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THE ROYAL CHAPEL OF NATIONAL PALACE OF SINTRA: A STUDY OF TIMBER ELEMENTS

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Abstract

On-site inspection work in the historical buildings requires a basic scientific knowledge to be conducted with technical and scientific credibility. This need becomes so absolute when the object is the historical heritage of high value. This paper presents the work of inspection and evaluation of timber elements held in the tribune of the Royal Chapel of the National Palace of Sintra, Portugal. It was carried out within the scope of a master's dissertation presented to the Higher Institute of Engineering of Lisbon in 2018. This palace is one of the most important Portuguese monuments, having been linked to the national history by many events. The Royal Chapel has several dates of construction and past interventions dated from the thirteenth to the fifteenth centuries. The Gothic, Mudejar and Manueline styles are perfectly combined in there.

The work consisted in the characterization and structural assessment of tribune´s first floor beams. Inspections took place between January and May 2018. The wood present in most of the structural and secondary elements is coniferous, most of which has been identified as Pinus Sylvestris, L. The work was carried out in situ by visual inspection and by non-destructive and semi-destructive tests. Water content, drill resistance and penetration resistance were measured. Physical-mechanical properties of the timber members were estimated based on the in-situ measurements and the scientific literature. Visual strength grading was also applied to the floor beams.

From the results obtained several important information were taken. Report and recommendations were presented as the conclusion of the study.

1 INTRODUCTION

Any intervention in the historical heritage requires a prior diagnostic study, which must overcome the common decision-making practice based on the appearance of the constructive element. The technician must also surpass the preconceived idea that he will have to replace all the non-rectilinear elements, of irregular section, with fissures, wane, knots or even surface degraded, just because they do not fit the typology of current structural elements. According to [1] traditional structures are often condemned to destruction by engineers and regulators, who require that they comply with current regulations. This is often inappropriate, because current regulations have been designed for other forms of construction, so their application in traditional materials, technologies and forms is too conservative [1].

Recent publications [2, 3, 4] offers a systematic view about the assessment of mechanical properties of timber members in situ by means of non-destructive or semi-destructive testing (NDT/SDT). The mechanical strength, modulus of elasticity and density, have been correlated with drill resistance and with penetration resistance results and have been shown as useful methods for assessing wood [5, 6, 7, 8, 9]. 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 [10, 11, 12].

The diagnostic study of a timber structure generally begins by conducting a preliminary visual survey which includes the identification of the wood species. In order to attribute parameters of strength and stiffness to timber members in service (strength class), several authors indicate that the selection of a visual strength grading (VSG) standard is still considered the fundamental tool. VSG was the first non-destructive testing method to be applied based on the apparent simplicity of its application, which does not require any special type of equipment [9, 4, 13]. However, VSG standards were developed having in mind the grading of sawn timber at sawmill yards. The full application on site of the rules applied at the sawmill yard can lead to gross underestimation of the real mechanical performance of timber members. But, combined with NDT/SDT evaluation methods, these evaluation methods can achieve a proficient level of reliability in the structural analysis, diagnosis and inspection of timber in service[9]. The difficulty of inspect all faces of the members and the fact that some features included on VSG rules do not have a direct impact on strength, led to simplified VSG rules [3, 4] and careful judgment is required on the influence of fissures and knots according to the type of member [4].

The identification of the strength class of each timber member is followed by the survey of the limit state requirements. The criteria used are those of the Eurocode 5 (EN 1995:2004). According to the EC5, safety checks are related with ultimate limit states (bending, shear and torsion) and serviceability limit states (deflection and vibration) [14]. The application of this standard may also not be faithful to the structural capacity of the historical element, as the EC5 was also designed with new structures in mind.

The work developed to assess the structure presented in this paper attempts to apply the guidelines emanating from recent publications, in keeping with existing legislation. This was a difficult conciliation exercise, but one that has been successfully achieved.

2 THE NATIONAL PALACE OF SINTRA – HISTORICAL BACKGROUND

The “Palácio Nacional de Sintra” is, as we know today, a product of several interventions over 800 years of Portuguese History. The first time that the existence of a palace in that place is mentioned goes back to the Xth century, by an Arab geography called Al-Bacr. It is thought that in that place existed a Moorish palace [15].

Later, after the conquest of Lisbon to the Moors the king D. Dinis [1279 - 1325] started the first interventions to requalify the palace. But it was just in the reign of D. João I [1385 - 1433] that were made most of the works to build the palace as we know today [16]. This period of time is known as "joanina's" period and in this time, it was built the kitchen, with their two characteristic chimneys, the Swan Room, "Pegas" Room, Mermaid Room, the Royal Chapel and some of the slipping rooms. In all these spaces it is possible to admire the gothic and "mudéjar" architectural styles [17, 18].

The king D. Manuel I [1495 - 1521] commanded the construction of more areas, one of those is the right wing of the main façade and the Tower of Blazons. This period of construction is named as "manuelino" and is characterized by a later gothic style with more elements about the sea and maritime navigation [17, 18].

This palace harmoniously combines the "manuelino", gothic and "mudéjar" styles, and was a witness of the Portuguese History. Here lived the king D. Afonso V [1438 - 1481] as a prisoner, and later, the queen D. Maria II [1826 - 1853] with her husband D. Fernando during the Pena's Palace construction. It was also here that was read for the first time the book of "Lusíadas" and was received the news about the discovery of Brazil and the sea route to India [16, 17, 18].

2.1 The Royal Chapel

The Royal Chapel was ordered to rise in the reign of D. Dinis in the same place where it is thought to have existed an Arab mosque.The ceramic pavement, still existing today, contains vestiges of this same mosque [19].

The Holy Spirit is the patron of the chapel, a request of the queen Saint Isabel. It is represented on the walls by white doves. The ceiling also represents the mudéjar and arabic styles with carpentry "alfarje" wood-paneled ceiling. The windows in ogive with stained glass evidence the gothic style, and the two windows near the altar have the manueline style.

2.2 The Royal Chapel's Structure

The Chapel is constituted by foundations and walls of regular masonry and his plan has a cross shape. The opposite side of the main altar have two floors supported by a timber structure (Figure 1). The first floor was the tribune and nowadays is where pass all visitors. The second floor was the chorus and nowadays is inaccessible to the public. The roof has tree roof slopes, with two hips in the main altar zone, and the other side is adjacent with other part of the building. The roof structure support, and his roof sheathing, formed by collars, purlins, principal rafters and tie-beam are all made in timber. Concerning to the species, considering the date of construction, it is thought to be Maritime Pine or Redwood [20, 21].

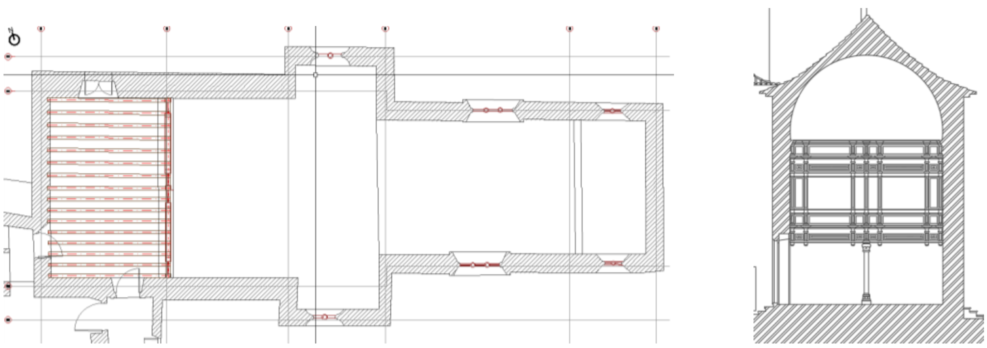


Figure 1: Royal Chapel's plan and section

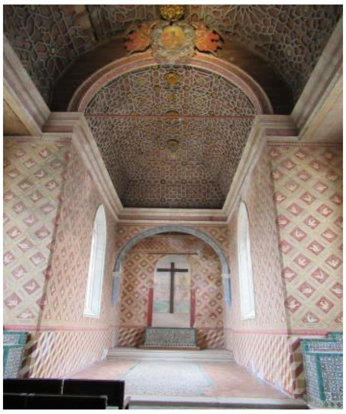
The chapel's ceiling is formed by a fake barrel vault decorated with elaborated ties, characteristic of "mudéjar" style (Figure 2b)). The floor's pavements are made of wooden beams and it is thought to be Redwood. After the beams there are two layers of wooden planks, arranged in orthogonal directions, and over these, the ceramic tiles. The beams are separated from each other by approximately 45 centimeters, and between them, there are wooden blocks that prevent lateral bending, helping to load distribution and reducing vibrations (Figure 2).

3 INSPECTION WORK IN TRIBUNE FLOOR'S BEAMS

The structure of tribune´s floor is formed by wooden beams, simply supported by a metallic beam that is supported on the walls having a stone column in the middle span. It is It was impossible to check the other side of the beams but is thought that is a fixed support on the wall. The length of the beams is approximately 5,30 meters, and the distance between the axis of the beams is about 45 centimeters. The cross sections of the beams are: height between 13 and 14 centimeters and width between 12 and 19,5 centimeters. Between the beams there are wooden blocks with a regular section (8,5 x 14,4 cm), and in the corners there is a diagonal wooden element which allows better connection between beam-block. The use of blocking has the main purpose of reduce transversal deformation, consequently increasing transversal stiffness. These details reveal a high carefulness in this important construction in that time. The area under study is just a half of the area of the tribune's floor, and it is constituted by 7 beams, which were numbered from B1 to B7 (Figure 2.a)). The beam B1 is the closest to the stone column and B7 one is nearby the wall.

The first visit was to do a geometric survey and analyze the conditions to do the inspection, a first global look to understand how the structure works and to see if the elements in study were damaged.

b)



b)

Figure 2: a) Tribune's beams b) Chapel and main altar view

3.1 Inspection methodology

A preliminary visual survey who included dimensioned drawings of the elements, identification of the structural system, physical problems, service classes, biological damage and its probable causes [4] was done.

Afterwards, the resistant properties were surveyed in order to carry out the safety assessment. Visual Strength Grading coupled with the use of NDT/SDT in situ testing allows these properties to be determined [6]. So, it was used the NDT/SDT tests of drilling resistance, penetration resistance and moisture meter, coupled with thermo-hygrometer. VSG was adapted to on service conditions, through the BS 4978:2007 schemes considering the knots size, rate of growth and slope of grain.

Relationships between tests performed, estimated properties, and structural checks are presented in the flow-chart shown in Figure 3.

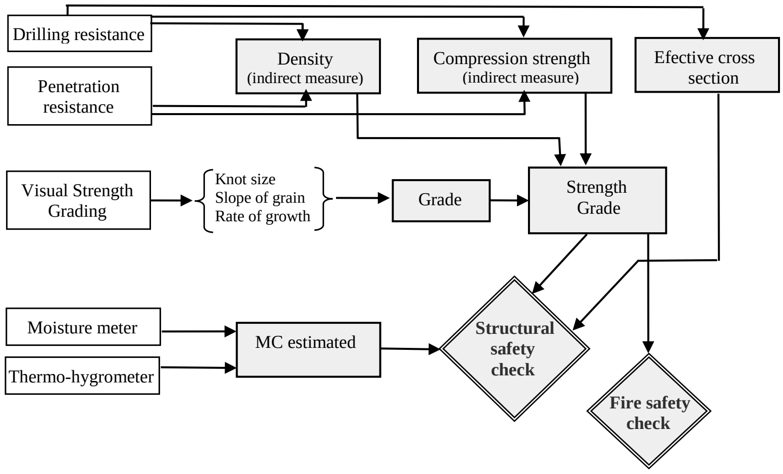


Figure 3: Flow-chart of NDT/SDT, properties and structural checks

3.2 Methods of diagnosis with semi and non-destructive testing

3.2.1 Moisture meter

The moisture content was measured in all beams, with measurements in three different zones, and in each zone, it was registered 5 values. It was used a capacitance type moisture meter to register these values. In some beams it was registered the moisture content in the interior of the beam using a resistance type moisture meter. The moisture content measured in the beams were 15,0±0,57%. Below MC=20% it is not expected active biological damage [22]. These values are in accordance to the ambiance temperature and relative humidity who were had the average of 19ºC and 70%.

3.2.2 Penetration resistance

The penetration test was carried out using a pilodyn 6J Forest equipment with impact energy of 6J. In current trials, one use doing several measurements, but in this case, it was decided to do just one measurement in each beam, in clear zones, because of the use conditions of the floor. The method consists on introducing a metal pin in the timber with a constant energy. The penetration depth is inversely proportional to the timber hardness in the cross section [12]. The results conducted to the estimation of wood density and compression strength, based on studies by [12] who correlated the dynamic penetration test with those reference properties, according to equations (1) and (2) [12].

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

$$Pd=-0.3572f_{c,0}+30.409 \quad (2)$$

where: Pd = penetration depth (mm), ρ = density of the pine wood (kg/m^3), $f_{c,0}$ = compressive strength (N/mm^2)

3.2.3 Drilling resistance

The drilling test was performed with a device model IML Resi PD 500. This test consists in driving a 1.5 mm diameter drill inside the timber at a constant feed speed of 25 cm/min. The relative measurements allow evaluating the hardness of timber and detected the softest zones of the material, giving out an on-line graph in real size that represents the drill resistance path through the section [23].

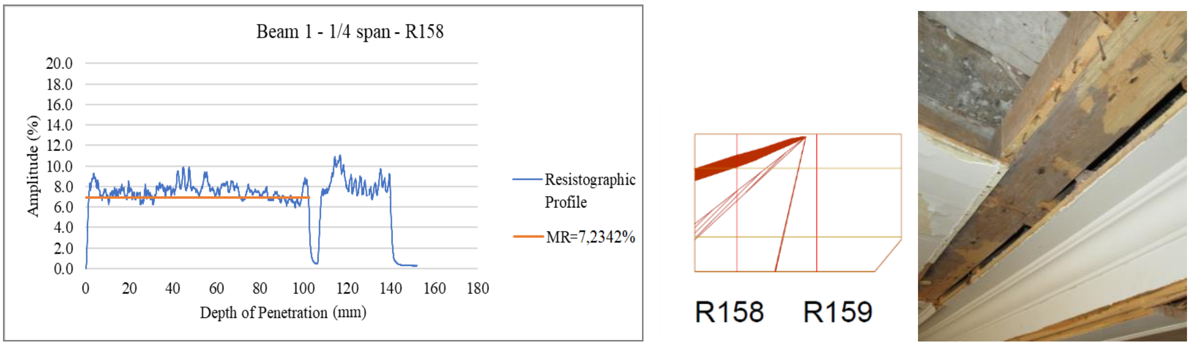
The resistographic measurement, RM, valid for sound and defects-free timber, is given by the ratio between the area integral and the drilling depth (Figure 4). The results conducted to the estimation of wood density, based on studies by [12] who correlated the drilling resistance test with those reference properties, according to equations (3) and (4) [12].

$$RM=0{,}0285\rho - 4.7291 \qquad (3)$$

$$RM=0{,}3363f_{c,0}-2.8454 \qquad (4)$$

where: RM = resistographic measure, ρ = density (kg/m^3), $f_{c,0}$ = compressive strength (N/mm^2)

In beam 1 it was taken three measurements, one of them is shown on 4 a), and in the other beams was take two measurements, in vertical sense and horizontal sense. The 4 b) presents a section of the beam B1 near to the support. The vertical lines represent the two drill tests. The two horizontal lines mark the marginal area used to evaluate the element to the existence of knots. There is an area totally full that represent a crack and the other two areas represent the knots.



a) b) c)

Figure 4: a) Resistographic Profile; b) Section of beam 1; c) View of beam B1

3.3 Visual strength grading – BS 4978:2007

The British Standard BS 4978:2007 (Visual strength grading of softwood – Specification) evaluates wooden structural elements, based on the visual defects, and classifies the elements for GS – General Structural or SS – Special Structural.

This standard was developed for grading timber at sawmill yards. In structural elements in service is very difficult to have the same conditions, sometimes it is impossible to observe the whole piece. Some defects that are considered in the standard just don’t affect the mechanical properties (like distortion and wane) of the element, they are taken in consideration because they may difficult it’s appliance in the construction site or result in a loss section. Another defect that invalids an element is the existence of biological damage. But in an old building some biological attack is expected, and so it can be accepted. This defect must be considered as a reduction of useful section to calculate the resistance of the element [7].

The difficulty in inspect all faces of the members and the fact that some features included on VSG rules do not have a direct impact on strength, led to simplified VSG rules [3, 4] and careful judgment is required on the influence of fissures and knots according to the type of member [4]. It is recommended to consider just the knots size, rate of growth and slope of grain of each timber element. By measuring each of the characteristics in three sections of the beam, the worst degree was assigned according to the permissible limits established in BS 4978.

Data of visual characteristics is presented in Table 1.

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

Beam	Length [m]	Section bxh [cm]	M.C. [%]	Grade BS 4978 simplified
B1	5,3	19.3x13.0	15.1±0.6	SS
B2	5,3	14.2x13.0	14.2±0.4	SS
B3	5,3	15.5x13.5	15.2±0.3	SS
B4	5,3	12.0x13.0	16.8±1.0	SS
B5	5,3	15.0x14.0	17.8±0.6	SS
B6	5,3	12.5x14.0	15.7±0.4	SS
B7	5,3	12.5x14.0	14.5±0.4	GS

4 SAFETY ASSESSMENT

4.1 Discussion of results

The wood properties were estimated by SDT methods and the rules of VSG standard BS 4978:2007. Values of density and compressive strength were estimated through the penetration resistance and drill resistance methods. The mean value of these two methods was calculated. Average modulus of elasticity on bending, mean density and characteristic value of compressive strength were obtained by VSG and correspondent strength classes. All these values are presented in table 2.

Table 2: Properties obtained from SDT and Grading Standards.

Beam	Penetration resistance		Drill resistance		Mean SDT		VSG, Strength properties				
	$\rho_{m,SDT}$ [kg/m^3]	$f_{c,0,SDT}$ [MPa]	$\rho_{m,SDT}$ [kg/m^3]	$f_{c,0,SDT}$ [MPa]	$\rho_{m,SDT}$ [kg/m^3]	$f_{c,0,SDT}$ [MPa]	Grade	Strength class EN 338	$E_{0,mean}$ [GPa]	$\rho_{m,VSG}$ [kg/m^3]	$f_{c,0,k}$ [MPa]
B1	450	31,9	458	33,4	**454**	**32,6**	SS	C24	11	**420**	**21**
B2	-	-	-	-	**-**	**-**	SS	C24	11	**420**	**21**
B3	418	29,1	-	-	**418**	**29,1**	SS	C24	11	**420**	**21**
B4	482	37,5	428	30,2	**455**	**33,8**	SS	C24	11	**420**	**21**
B5	418	29,1	433	31,3	**426**	**30,2**	SS	C24	11	**420**	**21**
B6	483	34,7	454	33,1	**468**	**33,9**	SS	C24	11	**420**	**21**
B7	514	37,5	430	31,1	**472**	**34,3**	GS	C16	8	**370**	**17**

It is observed that the values of the density are, for beams B1 to B6, only slightly higher than the average value established by the standard. Just the density of the beam B7 estimated by the SDT is well above the average corresponding to the resistance class C16, because, in the first case, it was estimated for wood free of defects. As for the values of the compressive strength, much higher values were obtained in the study by SDT. This can be explained because in the first case it is about mean values and in the case of VSG, these are characteristic values. In all cases the study by SDT is more conservative than by VSG.

Through the standard EN 1912:2013 it is possible to correlate the strength grade with the strength class. Considering the beam's specie is Redwood, then the beam B7 is classified as C16 and the others as C24. In the standard EN 338:2003 it is possible to consult the strength and stiffness properties.

4.2 Structural Safety Check

According to the Eurocode 5 (EN 1995-1-1) safety checks are related to ultimate limit states (bending, shear and torsion) and serviceability limit states (deflection and vibration). This study doesn't consider torsion neither vibration because it is admitted that the blocks between beams avoid and decrease strongly these effects. In addition, the Eurocode 5 refers that an increase of 10% should be allowed to the strength of timber members in cases of load-sharing, as verified in this case with the blocks between beams. This allowance enables a single poor quality or severely damaged member to be retained if the adjacent members can carry the additional loads [4].

At time of the inspection work (June) it was registered interior temperature of 21,5°C, and Relative Humidity average near 80%. Once the structure is in an interior environment, the conditions for assigning Service Class 1 are confirmed.

According to the Eurocode 1, it was assigned a Category Use C3, and for this category the imposed load to use must be between 3,0 and 5,0 kN/m². It was defined 3,50 kN/m² for the imposed load. It was considered permanent load for the wooden planks and ceramic tiles. Timber members were considered simply supported and whose grain runs essentially parallel to its length.

4.2.1 Ultimate Limit Test

A check of safety to simple bending and shear with the considerations exposed before, and according to the Eurocodes 0, 1 and 5 was done. It was concluded that any beam verifies the safety to simple bending, and in the calculations to shear, just the beam B7 did not verify.

However, it is known that the used standards are made for new structures, with very strict rules, and the structure in analyze is service for many years. So, it was decided to make the calculations to determine the recommended number of people to be at the same time in the tribune. The calculations were made considering people with 80 kg and after some iterations it was concluded that for the complete structural safety it is appropriate to limit the number of people in the tribune at the same time.

4.2.2 Serviceability Limit Test

As the same form, the security to the deflection was verified. Basically, it was calculated the final deflection of each beam and confirm if it is under the limiting values for deflection of beams. With an imposed load of 3,50 kN/m² all beams verify the safety to deflection.

4.3 Fire Safety Check

To do the fire verification it was calculated the effective charring depth. Then this value is removed in the dimensions of the beam section, considering that just three faces are exposed to the fire for thirty minutes. After that the verifications for simple bending and shear with the residual area and fire parameters were done.

It was concluded that the beams B4 and B7 did not verify the simple bending's safety, but all beam verified the shear safety.

5 CONCLUSIONS

In general, it is recognized a great care in the choice of materials and in the construction technology for the construction of the royal chapel. Proof of this are the numerous locking blocks between the beams and the diagonal pieces in the corner areas.

Regarding damage or degradation, can be referred the big crack in beam B1 in a plane almost horizontal. So, requested to bending, it ends up closing and seems not have significant impact in its loss of resistance to the simple bending. There also seems to be some degradation by beetles spread in the non-visible face of the beams. This situation will have to be checked.

The grade with VSG rules is somewhat subjective, as it depends a lot on the knowledge and experience of the survey technician and then analyzes the data collected. The analysis elaborated at this level is insufficient, since it is not possible to observe all the parts of the elements under study and therefore it is not possible to evaluate some parameters.

Related to the safety assessment it is recommended to do the reinforcement of the beam B7 or the limitation of the number of visitors over the floor at the same time. Allied to the non-verification of simple bending safety, this revealed many visual defects leading to a strength classification C16. For the fire assessment, it is recommended to do the reinforcement increasing section or by the application of a fire-retardant product at the beams B4 and B7.

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