Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

ASSESSMENT OF STRENGTH AND STIFFNESS VARIATION WITHIN OLD TIMBER BEAMS

Sousa H.S.[1], *Branco J.M.*[2], *Lourenço P.B.*[3]

ABSTRACT

The mechanical properties of timber elements vary significantly along its extent due to natural variability of wood cellules and presence of defects. In this work, the variability of stiffness and strength properties of old chestnut (*Castanea sativa* Mill.) floor beams with more than 100 years, was experimentally assessed and mechanical properties were correlated. Visual inspection, non-destructive and destructive tests (bending, compression and tension parallel to grain) were considered in different scales aiming to obtain reliable information for predicting the mechanical properties of old timber elements by use of small clear samples and defect concentration. For that purpose, the timber elements were systematically cut to smaller samples, to minimize the presence of defects, and tested in each phase. Visual inspection evidenced large variability in old timber elements' properties and proved to be qualitatively useful in predicting its performance, although conservative for higher visual strength classes. Strong correlations between moduli of elasticity in bending were found in sawn beams and boards ($r^2 = 0.82\text{-}0.89$), however with weak correlations to non-destructive tests except for ultra-sound tests ($r^2 = 0.51\text{-}0.87$). The bending results in sawn boards revealed that stiffness properties vary both in height and length of each beam in different proportions. Also variation within an element was lower compared to the variation within the full sample. Density was found to be an important parameter for properties correlations determination. Finally, knot area ratio was used to correlate the influence of defects with stiffness properties of the existing timber elements.

Keywords: *Timber structures, Experimental evaluation, Stiffness variation, Properties correlations, Defect influence*

1. INTRODUCTION

Along a timber element it is expected to find different natural defects which influence its mechanical properties. Size, length and also the distance between different defects are parameters that will condition the mechanical behaviour of the affected cross-sections and nearby sections. The properties of wood located between defects (clear wood) are expected to correspond to both higher strength and modulus of elasticity (MoE) and to present less variability compared to sections of timber influenced by defects. Thus, it is not prudent to consider only the results of mechanical tests of small samples without defects since its presence may largely influence the element's structural behaviour. In this work, 20 chestnut beams were studied with resource to different types of tests and size scales, aiming in analysing the influence of defects in timber elements regarding different scales and assessing the correlations between non-destructive tests (NDT) with destructive tests (DT). For that purpose, the timber elements were systematically cut in order to minimize the presence of defects and tested in each phase. Particular attention was given to the MoE in bending and its variation.

2. EXPERIMENTAL CAMPAIGN

2.1. Test samples and testing sequence

The tested elements correspond to 20 old chestnut (*Castanea sativa* Mill.) beams obtained from a construction site located in North Portugal. They served as structural floor beams supported, in both

[1] PhD student, ISISE, Dept. Civil Engineering, University of Minho, hssousa@civil.uminho.pt
[2] Assistant Professor, ISISE, Dept. Civil Engineering, University of Minho, jbranco@civil.uminho.pt
[3] Professor, ISISE, Dept. Civil Engineering, University of Minho, pbl@civil.uminho.pt

endings, by granite masonry walls. The elements are over a century old (beginning of the XX century) and were replaced due to remodelling of the building. The length of the elements varied between 4 to 6 m with mean value of 5.3 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, which due to its age were corroded and started to affect the nearby wood. The experimental campaign was composed by four main phases, regarding the size scale of the elements (Fig. 1).

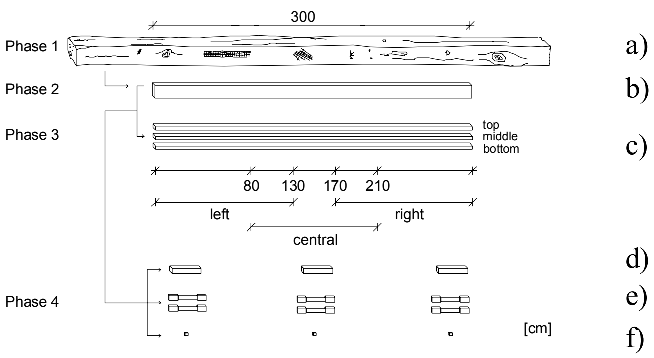


Fig. 1 Samples used for each test: a) original beams; b) sawn beams; c) sawn boards; d) compression tests; e) tension tests; f) density and moisture content measurements

Phase 1 dealt with visual inspection and grading of the old beams [1-3] complemented with NDT (penetration impact and drilling resistance). In phase 2, the beams were cut to 7 × 15 × 300 cm^3 samples without superficial decay, and defects were accounted in 7 consecutive segments of 40 cm. Then, 4 point bending tests [4] were made to each beam obtaining local ($E_{m,l}$) and global ($E_{m,g}$) MoE in bending whose differences are described in [5]. The timber beams were assessed, before and after the bending tests, by ultra-sound pulse velocity tests (UPV) in indirect method on each segment's bottom and lateral faces. In phase 3, the undamaged beams were sawn into 3 boards with 7 × 4 × 300 cm^3 (48 boards), visually inspected and assessed by NDT. To each segment of each board a 4 point bending test was made to assess the variation of MoE along the element's length (336 tests) (Fig. 2). In phase 4, clear wood samples were considered for compression, tension parallel to grain tests and to density and moisture content (MC) measurement. For each beam, 3 compression, 6 tension and 3 density samples were taken and UPV tests were made. DT were made with displacement control, obtaining MoE and ultimate strength. To calibrate the NDT, reference tests were made in areas without visual indication of superficial decay. For NDT the considered parameters were the resistographic measure, *RM*, for drilling resistance (ratio between area of the resistographic diagram and height of sample), penetration depth, d_{pil}, for impact penetration and propagation velocity, v_{p}, for UPV. The v_{p} of a material may be related to the static E_{sta} and the dynamic E_{dyn} MoE, through Equation (1) [6]. The relation between E_{sta} and E_{dyn} ($E_{\text{dyn}} \geq 0.90\ E_{\text{sta}}$) may be explained by wood’s viscous-elastic behaviour [7].

$$E_{\text{sta}} = K \cdot E_{\text{dyn}} = K \cdot v_p{}^2 \cdot \rho \tag{1}$$

where: ρ = density, K = proportionality constant dependant of the timber specie. Density and MC tests to the samples after stabilized (in climatic chamber under conditions of 20°C and 59.6% RH) [8-9].

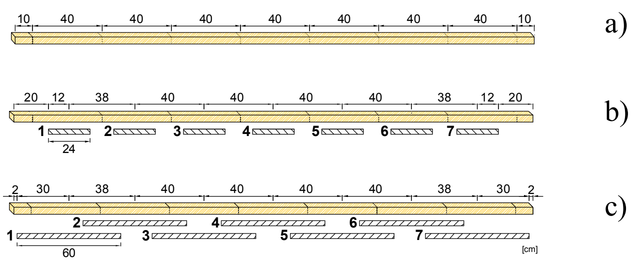


Fig. 2 Location of the sequential bending tests per board: a) visual inspection segments; b) gauge length for $E_{m,l}$ (in shade); c) gauge length for $E_{m,g}$ (in shade)

2.2. DATA ANALYSIS AND RESULTS

2.2.1. *Phase 1: old beams*

After removed from the building, the timber beams were marked A to T, visually inspected, graded [1-3] and assessed by NDT. For each 40 cm segment the beams were graded in order to define critical sections and to evaluate the variability of visually assessable properties along their length. Visual inspection is one of the first and most important step in a structural diagnosis and should be carried out with aim to study both causes and future consequences of the problem. The Italian norm [3] methodological approach consists in visual inspection combined with NDT for diagnosis of the conservation state and estimation of the mechanical properties of structural wood in cultural heritage buildings. For strength grading, this norm considers three classes (I, II and III) regarding onsite diagnosis. Data is gathered to define the general state of the structure and, different evidences of structural pathologies are documented and classified according to its extent and severity. In this study, the most commonly found defects were knots and misalignment of grain. The ends of the beams were quite decayed, whereas a more superficial damage was found along their length (Fig. 3).

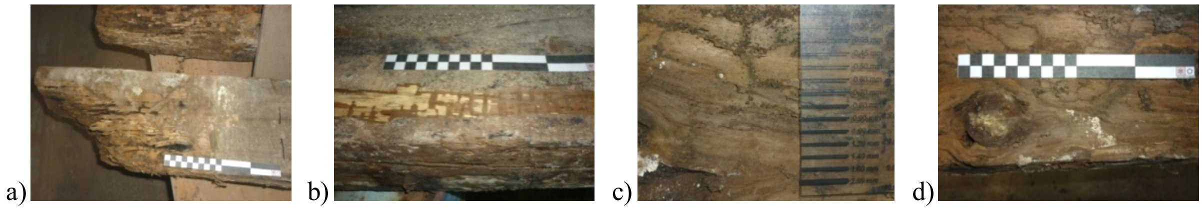


Fig. 3 Defects and anomalies found in the timber elements: a) deterioration of internal fibbers by xylophagous insects; b) decay by fungi; c) superficial attack of xylophagous insects; d) knots and grain misalignment

Also chamfering of the elements was found, more due to the initial sawing process rather than to loss of cross-section integrity. In phase 1, the segments were visually strength graded considering as main features the knot incidence and slope of grain, and omitting the parameters originated by external damage (structural or environmental). This process intends to obtain the mechanical properties related to the material itself and its defects rather than to the state of conservation, which may be assumed by the reduction of the effective cross section [10]. In [11] the knot incidence and slope of grain were also considered as the most important influencing parameters and those that lead to more significant MoE reduction. Also in [12] it is stated that knots are by far the most important defects in the reduction of visual grading, being quite significant in the case of thick elements, like beams. Aiming for a consistent and comparable indicator between phases, visual inspection was redone to the beams after being sawn into regular straight elements and to each set of three sawn boards, being the results of the visual inspection for all phases presented, for better comparison, in Fig. 4.

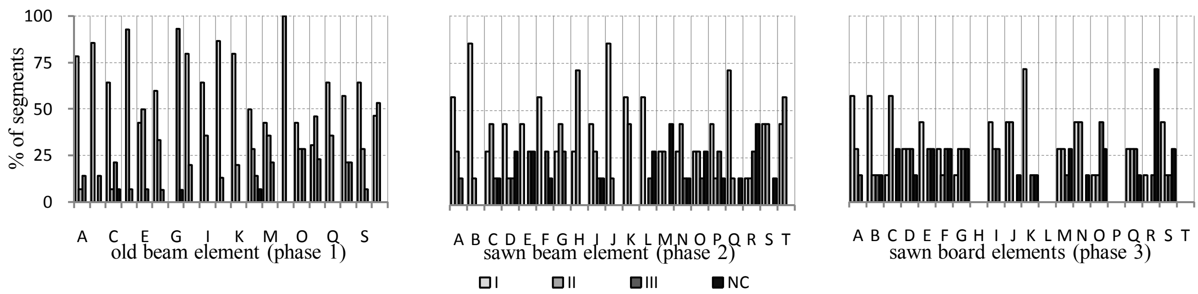


Fig. 4 Percentage distribution of segments included in each class of the visual inspection [3], for phases 1 to 3

Complementing the visual inspection with NDT results permitted to verify that the decay found along the span of the timber beams was mainly superficial, since the d_{pil} between visible decayed and undecayed segments had only an average increase of 1.1 mm. Drilling resistance tests made to the segments near the endings of the beams denoted that even if the outside layer presented poor visual condition the core of the element was still in good conditions and without significant voids.

2.2.2. *Phase 2: sawn beams*

After visual inspection, UPV in indirect method was made on each segment. The mean value of v_p for all beams was 4846.5 m/s in bottom face and 4821.6 m/s in lateral face with CoV of 8.6 and 6.6%, respectively. The average of the CoV for the measurements in each beam was 6.3 and 4.9%, respectively for bottom and lateral faces. The decrease of the variation between the measurements of all beams and measurements within a same beam, represent an increase of variation when assessing different timber elements, even from the same structure and timber specie. The average difference between v_p in bottom or lateral faces was less than 10%. All beams were then submitted to bending tests in elastic regime to obtain $E_{m,l}$ and $E_{m,g}$. Four beams were tested until failure (beams H, L, P,T). A mean value of 10841 N/mm^2 was found for $E_{m,l}$ and 10940 N/mm^2 for $E_{m,g}$ (CoV = 25.3% and 22%, respectively). Similar CoV for MoE is suggested in [13] although for softwoods, whereas in [14] a CoV between 9 to 23% may be found for MoE in bending of small clear wood specimens. However, it must be noted that variation is lower for small clear specimens and highly depends on the source of information reliability. Also the correlations between properties are higher for small clear specimens and lower for large members [15]. A strong correlation is found between $E_{m,l}$ and $E_{m,g}$ ($r^2 = 0.82$). Also, it is visible that more than 50% of the values of both MoE are distributed within [9;13] kN/mm^2. A mean bending strength, f_m, of 23.11 N/mm^2 (CoV = 10.5%) was found ($f_{m\_beamH} = 23.66$ N/mm^2; $f_{m\_beamL} = 19.53$ N/mm^2; $f_{m\_beamP} = 24.58$ N/mm^2; $f_{m\_beamT} = 24.69$ N/mm^2). Visual inspection proved to be correct in assessing qualitatively the four beams. Beam T presented higher f_m than the remaining three beams, consistent with the previous visual inspection where beam T had higher percentages of visual classes I and II. On the other hand, the beam with lower f_m (beam L) had the higher percentage of NC sections. In all cases, the beam failure initiated in a segment with higher percentage of defects. After the tests, UPV was redone in the beams that were not taken to failure, obtaining no significant differences with the prior UPV (<10% mean difference), thus confirming that the tests were made in the elastic regime without inducing damage to the elements. Then, E_{dyn} (considering ρ_{mean}) was compared to $E_{m,l}$ regarding the segments within the respective gauge length. Through the analysis of the results it was found that different ratios $K = E_{dyn} / E_{m,l}$ were found for two groups. A group with 75% of the beams (G1) evidenced a mean $K = 0.86$, whereas a second group with 25% of the beams (G2) evidenced a mean $K = 0.56$. Considering separate groups in the comparison between E_{dyn} and $E_{m,l}$, strong correlations were found and also it is evidenced that the linear regression lines of the two groups have similar inclinations, denoting two results clusters (Fig. 5). Although from the same wood specie, its origin and conditions of growth were unknown, which may account to the found differences. Regarding these results, the correlations between different scales are also referred to each group separately.

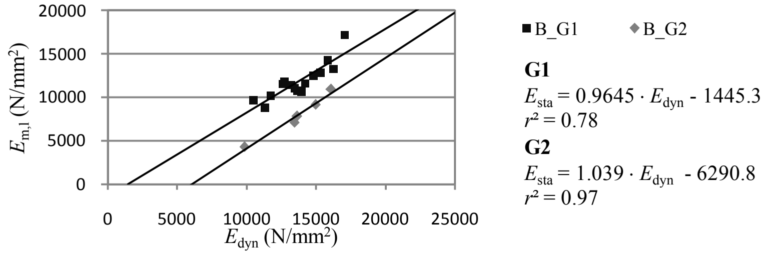
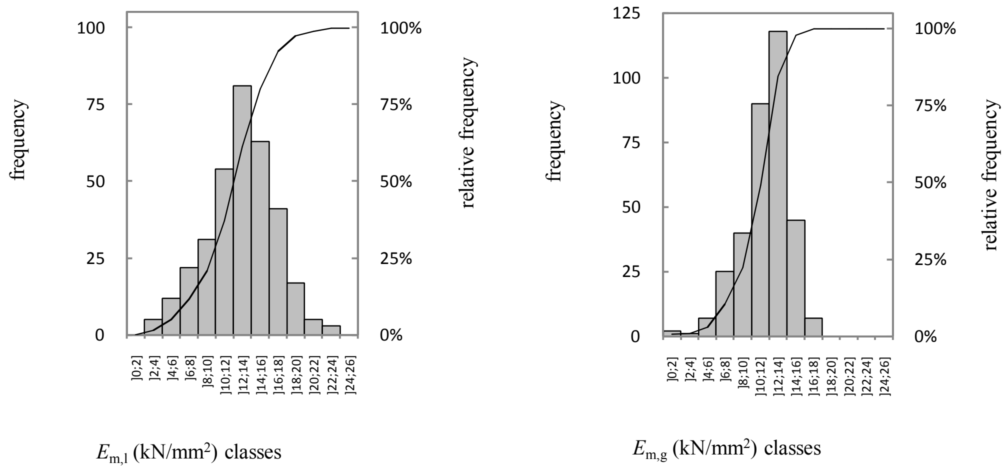


Fig. 5 Correlation between $E_{m,l}$ and E_{dyn} in phase 2

2.2.3. *Phase 3: sawn boards*

After visual inspection, UPV tests in indirect method were made on each segment. The mean value of v_p for all boards was 4861.5 m/s. A decrease of variability was found when assessing smaller size scale elements, such that the CoV between the measurements of all boards equals 8.4%, the CoV of measurements within a same set of three boards (a beam) equals 6.9% and the CoV of measurements within a same board equals 6.3%. Then, all sawn boards were submitted to bending tests in elastic regime in order to obtain $E_{m,l}$ and $E_{m,g}$. The results are given in form of histograms and cumulative distribution functions in Fig. 6. A mean value of 12190 N/mm^2 was found for $E_{m,l}$ and 11661 N/mm^2 for $E_{m,g}$ with CoV approximately of 30% and 23%, respectively. The values given by segments for a given beam were averaged and a strong correlation is found between $E_{m,l}$ and $E_{m,g}$ ($r^2 = 0.89$). This correlation is stronger than the correlation when analyzed the values given in the full size beam bending tests. Also, it is visible that more than 50% of the values of both MoE are distributed within the range [10;16] kN/mm^2. The measurements also revealed that stiffness properties vary in height and length of each beam in different proportions, being the variation higher when higher concentration of knots were found, such is shown in Fig. 7 where for segment 4 of the bottom board of beam J, a significant knot lead to a decrease in v_p and MoE. The mean CoV of measurements made to the same segment of each set of boards (variation in height) is equal to 20.1% and 15.7%, respectively $E_{m,l}$ and $E_{m,g}$, whereas the mean CoV of measurements made to all segments of a given board (variation in length) is slightly higher being equal to 25.8% and 17.9%, respectively $E_{m,l}$ and $E_{m,g}$.



$$E_{m,g} = 0.65585 \cdot E_{m,l} + 3208.6 \ (\boldsymbol{r^2 = 0.89})$$

a) b)

Fig. 6 Histograms and cumulative distribution functions in phase 3 for: a) $E_{m,l}$; b) $E_{m,g}$

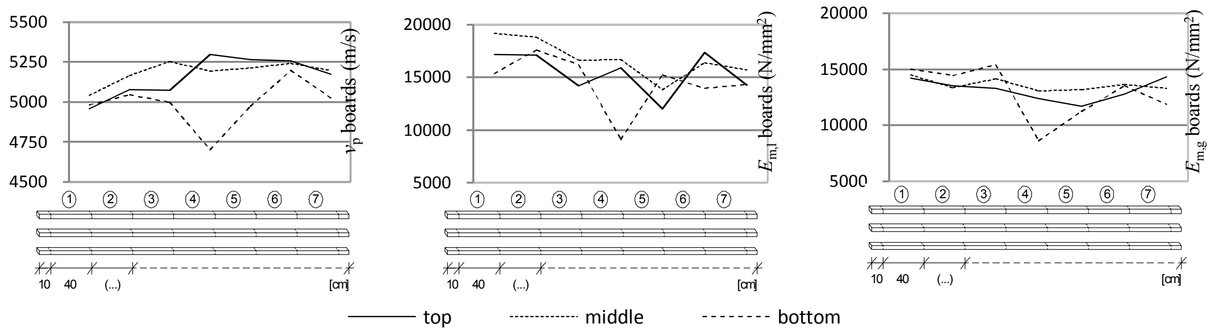
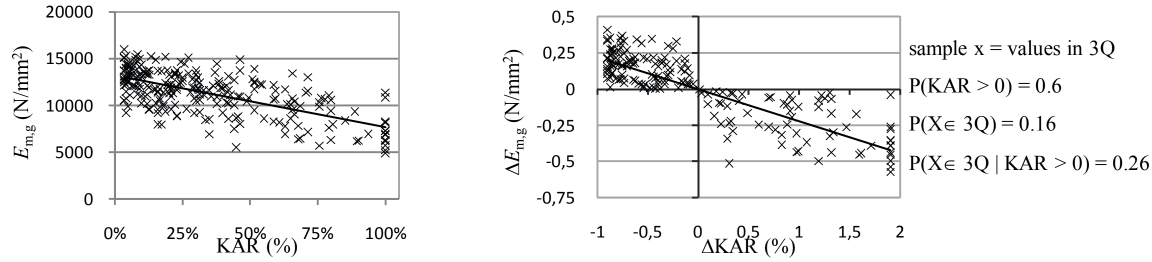


Fig. 7 Variation by segments and boards, in beam J, of: a) v_p; b) $E_{m,l}$; c) $E_{m,g}$ (sections spacing = 40 cm)

Among natural defects of timber, knots are considered as the most conditioning parameter for grading. The downgrading is most likely caused by the combination of local grain deviation (most significant) and reduction of clear wood area [16]. Its influence is assessed by several criterions such as the knot area ratio (KAR), which considers the knot incidence within the cross-section area. The geometry of a knot is approximated to a cone radiating from the pith, thus KAR can be computed considering the projection of the cone on the correspondent cross-section. This is generally possible in relatively thin boards, in the case the knot is visible on two faces of the element, or conversely in un-sawn timbers or large scantlings including the pith [12]. In this work, segments without knots or with minor knots (minor diameter < 5 mm) were not considered, also within a segment the KAR of the most critical isolated and/or cluster of knots was considered to a maximum of 100%. Figure 8a presents the correlation between KAR and $E_{m,g}$ for each segment of sawn boards. A median correlation was obtained ($r^2 = 0.42$), but it is visible that when KAR increases $E_{m,g}$ tends to decrease (inverse proportionality). Figure 8b presents the difference around the average of KAR and $E_{m,g}$, such that coordinates (0,0) correspond to mean KAR and mean $E_{m,g}$, and positive values correspond to an relative increase of that parameter while negative values to a relative decrease. Therefore, in the second quadrant (2Q) a decrease of the KAR leads to a increase of the $E_{m,g}$ around the means and vice-versa for the fourth quadrant (4Q). In this analysis the first and third quadrants (1Q and 3Q) would correspond to a direct proportionality between parameters and thus were not considered. Nevertheless, since the exclusion of 3Q represents a potential unsafe case, the probabilities that define sample x in that quadrant are calculated (Fig. 8b). Notice that the results produce a strong correlation between KAR and $E_{m,g}$ and that the regression line includes the coordinates of the mean values (0,0).



$E_{m,g} = -5519.1 \cdot KAR + 13204$ (r^2 **= 0.42**)
a)

$\Delta E_{m,g} = -0.2222 \cdot \Delta KAR$ (r^2 **= 0.72**)
b)

Fig. 8 Correlation of $E_{m,g}$ and KAR in phase 2: a) all measurements; b) values of 2 and 4Q around the mean

NDT made to the segments of sawn boards lead to weak correlations ($r^2 < 0.07$). Although still low, correlations were found stronger when considering the mean values per board and tests made perpendicularly to the lateral face (Table 1). For all measurements mean d_{pil} = 8.3 mm (CoV = 14.6%) and RM = 302.4 bit (CoV = 10.4%) were found. The average values of d_{pil} between lateral and bottom faces were similar with a minor increase of 0.3 mm for the bottom faces.

Table 1 Correlation between NDT, d_{pil} (mm) and RM (bit), and MoE (N/mm^2) in phase 3

correlation	**penetration impact tests**		**drilling resistance tests**	
NDT	$d_{pil\_lat} = 0.6500 \cdot d_{pil\_bot} + 2.6625$	(r^2 **= 0.56**)	$RM_{lat} = 0.7183 \cdot RM_{bot} + 75.380$	(r^2 **= 0.70**)
$\mathbf{E_{m,l}}$	$E_{m,l} = -1571.9 \cdot d_{pil\_lat} + 25685.3$	(r^2 **= 0.25**)	$E_{m,l} = 69.967 \cdot RM_{lat} - 7930.9$	(r^2 **= 0.38**)
$\mathbf{E_{m,g}}$	$E_{m,g} = -1419.4 \cdot d_{pil\ lat} + 23095.8$	(r^2 **= 0.30**)	$E_{m,g} = 60.337 \cdot RM_{lat} - 6415.8$	(r^2 **= 0.41**)

2.2.4. Phase 4: small clear specimens

Compression and tension parallel to grain tests were made and the results are presented in Table 2. Also density and moisture MC were determined. The results show a smaller variation within the same beam compared to the variation of all samples, as already evidenced in the previous test phases. Different types of failure modes were observed for the parallel to grain tests and regarding those failures an analysis of variance (ANOVA) was made. For characterization of failure in the compression tests the following failure types were considered: crushing, wedge splitting, shearing, splitting, crushing and splitting and brooming. In tension tests the following were considered: splintering tension, combined tension and shear, shear and brittle tension [17] considering also failure in the gripping area or due to defects. Regarding a single-factor ANOVA and a confidence level of 95% a non-significant variance in $E_{c,0}$ or $f_{c,0}$ was found, however $E_{t,0}$ and $f_{t,0}$ revealed a significant variance between the different failure modes ($F > F_{crit}$ and $p\text{-}value < 5 \times 10^{-2}$). The correlations between properties tested in phase 4 are presented in Table 3 considering the samples location in the beam, whereas in Table 4 the correlations are given for the mean value of a property within a beam. The overall correlations are weak to moderate, however it is found that stiffness properties are better correlated than strength properties. Density correlations are only presented in Table 4 since significant correlations were only found for mean value per beam, mainly in G1.

Table 2 Results of mechanical tests in phase 4

Property		**mean**	**CoV (%)**		**Property**		**mean**	**CoV (%)**	
			all	**beam**				**all**	**beam**
Compression // to grain (N/mm^2)	$v_{p,ind}$	4887.4	9.7	7.9	Tension // to grain (N/mm^2)	$v_{p,ind}$	4192.8	3.7	2.6
	$v_{p,dir}$	5218.6	3.9	2.6		$E_{t,0}$	12783	12.9	8.0
	$E_{c,0}$	12621	15.7	11.6		$f_{t,0}$	73.48	26.7	24.7
	$f_{c,0}$	42.99	17.2	15.2					
Density (kg/m^3)	ρ_{12}	571.16	7.9	5.5	MC (%)	MC	12.21	8.1	3.8

Table 3 Correlation per sections between stiffness and strength (N/mm^2) tested in phase 4

Properties (same test)	Total sample	G1	G2	Properties (distinct tests)	Total sample	G1	G2
$f_{c,0} = E_{c,0} \cdot a+b$	a = 0.0023 b = 13.85 r^2 = **0.38**	a = 0.0026 b = 8.12 r^2 = **0.49**	a = 0.0023 b = 13.58 r^2 = **0.11**	$E_{t,0} = E_{c,0} \cdot a+b$	a = 0.6034 b = 4965.7 r^2 = **0.23**	a = 0.4954 b = 6472.8 r^2 = **0.18**	a = 0.5982 b = 5058.5 r^2 = **0.61**
$f_{t,0} = E_{t,0} \cdot a+b$	a = 0.0068 b = -13.65 r^2 = **0.30**	a = 0.0087 b = -37.44 r^2 = **0.25**	a = 0.0060 b = -3.51 r^2 = **0.36**	$f_{t,0} = f_{c,0} \cdot a+b$	a = 0.7408 b = 39.96 r^2 = **0.08**	a = 1.6571 b = 2.69 r^2 = **0.03**	a = 0.4042 b = 55.48 r^2 = **0.34**

Table 4 Correlation per beams between stiffness, strength (N/mm^2) and density (kg/m^3) tested in phase 4

Strength / Stiffness	Total sample	G1	G2	with Density	Total sample	G1	G2
$f_{c,0} = E_{c,0} \cdot a+b$	a = 0.0016 b = 23.46 r^2 = **0.22**	a = 0.0032 b =1.28 r^2 = **0.09**	a = 0.0015 b = 23.95 r^2 = **0.32**	$E_{c,0} = \rho_{12} \cdot a+b$	a = 11.407 b = 6105.5 r^2 = **0.10**	a = 9.243 b = 7186.2 r^2 = **0.29**	a = 11.821 b = 6044.9 r^2 = **0.09**
$f_{t,0} = E_{t,0} \cdot a+b$	a = 0.0078 b = -26.51 r^2 = **0.53**	a = 0.0116 b = -73.52 r^2 = **0.87**	a = 0.0060 b = -4,21 r^2 = **0.36**	$f_{c,0} = \rho_{12} \cdot a+b$	a = 0.043 b = 18.631 r^2 = **0.13**	a = 0.168 b = -57.890 r^2 = **0.90**	a = 0.030 b = 26.824 r^2 = **0.08**
$E_{t,0} = E_{c,0} \cdot a+b$	a = 0.5674 b = 5459.5 r^2 = **0.37**	a = 0.3252 b = 8703.5 r^2 = **0.85**	a = 0.6148 b = 4844.9 r^2 = **0.33**	$E_{t,0} = \rho_{12} \cdot a+b$	a = 16.27 b = 3327.3 r^2 = **0.17**	a = 35.91 b = -9091.5 r^2 = **0.54**	a = 15.78 b = 3903.5 r^2 = **0.19**
$f_{t,0} = f_{c,0} \cdot a+b$	a = 1.8584 b = -8.65 r^2 = **0.29**	a = 2.5817 b = -38.53 r^2 = **0.56**	a = 1.2555 b = 18.35 r^2 = **0.13**	$f_{t,0} = \rho_{12} \cdot a+b$	a = 0.146 b = -11.88 r^2 = **0.12**	a = 0.468 b = -209.02 r^2 = **0.59**	a = 0.103 b = 14.67 r^2 = **0.08**

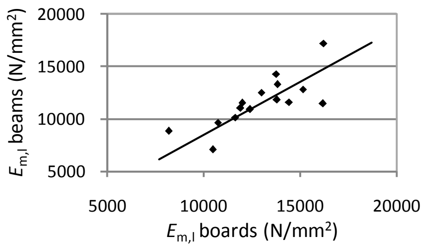
2.2.5. Correlation between phases

With respect to visual strength grading of the original beams, over conservative values were found compared to the results obtained in the DT of phases 2 and 4. In phase 3, it was found that the samples of segments classified with different visual classes presented a significant variance in a single-factor ANOVA. Also the mean value of MoE in a given sample tended to decrease in correspondence to a decrease in visual grading class. In the case of $E_{m,l}$, decreases between the mean value for classes I of 6, 21 and 27% were found respectively to classes II, III and NC, similar to the values given in [3], whereas to $E_{m,g}$, decreases between the mean value for class I of 9, 16 and 36% were found respectively for classes II, III and NC. Regarding density variation it was found that the number of samples is relevant, since the consideration of ρ_{mean} per global set of the 20 beams produced different values of correlation when considering the ρ_{mean} per beam or per region. For full size beams or boards the ρ_{mean} regarding all 20 beams produced better correlations, whereas the ρ_{mean} per beam produced better correlations for the tested clear samples. Nevertheless, it was found that it is advisable to use the ρ_{mean} of three measurements of density per beam even regarding the clear samples. In terms of non-destructive testing and considering E_{sta} and E_{dyn} for each test phase, sample G1 evidenced stronger correlations than the other samples (Table 5).

Table 5 Correlation between E_{sta} and E_{dyn} for phases 2 to 4

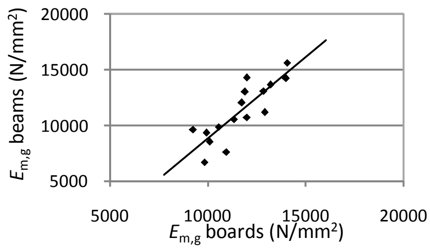
Phase	E_{sta} correlated with E_{dyn}			
2	$E_{m,l} = 1.053 \cdot E_{dyn} - 2427.1$	(r^2 = **0.70**)	$E_{m,g} = 1.189 \cdot E_{dyn} - 4510.4$	(r^2 = **0.76**)
3	$E_{m,l} = 1.579 \cdot E_{dyn} - 8559.2$	(r^2 = **0.82**)	$E_{m,g} = 1.147 \cdot E_{dyn} - 3980.2$	(r^2 = **0.87**)
4	$E_{c,0} = 0.939 \cdot E_{dyn} - 1916.9$	(r^2 = **0.51**)	$E_{t,0} = 1.384 \cdot E_{dyn} - 1017.5$	(r^2 = **0.67**)

In bending tests, the mean values of all sawn boards measurements are higher than the equivalent values obtained for sawn beams. The biggest difference is observed between $E_{m,l}$, with larger CoV in the case of sawn boards. This is an expectable result since the gauge length for the determination of $E_{m,g}$ for the sawn beams included all the gauge length of the $E_{m,g}$ for the sawn boards, whereas the gauge length for the $E_{m,l}$ of the sawn beams only considers segments 3, 4 and 5 of the sawn boards. Considering the mean value for that segments, a $E_{m,l}$ of 12721 N/mm^2 is obtained which is closer to the value of the $E_{m,l}$ for the sawn beams. Nevertheless, even comparing the equivalent segments in terms of gauge length measurement, the values of stiffness for the sawn boards are 18% and 7% higher, respectively, $E_{m,l}$ and $E_{m,g}$, compared to the sawn beams. This increase of stiffness may also be explained due to the lower influence of defects in the global behaviour when the beam was divided into boards, resulting also in a higher CoV due to the higher difference obtained between segments with and without defects. Moderately strong correlations were found between the results of phase 2 and 3 regarding MoE, being the correlation between $E_{m,g}$ higher than between $E_{m,l}$ (0.71 > 0.66), even if only considering segments 3 to 5 in the analysis of $E_{m,l}$ per mean group of boards (Fig. 9).



a)

$E_{m,l\ beams} = 1.0076 \cdot E_{m,l\ boards} - 1601.2$ (**r^2 = 0.66**)



b)

$E_{m,g\ beams} = 1.4584 \cdot E_{m,g\ boards} - 5732.1$ (**r^2 = 0.71**)

Fig. 9 Correlation of bending tests in phase 2 and 3: a) between $E_{m,l}$; b) between $E_{m,g}$

3. CONCLUSIONS

Aiming to analyse the stiffness and strength variation in 20 chestnut timber beams, correlations within and between different size scale samples were established. These correlations were complemented with information of visual strength grading. A considerable test campaign (divided in 4 phases) was made in order to assess the mechanical properties of the elements and to provide a suitable strength grading. For that purpose, different tests in different scales were made to analyse the influence of defects in local and global behaviour of the timber elements. In the experimental campaign, it was concluded that visual inspection by segments may reveal large variability in the properties of existing timber elements along its length. Also the consideration of knot incidence and slope of grain, as main features, lead to comparable results between experimental phases (in terms of percentage of segments in a given class). Visual inspection was also useful for qualitatively predict the performance of the timber elements, since elements with higher NC percentage had lower values of MoE despite it proved to be conservative for the elements with higher class I and II percentages and low NC percentage.

In phases 2 and 3, strong correlations between $E_{m,l}$ and $E_{m,g}$ were found ($r^2 = 0.82$ in beams and $r^2 = 0.89$ in boards). However, the MoE mean values of all sawn boards bending tests measurements were higher than the equivalent values obtained for the sawn beams, likely due to the isolation of defects in smaller segments of timber. The bending results in sawn boards, besides permitting a better definition of defect influence in stiffness and strength by NDT and DT, also revealed that the stiffness properties vary both in height and length of each beam in different proportions, being the variation higher when a larger concentration of knots was found in one of the boards. The variation in length was found to be slightly higher than the variation in height. Also the variation within a same element was found to be lower compared to the variation within the full sample.

KAR was used to assess the influence of defects, obtaining a moderate correlation with $E_{m,g}$ ($r^2 = 0.72$), regarding an inverse proportionality between those parameters around their mean values. Correlations between NDT and mechanical properties were found to be weak, except for the ultra-sound tests. Different sample groups were considered regarding correlations with E_{dyn} to provide better correlations evidencing that, even within the same timber species, NDT must be calibrated to the members in study. Therefore, the results obtained in this work are applied to the material in study, moreover, can be used as reference for historical structures with chestnut beams where no prior information is available. E_{dyn} was correlated to the stiffness properties found in phases 2, 3 and 4 with moderate to strong correlations ($r^2 = 0.51 - 0.87$). The results evidenced that NDT results are better used for determination of stiffness rather than strength, and that the consideration of small clear

specimens can only be used to assess the mechanical properties of full-scale beams when considered together with analysis of a visual inspection where defects and deterioration are accounted for.
Due to density variation it was found that the number of samples to be taken is relevant. For full size beams or boards the mean density regarding all 20 beams produced better correlations, whereas the mean density per beam produced better correlations for the tested clear samples.
The correlations and findings gathered in this work present a first step into the construction of a hierarchical model based on the variation of mechanical properties within different scales of an existing timber element.

ACKNOWLEDGEMENTS

The first author gratefully acknowledges the financial support of the Portuguese Science Foundation (Fundação de Ciência e Tecnologia, FCT), through grant SFRH/BD/62326/2009.

REFERENCES

[1] UNI 11035-1 (2003) *Structural timber – Visual strength grading: terminology and measurement of features*, ENIU.
[2] UNI 11035-2 (2003) *Visual strength grading rules and characteristic values for Italian structural timber population*, ENIU.
[3] UNI 11119 (2004) *On site inspections for the diagnosis of timber members*, ENIU.
[4] EN 408 (2003) *Structural Timber and Glued Laminated Timber. Determination of Some Physical and Mechanical Properties*, CEN.
[5] Solli K. H. (2000) Modulus of elasticity – local or global values. In: *Proc. World Conference on Timber Engineering* Vancouver, Canada.
[6] US Forest Products Laboratory (1999) *Wood Handbook – Wood as an Engineering Material*. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison.
[7] Bonamini G., Noferi M., Togni M. and Uzielli L.(2001) *Il Manuale del Legno Strutturale, Volume I, Ispezione e diagnosi in opera*. Mancosu Editore, Roma.
[8] ISO 3131 (1975) *Wood-Determination of density for physical and mechanical tests*, ISO.
[9] ISO 3130 (1975) *Wood-Determination of moisture content for physical and mechanical tests,* ISO.
[10] Sousa H. S., Lourenço P. B. and Neves L.C. (2010) Safety evaluation of timber structures through probabilistic analysis. *Advanced Materials Research*, 133-134:337-342.
[11] Cavalli A., Togni M. (2011) Combining NDT and visual strength grading to assess ancient timber beams stiffness to evaluate strengthening interventions suitability. In: *17th International Nondestructive testing and evaluation of wood symposium*, (2) 593-601.
[12] Piazza M., Riggio M. (2008) Visual strength grading and NDT of timber in traditional structures. *Journal of Building Appraisal* 3:267-296.
[13] Joint Committee on Structural Safety (2006) *JCSS Probabilistic Model Code, Part 3: Resistance Models – 3.5 Properties of Timber*, JCSS.
[14] Burley J., Evans J. and Younquist J. (ed) (2004) *Mechanical properties of wood. Encyclopedia of Forest Science.* Elsevier Publishing Co., Oxford, England.
[15] Kasal B. (ed) (2010) *State-of-the-art in in-situ assessment of timber*. RILEM CAST 215 Special Publication. Springer Verlag/RILEM Paris.
[16] Kollmann F. F. P., Côté W. A. (1984) *Principle of Wood Science and Technology. Vol. I: Solid Wood*. Springer-Verlag Berlin.
[17] Bodig J., Jayne B. A. (1993) *Mechanics of Wood and Wood Composites*, Krieger Publishing.