Mechanical characterization of old chestnut beams

Jorge Branco[1], Tiago Peixoto[2], Paulo Lourenço[3], Pedro Medeiros[4]

Abstract The main objective of this work is to evaluate, by non-destructive techniques, seven old Chestnut beams. For that, after the geometric assessment and the detailed visual inspection that allowed to strength grade the beams, a series of non-destructive tests was setup. In a first step, non-destructive bending tests, under the elastic limit, were performed to quantify the modulus of elasticity in bending (MoE) of the seven beams. Then, Resistograph® and Pilodyn® tests were done to assess the superficial decay and to have a clearer idea of the voids dimensions. Then, two beams were tested in bending until failure to evaluate the bending strength. In a second step, end parts were cut from the beams, one per end of the beams, to perform Resistograph®, Pilodyn® and ultrasound tests, to quantify the density of the beams and to extract meso-specimens to be used in tension parallel to the grain tests.

Keywords visual inspection, evaluation, NDT, chestnut beams

1. GEOMETRIC ASSESSMENT AND VISUAL GRADING

The beams used in this work were recovered from an old factory in Guimarães that was partially demolished for the construction of a Museum. Beams are made of Chestnut (*Castanea sativa* Mill) with lengths between 3,6 m and 5,6 m. Their cross-section is defined by the trunk geometry and therefore, significant variability in the cross-section dimensions exists.

In order to have an adequate report of those variabilities, a detailed geometric assessment of the beams was performed. Every 40 cm, each beam was marked, named and the cross-section measured. Those cross-sections were used also in the non-destructive tests conducted and reported in following items. Figure 1 presents the variation of the height of the beams along their length.

The geometric assessment presumes a detailed visual inspection through the detection of visible mechanical damages, fissures, external wood decay, moisture stains, etc. Moreover, it is possible to grade timber elements based on the premise that mechanical properties of lumber differ from mechanical properties of clear wood due to several growth characteristics, which can be identified and evaluated visually. In the absence of other grading criteria, the ones proposed by the Italian standards UNI 11119:2004, UNI 11035-1:2003 and UNI 11035-2:2003 for Chestnut were used. While the first standard is addressed for in-situ evaluation, the UNI 11035 defines the visual strength grading rules and characteristics values for the most representative Italian structural timber population.

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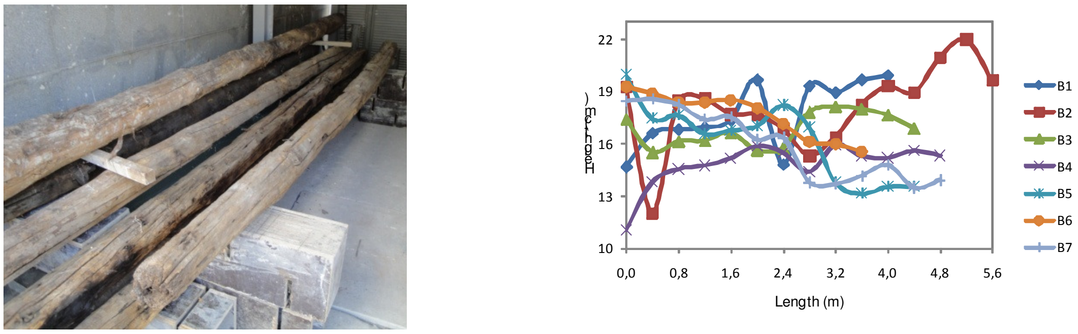


(a) (b)

Figure 1 – Variability of the cross-section of the beams. (a) Overview of the evaluated Chestnut beams and (b) height values along the beams length.

Unlike an on-site inspection, it was possible to examine, in laboratory, all the faces and ends of the elements. As already referred, each element face and each face portion (approximately 40 cm wide) has been identified with a numbered section. Hence, all the defects present on each face, were localized, measured and mapped. According to UNI 11035 (2003), single knots were measured considering the ratio A of the minimal diameter to the width of the element face, while knot clusters were evaluated through the ratio A_g of the sum of the minimal diameters of all the knots, in a 150 mm range, to the width of the element face. General slope of grain was detected by means of a scribe, or when present, by measuring shrinkage splits on the longitudinal faces.
Table 1 presents the visual grading results for all Chestnut beams using both Italian standards.

Table 1 – Visual strength grading of the Chestnut beams according to UNI 11119:2004 and UNI 11035:2003.

	UNI 11119:2004				**UNI 11035:2003**				
	Class	$E_{0,mean}$[MPa]	$f_{m,k}$ [MPa]	$f_{t,0,k}$ [MPa]	Class	ρ_m [kg/m^3]	$E_{0,mean}$[MPa]	$f_{m,k}$ [MPa]	$f_{t,0,k}$ [MPa]
B1	III	8000	8	6	a)	-	-	-	-
B2	II	9000	10	9	S				
B3	I	10000	12	11	S				
B4	II				S	550	11000	28	17
B5	II	9000	10	9	S				
B6	II				S				
B7	II				S				

a) Beam B1 was not considered as belonging to class S, according to EN 11035:2003, as consequence of the decay signs, group of knots and deviation of the grain.

2. EXPERIMENTAL CAMPAIGN

The main objective of this work is to evaluate by non-destructive techniques seven old Chestnut beams. For that, after the geometric assessment and the detailed visual inspection that allowed to strength grade the beams, a series of non-destructive tests was set-up.
In a first step, non-destructive bending tests, under the elastic limit, were performed to quantify the modulus of elasticity in bending (MoE) of the seven beams. Then, Resistograph® and Pilodyn® tests were done to assess the superficial decay and to have a clearer idea of voids dimensions. Then, two beams, B4 and B5, were tested in bending until failure to evaluate the modulus of rupture (MoR) and the bending strength. In a second step, end parts were cut from the beams, one per end of the beams, to perform Resistograph®, Pilodyn® and ultrasound tests, to quantify the density of the beams and to extract meso-specimens to be used on tension parallel to the grain tests.
This section presents the tests procedures and the results obtained in each kind of tests performed in the experimental campaign.

2.1. Moisture content and density

The moisture content of the beams was evaluated through two methods: based on three readings of a thermo hygrograph following the measuring scheme of UNI 11035-1:2003; and, using the oven dry method suggested by UNI EN 13183-1:2003. However, for the further analysis, the values assumed for the moisture content were based on the oven dry method applied on small specimens removed from the end parts of the beams and, in the case of the destructive tests, taken near the failure zone of the beam (beams B4 and B5). On the other hand, density has calculated following the NP 616:1973 prescriptions, dividing the mass by the volume of those small specimens. The values obtained represent the density values for the moisture content at the time of the measurement. Values obtained for the moisture content and density are presented in Table 2.

2.2. Pilodyn

For all beams, in each section used for the geometric assessment, the penetration depth obtained through the Pilodyn® in 2 faces was measured, in a total of 156 tests. Tests results vary between 5 and 14 mm conducting to average values of 9 or 10 mm for all beams. No evidence of local degradation was found. Based in correlation between the penetration depth and the density values of defect-free chestnut specimens proposed by Feio (2006), a prediction of the density of each beam was performed.
Table 2 presents the main results obtained through the Pilodyn test for each beam, the predicted values for the density using the correlation proposed by Feio (2006) and the density values obtained for small specimens removed from the beams. Moreover, the moisture content values of each beam are exposed, as the moisture content affects the empirical relationships between the penetration depth and the material density.

Table 2 – Moisture and density values, penetration depth values obtained in the Pilodyn tests and density prediction.

Beam	N.º of tests	Moisture [%]	Density [kg/m^3]	Penetration depth D [mm]		Predicted density [kg/m^3]
				Mean	Range	ρ=1115,16-60,1D (Feio, 2006)
B1	24	11,23	550	10	8-13	487
B2	22	12,78	632	9	5-13	572
B3	22	11,18	602	9	6-12	547
B4	22	10,98	564	10	7-14	504
B5	22	12,67	571	9	6-12	567
B6	22	10,37	575	9	7-12	550
B7	22	12,62	566	10	8-14	526

No correlation exists between the predicted values for the density according to Feio (2006) and the one obtained from the small specimens following NP 616:1973. It is important to point out that small specimens, free from defects were used by Feio (2006) while the Pilodyn values presented here, were obtained from tests made over full-scale beams without any preparation of the timber surface.

2.3. Resistograph

In this work, Resistograph® was mainly used with the purpose of detecting deterioration and evaluating the voids existing inside the timber beams. The main objective of using this technique was not to predict mechanical properties but to complete the information given by the other non-destructive tests realized. In particular, the evaluation of the deterioration level and the voids existing inside the beams, and because of that not visible, were the main purpose of the use of Resistograph®.

For that, 3 sections, among the ones defined in the geometric assessment task, of each beam were used to collect Resistograph® charts. Moreover, two more Resistograph® tests were performed in each end part of the beams.
During those tests, apart some drying cracks, no particularities were detected such as voids or rot. Only the charts obtained in beam B5 deserve more attention. In fact, the chart indicates some reduction inside the cross-section that could explain the results obtained further in the bending tests (Figure 2).

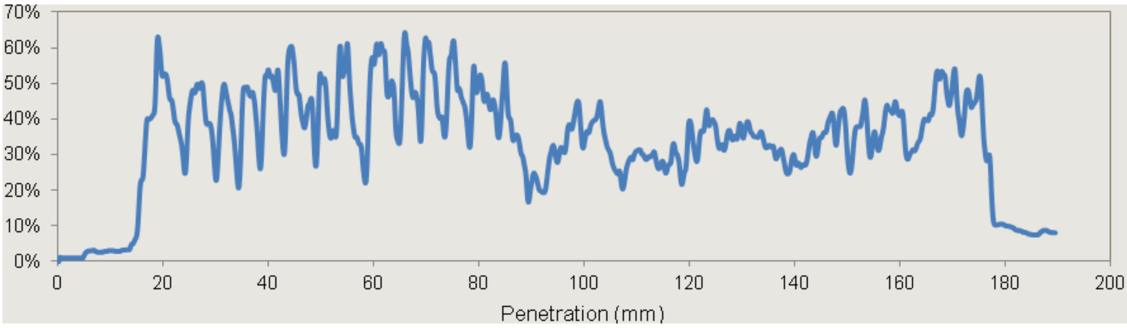


Figure 2 – Resistograph® chart obtained in beam 5, section E.

2.4. Bending tests

The stiffness of the timber beams, which is normally expressed as MoE (Modulus of Elasticity in bending), was determined by means of four-point loading bending tests. MoE for timber contains not only information about the clear wood strength properties, but also to a large extent about defects affecting the stiffness. Therefore, results of bending tests have been used in this research to assess the reliability of visual grading and NDT results.
Static bending tests were conducted in accordance with the four-point loading method proposed by EN 408:2003. Each test was composed by three quasi-static loading cycles below the elastic limit, under a displacement rate of 0,125 mm/s until a maximum deflection of 50 mm. The MoE of the chestnut beams was assumed equal to the local modulus of elasticity in bending ($E_{m,l}$) defined by this standard.
Then, after those bending tests under the elastic limit, destructive bending tests were performed by loading beams B4 and B5 until failure. The objective was to quantify the bending strength (f_m) of the chestnut beams. Table 3 presents the main results obtained in the nine bending tests performed. Because of their importance for the analysis of the bending tests results, the values of the density and the moisture content of each beam are also presented.

Table 3 – Bending tests results.

	B1	B2	B3	B4	B5	B6	B7
$E_{m,l}$ [MPa]	10987	7935	7532	11493	5102	11753	11072
f_m [MPa]	-	-	-	35,75	14,38	-	-
Density [kg/m^3]	550	632	602	564	571	575	566
Moisture content [%]	11,23	12,78	11,18	10,98	12,67	10,37	12,62

Despite based on a short number of tests, results shows a correlation between density and the local modulus of elasticity ($E_{m,l}$), Figure 3.

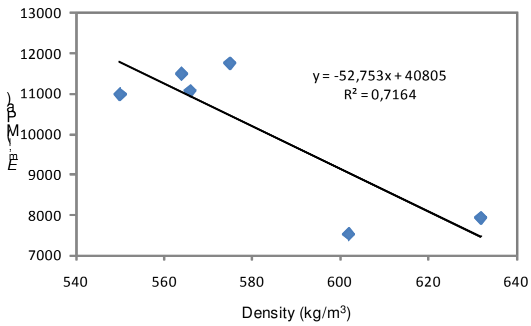


Figure 3 – Correlations between density and local modulus of elasticity in bending ($E_{m,l}$).

2.5. Ultrasound

Ultrasound tests, using the direct method were performed on the end parts removed from beams B2, B3, B4, B5, B6 and B7, in a total of 14 tests. As ultrasound equipment, a Proceq model TICO was used with 54 kHz transducers. A mineral gel was used to provide a better transmission of the ultrasounds in the interface of the transducers with the timber samples. Also a constant pressure in the application of the transducers was provided during the tests.
Despite the short number of tests performed, the velocity measured with the ultrasound shows a correlation with density (Figure 4). Higher velocity corresponds to higher density values.

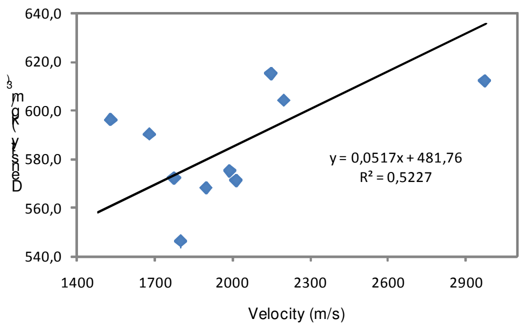


Figure 4 – Correlations between ultrasound velocity and density.

In addition, attempts were made to apply the ultrasound through the indirect method however, as referred in bibliography (Baldassino, 1996), the accurate determination of the modulus of elasticity request that the surface is sufficiently free from fissures or from biological degraded regions.

2.6. Tension tests

Tension tests were performed on meso-specimens removed from the end parts of beams. From beam B2 and beams B3, B4, B5, B6 and B7, a total of 6 and 4 meso-specimens, respectively, were used to study the tension properties, stiffness and resistance, in the grain direction. The meso-specimens geometry is presented in Figure 5.

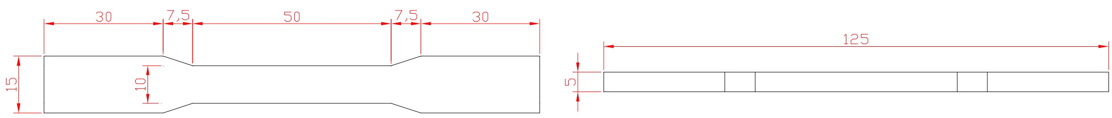
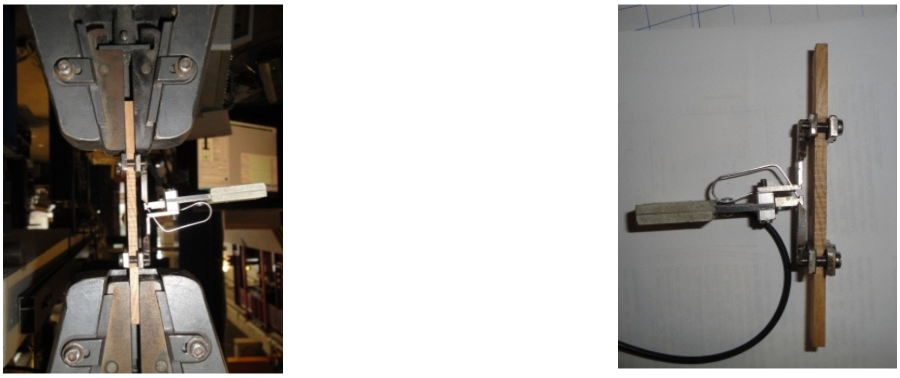


Figure 5 – Geometry of the meso-specimen used in the tension parallel to the grain tests (dimensions in millimeters).

Tests were carried out in a SENTUR device with a 50kN load cell. A displacement control was used with an increment ratio of 0,0124 mm/s with the intent of reaching the maximum applied load in the interval of 300 s +/- 120 s. The grips that were used could assure a 50 kN gripping force. For extension measurement a clip gauge of +/- 2,5 mm sensitivity was used in the central region of the meso-specimen.



(a) (b)

Figure 6 – Tension tests setup. (a) Overview and (b) detail of the clip gauge used.

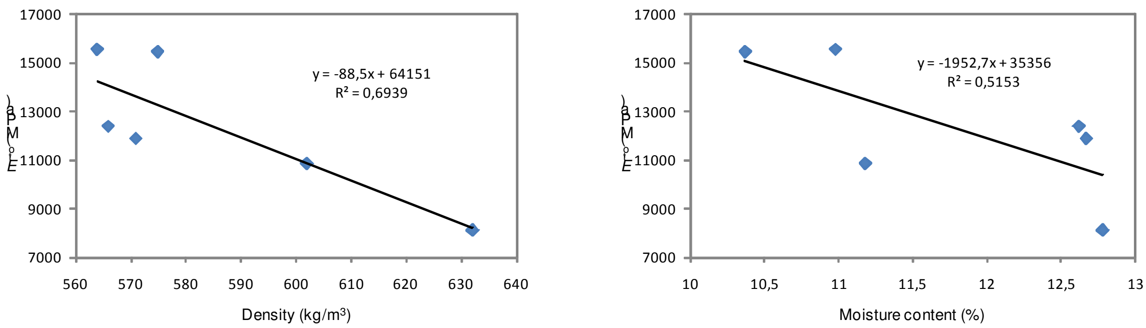
Table 4 presents the results obtained from the tension tests performed using the meso-specimens, namely, the tension strength parallel to the grain ($f_{t,0}$) and the modulus of elasticity in tension parallel to the grain ($E_{t,0}$).

Table 4 – Tension tests results.

	Beam	B2	B3	B4	B5	B6	B7
Density	[kg/m^3]	632	602	564	571	575	566
Moisture content	[%]	12,78	11,18	10,98	12,67	10,37	12,62
$f_{t,0}$	N.º tests	6	4				
	Mean [MPa]	62,94	62,97	66,90	61,10	62,08	52,01
	CoV [%]	36,2	6,0	14,3	14,9	15,9	6,88
$E_{t,0}$	N.º tests	6	4				
	Mean [MPa]	12379	13465	11742	12043	13229	11636
	CoV [%]	23,0	5,7	11,7	15,3	10,9	4,7

Despite the short number of tests performed, it is possible to point out the consistency of the tests results obtained for beams 3 and 7, and as expected, to observe the better performance of the test to assess the modulus of elasticity.

No correlation is possible to be defined between $f_{t,0}$ and $E_{t,0}$. On the other hand, tests results obtained for $E_{t,0}$ shows a correlation with density and moisture content (Figure 7). Tests results obtained for the modulus of elasticity in tension parallel to the grain are function of density and moisture content, decreasing with the increase of both values.



(a) (b)

Figure 7 – Correlations based on the tests results. Between (a) $E_{t,0}$ and density and (b) $E_{t,0}$ and moisture content.

3. DISCUSSION OF TESTS RESULTS

The analysis and discussion of the methodology adopted to classify the Chestnut timber beams must be based in the comparison between the results obtained from the different performed tests (Table 5).

The visual grading carried out using the Italian standards UNI 11035:2003 and UNI 11119:2004 proved to be a feasible and easy task to be performed. By evaluating a small number of parameters it is possible to have some references values for the strength and stiffness.

The values measured for the density of each beam are always higher than the value indicated by UNI 11035:2003. In terms of $E_{0,mean}$, the visual grading is less reliable. Firstly, the UNI 11035:2003 has no sensitivity to take into account different performances of the chestnut beams. On the other hand, the values indicated by UNI 11119:2004 for the $E_{0,mean}$ indicates different performances of the beams, fact that was confirmed by the mechanical tests following the EN 408:2004.

Despite being less sensitive to the heterogeneity of the response of the chestnut beams, UNI 11035:2003 proposes a value for the bending strength ($f_{m,k}$) close to the result obtained in the mechanical tests of beam B4. The value obtained for $f_{m,k}$ of beam B5 can be considered an outlier due to the existence of local damage in the central part of the beam, as confirmed by the lower value obtained for $f_{m,k}$ by this beam. An important difference exists between the tests results obtained through EN 408:2004 for the tension strength parallel to the grain ($f_{t,0,k}$) in comparison with the values suggested by both UNI standards. However, it is important to keep in mind that the tension tests were performed in meso-specimens in which the influence of defects is very limited.

Table 5 – Comparison between different tests results.

	Beam	B1	B2	B3	B4	B5	B6	B7
Moisture content	[%]	11,23	12,78	11,18	10,98	12,67	10,37	12,62
Density [kg/m^3]	NP 616:1973	-	632	602	564	571	575	566
	UNI 11035:2003	-	550					
$E_{0,mean}$ [MPa]	UNI 11119:2004	8000	9000	10000	9000			
	UNI 11035:2003	11000						
	EN 408:2004	10987	7935	7532	11493	5102	11753	11072
$f_{m,k}$ [MPa]	UNI 11119:2004	8	10	12	10			
	UNI 11035:2003	-	28					
	EN 408:2004	-	-	-	35,75	14,38	-	-
$f_{t,0,k}$ [MPa]	UNI 11119:2004	6	9	11	9			
	UNI 11035:2003	-	17					
	EN 408:2004	-	62,94	62,97	66,90	61,10	62,08	52,01

Despite the limitation evidenced by the visual grading, in the absence of other non-destructive tests or complementary analysis, both standards used indicative reference values for the main properties of existing timber elements.

Besides the correlation already presented during the presentation and discussion of the results obtained from each non-destructive test, no other relation can be point out between the non-destructive tests that were carried out. However, tests results showed a correlation (R^2=0,7164) between density and local modulus of elasticity in bending $E_{m,l}$ obtained from the mechanical tests on the full-scale beams according to EN 408:2004. This result confirms the direct relationship between density and MoE reported in the bibliography (Dinwoodie, 1989). The particularity of this case is that the bending tests were performed on full-scale existing beams, with several variabilities in the geometry. Therefore it is possible to conclude that the measurement of the density represents an excellent method to assess indirectly the MoE of existing chestnut beams. To quantify the density the requirements of the NP 616:1973 can be followed, and therefore, a small specimen must be removed from each element evaluated. Otherwise, ultrasound test can be conducted to quantify density. Tests results obtained from the ultrasound through the direct method showed an interesting correlation with density. However, those results presume the possibility to apply the direct method in the longitudinal direction of the beams, and therefore, both ends of the beams must be accessible.

4. CONCLUSIONS

Seven old chestnut beams recovered from a demolishment were evaluated. A detailed visual inspection was performed allowing visual grading based on two Italian standards. Then, non-destructive tests including mechanical tests under the elastic limit were carried out, as well as mechanical tests until failure. Because of the significant influence on the mechanical properties of wood, density and moisture content of each beam was quantified.
Despite the short number of performed tests, all tests results confirmed the relations existing in the bibliography. Density showed to be important as a parameter, possible to be correlated with stiffness properties. Tests results showed correlations between density - modulus of elasticity in bending and density - tension parallel to the grain.
No correlation was defined between the results of different non-destructive tests. This difficulty can be explained by the short number of tests carried out and by the fact that the tests were performed on full-scale beams without any kind of surface preparation. This fact is particular important in the analysis of the results obtained in the Pilodyn® and Resistograph® tests.
After all, the effectiveness of the visual grading was pointed out. In fact, in the absence of more detailed information or data, the visual grading performed based on the UNI 11035:2003 and UNI 11119:2004 indicated acceptable reference values for the main mechanical properties of the beams.

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