atmospheric impacts have caused corrosion of many of the elements making up the rafter framing – damage to rafters, braces, loosening of joints, damp in the ends of the jack rafter beams where these are supported by walls and wall plates. Considerable displacement in joints was observed (links between the main rafter beam and the gallery pillar) – displacements of the pillar capitals in the highest gallery level in relation to the base reached 20 cm.

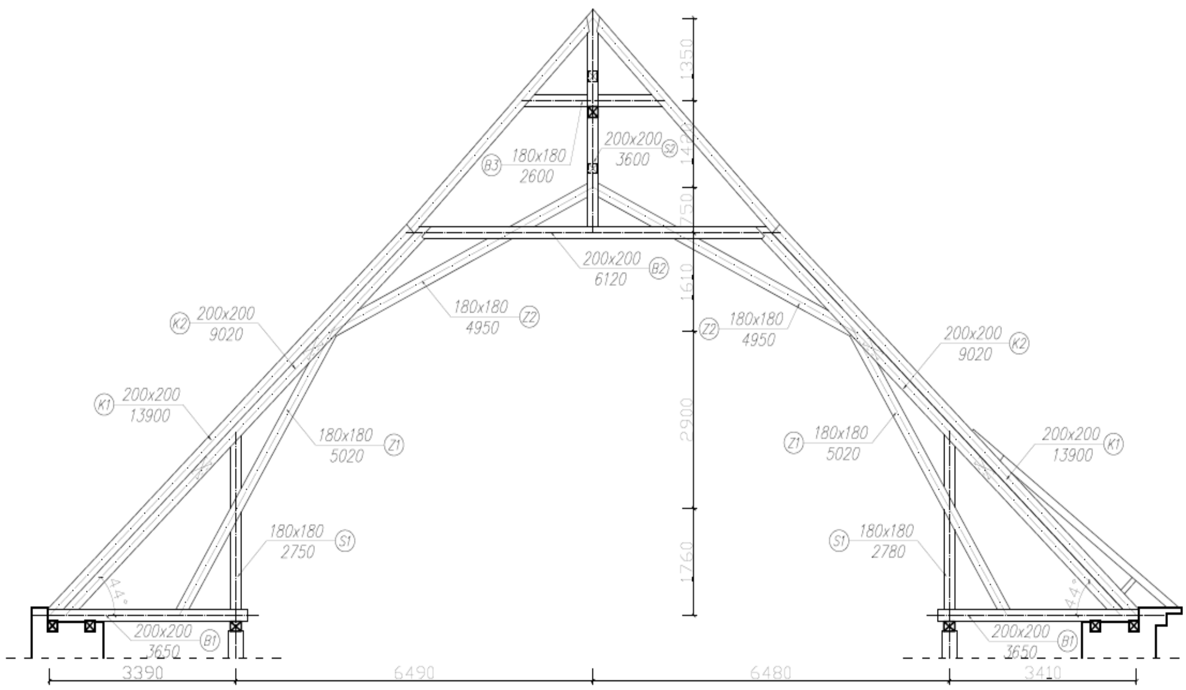

Figure 10: Main truss.

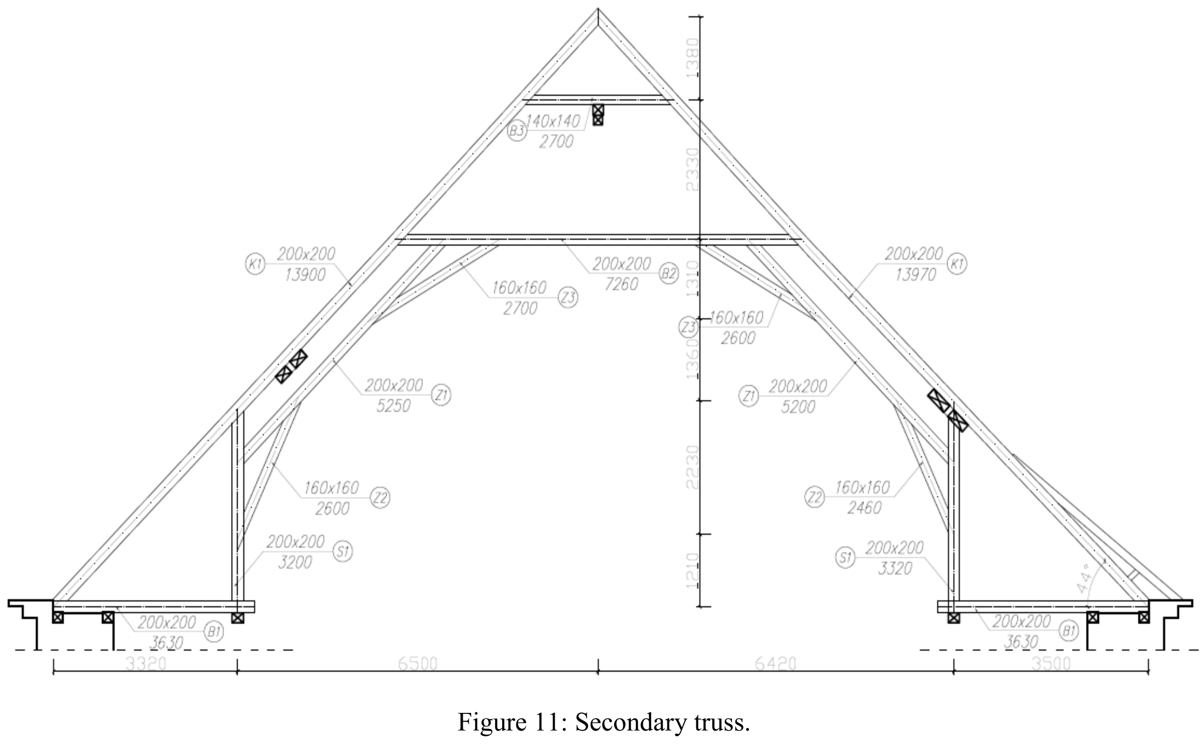

Figure 11: Secondary truss.

For the purposes of calculations relating to the wooden structure, it was assumed that the timber used for construction had parameters close to that of wood strength class C18. Calculations took into account the actual cross-sections and the condition of the wood as determined by the resistograph testing. Calculations of the strain of structural elements were carried out for four situations: assuming a 30% reduction in cross-section, lack of the gallery supporting pillar, lack of the rafter and displacement of the supporting joint by 5 cm. The Autodesk Robot Structural Analysis 2011 programme was used for carrying out the relevant calculations.

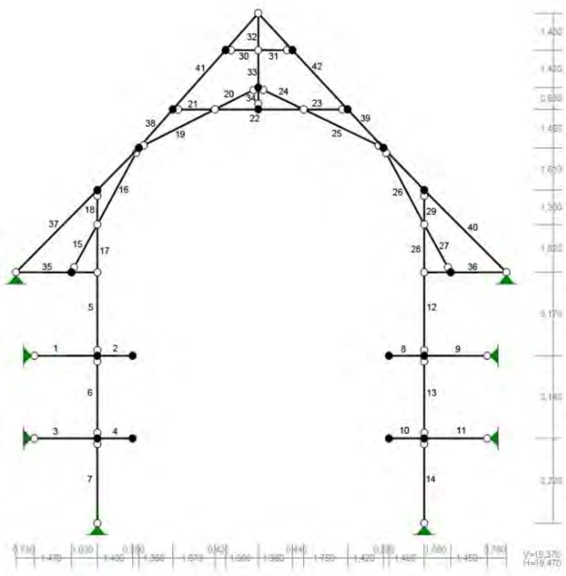

Figure 12: Static diagram.

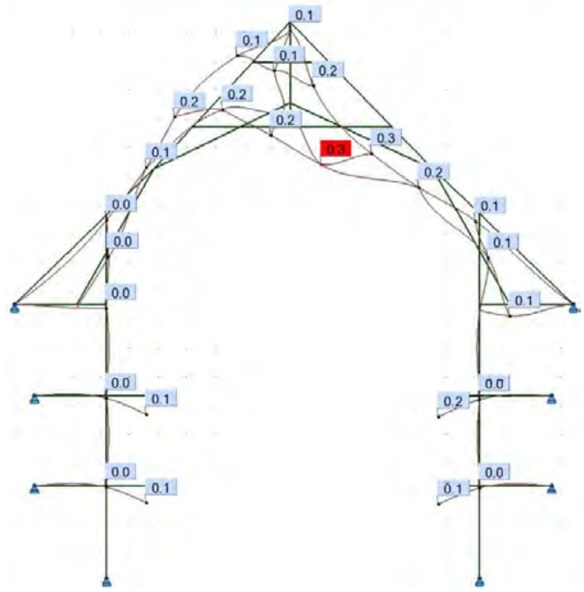

Figure 13: Deformations of a main truss.

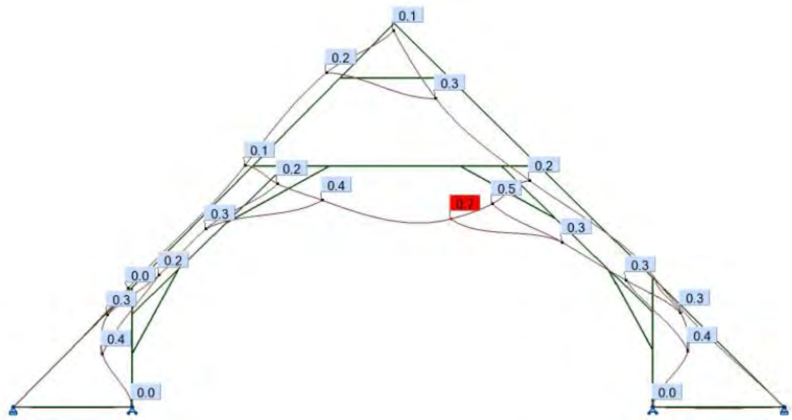

Figure 14: Deformations of a secondary truss.

Structural stability calculations indicate that the load-carrying capacity of the timber elements is sufficient. Strain of some elements exceeds acceptable levels in situations where the cross-section is reduced by 30%. Although these are not significant, it should be noted that the condition of the rafter framing especially where there is constant damp can experience a more rapid deterioration of durability parameters, and different types of damage can accumulate within a single truss.

The wall of the elliptical church structure is constructed of bricks and sandstone to a width of 1.2 m and a height of 9.5 m, and is held together with lime mortar and plasterwork on both sides. Window openings 1.4 m wide and set out along twenty axes. In the upper level, window openings are rectangular, whereas they are semi-circular in the lower level. Door openings with segmented arches are located on the axes of the elliptical structure. From the south side, the wall joins onto a tower, which is 3.4 m x 3.4 m in cross-section and 32 m high. The inclination of the wall measured from floor to cornices reaches approx. 15 cm (1°). Vertical and diagonal fissures and cracks are visible in the lintels over the windows in the area of the crown/ crest cornice. Plasterwork is loosened and peeling in places and there are deep cavities in mortar in wall pointing.

Calculations relating to the structural properties of the wall were based on results of compression testing of bricks undertaken in laboratory conditions. The load bearing capacity of the wall was estimated as sufficient when taking into account current assumed loading levels.

The cause of structural wall damage was first and foremost the destructive action of water, which involved washing out lime mortar from joints, accumulation of moisture in the wall structure and damage resulting from freezing temperatures. The consequence of no roof flashing and a leaky roof cover is the penetration of moisture into the whole expanse of the wall. The most probable causes of cracks are subsidence of the wall and expansive forces transferred via rafters in the roof structure.

5 ACTION PLANNING – PROPOSED INTERVENTIONS

5.1 Strengthening

The current state of the building structure results above all from the destructive action of atmospheric conditions and from biological degradation of wooden elements coupled with ageing of materials, which translate into reduction of load bearing capacity. The lack of ongoing maintenance has led to relatively rapid degradation of the building. The current technical state of the church demands immediate conservation intervention. The bad state of the cornice zone of the church walls and loss of load bearing capacity in the lintel areas penetrated by rainwater threaten further degradation of the building structure. In a situation where a lintel is damaged, and a roof beam is supported directly above it, there is serious danger of the rafter framing collapsing. Roof rafters are in need of repair, especially in places where there is damage to the roof cover. Securing walls against rainwater and capillary processes is essential. A geotechnical analysis needs to be carried out to assess the conditions of subsidence.

Missing elements along with wooden joints need to be restored, whereas damaged and loosened wooden structural elements need to be repaired. The application of toothed wood connectors (‘Geka’ rings) and screws is recommended as well as restoration of wooden joints by replacing damaged beam and rafter fragments and augmenting degraded cross-sections through insertion of steel rods (based on resistograph testing).

Strengthening masonry walls requires additional structural support, for example in the form of a supporting band or rim embracing the whole structure.

In the upper parts of the walls, where damage is considerable, it is important to remove damaged, damp bricks and ensure essential refilling and new masonry in window lintels and cornices using both recycled and new brick in line with the dimensions and aesthetics of the original.

Based on analysis of the damage in many places and cracking of wall structures, wall strengthening is recommended involving injecting infill into fissures and cracks, introducing encircling bands, strengthened with C-FRP (Carbon Fibre Reinforced Polymers) carbon tapes and covering the surface with C-FRCM (Fibre Reinforced Cementitious Matrix) carbon mesh under the plaster layer [12], [13], [14], [15].

Factors arising from the social and historical context – population migrations and cultural changes, mean that there is a need to deal with the challenge of adapting the building to a use other than its original function. The project to adapt the church should be realised in a way that is in line with conservation doctrine, namely in a way that preserves the historic building substance and provides an opportunity for the building to survive with its historical and artistic values intact for the benefit of future generations.

5.2 Laser scanning for monitoring degradation processes and for assessing the effectiveness of conservation interventions

Systematic monitoring undertaken using scanning is proposed as a quick and non-invasive method for monitoring the structural features of a building with the purpose of assessing adopted solutions and identifying areas, which may in the future require structural interventions.

The resulting digital information is a valuable tool for conserving heritage resources. Models developed on the basis of this information are used to assess the state of the building structure and also to identify factors contributing to its destruction.

Repeating 3D scanning and superimposing scans on one another provides a way of finding displacements and the development of cracks. The tool assures effective monitoring of the state of the structure in a way that does not require physical access to structural elements.

This technology can be used with a precision to a few millimetres to register degradation of surfaces, such as brick or stone masonry surfaces [2].

On completion of structural conservation work on the building, it is recommended to carry out periodic scanning to check whether the deformation of rafter framing and masonry structure has been stopped.

6 CONCLUSION

The paper presented a method based on monitoring the geometry of an existing historical building in conjunction with analysis and technology for repair and strengthening. The model developed on the basis of numerical data provided a means for accurate study of the structural state of the church.

Materials testing, calculations of structural stability and the overall technical state of the church all point to a need for rapid conservation intervention. Results of the compression testing of bricks suggest that the ceramic material is good quality, and that the main cause of damage in the wall structure in the area around cornices and lintels results from degradation of mortar. The bricks sampled in the area most prone to water damage are characterised by sufficient durability parameters. The displacement of the coping/ crest of the wall is caused by the spreading force transmitted from the roof rafters.

In the near future, it is recommended that action be taken to stabilise the coping/ crest of the wall. As the way in which jack rafter beams are supported by the wall has not been fully investigated and assumed only on the basis of assessment of accessible sites, full verification of these assumptions needs to take place. At present, due to damage in the cornice zone, location of wall plates and the need for associated masonry work, stabilising the coping/ crest of the wall requires an encircling band, which will transmit the spreading force from the roof rafters to the wall structure in a uniform way.

Missing elements of the wood structure should be replaced, whereas damaged materials need to be subjected to assessment and if warranted, to be identified as requiring replacement, whereas damaged nodes should be repaired. Based on the resistograph tests, it is possible to conclude that wooden structural elements, which were not subjected directly to the action of water, remain in good condition and should be preserved or their cross-sections should undergo conservation action locally.

Carrying out the actions described above will assure structural stability of the building and will provide the basis for further conservation work.

An effective way of recording the structural behaviour of the building is to use periodic monitoring to register systematically cracks, displacements, to carry out measurements of geodetic reference points, and to undertake regular monitoring of geometry using an HDS 3D scanner.

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