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*Original Research Article*

# NON-DESTRUCTIVE TESTING OF WOODEN ELEMENTS IN HISTORIC BUILDINGS - AN EXAMPLE OF TESTING A 19$^{TH}$ CENTURY ROOF TRUSS STRUCTURE

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Abstract

Destructive tests are not usually allowed in historic buildings; only non-destructive tests can be performed there. The obtained results should deliver the repair solutions that do not interfere into the historic layout of the church architecture and structure. One of the rarest areas subjected to non-destructive testing is diagnostic testing of wooden structures. However, calculations of strength verification cannot be performed if the wood class and quality are not determined. This paper describes in situ non-destructive testing of timber structural components of the roof truss system in the 19th century church in Osiecznica. The applied techniques were the standard ultrasonic and sclerometric methods, and additionally the original ultrasonic method with an instrument for analyzing the flow velocity of transverse waves.

Keywords: diagnostic testing of wooden structures, non-destructive tests, historic frame structures

## 1. INTRODUCTION

Timber frame structures had been used in Western Europe since 12th century [1]. Following the German frame architecture, frame-structured peasant cottages, taverns, inns, farmhouses, town houses, churches, and presbyteries had been built in the Middle Odra Region since the 17th century, Rich German ornamentation of façades was however reduced to simple systems of columns, bracing, and horizontal members. Many of these building have survived until present times, but they need renovation works.

The method of renovating a building depends on the results from diagnostic testing [3-7]. For frame-structured buildings it is important to specify mechanical properties of their structural components [8-11]. Mechanical properties of structural components in buildings not listed in the heritage registration are determined by destructive techniques. But high interference into the building environment of historic buildings is unacceptable. All tests conducted on historic buildings, apart from meeting standard guidelines, also have to satisfy requirements of the heritage protection. Diagnostic

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testing of structural components in buildings listed in the heritage registration may be performed with in-situ non-destructive [12-16] or minor-destructive [17-19] techniques. The obtained test results are the base for undertaking further restoration actions, developing repair solutions that do not interfere into the architectural and structural layout of the building.

## 2. DESCRIPTION OF THE BUILDING

The neo-Gothic Church of the Holy Apostles Peter and Paul in Osiecznica, Lubuskie Province, is an example of the timber frame structure. It was built in 1816 according to the design of Karl Friedrich Schinkel (Fig. 1), considered as an attempt to create the reference church for the frame structure [20, 21]. The present view of the church is shown in Fig. 2. The building is situated on a small hill, within a short distance to the Odra River. The church, which was originally the evangelical church, is rectangular, with a building shape close to the basilica layout with a higher central part, and the attic covered with a gable roof, and two one-storey lateral parts covered with mono-pitched roofs. Above the church body, in the central part of the west façade, there is a square turret with a polygonal spire on its top. The entrance hall with the gable roof is attached to the north façade.

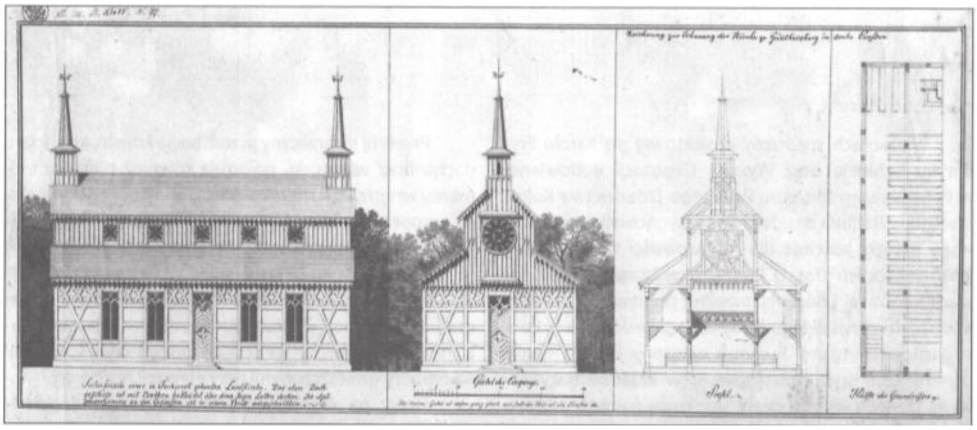

Fig. 1. Design for the church by Karl Friedrich Schinkel [22]

a)

b)

Fig. 2. View of the church: a) front façade (photo by J. Drobiec), b) west façade (photo by B.Nowogońska)

The walls are built into the timber frame structure with brick infill. The frame structure is composed of columns and horizontal members, and cross braces in the corners. The below-cornice part of the walls in aisles is additionally strengthened by bracing in the shape of St. Andrew's cross with some ornaments. The roof is covered with flat tiles, and the spire is made from sheet zinc. The exterior walls in the masonry areas are covered with polished cement-lime plaster leaving the noticeable timber frame structure. After the war the original neo-Gothic pointed arch windows were replaced with simple divided-light windows.

The church interior originally had an open space with organ galleries at side and east rear walls (Fig. 3). Nowadays, there are two rooms: a vestry and a utility room in the north-western and south-western corners. At the west wall there is a new post-conciliar alter in the place of the original pulpit altar characteristic for Protestant religion. All interior walls are covered with wooden panelling. The ceilings over organ galleries and the main part of the church are wood slab ceilings, stairs to these organ galleries and to the attic are wooden stringer stairs. The Polish cross gable roof forms the timber roof structure (Fig. 4). The roof over the central nave has a collar beam structure with a queen post truss and ridge purlin.

Fig. 3. A detail of the inner space of the church (photo by B. Nowogońska)

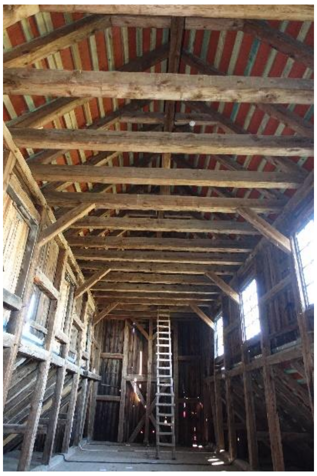

Fig. 4. A detail of the attic (photo by J. Drobiec)

## 3. DIAGNOSTIC TESTING OF COMPONENTS OF ROOF TRUSS

The church was renovated in 2020. The scope of works included: (1) repair works of the north and west walls that involved replacing timber elements by replacement in kind or replacement with new elements, local rebuilding of masonry and performing new thin coat finish in the masonry areas (2), necessary carpentry works that covered local strengthening of structural components of the roof truss, and (3) replacement of roof cover, detailing and gutter system. The second stage of works is planned for 2024 and will include restoration of the south and east walls, and potential strengthening of the roof truss depending on the results obtained from diagnostic testing.

The tests to determine mechanical properties of structural components of the roof truss system were conducted in October, 2023. The following tests were performed: semi-destructive tests with the hammer for wood Wood Peker DRC 19C0085M (Fig. 5a), ultrasonic tests with the instrument UK 1401 SURFER (Fig. 5b) which measures the flow velocity of transverse waves along grains, and with the instrument UK 1410 PULSAR (Fig. 5c), which measures the velocity of longitudinal ultrasonic wave propagating across grains.


Fig. 5. Instruments for in-situ tests:
a) Wood Peker DRC 19C0085M, b) UK 1401 SURFER, c) UK 1410 PULSAR

a) b)

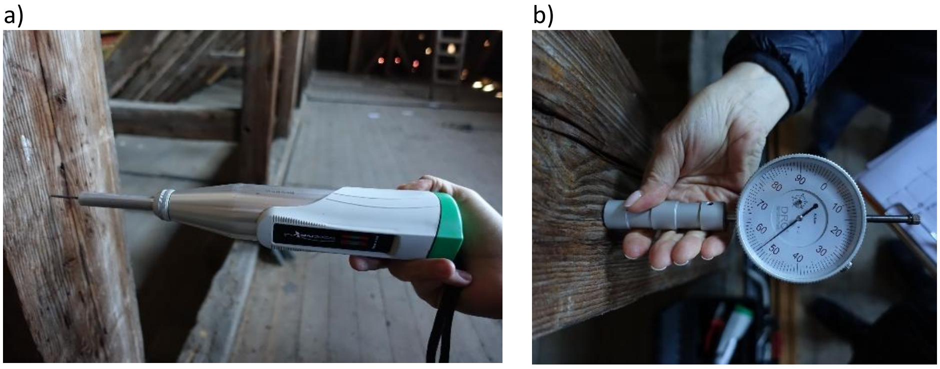

Fig. 6. Sclerometric tests:
a) hammering the needle into the wood element, b) measuring a sticking part of the needle

a) b)

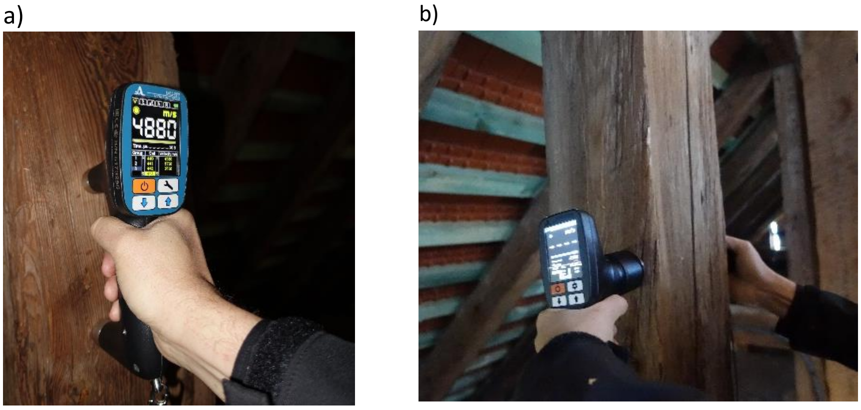

Fig. 7. Ultrasonic tests conducted with: a) UK 1401 SURFER instrument, b) UK 1410 PULSAR instrument

### 3.1.Semi-destructive testing of components of the roof truss using the hammer for wood

The hammer test consists in hammering the needle with a diameter of 2.5 mm and a length of 50 mm into the analysed component. The needle is made of stainless-steel grade with 60 HRC with a 35°-angled cone. The impact energy is 2.207 Nm. The needle penetration was measured after 5-time hammering using a dial indicator. The tests were performed on the selected components of the roof truss system (Fig. 6, 7). The tested components had no signs of biological corrosion or had some visible signs of damage. The test results are presented in Table 1.

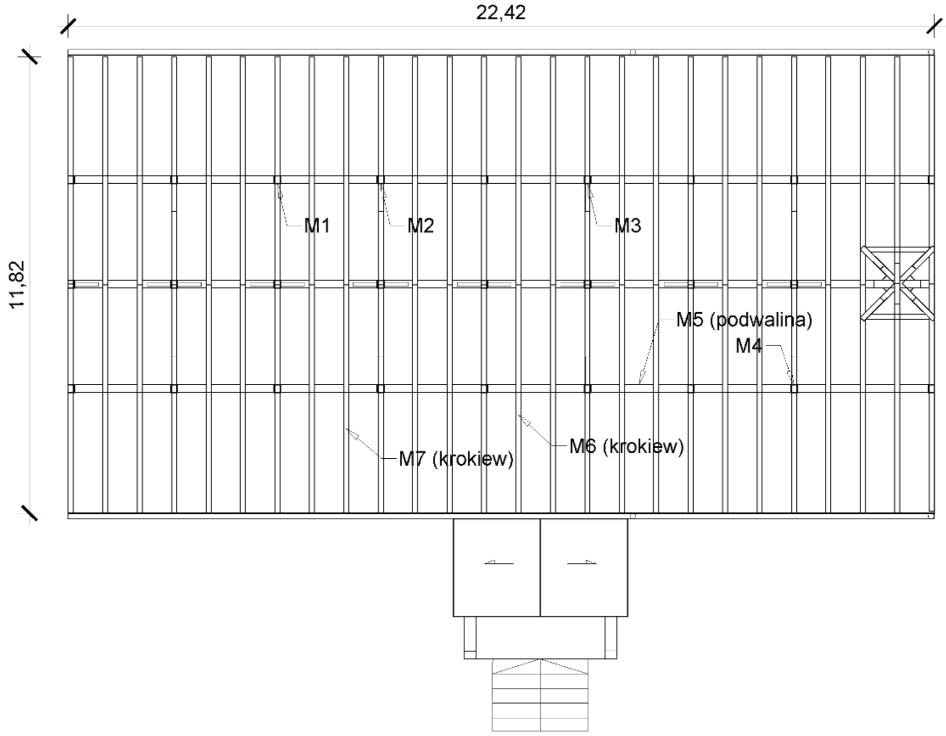


Fig. 8. Test sites of the roof truss components using the hammer for wood

Table 1. Results from sclerometric tests

| Test site | Biological corrosion | Depth of needle penetration, mm |
|---|---|---|
| M1 (column) | No | 20.47 |
| M2 (rafter) | No | 23.6 |
| M3 (left footing beam) | No | 23.63 |
| M4 (horizontal member, left side) | No | 23.44 |
| M5 (column) | Yes | 33 |
| M6 (rafter) | Minor | 29.06 |
| M7 (column) | No | 24.2 |

## 3.2. Non-destructive ultrasonic testing of components of the roof truss system

Hearmon [23] was the first person who recommended the use of ultrasonic waves for describing the wood flexibility. Non-destructive testing with ultrasonic waves consists in measuring the time required for ultrasonic waves to pass through the wood elements. The instruments record the passing time of the ultrasonic wave and automatically compute the velocity of the ultrasonic wave on the basis of the distance between heads of transmitting and receiving heads. The instrument UK1401 Surfer uses the transverse ultrasonic wave, and the test is conducted along grains of the wooden element. The instrument UK1410 Pulsar uses the longitudinal ultrasonic wave, and the test is conducted across grains. Both instruments are equipped with exponential ultrasonic transducers, which do not require any additional acoustic coupling. The instrument UK1401 Surfer has two heads at the constant spacing of 15 cm, and the instrument UK1410 Pulsar has 2x 7 heads. The employed heads are spring-loaded heads that are adjustable to surfaces of tested elements. Both instruments allow the tests through the wood defects (e.g. knots).

The in-situ tests were performed in the selected sites of the roof truss system shown in Fig. 8 and 9. The tests conducted with the instrument UK1401 Surfer were marked with the letter U, and the tests conducted with the instrument UK1410 Pulsar were marked with the letter UP. The tests were performed both in sites without any defects and in sites with visible biological corrosion. Additionally, the instrument UK1401 Surfer was used to measure the velocity of ultrasound flow through the wood defects (knots). The test results are presented in Table 2 and 3.

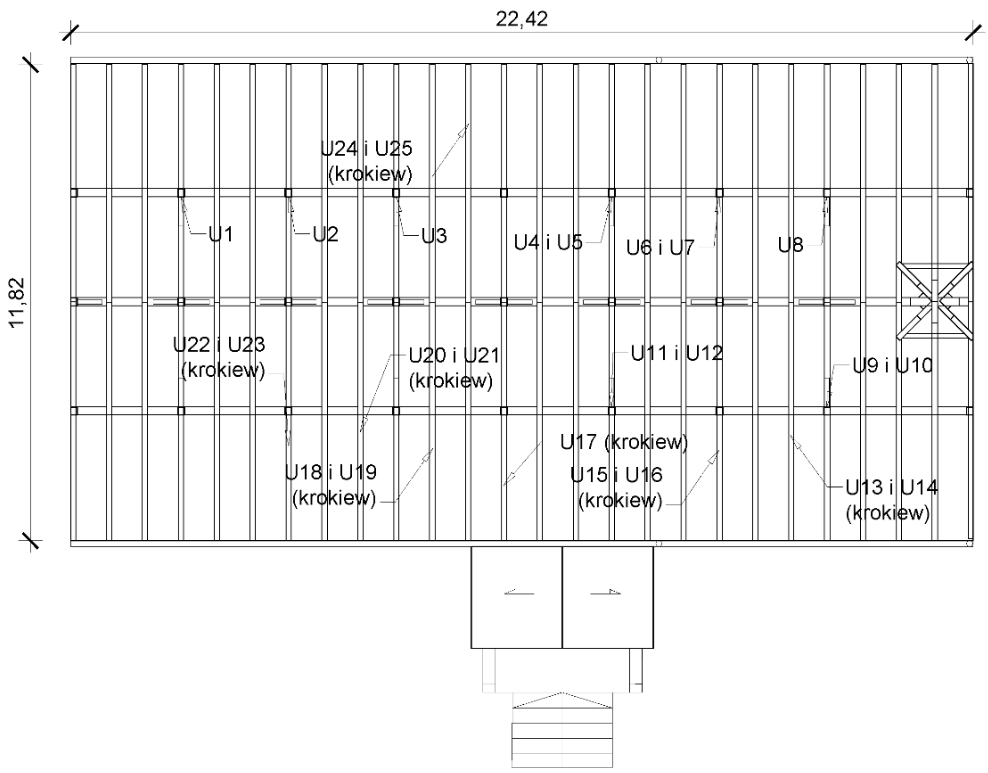


Fig. 9. Test sites of the roof truss components using the instrument UK1401 Surfer

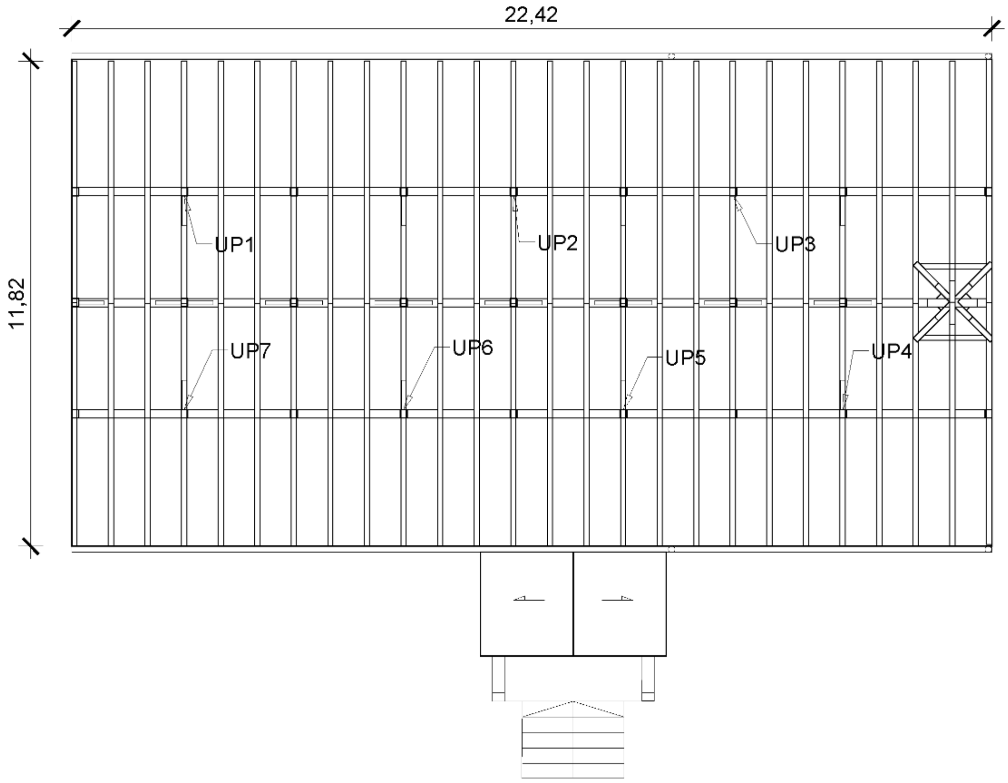


Fig. 10. Test sites of the roof truss components using the instrument UK1410 Pulsar

Table 2. Results from the tests conducted with the instrument UK1401 Surfer

| **Test site** | **Biological corrosion** | **Wood defect** | **Ultrasonic velocity m/s** |
|---|---|---|---|
| U1 (column) | No | No | 5510 |
| U2 (rafter) | No | No | 5360 |
| U3 (left footing beam) | No | No | 5180 |
| U4 (horizontal member, left side) | Yes | No | 4930 |
| U5 (column) | Yes | No | 4590 |
| U6 (rafter) | No | No | 5730 |
| U7 (column) | Minor | Yes | 3530 |
| U8 (rafter) | Yes | No | 4880 |
| U9 (left footing beam) | No | No | 5200 |
| U10 (horizontal member, right side) | No | Yes | 3980 |
| U11 (column) | No | No | 5270 |
| U12 (rafter) | No | Yes | 4900 |
| U13 | No | No | 5080 |
| U14 | Yes | Yes | 2680 |
| U15 | No | No | 5230 |
| U16 | No | Yes | 4120 |
| U17 | No | No | 5440 |

| | | | |
|---|---|---|---|
| U18 | No | No | 5130 |
| U19 | No | Yes | 4010 |
| U20 | Yes | No | 4270 |
| U21 | No | Yes | 4150 |
| U22 | No | No | 5250 |
| U23 | No | Yes | 4380 |
| U24 | Yes | No | 4980 |
| U25 | No | Yes | 3910 |

Table 3. Results from the ultrasound tests conducted with the instrument UK1410 Pulsar

| **Test site** | **Biological corrosion** | **Timber defect** | **Ultrasound velocity, m/s** |
|---|---|---|---|
| UP1 | No | - | 2000 |
| UP2 | No | - | 1780 |
| UP3 | Minor | - | 1150 |
| UP4 | No | - | 2200 |
| UP5 | No | - | 2030 |
| UP6 | No | - | 1960 |
| UP7 | Minor | - | 1590 |

## 4. ANALYSIS OF THE RESULTS

The qualitative assessment of wood was performed on the basis of the results from sclerometric tests. The needle penetration was deeper in case of corroded elements. An average depth of the needle penetration into the undamaged elements was 23.07 mm at the standard deviation of 1.48 mm (the coefficient of variation was 6.4%), whereas an average depth of the needle penetration into the damaged elements was 31.03 mm.

It was not possible to determine the wood strength from the tests with the hammer for wood. Its manufacturer provides the correlation between a penetration depth of the steel needle and the flexural strength, but only for Italian species of trees, such as fir, chestnut, and oak. The analysed roof truss was made from Polish spruce wood. The manufacturer also specifies this correlation for the range of penetration depth of 12÷18 mm. In the described case, the needle penetrated deeper. Hence, the curves for the relation between a penetration depth of the needle and the wood strength developed by the manufacturer were not applicable for the analyzed case.

The qualitative analysis of the wood was conducted on the basis of the performed ultrasonic tests. An average ultrasonic velocity for the undamaged elements tested with the instrument UK1401 Surfer (a transverse ultrasonic wave) was 5330 m/s at the standard deviation equal to 184 m/s (the coefficient of variation 3.5%). An average ultrasonic velocity for the components with biological corrosion was 4266 m/s at the standard deviation equal to 865 m/s (the coefficient of variation 20%). The instrument UK1401 Surfer was also used to test defects (knots). Nine defect sites were tested with the transducer head placed on both sides of the knot (Fig. 11). The determined average ultrasonic velocity was 3962 m/s at the standard deviation equal to 607 m/s (the coefficient of variation 15%). It was clear that ultrasonic velocity near the defect decreased by 25% as the path of the ultrasonic wave flow elongated (the wave passed by the defect).

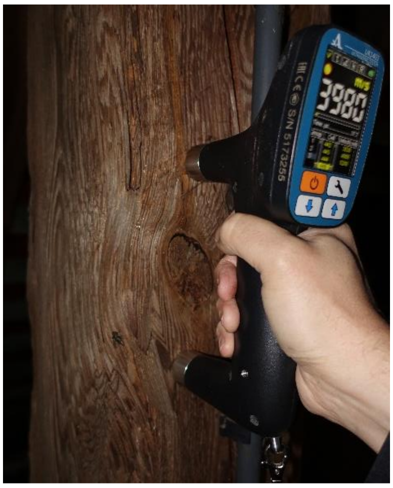

Fig. 11. Method of testing the area near timber defect (knot)

An average ultrasonic velocity for the undamaged components tested with the instrument UK1410 Pulsar (the longitudinal ultrasonic wave) was 1994 m/s at the standard deviation equal to 150.1 m/s (the coefficient of variation 7.5%). This velocity for the damaged elements was lower by 32% and equal to 1370 m/s.

The ultrasonic testing also did not allow the determination of the wood strength as correlation curves in the available literature did not refer to domestic antique wood. For example, the paper [24] presented non-destructive tests with the longitudinal ultrasonic wave to determine the conditions of the wooden ceiling in the historic building in Seville. However, both Polish and foreign literature did not present correlation curves that illustrate the relationship between wood strength and the velocity of transverse ultrasonic wave.

## 5. CONCLUSIONS

On the basis of the conducted tests, the range of repair works for the components of the roof truss system was found to be minor. No signs of fungal decay or characteristic musty odour were noticed. The results from sclerometric and ultrasonic tests were the base for the positive qualitative evaluation of the wood.

However, the performed tests demonstrated that non-destructive and semi-destructive techniques were relevant for the qualitative evaluation of the wood, and not for the determination of its strength. These methods were suitable for determining the sites with biological corrosion and estimating the impact of internal defects on wood quality, The wood strength can be determined by developing correlation curves that describe the relationship between results from non-destructive testing and the wood strength. They can be determined by performing non-destructive and destructive tests on antique wood in the laboratory conditions. Such tests are currently performed by authors of the paper on full-size beam elements from historic buildings.

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