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Structural and health assessment of historic timber roofs from the Convent of Christ in Tomar

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Structural and health assessment of historic timber roofs from the Convent of Christ in Tomar

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Abstract:

Before coming up with any important decision of intervention in the restoration process of existing buildings, the assessment of the conservation state is required as regards heritage timber structures, and especially, for those that suffered a lack of maintenance in their service life. In that context, three timber roof structures from the Convent of Christ in Tomar, Portugal, have been selected and investigated. To this end, a research methodology has been introduced and applied to these case studies into four main steps: (i) Visual inspection; (ii) Non-destructive wood diagnosis; (iii) Structural safety evaluation; (iv) Prevention and intervention measures. For the visual inspection, every element and joint constituting the roof structures have been received scrutiny through stressing the wood species, the different construction stages, and last but not least, their respective geometry. As regards the encountered pathologies, structural disorders (e.g. accidental failure, serviceability defects...) and wood-deteriorations due to biological agents (e.g. wood-destroying fungi or insects) have been reported, which ineluctably leads to a likely decrease of the mechanical performances of the roof structure. In order to estimate the residual element cross-section and elastic modulus, wood diagnosis has been carried out through using three relevant non-destructive tests: (i) Ultrasonic Pulse Velocity; (ii) Drilling Resistance; (iii) Impact penetration. From the collected data, the three timber roof structures have been modelled on a commercial software in order to check their safety and integrity. Based on those outcomes, some prevention and intervention measures haves been lastly proposed case by case.

Keywords:

Timber roof structures; Diagnosis; Pathologies; Non-destructive testing; Modelling

1. Introduction

Nowadays, it is generally agreed that existing buildings of heritage values constitute an integral part of the historic legacy of humanity to be preserved for many further generations to come. With modern societies targeting further the matter of sustainability, the conservation of such buildings appears to be a good alternative from the economic, environmental, social and cultural points of view. Even if this concept only came up in the last decades, a generalized degradation and abandonment state were already reported for the greatest part of the built heritage. Due to lack of maintenance often leading to excessive moisture content exposure, various pathologies of a biological, physical or chemical nature may develop within timber structures, resulting in the reduction of their long-term mechanical performances in their service life [1]. Although structural disorders (e.g. instability, high deformation, accidental failure of elements or joints...) caused by a bad design at the initial construction stage are rarely met, they may still appear as a consequence of a significant loading change, over many intervention periods in the edifice history.

Prior to any decisive intervention in buildings of heritage values, it is crucial to develop a multidisciplinary method that combines several tasks and aspects from different fields of knowledge. As regards the diagnosis and restoration of historic timber structures, many guidelines and methodological approaches can be found from the available literature [2, 3, 4, 5, 6]. Furthermore, two charters from ICOMOS [7, 8] also give some principles for the analysis, conservation and structural restoration of architectural heritage, with a focus on the preservation of historic timber structures. As reference to case studies and state-of-the arts dealing with timber roof structures, it can be stated many works [9, 10, 11, 12, 13, 14, 15, 16] in which are introduced efficient methodologies of inspection and diagnosis completed till reaching the decision of intervention, mostly driven by the conservation with strengthening or repair possibilities.

Wood can be considered as a very important raw material throughout the ages, with a fundamental structural role in historic buildings around the world. In that context, the present work aims at assessing the conservation state of existing timber structures, and finally, at proposing appropriate prevention and intervention means to ensure good maintenance conditions in the near future. To this end, the Convent of Christ in Tomar (Portugal) has been chosen, with the evaluation of three timber roof structures badly preserved over time. Thereby, a methodology of inspection and diagnosis has been proposed and applied to these case studies into four main steps: (i) Visual inspection; (ii) Non-destructive wood diagnosis;

(iii) Safety structural evaluation; (iv) Prevention and intervention measures. Before going ahead with the assessment of timber roof structures, a few words should be said about the history of the building, namely the Convent of Christ, and the research methodology selected in the present work.

2. Materials and method

2.1. The Building: Convent of Christ

Standing at the top of the hill, the Convent of Christ (Fig. 1) overhang the historic city-centre of Tomar, in Portugal, as a strong national symbol of “Reconquista Portuguesa”, and afterwards, of the opening up towards other civilizations through overseas explorations. The whole historic building is the testimony to an eclectic architecture over a five-hundred-year period, combining Romanesque, Gothic, Manueline, Renaissance, Mannerist and Baroque elements. As first traces of the monumental complex, the 12th century Tomar Castle was built by D. Gualdim Pais, for which the Oratory “Charola” and walls surrounding the convent still remain nowadays. In the 14th century, the Order of Christ substituted the Order of Knights Templar, through progressively restraining the activities of friars to religion only. The next three centuries disclosed, step by step, the construction of many edifices which will give to the convent its heritage grandeur and appearance as we know today.

Thereby, it can quickly be stated different elements of the monastic complex (Fig. 2) in a chronological order: (i) Centre – Romanesque Oratory “Charola” and gothic Capitulum Room; (ii) East – Two gothic cloisters; (iii) South – Gothic Church in ruins and the gardens; (iv) North, West and South – Five renaissance styled cloisters forming with the Charola a huge Latin cross set of new dormitories; (v) North-East – Infirmary and new Pharmacy including the Knights’ Hall. Further information (not detailed in the present work) about the history and composition of the convent can be found in the following literature [17, 18, 19].

After the Portuguese Liberal Revolution, the Order of Christ was extinct in 1834 with the forced departure of the religious friars. From the early beginning of the 20th century, some edifices were then occupied by either the Army or the Overseas Missions Seminar. In the 1980´s, the Portuguese State reacquired the whole monumental complex, designated as Convent of Christ, for cultural and touristic activities that still run nowadays. It should be noted that the Convent of Christ was classified as a national monument in 1907, and only much later in 1983, registered in the World Heritage Site List from UNESCO. With the progressive abandonment of unoccupied convent parts in the 1970s and 80s, many timber structures came up with pathologies, such as leaking water in the roof covering that triggered the onset and development of biological wood-deteriorations over time.

In that context, three timber roof structures featuring major disorders have been investigated in the present work. They are respectively located in the dormitory Room 68 on the northern flank of the convent, and in the Knights' Hall at the north-eastern corner of the Infirmary complex (Fig. 2). Through applying an inspection and diagnosis methodology to those case studies, the resulting analysis and proposal of interventions could be extended in the near future to some auxiliary rooms that include similar roof structures and pathologies in the Convent of Christ. Concomitantly, a wood dendrochronological survey has mostly been carried out in the Room 68, while very recently, a further geometrical assessment of the ceiling structure through laser scanning and drill resistance testing has been achieved by Cuartero et al. [20] in the Knights' Hall.

2.2. Inspection and diagnosis methodology

Many methodological approaches for a mono- or multi-level characterization of timber structures *in-situ* can be found from the literature [2, 3, 4, 5, 6]. Including a variety of actions and solutions, different methods may be feasible if they have been chosen wisely on case by case basis. Regarding the assessment of timber roof structures in the Convent of Christ, a methodology of inspection and diagnosis (Fig. 3) has been proposed into three main steps: (i) Preliminary evaluation; (ii) Structural analysis and detailed diagnosis; (iii) Results and future interventions.

- The preliminary evaluation firstly consists in a desk survey, through gathering all handwritten and/or computer documents available (e.g. blueprints, reports, pictures...) dealing with the history of the building and timber structures investigated. Afterwards, a visual inspection takes place *in-situ* in order to report the current state of timber structures in their service life, and if appropriate, their pathologies (e.g. structural disorders, biological wood-deteriorations, serviceability defects...). A geometric survey is also performed *in-situ* in order to identify and measure the structural elements and joints. Furthermore, it helps in defining better the main construction and/or modification stages of the structure in the building history;
- The structural analysis and detailed diagnosis mainly aim at completing the information already collected in the first step. Before performing the structural analysis, the impact of the pathologies observed for the visual inspection on the wood mechanical properties has to be investigated. To this end, a wood diagnosis is carried

out *in-situ* through using non- and/or semi-destructive tests wisely selected on case by case basis. [21]. In fine, the timber structure is analysed on numerical software in order to detect the elements or joints featuring potential problems that could threaten the structural safety and integrity.

- Based on the results obtained from the last two steps, preliminary and diagnosis reports are written as the assessment of the timber structure is going. In addition to this, the third step aims at proposing a work-plan of feasible interventions, in the respect with the restoration principles stated in both charters from ICOMOS [7, 8], in order to solve current problems and prevent the onset and development of any further pathology. Thereby, the safety and integrity of timber structures will be preserved in the future through enabling maintenance actions from time to time.

3. Visual inspection

3.1. Room 68

In the dormitory Room 68 located on the northern flank of the Convent of Christ, the roof structure and the ceiling planks (Fig. 4-a) have been selected as the first case study due their badly state of conservation in the 20th century [17, 18]. In order to ensure the visual inspection and diagnosis *in-situ*, it has been decided to remove some ceiling planks that covered the rafters and joists of the roof structure (Fig. 4-b). Also, only the northern and western parts of the structure have been investigated since they were highly subject to leaking water due to maintenance lack of roof covering, which made easier the onset and development of biological deteriorations over time on those areas.

Based on the 3D modelling of the old roof structure illustrated in Fig. 5, different timber elements can be gathered into two categories: (i) Ceiling structure; (ii) Primary roof structure. The joists and edge beams belong to the ceiling structure whereas the struts, purlins, rafters, collar ties and wall plates make up the primary structure which formerly counteracted the roof covering and outside loadings. It should be noted that all the timber elements are tied in to each other, side by side, with nails. The birdsmouth joint, which links the rafter-end with the wall plate, also includes one or two nails in order to avoid any out-of-plane displacement of the generating truss constituted by the rafter, collar tie and strut of the rafter. The remaining purlins formerly bearded into three local points the rafters subject to bending due to the action of the roof loading.

As shown in Fig. 6-a, two different timber structures coexist underneath the roof of the Room 68. The old structure under investigation had been built in the first half of the 16th century with the dormitory rooms whereas the new one was recently settled when restoring the whole roof covering in 2007 [18]. Since the new structure bears the roof and outside loads, the old one has been restrained in its initial structural role, being now subject to its own weight and those from the ceiling planks only. Also, the top part of the rafters was cut and removed from the old structure because they were severely damaged due to biological agents. Nowadays, fungal decay at the rafter-ends and insect wood-deterioration on the external surfaces can still be observed (Fig. 6-b), resulting in a significant reduction of the timber element cross-sections. Indeed, many rafter-ends, including birdsmouth joint, and some parts of the wall plates are featured by a deterioration level so high that some of them (I, IV, V, VI and X) are nearly free of any support, leading to potential structural disorders.

Old and new roof structures present different wood species. As per Silva [18], Oak was identified as the main wood species for the old structure whereas the new one appeared to be made of Pine wood. Furthermore, preliminary visual investigation concluded that the rafters, joist, edge beams, collar ties, purlins and struts could be made of chestnut (*Castanea sativa* Mill.), but of Portuguese oak (*Quercus faginea* Lam.) for the wall plates. Regarding ceiling planks, maritime pine (*Pinus pinaster*) is the most likely wood species.

This information was confirmed in the dendrochronological study performed by the researchers from the University of Coimbra, through sampling wood carrots within the old roof structure, mostly in the rafters. As another outcome from this study, average wood density of 613 kg/m³ can be assumed for all the timber elements made of *Castanea sativa*. As detailed in Table 1, this mean value is reliable when comparing with the European Standards (e.g. EN 350 [22], EN 1912 [23] and EN 338 [24]), although it seems higher than the value recommended by the Italian Standard UNI 11035-2 [25].

3.2. Knights’ Hall

3.2.1. Octagonal dome

In the north-eastern corner of the Convent of Christ, the timber structure covering the Knight’s Hall has been chosen as second case study in the present research project. The “dome” stands for a 8-face pyramidal structure whose the top is featured by a void due to the geometrical assemblage of the ceiling planks (Fig. 7-a). On the bottom part of the timber structure, decorative paintings classified as artwork under heritage protection can be observed on the ceiling planks (Fig. 7-b). The octagonal dome and the ceiling paintings had been completed in the second half of 17th century [17, 18], in the same period than the convent Infirmary and Pharmacy. It should also be noted that some conservation and restoration works were performed on the structure between 1965 and 1970 [19].

Based on the visual inspection, each component of the octagonal dome has been modelled, as shown in Fig. 8. Thereby, it can be stated: (i) 8 pyramid-edges constituting of 3 beams each one; (ii) 6 panels of 9 joists (faces I-II-III-V-VI-VII); (iii) 2 panels of 10 joists (faces IV-VIII); (iv) 12 wall and 4 support beams making up the base of the structure. Again, the timber components are connected side by side with nails while the nailed birdsmouth joint links the ceiling joists and pyramid-edge beams to the wall and support beams. Exempt of any structural role as regard the roof covering, the octagonal dome was designed to only bear the decorative ceiling planks and the pendant light. Since the pyramidal ceiling structure in the Knights' Hall and the roof structure in the dormitory Room 68 share similar texture, colour and dating of wood, it can thus be inferred that the wood species is still chestnut (*Castanea sativa*). On the other hand, the decorative ceiling planks are probably made of maritime pine (*Pinus pinaster*). From the work of Cuartero et al. [20], some attempts in assessing a detailed geometry of irregular cross-section of timber elements, with non-visible faces and affected by biological wood-deterioration, have been carried out very recently, through a campaign of laser scanning and Drilling Resistance testing for the whole octagonal dome.

As structural disorder, the valley rafter from the northern roof under collapsing process tends to locally press the top of the octagonal dome (Fig. 9-a), in the vicinity of three pyramidal-edge beams between the faces V and VI, leading to a transfer of extra loading. On the other hand, slight and moderate insect wood-deteriorations can be noticed on the external surfaces of joists and edge beams. Furthermore, the joists (7-8-9) from the face V have been indicated as highly degraded due to the same biological agent, resulting in a significant reduction of their cross-sections (Fig. 9-b). Also, those timber elements may occasionally be wet due to the water dripping from the roof covering badly maintained. If those pathologies stated for the visual inspection still remain in the future, the structural integrity of the dome as well as the conservation of the classified paintings on the ceiling planks may be threatened in a long term, resulting in severe and irreversible consequences.

3.2.2. Carpentries set

A complex timber carpentries set, standing above the octagonal dome in the Knights' Hall, has been chosen as third case study. After assessing the geometry, position and orientation of each timber components *in-situ*, the whole carpentries set has been modelled successfully

(Fig. 10). As a result, 50 timber elements have been identified in total and sorted out into 6 groups: (i) 2 horizontal beams; (ii) 12 purlins; (iii) 4 ridges; (iv) 15 struts; (v) 2 timber trusses; (vi) 4 valley rafters. For each group, the timber components are connected side by side with nails. It should be noted that the purlins, ridges and horizontal beams are supported at their end on masonry pillars that appear to be settled and covered with lime mortar.

Among this myriad of timber elements, two categories of truss stand out: (i) The King-post truss (Truss A); (ii) The A-shaped truss (Truss B). The King-post truss (Fig. 11-a) is made up of two rafters (1 and 5), one collar tie (22) in tension, and one king-post (23) connected with four struts (24, 25, 26 and 27) that bear the respective valley rafters (37, 49, 43 and 30) from the roof covering. Furthermore, metallic U-shaped binding strips with bolts were used to strengthen the Single Step Joints between the rafters and collar tie, while this technique restrained any out-of-plane displacement of the king-post-end. On the other hand, the A-shaped truss (Fig. 11-b) includes two rafters (17 and 18), one collar tie (19) in compression, and two struts (20 and 21) that hold the respective purlins (45 and 47) from the roof covering.

Although the Knights' Hall had been built with the infirmary and pharmacy in the second half of the 17th century [17, 18], the existing carpentries set appears to belong to the 19th or 20th century. Indeed, the rendering of the timber components looks much more refined, suggesting that bench works in wood or modern manufacturing methods (e.g. sawing and machining) were used for that purpose. Even if there is no certified manuscript or report, the roof structure might have been built in 1970, during the major works standing for the repair and substitution of the whole roof in the Infirmary and Pharmacy, including the Knights' Hall [19]. With the exception of 10 struts (2, 4, 14, 15, 19, 20, 21, 28, 29 and 48) that are made of chestnut (*Castanea sativa*), eucalyptus (*Eucalyptus globulus* Labill.) is the main wood species observed for the whole carpentries set.

Apart from 4 timber elements (14, 15, 49, 50) superficially deteriorated due to former insect attacks, no significant biological degradation has been noticed within the whole carpentries set. On the other hand, many structural disorders can be reported: (i) Out-of-plane displacement of the king-post-end (23) within the King-post truss (Fig. 12); (ii) Slightly twisted timber elements (1, 5, 6, 11, 22, 35, 45) over their whole length (Fig. 12); (iii) Tensile crack at the mid-span of the horizontal beam (11) under excessive bending (Fig. 13-a); (iv) Collapse of the purlins (36, 38, 39, 41, 42, 44) due to the partial or complete failure of their respective masonry supports (Fig. 13-b). All these pathologies previously stated constitute the proof that the northern part of the roof has already started to collapse since a while. As transient prevention mean, metallic struts were thus added accordingly, by holding on two purlins (35, 44) in the vicinity of the masonry supports.

4. Non-destructive wood diagnosis

Among different non-destructive methods proposed to establish a better diagnosis of historic timber structures [21], Ultrasonic Pulse Velocity, Drilling Resistance and Impact Penetration tests have been selected and performed *in-situ*, in respect with the observations previously made from the visual inspection. Thereby, the non-destructive wood diagnosis mostly focuses on the roof structure in the Room 68 and the octagonal dome in the Knights' Hall, since they both feature significant wood-deteriorations due to xylophagous insect and decay fungi. On the other hand, the carpentries set, reported as a sound and recent timber structure in accordance with the visual inspection, has been disregarded from this step.

4.1. Ultrasonic Pulse Velocity test

Ultrasonic Pulse Velocity (UPV) test enables to measure the propagation time, and thus, the propagation velocity of stress waves inside wood, between the transmitter and receiver probes [26, 27, 28]. Furthermore, UPV method can be considered as a quality index of wood since it can detect any superficial or internal defect (e.g. cracks, knots, biologically wood-deterioration, foreign body...). Indeed, lower velocities or longer propagation times disclose bad conditions of wood in term of physical and mechanical properties. The propagation velocity of stress waves v [m/s] essentially depends on the density ρ [kg/m³], stiffness, and thus, the elastic modulus of wood E [N/mm²], which can be estimated by the empirical equation simplified (1)[28]. According to the same authors, the elastic modulus could then be correlated with the compressive and tensile strengths of wood parallel to the grain through empirical equations, featuring low and moderate coefficients of determination though.

$$E = v^2 . \rho \tag{1}$$

Due to heterogeneous contact conditions on external surfaces of the structural element (gaps, rough or rounded surface), it is sometimes challenging to ensure a good propagation of stress waves inside wood between both probes. For that reason, UPV testing, through using the equipment Pundit Lab® with two 54 kHz frequency transmission transducers, has only been performed for the rafters located in the Room 68. Conform with the work of Feio et al. [28], two types of UPV tests have been performed in-situ in order to estimate the wood compressive elastic moduli parallel and perpendicular to the grain: (i) Indirect Method parallel to the grain (Fig. 14-a); (ii) Direct Method perpendicular to the grain (Fig. 14-b). It should be noted that both methods require having access to at least two opposite faces of the investigated element. In all tests, a constant pressure has been applied by means of a rubber in order to make easier the transmission of ultrasounds inside wood between both probes.

As a result, elastic moduli parallel and perpendicular to the grain, noted $E_{c,0}$ and $E_{c,90}$ respectively, have been calculated by the equation (1), through taking into account the average wood density ρ=613 kg/m³ given in Table 1 for chestnut (*Castanea sativa*). Besides, each part of the rafters assessed through UPV tests have been sorted out into four biological wood-deterioration groups (Fig. 15), in respect with both compressive elastic moduli $E_{c,0}$ and $E_{c,90}$: (i) Sound; (ii) Slightly damaged; (iii) Moderately damaged; (iv) Severely damaged. Lower bound values regarding the "Sound" group have been inferred from the characteristic and mean values of both properties $E_{c,0}$ and $E_{c,90}$, in respect with the strength class D18 assigned to the chestnut (*Castanea sativa*) in accordance with the Standard EN 338 [24]. It has been shown that biological wood-deteriorations, mainly due to insect attacks, are randomly distributed on the external surfaces of studied rafters. Nonetheless, three rafters (X, XI, XII) and most of the rafter-ends in the vicinity of the decayed birdsmouth should draw some attention, since the related external surfaces have been reported as severely damaged. Furthermore, low values of $E_{c,90}$ recorded may also be explained by the presence of internal cracks in the element cross-section.

4.2. Drilling Resistance test

The Drilling Resistance (DR) test consists of measuring wood drilling resistance as a function of penetration depth [28, 29, 30, 31]. Since the diameter of the drilled hole in the element does not exceed 3 mm diameter, the DR regarded as a quasi-non-destructive test has no impact on the wood mechanical performances, neither on the integrity of heritage structures assessed *in situ* (Fig. 16).

Information given from DR test includes: (i) The wood drilling resistance; (ii) The cross-section dimensions of the timber element studied; (iii) The detection and location of inner defects or structural discontinuities (e.g. knots, cavities, cracks, deteriorated wood...) that could not be noticed for the visual inspection; (iv) The annual wood growth rings; (v) A qualitative interpretation of wood density.

Whereas visual inspection often overestimates the amount of strength loss due to decay, DR testing may disclose significant drilling resistance in the reduced cross-section [30]. In that case, preservation of the timber element should be promoted, instead of removing it permanently. To this end, the Resistance Measure (RM) [28] is calculated by the equation (2), which takes into account the grey area under the drilling resistance profile (Fig. 17) and the drill penetration depth noted h in the element cross-section.

$$RM = \frac{\int_0^h Area}{h} \quad (2)$$

From the literature [28, 29, 31], low and moderate correlations between RM, wood density and mechanical properties have been established up to now. Meanwhile, assigning the wood strength class from Standards (e.g. EN 1912 [23] and EN 338 [24), to the elements investigated should not be based on qualitative RM values only. On the other hand, the wood moisture content should be assessed when performing DR testing, since it conditions the parameter RM as well as the wood mechanical performances.

Regarding the old roof structure (Room 68) and octagonal dome (Knights' Hall), DR testing has been performed for the rafters and joists, through using the Resistograph® 3450 RINNTECH (Fig. 16), in the vicinity of the birdsmouth joint. After plotting the drilling resistances on graph (Fig. 17), two different parameters RM have been calculated by (2), one without defects, and the other one with defects (e.g. internal cracks and biologically deteriorated wood). For both parameters, Table 2 provides the mean values, maximum, minimum, amount of performed DR tests, standard deviation (SD) and coefficient of variation (COV). Based on very similar data distributions with COV<10%, it can be stated that the RM value with defects is, on average, 20% lower than the RM value without defects, resulting in a likely decrease of the wood mechanical performances as previously reported from UPV tests. As another outcome from DR testing, the thickness of the external surfaces featuring insect wood-degradations should be taken as 10 mm on average, when estimating the residual element cross-section.

4.3. Impact Penetration test

Impact Penetration (IP) test, also known as Pilodyn® Method or Dynamic Pin Penetration Method, consists of applying an impact force, through the release of a spring, by a slender steel rod on the external wooden surfaces [28, 29, 30]. Being also considered as quasi-non-destructive, IP test enables to measure the penetration depth of the rod, which is inversely proportional to density and hardness surface of wood. On the other hand, the penetration depth increases with the wood moisture content, since the latter conditions the hardness and other mechanical performances of wood. Until a maximal penetration depth of 30-40 mm, this method can be used to detect the presence of superficial defects (e.g. cracks, knots, biological wood-deterioration). Based on the penetration depth of the rod $d_{p,rod}$ [mm] obtained from IP tests, the related wood density ρ [g/cm³] can be estimated by the empirical equation (3) [29], with wood moisture content of 12%.

$$\rho = -0.027102\,.\,d_{p,rod} + 0.727987 \quad (3)$$

As regards the octagonal dome in the Knights' Hall, IP testing has been performed for the joists, through using the dynamic indentor Pilodyn® 6J Forest (Fig. 18), in the vicinity of the birdsmouth joint. After taking measurements of the penetration depth, the wood density has been calculated by (3), while ensuring a wood moisture content of 12% on the external wooden surfaces through using the electrical resistance moisture meter Protimeter Surveymaster®. Thereby, the mean values, maximum, minimum, amount of performed IP tests, standard deviation (SD) and coefficient of variation (COV) are given in Table 3 for three parameters: (i) Penetration depth of the rod $d_{p,rod}$; (ii) Wood density ρ; (iii) External layer thickness of deteriorated wood t_D.

The maximal density ρ=619 kg/m^3, that has been inferred from the minimal penetration depth $d_{p,rod}$=4 mm, may belong to sound wood, within the range of density values detailed in Table 1 for chestnut (*Castanea sativa*). The external layer thickness of deteriorated wood t_D has then been determined through reducing the measured penetration depths $d_{p,rod}$ by 4 mm, as a reference value standing for sound wood. As a result, the parameter t_D may vary between 0 and 11 mm, with a mean value of 5 mm. Since empirical equations from the literature [28, 29] have presented low coefficients of determination up to now, it has been decided not to estimate the wood mechanical properties based on the penetration depth.

5. Structural safety evaluation

After completing the preliminary inspection and non-destructive wood diagnosis, the safety evaluation of three timber structures, namely the old roof structure in the dormitory Room 68, the carpentries set and octagonal dome in the Knights' Hall, has been carried out on the Finite Element software RFEM 5.19.01 [32], by taking into account the impact of biological wood-deteriorations and other disorders noticed *in-situ* on their mechanical performances. To this end, the ultimate limit states (ULS) and serviceability limit states (SLS) have been checked for each timber roof structure, in accordance with EN 1995-1-1 (Eurocode 5) [33]. From this Standard, the coefficient of material γ_M=1.3 and the modification factor for duration of load and moisture content k_{mod}=0.6 (assumption of permanent action and service class 2) have been chosen to calculate the design values of wood strength properties, on the basis of the characteristic values provided by EN 338 [24] and UNI 11119 [34]. For each case study, the minimal design bending strength M_{Rd} [kNm] has been estimated in respect with the lowest timber element cross-section. Besides, both values delimiting the range of maximal deflection permitted to still ensure a good serviceability of the structure *in-situ*, namely $w_{L/300}$=L/300 and $w_{L/150}$=L/150 [mm], have been taken into account, for which the parameter L [mm] stands for the span of the timber element under bending on two supports.

5.1. Roof structure – Room 68

Within the old timber roof structure located in the dormitory Room 68, the numerical analysis focused on the rafters and ceiling joists in the northern and western parts suffering from a lack of maintenance over time. From the preliminary inspection and diagnosis, the element cross-sections have been determined, with the strength class D18 as mechanical properties attributed to sound chestnut (*Castanea sativa*), in accordance with EN 338 [24]. Furthermore, the roof structure belongs to the visual grade I (UNI 11119 [34]), for which three characteristic values of chestnut strength properties have been considered: (i) Compression strength parallel to the grain $f_{c,o,k}$=11 MPa; (ii) Tensile strength parallel to the grain $f_{t,o,k}$=11 MPa; (iii) Bending strength $f_{m,k}$=12 MPa.

Nonetheless, the elastic moduli have been modified in accordance, through partitioning each rafter, based on the results obtained from the Ultrasonic Pulse Velocity test. Concerning the definition of the residual element cross-section, a remaining capacity factor with a value between 0 and 0.5 could be assigned to the area attacked by a biological deteriorating agent [35]. In order to simplify the current model, it has been decided to reduce the cross-sections of the rafters and joists by an average thickness of 1 cm that stands for the external wooden layer featuring insect degradations with no remaining capacity factor, conform with the outcomes obtained from the Drilling Resistance test.

Because the old structure does not have to bear anymore the roof covering loadings since the restoration works performed in 2007, only two own-weights should be considered: (i) Weight of the roof structure (6.13 kN/m³) made of chestnut (*Castanea sativa*); (ii) Weight of the ceiling planks (0.2 kN/m²), made of maritime pine (*Pinus pinaster*). As illustrated in Fig. 19-a and -b, the internal forces (ULS) and local deformations (SLS) obtained after running the numerical analysis in RFEM present very low values, namely a maximal bending moment (M=0.07 kNm) and maximal deflection (w=2 mm) over 2000 mm span length, in comparison with the minimal bending strength (M_{Rd}=0.4 kNm) and the inferior boundary value of the maximal deflection range ($w_{L/300}$=6.7 mm). Although the whole roof structure has remained safe so far, several decayed birdsmouth joints linking the rafter-end to the wall plate should be repaired in order to avoid any global disorder in the near future.

5.2. Carpentries set – Knights' Hall

Regarding the carpentries set standing above the octagonal dome in the Knights' Hall, severe structural disorders have been noticed, such as the tensile crack at the mid-span of the horizontal beam (11) under excessive bending and the failure support of the purlin (42) that both lead to a progressive collapse of the northern roof part. In order to figure out how these disorders came out and developed over time, two case studies have been tackled: (i) Initial design configuration of the carpentries set without any disorder; (ii) Carpentries set including one purlin (42) free of any support. Featuring no biological degradation, the element cross-sections have been defined with the strength classes D18 and D30, for the chestnut (*Castanea sativa*) and eucalyptus (*Eucalyptus globulus*) respectively, from EN 1912 [23], and EN 338 [24].In addition to the own-weight of the carpentries set (6.4 kN/m³), the permanent load related to the roof covering (0.8 kN/m²) has to be taken into account, encompassing the weight of the wooden planks and ceramic tiles.

For the case study I (Fig. 20-a and -c), the maximal value of internal bending moments, located at the mid-span of the horizontal beam (11), almost exceeds 50% of the bending strength of the timber element (M_{Rd}=9.2 kNm), while the related deflections reach the inferior boundary value of maximal deflection range ($w_{L/300}$=19.4 mm). Although the structural safety has been checked, the initial design of the carpentries set presents a weak stiffness for both horizontal beams (11) and (6).

Regarding the case study II (Fig. 20-b and -d), higher values of internal bending moments (M=7.45 kNm) have been recorded, as equivalent to 80% of the bending strength of the horizontal beam (11), resulting in a tensile failure under excessive bending and lateral torsional buckling. Besides, significant deflections higher than the superior boundary value of maximal deflection range $w_{L/150}$=38.8 mm have been reported. It has been concluded that the deficient anchorage of the purlin (42) in the masonry pillar has progressively failed over time, leading to the collapse of the northern roof part observed nowadays within the carpentries set.

5.3. Octagonal dome – Knights' Hall

Within the octagonal dome above the Knights' Hall, low and moderate insect wood-deteriorations have been noticed on the external surfaces for most of the joists and pyramidal-edge beams assessed. Likewise in the roof structure from the dormitory Room 68, wood mechanical properties have been defined for the structural elements constituting the dome, as belonging to strength class D18 and visual grade I for sound chestnut (*Castanea sativa*), in accordance with Standards EN 338 [24] and UNI 11119 [34]. Conform with the outcomes obtained from the Drilling Resistance and Impact Penetration tests, the element cross-sections, previously determined from the visual inspection, have been reduced by an average thickness of 6 mm, through considering the external wooden layer degraded due to insect attacks with no remaining capacity factor [35].

Since the octagonal dome stands for a ceiling structure, three own-weights have to be taken into account: (i) Weight of the structural components (6.13 kN/m³) made of chestnut (*Castanea sativa*); (ii) Weight of the decorative ceiling planks (0.2 kN/m²), made of maritime pine (*Pinus pinaster*); (iii) Decorative iron pendant light (0.5 kN). With the collapse of the northern roof part, the rafter valley (43) from the carpentries set tends to press the top of the octagonal dome. In order to model this structural disorder, an extra permanent load (3.5 kN) has been applied on the upper part of the pyramidal-edge beams between the panels V and VI. As a result, it has been shown that the maximal value of internal bending moments (ULS), at the location point of the extra load that simulates the consequences of the northern roof part falling on the octagonal dome, does not exceed 50% of the minimal bending strength, namely M_{Rd}=3 kNm (Fig. 21-a). The latter term has been estimated based on the lowest cross-section among all the ceiling joists, while the extreme values of the maximal deflection range have been calculated by considering a maximal joist length L=3200 mm. On the other hand, significant deflections (SLS) measured for three joists (III-7, V-8, VIII-3), from the panels III, V and VIII respectively (Fig. 21-b), almost reached the superior boundary value of the maximal deflection range $w_{L/150}$=21.3 mm. Although the structural safety of the octagonal dome has been checked, the singular deflections observed for those three joists should be reduced in order to avoid any damage of the decorative ceiling planks in the future.

6. Prevention and intervention measures

In this chapter, several prevention and intervention measures have been proposed for the three timber roof structures investigated, by taking into account the outcomes from the visual inspection, non-destructive wood diagnosis and structural analysis. As regards the latter, the safety and integrity of structures have to be preserved and/or enhanced, by preventing the onset and development of severe pathologies in the future. Many examples of prevention and intervention measures to preserve long-term performances of timber structures in their service life can be found as a non-exhaustive list from the literature review of Verbist et al. [1].

6.1. Minor interventions

As first minor intervention, cleaning the roof in the dormitory Room 68 and Knights' Hall must be performed by removing dust, mud, wooden waste or rubbles accumulated near the masonry support, since their presence, to say nothing of the adequate range of temperature and humidity, may trigger and speed up the long-term degradation of timber structures due to biotic agents, such as wood-destroying insects and fungi. Also considered as a source of future biological infestation, the external layer of joists and rafters, which has been reported as degraded due to insect attacks for the visual inspection, has to be removed as well, through using wood carving chisel tools for instance. Afterwards, surface and/or inner treatments against this pest should be selected wisely and applied *in-situ* on the remaining timber elements. Besides ensuring a proper air ventilation, monitoring the indoors exposure conditions of timber roof structures (i.e. ambient temperature, relative humidity and wood moisture content) should be promoted in order to faster detect wood deteriorations and stop their development over time. In the dormitory Room 68, the totality of decayed ceiling planks under the old roof structure should be replaced by new ones made of the same wood species (i.e. *Pinus pinaster*), and treated in respect with the current design configuration. On the other hand, conservation works should be hold from time to time in order to preserve the decorative ceilings as heritage values, underneath the octagonal dome, in the Knight's Hall.

Since the repair and substitution works performed in 1970 in the Knights' Hall, the 50-years old roof covering has been eroded over time, for lack of maintenance, leading to service nuisances such as leaking water within the carpentries set and octagonal dome. Therefore, it is now crucial to promote a maintenance campaign of the roof covering, which will help in preventing leaking water in long-term, and thus, the onset and development of biological wood-deteriorations threatening the mechanical performances of timber roof structures in their service life. To this end, the roof covering has to be dismantled firstly, through sorting out the well preserved ceramic tiles to reuse, from those ones damaged that have to be substituted by new ones. Once the structural disorders present within the carpentries set will be corrected and the timber structure returned to its initial design configuration, the waterproofing of the roof covering should be ensured, or else enhanced. To this end, an elastomeric waterproofing coating should be settled, underneath the ceramic tiles, on the covering wooden planks. In addition to this, a mortar bed could be applied liberally to fill potential gaps in-between ceramic tiles in their final implementation. Lastly, a constant monitoring of all roofs from the Convent of Christ should be promoted in the near future to assess their conservation state over time.

6.2. Major interventions

Although the safety of the old timber roof structure has been checked in the dormitory Room 68, biological wood-deteriorations, namely fungal decay, have been noticed for many birdsmouth joints at the rafter-end linked with the wall plate. Since those connections are crucial in the stability of the whole structure, the rafters (I, IV, V, VI and X) featuring high advanced stage of fungal decay at their respective end should be either strengthened or repaired. Nonetheless, the entire removal and substitution of deteriorated timber elements from historic roof structures by new clear ones should be excluded for conservation reasons. Adapted from the interventions applied for the decayed timber beam-end [36], different techniques can be sorted out into two main categories for the birdsmouth joint (Fig. 22):

- Retrofitting through adding new partial or full-length timber element(s) made of the same wood species than the existing one, with or without fasteners/binding strips connectors (e.g. steel, FRP...);
- Repair through settling prosthesis made of, either the same wood species than the existing one, or another material (e.g. epoxy resin mortar, concrete...), with glued-in plates or rods (e.g. steel, FRP...). Note that the connection of the prosthesis with the existing element can also be external (e.g. fasteners, screwed plates...) when the aesthetical value is not considered as an important intervention criterion.

Repair techniques are often seen as an onerous alternative that requires available passages large enough to easily reach the intervention region, namely when cutting the decayed part and substituting it by a prosthesis, which is sometimes very challenging to ensure within existing timber structures. Therefore, retrofitting techniques should be preferred when intervening in the dormitory Room 68. Regarding the octagonal dome in the Knights' Hall, significant deflections have been reported from the structural safety evaluation for three ceiling joists (III-7, V-8, VIII-3) under bending featuring very low cross-sections. Again, their removal and substitution by new timber elements should be excluded for conservation reasons. Therefore, retrofitting techniques should be considered through adding new full-length elements, made of chestnut (*Castanea sativa*), connected alongside the existing ceiling joist with metallic fasteners and/or binding strips in order to reduce their current deflections. In that way, the conservation of decorative planks underneath the octagonal dome will be guaranteed.

For the carpentries set in the Knights' Hall, the collapse of the northern roof part has been noticed *in-situ* for the visual inspection, and afterwards confirmed from the structural analysis through simulating a support failure. In that context, major intervention measures into four main steps should be promoted in order to permanently stabilize the carpentries set:

- Holding the northern part of the roof structure back in its initial design configuration through using metallic struts or even outdoors crane, bearing the respective purlins and valley rafters, during the whole intervention period. Note that the roof covering (i.e. wooden planks and ceramic tiles) should be removed beforehand;
- Strengthening the contact support between the purlins (35, 36, 38, 39, 41, 42, 44, 45) and the masonry walls with a metallic bracket anchored inside (Fig. 23). To ensure good anchorage conditions, metallic rods should be introduced inside the masonry wall, if adequate, and attached in their upper part to the bolts from the metallic bracket, which afterwards will be encased together in a concrete block;
- Substituting the damaged horizontal beam (11) by a new element made of the same wood species (*Eucalyptus globulus*), but with a higher cross-section in order to avoid any mid-span failure due to excessive bending underneath the contact area with the valley rafter. In order to enhance the compressive loads transfer, the contact surface between the horizontal beams (6, 11) and the respective valley rafters (37, 43) should be enlarged through adding some wooden wedges connected with metallic fasteners (e.g. nails, screws…) in-between both structural elements (Fig. 24);
- Removing back the metallic struts or crane that had been used to hold on the roof structure during the intervention. Lastly, putting back the roof coverings where they were before the intervention.

7. Conclusions

The present work has focused on the assessment of three historic timber roof structures, badly preserved over time, from the Convent of Christ in Tomar (Portugal) as a case study. From an adequate methodology of inspection and diagnosis, the roof structure in the Room 68, the octagonal dome and the carpentries set in the Knights' Hall have been assessed successfully, into four main steps: (i) Visual inspection; (ii) Non-destructive wood diagnosis; (iii) Structural safety evaluation; (iv) Prevention and intervention measures.

For the visual inspection, the geometric survey has been performed through identifying and measuring each structural component. As regards the pathologies noticed *in-situ*, the old roof structure in the Room 68 and the octagonal dome in the Knights' Hall feature decayed birdsmouth joints and elements superficially deteriorated due to insect attacks. On the other hand, it has been reported several structural disorders within the carpentries set in the Knights' Hall, triggering the progressive collapse of the northern roof part over time.

Concerning the non-destructive wood diagnosis, it has been shown the efficiency of three non-destructive tests, namely the Ultrasonic Pulse Velocity, the Drilling resistance and the Impact Penetration tests, in the detection of wood defects within the three roof structures assessed *in-situ*. Based on the results obtained from the Ultrasonic Pulse Velocity test, the elastic modulus has been estimated in respect with the wood density for the external surfaces of sound and biologically deteriorated elements. On the other hand, their residual cross-sections have been inferred through combining the drilling resistance graph with the penetration depth obtained from the other two non-destructive tests.

In the third step, the three timber roof structures have been successfully modelled on the Finite Element software RFEM®, by taking into account the impact of pathologies noticed *in-situ* on their mechanical performances. It has been concluded that the progressive collapse of the northern roof part in the Knights' Hall has been triggered by a failure support followed by a tensile crack of a beam under excessive bending, within the carpentries set. On the other hand, the safety of other two roof structures investigated has been checked although some decayed birdsmouth joints should draw some particular attention in the future.

Lastly, some prevention and intervention measures have been proposed, based on the outcomes obtained from the previous steps, for the three timber roof structures investigated, in order to preserve and enhance their safety and integrity in the future within the Convent of Christ. Nonetheless, a strong collaboration between architects, engineers, historians and artisans is necessary to ensure economically-viable, sustainable, and reversible if possible, solutions in the respect with the restoration principles and present heritage values.

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Figure 1 – Aerial view of the Convent of Christ, in Tomar, Portugal.

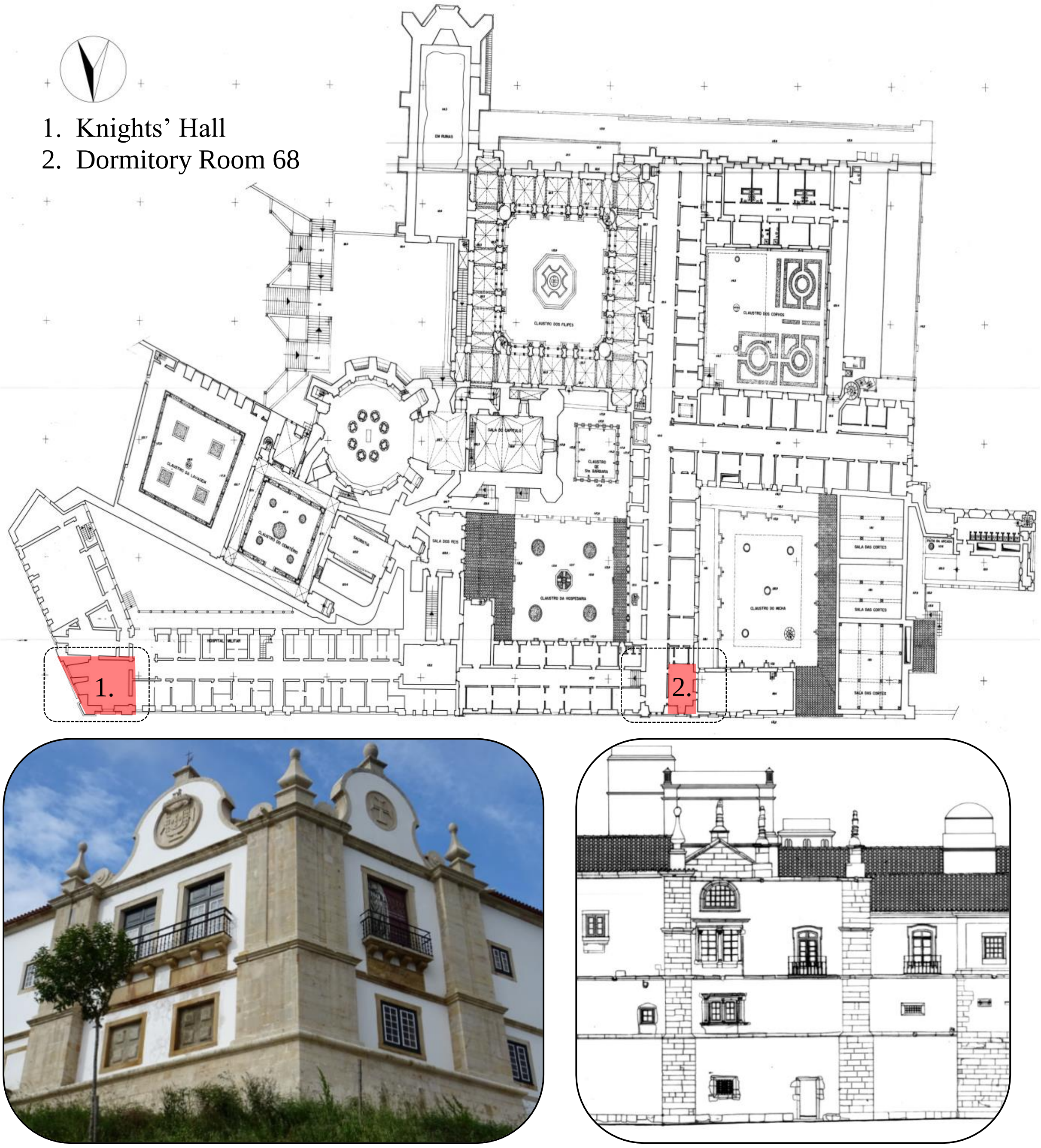


Figure 2 – Second floor plan from the Convent of Christ in Tomar, with the location of timber roof structures under investigation (red areas).

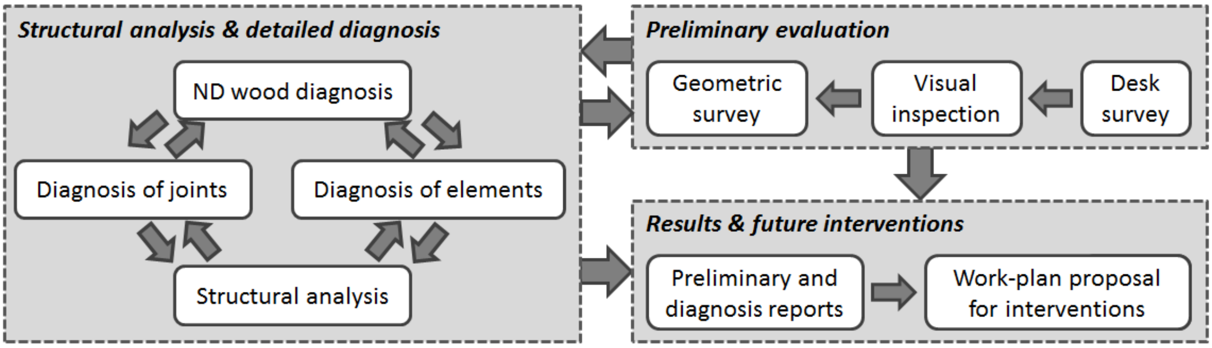


Figure 3 – Methodological steps required for a complete inspection and diagnosis in historic timber structures (modified from [5]).

(a) (b)

Figure 4 – Western rafters and northern joists made visible before (a) and after (b) removing the ceiling planks.

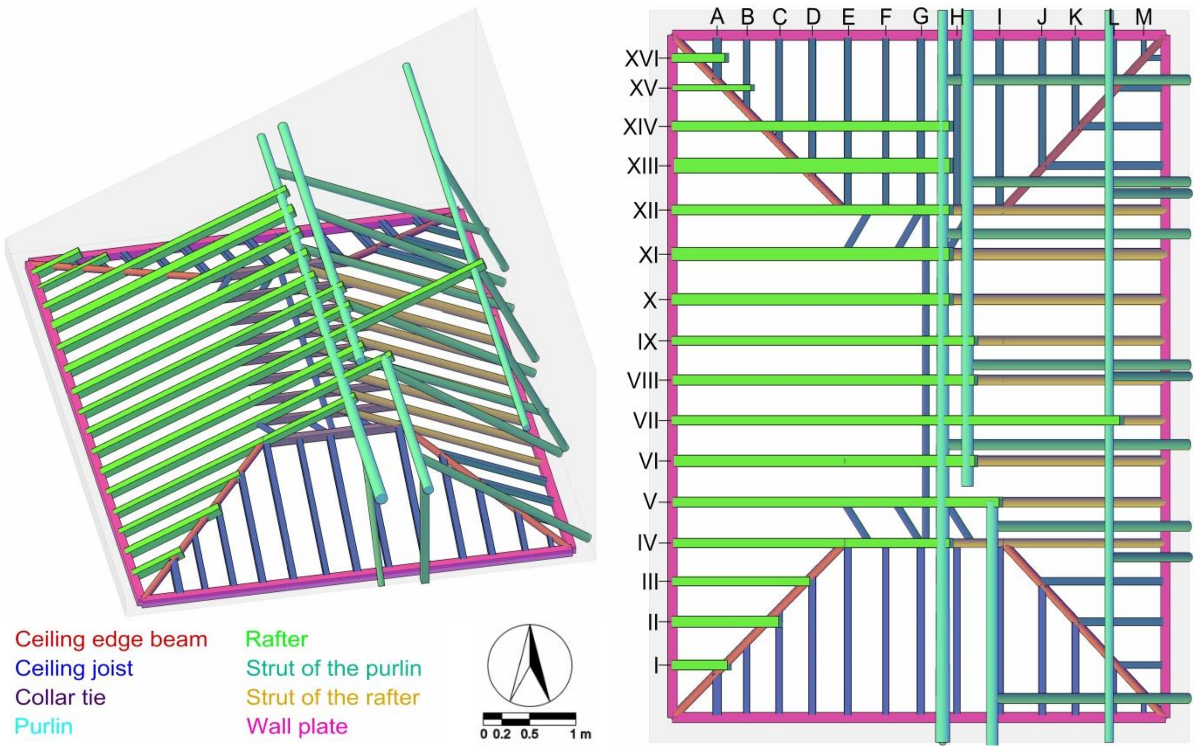


Figure 5 – 3D modelling and horizontal blueprint of the old roof structure in the dormitory Room 68.

(a) (b)

Figure 6 – Coexistence between old and new timber roof structures above the dormitory Room 68 (a). Rafters featuring insect wood-deteriorations on their external surfaces, and fungal decay at their ends (birdsmouth joint) with the wall plates (b).

(a) (b)

Figure 7 – Upper view of the octagonal dome (a). Paintings on the ceiling planks constituting the visible bottom part of the octagonal dome in the Knights' Hall (b), from [20].

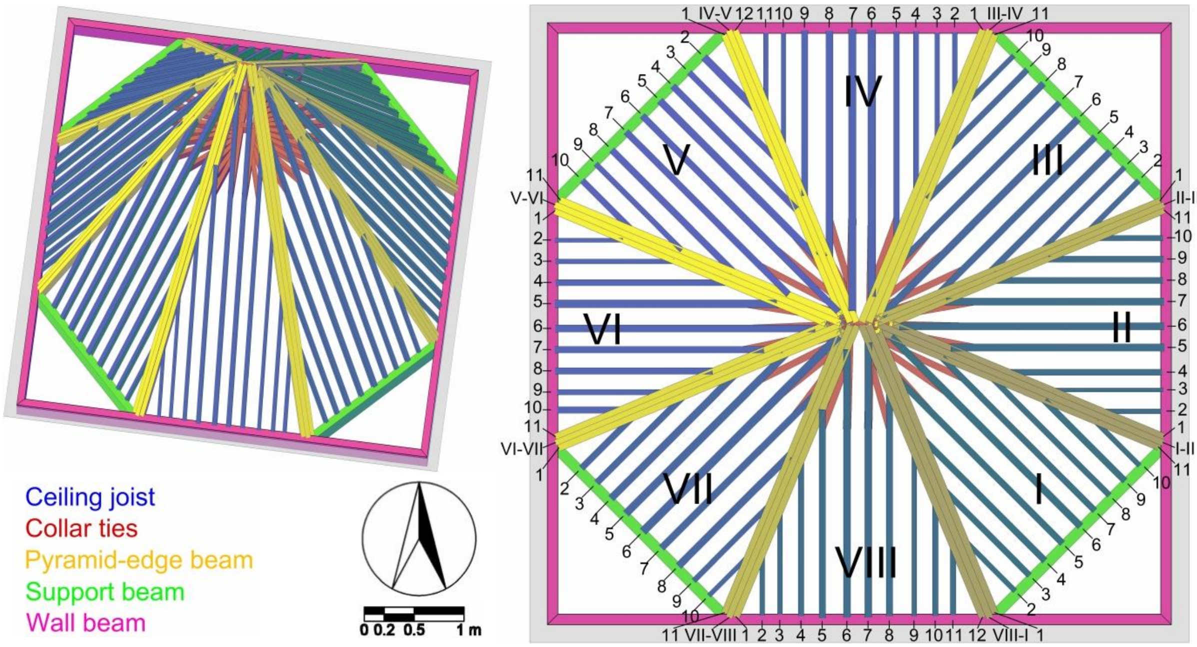


Figure 8 – 3D modelling and horizontal blueprint of the octagonal dome in the Knights' Hall.

(a) (b)

Figure 9 – Beam of the northern roof structure pressing the top of the octagonal dome (a).

Severe insect wood-deterioration on the external surfaces of the joists from the panel V (b).

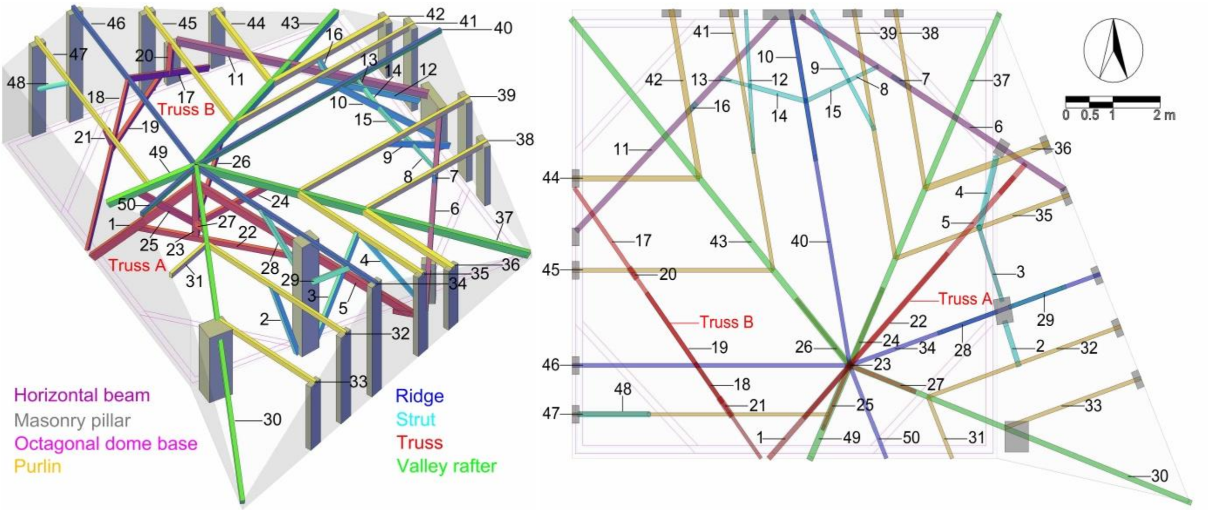
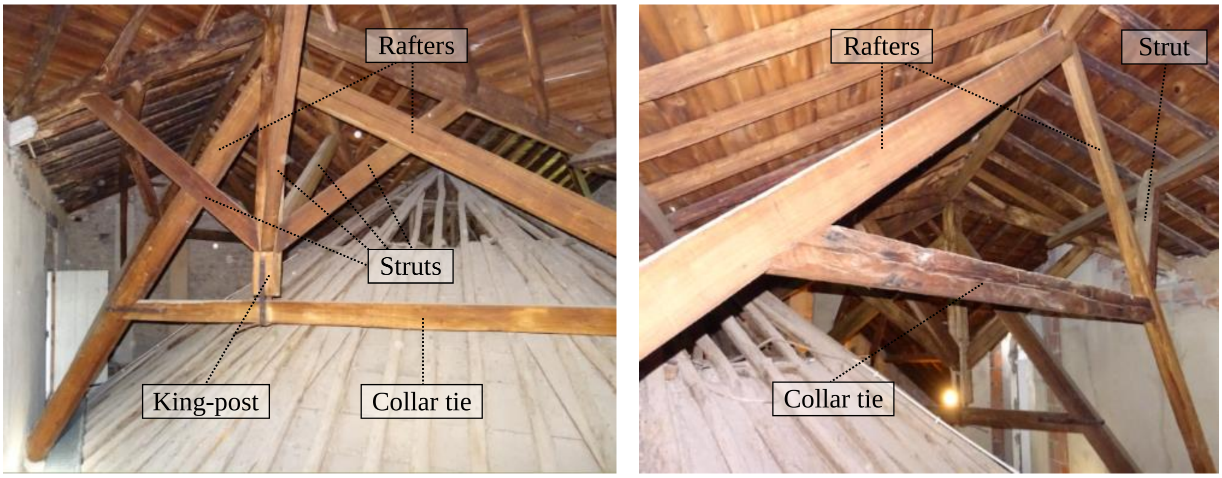


Figure 10 – 3D modelling and horizontal blueprint of the carpentries set above the octagonal dome in the Knights’ Hall. King-post truss (Truss A) and A-shaped truss (Truss B).



(a) (b)

Figure 11 – Components of the King-post truss (a) and the A-shaped truss (b).

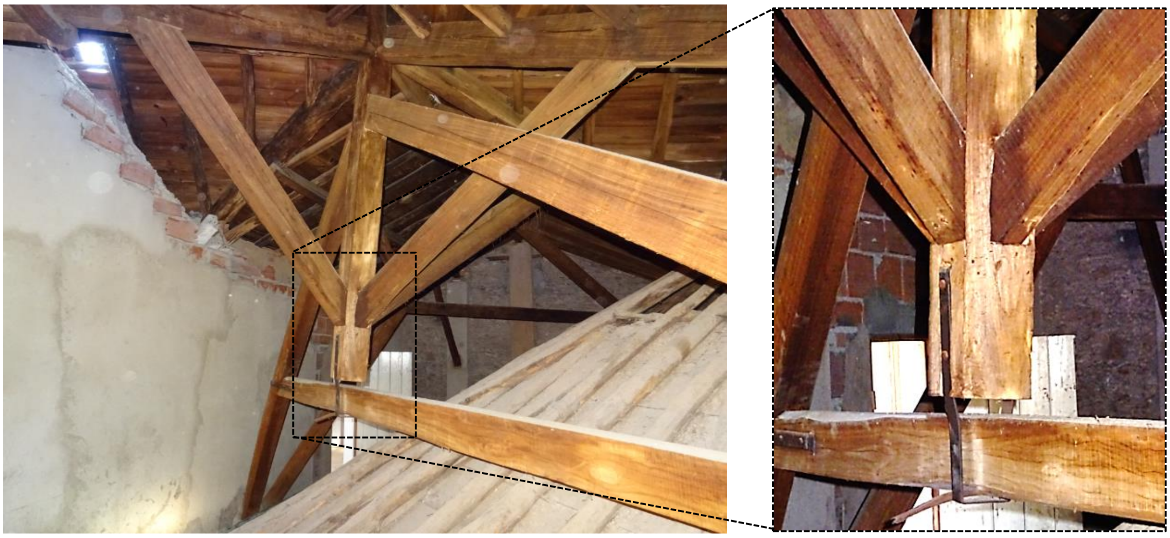
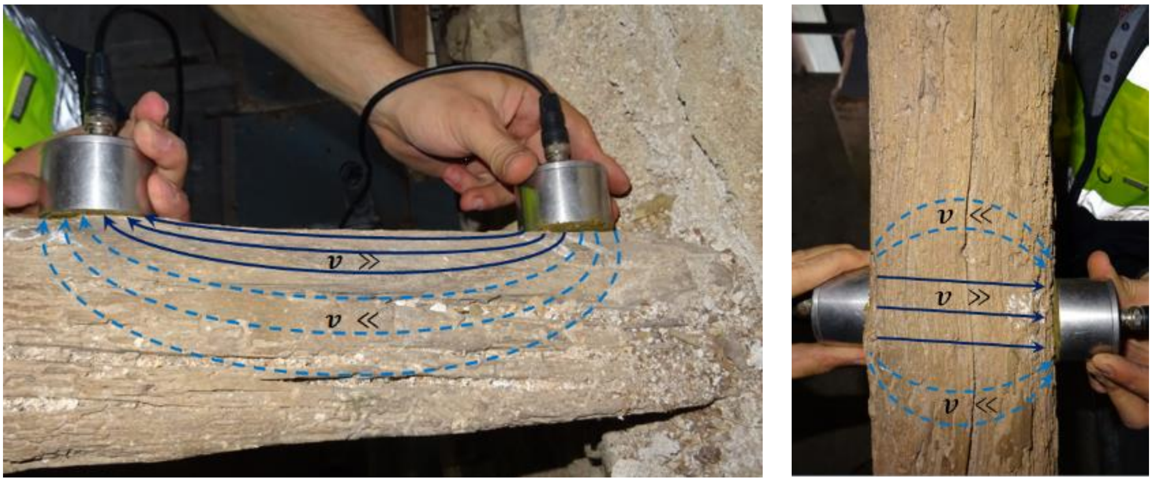


Figure 12 – Collar tie (22) and both rafters (1, 5) slightly twisted over their whole length. Out-of-plane displacement of the king-post-end (23).

(a) (b)

Figure 13 – Tensile crack of the horizontal beam (11) under excessive bending (a). Collapse of the purlin (42) due to the failure of the masonry support (b).



(a) (b)

Figure 14 – Wave’s propagation in respect to Indirect Method parallel to the grain (a) and the Direct Method perpendicular to the grain (b), through using the equipment Pundit lab®.

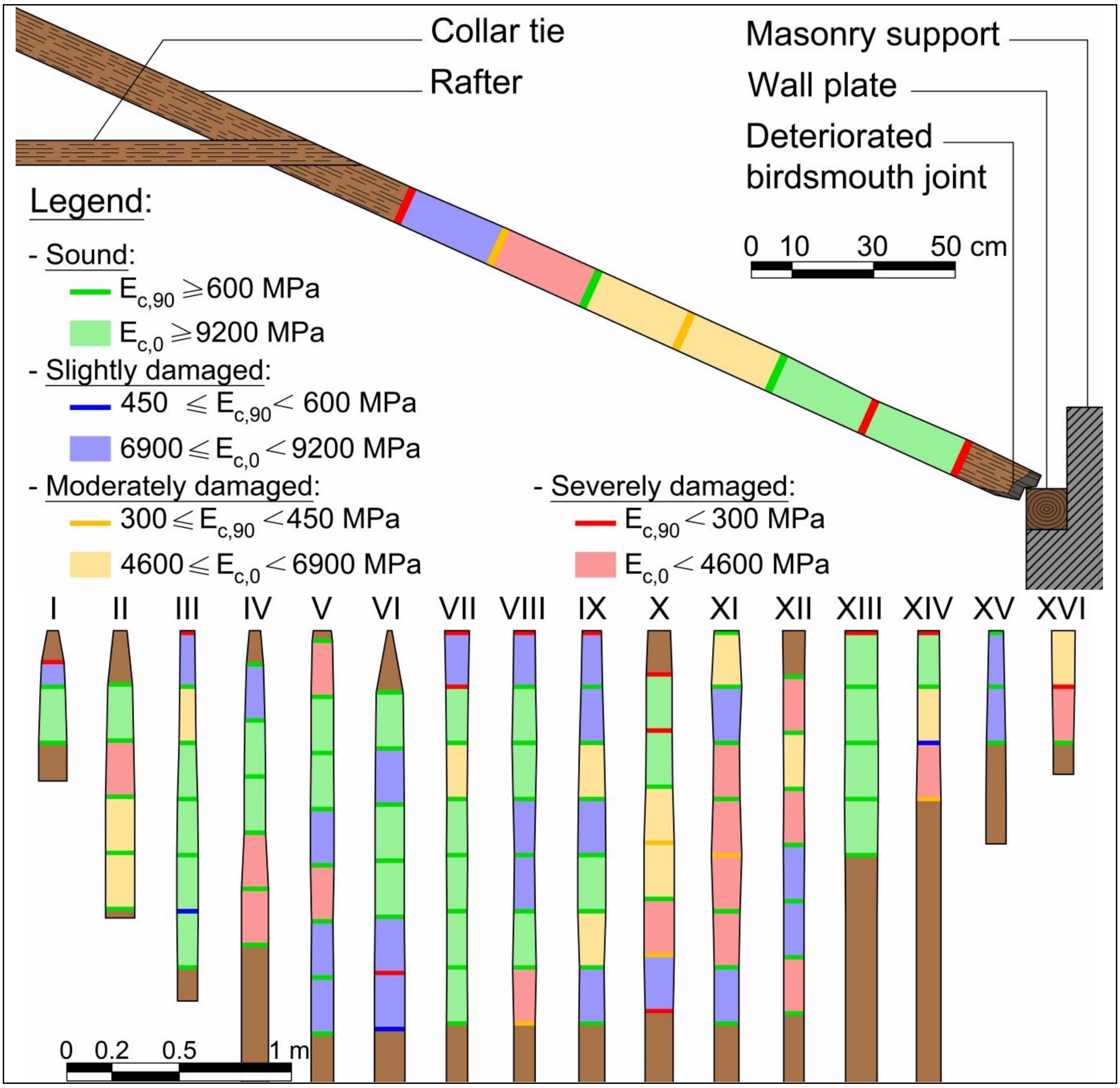


Figure 15 – Classification of external surfaces exposed to biological deteriorations, according to the wood compressive elastic modulus parallel ($E_{c,0}$) and perpendicular ($E_{c,90}$) to the grain, for the rafters in the Room 68.

Figure 16 – Resistograph® 3450 RINNTECH used for the Drilling Resistance tests.

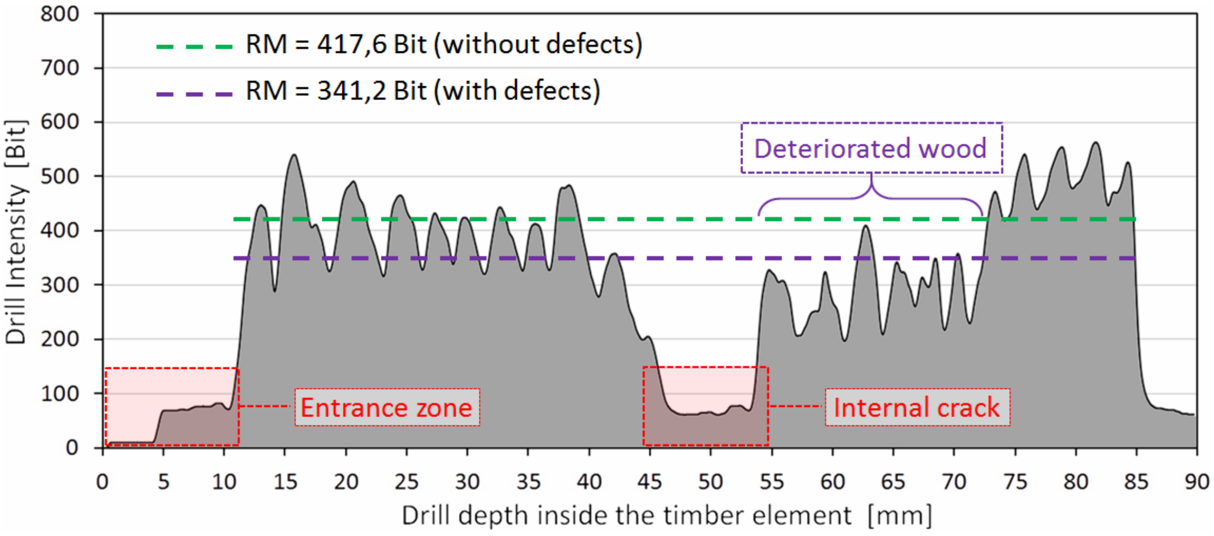
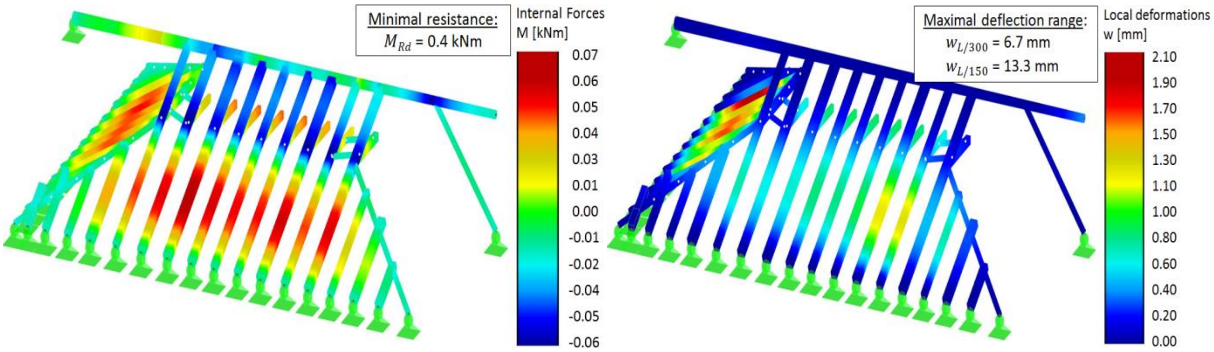


Figure 17 – Drilling resistance graph in respect with the drill penetration depth, including Resistance Measure (RM) values with and without defects.

Figure 18 – Dynamic indentor Pilodyn® 6J Forest used for the Impact Penetration tests.



(a) (b)

Figure 19 – Internal bending moments (a) and local deflections (b) within the old roof structure in Room 68.

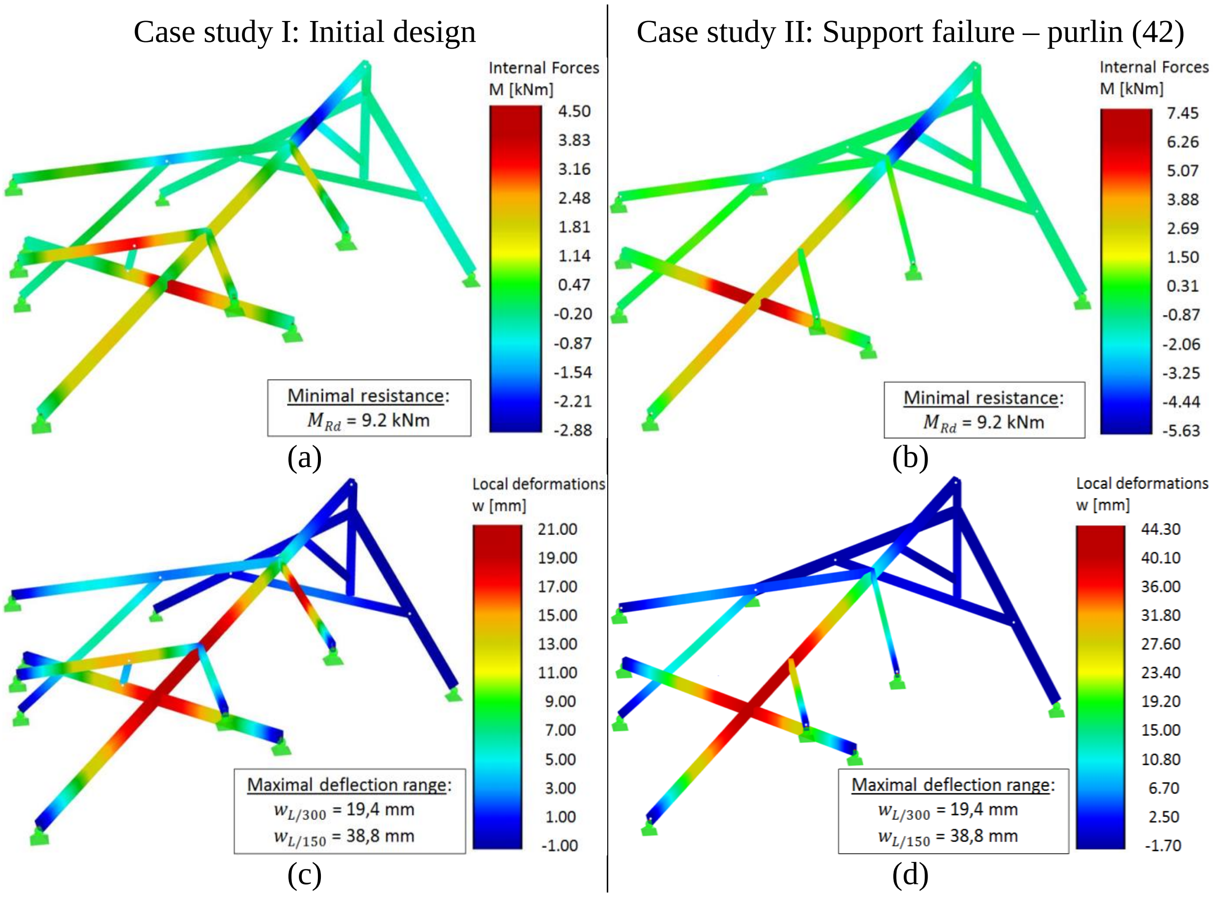
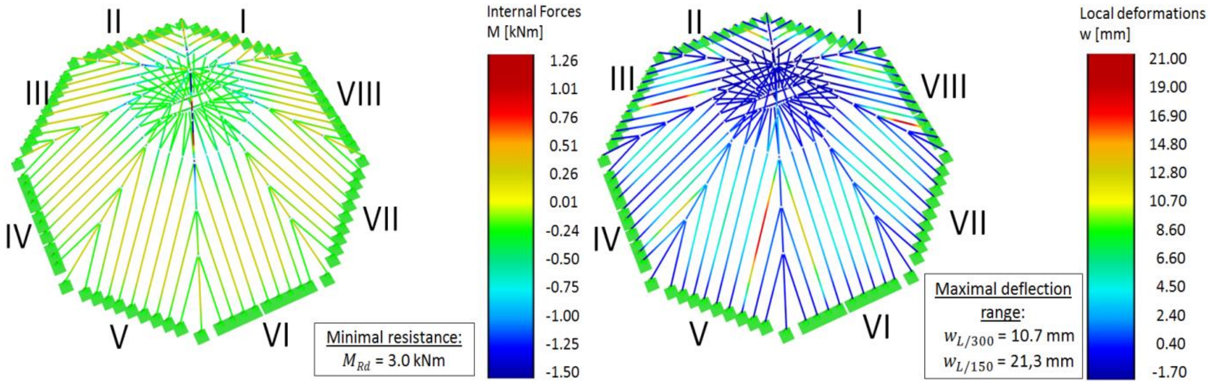
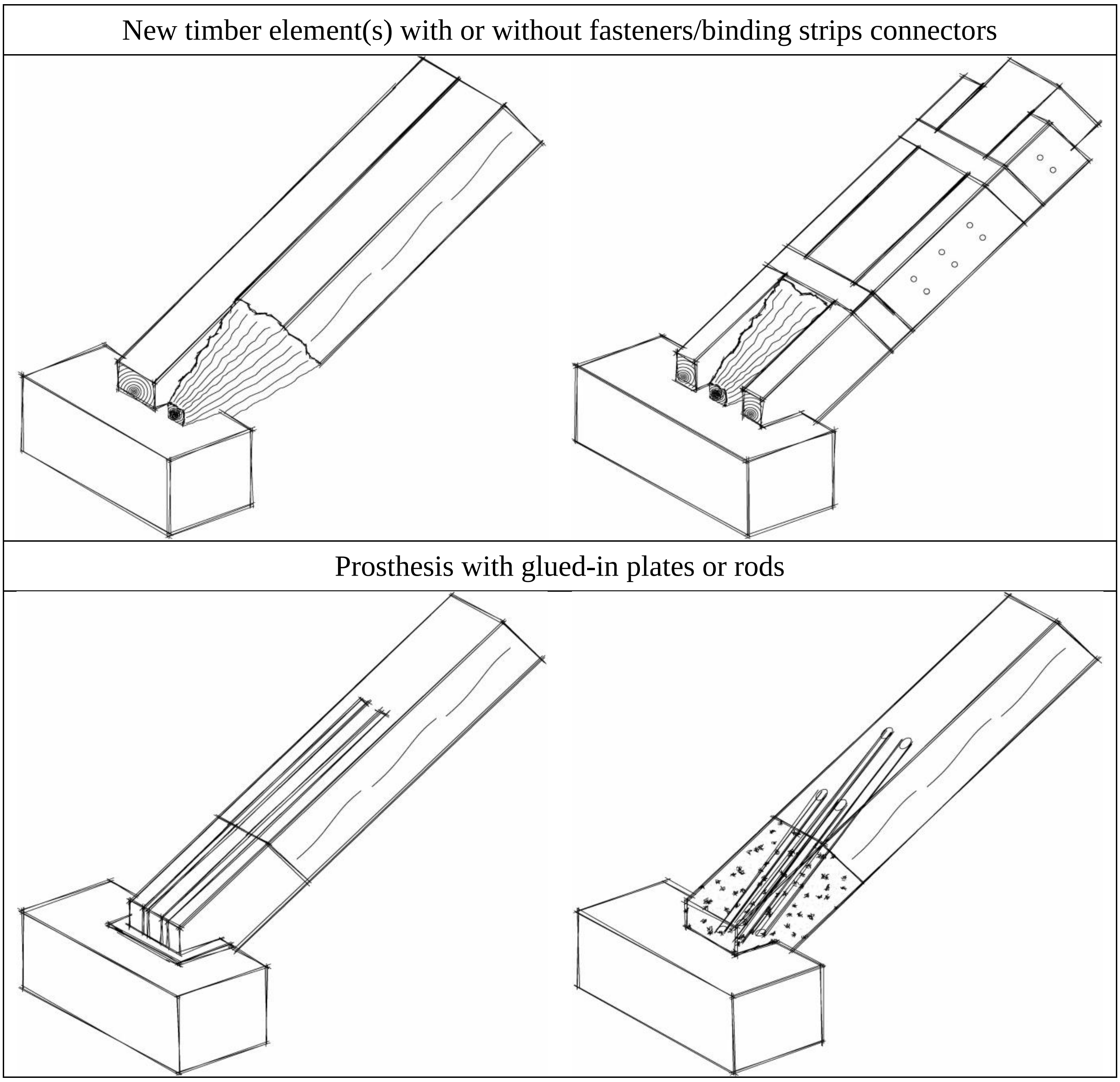


Figure 20 – Internal bending moments (a, b) and local deflections (c, d) of the carpentries set in Knights' Hall, for both case studies I (a, c) and II (b, d).



(a) (b)

Figure 21 – Internal bending moments (a) and local deflections (b) of the octagonal dome in Knights' Hall.



New timber element(s) with or without fasteners/binding strips connectors

Prosthesis with glued-in plates or rods

Figure 22 – Techniques to retrofit or repair decayed birdsmouth joints (adapted from interventions on the decayed timber beam-end [36]).

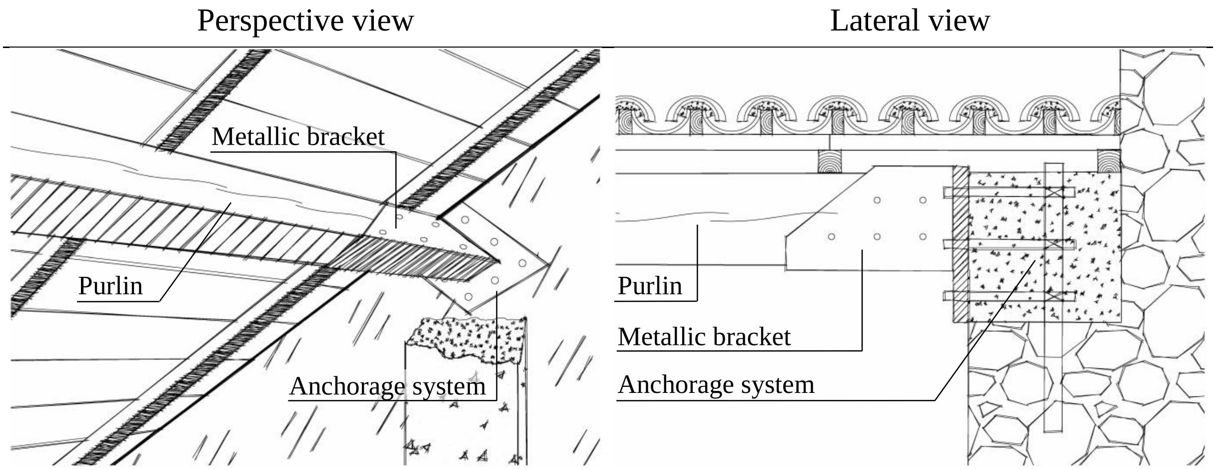


Figure 23 – Strengthening of the purlin support with a bracket anchored in the masonry wall.

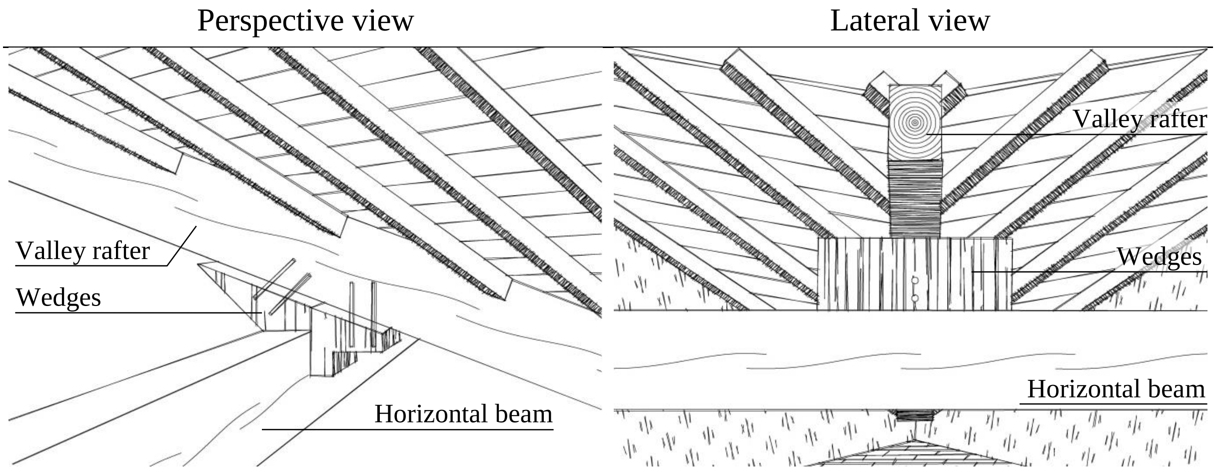


Figure 24 – Substitution of the failed horizontal beam and enhancement of the compressive contact area with the valley rafter.

Table 1 – Wood density $\boldsymbol{\rho}$ for the chestnut (*Castanea sativa* Mill.). European Standards VS dendrochronological sampling.

	ρ [kg/m³]
EN 350 [22]	540 - 650
EN 1912 [23] / EN 338 [24]	630
UNI 11035-2 [25]	550
Average of measured densities	613

Table 2 – Summary of the average Resistance Measure (RM) from the Drilling Resistance test performed in the Room 68 and Knights' Hall.

	RM [Bit] – Room 68		RM [Bit] – Knights' Hall	
	With defects	Without defects	With defects	Without defects
Average	355.6	462.6	389.2	466.2
Minimum	292.5	421.8	356.0	415.9
Maximum	417.5	525.9	415.2	544.7
Amount	33	21	9	15
SD [%]	33.2	31.2	22.3	34.3
COV [%]	9.3	6.7	5.7	7.4

Table 3 – Penetration depth of the rod $d_{p,rod}$, wood density ρ and external layer thickness of deteriorated wood t_D, inferred from the Impact Penetration test in the Knights' Hall.

	$d_{p,rod}$ [mm]	ρ [kg/m³]	t_D [mm]
Average	9	473.9	5
Minimum	4	321.5	0
Maximum	15	619.6	11
Amount	28	28	28
SD [%]	0.3	74.0	0.3
COV [%]	29.1	15.6	51.0