Selected case studies for ancient Portuguese timber structures

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Abstract
The present paper presents some of the recent activity of University of Minho, regarding case studies for Portuguese timber structures in four ancient buildings, including the Cathedral of Porto, a Church in Coimbra and a Church in Braga. NDE is combined with analysis methods aiming at non-invasive strengthening solutions or replacement of the timber structure (only as a last resort).

Introduction
Masonry and timber are traditional building materials that still face wide application today in modern building industry. Most ancient constructions adopt building systems in timber either for floors or roofs. In particular, the association of a double roofing system with a masonry vault (for fire protection) and timber roof with clay tiles (for water protection) is common in several European monuments. In general, a large number of timber structural systems remain active today in Portugal (even if a significant part of roofs have been replaced in the 20th century by light reinforced concrete slabs), which requires often an assessment of the actual safety conditions and monitoring, together with conservation and remedial measures. In the case of floors, it is also often the case that higher live loads are applied due to a change of use, which requires structural analysis and, if necessary, strengthening.

In the present paper, case studies of monuments in Portugal including roof and floor structures are briefly presented. University of Minho has been involved as a consultant in several case studies in the last five years. With the exception of the first case study, in which replacement of the structure resulted from the owner decision and extensive damage, the rest of the case studies have been solved with non-invasive and traditional techniques.

Reliquary Room of Santa Cruz, Coimbra
The origin of this monastery dates back to 1131. The reliquary room exhibits considerable deformation and cracking of a timber vault, due to deformation of the roof above it, see [1] for details. The dimensions of the room are 12.5 × 15 m² in plan, with a four-sloping roof with clay tiles and a timber lathwork vault rendered with stucco, see Figure 1.

The roof timber structure is extremely complex as a result of additions and successive attempts to correct the observed damage, see Figure 2a. Damage includes humidity stains and rotten roof sheathing (the estimate is that 30% of the sheathing needs replacing), see Figure 2b. Several truss elements exhibit excessive deformation, which is leading to cracking and damage of the lathwork vault, see Figure 2c. As a result of the deformation of the truss elements, struts and wedges supported in the timber vault have been added to the structural system.
Figure 1 – Reliquary Room: (a) plan with main vault and secondary vaults; (b) main roof structure; (c) view of lathwork vault; (d) detail of vault structure

Figure 2 – Aspects of the roof: (a) complexity of the structural system; (b) moisture; (c) excessive deformation and rotten wood; (d) defects
The wood elements are generally attacked by xylophagous insects, usually limited to the sapwood. Larger defects are also present, see Figure 2b,d, together with inefficient connections and corroded ties. The vault ribs are widely attacked by the common beetle, see Figure 3.

In order to assess the timber condition, the following techniques were used in combination with visual inspection and wood tapping: (a) Pilodyn to characterize the strength to superficial penetration [2]; (b) a chisel to inspect internal surfaces; (c) Resistograph to inspect the density profile of wood and the quality of the inner part of the logs [3]. The results indicated that only the sapwood of the structural elements is attacked and the supports of the timber logs are in good condition. The thinner elements (sheathing) are usually strongly deteriorated.

![Figure 3](image_url) – Details of the generalized infestation and the irregularity of the cross section of the ribs due the attack

![Figure 4](image_url) – Details of the replacing roof structure: (a) structure (plan, sheating and strips); (b) sections AB and CD; (c) detail of the central truss support; (d) steel beam for central truss support
Two solutions have been proposed to the owner: (a) keep the existing timber structure using new curved elements supported on the side walls (preferred solution); (b) adopt a new timber structure. The owner did not want to keep the existing roof structure due to the fact that previous remedial measures did not provide a solution and the vault was in bad conditions. Therefore, a new roof structure was designed using pine sheathing and pine truss elements, plus an ONDULINE type waterproof sub-roof system and clay tiles. It is stressed that the presence of the inner vault does not allow a traditional roof structure using a tie beam. Therefore, the solution includes four diagonal rafters and a ridge board, together with a set of purlins at mid-height of the rafters, two central trusses and four side trusses, aiming at reducing the span of the main truss elements, see Figure 4. The supports of the diagonal rafters and the side trusses will be made in existing recesses in the ring beam present in the masonry walls. The supports of the central trusses will be made in steel corbels connected to an additional beam, so that the bending moment in the masonry walls is reduced.

The steel connections of the new timber structural system are nailed or bolted with steel plates. All steel elements are made using stainless steel type AISI 316. The top ridge tiles are to be placed dry, in order to allow ventilation. The airflow is to be ensured by small plastic tubes located in the bottom part of the roof.

Figure 5 – Typical roof details: (a) roof during and after works; (b) structural details and local replacements; (c) clay tiles details
Cathedral of Porto, Porto
The origin of this building dates back to the middle of the 12th century and large conservation works have been carried out recently. With respect to waterproofing and roof structures, the works aimed at using traditional techniques and keeping remedial measures to the minimum. Remedial measures included cleaning, application of biocide, application of preservation products, consolidation, strengthening and local replacement, see Figure 5. The decision was based in continuous in situ diagnosis and structural assessment.

City Hall, Arcos de Valdevez
This case study resulted from works non-carefully carried out in the audience room of this City Hall. During general rehabilitation works of the building, a timber board and a leveling light concrete layer have been added to the floor structure without any consideration about possible structural strengthening and composite action. Afterwards, upon doubts about the load bearing capacity of the floor structure, an in situ load test has been carried out.

The load test was carried out for a live load of 3 kN/m², see [4] for more details. The oak timber structure of the floor has a span around 6.5 m, see Figure 6, being composed by: (a) a set of main beams, placed each 0.70 m; (b) secondary beams located only in the area closer to the main façade; (c) a set of transverse beams, placed each 0.46 m. On top of the transverse beams, a 24 mm thick MDF board has been laid and a 10 cm thick light concrete leveling layer as also been added. Such additions multiplied the self-weight of the floor around three times (per square meter).

The structure was visually inspected and tapped. It was possible to verify that the timber is globally in good condition and exhibits no structural damage, even if treatment against xylophagous insects in needed. Before carrying out the load test, the structure was analysed and it could be concluded that, without the floorboard, the structure would not be able to withstand the requested live load. Therefore, a safety system using temporary propping was required (minimum distance between props and floor was 50 mm, so that contact with the floor structure was impossible during the loading process).

The load test was carried out according to [5], given the lack of national or international normative. The load was applied using a flexible water reservoir without bottom, so that no favourable action from the deposit would affect the structure, see Figure 7. Nine displacement transducers were used to control the test.
The load test was carried out in four loading steps: (a) 50% of the total load; (b) 100% of the total load; (c) unloading up to 50% of the total load; (d) total unloading. Each load step lasted between 25 and 40 minutes, making a total test duration of 5 hours, including the time intervals for loading / unloading decision. Upon completion of the test, residual displacements were observed in all displacement transducers, which is normal for any *in situ* load test. Figure 8 illustrates the flexural response of beams V2 and V3. The maximum displacement measured in beam V2 is 18.3 mm, value that should be lower than 1/300 of the span for short term loading (21 mm). The average residual displacement is 9%, which is more than reasonable for this type of structure. Therefore, the floor structure can be used for a load of 3 kN/m², without strengthening.

![Image](image_url)

**Figure 7** – Load test: (a) water reservoir for load application; (b) detail of fixings for vertical displacement transducers; (c) location of reservoir; and (d) location of displacement transducers

**Figure 8** – Load test results for beams V2 and V3: (a) diagram of vertical displacements vs. time; (b) maximum displacements at mid-span and residual deformation
Our Lady of Conception, Braga
The present study aims at assessing the safety conditions of a floor structure in a church subjected to a change of use (from a choir not opened to the public in general, to a museum), see [6] for details. The floor is located in the Church of Our Lady of Conception, which dates from 1625, see Figure 9, and exhibits considerable permanent deformation (sagging).

Figure 9 – Choir floor: (a) view from below; (b) view from above

The span of this floor is large (around 9.15 m) and the structure is composed by the following elements: (a) a set of main beams, placed each 3.40 m; (b) a set of secondary beams, perpendicularly to the main beams, with a distance of 0.50 m; (c) a set of smaller cross-beams that provide support for the floorboard; (d) a set of steel props, located at one-third span of the main beams, see Figure 10a.

The main beams have a square cross-section with a size of 300 mm, as shown in Figure 10b, whereas the secondary beams have a rectangular cross-section with $65 \times 100$ mm$^2$ (see Figure 10c). The cross-beams are also square, with a cross section of $65 \times 65$ mm$^2$. The floorboard has a thickness of 30 mm. All structural elements are in chestnut, with the exception of the cross-beams, in eucalyptus and more recently laid. The floorboard is partly in chestnut (original and turned upside down from a previous repair) and partly in pine (more recent).

Again, a visual inspection was combined with tapping, in order to assess the condition of the timber. In addition, the resistograph was used close to the supports of the main beams. In general, the structural elements are in good condition, with the exception of one beam, see Figure 11. The floorboard close to the walls has a considerable reduction in the effective cross-section due to active biological attack. The biological attack in the structural elements is mostly superficial.

The floor structure was then analyzed according to EC5. The structural analysis indicated that the secondary beams, the main beams and the steel props are not sufficient to support the code live load of 3 kN/m$^2$. Therefore, strengthening is necessary. The aspects taken into account for strengthening design were: (a) keep the present floor configuration and preserve the existing materials; (b) economy; and (c) do not remove the polychromatic sheating under the floor, due to its artistic value.

The following strengthening solutions were suggested to the owner: (a) strengthening of the secondary beams, using a new set of timber beams in between the old beams, and addition of a steel profile for strengthening the main beam as a steel-timber composite beam (the steel props would be removed and the main beams would be forced back to the original position); (b) strengthening of the system by new steel columns (replacing the existing props) and, again, adding a new set of secondary beams.
Figure 10 – Timber structure: (a) plan; (b) cross-section of the main beams; (c) cross-section of the secondary beams

Figure 11 – Details about timber condition: (a) near support of a damaged beam; (b) biological attack at the floorboard; (c) Resistograph results
Conclusions
Different case studies regarding ancient timber structures in Portugal have been presented. After a period in the recent past, in which timber structures have been replaced by steel and concrete structural systems, today’s practice is back to conservation of existing timber structures.

The combination of knowledge, inspection techniques and structural analysis make possible such an approach. In the case of monuments, the type of wood (hardwood) and the quality of the construction make conservation possible in most cases. In the case of historical centers (vernacular anonymous architecture), sometimes the combination of heavy deterioration and original low cost construction, make impossible such a conservation approach.

References