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On the current state of dovetail wall-corner joints in wooden Greek Catholic churches in Polish Subcarpathia with structural and sensitivity analyses

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On the current state of dovetail wall-corner joints in wooden Greek Catholic Churches in Polish Subcarpathia with structural and sensitivity analyses

This paper describes the current condition of some dovetail joints which form the wall corners of two Greek Catholic churches of wooden construction in Polish Subcarpathia. It also gives the historical background of the sacral architecture of that region. The two structures, which represent the same type of log corner joints are situated in Chotylub and Cewków. The buildings were examined e.g. for damage, wood moisture content, out-of-plane deviations and changes in the geometry of the walls. The study is based on in-situ examination and structural analysis of the joints. Finite element simulations of the statics of joints built of old, and mixture of old and new, wood are performed in order to show how the change of material properties affects their structural behaviour. Also a sensitivity analysis is performed to describe the effect on potential repairs that combining old damp wood with new and dry joint members might have.

Keywords: historic structure, log corner joints, dovetail, timber structures, Greek Catholic church structure, structural analysis, sensitivity analysis

1. Introduction

1.1 Polish Subcarpathia. The region and people

Polish Subcarpathia (Podkarpacie) is the north-western part of so-called Red Ruthenia (Lat. *Ruthenia Rubra*), i.e. the historical region now situated mostly within the borders of present-day Ukraine. Between the second half of the 14th century and the years 1772/1795 Red Ruthenia was part of the Polish-Lithuanian Commonwealth (the

Ruthenian Lands of the Crown) and from 1921 to 1939 part of the revived Republic of Poland.

The western parts of Red Ruthenia were populated, in various proportions, by Ruthenian (predominantly Greek Catholic), Polish (Roman Catholic) and Jewish communities. Interestingly, the Ruthenian and Polish communities, mostly rural, were often connected not only by neighbourly bonds but also by family ties. The way of founding churches is a reflection of such a social situation. The founders and benefactors of Greek Catholic churches in Red Ruthenia were usually Polish magnates and nobles who were generally Roman Catholics of both Polish and Ruthenian ethnicity, dignitaries and clergy of the Greek Catholic Church, and local communities supported by donors.

Subcarpathia owes its wealth of wooden sacral architecture to its colourful and complicated history. For centuries it constituted a cultural borderland between the Latin West and the Byzantine East (Czuba 2007).

When Poland was baptized by Rome ten centuries ago, it entered the Western European cultural sphere whereas the Christianization of Ruthenia, which took place under the auspices of Constantinople, brought it into the Greek Orthodox fold.

Diverse attitudes to Christian thought and its associated traditions and philosophy determined the different features of the cultural legacies left by the communities living here as much in the fields of art and sacral architecture as elsewhere. However, the increase in national aspirations in Eastern Europe at the turn of the 19th century as well as the First and the Second World Wars (1914-1918, 1939-1945) resulted in numerous tragic and frequently extremely bloody local conflicts, which led to political repressions against national minorities. The situation in Polish Subcarpathia was a good example of such a sequence of events - fighting between Poles and Ruthenians (now Ukrainians) ended only in the 1950s with compulsory mass resettlement of the latter from more unstable regions to the western and northern areas of post-war Poland or to the Soviet Union. Their depopulated and abandoned villages, sometimes almost obliterated, with ruined or desolate wooden churches were the landmarks of Polish Subcarpathia until the late 1980s.

1.2 Wood in Polish architecture

The first serious literature on wooden architecture in Poland – perceived as a part of cultural heritage – started appearing around 1910 (Z. Gloger 1907), but it was not until the second half of the 20th century that a significant number of books and articles were published devoted to the Greek Catholic churches of the present and former Polish territories of historical Red Ruthenia. The most comprehensive of these is the work of Ryszard Brykowski on the wooden Greek Catholic churches (Brykowski 1995), which also provides references to studies by Ukrainian (and Russian) architectural historians. There are other works which have also provided a valuable input here, see e.g. (Giemza 2016), (Zieliński 2015). Studies concerning historic timber churches in other regions of Europe, e.g. in Balkan countries have also been carried out (Mosoarca and Gioncu 2013).

Similarly to other regions of Eastern Europe, in the historical regions of Poland wood was the basic material for construction purposes until the second half of the 19th century. It is estimated that prior to 1960, 75-95% of rural and agricultural buildings were still constructed of wood in the eastern part of the country (Tłoczek 1980), (Prokopek 1976). In its long history, wooden architecture developed extensively into numerous local varieties and types of building.

However, the susceptibility of wood and wooden structures to natural decay and above all, man-made damage has brought about a steady but severe reduction in the number of historic timber buildings. At present the most important destructive factor seems to be the lack of preventive maintenance caused both by negligence and by insufficient funds available to owners and administrators for repairs or restoration (Kurek 2019). The next most common problem is the lack of well-qualified craftsmen (e.g. carpenters, thatchers etc.).

This situation has escalated dramatically, especially in recent decades. According to research carried out in the 1980s, there were approximately 10 000 buildings of various kinds constructed before 1850, namely 2000 churches and synagogues, 120 public buildings, 300 manor houses, 6000 dwellings and farmhouses as well as farm outbuildings and industrial facilities. The next 30 000 structures in age date back to 1850-1950. Newer, unfortunately incomplete, research from 2013 showed that there were only 5455 historic wooden buildings remaining, a lot of them in a deplorable condition (Ruszczyk 2007), (Szałygin 2013). Only a small number of constructions (mostly older churches) seem to be well preserved and relatively safe. Therefore, wooden architecture has practically disappeared from the landscape of Poland despite heroic and, from time to time, successful efforts undertaken by owners, local enthusiasts and conservation officers.

1.3 Structure of wooden Greek Catholic churches in Polish Subcarpathia

In the SubcarpathianVoivodeship, part of which comprises the north west of historical Red Ruthenia, there are approximately 118 wooden churches (mostly Greek Catholic but also Roman Catholic), built between the turn of the 16th century and the early decades of the 20th century ("The National Inventory of Historical Monuments - Subcarpathian Voivodeship"). Although preserved in varying conditions, the majority of them are still used for religious purposes, which portends well for their future.

Although it is known that the design of domed wooden Greek Catholic churches is adapted from Byzantine patterns, and despite there being a large amount of literature on the subject, the precise genesis of their forms remains a contentious issue. The design presumably developed during the reconstruction of Ruthenia in the 15th century after the Mongol and Tartar invasion. Their direct prototype might have been small Byzantine churches, whose architecture was translated into forms of wooden construction borrowed from local and gothic carpentry.

The majority of churches were longitudinal in plan. In accordance with the rules of the Eastern liturgy, the sequence of spaces was as follows (starting from the west) - a women's section (equivalent to the *narthex*), the nave (*naos*) and the sanctuary (separated from the nave with an *iconostasis*). There exists also a second, and less popular type of church, built on another central plan (e.g. a Greek-cross with an octagonal nave), see e.g., (Brykowski 1995). However, the two churches which are the subject of this paper represent the first type.

Two further rooms adjacent to the sanctuary were *pastophoria* – the *prothesis* and the *diaconicon*. Sometimes only one of them was built (as it is e.g. in Chotylub) and in some small churches they were not constructed at all. The nave and the sanctuary were topped with a dome and generally, although it was not the rule, the women's section was also covered with a wooden dome or at least a wooden vault as it is in Cewków and Chotylub. In some types of churches, the *narthex* was the basement of a tower.

1.4 Construction

Some degree of aptitude in woodworking was common so relatively low skilled craftsmen, as well as highly qualified carpenters, were employed for construction. This, together with the fact that the craftsmen were of various ethnicities, resulted in a variable quality of construction and a variety of styles.

Both of the churches in this study were constructed of various types of wood. Oak and larch were the most durable and resistant to moisture and precipitation and the most expensive. Other woods, such as spruce, fir, beech, linden or pine were also commonly used in construction. In older structures, the beams had a cross section of 50-60 cm, but since the 18th century thinner elements with a cross section of 20-25 cm have been used most often.

The churches always had log walls. There is no evidence of using any other technology in Red Ruthenia between the 16th and the 20th centuries. The most popular were hewn logs flattened on four sides. Yet here and there round logs (or semi-round D-logs) were also used, especially in cheaper structures made by less-qualified builders. The round logs were most popular in the eastern regions, e.g. in the Muscovite Rus′. Generally, it seems that the standard of work decreased over time as the traditions of fine gothic carpentry faded.

The foundations were usually made of single stones located mainly at the corners. Sometimes stone walls were constructed because brick foundation walls were only introduced in the 19th century. Single stones or loosely laid stone walls were, however, better than brick walls, because they allowed for the constant ventilation of low parts of buildings, i.e. ground beams and the floor, which prevented the wood from decaying. Interestingly, there exists evidence that in some earlier constructions palisades were used as foundations. Ground beams were generally wider and higher than wall logs. As moisture resistance was required, they were made of oak or larch wood. Wall logs had to be joined firmly and tightly so the beams were dowelled and insulated and weather stripped with dry moss or straw plaiting. The walls were crowned with cornice beams wider than the wall itself in order to protect it from moisture (dripping water.)

The four most popular types of joints (Nowak, Karolak, and Jasieńsko 2014) were used to fit together walls made of hewn logs (Figure 1):

(1) double notch,

(2) half notch (a square joint),

(3) “the lock”, also called a “German” or “Saxon” joint. It can be seen to the east of the Carpathian mountains, e.g. in Maramures, northern Romania, and is also known in Finland as *Hammasnurkkaa* or a “toothed” corner joint.

(4) full dovetail (“fishtail”) notch. (Half dovetail notch has probably never been used in this kind of carpentry.)

The joints were usually dowelled, but round logs were commonly connected with “saddle notch” joints which were not dowelled. Different kinds of joints were sometimes used in different parts of a wall. The double notch, probably the most archaic type, was used directly under deep eaves; the half notch was constructed above the eaves where the walls were to be planked or shingled. “The lock” was used for fitting ground beams among other things. The full dovetail notch probably came into common use in the 18th century. It seems, however, that where the quality of craftsmanship was high a single type of joint was used in the entire structure (Phleps 1942).

1.5 The framework of the study

The paper deals with the analysis of the current state of dovetail wall-corner joints in wooden Greek Catholic Churches in Polish Subcarpathia. Two structures representing the same type of corner joint situated in Chotylub and Cewków are considered in the study. There have been many articles and books on the history and architectural issues of Greek Catholic churches in Polish Subcarpathia (see e.g., (Kurek 2019), (Nowak et al. 2018) especially those that became a part of UNESCO World Heritage List (Wrana and Fitta-Spelina 2015; Gleń 2015; Czuba 2007). However, none of them described the technical, mechanical and conservational problems of wall-corner joints for this group of preserved objects. The structures described in this study are also in their original condition and thus more suitable for study than others that have already been renovated or rebuilt for different reasons.

The necessary maintenance and repair of old structures is often performed using structural elements made of new wood (see e.g. (Fajman and Máca 2018), (Kunecký et al. 2018)) since suitable old wood is in short supply. This usually means that the new elements have different material properties, such as strength, modulus of elasticity and moisture content, from those made of old wood (see e.g. (Nowak, Jasieńko, and Hamrol-Bielecka 2016), (Sonderegger et al. 2015)). This may affect the structural behaviour of the joints after repair. Even the use of old material in repairs may result in changes in structural behaviour of the timber joints as its stiffness and strength strongly depend on its humidity (see e.g., (Pestka et al. 2018)). This paper also presents some numerical results from a structural analysis performed on short-corner dovetail joints which are typical of the churches studied. The joints are built of logs of different kinds of wood, old and new as well as damp and dry. In the study the authors attempt to show how the use of old or new wood in a repair process affects the mechanical performance of a timber log joint. The material properties of old wood are not easy to assess without destructive tests which are practically impossible to apply to a historic structure (Morales-Conde and Machado 2017). Therefore, a sensitivity analysis is applied here to evaluate the influence of the variation of those parameters on the mechanics of the joint.

2. Case study. Analysis of selected historic structures

The two churches selected for the field test; in Cewków (Figure 2) and in Chotylub (Figure 3) are registered in the National Inventory of Historical Monuments ("The National Inventory of Historical Monuments - Subcarpathian Voivodeship"). They are located in the Subcarpathian Voivodeship and were built in the 19th century (Cewków in 1842, Chotylub in 1888.)

The churches were selected according to these four criteria:

(1) Authenticity of construction and materials. In archival sources is no information about the renovation or maintenance of church walls (Giemza 1997),·(Zawałeń 1997). The churches have not changed since they were built so they are authentic constructions from the 19thcentury.

(2) Both churches have log walls without shingle siding, which makes it possible to measure their physical and geometrical properties.

(3) Both churches were built in the 19thcentury.

(4) Curators granted permission to conduct this research.

A full dovetail notch (Figure 1) was made using a template (Figure 4), where the basic parameters are the height (*h*) and width (*b*) of the beam. The pattern was a thin trapezoidal board with a scale, where the graduation (*a*) was equal to 1/12 of the beam height. The dimensions of the template are as follows: the lower base is 1/3 of the beam height, the middle part is 1/4 of the beam height, and the upper base is 1/6 of the beam height. The template height is equal to double the width of the beam. Before the wall assembly started, the beam ends were cut out accordingly using the template. They were then stacked one on top of the other to form a wall (Kopkowicz 1958).

The assessment of the condition of both churches was made on the basis of:

- *a measured survey* (Cruz et al. 2015) - the on-site verification undertaken in August 2018, during which the following parameters were measured: the cross section of the timber beams, the humidity of the construction material, the angles of the walls inside the churches and their out-of-plane vertical deviations,
- *a desk survey* (Cruz et al. 2015)- the analysis of historical and conservation documentation regarding renovations and construction works from the following

archival sources: The National Heritage Board of Poland in Rzeszów, Provincial Office of Monument Preservation in Przemyśl and the Museum of the Eastern Borderland in Lubaczów,

- interviews with guardians of both churches,
- photographic documentation showing the current condition of construction elements.

The walls inside and outside the churches had no shingle siding and were not covered with polychrome or other finish. Furthermore, there was no equipment or sacred art close to the walls.

The humidity level was measured by a pin-type moisture meter. The device chosen for the measurement was HYGROPEN® Moisture Meter manufactured by TANEL (Gliwice, Poland), a universal, state-of-the-art, electronic device for measuring moisture content in different kinds of wood, and building materials. It can also measure air humidity and temperature. The measurement of wood moisture content allows compensation for wood type and temperature. During the measurement five timber beams, which were close to each other, were checked in every corner. The final result of wood humidity was calculated as the arithmetic mean of the five values read.

2.1 The church in Cewków

The church in Cewków is dedicated to St. Dmitri and was built in 1842. Its construction was initiated by Father Antoni Byliński. It was built by Werchowycz, a carpenter, on the site of a previous 17th century church. After 1945 all Ukrainians were resettled and due to this the church was abandoned and lost its religious function. The building, which is located in the village centre and by the local road, was surrounded by trees in the past. Currently the church (Figure 2) is not in use (Zieliński 2015).

The foundations of the church are made of brick and stone and the dovetail log walls are constructed of softwood. There are remnants of the old shingle siding on the external walls. The rafter framing of the church is of the collar-beam type and the roof is covered with galvanized steel sheets. The entrance to the church is through a porch supported on six columns. The church is longitudinal in plan and consists of three main parts: the women's section (the *narthex*), the nave and the sanctuary. On both sides of the sanctuary there are two additional rooms: the treasury and the sacristy (Figure 5). The dominant feature of the church is the octagonal roof situated over the nave and topped with an onion-shaped dome(Giemza 1997).

The current condition of the walls is good. The church has log walls with dovetail notches (Figure 6). The walls are made of wood beams with a rectangular cross-section of 21 x 30 cm. No significant moisture was found and the humidity of the corners remains at 12.2% on the south side and at 16.2% on the north side (Figure 7). The horizontal damp proof course in the foundations is not broken and the roof covering is rain-tight. There are some visible longitudinal cracks and a few transverse cracks in the beams. There also exist some signs of damage caused by insects and some minor local cavities in the wall structure (Figure 6). The vertical out-of-plane deviations of the walls are relatively small – from 0.46 cm to 0.53 cm. The internal angles have not changed since the church assembly - deformations inside and outside the building amount range from 88.6° to 91.5°. The same is true for the whole construction which has never been rebuilt and hence there are no additional loads on the walls. Moreover, the gravity ventilation of the facility is intact. At present the church is not in use but local authorities have designated a person responsible for taking care of it. Due to this the building is closed and protected against vandalism and the area around it is well kept.

2.2 The church in Chotylub

The church dedicated to the Protection of the Most Holy Mother of God (*Theotokos*) in Chotylub was built in 1888 on the site of a previous 17th century church. The initiator of the construction work was Father Piotr Gissowski. After the Second World War the Ukrainian population was resettled. In 1947 the church was taken over by the Roman Catholic Church – the Parish of Cieszanów. At the turn of the 1960s and 1970s the facility underwent restoration works. A new roof was made and the old windows were replaced with new ones. In 1986 a vestibule was added to the church. In 2001 the construction of a new church in Chotylub was completed and since then the old one has not been in use (Zieliński 2015).

The church is located in the village centre, on a hill by the local road. It is surrounded by rural buildings. The church foundations are made of crushed stone and lime mortar. Dovetail log walls are made of fir wood and have no wood siding so the log construction is visible inside and outside the church. The construction of the roof is of the rafter-collar type and the roof is covered with galvanized steel sheets. The church is longitudinal in plan with the entrance through the vestibule (Figure 8). The church is tripartite and consists of the women's section, the nave and the sanctuary with the sacristy. The dominant feature of the church is the dome situated above the nave and topped with an iron cross (Zawałeń 1997).

The current condition of the walls is good. The church has log walls with dovetail notches (Figure 9, 10). The walls are made of wood beams with a rectangular cross-section of 15 x 21 cm. No significant moisture has been found and the humidity level of the corners remains at 12.5% on the south side and 17.8% on the north side (Figure 11). The horizontal damp proof course in the foundations is not broken and the roof covering is rain-tight. There are some visible longitudinal cracks (Figure 10) and a few transverse cracks in the beams. There are also some signs of damage caused by insects and some minor local cavities of the structure. The out-of- plane vertical deviations of the walls are relatively small - from 0.15 cm to 1.2 cm. The internal angles have not changed since the church assembly - deformations inside and outside the building range from 88.9° to 90.5°. The same is true for the construction as a whole which has never been rebuilt and hence there are no additional loads on the walls. Moreover, the gravity ventilation of the object is intact. At present the church is not in use but local authorities have designated a person responsible for taking care of it. Owing to this the building is closed and protected against vandalism and the area around it is well kept.

3. Structural and sensitivity analysis of dovetail corner joints

3.1 Structural analysis of dovetail corner joints

Damage to the wooden structure may require some logs and joints to be replaced, which can be done with new wood or old, if available. This implies a change of material properties of neighbouring logs (see e.g., (Drobiec and Pająk 2018)) and may affect the mechanical behaviour of the joint. This may occur in particular, when the moisture level of the wooden members significantly differs (see e.g., (Ormarssonand, Petersson, and Dahlblom 2000)) or new and old wood is mixed in the joint, especially when the new wood is dry and well prepared for construction and the old wood is degraded and damp. This is a common problem in old structures (Wikłacz 2018).

This motivated the authors to perform a study of the influence of a change in the material properties of joint members on the mechanical behaviour of dovetail corner joints. Numerical models of dovetail corner joints containing 5 logs (Figure 12) representing the joints observed in the churches were defined by means of the finite element method. This methodology is used in assessments of the state of historic structures for timber buildings (see e.g., (Armesto et al. 2009)) as well as masonry ones (see e.g., (Ayensa et al. 2015)). As future laboratory experiments at a scale of 1:2 are planned, the geometry of the joints was created based on the studies of (Kopkowicz 1958) at a scale of 1:2. The logs were 0.7 m long. The cross-sectional dimensions of a single log were 75 x 135 mm.

Geometrically nonlinear static analysis with the updated Lagrangian approach and Newton iterations was performed using Abaqus/Standard software. The numerical models were discretised by 123 372 stress/displacement 8-node linear hexahedral solid elements with 3 degrees of freedom in each node, reduced integration and hourglass control. The finite element mesh was regular (Figure 12) with an approximate element size of 8 mm. The surface-to-surface contact discretisation was applied with the finite-sliding tracking approach. In the Abaqus/Standard software configuration, normal contact behaviour is set to “hard” with separation after contact allowed. The tangential behaviour uses the penalty friction formulation, (Wriggers 2006) with the coefficient of friction between logs equal to 0.2 following (McKenzie and Karpovich 1968) and (Blau 2001). In this type of analysis, when surfaces are in contact, any contact pressure can be transmitted.

This model has some limitations such as the fact that there are no imperfections assumed of the surfaces in contact assumed in the model, although in old timber structures the contact between logs cannot be ideal due to the surface roughness and geometrical irregularities. The microscopic irregularities (roughness) are captured by the friction coefficient but macroscopic irregularities (change of geometry) that may cause residual stress and local stress concentration are not considered in this study and will be investigated later.

Three different cases of the joint material were analysed: old wood, new wood and old joints where only one log has been replaced with new wood. The orthotropic elastic material model (see e.g., (Oudjene and Khelifa 2009)) was applied since the material properties of wood vary with the direction of fibres. The properties of pinewood were used since they were available for both new and old wood (internal report of Grant No. 2015/17/B/ST8/03260). The mean value of the Young's modulus E_L was experimentally determined to be 11.95 GPa in case of dry wood (humidity 7-14%) and 5.38 GPa for damp (humidity 24-40%) old wood according to laboratory tests of new pinewood and 19th century damp pinewood whose age was determined on the basis of dendrochronological dating. The E_L is a longitudinal modulus of elasticity (along the direction of the surface of each layer of the fibres). The moduli of the other directions (radial –R and tangential – T) were calculated in relation to E_L according to the formulae $E_T / E_L = 0.068$, $E_R / E_L = 0.102$, $G_{RT} / E_L = 0.05$, $G_{TL} / E_L = 0.046$, $G_{LR} / E_L = 0.049$, and appropriate Poisson ratios were determined as $\nu_{RT} = 0.469$, $\nu_{TL} = 0.024$, $\nu_{LR} = 0.316$ according to (Green, Winandy, and Kretschmann 1999) and described in (Kłosowski et al. 2018). All material parameters used in the analysis are summarised in the Table 1, where G is a shear modulus and v Poisson ratio.

Table 1. Material parameters of pinewood

Dry new wood – humidity 7.2%								
E_L [GPa]	E_R [GPa]	E_T [GPa]	G_{LR} [GPa]	G_{LT} [GPa]	G_{RT} [GPa]	ν_{LR} [-]	ν_{LT} [-]	ν_{RT} [-]
11.95	1.219	0.812	0.585	0.549	0.0597	0.316	0.0236	0.469
Old wet wood – humidity 24%								
E_L [GPa]	E_R [GPa]	E_T [GPa]	G_{LR} [GPa]	G_{LT} [GPa]	G_{RT} [GPa]	ν_{LR} [-]	ν_{LT} [-]	ν_{RT} [-]
5.4876	0.559	0.373	0.268	0.252	0.0274	0.316	0.0236	0.469

Excessive deformations of wooden beams in the joints are the factors that may cause damage to the structure so the numerical calculations were performed with boundary conditions reflecting horizontal displacement of the logs (along the logs longitudinal axis). The outside cross-sectional faces (75x135 mm) of the three logs forming one side of the joint were fixed. This means that in the numerical model all three degrees of freedom of each node of the logs cross-sections were fixed while the other two logs were displaced along the *y*-direction by u_y = 5 cm in the global system of coordinates of the model (the local *z*-direction, see Figure 12) resulting in a change of the corner angle. The applied displacement is greater than that observed in the churches investigated but in this way the trend in the mechanical behaviour is highlighted. The bottom surfaces of most bottom logs and the top surfaces of most top logs were fixed in the global *z*-direction (vertical) as shown in Figure 12 to reflect the effect of the foundations and the rest of the wall.

h and *p* type convergence analysis was performed by refining the mesh up to 740 190 linear finite elements and using 180 325 2nd order elements. The total number of degrees of freedom in the three models discretised by linear elements, linear refined elements and quadratic elements was 408 156, 2 430 858 and 1 254 384, respectively. The maximum difference in the resultant force obtained did not exceed 1.5% which ensures the convergence of the numerical solutions presented.

Significant deformations of the logs cause high stress on some contact surfaces. Large displacements can also expose the inside surfaces of the timber joints to environmental and biological degradation. The area of stress concentration area was therefore analysed and compared in the models considered. The principal stress and resultant force R_y were the significant quantities in the analysis. The maximum and minimum principal stress maps covering the three studied cases are shown in Figures (13-14). The comparison of the calculated values of the stress *S* and force R_y corresponding to the maximum lateral displacement u_y of each joint in each case studied is summarised in Table 2. The maximum principal stress is almost doubled when one member of an old joint (S_{max} = 12.31 MPa) is replaced with one made of dry new wood (S_{max} = 22.82 MPa).

The minimum principal stress differs less and it is equal to S_{min} = 14.66 MPa in the case of old wood and S_{min} = 15.87 MPa with one new log in the joint. Under the applied displacement the stress concentration does not exceed the ultimate stress identified and described by (Pestka et al. 2018) as 71.9 MPa for dry wood . Moreover it appears is concentrated in the new log where the ultimate stress is higher than in the case of the old wood, which according to (Pestka et al. 2018) is 39.6 MPa. However, it indicates how such a replacement may affect the stress concentration in the joint. The force necessary to move the logs by 0.05 m, along their longitudinal axis is R_y = 1.99 kN in the case of the old joint, R_y = 4.42 kN in the new joint and R_y = 2.20 kN in the old joint with one log exchanged for new wood.

Table 2. Numerical results of stress and force in joints under applied displacement of u_y = 0.05 m

	Joint made of old, damp wood – 5 logs	Joint made of new, dry wood – 5 logs	Joint made of mixed wood – 4 old, damp logs, 1 new, dry log
S_{max} [MPa]	12.31	27.34	22.82
S_{min} [MPa]	14.66	32.62	15.87
R_y [kN]	1.99	4.42	2.20

To assess the influence of wood stiffness change, which can be caused by moisture, ageing or a degradation process (see e. g., (Cavalli et al. 2016), (Jasieńko, Nowak, and Hamrol 2013)) on joint behaviour, a sensitivity analysis has been performed.

3.2 Sensitivity of the behaviour of dovetail corner joints to the change of properties of the wood

The material properties of wood in old historic structures are usually unknown since destructive tests on such buildings are mostly unavailable. Thus a sensitivity analysis is a way to assess how changes in these properties affect the joint's structural behaviour. Since the material parameters in the assumed model depend on the Young's modulus of the wood, the longitudinal modulus E_L has been taken as the parameter E. A sensitivity analysis of the reaction force in the joint due to the variation of the modulus of elasticity of the old and new wood was performed.

Owing to the local character of the sensitivity analysis that we carried out, we do not consider the material behaviour throughout the whole range of strain but only near the actual state of stress. Here, the linearization reveals the proper results. The range of variation of E was narrowly focused around the basic value of E_L = 5.487 GPa in the case of old, damp wood, and around 11.95 GPa in the case of dry wood. The analysis is carried out following the method presented by (Chen and Ho 1994). In this method, the derivative is calculated directly from the definition using the discrete results of finite element analysis (see also (Iwicki 2007)) according to central difference equation (1).

$$\delta R_j = \frac{R(E+\delta E)-R(E-\delta E)}{2}, \tag{1}$$

where E is the Young's modulus, δE - variation of the Young's modulus, which takes value of 0.5% of E in the numerical analysis, R is the resultant force at the j-end of the joint and δRj is the variation of Rj.

This can be transformed by multiplying the numerator and denominator by δE in (2) and dividing by Rj in (3)

$$\delta R_j = \frac{R(E+\delta E)-R(E-\delta E)}{2\delta E}\delta E \tag{2}$$

$$\frac{\delta R_j}{R_j} = \frac{R(E+\delta E)-R(E-\delta E)}{2\delta E}\frac{1}{R_j}\delta E \tag{3}$$

where part of the formula defines the sensitivity coefficient (4)

$$W_{jE} = \frac{R(E+\delta E)-R(E-\delta E)}{2\delta E} . \tag{4}$$

After these transformations we obtain formula (5) representing the relative value of the variation of resultant force in relation to the relative change of the Young's modulus

$$\frac{\delta R_j}{R_j} = \frac{R(E+\delta E)-R(E-\delta E)}{2\delta E} \frac{1}{R_j} \frac{\delta E}{E} E = \overline{W}_{jE} \frac{\delta E}{E} \tag{5}$$

Defining the relative coefficient of sensitivity of the resultant force with respect to the variation of the Young's modulus $\overline{W}_{jE}$ as follows:

$$\overline{W}_{jE} = \frac{R(E+\delta E)-R(E-\delta E)}{2\delta E\, R_j} E \tag{6}$$

And substituting into (1), we obtain

$$\frac{\delta R_j}{R_j} = \overline{W}_{jE} \frac{\delta E}{E} . \tag{7}$$

Writing $\frac{\delta R_j}{R_j} = \delta \overline{R}_j, \quad \frac{\delta E}{E} = \delta \overline{E}, \quad \overline{W}_{jE} = W_{jE} \frac{E}{R_j}$ yields

$\delta \overline{R}_j = \overline{W}_{jE} \delta \overline{E}$, where $\overline{R}_j$ and $\delta \overline{E}$ are appropriate relative values. (8)

Two types of joint were considered in the study. First it was assumed that the joint is made of dry wood. In this case the Young's modulus does not differ much between old and new wood according to laboratory tests (internal report of Grant No. 2015/17/B/ST8/03260). The Young's modulus in the analysis varies from 11.233 GPa to 11.95 GPa. In the case of a parametric change of the material properties of the whole joint, the change of the reaction force is almost linear so the sensitivity is represented by a constant function (Figure 15). Here it will be represented by the relative sensitivity coefficient which is close to 1. In the second variant, the joint was built of old, damp wood but one of the five logs had been replaced with a new one. The elasticity moduli of the old logs (5.38 GPa) and the new ones (11.95 GPa) in the same joint then differ significantly. In this variant some variations was assumed of the Young's modulus of the old wood, since the material properties in this case may not be easy to identify. The range of E_L in the analysis is 5.218 GPa to 5.514 GPa. In this case the sensitivity of the reaction force R_y due to the change of the stiffness of the old wood is nonlinear, and the value of the relative sensitivity coefficient changes with the change of E_L as shown in Figure 16. It increases as the stiffness of the old wood decreases. It therefore also grows with the difference between the two Young's moduli.

4. Conclusions

The wooden churches that have been preserved in Cewków and Chotylub are elements remnants of the local cultural heritage as well as the carpentry traditions of Polish Subcarpathia. They exemplify the durability of wooden structures which, if properly maintained, can survive for hundreds of years.

The dovetail walls examined in both churches are in good condition due to several factors. First of all, there is no destructive impact of water. Wooden elements are not exposed to it, because neither the horizontal damp proof course of the foundations, nor the roofing are damaged. The humidity of the log walls remains in the range of 12.2% - 17.8%. This is the correct value for construction elements in accordance with PN-EN 1995-1-1: 2010 (NA.8.1– National Annex to Eurocode 5 – EN 1995-1-1: Design of timber structures, Part 1-1: General- Common rules and Rules for buildings, point 8.1 – Limit of timber humidity for structural elements). The humidity level for structures protected against moisture should not exceed 18%. Furthermore, there is no accumulation of moisture inside the churches, because the natural air circulation has not been disturbed there.

It is worth noting that neither of the churches have ever been rebuilt, and hence there are no additional loads that could exert a negative impact on the structure and statics of the entire building. Cracks and minor out-of-plane vertical deviations (ranging from 0.15 cm to 1.2 cm) are the natural result of ageing and working of wooden elements. There are small cavities which result from insects' activity and local biological corrosion.

The environment also contributes to the preservation of these monuments in good condition. Both churches are located in a rural area. In their surroundings there is not much air pollution or acid rain that could result in significant damage to the wood. Moreover, the churches are not exposed to additional vibrations caused by high traffic or industrial processes.

The churches are no longer used for religious purposes but local custodians are still in charge of them. The buildings are closed and thus protected against theft and vandalism. Constant supervision and regular minor repairs greatly contribute to preserving the monuments in good condition. The churches still require conservation and protection against insects and biological corrosion.

The structural elements analysed demonstrate high load bearing capacity, which allows them to be reused during renovation works. Such proceedings are absolutely correct from the point of view of the conservation doctrine, as remarked e.g., by (Kunecký et al. 2018) and (Drobiec and Pająk 2018), where the most important goal is to preserve as much original construction as possible. However, the mechanical analysis of the dovetail joints made of old damp and new dry woods showed how the change of material properties affects the stress in the joint and the force needed to displace the logs. It shows that even such a minor change as the exchange of one log in the joint causes the force to increase by more than 10% which means that the joint becomes less compliant to horizontal displacements. This should not be observed when the old wood is dry, as in the churches considered, since the difference in the elasticity modulus as well as the ultimate stress is relatively small. As it is shown in the study the exchange of logs in a joint constructed of old but dry wood does not change its mechanics significantly. The sensitivity analysis of the horizontal force displacing the logs due to the change of the elasticity of the wood shows that exchanging some existing elements of the old wooden structure can significantly affect the structural behaviour of the building, especially when the existing parts are made of old and damp wood, while the new material is dry and so has higher stiffness. Thus when repairing a very damp and damaged joint attention should be paid to the remaining elements and their state. Perhaps even the exchange of damp elements that seem to be in a good state could be better for the overall conservation of the structure than using the new ones. Old dry wood having similar stiffness to new wood can be reused in the conservation process in a similar way to new wood and it may not change the joints mechanics so much. However, repairs of old wet structures with old but dry wood may significantly affect their post repair behaviour.

Attention should therefore be paid to all these observations when planning repairs using old and new wooden beams.

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Declaration of interest statement

No potential conflict of interest was reported by the authors.

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Figure captions

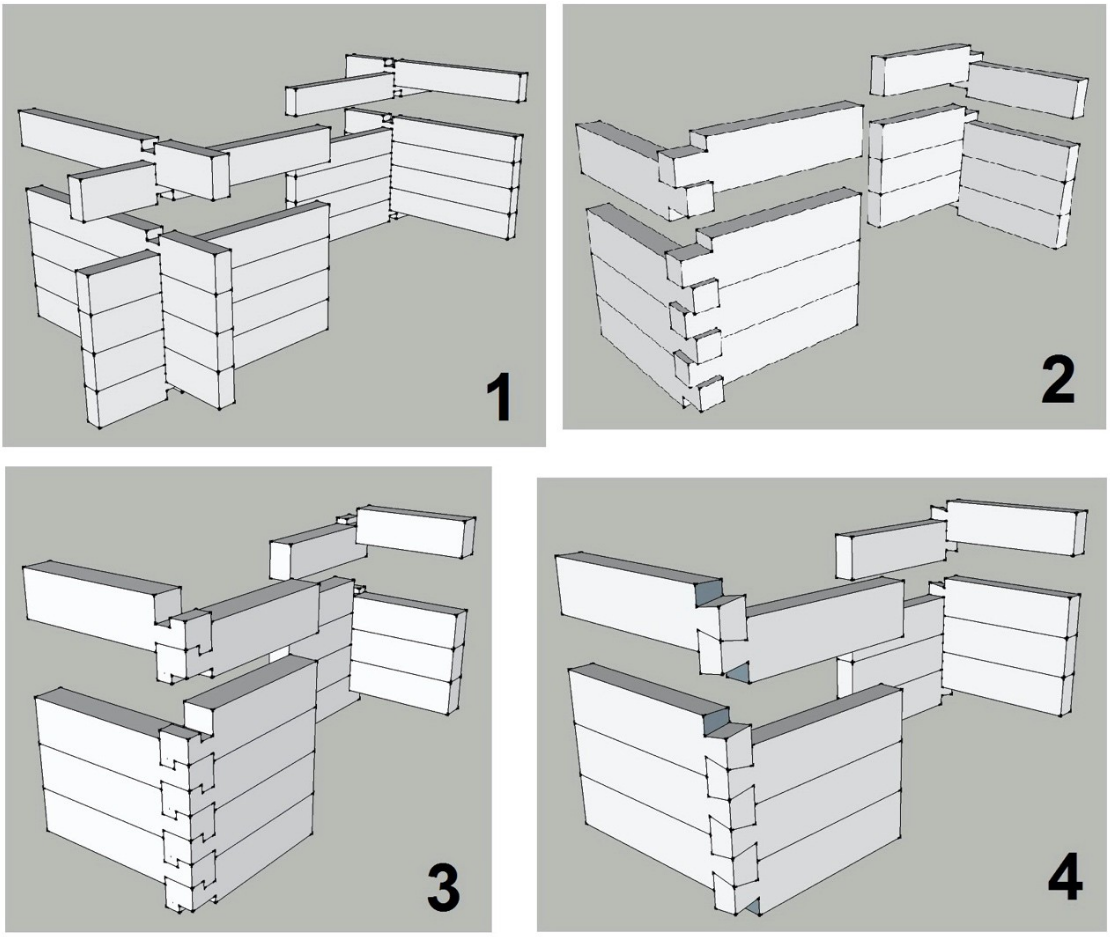

Figure 1a. Four types of carpentry joints (outside and inside).

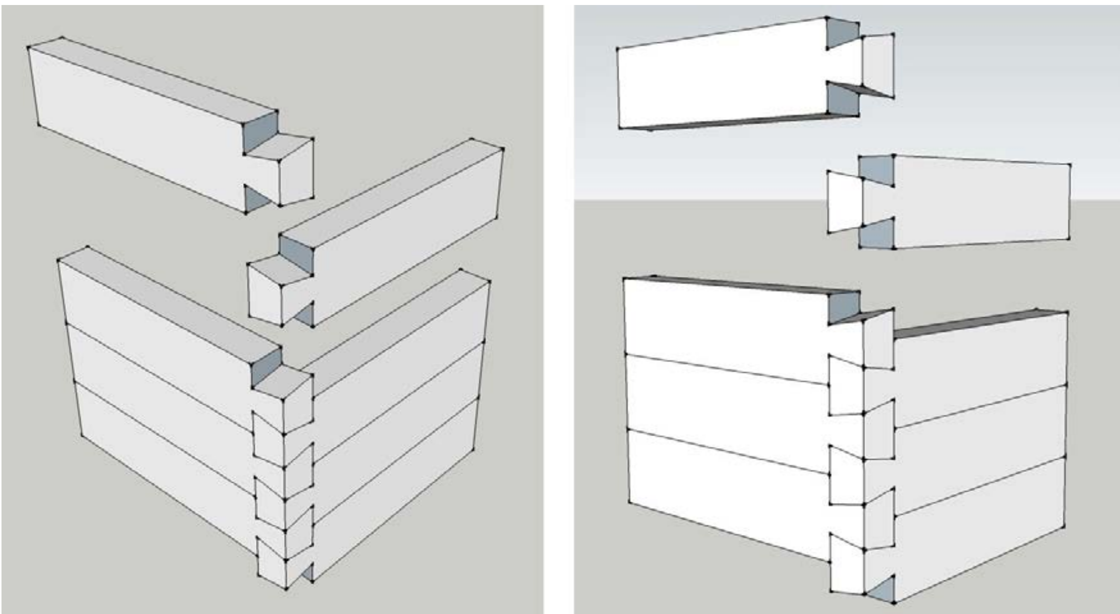

Figure 1b. Dovetail notch – detail.

Figure 2. The Church in Cewków.

Figure 3. The church in Chotylub.

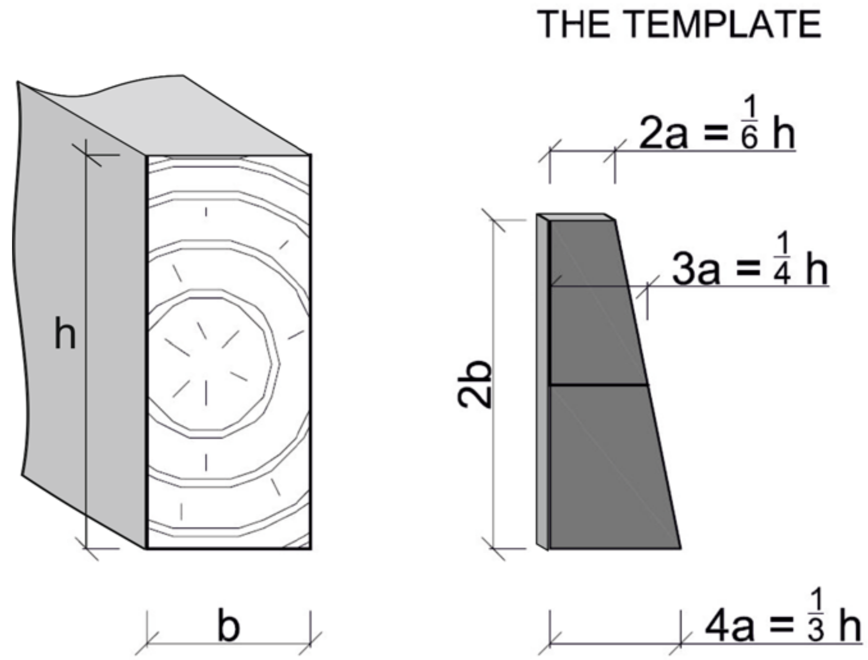

Figure 4. Template of the dovetail joint and its basic parameters

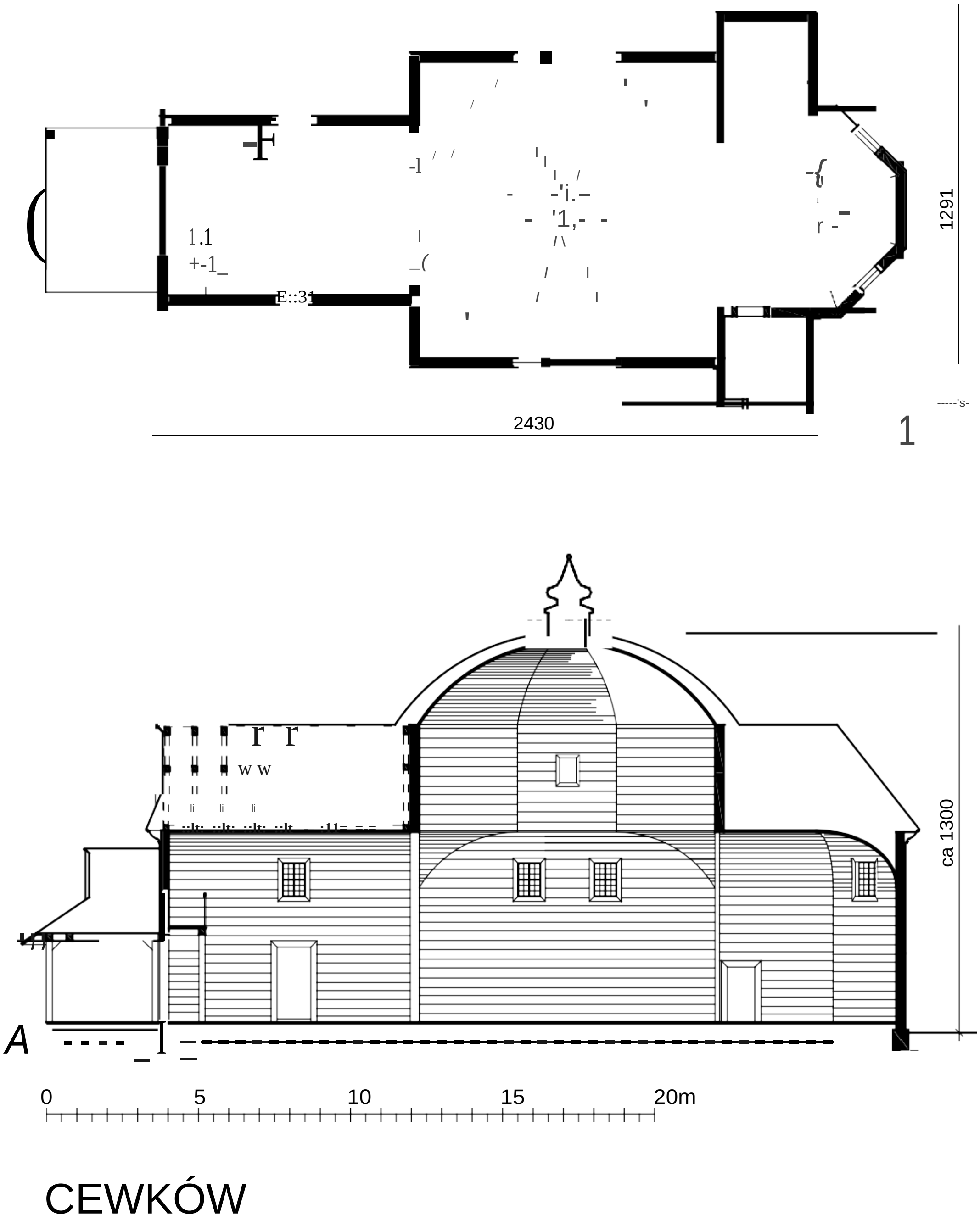

Figure 5. Longitudinal cross-section and plan of the church in Cewków.

Figure 6. The church in Cewków: wall corner, longitudinal cracks in the wall, visible cavities in the wall.

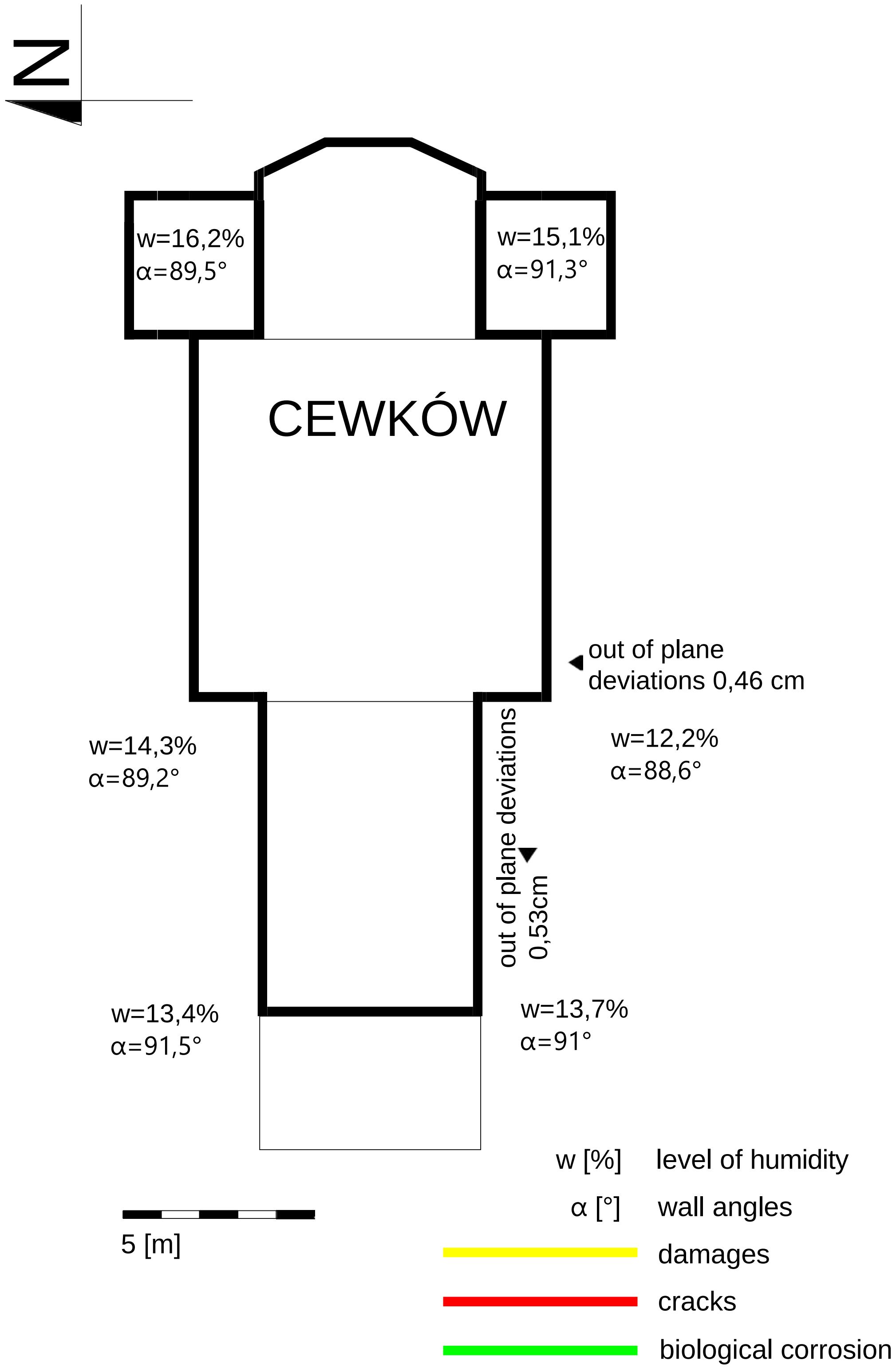

Figure 7. Results of measurments in the church in Cewków. The plan shows the level of humidity, angles, the scale and direction of deviations. Colors denote places where damage, cracks and biological corrosion occur.

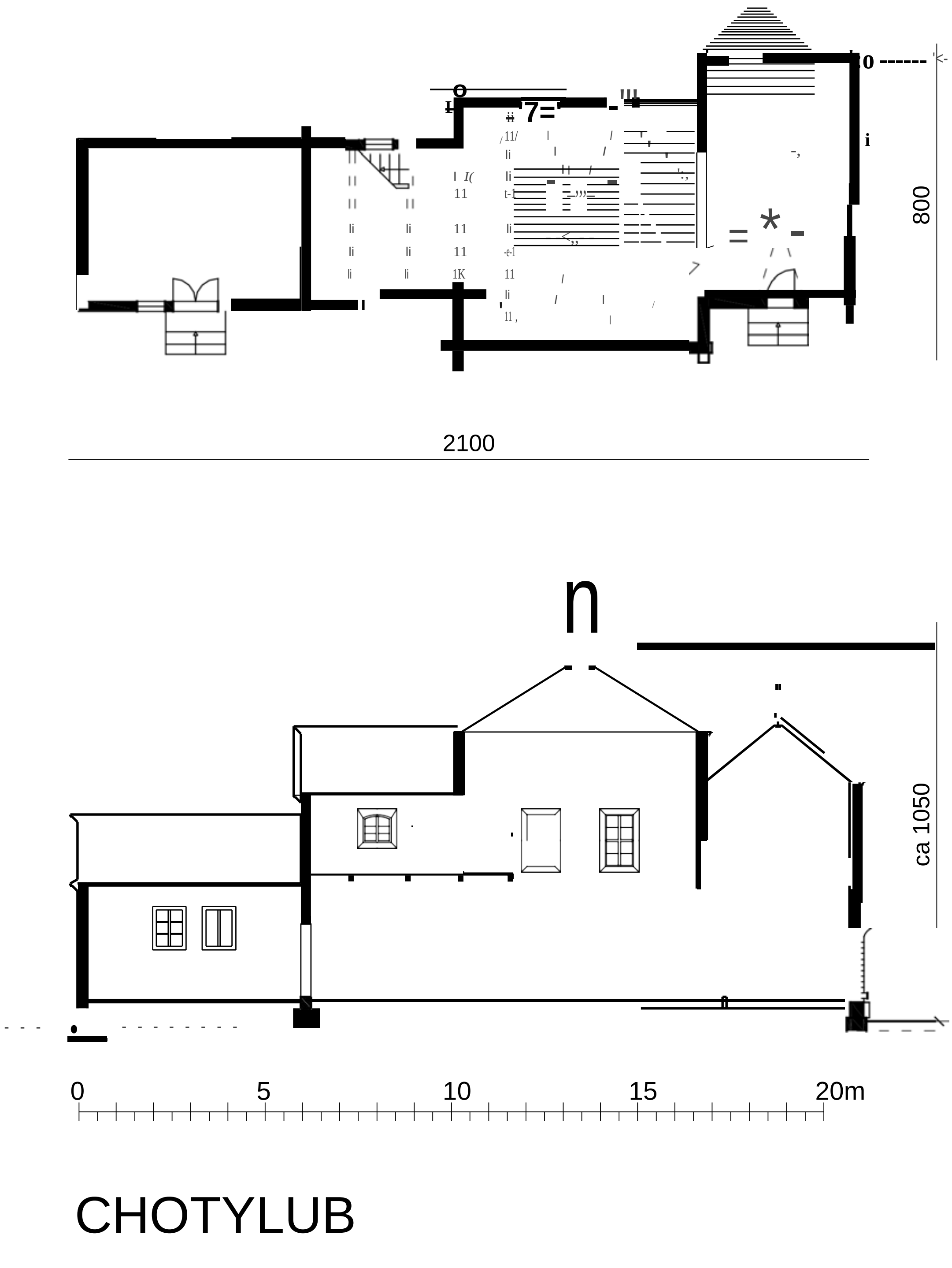

Figure 8. Longitudinal cross-section and plan of the church in Chotylub.

Figure 9. Current condition of log walls with dovetail notches in Chotylub outside and inside.

Figure 10. Current condition of log walls with dovetail notches in Chotylub: cracks in log walls in and contemporary repairs of the eaves roof.

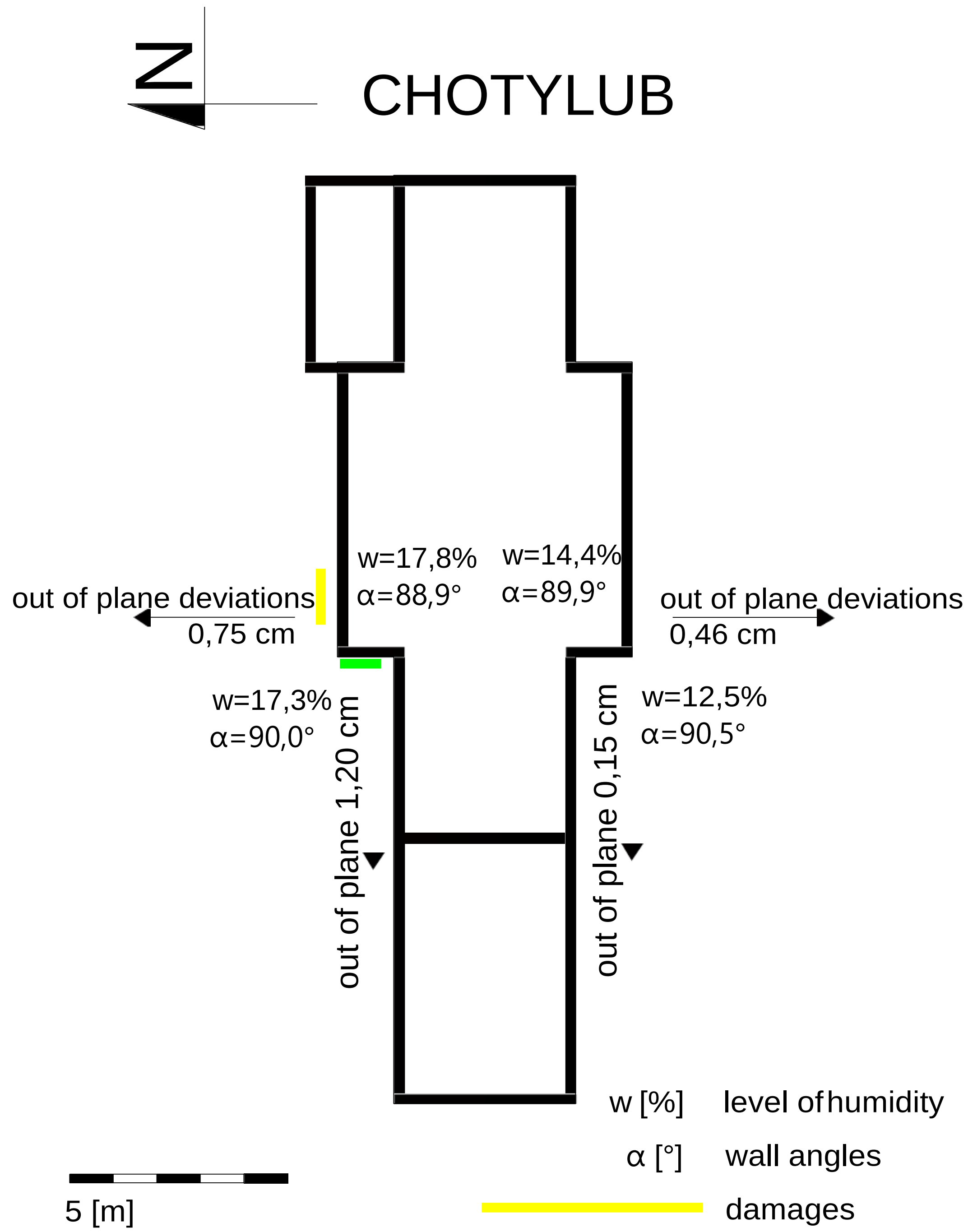

Figure 11. Results of measurments in the church in Chotylub. The picture shows: the level of humidity, the angles and the scale and direction of deviations. Colours indicate places where damage, cracks and biological corrosion occur.

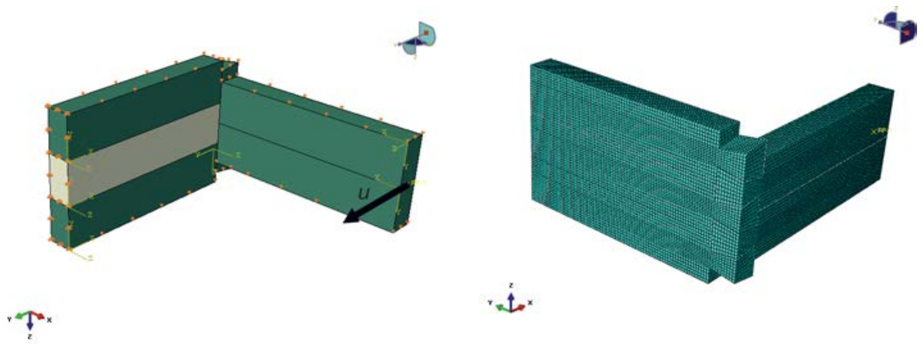

Figure 12. Dovetail log joint model for FEM analysis, boundary conditions and finite element mesh.

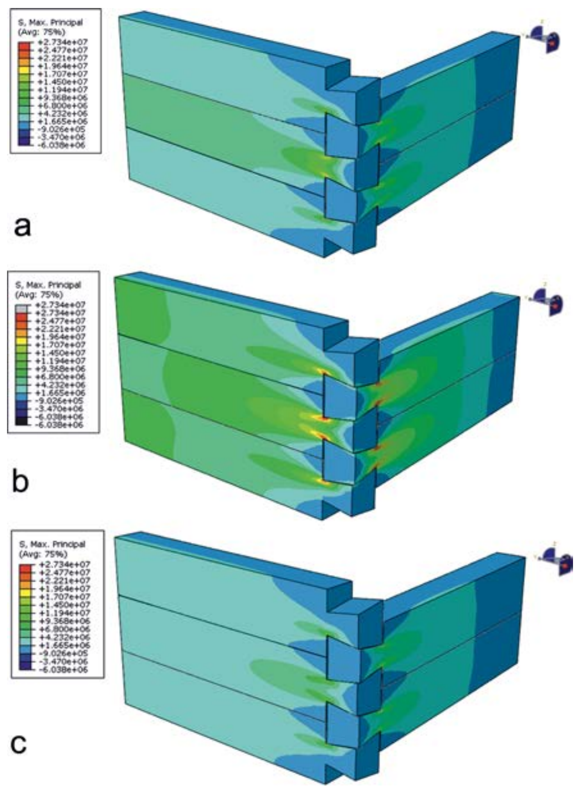

Figure 13. Maximum principal stress in the joint where a) one log has been exchanged into a new wood; b) all logs are made of the same new wood; c) all logs are made of the same old wood.

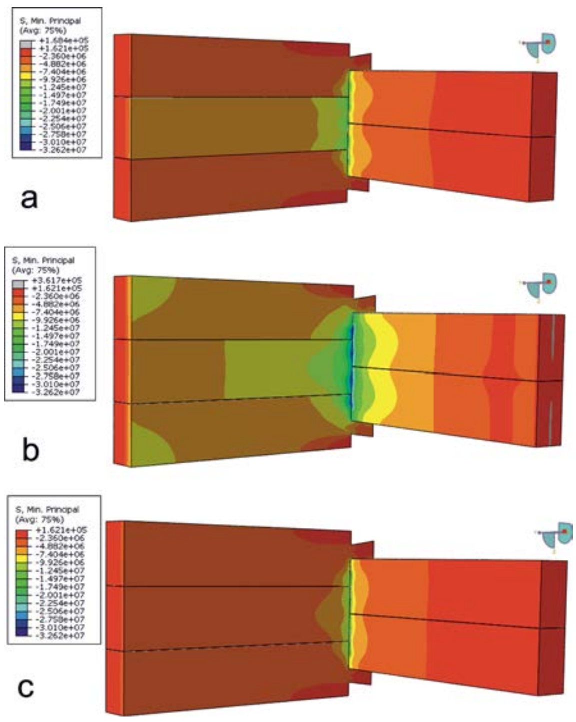

Figure 14. Minimum principal stress in the joint where a) one log has been exchanged into a new wood; b) all logs are made of the same new wood; c) all logs are made of the same old wood.

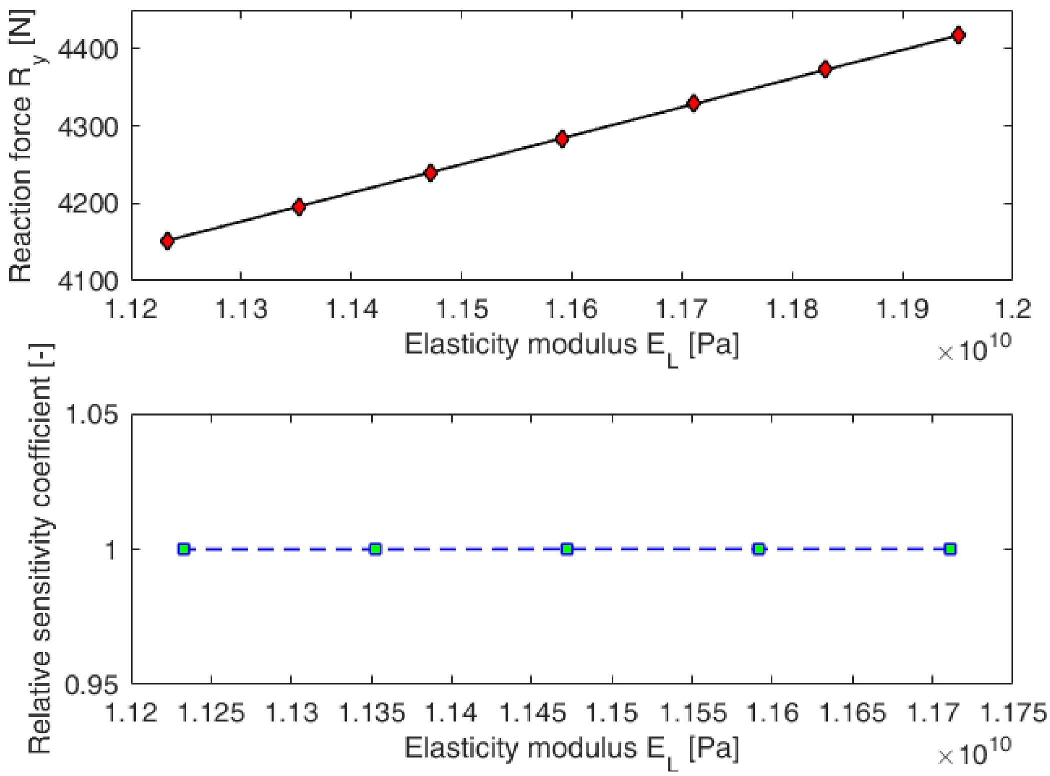

Figure 15. Sensitivity of reaction force due to variation of the modulus of elasticity in dovetail joint where all five logs have the same variable stiffness.

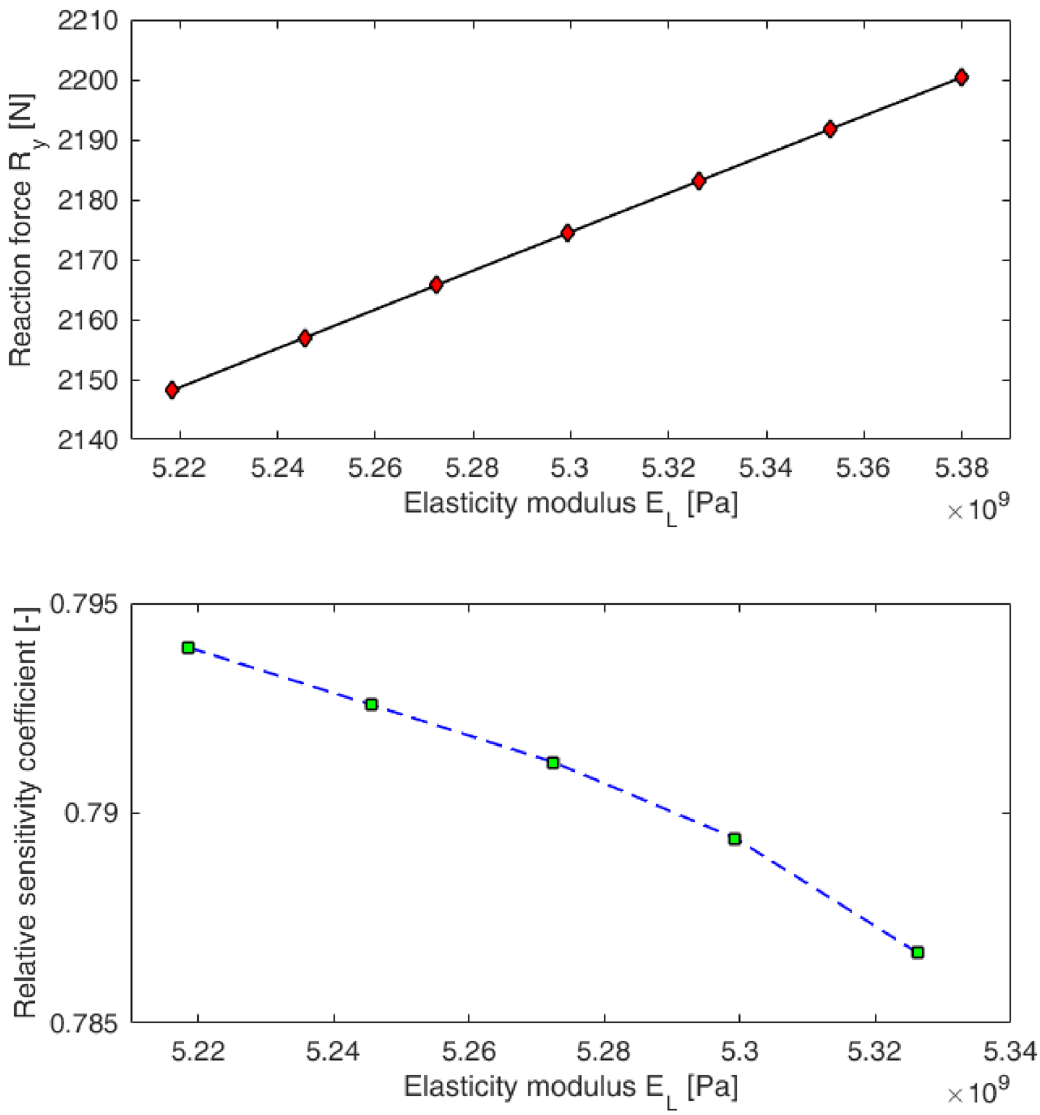

Figure 16. Sensitivity of reaction force due to variation of the modulus of elasticity in four logs of dovetail joint while one log is new and its stiffness is known and does not vary.