

Estimation of Timber Members' Properties Combining Direct and Indirect Information: Two Applications

D. Henriques^{1,2}, A. Cândido¹

¹ ISEL-Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa

² CERIS - Investigação e inovação em engenharia civil para a sustentabilidade

* Corresponding author, e-mail: (of corresponding author)

Received: 13 December 2016 / Accepted: 20 September 2017

This paper was presented in SHATIS'17 (4th International Conference on Structural Health Assessment of Timber Structures)

Abstract: In conservation or rehabilitation works of ancient buildings serious doubts are often raised about the real condition of its structural timber members. Improving the practical knowledge upon visual and local recognition of the members in service and their connections is therefore of huge importance. This subject is nowadays under discussion and international committees (RILEM, COST E55, COST IE0601, COST FP1101) have recently promoted some guidance documents to support actions to assess the structural condition of timber members.

This research presents two practical situations. The assessment of two pine wood structural elements included in historic buildings located in the center of Lisbon city: a timber floor and a timber roof truss. These structural elements, composed for several timber members were submitted to: i) visual strength grading according to national and international standards; ii) semi-destructive testing; iii) safety assessment. Methodologies for property estimation of timber members in service are applied and their results discussed.

Through the development of this study it became clear the importance of visual inspection for this kind of cultural heritage buildings. The use of a visual strength grade standard specific for timber members in service is also very important. In this case, the standard used accepted four beams that would have been replaced if only other methods had been used. On the other hand, the closer estimation of the density of the elements leads to a more real safety assessment. This study gains great relevance in the current reality in which the industry of building rehabilitation is on the rise but is not always accompanied by the necessary technical knowledge of the technicians involved and often leads to the removal of timber structural members in perfect physical and mechanical conditions..

Keywords: Timber members, Ancient buildings, Mechanical properties, Visual strength grading, NDT/SDT

INTRODUCTION

1 INTRODUCTION

Evaluation of ancient timber structures in service has become a subject of great interest in the last decades. In fact, this initial evaluation deeply influences the crucial decisions in the process of rehabilitation. But the problem faced by the technicians remains as twenty years ago “the lack of data about the real load bearing capacity of ancient wooden members, due to a diffuse bad knowledge of wood mechanical properties by architects and engineers and to a lack of appropriated standards about the mechanical grading of old wood. From this situation derives the need of an in situ diagnostic technique, based on reliable and quick non-destructive technologies, from which is obtained some data about the structural characteristics of each single wooden member” [1].

In this sense, research on the knowledge of the resistant properties of timber structures in service in old buildings and their evaluation processes have been intensely developed by the scientific community in recent years. Several international committees (RILEM, COST E55, COST IE0601, COST FP1101) have recently promoted some documents to support actions to assess the structural condition of timber elements [2, 3, 4, 5].

The physical-mechanical assessment of timber on site by non-semi-destructive methods (NDT / SDT) has been the object of important studies involving laboratorial research for over three decades [6, 7, 8, 9, 10, 11, among others]. A state-of-the-art report on “Combined use of NDT / SDT methods for assessment of structural timber members”, promoted by COST FP1101, has recently been published, gathering opinions from the most eminent European researchers on the subject [5]. While stress waves, spectrography, tomography and other methods have provided promising results, drill resistance and penetration resistance tests deserve to be in the limelight for their simplicity of use and the relative adequacy of the response to the objectives. The mechanical strength, modulus of elasticity and density, have been correlated with drill resistance and with penetration resistance results and shown as useful methods for assessing wood [10, 11, 12, 13, 14, 15].

Core drilling is a multifunctional semi-destructive method (SDT) of great utility, since it makes direct readings, providing information on wood species, water content, resistance and density [16]. It can also be used as a method of calibrating the data obtained indirectly by the correlation with the tests of resistance to drilling and penetration. The authors of [17, 18] have developed several techniques to obtain other resistance parameters from the carts extracted from structural elements, such as tensile strength and compression, which have been shown to be more accurate than indirect readings.

Density knowledge is critical since it is an important property due to its direct positive impact on the strength and stiffness of the wood. This parameter is also used to predict the modulus of elasticity. Density can be estimated using SDT methods as core drilling, drill resistance and penetration resistance [14, 16, 19].

Regarding the attribution of parameters of strength and stiffness to timber members in service, several authors indicate that visual strength grading (VSG) will remain as the basic method for assessing the mechanical performance of timber members in situ [11, 20, 21]. Quantification of the original mechanical resistance is related to the presence of natural defects such as knots, slop of grain, cracks and others, through the definition of quality classes by the application of national standards. However, VSG standards were developed having in mind the grading of sawn timber at sawmill yards. So, the full application on site of the rules applied at the sawmill yard is not possible or logical and leads to gross underestimation of the real mechanical performance of timber members [21]. Several studies agree on the fact that the sole use of the VSG method can lead to the demolishing of safe structures and that other NDT/SDT methods should be used to ensure a proper assessment procedure. Combined with

a visual grading survey, these evaluation methods are an excellent complement to achieve a proficient level of reliability in the structural analysis, diagnosis and inspection of existing constructions [22]. But an important characteristic of several ancient timber structures is that they can effectively bear higher loads than expected [20], which stresses the need of adequate procedures for diagnostic and assessment of the real bearing capacity [22]. UNI 11119:2004 is a standard that establishes criteria for the diagnosis of old timber elements and strength grading and can be performed using both on-site inspections and NDT techniques. This standard and the authors of the document [4] propose conditioning the VSG upon the stress condition and the position of defects in relation to applied stress [21].

2 SURVEY DEVELOPMENT

2.1 Timber structures

This work presents two practical situations located in the center of Lisbon city in which evaluation conditioned the future use of the structure. The first case was performed by [23] in which a wooden floor with a structure of 14 joists of a XIXth century palace was assessed. The second case is a timber truss representative of all roof in an early XXth century wooden building.

2.2 Materials and methods for diagnosis

First step for the in-situ assessment of old timber beams is usually the visual inspection. It can be done thoroughly, but generally the main information on the history and actual conditions of the material is achievable through this kind of approach [24]. In this sense, preliminary stage of survey consisted in a general assessment of timber structure, acknowledgement of its main defects and risks as well as a first approach of identification of the wood species. There was also carried an historic and technical survey about the target building. The structural frames of the chosen areas were also analyzed, regarding the construction processes, wood species and moisture content of the wood. There were made five to seven moisture content readings per element, with the purpose of allowing a proper evaluation of the average moisture content in each area. Two different moisture meters were used: one using the resistance method and another using the capacitance method (see [25]).

In this stage, it is also important to ensure, whenever possible, conditions of accessibility, lighting and cleaning, for the next survey stage [4].

The second and more detailed stage of survey consisted in a thorough visual inspection and application of non-destructive inspection techniques [4]. Wood was tested initially using a cutting object (knife or chisel) and a scale, both to check fissure deep and width, as well as surface integrity. This kind of sharp tools can also be used to evaluate the progress of biological degradation, by detecting soft or disintegrating material. For this purpose, a series of micro-drilling tests with the Resistograph® IML Resi-B-1280 regulated to a penetration speed of the needle of 20 cm/min were carried out. The residual cross section could be estimated on this basis. All measuring obtained data was later registered using 3D design software. Based on the service situations of each timber structure, the use classes from EN 335-2:2011, related with the hazard of biological attack were defined.

Then a series of penetration resistance tests was carried out with the Pilodyn® 6J equipment in each timber member taking the caution of performing the test in the radial direction of the growth rings, whenever possible. This test gives direct information on the surface hardness of the wood and indirectly on its density [26].

To predict the mechanical strength of each timber member by Visual Strength Grading (VSG), there were followed two different standards: Portuguese NP 4305:1995 and Italian UNI 11119:2004. Visual grading assigns quality grades to wood elements, which are related with strength grades and corresponding mechanical properties, such as: characteristic value, modulus of elasticity, shear modulus, material density, bending strength, and compression strength both parallel and perpendicular to the grain.

Portuguese visual strength grading standard applies to maritime pine wood (*Pinus pinaster*, Ait.) for structural purposes graded in sawmill. Its objective is to estimate the mechanical strength and stiffness through visual evaluation, covering aspects as: wood density; presence of pitch; occurrence of defects such as knots, slop of grain and resin pockets; wane; damaged material due to biological degradation, shakes and distortion. EE (special structural timber) and E (regular structural timber).

Italian visual standard establishes objectives, procedures and criteria in the evaluation of the state of conservation and assessment of load-bearing timber members in service in cultural heritage buildings. This standard considers the evaluation of a critical zone, which corresponds to the most stressed area of the element, considering visible surface alterations and/or defects that can influence strength and stiffness characteristics, thus influencing mechanical performance of the timber element. The analysis of these defects should be made over a minimum length of 150 mm, which can be extended if the critical section is close to the end of this range. For diagnosis purposes, only the residual resisting cross sections should be considered. This standard includes three quality grades (I, II, III) which are related with verified aspects on site such as wane, single knots or group of knots, slope of grain, shrinkage checks, frost cracks and ring shakes.

2.3 Safety assessment

According to the Eurocode 5 (EN 1995:2004) safety checks are related with ultimate limit states (bending, shear and torsion) and serviceability limit states (deflection and vibration). This study presents the safety assessment deal with the ULS of bending and the SLS of deflection for the timber floor joists. In fact, this limit states are usually the most penalizing. The defined load combinations were based on Eurocode 0 (EN 1990:2009). For the timber truss were checked the safety measures related to all limit states.

2.4 Background

Estimation of the wood density was based on studies by [19] who correlated the resistance to penetration of the wood with its density applying the dynamic impact method. The method consists of introducing a metal pin in the timber with a given energy. The penetration depth obtained is inversely proportional to the timber hardness in the cross-section and can be used as a measure of the timber's density [26]. This research was carried out with different pine timbers (*Pinus pinaster* and *Pinus sylvestris*) new and collected in two buildings that were 80 and 150 years old. The 65 samples used were free of defects, with both sapwood and heartwood and with the fibres parallel to the piece axis. It was obtained a very good correlation with a determination coefficient $r^2=0,80$ using the Pilodyn 6J Forest equipment.

The equation (1) of the correlation model [19] is shown below.

$$Pd = -0.0312 \rho + 33.043 \quad (1)$$

where: Pd = penetration depth (mm), ρ = density of the pine wood

3 TIMBER FLOOR

3.1 Presentation

The timber floor was composed by fourteen joists and two sets of blockings (Figure 1). It makes up the floor of a division on the top level of a Lisbon’s palace dated from 1877. This floor is a valuable component of ancient interiors due not only to its historical value but also to the rich stucco-decorated ceiling that it supports.

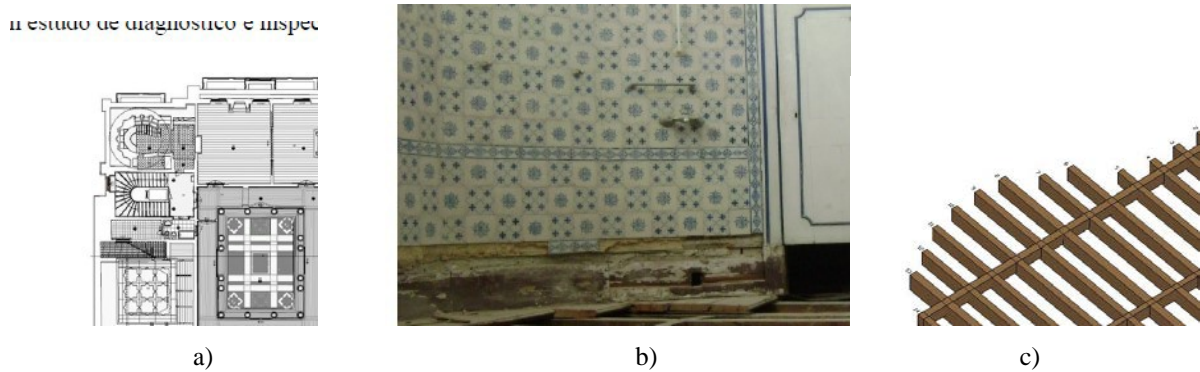


Figure 1: Timber floor: a) location in the building; b) view; c) structure draw

3.2 Survey results

3.2.1 Visual characteristics

Based on NP EN 335-2:2011 studied area was classified as use class 1. At inspection, the room had a temperature medium of 23°C and Relative Humidity medium of 58%. The timber elements don't shown signs of high moisture content nor in the present situation nor in the past. The moisture content medium measured was within the expected values (Table 1). The area was well lighted and wide thus easing handling of inspection equipment. In four joists, the n.º 3, 8, 11 and 13, was verified biological damage caused by boring beetles attack, identified for a rough surface and the presence of sawdust. The wood was identified as pine, probably maritime pine. The VSG according to the standard NP 4305 (related to maritime pine in sawmill) was done to each joist covering aspects as: presence of pith; growth rate; occurrence of defects such as knots, slop of grain and resin pockets, wane, cracks and distortion. The class assignment was done not considering biological degradation. The VSG f according to the standard UNI 11119 (related to all timber species in load-bearing structures' members) was done to each beam considering the position of defects in relation to stress condition who is for all joists in the mid span. The critical sections were defined there.

Data of visual characteristics is presented in Table 1.

Table 1: Characteristics of timber floor members obtained on-site.

Joist n.º	Length [m]	Section* [cm]	M.C. [%]	Grade NP 4305	Grade UNI 11119
1, 3	1.98	22x9	10.9±0.5	E	II
2, 4, 5, 14	1.73 to 2.20	22x9	10.1±0.2	E	I
6, 12, 13	2.82 to 3.20	22x8.5	9.4±0.6	E	I
7	3.33	22x9	9.7±0.6	EE	I
8	3.89	21x11	10.0±0.3	E	III
9, 10	3.88 to 3.95	22x9	9.8±0.8	E	I
11	3.69	21x8.5	10.4±0.3	E	I

* Section of sound wood

3.2.2 Reference properties

Two reference properties for the studied floor are presented in table 2. Density was estimated through the penetration resistance method. Average modulus of elasticity on bending was estimated by VSG using two different standards: NP 4305 and UNI 11119 for pine wood.

Table 2: Properties obtained from SDT and Grading Standards.

Joist n.º	Pilodyn®			NP 4305			UNI 11119			
	Penetration depth [mm]	$\rho_{m,SDT}$ [kg/m³]	Grade	Strength class EN 338	$E_{0,mean}$ [GPa]	$f_{m,k}$ [MPa]	$\rho_{m,VSG}$ [kg/m³]	Grade	$E_{0,mean}$ [GPa]	$f_{m,k}$ [MPa]
1, 3	18,1±1,5	479	E	C18	9	18	380	II	12	10
2, 4, 5, 14	18,4±1,8	469	E	C18	9	18	380	I	13	12
6, 12, 13	17,2±1,8	508	E	C18	9	18	380	I	13	12
7	17,8±0,4	489	EE	C35	13	35	480	I	13	12
8	18,5±1,9	465	E	C18	9	18	380	III	13	8
9, 10	18,0±1,1	483	E	C18	9	18	380	I	11	12
11	17,5±1,7	496	E	C18	9	18	380	I	13	12

As shown in table 2 the estimated values of density by SDT are much higher than those corresponding to the strength classes of EN 338. This can succeed due to particular characteristics of the wood species under assessment.

Considering the modulus of elasticity, it is also clear in table 2 that the values estimated through the grade attributed by UNI 11119 are much higher than those by NP 4305.

3.2.3 Biological degradation

Biological degradation caused by boring beetles attack was detected in the joists n.º 3, 8, 11 and 13, identified for a rough surface and the presence of sawdust. With the help of a knife the powdered wood was removed and sound wood was found at a depth of 0.5 to 2 cm from the face (Figure 3 a)). This fact was confirmed with the use of the resistograph® by means of several profiles performed in the degraded zones. Figure 3b) shows a drill resistance profile that detected two weaker spots (A and B) located 1 or 2 cm away from the faces. These weaker areas can be related with biological degradation by house longhorn beetle.

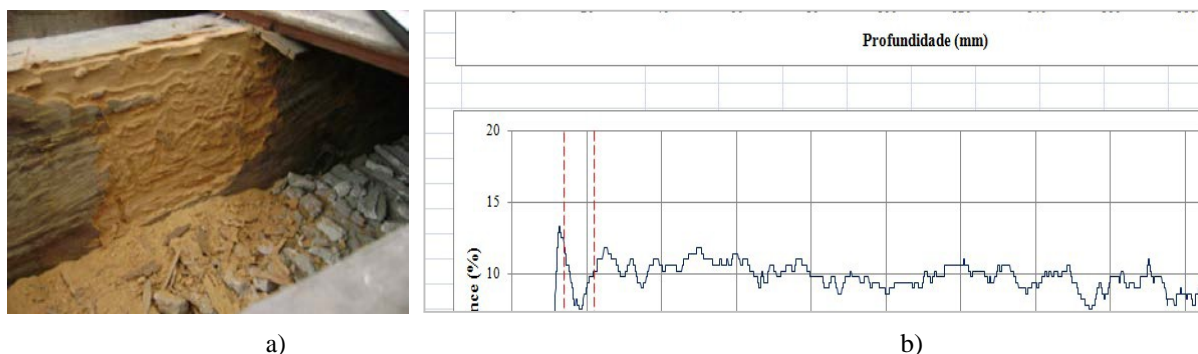


Figure 3: Beetle attack in a joist of the timber floor: a) view; b) drill profile

3.3 Safety assessment

Beams were defined as being simply supported with a uniformly distributed load along the length of the element. According to Eurocode 1 (NP 1991:2009), regarding type of occupancy and use of the room, the studied area belongs to category A. For the safety calculation were used higher density values for safety reasons and the effective section for the degraded joists n.º 3, 8, 11 and 13.

For service class 1, the deflection modification factor (k_{def}) for solid timber is 0.6. The final deflection, w_{fin} , was calculated for the quasi-permanent combination of actions. The deflection which results from the effects of actions (such as axial and shear forces, bending moments and joint slip) and from moisture shall remain above the limiting value $l/250$ (l – span of a beam on two supports) (EN 1995:2004 -National Annex). A ratio above one is not acceptable. The ratio between final deflection and limiting deflection was calculated using the following values of $E_{0,m}$: i) according to NP 4305; ii) according to UNI 11119 (Figure 4). Regarding bending situation of the joists, the safety condition is that the ratio between bending stress and bending strength is less than or equal to 1. The partial factor for material properties (γ_M) for solid timber is equal to 1,3. For the modification factor for duration of load and moisture content (k_{mod}), it was admitted that this case fits in service class 1, giving values of 0,6 for permanent loads and 0,8 for variable loads.

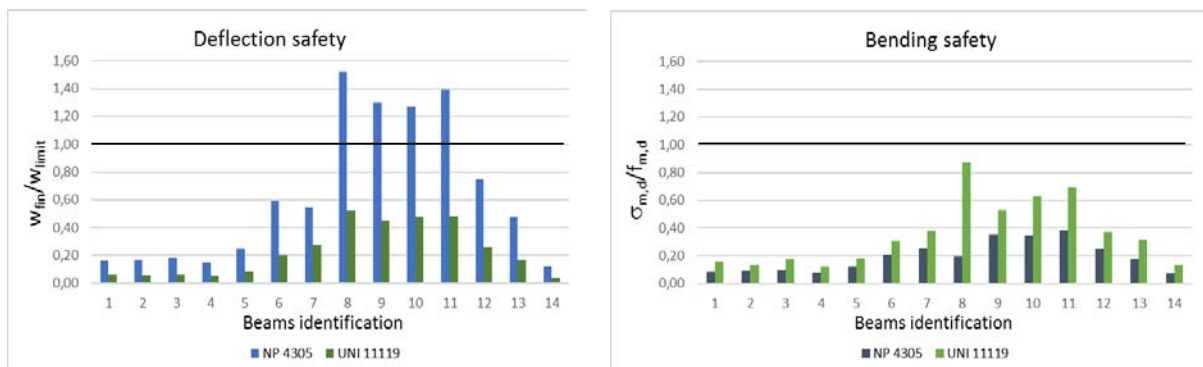


Figure 4: Safety assessment of deflection and bending for values of $E_{0,m}$ and $f_{m,k}$ according to two standards

As shown in the Figure 4 a), for the values of $E_{0,m}$ according to NP 4305 the beams of larger spans (3.70 to 3.95 m), numbers 8, 9, 10 and 11 present a deflection above the limiting value. But, for the values of $E_{0,m}$ according to UNI 11119, all joists are under the limit of deflection, even joist 11 that has a cross section reduction due to by biological attack. In fact, using the values of $E_{0,m}$ provided by UNI 11119, even for the beams degraded by beetles, the effective cross sections remaining are still enough for safety. With regard to bending safety, as shown in Figure 4 b), the joists are safe for values of $f_{m,k}$ according to both standards, even for the beams degraded by beetles. However, to avoid the progress of the biological attack, the application of a preservative treatment is recommended.

4 TIMBER TRUSS

4.1 Presentation

The present truss belongs to a timber roof truss of a wooden building dated from 1902 and located in the center of Lisbon city. Trusses occur at regular intervals, linked by longitudinal timbers such as purlins (Figure 4). It is like a common king-post timber truss. Consists of two diagonal principal rafters that meet at the top of the truss, one horizontal tie beam, one central

vertical king-post, two diagonal struts and two more small struts near the ends of the tie beam. Tie beam is connected vertically through pairs of wooden planks nailed with three members: the king post and the two rafters.

King post is working in tension to support the tie beam below from a truss top above. Tie beam is under tension because it ties the bottom end of the two principal rafters and is also under bending due to the king post and the wooden planks nailed to the rafters, and even due to the small struts who overload the beam. Diagonal members of the truss (principal rafters and struts) are working in compression, but principal rafters are also under bending due to the purlins (Figure 5).



Figure 5: Timber roof truss: a) location on the roof; b) view; c) structure draw

4.2 Survey results

4.2.1 Visual characteristics

All timber members were visually inspected and all measurements done. At inspection, the space had a temperature average of 19°C and Relative Humidity average of 67%. The moisture content of each member was measured with both the moisture meters, one using the resistance method and another using the capacitance method (Figure 6a)). The data were calibrated with each other.

Based on NP EN 335-2:2011, studied area was classified as use class 2 due the risk of wetting through the roof. At inspection, the timber elements don't show signs of high moisture content nor in the present situation nor in the past. None of the members revealed signs of biological degradation. The wood was identified as pine, probably maritime pine.

The VSG according to the standard NP 4305 was done to each timber member covering aspects as: presence of pith; growth rate; occurrence of defects such as knots, slop of grain and resin pockets, wane, cracks and distortion. The VSG f according to the standard UNI 11119 was done to each member considering the position of defects in relation to stress condition of each member. The critical sections were defined there.

Data of visual characteristics are presented in Table 3.

Table 3: Characteristics of timber truss members obtained on-site.

Truss member	Length [m]	Section [cm]	M.C. [%]	Grade NP 4305	Grade UNI 11119
Tie beam	5.80	17.0x7.5	14.9±0.6	EE	I
Principal rafter SW	3.20	10.0x7.5	12.1±0.2	E	I
Strut SW	1.20	9.5x7.5	13.4±0.3	E	II
King-post	1.55	9.5x9.5	13.7±0.6	E	II
Strut NE	1.20	10.0x7.5	12.8±0.8	E	III
Principal rafter NE	3.20	13.0x8.5	13.4±0.3	EE	I

All members were graded as structural timber according to NP 4305.

The grain was straight in all the structural elements and the knots relatively small and concentrated in the middle area of the timber members. Only the NW strut had medium-sized but still acceptable knots. The growth rate was relatively easy to measure due to the radial cut of almost all the elements (Figure 6 b)). The king post was cut with the pith inside.

The joints are in good condition, but show some small gaps in the contact areas. These gaps can drastically reduce the stiffness and strength of the joints by causing a high concentration of stresses in the areas that are in contact [4]. It is therefore recommended that when necessary, the gaps be sealed with metal or hardwood wedges, properly nailed or screwed in order to improve the adjustment of the surfaces in contact.

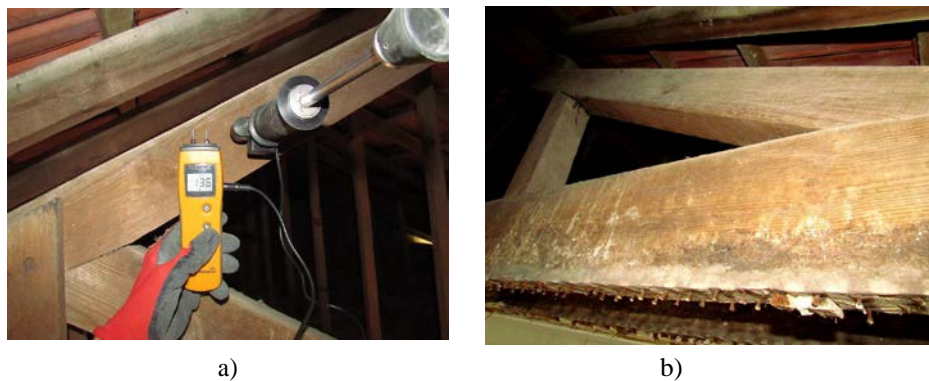


Figure 6: a) Moisture meters; b) view of characteristics of tie beam and principal rafter NE

4.2.2 Reference properties

The estimated values for the average density get with the penetration resistance method were 600 to 670 kg/m³ for all members except the strut NE. These values were in general higher than the average value measured for clear maritime pine wood to 12% moisture content (530 to 600 kg/m³) [27] and much higher than the mean values attributed by EN338 for the resistance classes C18 or C35.

Table 4: Properties obtained from SDT and Grading Standards.

Truss member	Pilodyn®			NP 4305				UNI 11119		
	Penetration depth [mm]	$\rho_{m,SDT}$ [kg/m ³]	Grade	Strength class EN 338	$E_{0,mean}$ [GPa]	$f_{m,k}$ [MPa]	$\rho_{m,VSG}$ [kg/m ³]	Grade	$E_{0,mean}$ [GPa]	$f_{m,k}$ [MPa]
Tie beam	12.1±1.8	672	EE	C35	13	35	480	I	13	12
Principal rafter SW	14.5±0.8	594	E	C18	9	18	380	I	13	12
Strut SW	13.0±1.4	642	E	C18	9	18	380	II	12	10
King-post	11.8±0.4	681	E	C18	9	18	380	I	13	12
Strut NE	20.2±0.8	412	E	C18	9	18	380	III	11	8
Principal rafter NE	13.0±0.9	642	EE	C35	13	35	480	I	13	12

4.3 Safety assessment

With the application of a structural analysis software were made the calculus of safety assessment for the higher values of density and of modulus of elasticity.

It was concluded that the timber truss is in good structural condition for grades assigned by both standards.

5 CONCLUSIONS

This evaluation and survey process highlighted the need to obtain data from diverse sources, even with limited technical means. However, in the two cases under study the data obtained were quite different, which leads us to the conclusion that the work done would have to be complemented with other inspection SDT/NDT techniques, laboratory tests and/or destructive testing on wood samples.

In respect to the condition of the timber elements studied, is clear that the materials used in the construction of these buildings had an above average quality. This is particularly relevant considering the buildings' age, which is of more than a century, and that was not verified the occurrence of severe degradation that could compromise the structural safety. The verified degradation was very localized, and the biological agents were all verified. This way it is possible to obtain the effective cross section on structural strength.

Through the development of this study it became clear the importance of visual inspection for this kind of cultural heritage buildings. The use of a visual strength grade standard specific for timber members in service is also very important. In this case, the standard used accepted four beams that would have been replaced if only other methods had been used. On the other hand, the closer estimation of the density of the elements leads to a more real safety assessment.

ACKNOWLEDGEMENTS

The authors would like to thank the Instituto Politécnico de Lisboa (IPL) for the financial support in the WOODINSITU project (ref. IPL/2016/WOODINSITU), to the CERIS and to the Eng. Francisco Calhau.

REFERENCES

- [1] Macchioni N. 1998. "Inspection techniques for ancient wooden structures", in: P. Roca, J.L. Gonzalez, E. Onate, P.B. Lourenco (Eds.), Structural analysis of historical constructions II. CIMNE, Barcelona, pp. 149-162.
- [2] Kasal B. and Tannert T. (Eds). 2010. In situ assessment of structural timber. State-of-the-Art Report of the RILEM Technical Committee 215-AST. Springer
- [3] Dietsch P and Köhler J (Eds). 2010. Assessment of timber structures, Shaker Verlag GmbH, Aachen
- [4] Cruz H., Yeomans D., Tsakanika E., Macchioni N., Jorissen A., Touza M., Mannucci M., Lourenço P. 2015. "Guidelines for On-Site Assessment of Historic Timber Structures". International Journal of Architectural Heritage. 9:3,277-289

- [5] Machado J. S, Riggio M., Descamps T. (Eds) 2015. Combine use of NDT/ SDT methods for assessment of structural timber members. COST fp1101 State-of-the-Art Report_TG2 e-book. UMONS - Université de Mons. ISBN 978-87325-094-2
- [6] Uzielli, L. 1992. 'Evaluation of timber elements bearing capacity'. *L'Edilizia*. 12, pp. 753-762
- [7] Baldassino, N., Piazza, M., Zanon, P. 1996. "In situ evaluation of the mechanical properties of timber structural elements". 10th International Symposium on Nondestructive Testing of Wood, Lausanne, Switzerland
- [8] Ronca, P. & Gubana 1998, 'Mechanical characterisation of wooden structures by means of an in situ penetration test' *Construction and Building Materials*, 12 (1998), pp. 233–243.
- [9] Machado, J.S., 2000, Avaliação da variação das propriedades mecânicas de pinho bravo (*Pinus pinaster* Ait.) por meio de ultra-sons. PhD thesis Technical Univ. of Lisbon, 265 pp
- [10] Feio, A.O. 2006, Inspection and Diagnosis of Historical Timber Structures: NDT Correlations and Structural Behaviour, PhD Thesis in Civil Engineering, Univ. of Minho, Portugal.
- [11] Piazza M., Riggio M. 2008. "Visual strength-grading and NDT of timber in traditional structures". *Journal of Building Appraisal*. 3, 267-296.
- [12] Branco, J.M., Piazza, M., Cruz, P.J.S. 2010, "Structural analysis of two King-post timber trusses: Non-destructive evaluation and load-carrying tests", *Constr. Building Materials*, 24, pp. 371–383.
- [13] Ceraldi, C., Mormone, V., Ermolli, E.R.; 2001 "Resistographic inspection of ancient timber structures for the evaluation of mechanical characteristics" in *Materials and Structures*, vol. 34, n° 1, pp. 59-64.
- [14] Jasienko, Nowak, Hamrol; 2013. "Selected methods of diagnosis of historic timber structures - principles and possibilities of assessment". *Adv. Mat. Research* Vol. 778. pp225-232.
- [15] Henriques D.F. & Neves A.; 2015. "SDT methods as part of a conservation process". In: *Combine use of NDT/SDT methods for assess. struct. timber members-State of the art report*. J. S. Machado, M. Riggio, T. Descamps (Eds), p. 255-263.
- [16] Machado, J. 2015. Reliability of prediction by combining direct and indirect measurements. In: *Combine use of NDT/ SDT methods for assessment of structural timber members*. J. S. Machado, M. Riggio, T. Descamps (Eds), p. 1-13.
- [17] Morales-Conde, M.J.; Rodríguez-Liñán, C.; Saporiti-Machado, J.; 2014 "Predicting the density of structural timber members in service. The combine use of wood cores and drill resistance data". *Mater. Construcc.*
- [18] Kloiber, M. & Drdácý, M.; 2015. SDT methods as part of a conservation process. In: *Combine use of NDT/SDT methods for assessment of structural timber members - State of the art report.*, p. 69-91.
- [19] Henriques D.F., Nunes L., Machado J.S., Brito J. de. 2011 "Timber in buildings: Estimation of some properties using Pilodyn and Resistograph". XII DBMC – International Conference on Durability of Building Materials and Components. Porto, Portugal, pp. 949-956;
- [20] Cavalli A., Togni M. 2013. "How to improve the on-site MOE assessment of old timber beams combining NDT and visual strength grading". *Nondestructive Testing Evaluation*, vol. 28, No.3, 252-262.

- [21] Machado J.S., Feio, A. 2015. “In-situ assessment of timber structural members: combining information from visual strength grading and NDT/SDT methods. A review” *Construction and Building Materials*, 101 (2015) Pp. 1157–1165
- [22] Feio A., Machado, J.S. 2015. Combine information from visual and NDT/SDT methods. In: *Combine use of NDT/ SDT methods for assessment of structural timber members*. J. S. Machado, M. Riggio, T. Descamps (Eds), p. 1-13
- [23] Cândido, A., Henriques, D.F. 2014 “Inspection and diagnosis of timber structures by non-destructive methods” *MONUBASIN – 9th international symposium on conservation of monuments in mediterranean basin*, 3-5 june 2014, Ankara Turkey
- [24] Ceccotti A., Togni M. 1996. “NDT on ancient timber beams: assessment of strength/ stiffness properties combining visual and instrumental methods” in *10th International Symposium on Nondestructive Testing of Wood*, Lausanne, Switzerland
- [25] Riggio M., Anthony R.W., Augelli F., Kasal B., Lechner, T., Muller W., Tannert T. 2013. “In situ assessment of structural timber using non-destructive techniques”. *Materials and Structures*. DOI 10.1617/s11527-013-0093-6
- [26] Íñiguez G., Arriaga, F, Esteban M., Bobadilla I., González C., Martínez R., 2010 “In situ non-destructive density estimation for the assessment of existing timber structures” in *proceedings of 10th Word Conference on Timber Engineering*, Trento, Italy.
- [27] Cruz H., Machado, J.S., Rodrigues M., Monteiro G. 1997. *M2 - Maritime pine for structures* (in Portuguese). LNEC–Laboratório Nacional de Engenharia Civil. Lisbon, Portugal p. 1-12