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CHARACTERIZATION OF OLD CHESTNUT BEAMS SECTIONS WEAKENED BY DECAY

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ABSTRACT

The objective of this work was to experimentally assess the material properties of old chestnut *(Castanea sativa* Mill.) sections weakened by decay. Specimens were taken from critical zones of twenty floor beams, mostly corresponding to the ending parts in contact with granite masonry walls. These specimens were compared with clear wood reference specimens taken from undecayed parts of the same old beams. The experimental campaign comprised in visual inspection, non-destructive testing (ultra-sound, impact penetration and drilling resistance tests) and compression parallel to grain tests. Penetration tests presented an increase in the penetration depth of 36% for the decayed specimens, proving the decrease in resistance of the superficial layer. To evaluate the difference in the stiffness and strength results from the mechanical tests, the cross sections near the failure zones were identified and analyzed. The results of the decayed specimens exhibited a decrease of approximately 30% in the compression strength parallel to grain, mainly because of the presence of knots, misaligned fibers and decrease of the mechanical properties in the decayed areas. Also a reduction of approximately 5% was found for the dynamic and elastic moduli. For all cases, the coefficient of variation for decayed specimens results were significantly higher. Finally, the results of the experimental campaign were applied to calibrate a bi-parametrical decay model for above ground timber structures, considering a linear relation between time and decay depth.

Keywords: *Timber structures, Weakened sections, Decay, Experimental evaluation, Compression parallel to grain*

1. INTRODUCTION

1.1. Influence of decay in mechanical properties of timber

In the case of historical constructions the effects of ageing and decay must be considered, since the exposure of timber elements to the surrounding environment and to pathological agents leads to a downgrading of the mechanical properties along time. Considering the ageing process, concerning the normal life expectance of structural timber, it is possible to affirm in many cases that load history and time do not change significantly the mechanical and physical properties of sound wood when decay is not present [1]. Decay, on the other hand, has an important effect in the mechanical properties of wood even in early stages of development, such as in incipient stages of decay by fungal attack. Incipient decay may be considered when wood although with discoloration or, with a mottled appearance, has not underwent obvious changes in appearance and even in microscopic examination, below about 10% decay induced weight loss, its identification might be uncertain [2]. Despite the fact that incipient decay may be difficult to visually detect with certainty, it can cause significant reductions in wood strength. For example, compression parallel to the grain and shear parallel to the grain can be reduced in approximately 20% before decay is reliably identified, with bending strength being even more sensitive to incipient decay than these two parameters [3]. With a weight loss of only 5 to 10%, the associated probable strength loss in softwood can be as large as 80% (Table 1) [4]. In general, fungal decay produces a decrease on strength properties of wood, particularly toughness and impact bending [3], thus

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should be prevented or, in case of existence, characterized and its influence assessed. In Carll and Highley [5] it was found that the evolution between various stages of decay was quantitatively accompanied by the cell wall thinning even for early stages of brown rot fungus attack. However, Yang *et al.* [6] mentions that it is difficult to determine the presence and the stage of decay from density alone, due mainly to the natural variability in wood density and lack of information on density loss at various stages of decay. It is also referred that increasing decay had little effect on the elastic modulus in static bending (MoE) and that a reduction would be more likely to occur for modulus of rupture (MoR).
Fungal growth is assumed to take place especially for moisture contents over 20% [7], which are also favorable conditions for insect attack, since elevated moisture within a member might be considered as the most significant contributing cause of insect attack [8]. In fact, 90% of decay observed within buildings may be associated with the incidence of a water leakage [9] and, thus, is usual to find biological attack as the most significant damage in heritage timber structures. Common to insect and fungal attack is the destruction of wood constituents responsible for its structural strength and also its progressive spread to unaffected wood if no action is taken. Thus, it is usually recommended that any project for continued or new use of a building with structural timber must include an inspection of the signs of biological attack and, if found even in small percentages, an assessment of its significance and influence to the mechanical properties of the element itself and neighboring elements [10].

Table 1 Percent loss of mechanical properties due to early decay [4]

Strength Property	Average strength loss due to decay (%)
Static bending	70
Impact bending	80
Modulus of elasticity	70
Compression parallel to grain	45
Tension parallel to grain	60
Compression perpendicular to grain	60
Shear	20

This work intends to characterize some of the mechanical properties of sections weakened by decay in old chestnut (*Castanea sativa* Mill.) floor beams. Chestnut is a very common wood species found in historical constructions in North of Portugal (Southwest Europe) mainly due to its availability in the past and also due to its good mechanical properties and durability. The decay stage analyzed in the weakened sections was visually detectable and both non destructive and destructive tests were made to those sections with comparison to sections without decay.

1.2. Decay modeling

After a decay process is initiated, its growing/evolution depends mainly in wood moisture and temperature conditions [7]. Therefore, it is plausible to predict the evolution of a given pathological decay agent regarding the growth environment. Within the decay process, the evolution of decay is taken into account by a transition zone that separates undecayed wood from fully decayed wood (Fig. 1b). That transition zone is populated by active biological agents that are the reason of the decay progress within the element. The evolution of decay along time has been studied regarding the possibility of using models that may predict performance in a quantitative and probabilistic format [11, 12]. On those models, it is assumed that undecayed wood suffers no strength loss and that the transition zone is a narrow band. The decay models are assumed as bi-parametrical idealized models given by a bilinear function (Fig. 1a).

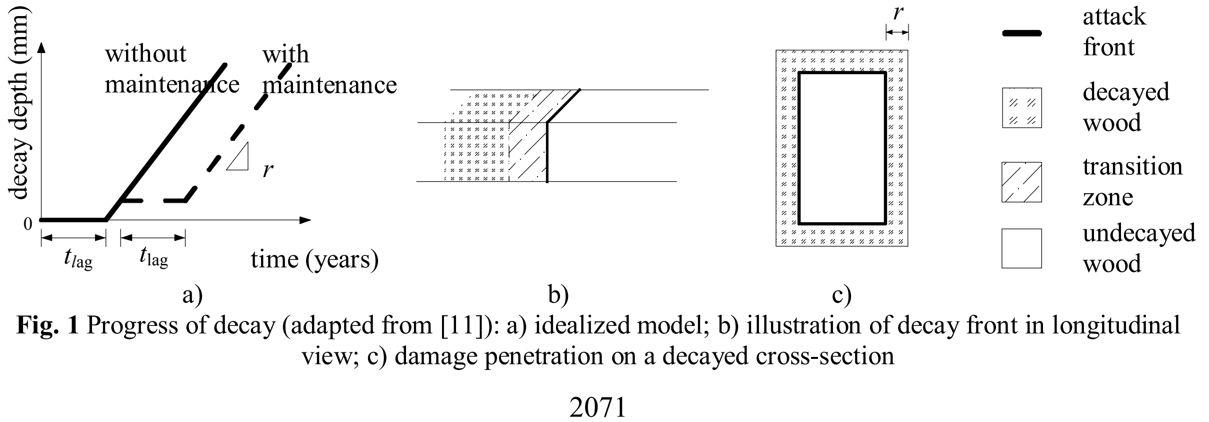


Fig. 1 Progress of decay (adapted from [11]): a) idealized model; b) illustration of decay front in longitudinal view; c) damage penetration on a decayed cross-section

The two parameters are t_{lag} (year) corresponding to the time before noticeable decay commences and r (mm/year) corresponding to an annual decay penetration rate depending on climate, durability and structural conditions of the timber element (eq. 1 and 2) [13].

$$t_{lag} = 8.5 \cdot r^{-0.85} \tag{1}$$

$$r = k_{climate} \cdot k_{wood} \cdot k_t \cdot k_w \cdot k_n \cdot k_g \cdot k_p \tag{2}$$

where: $k_{climate}$ = climate parameter, k_{wood} = wood durability parameter, k_t = thickness parameter, k_w = width parameter, k_n = connector parameter, k_g = geometry parameter, k_p = paint parameter.
In this work, it was also assumed that decay is regularly spread along the perimeter of the cross section progressing to the core of the element (Fig. 1c). This situation was found to be common for the samples derived from the ending parts of beams elements surrounded by masonry blocks when the perimeter of the section was mainly composed by sapwood.

2. EXPERIMENTAL CAMPAIGN

2.1. Samples and testing methodology

The tested elements correspond to twenty old chestnut (*Castanea sativa* Mill.) beams retrieved from a construction site located in North Portugal. They served as structural floor beams and were supported, in both endings, by granite masonry walls. The elements are more than a century old and were removed and replaced due to remodeling of the building (by oral statements it was found that the building was built in the beginning of the XX century). Although from the same construction site the origin of the wood is not known but assumed to be from the same region, since chestnut was commonly found in that place and time. The length of the elements varied between 4 m to 6 m with mean value of 5.32 m and coefficient of variation (CoV) of 11.8%. The floor consisted in a traditional structural solution with wooden boards connected to the top surface of the beams by iron nails that due to its age were corroded and started to affect the nearby wood.
Initially the beams were visually inspected [14, 15] and critical sections were chosen concerning the presence of decay. The study of the elements was divided into two separate analysis regarding the decayed sections and undecayed reference sections (Fig. 2).

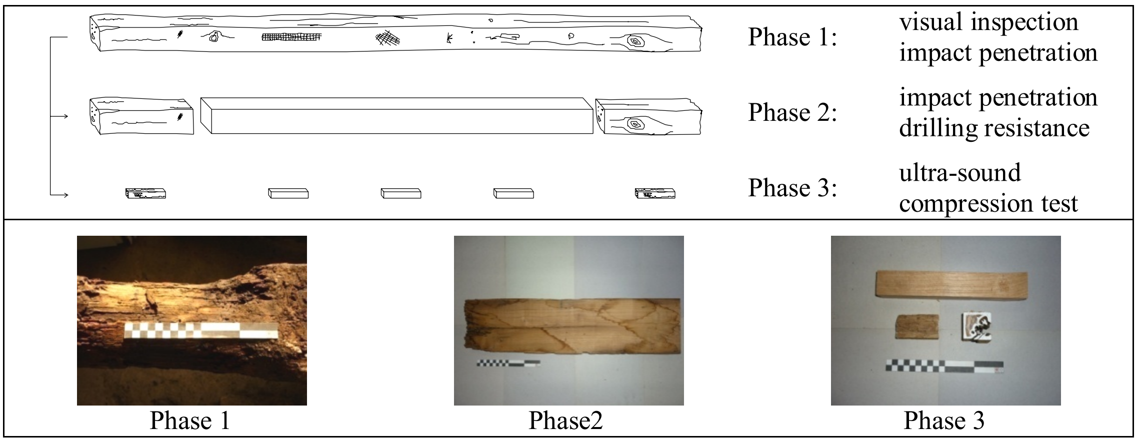


Fig. 2 Test sequence and samples

The decayed sections were mainly found in the ending part of the beams that were in contact with the masonry walls and were, therefore, more likely exposed to higher moisture contents. The reference samples were obtained by removing the external layer of decay, taking small clear specimens from the undecayed interior of the beams. In both cases, the sections were tested by impact penetration and drilling resistance tests and samples were taken in order to perform ultra-sound measurements and compression parallel to grain tests according to EN 408 [16]. Regarding the compression tests, three reference samples were taken from the middle segments for each beam. For the decayed region, one sample per ending was taken provided that it could give two adequate parallel surfaces for testing support. The values of compression parallel to grain strength in decay specimens were deduced regarding the cross section area near the failed section of the sample.

2.2. Visual inspection of the beams and definition of critical sections

Visual inspection is one of the first and most important steps to be carried out in a structural diagnosis. By using proper inspection methods it is possible to document and classify a specific type of damage according to its extent and severity. This information is both important to assess the global state of conservation of a timber element and also for analyzing the variation found within a same element or group of elements. Furthermore, some norms [14, 15] also propose indicative values for visual strength grading that allow for a first analysis of the mechanical properties of the timber element, although often over conservative. In this work, the old chestnut beams were visually inspected regarding the Italian norm UNI 1119 [15] and critical sections were considered with respect to the sections with higher level of visible decay. This norm considers three classes (I, II and III) for strength grading of a single element, regarding onsite diagnosis for a given wood specie (Table 2). A wood element corresponds to a given class if it fulfils all the imposed requirements and considered as non-classifiable if it does not fit to neither class. For the purpose of characterization of sections weakened by decay, the critical sections were considered to be the ending parts of the beams since those segments revealed the most severe state of decay due to biological attack, both insect and fungi. The extent of decay, either depth or extent, was not uniform between beams. The studied critical sections were considered to be non-classifiable regarding the high level and extent of decay and thus by assuming the proposed indicative values a decrease of at least 36% for compression parallel to the grain could be expectable from reference values (class I) to the decayed segments.

Table 2 Mechanical properties for Chestnut (*Castanea Sativa* Mill.) in a visual strength grading [15]

Class	Mechanical properties (N/mm^2)					
	compression		static bending	tension // to grain[1)]	shear // to grain	MoE in bending
	// to grain	⊥ to grain				
I	11	2.0	12	11	0.8	10000
II	9	2.0	10	9	0.7	9000
III	7	2.0	8	6	0.6	8000
NC[2)]	-	-	-	-	-	-

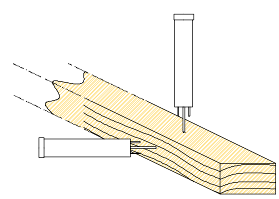
[1)] tension ⊥ to grain is conventionally assumed to be equal to zero
[2)] NC: non-classifiable

2.3. Non destructive assessment

2.3.1. Impact penetration tests

For the impact penetration test a Pilodyn 6J device was used, that through the release of a spring, transforms the elastic potential energy into impact energy. The penetration of a metallic needle with 2.5 mm of diameter can be measured and the depth is inversely proportional to the density of the wood, which is rather interesting to measure surface fungi deterioration [17]. Measurements were made to the old beams with the existing superficial decay in the middle segments with lower percentage of visible decay, to the most decayed regions and also to the reference samples (sawn timber with removal of exterior decay layer) (Table 3).

Table 3 Impact penetration test results

Segments	Penetration depth (*d* in mm)				
	minimum	maximum	mean	CoV (%)	
Old beams: decayed endings	6	22	12.16	14.7	
Old beams: undecayed regions	6	16	11.05	16.3	
Sawn timber: no decay	5	15	8.31	14.5	

The results obtained show that the difference between visible decay segments and other regions of the old beams only represent a mean increase of 1.11 mm depth. Thus, the external layer that gave timber a poor aspect was found to be, in this case, rather small. Nevertheless, when comparing to the reference values, a difference of 3.85 mm is found, representing an increase of penetration depth of 32% between reference values and sections with visible decay. Assuming these measurements a multi layer stratified cross-section may be considered for the different segments of the beam regarding its decay visual inspection (Fig. 3), analogous to the previous presented model (Fig. 1b). The CoV between different segments presented similar values varying from 14.5 to 16.3%. Also a comparison was made to decayed and reference values within the same beam, finding a mean increase of penetration depth of 36% (with CoV = 16.2%). Besides decay, the difference of penetration depth is also explained when the tests are made to segments with higher percentage of sapwood or heartwood. The studied values are representative of the decay level since the impact penetration tests were made along the whole perimeter of the cross sections measuring several sections with different percentages of sapwood and heartwood.

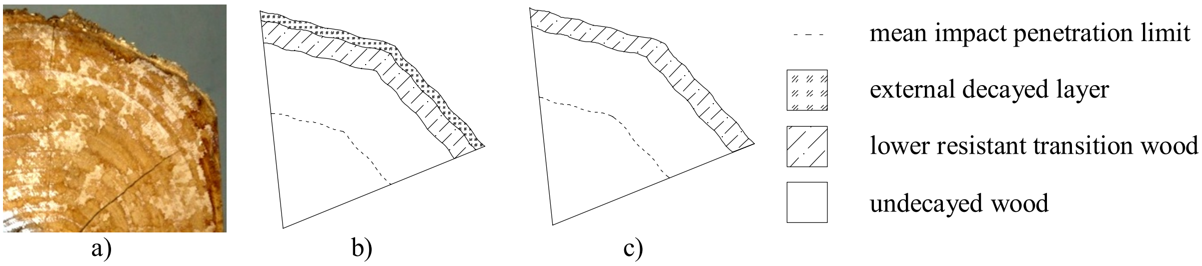


Fig. 3 Stratification of a cross section with decay: a) example of study; b) section with visible external decayed layer (ending of beams); c) section with no visible external decayed layer (middle segments of beams)

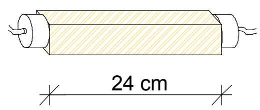
2.3.2. Drilling resistance tests

In order to assess the severeness of decay in the critical sections, a Resistograph 3450 equipment was used. The Resistograph is a commercial testing equipment based in micro-drilling wood at constant speed, and measuring the energy required for maintaining that speed. It is usually adopted to obtain density profiles and allows to characterize the full size of the specimen [18]. The result of a drilling resistance test is often taken by the resistographic measure (*RM*) given by the integral of the area beneath the resistance profile in respect to the length of drilling path. Drilling resistance tests were made in the sections that exhibited higher superficial decay but had not suffered severe cross-section reduction. The tests were so performed in the ending parts of the beams (segments that presented poorer visual condition) in a section that still presented a defined cross-section obtaining values of RM_{decay}. The mean values of RM_{decay} were compared to the results of drilling resistance tests made to the reference values $RM_{reference}$ and no significant difference was found ($RM_{decay,mean}$ = 302.5 bit ≈ $RM_{reference,mean}$ = 302.4 bit), however the coefficient of variation for decayed samples is double of that value for the reference samples (CoV_{decay} = 20.8% > $CoV_{reference}$ = 10.4%). In respect to these values, resistograph measure was not able to detect the difference between decayed and undecayed segments, since the layer of decay was relatively small and the inner core of wood maintained similar properties in both samples. Actually, the most significant data obtained in these tests was the qualitative information about the existence of inner voids or decay, which in either samples were not found.

2.3.3. Ultra-sound tests

The ultra-sound tests were made with a Pundit Lab equipment with 54 kHz frequency transmission transducers. Samples had a square cross section with 4 cm width and a length of 24 cm. The samples were taken from the ending parts of the beams with signs of decay and from the reference segments being analyzed by direct ultra-sound measurements. For each sample, two measurements were taken and averaged, if the two first measurements differed more than 5% then an additional third measurement would be taken and the average would be done with the three measurements. The propagation velocity decreased 2.11% in the decayed samples regarding all reference samples of the 20 beams (Table 4).

Table 4 Direct ultra-sound test results relative to propagation velocity

Samples ($4 \times 4 \times 24$ cm^3)	**Propagation velocity (v_p in m/s)**				
	minimum	**maximum**	**mean**	**CoV (%)**	
Decayed	4569.2	5650.6	5108.6	6.5	
Undecayed (reference values)	4724.6	5627.2	5218.6	3.7	

The propagation velocity may be related to the static and dynamic moduli of elasticity (E_{sta} and E_{dyn}) if the density of the timber element is known (eq. 3) [19].

$$E_{sta} = K \cdot E_{dyn} = K \cdot v_p^2 \cdot \rho \tag{3}$$

where: K = proportionality constant dependant of the timber species, v_p = propagation velocity, ρ = density. For practical purposes, the relation between E_{sta} and E_{dyn} is particularly relevant ($E_{dyn} \geq 0.90\ E_{sta}$). This relation is explained by the viscous-elastic behavior of wood [20].
Density was determined for the reference samples by ISO 3131[21] obtaining a mean value of 571.2 kg/m^3 (CoV = 7.9%). Although, density is likely to be lower in the decayed regions due to loss of cellular wall destroyed by decay agents its exact determination by common methods is not feasible, therefore if considering the same density for both decay and undecayed regions a decrease of 3.9% in E_{dyn} for decayed regions in respect to the reference values was obtained. With decrease of density in the decayed segments this reduction would even be more significant.

2.4. Compression parallel to grain tests

Compression parallel to grain tests were made regarding EN408 [16] with samples of 4 × 4 cm^2 cross-section and 24 cm height (six times the smallest cross section dimension). Deformation was measured over a central gauge length of 16 cm (four times the smallest cross section dimension), using one pair of LVDTs (range ±12.5 mm) placed on opposite faces to take into account the effect of possible distortion. Compression parallel to grain strength $f_{c,0}$ and elastic modulus in compression $E_{c,0}$ were obtained (eq. 4 and 5).

$$E_{c,0} = \frac{l_1 \cdot (F_2 - F_1)}{A \cdot (w_2 - w_1)} \tag{4}$$

where: $(F_2 - F_1)$ = increment of load (N) on the straight line portion of the load deformation curve, $(w_2 - w_1)$ = increment of deformation (mm) corresponding to $(F_2 - F_1)$, A = cross sectional area (mm^2), l_1 = gauge length (mm) for the determination of $E_{c,0}$ (N/mm^2).

$$f_{c,0} = \frac{F_{max}}{A} \tag{5}$$

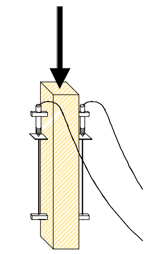
where: F_{max} maximum load applied (N), A = cross-sectional area (mm^2).

For undecayed specimens the value of A was calculated as the average value of two measurements taken at a distance not closer than 50 mm to the ends of the samples by an electronic caliper. A for decayed specimens was obtained by image processing (Fig. 4) of two sections cut within l_1 for calculus of $E_{c,0,decay}$ and of a section cut near the failure section for calculus of $f_{c,0,decay}$.
The results of the compression parallel to grain tests (Table 5) evidenced that the decayed samples present a decrease of 33.14% for $f_{c,0}$ and 6.17% for $E_{c,0}$. The variation of results for decayed samples is significantly higher than for the reference values. A significant decrease is found for $f_{c,0}$ might also be considered due to buckling instability in consequence of the increase of slenderness resulting from the reduction of effective cross-section. The loss of cross section due to decay must be considered for buckling limit state verification however the decayed area, although with lower compressive strength, stills provides a level of confinement to the other undecayed fibers and thus must be considered in the residual cross section [22].

a) b) c)

Fig. 4 Image processing for cross sectional area determination: a) example of decayed cross section, b) scanned cross section; c) computerized cross section drawing

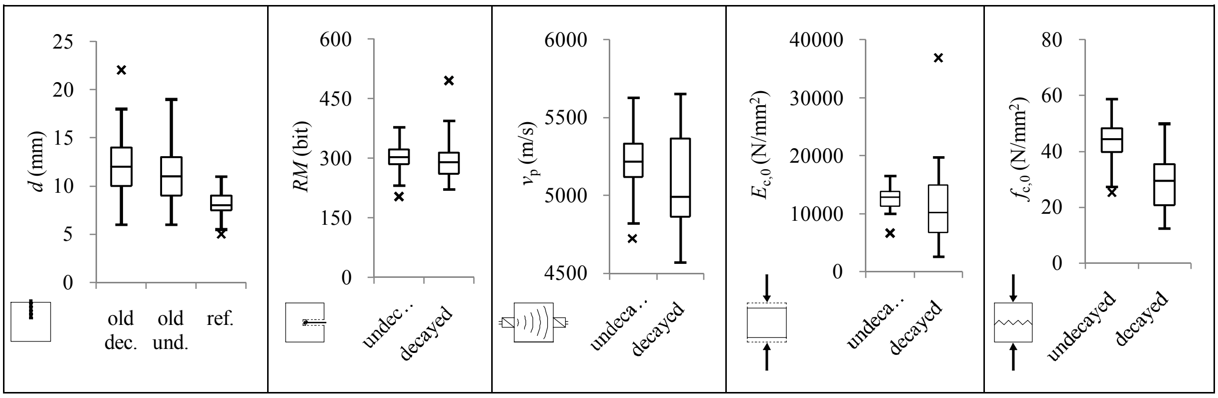
Table 5 Compression parallel to grain test results

Samples (4 × 4 × 24 cm³)		Compression // grain (N/mm²)				
		minimum	maximum	mean	CoV (%)	
Decayed	$E_{c,0,decay}$	2566.0	36840.0	11841.9	64.2	
	$f_{c,0,decay}$	12.40	49.90	28.75	35.0	
Undecayed (reference values	$E_{c,0,undecay}$	16501.5	6684.8	12620.9	15.7	
	$f_{c,0,undecay}$	24.96	58.82	42.99	17.2	

[1)] undecayed sample with respect to the beams from which decayed samples were removed

2.5. Test results and dispersion of values

The results of the different test phases are presented in form of box plots for better definition of the dispersion of values regarding the first, second and third quartiles (Fig. 5). Definition of outliers are also considered, with minimum and maximum limits for non outlier values defined by the distance of 1.5 times the interquartile difference.



a) b) c) d) e)

Fig. 5 Box plots of test results for undecayed (reference) and decayed samples in: a) impact penetration; b) drilling resistance; c) ultra-sound; d) and e) compression parallel to grain

3. DECAY MODEL AND PARAMETER CALIBRATION

Although decayed cross section regions may still present residual load bearing capacity the loss of load bearing capacity is inevitable due to the loss of cross section area. A larger or smaller variation on the mechanical properties of timber due to decay depends of its stage of development and extent, thus it is important to predict the evolution of decay along time in order to define when a limit residual cross section is obtained. Assuming the proposed model in [13] for above ground timber elements in a temperate environment and with consideration to the ending parts of the beams previously in contact with the masonry walls, the decay model parameters were calculated. A predicted $r = 0.36$ mm/year and $t_{lag} = 22.1$ years were obtained. Assuming the same period of time before visible decay commences, but taking into account the decay depth present in the studied elements an experimental decay rate was also calculated. In this case, the decay depth was assumed by accounting the difference between the area of sections without visible decay and the decayed sections in the old beams and also accounting the penetration depth difference, given by the impact penetration tests, between old decayed sections and undecayed reference samples. A mean penetration depth of 10.35 mm was found. The consideration of a 100 years lifetime would result in a experimental $r = 0.13$ mm/year, which is significantly smaller than the predicted one. The main reason to this difference is the parameter related to the environmental conditions which was not calibrated for these climatic conditions. In order to obtain a similar decay rate, maintaining the parameters related to the structural system and wood durability, a $k_{climate} = 0.21$ should be considered and t_{lag} should be taken with respect to in situ observations.

4. CONCLUSIONS

Decay is commonly present in existing timber structures where environmental conditions are favorable to biological growth and no preventing actions have been taken to minimize it. Besides evidencing a poor visual condition, decayed sections have a reduced cross section not only in terms of residual area but also in terms of effective strength and stiffness, even for early stages of decay. Therefore decay should be prevented and when existing should be assessed and its influence analyzed.

In order to characterize the weak sections of old chestnut beams, an experimental campaign was made regarding both non destructive and destructive testing. In all tests, the existence of decay resulted in larger dispersion of values and thus higher coefficients of variation. Both strength and stiffness properties decreased for decayed sections, with a difference of 32% in impact penetration depth, 2.11% in propagation velocity (corresponding to at least 3.9% in dynamic modulus), 33.14% for compression parallel to grain strength and 6.17% for elastic modulus of elasticity in compression parallel to grain. Visual inspection and non destructive tests were in correspondence to the destructive tests and the reduction of strength and stiffness between decay and undecayed samples was equivalent along the different methods. Nevertheless in this case study, drilling resistance was not considerably affected by decay.

A decay model was also considered in order to analyze and predict a reasonable decay rate, however was found to present significantly higher values than the expected by analysis of the experimental campaign ($r_{predicted} = 0.36 > r_{experimental} = 0.13$ mm/year). In order to obtain a similar decay rate, maintaining the parameters related to the structural system and wood durability, a $k_{climate} = 0.21$ should be considered and t_{lag} should be taken with respect to in situ observations.

Further study might be considered regarding the variability of mechanical properties by defining different stages of decay, posing as a first step to the definition of a multi-scale decay model with different decay rates along the lifetime of the structure.

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