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Editors

Emine Nevin Caner-Saltık, Ayşe Tavukçuoğlu
Middle East Technical University, Turkey

and
Fulvio Zezza
University IUAV of Venice, Italy

MIDDLE EAST TECHNICAL UNIVERSITY

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Editors: Emine Nevin Caner-Saltık, Ayşe Tavukçuoğlu, Fulvio Zezza
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INSPECTION AND DIAGNOSIS OF TIMBER STRUCTURES BY NON-DESTRUCTIVE METHODS

Cândido Ana[1,a]; Henriques Dulce[1,b]
1 - Instituto Superior de Engenharia de Lisboa
Rua Conselheiro Emídio Navarro 1, 1959-007 Lisboa, Portugal
a - anasacandido@hotmail.com ;b - mfhenriques@dec.isel.ipl.pt

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ABSTRACT

Many buildings with significant historical value are located in Portuguese old towns. In most cases these types of buildings have timber structures which need specific care to keep, at least, reasonable levels of conservation and safety. Thus, research and development of more efficient inspection and diagnosis methods are essential to verify the needs of rehabilitation. The building studied is a palace named Ribeiro da Cunha located in a major historical area of Lisbon, Portugal. Its construction dates from 1877, thus being an important part of local heritage. The main objective of this study is the application of non-destructive tests in timber structure elements. To achieve this, three different areas of the timber structure were subjected to a thorough inspection plan, which included visual inspection and non-destructive testing. The biological wood degradation was also under analysis, through the identification of beetles, subterranean termites and fungi.

The visual inspection proved very useful, supporting testing results for the assessment of timber structures. Nowadays, visual grading of timber structures is subject to regulation in many countries. Thus, the employment of some of these standards, and further explanation of the difficulties and limitations related with their application on-site, is one of the objectives of this study. In addition, Eurocode 5 (EN 1995:2004) is also addressed, in order to verify whether the safety conditions are satisfied, despite the observed damage level. The choice of non-destructive tests have proven useful, not only because it allows for a better mechanical characterization, but also because of its careful approach resulting in no damage, much needed in buildings with such architectural value.

Therefore, this study can be useful in an initial inspection and diagnosis phase of the building's timber structure elements rehabilitation needs.

INTRODUCTION

The private construction sector played the main role in settling the housing shortage in Portugal in the second half of the 20th century. Thus preservation and conservation of heritage buildings turned into a less important issue, resulting in a progressive deterioration of many architectural value buildings. In order to reverse this trend, the conservation sector has been the target of some political incentives, such as tax breaks and subsidized construction contracts.

There is a large number of timber structures in Portugal, mainly located in old town areas, thus preserving these buildings is a never-ending task [1]. Wood can be described as a complex composite consisting of cellulose, lignin and hemicelluloses and in the natural environment, is subject to the activities of decomposer organisms [2]. If properly maintained, this type of structures can be highly durable, even lasting for centuries. From the 1755 Lisbon earthquake, timber gained a major importance as construction material, and was essentially applied on floors, walls and roofs. A large part of the buildings from that era are still occupied, despite most of them suffering a high level of deterioration, resulting from the lack of protection against decomposer organisms. For this reason the analysis of degradation processes by these organisms, together with results from non-destructive inspection techniques, is crucial to evaluate the real state of the structure, so that a proper rehabilitation can be made [3].

The main targets of this study were the following: application of non-destructive techniques in the inspection of wooden structures, such as visual inspection, moisture content meter, *Resistograph* and *Pilodyn*. The results were then interpreted and used to evaluate the following: state of preservation of each timber element, and ultimately the whole structure; decomposer organisms detected in timber elements, regarding in particular to their lifecycle, degradation processes, as well as environmental specific parameters; Ultimate Limit State safety check for Bending, as specified in Eurocode 5 (EN 1995:2004), which is related to the residual (or efficient) resisting cross section of each element; application and comparison of two visual grading standards: NP 4305:1995 (Portugal) and UNI 11119:2004 (Italy).

Description of building

The case study, named Palacete Ribeiro da Cunha, is located in Príncipe Real (Lisbon, Portugal) and his design is from 1877.
The building has high architectural value because of various elements such as stained glass, frescos, neo-moorish inner courtyard, grand staircase, art nouveau fireplace and his closeness to the Botanical Garden (Figure 1). The mansion is a four floor building and has a total area of 2500 m^2. The structure of the interior walls, pavements, stairs and roof are exclusively made of timber.

Figure 38. Palacete Ribeiro da Cunha: facade, neo-moorish inner courtyard and grand staircase

EXPERIENTIAL CAMPAIGN

There were selected timber elements from three specific areas of the fourth floor: bathroom pavement, storeroom roof and roof lanterns (Table 1). The structure was constructed most likely from two wooden species: *Pinus Pinaster* and *Pinus sylvestris L*. The confirmation of wood species would require gathering of samples for laboratory tests.

The bathroom is a well-lighted and ventilated room, the division walls are covered with ceramic tiles and the pavement structure consists of joist (14) and blocking (2). The use of blocking has the main purpose of reduce transversal deformation, consequently increasing transversal stiffness [4]. Joists are placed perpendicular relatively to the main building facade, thus being the blockings parallel.

Table 5. Studied areas

Bathroom pavement	Roof	
	Storeroom	Lantern
		

The storeroom is linked to the bathroom, and is poorly lighted and bad ventilated. Its roof has a triangular non-traditional shape, and is composed of a half truss. The analyzed elements in this area were two rafters and two purlins. The last analyzed area is a hipped roof lantern made of glass with quadrangular shape. All timber elements in this site have a whitewash painting. The study focuses in two timber element sets, composed by two vertical struts, two diagonal struts and one tie. The average dimensions are reported in Table 2.

Table 6. Average measurements

	Average	Height (m)	Width (m)
Pavement	Joist	0,217	0,092
	Blocking	0,175	0,071
Storeroom roof	Rafters	0,145	0,093
	Purlins	0,154	0,048
Roof lantern	Vertical struts	0,146	0,094
	Diagonal struts	0,136	0,094
	Tie	0,152	0,094

The diagnosis was composed by two stages of inspection: preliminary and detailed stage. Preliminary stage of inspection, consisted in a general assessment of timber structure, acknowledgement of its main defects, risks as well as a first approach of identification of

wood species. An historic and technical survey about the target building was also carried out. The structural frames of the chosen areas were also analysed, regarding its construction processes and timber elements. In this stage it is also important to ensure, whenever possible, conditions of accessibility, lighting and cleaning, for the next inspection stage [3].
The second and more detailed stage of inspection consisted in a thorough visual inspection and application of non-destructive inspection techniques. This kind of inspection is considered as a first process of a non-destructive evaluation [5]. At a mechanical level, wood was tested 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. The efficient or residual resisting cross section can be estimated on this basis (Figure 2).

A photographic recording of the three areas was conducted, as well as specific deteriorated spots. The length, width and height of all timber elements were measured.

Figure 39. Residual cross section measurement and lenght joist measurement

All obtained data was later registered on wood elements, using 3D design software (Figure 3). The use classes from EN 335-2:2011, related to the occurrence of biological agents were defined based on the localization of each element.

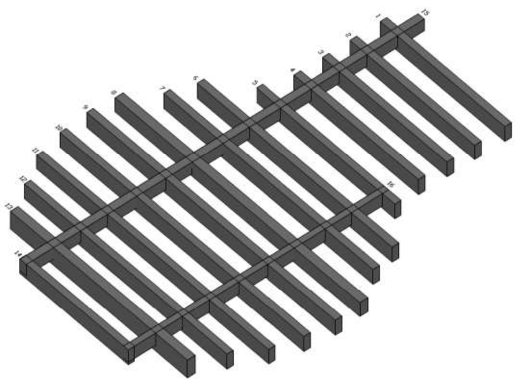


Figure 40. Bathroom pavement structure (joist and blockings)

There were made three moisture content readings per element, in order to allow for a proper evaluation of the average moisture content in each area. Then a series of micro-drilling tests with the *Resistograph* were carried out, as well as five *Pilodyn* tests for each *Resistograph* test. *Resistograph* is a non-destructive inspection technique for elements in healthy or deteriorated state. The output data is uploaded digitally (*B-tools-Pro*) allowing for the estimation of resistographic measurement (RM). As previously stated, five *Pilodyn* tests for each *Resistograph* test were carried out. This test gives information about superficial wood hardness. The described inspection equipment is shown in Figure 4.

Figure 41. Moisture content, *Resistograph* and *Pilodyn*

In order to study some of the *in situ* visual grading standards, two different standards were followed: Portuguese NP 4305:1995 and Italian UNI 11119:2004. All collected data was registered on visual grading tables. Portuguese visual grading standard applies to pine wood made in Portugal for structural purposes. Its objective is to estimate the mechanical 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 [3]. Visual grading assigns quality grades to wood elements, which are then related to strength grades and corresponding mechanical properties, such as: characteristic value, Young modulus, shear modulus, material density, bending strength, and compression strength both parallel and perpendicular to the grain. This standard includes the following quality grades: EE (special structural timber) and E (regular structural timber).

The Italian standard followed in this study was UNI 11119:2004. This standard establishes objectives, procedures and criteria in the evaluation of the state of conservation and assessment of timber members from cultural heritage buildings. The evaluation is made in function of the 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. The critical section is the cross section that includes all the defects, anomalies, alterations and damage, among other aspects located in the critical zone that can influence its strength, thus representing the critical zone. Whenever necessary, on-site inspections can be complemented by one or more non-destructive methods, thus aiming at the determination of relevant physical and mechanical parameters. For diagnosis purposes, only the residual resisting cross sections should be taking into account. This standard includes three quality grades (I, II, III) which are related to verified aspects on site, such as wane, single knots or groups of knots, slope grain, shrinkage checks, frost cracks and ring shakes. Such as it does in Portuguese standard, the Italian standard quality standards are related to specific strength classes and mechanical properties.

According to Eurocode 5 (EN 1995:2004) safety checks are related to ultimate limit states (bending, shear and torsion) and serviceability limit states (deflection and vibration). This study only deals with bending strength of floor joists, considering the residual resisting cross

sections, which in some cases can suffer decreases due to beetle attack. Thus, the stress was calculated for each element considering the original and the real resisting cross section, for comparison purposes. The defined load combinations were based on Eurocode 0 (EN 1990:2009). In order to simplify the structural analysis, the joist were defined as being simply supported, as shown
in Figure 5, where P corresponds to the value of uniformly distributed load and l to element length.

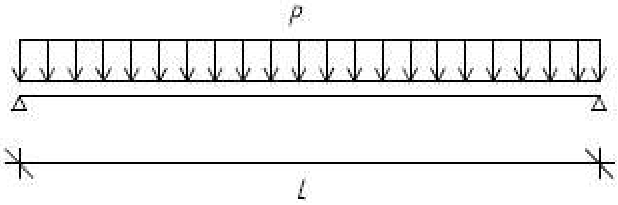


Figure 42. Simply supported beams load model

The select material density corresponds to pine wood, as specified in Portuguese standard (NP 4305:1995) for E or C18 grade. According to Eurocode 1 (NP 1991:2009), regarding type of occupancy and use of the room, the studied area belongs to category A. 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 2, giving values of 0,6 for permanent loads and 0,8 for variable loads.

RESULTS AND DISCUSSION

Preliminary and detailed diagnosis

Based on EN 335-2:2011, all studied areas were classified as use class 2, due to the possibility of moisture content in bathroom divisions. The storeroom and roof lantern areas were also classified as use class 2 because of the same reason (moisture content, for example from a broken roof tile). At inspection, none of three areas showed signs of moisture content. Storeroom roof showed some dirt spots throughout the timber elements. However, the moisture content measurement in this area is slightly higher than the other areas, as can be seen in Table 3.

Table 7. Mean values of moisture content (%)

Bathroom pavement	Storeroom roof	Roof lantern
9,2	12,5	8,5

Both bathroom pavement and storeroom roof are well lighted and wide areas, thus easing handling of inspection equipment. On the other hand, storeroom is a poor lighted smaller area, thus increasing difficulty of inspection procedures. Biological damage caused by boring beetles attack in all analyzed areas was verified. Some elements had a rough surface and the presence of sawdust could be verified with a sharp object (Figure 6).

Figure 43. Biological damage caused by boring beetles attack

The presence of oval shaped exit holes was confirmed, suggesting the presence of house longhorn beetle, as well as circular shaped exit holes, usually related with common furniture beetle (Figure 7). The exit holes had an approximate diameter of 8 mm for house longhorn beetle and 2 mm for common furniture beetle.

The biological degradation by wood boring beetles revealed more severe near the wall pavement connection. One of the larger joists had an effective cross section reduction of 18,8%. If not properly treated, this state of decay may lead to joist collapse, due to excessive loss of cross section and therefore strength, resulting in safety risks to the residents. In the resistographic profile two weaker spots were detected (A and B), as shown in Figure 8. These weaker areas can be related to biological degradation by house longhorn beetle.

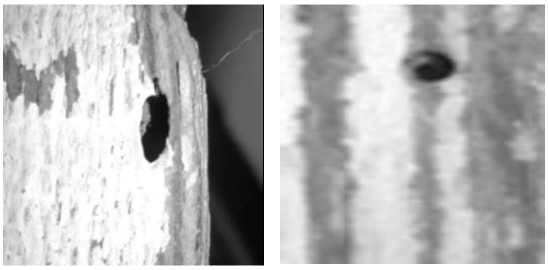


Figure 44. Exit holes: house longhorn beetle and furniture beetle

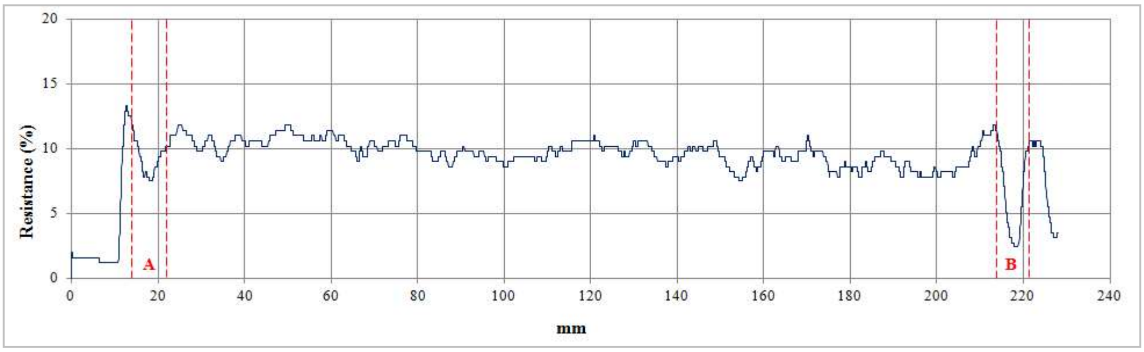


Figure 45. Resistograph profile of a degraded element by house longhorn beetle

The subterranean termites were the most frequent biological agent on the storeroom roof. The attacked elements by these insects show galleries or "shelter tubes" made of soil through which
they reach their source of food (Figure 9). In this elements neither insects nor swarms were found. The most severely attacked element had an effective cross section reduction of 12,8%.

Figure 46. Biological damage caused by subterranean termites

The following resistographic profile shows that almost half of the timber element is degraded by subterranean termites (Figure 10). Since verified moisture content values were below 20% the termite attack had ceased to exist, not requiring any treatment.

In this area it was also verified biological degradation by white rot fungi. The degraded element has a fibrous appearance, with transversal superficial shakes (Figure 11). The current moisture content does not allow the development of this kind of biological agent. It is assumed that its occurrence may have been possible due to periods with an higher moisture content.

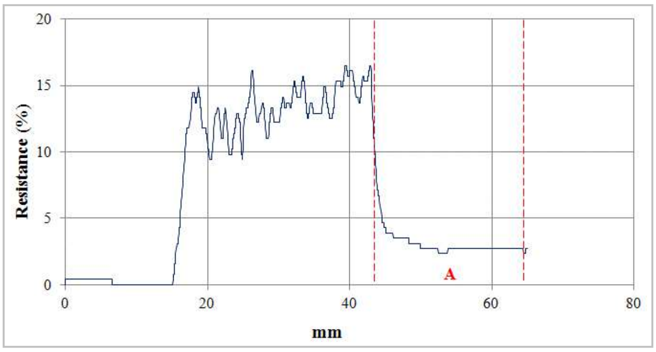


Figure 47. Resistograph profile of a degraded element by subterranean termites

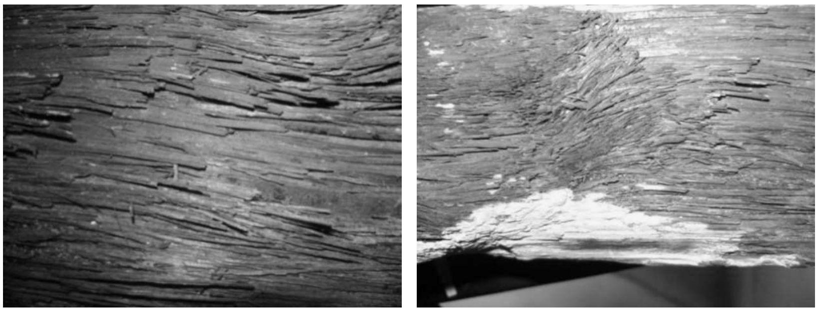


Figure 48. Biological damage caused by white rot fungi

In the following resistographic profile (Figure 12) two areas with degradation by house longhorn beetle (A) and white rot fungi (B) were detected.

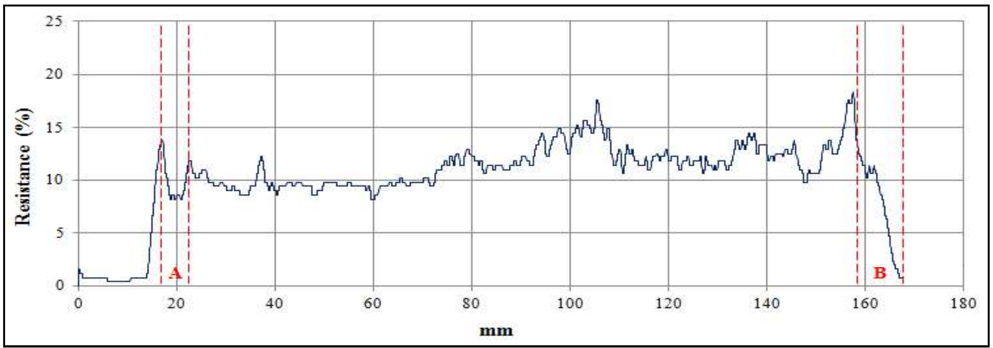


Figure 49. Resistograph profile of a degraded element by house longhorn beetle and white rot fungi

Pilodyn test results are shown in Table 4. The majority of results are within the initially range of expected values, thus confirming wood species. In the storeroom roof, the average penetration deep of Pilodyn tests were slightly lower, which can be related to some specific element defect. Thus, it can be assumed that most elements are healthy and do not show signs of biological attack. The attacked elements only show localized degradation, with the exception of two elements from the bathroom pavement and storeroom roof. Nevertheless, in order to avoid or stop biological attacks, it is recommended to apply preservative treatments against wood decay organisms in function of the type of attack (wood boring beetles, termites or rot fungi).

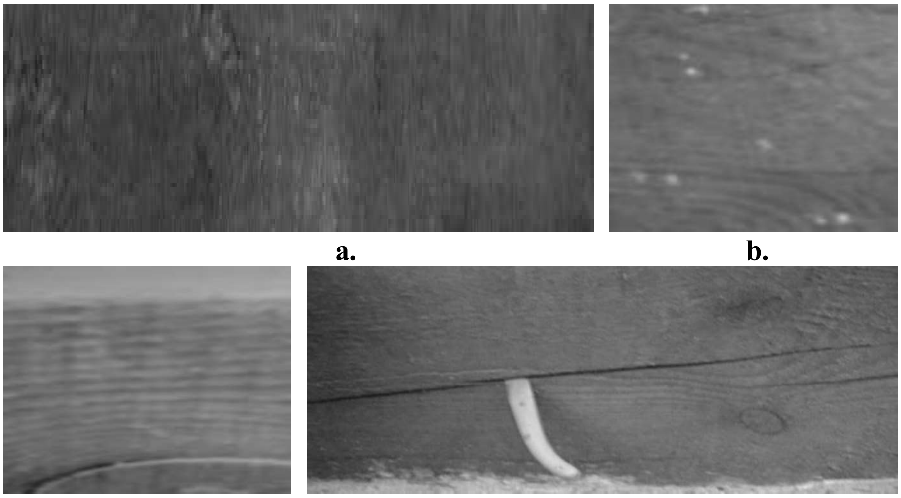
Table 8. Average penetration deep of Pilodyn tests (mm)

Bathroom pavement	Storeroom roof	Roof lantern
18,3	18,0	16,8

Visual grading

The Portuguese standard approach begins with the assignment of quality grades to each element. This standard is intended for maritime pine wood for structural purposes. Thus its strict follow may be too conservative, hence not suitable for heritage buildings. In order to ensure a proper application of this standard for this type of buildings, some of its limits and criteria must be properly adjusted such as is shown in [3]. Thus, only the forces that influence the defects should be analyzed, considering its relative position of the element, as well as the type of stress. The application of this standard revealed as a slow and complex process, but extremely important revealing some mechanical properties of the material studied. The accessibility conditions had indeed a real influence on the inspection of some timber elements [3].

The Italian visual grading standard is intended for on-site inspection of timber elements from cultural heritage buildings. Thus there is a greater tolerance regarding defects, when in comparison with other standards that do not target only heritage buildings. Therefore, it is assumed that the obtained results from the application of this standard must be closer to the actual condition of timber structure. However, the values for mechanical properties for pine species in this standard are not exactly equal to the pine species found in Portugal. This may have some influence on the results and conclusions.
For both standards, the most influential and frequent verified defects were knots, cracks and slope of grain (Figure 13).



a. b.

c. d.

Figure 50. Timber defects: wane (a), knots (b and c) and cracks (d)

The results from visual grading are shown in Table 5. According to the Portuguese standard, about 48% of timber elements have E and EE quality grades. It is clearer that a convenient adaptation of this standard in function of the wood specie is crucial. Still the results express well the quality of the material, despite its age.

According to the Italian standard, 92% of analysed elements fit into one of the quality grades (I, II and III), and only 8% does not meet minimum requirements. However, most elements (56%) belong to the first quality grade (mechanically stronger).

Table 9. Visual grading results

Standards	NP 4305:1995		UNI 11119:2004	
Grades	EE	12,0%	I	56,0%
	E	36,0%	II	32,0%
			III	4,0%
	Unrated	52,0%	Unrated	8,0%

Ultimate limit states for bending

The design bending strength of pavement joists shall be satisfied:

$$\sigma_{m,d} \leq f_{m,d} \qquad \left[\frac{kN}{m^2}\right]$$

$$\sigma_{m,d} \leq k_{mod} \times \frac{f_{m,k}}{\gamma_M} \qquad \left[\frac{kN}{m^2}\right]$$

Where:

$\sigma_{m,d}$ – Design bending stress
$f_{m,d}$ – Design bending strength
$f_{m,k}$ – Characteristic bending strength
k_{mod} – Modification factor for duration of load and moisture content
γ_M – Partial factor for material properties, also accounting for model uncertainties and xxxxdimensional variations

The following table shows the results of bending strengths for initial and effective (residual) cross section (Table 6).

Table 10. Results of bending strengths for initial and effective (residual) cross section

Element	Cross section				Effective cross section			
	$\frac{\sigma_{m,d\ total}}{\mathrm{k_{mod}}}$	$\frac{f_{m,k}}{\gamma_M}$	$\sigma_{m,d} \leq f_{m,d}$	$\frac{\sigma_{m,d}}{f_{m,d}}$	$\frac{\sigma_{m,d\ total}}{\mathrm{k_{mod}}}$	$\frac{f_{m,k}}{\gamma_M}$	$\sigma_{m,d} \leq f_{m,d}$	$\frac{\sigma_{m,d}}{f_{m,d}}$
1	3058,0	13846,2	**OK**	0,22				
2	3100,4	13846,2	**OK**	0,22				
3	3058,0	13846,2	**OK**	0,22	3315,1	13846,2	**OK**	0,24
4	2838,5	13846,2	**OK**	0,21				
5	4129,6	13846,2	**OK**	0,30				
6	7141,5	13846,2	**OK**	0,52				
7	8741,3	13846,2	**OK**	0,63				
8	10699,7	13846,2	**OK**	0,77	13389,2	13846,2	**OK**	0,97
9	12170,4	13846,2	**OK**	0,88	13494,3	13846,2	**OK**	0,97
10	12124,7	13846,2	**OK**	0,88	12079,8	13846,2	**OK**	0,87
11	12272,9	13846,2	**OK**	0,89	13317,3	13846,2	**OK**	0,96
12	8632,4	13846,2	**OK**	0,62				
13	5749,9	13846,2	**OK**	0,42	6013,6	13846,2	**OK**	0,43
14	2567,9	13846,2	**OK**	0,19				

Despite cross section reduction due to by biological attack, the effective cross section is still enough for safety. However, for two elements the ratio stress-strength is very close to one, which leads to safety risks if biological attack is not stopped. Therefore, in order to avoid the progress of the biological attack, the application of a preservative treatment is highly recommended.

CONCLUSIONS

With this evaluation and inspection process, it is clear that the materials used in the construction of this building had an above average quality. This is particularly relevant considering the building age, which has more than a century, and that was not verified the occurrence of severe degradation that could compromise the structural safety. The verified degradation was really localized, and the biological agents were all checked. The most frequent biological agent was the wood boring beetle (house longhorn and furniture beetle), termites and, although more rarely, rot fungi. It was relevant to estimate the effective cross section by deducting the portion affected by insects. This way it is possible to obtain the effective cross section involved in structural strength. In this analysis the joists (from bathroom pavement) bending strength were estimated according with 5. Thus the importance of controlling, or even cease, the development of biological attack was realized, due to risk of structural collapse or no action is taken.

In this study, only non-destructive inspection tests were employed. However, it is considered that other inspection techniques, such as laboratory and destructive testing on wood samples, could be relevant in order to further confirm results. In order to accomplish this study, it was required a research of, among other subjects, building history, biological degradation agents as well as some inspection techniques and devices. This established a combination between theoretical and practical knowledge.

In the development of this study, it was clear the importance of visual inspection for this kind of cultural heritage buildings. This inspection technique is crucial on supporting the data obtained from destructive and non-destructive testing. Beyond that, visual inspection allows for the detailed identification of studied areas. The differences between the two followed standards are clear, being the Portuguese standard specific to sawn timber for structural purposes, and the Italian standard for timber in cultural heritage buildings. However, the application of the different standards was not intended for comparison purposes but rather to study its different scopes and approaches on similar situations. The Portuguese standard only applies to pine wood being more specific, and the Italian standard applies to several wood species, thus being more adaptable.

For further studies, it is recommended to apply the NP 4305:1995 standard in a less restrictive way, adjusting it to this kind of buildings. If applied without any adaptation, the standard disregards many fairly well preserved timber elements, seriously decreasing the building's overall mechanical performance. The creation of a Portuguese standard targeting heritage buildings would be a significant contribution for the rehabilitation sector, due to the large volume of this kind of buildings nationwide.

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