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Typology, current state and non-destructive testing of timber roof trusses of historic churches in the West Vistula Delta, Poland

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Abstract

This paper presents the current state of conservation of historic roof churches located in the Żuławy of Gdańsk (Poland). It also describes the architecture of these temples, the region itself and old carpentry techniques for constructing roof trusses. Interdisciplinary tests were carried out in six churches. The geometry of the load bearing structures, the moisture content and the carpentry technique were specified. The field survey also included visual inspections and non-destructive testing of timber structural elements of the roof constructions. The ground penetrating radar and ultrasonic testing methods were used to assess the structure and extent of the damage to the timber elements. The interdisciplinary research presented in this article is important in the planning of historic buildings conservation works and it might be applied to other timber structures.

Keywords Architectural heritage, Timber structures, Timber roof trusses, Carpentry joints, Vistula Delta, Non-destructive testing, Ultrasonic transmission tomography, Ground penetrating radar

Introduction

The knowledge of historical wooden buildings, their number or state of preservation is still insufficient, despite constant interest and publicity about the subject. A special case of such constructions is sacred architecture, which is a very important but still unexplored area of research. There are a number of issues, such as architectural, structural and spatial solutions, construction materials, or carpentry techniques which are all interesting research topics. As in most European countries [1, 2], the attention of Polish specialists working in this field has been devoted to only a few most attractive regions and exceptional buildings [3, 4].

In Poland, one of the interesting regions where historical objects have not been fully explored yet is the Żuławy of Gdańsk, located in the Vistula Delta where there are many timber buildings and structures. The churches built there since the fourteenth century are some of the most important preserved elements of the region's architectural heritage. Unfortunately, the number of historic churches in the Vistula Delta decreased significantly during the Second World War.

Research on these churches has focused mainly on the history of architecture and art, as well as on the changes in their form over the centuries [5–11]. The subject that has not been thoroughly studied yet is the state of preservation and typology of the timber roof structures of the Vistula Delta churches. They are a special case of the region's material heritage and evidence of traditional construction techniques.

The earliest graphics and descriptions depicting the roof geometry of the churches located in the Vistula

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Delta can be found in the works of German conservators from before the Second World War. These include the churches in Miłobądz, Trutnowy [5], Marynowy, Miłocin, Orłowo, Mątowy Wielkie, Fiszewo [6], Pruszcz Gdański, Steblewo, Koźliny [7]. After 1945, works by Polish conservators containing information on the geometry of churches in: Kiezmark [12, 13], Pruszcz Gdański [14], Trutnowy [15] and others were described. The above-mentioned studies do not contain any information on the details of the roof structures, their construction technology, carpentry joints used or their comparison.

Innovative ways to better identify the state of conservation of timber elements include the use of ultrasound techniques and a ground-penetrating radar. These non-destructive methods are applied mainly to concrete, reinforced concrete and masonry structures [16–18]. However, recent studies show that they give encouraging results also for wooden components [19]. Unfortunately, it is difficult to find research papers in the world literature that describe the application of these methods to study historic wooden components, especially church roof trusses. In addition, there is still a lack of scientific studies on the sacred architecture of the Żuławy of Gdańsk, especially on its timber roof structures. In particular, there is insufficient information on their construction, typology, and state of conservation. Therefore, the aim of this work is to fill this gap.

The paper undertakes an interdisciplinary, architectural, structural and diagnostic study of the current state of the selected roof trusses in the historic churches in the Żuławy of Gdańsk. The history of the region is presented and a brief description of the churches is given as well. The research includes an architectural and structural inventory, and an conclusions from the analysis of the available archival source material. Ultrasonic and ground-penetrating radar methods were used to examine the condition of the load-bearing elements of the roof trusses. In addition, the roof trusses typology of the considered churches was developed.

Cultural heritage background—Vistula Delta, temples architecture, old carpentry techniques

The Żuławy of Gdańsk (called Żuławy in short) is a part of the Vistula Delta region located on the west side of the Vistula River, in Pomerania (northern Poland). It is a flat plain, partly below sea level, covering an area of 391 km^2 [20]. The delta formation ended in the tenth century with the creation of the Vistula Spit on the Baltic side. In the eleventh and twelfth centuries, Żuławy belonged to Gdańsk Pomerania and in 1308 it was incorporated into territory of the Teutonic Order. At that time, the construction of a system of canals and drainage ditches began and significant development of Żuławy took place. After the Thirteen Years' War in 1466, Żuławy was annexed to the Kingdom of Poland. The region remained within its borders until 1772. As a result of the loss of independence of the Republic of Poland, the region was annexed to Royal Prussia and later to the German Empire. After the First World War, Żuławy was included in the administrative boundaries of the Free City of Gdańsk. In 1939 it was annexed by the Third Reich, and after 1945, the entire Vistula Delta was incorporated into Poland [21].

Most of the churches in Żuławy were built in the fourteenth century during the reign of the Teutonic Knights [5]. After 1400, the number of new churches decreased significantly because there was no longer a need to build new temples [22]. More churches were built in new or expanding towns and villages. Most of the historic churches located in the western Vistula Delta are modest, single-nave temples without a separate presbytery, facing east. This is the basic and traditional type of temple in Żuławy [8–10]. Only the Gothic church in Pruszcz Gdański has side naves. At first, in the fourteenth century, the walls were half-timbered [7], later they were made as masonry. In the following centuries, the churches were extended with towers and naves added to them. The churches became local dominants in the flat landscape of the Vistula Delta [11]. Sacristies were usually located on the west or north side. The ceilings over the naves in most churches were wooden, sometimes with Gothic brick vaults [8].

Historical roof trusses covering brick, stone, and wooden buildings were made of timber. Among the many truss solutions used were: rafter, collar beam, king post, queen post, scissors, and attic rafter type (Fig. 1) [23, 24]. Timber for the construction of the Vistula Delta churches came from northern Poland or it was floated down the Vistula River from the south of the country. In the Middle Ages, wooden logs were worked by hand by carpenters using using saws and axes [25]. In the nineteenth century, wooden building elements were already prepared mechanically in sawmills. The elements were connected with carpentry joints [26] until the twentieth century, when the use of nails, screws or steel plates became common. Historical trusses were assembled on the ground near the building. At this level, the correctness of the connections and the geometry of the individual truss was checked [24]. To ensure that the components did not get mixed up in transport to the upper part of the structure they were marked with carpentry marks made with chisels. Single lines or Roman numerals were used as well [27].

Non-destructive testing of wooden elements

Several types of non-destructive testing techniques are currently used to assess the physical and mechanical

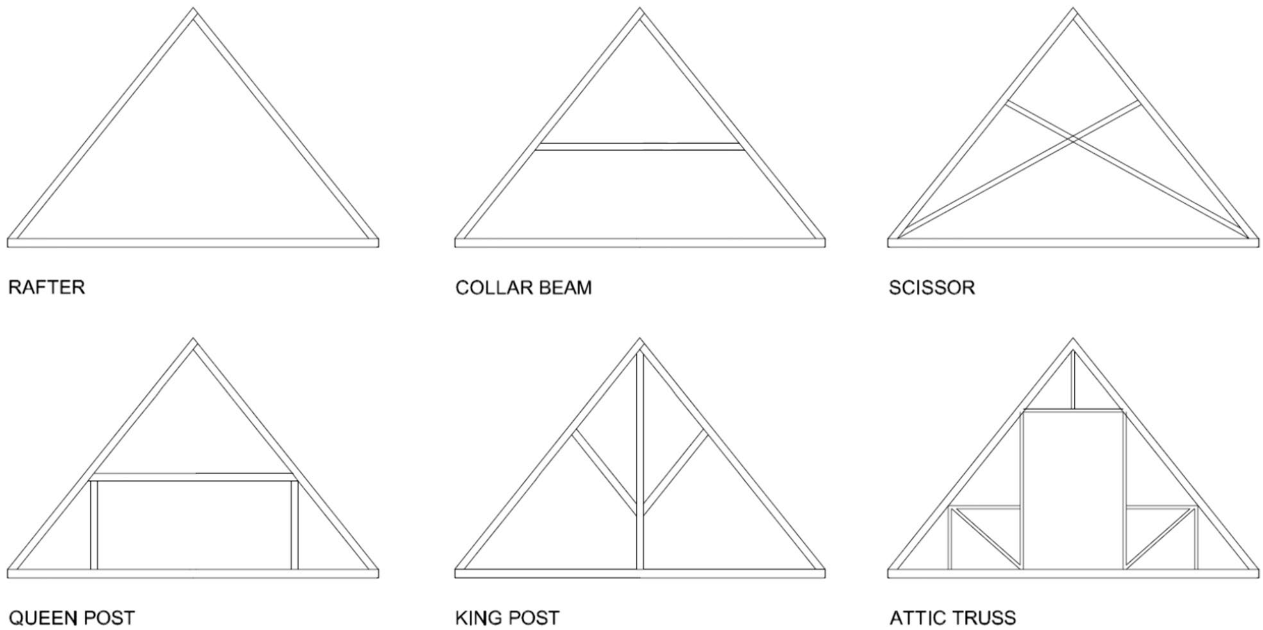

Fig. 1 Timber truss types

properties of timber structures in situ. One of these is the ground penetrating radar (GPR) method, which was first developed for soil testing, and has since been successfully applied to the inspection of masonry, concrete, reinforced concrete or timber. GPR images allow for the detection of different types of anomalies in the form of voids, discontinuities or inclusions and their spatial location. There are many aspects that make the ground penetration radar technique an attractive approach to wood diagnostics. GPR inspection is faster than point-by-point testing and it allows for in-situ testing, the instrumentation is commercially available to customers, and its use does not require coupling agents between the antenna and the surface of the object being tested. Interpretation of GPR results, while fairly intuitive in terms of locating internal features, requires experience in identifying the nature of the localized defect (air void, metal element, inclusion of other material, deterioration, knot).

In most types of wood, its dielectric properties, such as the mechanical properties, are cylindrically orthotropic and can be distinguished in three directions, namely in the longitudinal, radial and tangential [28, 29]. Moreover, the dielectric properties of wood depend on the humidity, temperature, density, type and species of wood. GPR tests performed on wooden elements in-situ are aimed at assessing the state of preservation of timber elements. In the previous studies, GPR was successfully used to evaluate the elements of wooden roofs [30], or floor beams [31]. Halabe et al. [32] used GPR to identify subsurface defects such as knots, decay and metal nails in timber beams that are not visible from the outside. Butnor et al. [33] found out that subsurface distribution and air-filled voids have unique electromagnetic signatures that can be separated from other defects, and GPR can be used successfully to estimate the percentage of air-filled cavities. Xiao et al. [34] proposed a method that combined GPR and laser scanning contour data for identifying internal abnormalities in trees and determining the size and location of the imperfections. Fu et al. [35] used the GPR tomography method to reconstruct the internal cross-sectional structure of a living oak trunk. The reconstruction of the shape and size of the trunk cross-section was made based on a point cloud. Martínez-Sala et al. [36] conducted GPR tests on sawn timber samples of different densities, proving differences in the propagation velocity as well as confirming that the amplitude of direct and reflected waves depends on the direction of the grain arrangement. Pérez-Gracia et al. [31] located the damaged timber floor beams using GPR. The study found that the differences in reflections caused by the damaged beams were clearly enhanced in GPR images, while the differences in healthy beams were less pronounced. Wen et al. [37] proposed a new model of the relationship between the dielectric constant and the moisture of willow, and then used it to detect internal defects in the wood. The influence of moisture variations in wood materials on GPR (ground penetrating radar) signals and the influence of the direction of wood fibres on the polarization of the electromagnetic field were investigated by Sbartai et al. [38], Reci [39], Mai et al. [40], and Redman et al. [41].

Another type of non-destructive testing that can be applied to wooden components is ultrasonic methods. Assessing the condition of wooden elements using ultrasonic tests is not a trivial task due to the anisotropy of wood. Thus these tests should take into account the location of the cross-section pith and the course of the wood grain, which then makes it possible to determine the velocity of propagation of the elastic waves in longitudinal, radial and tangential directions. A method for determining the location of the cross-section pith was proposed by Perlin et al. [42], who indicated this location as the area with the highest velocity of wave propagation. The anisotropy of wood affects the change in the trajectory of the wave propagating from the transmitter to the receiver. Usually, this path is not straight but curved, as studied by Espinosa et al. [43, 44] or Perlin et al. [45]. Ultrasonic transmission methods, based on the information obtained from the signals propagating through the tested element, are used to locate wood defects. Mousavi et al. [46] analyzed the signals propagating through damaged wooden elements. They argued that the use of the eigenvalue of the proposed covariance matrix is more sensitive to wood hole defects than the traditionally used measures such as time-of-flight. In order to reduce the number of difficulties caused by the randomness and anisotropy of wood, they then improved the methods of testing wood with ultrasounds by proposing a machine learning algorithm [47]. Liu and Li [48] performed ultrasonic tomography based on the wave time of flight in wooden elements, detecting their defects, and compiled maps made for straight and curved wave paths. Zielińska and Rucka [19] used ultrasonic tomography to assess the state of preservation of beams from a historic building. They proposed an innovative method of detecting damage in wooden beams.

Methods

Case studies and analyses criteria

The main criterion for the selection of objects to determine their state of preservation was their inclusion in the Register of Pomeranian Monuments [22]. There are currently 15 such sites on the list. Another criterion limiting the number of the objects studied was the possibility of carrying out tests in accordance with safety regulations. In addition, the consent of the church administrators was required to conduct the research. Thirdly, only the roof trusses that were at least 60 years old were selected for the study. Therefore the objects that have been rebuilt in recent years were not included in the field survey. Finally, it was possible to conduct out the research on 6 objects (Fig. 2). These were the churches in Miłobądz (#1), Pruszcz Gdański I (#2), Kiezmark (#3), Pruszcz Gdański II (#4), Koźliny (#5) and Trutnowy (#6).

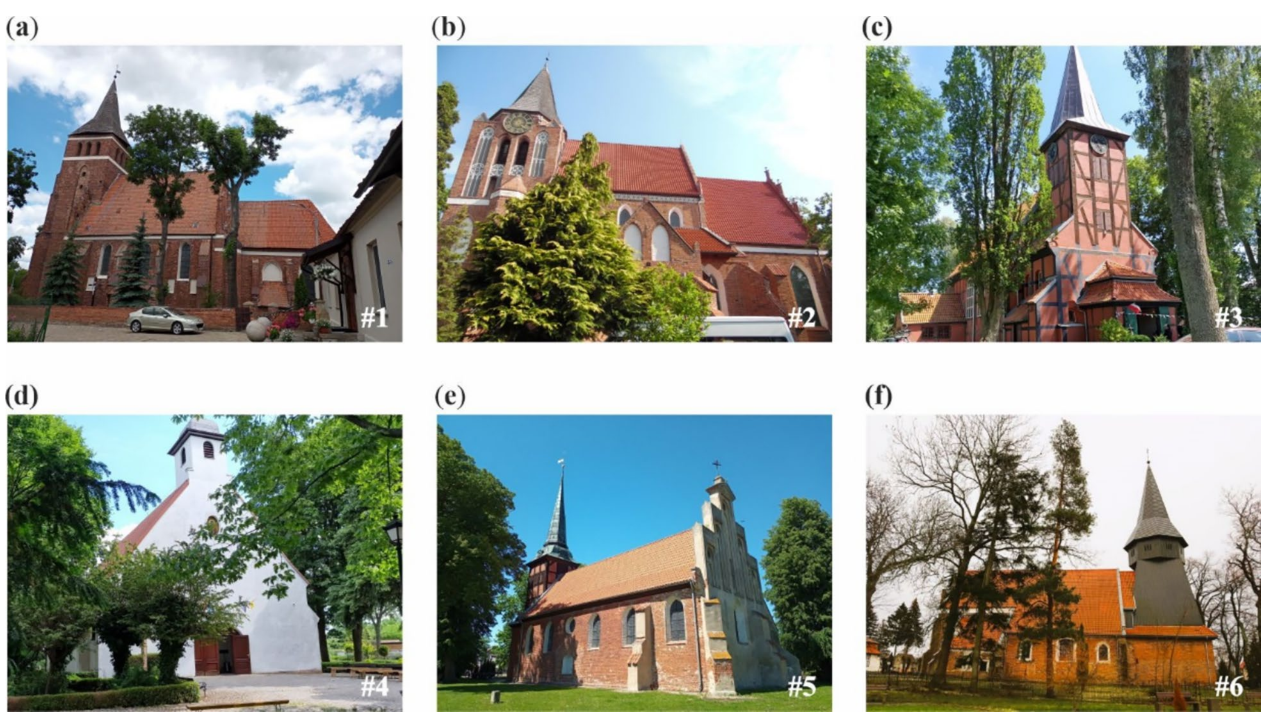

Fig. 2 Churches in: **a** Miłobądz (#1) **b** Pruszcz Gdański I (#2) **c** Kiezmark (#3) **d** Pruszcz Gdański II (#4) **e** Koźliny (#5) **f** Trutnowy (#6)

The research involved archival queries and fieldwork. In the first step, the available literature and source materials were analyzed. Field tests were then carried out to measure the geometry of the roof structure, including span, height, angle of inclination, number of trusses, and cross-sectional sizes of the main structural elements, excluding wind beams and battens. The study also included taking measurements of the moisture content of the timber elements (rafters), as well as the analysis of the joints and carpentry marks. The species of wood used for the roof trusses was also confirmed. Finally, non-destructive tests were carried out using ground penetrating radar and ultrasonic testing methods.

Analysis of historic roof trusses

The first stage of the research was a desk survey of the available published and unpublished sources [49]. Historical and conservation information was obtained from the National Heritage Board of Poland in Gdańsk, the Provincial Office of Monument Preservation in Gdańsk, the Library of Polish Academy of Sciences in Gdańsk, and the Library of Gdańsk University of Technology. One of the most important sources of information about the history, construction, wood species, number and extent of the renovations carried out in the past were the records of architecture and construction monuments. The basic information about church #1 was provided by Domagała [50] and Ruszkowska [51], about church #2 and #4 by Tukałło [52], Michno [14] and Styp Rekowska [53], about church #3 by Krzyżanowski [54], Barton et al. [13], about church #5 by Krzyżanowski and Tukałło [55] and Gzowski [56], about church #6 by Krzyżanowski and Tukałło [57] and Barton et al. [15].

Visual inspections were conducted in the six selected churches. The tests included all the girders in each structure. The survey consisted of a comprehensive examination of the timber structure, during which the state of preservation, wood species, geometry and technology of the roof trusses, technical interventions in the structure, defects and decay of the timber elements and cracks were checked [58, 59].

The age of the roof structures was determined on the basis of: historical documentation, conservation documentation and informations collected from the churches guardians.

In the analysis of historical roof trusses the indicator ($\overline{V}$) can be applied [60]:

$$\left[\overline{V} = \frac{V}{RL}\frac{\mathrm{m}^3}{\mathrm{m}}^2\right] \quad (1)$$

where:

V [m^3]—volume of the timber construction elements (rafters, collar beams, posts, purlins) of one girder,

R [m]—average spacing of particular roof trusses,

L [m]—roof truss span.

For example, the data for the church in Pruszcz Gdański I #2: the volume of the timber load-bearing elements of one girder V = 3.56m^3, L = 10.05 m, R = 0.9 m;

$$\overline{V} = \frac{3.56}{10.05 * 0.9} = 0.393\frac{\mathrm{m}^3}{\mathrm{m}^2}$$

The indicator ($\overline{V}$) describes the amount of structural timber required to construct the roof trusses. Its value can be helpful in determining the age of the object and to perform a comparative analysis of similar constructions. The value $\overline{V}$ is inversely proportional to the age of the structure. Calculations of the $\overline{V}$ index have been applied, among others, to the study of historical roof construction of churches in Gdańsk [60] or portico houses in the Vistula Delta [61, 62].

The state of conservation of the roof trusses was assessed on the basis of a four-point scale: very bad (structure failure, visible signs of object instability), poor (untight roof, deteriorating masonry), fair (small repairs are necessary), good (no significant repairs are needed) [63].

Moisture content measurements

One of the basic tests of timber structures is the measurement of moisture content [64] as it has an impact on the state of preservation of wooden elements[59]. The moisture content in roof trusses was tested using a Tanel® WIP-24 moisture meter manufactured by TANEL (Gliwice, Poland). It is designed for quick and non-destructive moisture measurements of wood and other building materials. The research was performed in June 2022, on non-rainy days. The tested points were located on the rafters (close to the tie beam) and elements adjacent to the roof covering because when a roof leaks, the rafters are most exposed to increased moisture levels. The wood moisture content was measured in accessible flat, smooth and clean rafter areas with the line connecting the probe points parallel to the rafter axis. The moisture meter with the test electrodes was placed firmly on the wood and held for a few seconds until the result was displayed. The end result was the arithmetic mean of 10 readings. The results of the measurements are given in Table 2.

Non-destructive tests procedures

In this study, the inspection of wood was conducted using two non-destructive techniques: ground penetrating radar and ultrasonic testing. In the case of GPR surveys, a pulse-echo system was used, while ultrasonic testing was performed in a transmission mode.

Fig. 3 NDT equipment used in in-situ tests: **a** ground penetrating radar **b** ultrasonic pulse velocity tester

GPR surveys were performed using the C-Thrue system (Fig. 3a), manufactured by IDS GeoRadar® (Pisa, Italy), equipped with a dual-polarization antenna unit operating at a central frequency of 2 GHz. The system included transmitting and receiving antennas as well as a data acquisition unit contained in one case. During measurements, the GPR device was moved along the tested element. The electromagnetic pulse was emitted from the transmitting antenna and returned to the receiving antenna having been reflected off an anomaly that differed in dielectric properties from the surrounding medium. Specific A-scans were taken at 2 mm intervals. The electromagnetic responses for each radar position were then processed and combined into radargrams (so-called B-scans or time-position planes). The dielectric properties of the medium under investigation affected the propagation velocity of electromagnetic waves, which is crucial in determining the depth axis. The electrical permittivity of the wood was set as 2.25 giving the velocity of the electromagnetic wave equal to 20 cm/ns. The effective depth of the GPR system was up to 80 cm.

The presented inspection was conducted on timber roof trusses in all the selected churches. In each one, three girders were examined, from which 4 beams were selected, which gave a total of 72 B-scans. Wooden elements were selected according to the visual inspection results. Depending on the type of roof truss and accessibility, these were floor beams, struts, rafters, and poles. Figure 4 shows the elements for which the measurements were made.

The ultrasonic measurements were performed using pulse analyser PUNDIT® PL-200 apparatus (Proceq SA, Schwerzenbach, Switzerland, Fig. 3b). Two exponential transducers with a frequency of 54 kHz and dry coupling were used. The time of flight was measured for each beam and the wave propagation velocity was determined based on its width. Ultrasonic measurements were taken for 72 beams previously selected for GPR tests.

Results and discussion

Results of roof analysis

Table 1 shows the results of the query of the available sources. It includes information on the date of the building construction and the roof repairs carried out in the past. The next part of the research summary is the specification of roof truss types, wood species, roofing and the church current technical state. Table 1 shows also details of the construction such as carpentry joints and a description of the carpentry marks. The dimensions of particular elements, the average span of trusses, the results of $(\overline{V})$ indicator calculations and the moisture measurements are listed in Table 2.

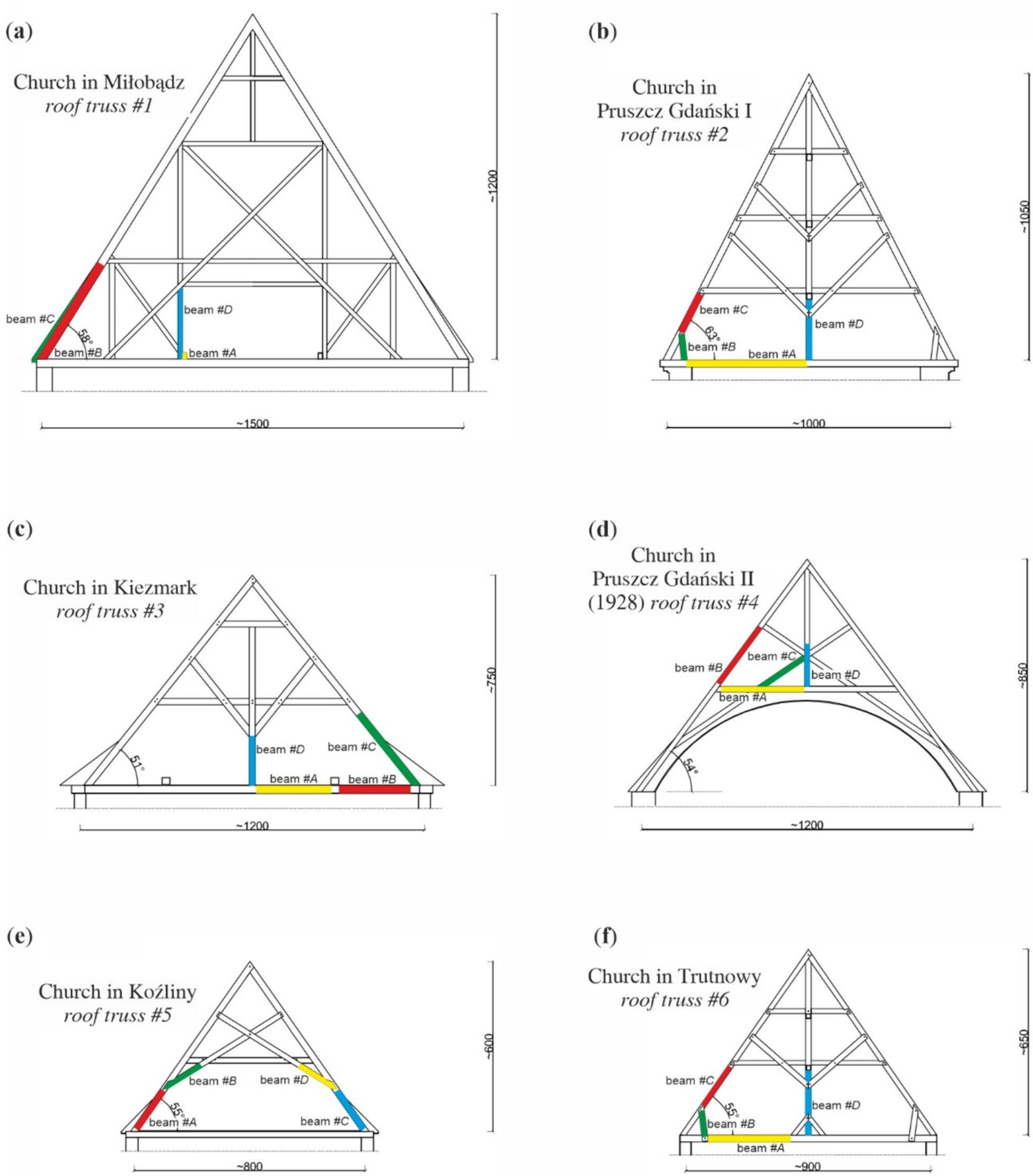

Fig. 4 Geometry and girders of the roof trusses with the indication of the measured timber elements, churches in: **a** Miłobądz (#1) **b** Pruszcz Gdański I (#2) **c** Kiezmark (#3) **d** Pruszcz Gdański II (#4) **e** Koźliny (#5) **f** Trutnowy (#6)

The analysis shows that the most common type of roof truss in the historic churches located in Żuławy is the king post truss (Figs. 4, 5b, c, f). In church #5 (Fig. 5e) there is a collar beam truss with struts, in church #4 (Fig. 5d) there is a scissor truss. In the church #1 (Fig. 5a) there is an attic truss shaped similar to that of the previous structure, that one from before the war damage.

Table 1 Results of the archival query and field research—general data

No. #	1	2	3	4	5	6
Location	Miłobądz	Pruszcz Gdański I	Kiezmark	Pruszcz Gdański II	Koźliny	Trutnowy
Date of church construction	14th	Mid-fourteenth century	1727	1928	Mid-fourteenth century	Mid-fourteenth century
Date of roof structure	1956	Fifteenth century	1727	1928	1686	Seventeenth century
Type of roof truss (Figs. 4 and 5)	Attic truss	King post truss	King post truss	Scissor truss	Collar beam truss wit struts	King post truss
Carpentry joint in the ridge (Fig. 6)	Pinned, bolted	Bridle joint	Bridle joint	Pinned, bolted	Bridle joint	Bridle joint
Carpentry joint: rafter and collar beam (Fig. 6)	Pinned, bolted	Lap joint	Mortise and tenon	Pinned, bolted	Mortise and tenon	Dovetail log
Wood species	Pine	Oak	Oak	Pine	Oak	Oak
Roof covering (Fig. 2)	Red tiles	Red tiles	Red tiles	Red tiles	Red tiles	Red tiles
State of conservation	Good	Good	Good	Good	Good	Good
Gracity ventilation of the attic	Intact	Intact	Intact	Intact	Intact	Intact
Carpenters' marks (Fig. 7)	None	Visible, Roman numerals II, III, IIII, V	Visible Roman numerals X, IX, IIIIX	none	Visible Roman numerals VIII, VIIII, XI and signts made with chisel or gouge	Visible Roman numerals IIII, IIIII and signs made with chisel or gouge
Remarks:	The church was burned in 1945, the roof truss was rebuilt in 1956, in 1984–1985 the roof construction was strengthened	The roof truss was rebuilt in the fifteenth century after the fire in 1460. Individual reinforcements and replacements of some structural elements carried out in the past are visible	1971–1972 roofing renovation, 2010–2012 church renovation was carried out	In 1945 the church was demolished. The roof was renovated in 2004, in 2022 a ventilation system was installed in the attic	The church was not damaged in 1945	the church tower was demolished by the Germans in 1945 before the Red Army entered. It was rebuilt in 2018 with the efforts of the parishioners

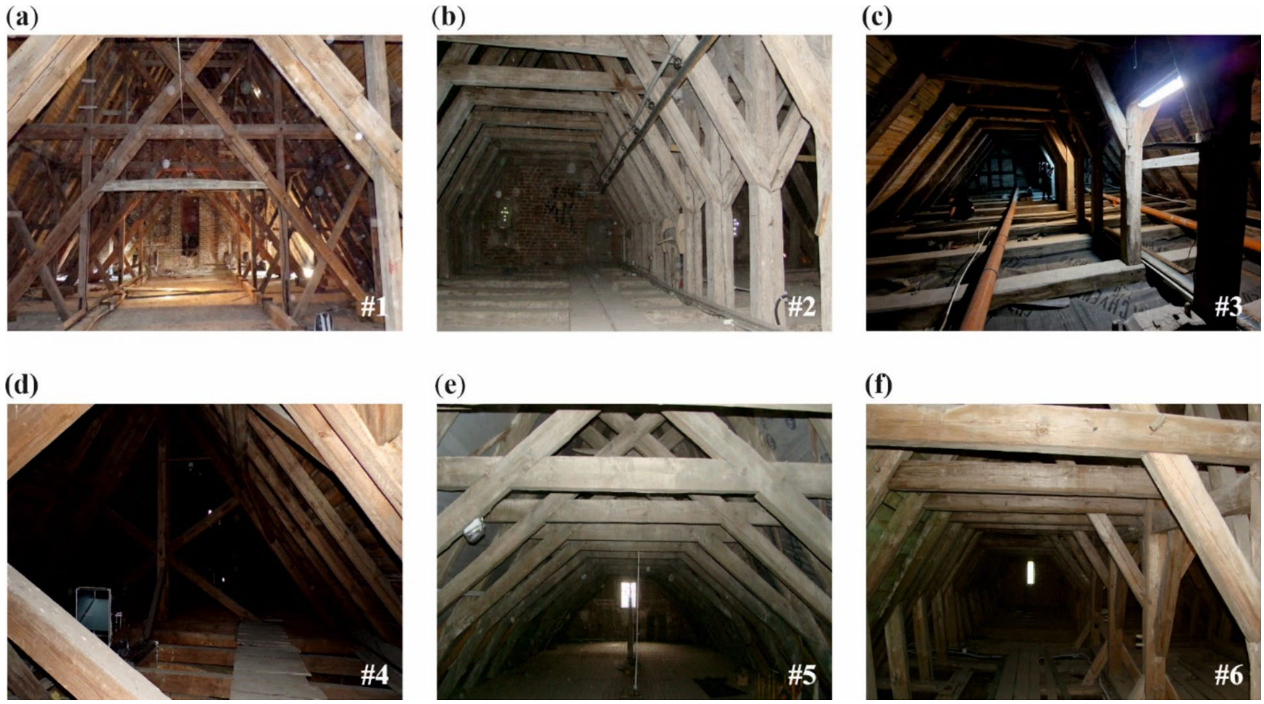

Fig. 5 Roof trusses in: **a** Miłobądz (#1), **b** Pruszcz Gdański I (#2), **c** Kiezmark (#3), **d** Pruszcz Gdański II (#4), **e** Koźliny (#5), **f** Trutnowy (#6)

The average indicator $\overline{V}$ of the roof trusses is 0.21 m^3/m^2, varying from 0.096 m^3/m^2 for the rebuilt roof truss in church #1, to 0.393 m^3/m^2 for church #2. The angle of inclination varies from 51° for church #3 to 63° for church #2, the average angle for all the objects being 56°. The height of the roof trusses ranges from 6 m for church #5, to 10.5 m for church #2. The trusses span varies from 8 m for church #5 to 15 m for church #1. The average girder span ranges from 0.5 m for church #4 to 3.5 m for church #1. The trusses of churches #1, 2, 3, 6 consist of: rafters, upper and lower collar beams, posts, struts and tie beams. The truss of church #4 does not have an upper collar beam or a tie beam. In church #5 the truss has only one collar beam and no post.

The rafters in the ridge of churches #2, 3, 5, 6 are connected with a bridle joint (Fig. 6f). The connections of rafters with collar beams are more varied. In churches #3 and #5 they are the same: mortise and tenon (Fig. 6c), in church #6 it is the dovetail log. The king post with struts is connected with a dovetail log (Fig. 6a) in church #2. The rafters and angle ties are connected with a lap joint in church #6 (Fig. 6b). In the roof trusses constructed in the twentieth century (churches #1 and #4), the carpentry joints are pinned and bolted (Fig. 6d, e) (Tables 1 and 2).

Older trusses are made of oak timber wheras twentieth century trusses are made of pinewood. All the examined roof trusses have the same type of roofing, i.e. red tiles (Fig. 2). The state of conservation of the trusses is good, the roofing is waterproof and the gravity ventilation of the attics is intact (Table 1). Only the roof trusses built before the twentieth century (churches #2, #3, #5, #6) have carpentry marks (Fig. 7).

The wood moisture content varies from 8.06% for the Gothic church #2 to 17.5% for church #6 (Table 2) with the values not exceeding 18%. They comply with the requirements of the technical standard for wooden structural elements to be protected from moisture [65].

Results of GPR tests

Due to a large amount of measurement data, Figs. 8, 9, 10, 11 present only the selected B-scans, from which conclusions can be drawn. The scans were combined with the photographs of the tested beams. The yellow arrows mark the traces of GPR measurements.

GPR is particularly sensitive in detecting metal components. In wood, these are mainly screws used to connect several beams or nails used to mount small elements such as lighting lamps or cable holders. Examples of the location of such elements in a plane parallel to the plane along which the antenna is led are shown in Fig. 8a–f. These elements are marked as a single hyperbolas and their distance from the tested surface depends on the depth at which a particular element is located.

Fig. 6 Carpentry joints in church roof trusses: **a** Miłobądz (#1), **b** Pruszcz Gdański I (#2), **c** Kiezmark (#3), **d** Pruszcz Gdański II (#4), **e** Koźliny (#5), **f** Trutnowy (#6)

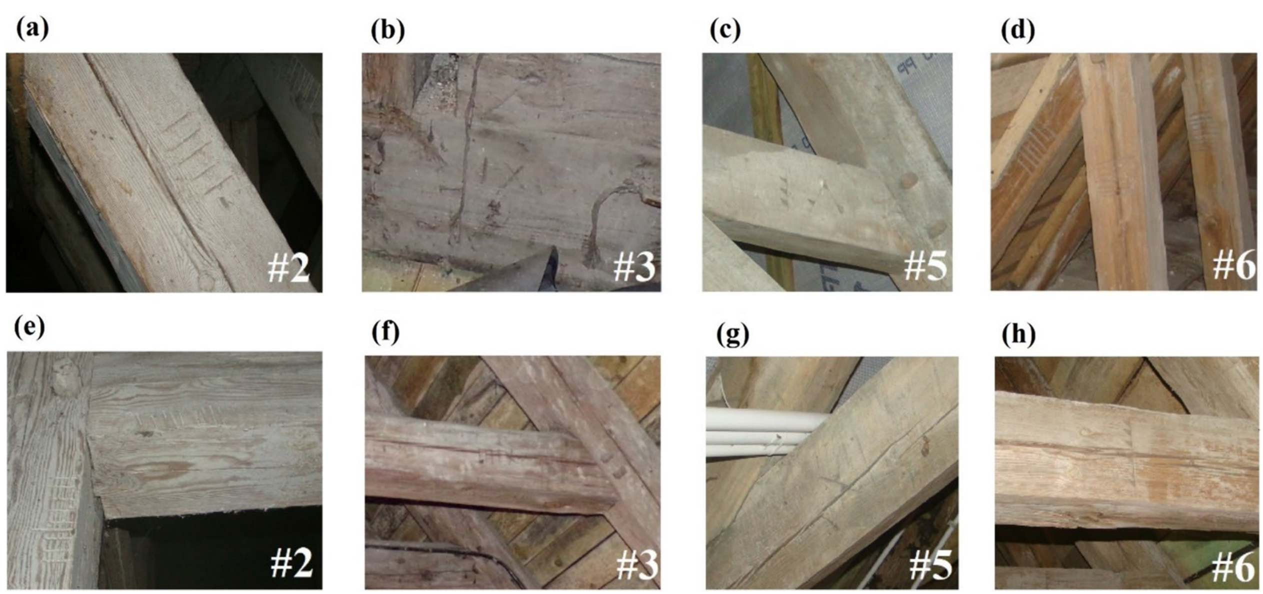

Fig. 7 Carpenters' marks on roof trusses: **a** and **e** Pruszcz Gdański I (#2), **b** and **f** Kiezmark (#3), **c** and **g** Koźliny (#5), **d** and **h** Trutnowy (#6)

In the case of screws and nails, where the main axis is perpendicular to the direction of GPR movement, their location is marked on the B-scan in the form of several hyperbolas located one above the other (Fig. 8g, h). GPR can therefore be used not only to locate a metal element but also to assess its orientation.

The joints of timber beams for roof trusses are usually carpentry joints (Fig. 9). Such connections are visible on the radargrams as the location of additional wave

Table 2 Results of the field research—construction details and wood moisture content measurements

No. #	1	2	3	4	5	6
Location	Miłobądz	Pruszcz Gdański I	Kiezmark	Pruszcz Gdański II	Koźliny	Trutnowy
Wing width (m)	15	10	12	12	8	9
Wing height (m)	12	10.5	7.5	8.5	6	6.5
Rafter (cm)	20×31	20×24	20×35	15×16.5	19×23	18×18.5
Bottom collar beam (cm)	16×16	15×22	14×22	11×18	16×22	16×17
Upper collar beam (cm)	16×16	15×22	14×22	[–]	[–]	16×17
Post (cm)	16×17	21×22	21.5×24.5	15×19	[–]	18×21
Strut (cm)	24×36	18×20	14×22	15.5×18	16.5×19	16×17
Tie beam (cm)	Under floor	27×28	25.5×30	[–]	Under floor	25×28
Average span of girder (m)	3.5	0.9	0.9	0.5	1.3	0.95
Number of trusses (-)	6	12	16	18	15	15
Angle (°)	58	63	51	54	55	55
∇ (m^3/m^2)	0.096	0.393	0.247	0.148	0.106	0.246
Wood moisture content (%)	12.65	8.06	14.3	13.48	14.73	17.5

reflections(Fig. 9a, c). A more pronounced effect can be seen where the beam was cut for wind girders. Examples of such reflections are shown in Fig. 9b. In the case of electrical cables, they are detected similar to screws and nails in the form of a single hyperbolas (Fig. 9d). In the case of wooden elements, the electrical cables are usually routed visibly on the beam, without cutting the wood.

The reflections from the boarding are also characteristic and they form a sequence of evenly spaced hyperbolas on the radargrams, indicating the locations of board joints (Fig. 10a, b). Damage to timber elements causes disturbances in GPR radargrams. Figure 10c shows a local failure on the lower part of the beam. The beam shown in Fig. 10d is completely and shallowly damaged, causing numerous reflections. Figure 11 shows beams from three different girders from the churches in Trutnowy, Pruszcz Gdański I, Kiezmark, and Koźliny, respectively which show varying degrees of destruction. The scans prepared for undamaged beams can be considered as reference. The reflections from the bottom of these beams are visible here, which allows the thickness of the element to be assessed. The scans prepared for the damaged beams indicate a significant disturbance in the propagation of electromagnetic waves. This demonstrates high sensitivity of the GPR method to any defect in a timber element. The reference scan is not always feasible, but it makes the interpretation of the results much easier.

Results of ultrasonic tests

The results obtained by ultrasonic measurements are summarized in Table 3. The average velocities of the elastic waves range from 1506.8 to 1689.6 m/s. Due to different degrees of beams destruction, the age of the elements tested, the density of the material and the type of wood, the minimum velocity is 893.9 m/s, while the maximum is 2777.8 m/s. The fact that the tests were carried out on three similar roof beams in each church made it possible to compare the signals for the beams of the same type, geometry and significance. Figure 12 a–e show graphs of the signals from measurements performed on two beams. Photographs of both beams are shown alongside the diagram. One of the beams is undamaged, while the other one shows varying degrees of damage in the form of voids (Fig. 12a–c), cracks (Fig. 12d) and moisture (Fig. 12e). The location of the measurement is marked in the photographs with blue and pink lines, for the undamaged and damaged beams, respectively. The TOF (time of flight) of the damaged elements is longer than that of the reference elements. The undamaged elements have similar velocities, ranging from 1627.9 (Fig. 12d) to 1788.1 m/s (Fig. 12e). The velocities in the damaged elements decrease significantly and reach the values of only 616.7 m/s (Fig. 12e) to 1149.4 m/s (Fig. 12a). It is worth noting that the amplitude of the signal also decreases for the damaged elements.

The ultrasonic wave signals propagating through the connections of the elements were analyzed. The measurements were made for straight overlap joints (Fig. 13). The first joint analyzed was in the church #2 and the second in the church #5. Both connections were bolted, and the second was additionally sealed with some adhesive. For the first analyzed joint, the measurements were taken at three levels: above the joint of the new beam, below the joint of the old beam, and at the level of the joint. The propagation velocities were 1589.4 m/s, 1632.7 m/s and 750 m/s, respectively. The signals obtained for the new

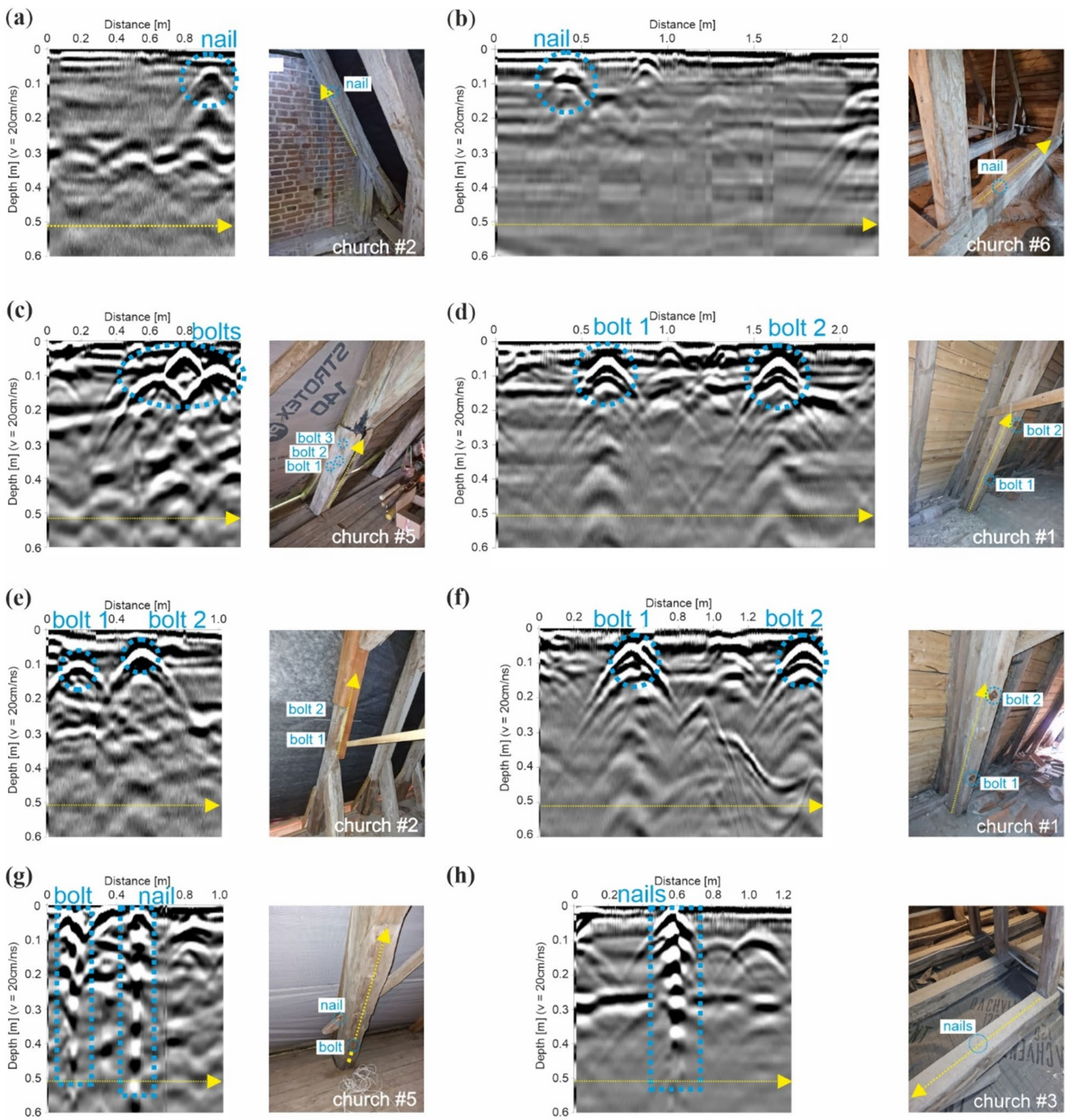

Fig. 8 GPR radagrams locating bolts and nails in timber beams a plane parallel (**a**–**f**) and perpendicular (**g**, **h**) to the moving GPR antenna

and old beams were similar. At the level of the connection, the signal weakened significantly and the propagation velocity decreased more than twofold. In the case of the second joint, where a sealing adhesive was used, the velocity of wave propagation decreased slightly from 1782.2 m/s for a full beam to 1629.6 m/s at the level of the connection. The results obtained prove high sensitivity of the ultrasonic method in the case of joints with air voids. For joints without voids, the ultrasonic wave propagates as in a solid element.

Conclusions

The analysis of the historical roof trusses of the churches located in Żuławy has revealed changes in their construction over the centuries. The roof structures built in the twentieth century are modern solutions. The traditional

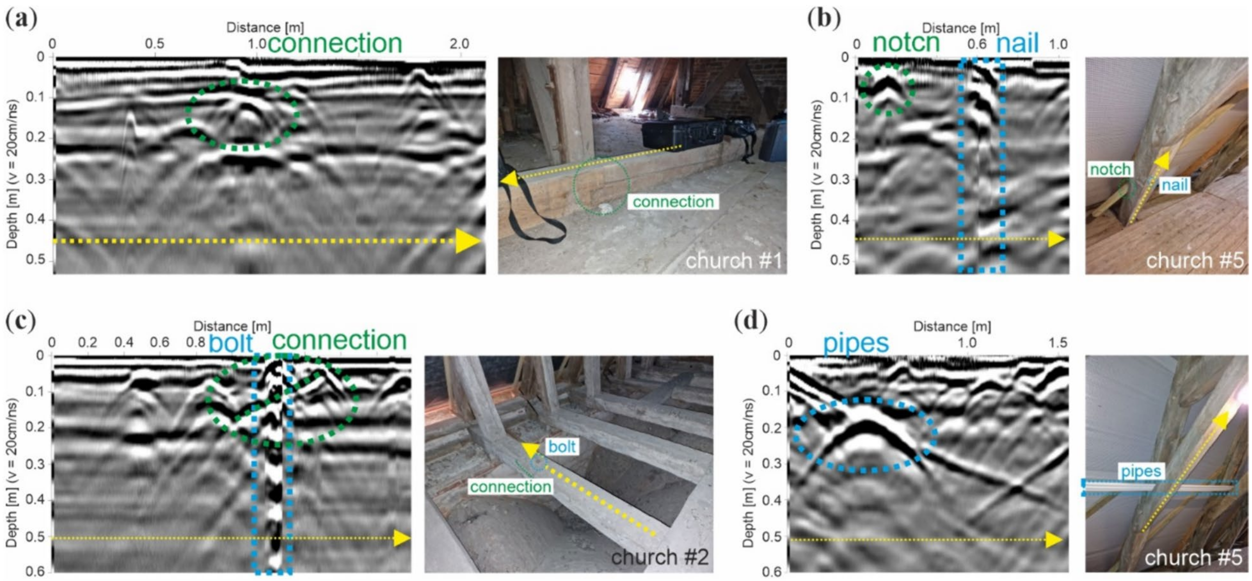

Fig. 9 GPR radargrams locating carpentry joints for electric cables in timber beams: **a**) Milobadz (#1); **b**) Koźliny (#5); **c**) Pruszcz Gdański I (#2); **d**) Koźliny (#5)

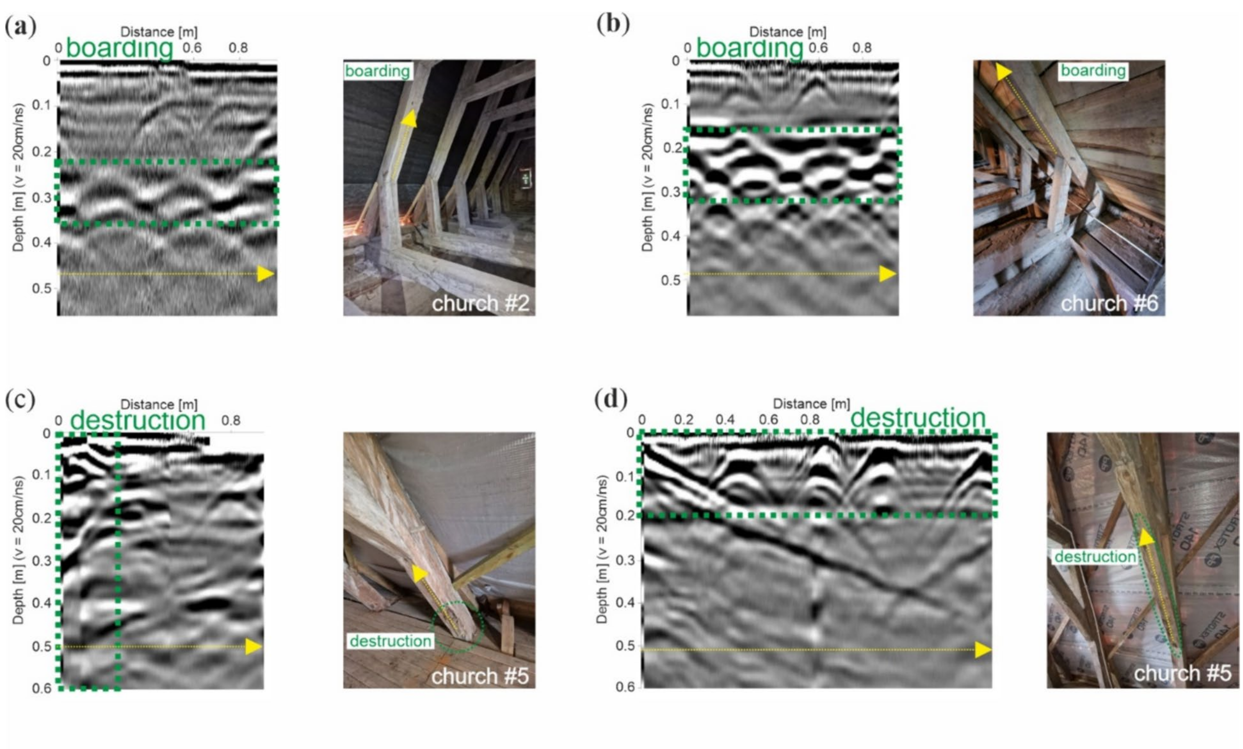

Fig. 10 GPR radargrams locating the boarding of the roof truss and decay of timber beams: **a**) Pruszcz Gdański I (#2); **b**) Trutnowy (#6); **c**) and **d**) Koźliny (#5)

roof trusses used in the past in the Vistula Delta are no longer built in this region. Only the shape, the angle of inclination and the roofing covering refer to historical schemes.

The performed calculations of structural timber ($\overline{V}$) also indicate a reduction in the amount of construction wooden elements needed for the roof trusses. The

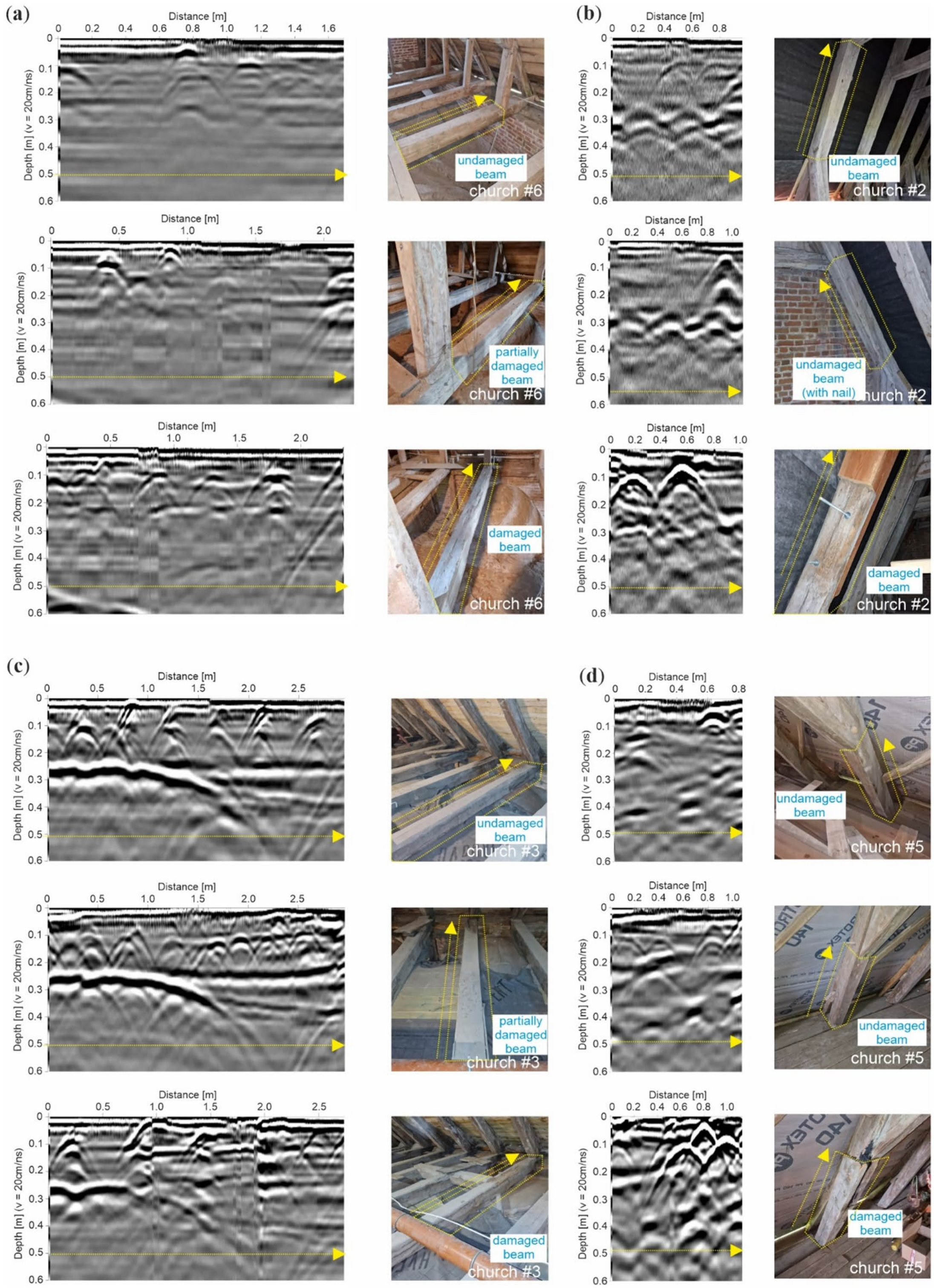

Fig. 11 Comparison of GPR radargrams of beams from three different trusses from churches in **a**) Trutnowy, **b**) Pruszcz Gdański I, **c**) Kiezmark and **d**) Koźliny

Table 3 Velocity of ultrasonic wave propagation for the tested beams

Beam no.		Ultrasonic velocity *v* (m/s)					
		Church #1	Church #2	Church #3	Church #4	Church #5	Church #6
Truss 1	Beam 1	1733.3	1666.7	1454.5	1810.3	1559.6	1255.8
	Beam 2	1521.7	1682.2	1750	2000	1165	1255.8
	Beam 3	1503.3	1395.3	1259.8	1666.7	1347.8	1764.7
	Beam 4	1811	1652.9	1839.1	1891.9	1422	1703.7
Truss 2	Beam 1	1707.3	1149.4	1681.4	1500	1559.6	1788.1
	Beam 2	1631.2	1360	1553.4	1730.8	1621.6	1788.1
	Beam 3	1554.1	1730.8	1782.2	1704.5	1025.6	1666.7
	Beam 4	1666.7	1818.2	1666.7	1627.9	2083.3	1760
Truss 3	Beam 1	1097.6	1639.3	893.9	1640.6	1634.6	1764.7
	Beam 2	1627.9	1792.5	1632.7	1144.1	1161.6	1764.7
	Beam 3	1632.7	1610.2	1650.5	1415.1	1648.4	1803.3
	Beam 4	1486.5	2777.8	1927.7	1007.2	1851.9	1885.2
Minimum velocity (m/s)		1097.6	1149.4	893.9	1007.2	1025.6	1255.8
Maximum velocity (m/s)		1811	2777.8	1927.7	2000	2083.3	1885.2
Velocity average (m/s)		1581.1	1689.6	1591	1594.9	1506.8	1683.4

contemporary solutions used in church #4 and in the rebuilt church #1 required a smaller amount of timber.

GPR appeared to be a useful tool for detecting irregularities of wooden beams in historic buildings. At the same time, the method revealed some limitations, mainly due to the lack of automated data analysis procedures, relatively imprecise accuracy of the defect localization and difficulties in determining the type of anomaly. The following results can be drawn from the conducted georadar surveys:

- The GPR method provided excellent penetration and showed the full depth of the inspected element.
- Metal elements in the wood caused strong reflections of the electromagnetic waves. Screws and nails located in a plane parallel to the plane of the moving antenna appear as single hyperbolas, while the elements located in the perpendicular plane appear as a series of hyperbolas one above the other.
- GPR made it possible to locate carpentry joints in timber beams, either along one axis or in several planes.
- The roof boarding appeared on GPR radagrams as a collection of regular hyperbolas, one next to another.
- Damage and air voids in the timber beams affected the path of electromagnetic waves in the wood, causing severe distortions.
- Comparing the results for several beams made of the same material, being the same age, shape, dimensions and location allowed for a more accurate analysis of the technical condition of the tested beams. With the undamaged reference element, it was possible to accurately assess the location of decay in the damaged beams.

The ultrasonic transmission method was found to be a good tool for assessing the condition of preservation of timber beams. The limitations of the method was the local measurement, which provides information only on the selected, single cross-section of the beam. The following conclusions can be drawn from the ultrasonic transmission tests carried out:

- The reference element (an undamaged beam) helped to determine the degree of failure of an element of the same geometry and importance degree.
- Damage in the form of voids, cracks and moisture significantly reduced the velocity of the ultrasonic wave.
- The diagnostic indicator based on ultrasonic wave velocity was sensitive in locating joints between elements with air voids. In the case of adhesive joints, the wave propagation velocity did not change significantly.

All the considered churches are still in use as sacred buildings and are local parishes. As a result, the community is able to finance or carry out ongoing renovations and simple repairs on their own. The facilities are cared for by priests, who are responsible for them and constantly inspect these historical monuments. The surveyed churches are listed in the Register of Monuments,

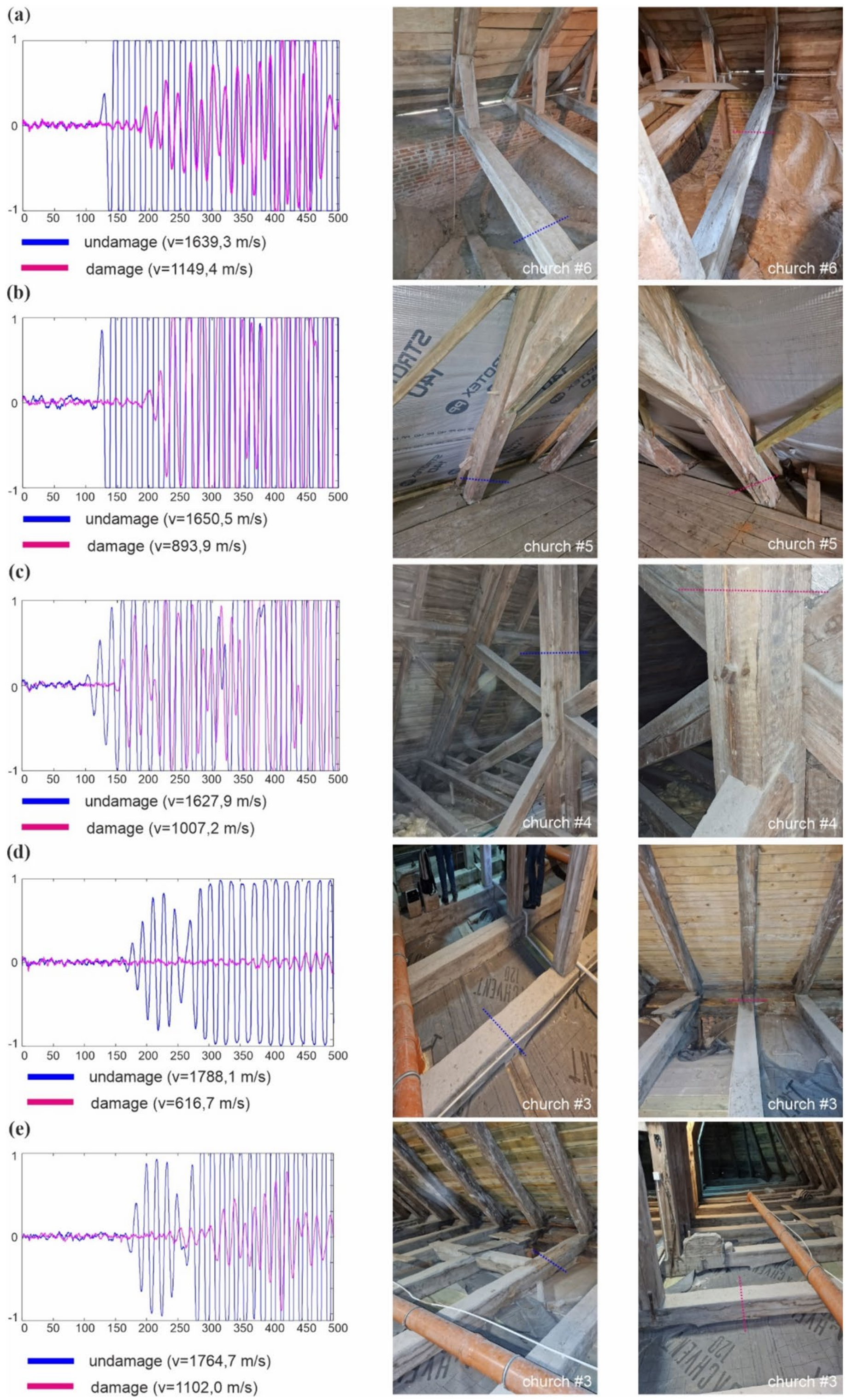

Fig. 12 Ultrasonic wave signals in undamaged and damaged elements with photos of the tested beams: **a**) Trutnowy (#6); **b**) Koźliny (#5); **c**) Pruszcz Gdański II (#4); **d**) and **e**) Kiezmark (#3)

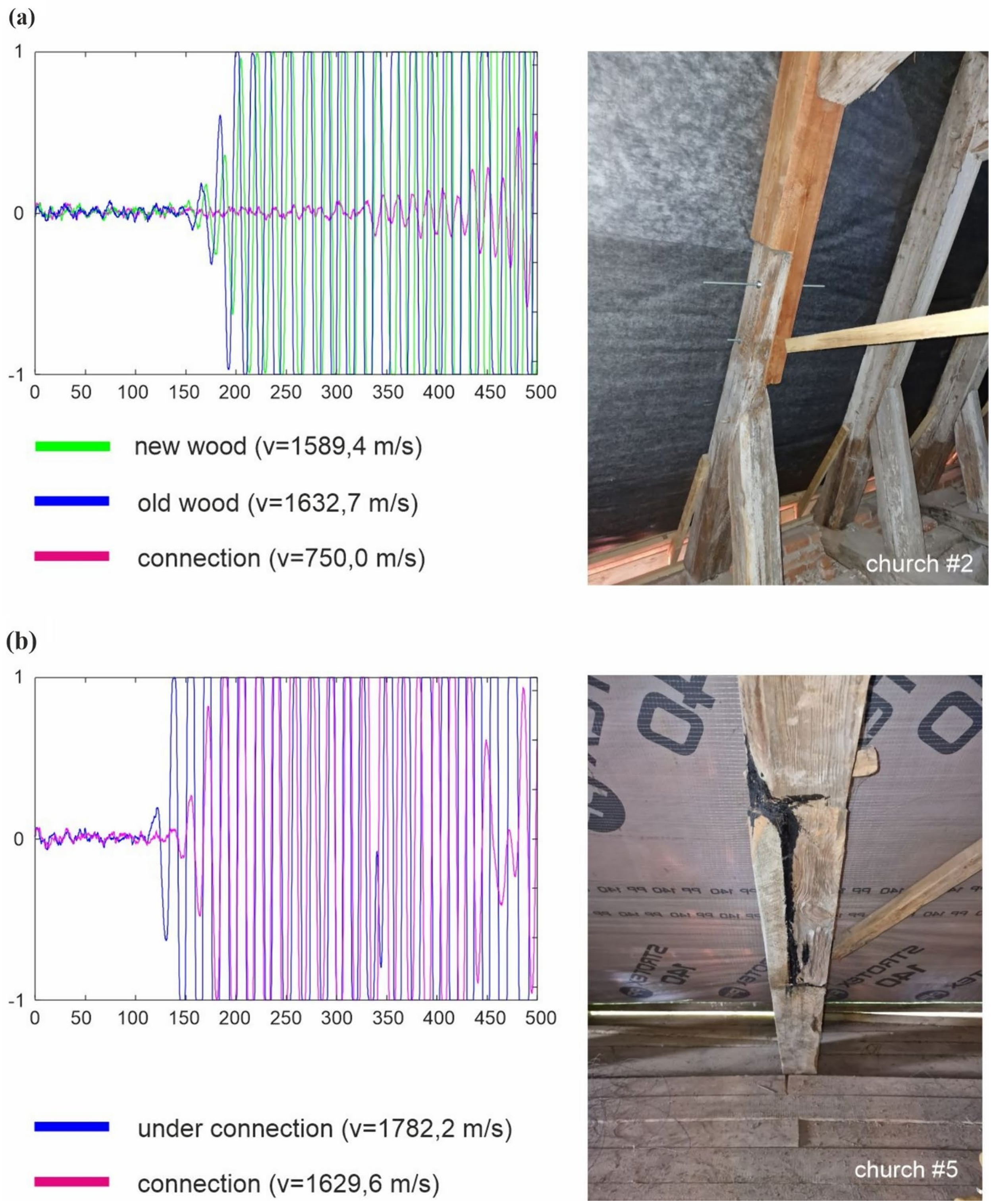

Fig. 13 Ultrasonic wave signals in wooden beam connections: **a**) Pruszcz Gdański I (#2); **b**) Koźliny (#5)

so this group of buildings is under the legal protection of the Provincial Conservator of Monuments. The moisture content of the roof trusses meets the requirements of the technical standards and consequently the risk of biological decay is low. Therefore, all the inspected roof trusses are in a good state of conservation.

The interdisciplinary research conducted in this article forms the basis for further investigations of churches in other regions, such as the East and South Vistula Delta. The GPR method is suitable for wooden elements and can be applied to similar objects.

Abbreviations

GPR Ground penetrating radar
TOF Time of flight

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Author contributions

TZ performed the case study and archival and historical query. JP and TZ performed the architectural survey, moisture measurements and described the outcomes from the field tests. MZ, MR and KG conducted NDT research and wrote out the results. All the authors participated in the discussion and data analysis. All the authors read and approved of the final manuscript.

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Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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