Selected research and case studies in ancient Portuguese structures

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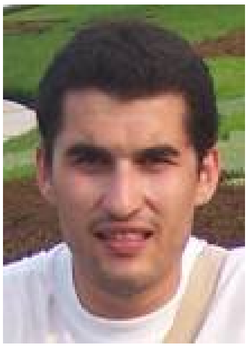


Ricardo Brites is a research Assistant since September 2004; PhD Student since February 2005 with the thesis "Safety evaluation of ancient timber structures" in UM. He has cooperated in several works with Masonry and Historical Constructions Group, UM.

Summary

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. NDT is combined with analysis methods aiming at non-invasive strengthening solutions or replacement of the timber structure (only as a last resort). Research studies carried out in UM and currently running on LNEC and UM are also presented, being showed the relevance of this research studies for the assessment and analysis of historical timber structures.

1. 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.

The process of assessment and analysis of Portuguese historical timber structures were improved by the studies developed in UM and currently taking place in LNEC and UM. These studies are briefly described and the major results of the finished research studies are presented, together with the main objectives of the currently running research.

2. Selected Case studies

2.1 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 x 15 m^2 in plan, with a four-sloping roof with clay tiles and a timber lathwork vault rendered with stucco, see Fig. 1.

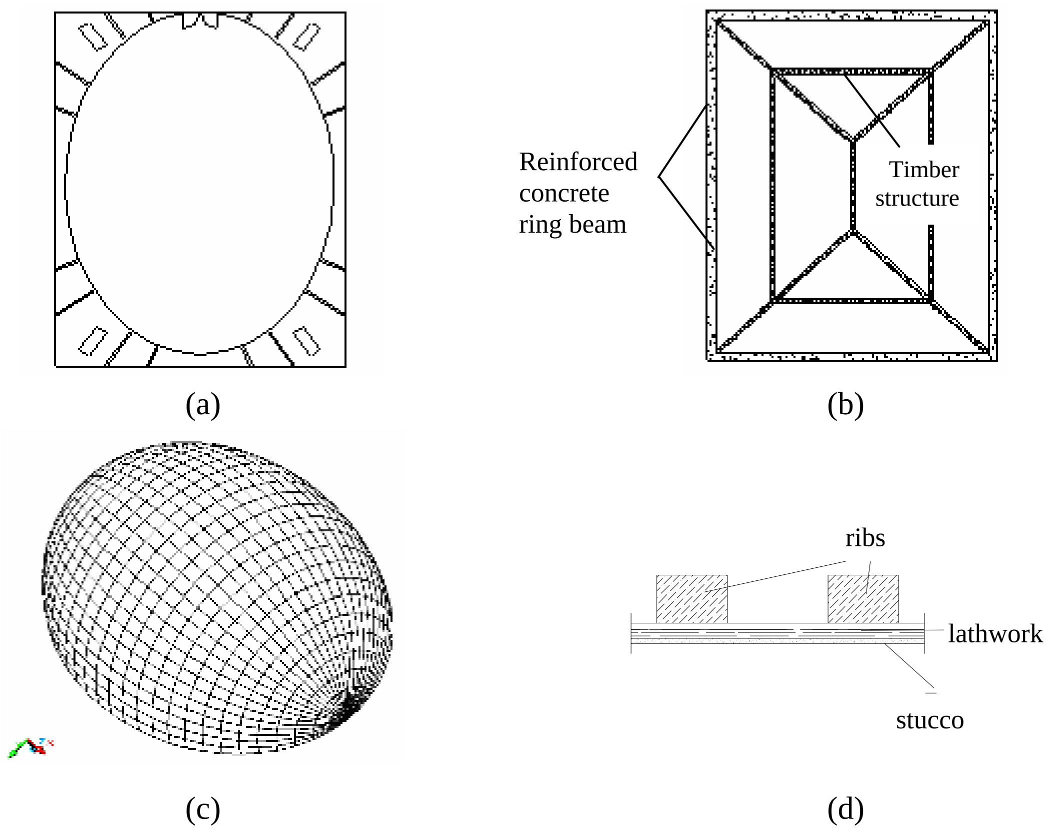


Fig. 1 Reliquary Room: (a) plan with main vault and secondary vaults; (b) main roof structure; (c) view of lathwork vault; (d) detail of vault structure

The roof timber structure is extremely complex as a result of additions and successive attempts to correct the observed damage, see Fig. 2a. Damage includes humidity stains and rotten roof sheating (the estimate is that 30% of the sheating needs replacing), see Fig. 2b. Several truss elements exhibit excessive deformation, which is leading to cracking and damage of the lathwork vault, see Fig. 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.

The wood elements are generally attacked by xylophagous insects, usually limited to the sapwood. Larger defects are also present, see Fig. 2b, d, together with inefficient connections and corroded ties. The vault ribs are widely attacked by the common beetle, see Fig. 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.

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) or (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 sheating 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.

(a)

(b)

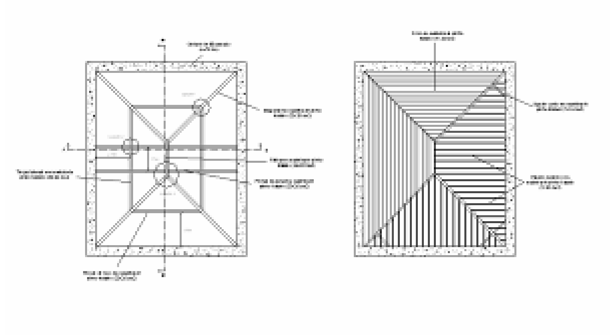
(c)

(d)

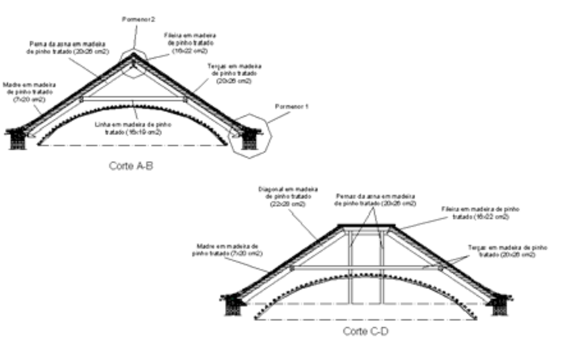
Fig. 2: Aspects of the roof: (a) complexity of the structural system; (b) moisture; (c) excessive deformation and rotten wood; (d) defects

Fig. 3: Details of the generalized infestation and the irregularity of the cross section of the ribs due the attack

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 Fig. 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.



(a)



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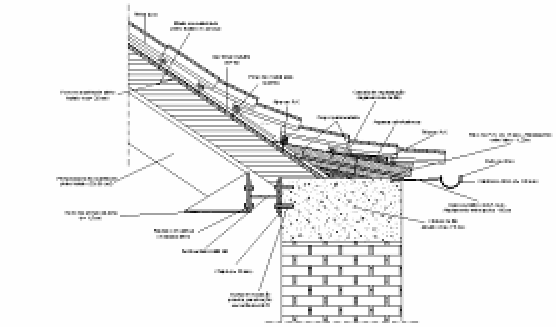

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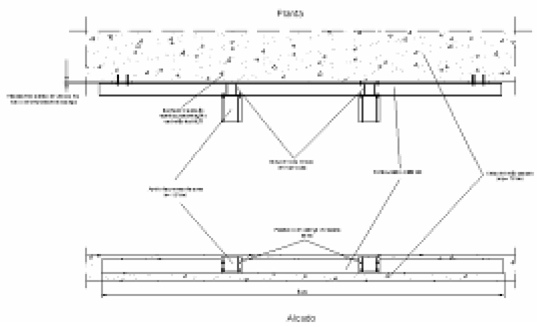

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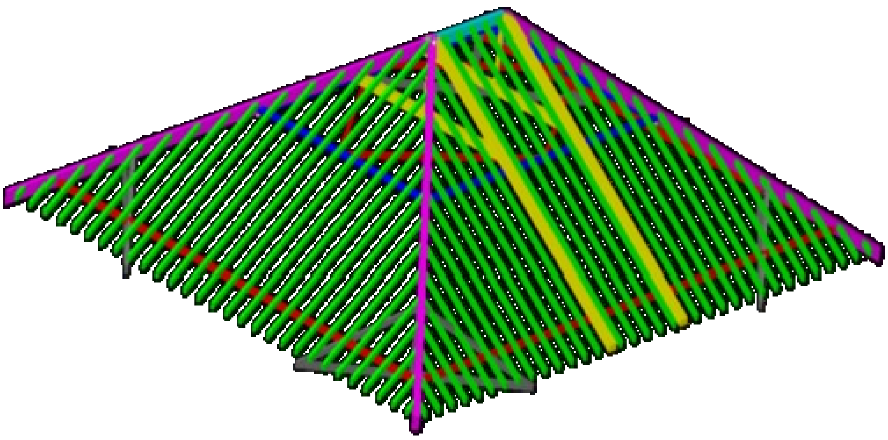


(e)

Fig. 4: 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; (e) 3D model of the new roof

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 will be ensured by small plastic tubes located in the bottom part of the roof. The final aspect of the new structure is shown in Fig. 5.

(a) (b)

Fig. 5: Final aspect of the new timber structure (a) general view; (b) new structure, above, and (old) lathwork, below

2.2 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 Fig. 6. The decision was based in continuous *in situ* diagnosis and structural assessment.

(a)

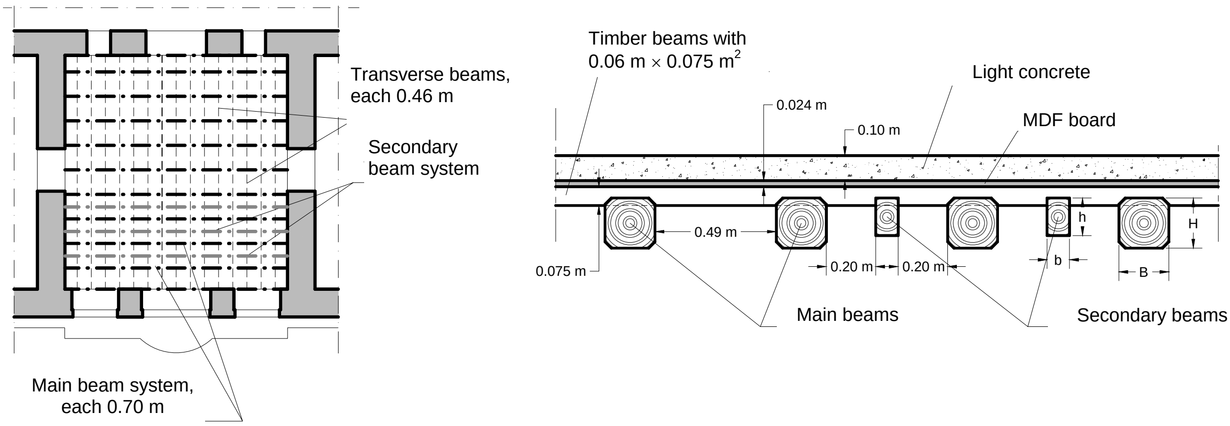
(b)

(c)

Fig. 6: Typical roof details: (a) roof during and after works; (b) structural details and local replacements; (c) clay tiles details

2.3 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 levelling 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/m^2, see [4] for more details. The oak timber structure of the floor has a span around 6.5 m, see Fig. 8, 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 levelling layer as also been added. Such additions multiplied the self-weight of the floor around three times (per square meter).



(a) (b)

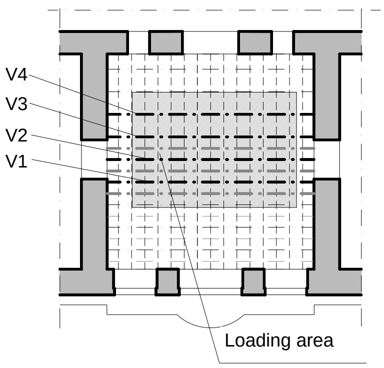
Fig. 7: Arcos de Valdevez City Hall's floor structure: (a) plan; (b) cross-section

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).

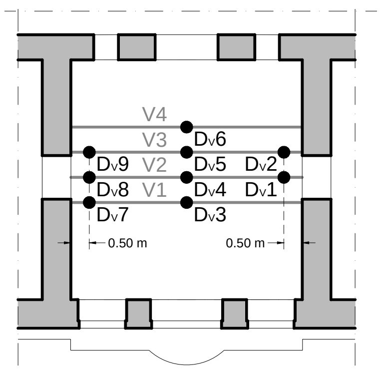
The load test was carried out according to [5], given the lack of national or international normative. The load was applied using a flexible water reservoir without bottom, so that no favourable action from the deposit would affect the structure, see Fig. 8. Nine displacement transducers were used to control the test.

(a)

(b)



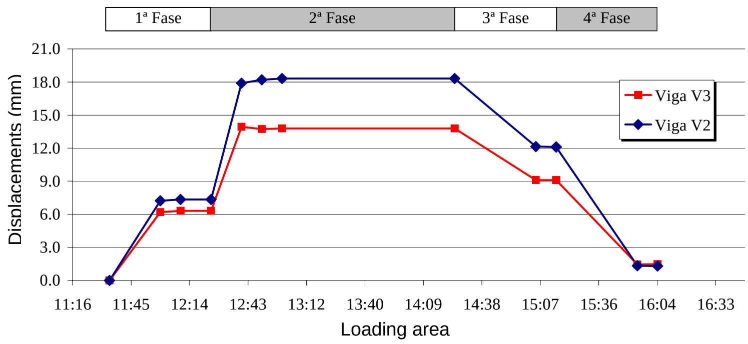
(c)



(d)

Fig. 8: 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

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. Fig. 9 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/m^2, without strengthening.



(a)

Beam	Maximum displacement	Residual displacement
V2	18.31 mm	7.15%
V3	13.93 mm	10.56%

(b)

Fig. 9: Load test results for beams V2 and V3: (a) diagram of vertical displacements vs. time; (b) maximum displacements at mid-span and residual deformation

2.4 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 dates from 1625, see Fig. 10, and exhibits considerable permanent deformation (sagging).

(a)

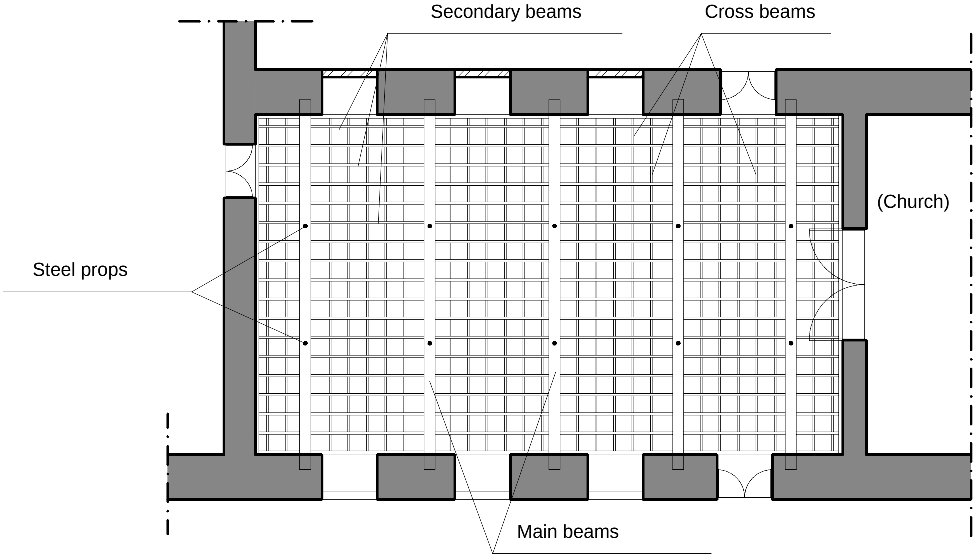
(b)

Fig. 10: Choir floor's views: (a) from below; (b) from above

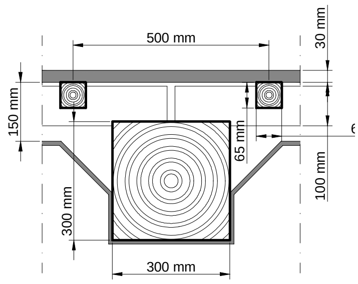
The span of this floor is large (around 9.15 m) and the structure is composed by the following elements: (a) a set of main beams, placed each 3.40 m; (b) a set of secondary beams, perpendicularly to the main beams, with a distance of 0.50 m; (c) a set of smaller cross-beams that provide support for the floorboard; (d) a set of steel props, located at one-third span of the main beams, see Fig. 11a.

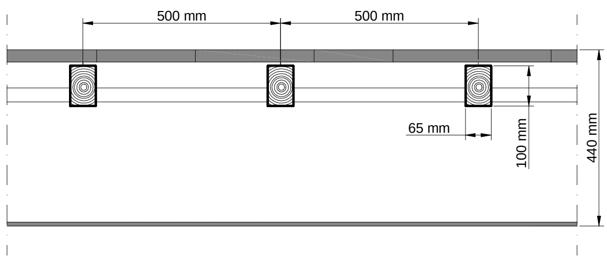
The main beams have a square cross-section with a size of 300 mm, as shown in Fig. 11b, whereas the secondary beams have a rectangular cross-section with 65 × 100 mm^2 (see Fig. 11c). The cross-beams are also square, with a cross section of 65 × 65 mm^2. The floorboard has a thickness of 30 mm. All structural 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).

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 Fig. 11a. 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.



(a)





(b) (c)

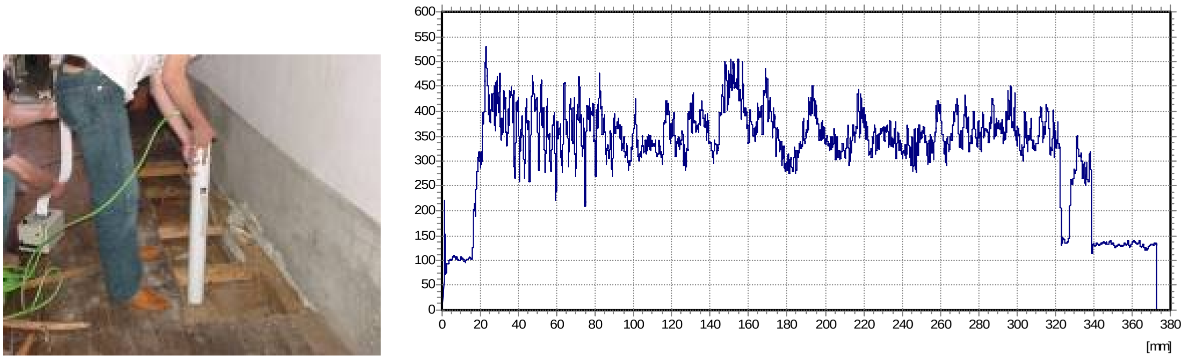
Fig. 11: Timber structure: (a) plan; (b) cross-section of the main beams; (c) cross-section of the secondary beams

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 enough 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.

(a)

(b)



(c)

Fig. 12: Details about timber condition: (a) near support of a damaged beam; (b) biological attack at the floorboard; (c) Resistograph results

3. Recent research in ancient timber structures taking place in U.M. and L.N.E.C.

In the last years, the Masonry and Historical Constructions Group of University of Minho has made some research studies, aiming a better and profitable assessment of ancient Portuguese timber structures, namely NDT correlations with destructive tests and structural behaviour.
It were tested several NDT correlations to chestnut wood (*Castanea sativa Mill.*), see [7] for details, due to its wide use in Portuguese historical timber structures, namely in the northern region of Portugal. In fact, the chestnut became dominant and indispensable for the survival of mountain populations, and this wood was considered as a noble wood, being used in palaces, castles or in the interior of churches. In the south of Portugal, Pine predominates.
The main results obtained in these studies will be now briefly described the and will be presented the research projects actually running in this area in University of Minho (UM) and National Laboratory of Civil Engineer (LNEC).

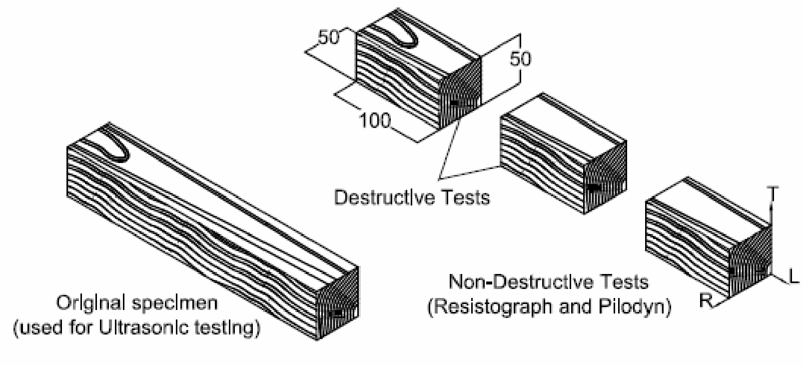
3.1 Non-destructive and destructive tests in new and old chestnut wood

Feio [7] made an experimental set-up in order to establish the mechanical properties of chestnut wood (*Castanea sativa Mill.*) by destructive and non-destructive tests in small clear test specimens, for new and old chestnut wood. Chestnut was chosen due to its wide use in historical timber structures in Portugal and the lack of knowledge about the mechanical properties of the old chestnut wood, used in some historical buildings.

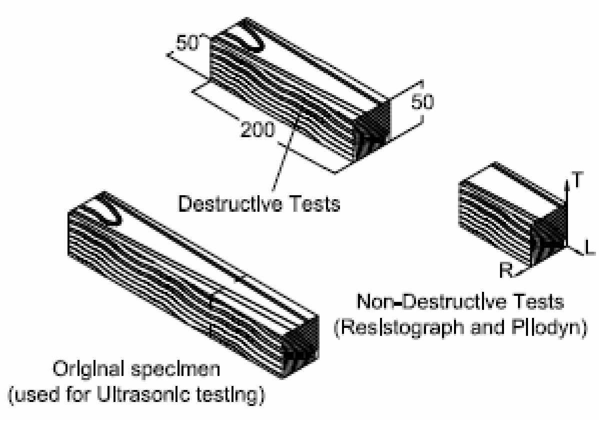
The main result obtained of this study is that the mechanical properties of the old chestnut wood (removed from an existing structure) are not worst than the new one, i.e., the mechanical properties obtained by destructive and non-destructive tests in old chestnut wood produces equal or even better results than the same tests made in new chestnut wood, for small clear test specimens. Hence, the chestnut wood has not suffered any mechanical damage during his lifetime, and therefore, the safety assessment of historical chestnut structures can be analysed with the same mechanical properties of new chestnut wood.

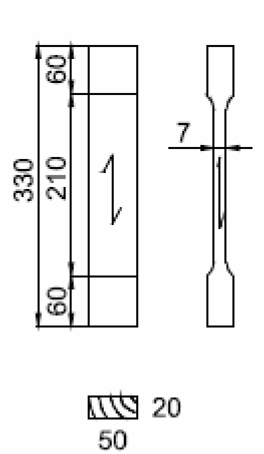
This work involved about 370 destructive tests (160 for compression perpendicular to the grain, 94 for compression parallel to the grain and 114 for tension parallel to the grain), half of these new chestnut wood (NCW), and the remaining, old chestnut wood (OCW). There were also made a set of non-destructive tests for correlation with the latter ones, namely Pilodyn, Resistograph, and Ultrasonic tests, see Fig. 13.

The load carrying capacity of traditional timber joint was also evaluated in this work, being compared destructive tests results and a FE model created for this purpose, with different mechanical properties, in order to formulate a sensitivity analysis.



(a)





(b) (c)

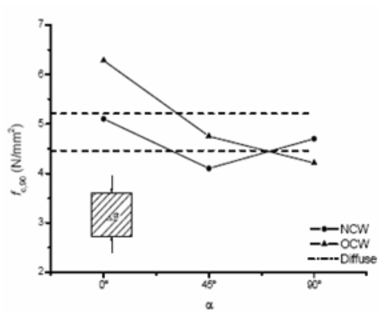
Fig. 13: Test specimens prepared by Feio[7]: (a) for compression perpendicular to the grain; (b) for compression parallel to the grain and (c)for tension parallel to the grain

Carried out tests allows to conclude that density has a significant influence on wood mechanical properties but cannot explain their variability and should not be relied upon as a predictor for mechanical properties, because the correlations obtained between density and mechanical properties are rather poor. In addition, the results indicated that a clear definition for the conventional compressive strength perpendicular to the grain is required. In particular, the characteristic value proposed by the EN 384 [8], and used as a design basis, seems to be unsafe and unable to provide a true indication of the compressive strength, see Tab. 1. Finally, an appropriate test method for tension parallel to the grain, defining the geometry and loading conditions, must be developed and standardized, since difficulties where found when using the Brazilian standard NBr 7190 (1997).

		Characteristic compressive strength values (N/mm²)							
		Radial		Diagonal		Tangential		Diffuse	
		NCW	OCW	NCW	OCW	NCW	OCW	NCW	OCW
EN 384	$f_{c,90,k}$	7.49	8.34	7.79	7.88	7.59	8.32	8.35	7.96
Exp. Tests	$f_{c,90,05}$	4.70	4.21	4.10	4.75	5.10	6.28	5.21	4.43
	$f_{c,90,mean}$	7.45	7.74	6.99	6.67	6.58	7.47	6.22	6.81

Tab. 1 – Experimental and Normative values for tension perpendicular to the grain, according to Feio [7]

Novel single-parameter linear regressions have been proposed for density, elasticity modulus and tensile/compressive strength parallel and perpendicular to the grain, using the Resistograph, Pilodyn and ultrasonic testing. The global conclusions are that, with respect to density, the Resistograph and the Pilodyn provide reasonable correlations. With respect to mechanical characteristics, correlations need a re-calibration with the wood population. As this is not reasonable for practical purposes, expressions with a lower 95% confidence of the mechanical parameters have been proposed for the ultrasonic testing. The usage of the Resistograph and the Pilodyn to obtain quantitive mechanical data is not recommended, due to the high dispersion found.



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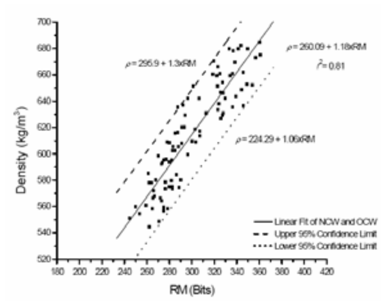

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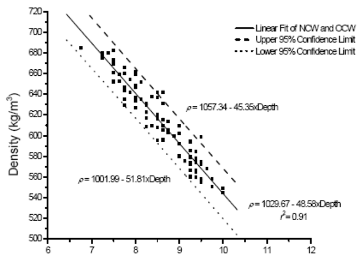

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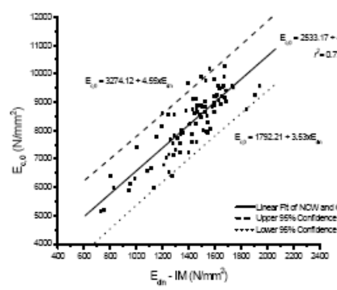
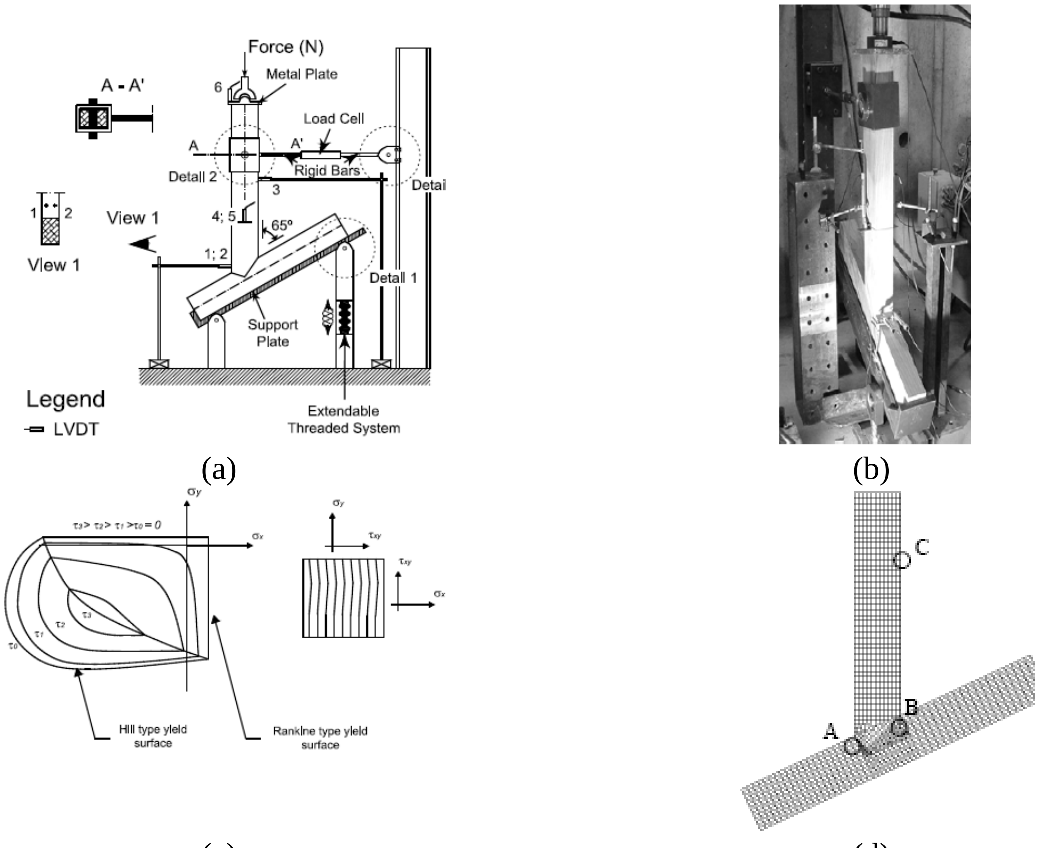


(d)

Fig. 14: Some of the key results obtained by Feio[7]: (a) compression perpendicular to the grain vs. angle; (b) Density vs. resistograph measure; (c) Density vs. Pilodyn depth; (d)$E_{c,0}$ vs. E_{din}, obtained by the indirect method;

The behaviour of a traditional mortise and tenon joint has been investigated experimentally and numerically under monotonic loading conditions, and a good agreement has been found between the numerical results and the experimental data, see Fig. 15. The experimental analyses allowed a better understand of the behaviour of the connection and discuss the influence of defects in the mechanical behaviour. The sensitivity of the results to the various material parameters, such as the normal and tangential stiffness of the interface, the elastic modulus of elasticity and the compressive strength, can be tested using a numerical approach. These models show that the influence of the interface stiffness between the two timber members is significant for the response. The proposed compressive constitutive material model (anisotropic Rankine-Hill composite yield criterion, with different strength values for tension and compression) improved the predictions of local and global behaviour, and was shown to be effective in the prediction of strength and stiffness properties of the tested specimens.



(a) (b)

(c) (d)

Fig. 15: Behaviour of the traditional mortise and tenon connection: (a) experimental set-up developed by Feio [7], (b) photograph of the test apparatus; (c)adopted constitutive model for FE analysis; (d) numeric model

The investigation led to an improvement of the global structural analyses of traditional timber structures, providing valuable information for the transition from classical schemes (hinged or fixed joints) to more sophisticated analysis with semi-rigid joints. In addition, the failure modes and the better understanding of the behaviour of the joint provide a clear guidance for strengthening strategies in this type of traditional timber joints.
Finally, the usage of non-destructive testing confirmed the good correlations between ultrasonic testing and the ultimate strength of the joint or the stiffness of the joint. Even if, the usage of the

novel correlations in engineering applications is questionable due to the small sample of joints tested, the results indicate clearly that, at least, adequate condition survey of existing joints using non-destructive testing is possible.

3.2 Modelling of the decay of timber structures

One of the main problems regarding the structural survey of timber structures is the assessment of the mechanical properties of their elements.
This problem is even grater if the structure has suffered from decay, because there are no direct prediction models for the decrease of mechanical properties due decay (the models actually used correlates the loss of mass with the loss of mechanical properties, but this is not useful for practical situations).
In order to overcome this issue, it has been started in National Laboratory of Civil Engineering (LNEC) a set of experimental studies regarding the definition of a model to help the survey of the remaining strength of existing structures, which have suffered a fungal attack. The aim of this study is to develop a relationship between the exposure time to fungal attack, the depth of that attack and the remaining load carrying capacity, in order to allow a prediction of the load carrying capacity.
The decay produced by fungus is very similar to the reduction of mechanical properties due fire in timber structures, therefore, the main idea is to develop a method based on that one. Hence, it will be calculated the rate of penetration of fungal attack per unit of time and, based on that, a relationship between time of exposure and remaining load carrying capacity.
The accurate determination of the depth of the attack will be made using FTIR analysis to define the rotted area, and the mechanical properties will be established by destructive and non-destructive tests, for correlations, in test specimens subjected to several exposure periods. It will be used several cross-sections, in order to establish the influence of the area/perimeter ratio in the results.
The apparatus to create decayed test specimens is to place them into a tube filled with an optimum environment for the development of fungus, composed by sawdust, LECA, vermiculite and malt extract, together with the fungus itself. In Fig. 16 is shown come decay columns actually mounted in LNEC. There will be used pine wood (*Pinus Pinaster ait.*) and chestnut wood (*Castanea Sativa Mill.*) in these tests, due to it wide use in Portuguese timber structures.

(a)

(b)

(c) (d)

Fig. 16: Decay tests currently running on LNEC: (a, b) mounting of a decay column; (c)Detail of the mixture used to fill the tube; (d) incipient decay detected in some test specimens

4. 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 centres (vernacular anonymous architecture), sometimes the combination of heavy deterioration and original low cost construction, make impossible such a conservation approach.
The recent studies in historical timber structures that is taking place in UM provides a valuable contribute for the assessment of existing Portuguese timber structures, allowing a more reliable knowledge of his behaviour and hence minimizing the intervention and the respective costs. The research that currently takes place in LNEC will give a step further in the assessing of historical timber structures that have some decay problems, that represents the majority of them.

5. References

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