USE OF RANDOM SAMPLING AND BAYESIAN METHODS IN THE PREDICTION OF CHESTNUT TIMBER BEAMS BENDING STIFFNESS

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ABSTRACT: The assessment of global bending stiffness of three old timber beams is predicted by use of random sampling and Bayesian Network approaches. The information for the prediction models derive from the visual grading and localized mechanical testing of 20 beams retrieved from the same building, which have been scope of analysis in previous studies. Although the results indicate moderate correlations between predicted and experimental results, significant percentage errors are also found. To minimize the percentage error between experimental and predicted values, coefficients corresponding to the scale effect relation between existing chestnut timber elements with round cross section and sawn beams of smaller dimensions with rectangular cross section were proposed.

KEYWORDS: Bending modulus of elasticity, Random sampling, Bayesian Networks

1 INTRODUCTION

Due to timber's inherent variability and susceptibility to decay, the safety evaluation of existing timber structures is a complex task, which requires obtaining information from different sources. Often, characterization of timber elements belonging to existing structures is made by the sum of several contributions including results from geometric characterization, visual inspection, non-destructive tests (NDT), mechanical tests, and others [1, 2]. In the case of the geometrical characterization of old timber elements, large coefficients of variation may be found in the definition of the cross section dimensions, reaching values of 20% for round elements and even up to 40% for decayed elements [3]. Moreover, variability of the mechanical properties of structural size timber elements are dependent on the relation between clear wood sections and sections with defects [4, 5]. Therefore, the mechanical grading of timber using only clear wood specimens has also to be complemented with visual grading [6].

With those results, a structural timber element can be assessed and graded regarding the combination of mechanical tests conducted to clear samples with the characterization and analysis of defects. Thus, it is of utmost importance to define methodologies which allow to incorporate information, given by these different sources, and to hierarchically classify them in such manner that are prone to be updated with posterior information.

Those methodologies have also to take into account the need to preserve the structural and, in many cases, the aesthetic conditions of the timber element. Therefore, the extraction of samples for testing should be avoided, or at least, taken to the minimum number of specimens required for the level of precision needed in the structural analysis.

In this scenario the use of probabilistic methods is a feasible approach to take into consideration the mentioned variability in timber's mechanical properties [7], cross section dimensions [8] and level of decay [9], in a hierarchical framework. Hence, this work presents different probabilistic approaches to infer the global bending modulus of elasticity ($E_{m,g}$) of three old chestnut (*Castanea sativa* Mill.) beams, with information of visual grading of structural size elements and information from a previously created database of local bending modulus of elasticity ($E_{m,l}$) tests on smaller size specimens.

In a first approach, and aiming at minimizing the number of specimens, prediction of $E_{m,g}$ is made by simulation of samples through random sampling of local data. After, inference on $E_{m,g}$ is considered by use of a Bayesian Network (BN) regarding information divided by size scale, visual grading and results of local bending tests.

2 BACKGROUND

In a prior work [10], a multi-scale experimental evaluation of 20 old chestnut (*Castanea sativa* Mill.) beams was considered, aimed at defining the correlations between

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bending modulus of elasticity (MOE) [11] in different scales of timber elements in combination with visual grading [12]. That experimental campaign was composed by three scales (Figure 1), where specimens of smaller dimensions were taken from existing timber elements and tested in 4-point bending tests along its length.
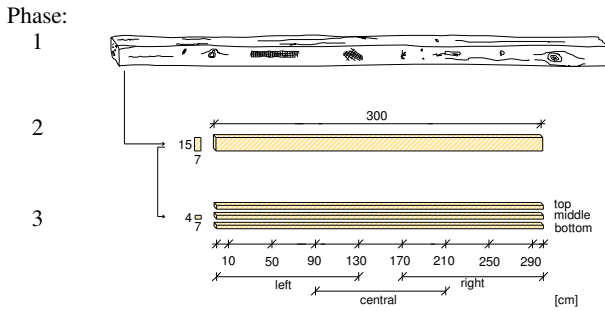

Figure 1: Definition of specimens for the different testing phases, adapted from [10]

The first phase considered the old beams with their round cross section and in the same state of conservation as they were in the construction site. So the old chestnut beams were visually inspected and graded with respect to Italian standards [12] and complemented with NDTs results.

The round cross section elements were then sawn to regular cross section elements in phase 2. Therefore, the second phase corresponds to the removal of the decayed surface and testing of sawn beams with $7 \times 15 \times 300$ cm^3 regular cross section. The beams were marked on 7 segments of 40 cm and the defects found in each segment were accounted. Then 4-point bending tests [11] were made to each beam, obtaining local ($E_{m,l}$) and global ($E_{m,g}$) moduli of elasticity in bending. After the bending tests, in phase 3, the beams were sawn into 3 boards with $7 \times 4 \times 300$ cm^3 regular cross section. Each board was then visually inspected on each 40 cm segment. To each segment of each board a 4-point bending test in elastic range was made in order to assess the variation of MOE along the element's length and height.

Regarding the results of the 4-point bending tests, strong correlations within the same size scale (coefficient of determination r^2 from 0.82 to 0.89) and moderate to high correlations for different phases (r^2 from 0.68 to 0.71) were found for bending MOE.

Following, by use of visual grading combined with bending MOE results in smaller size scale specimens (sawn boards' segments), models for prediction of $E_{m,g}$ of structural size members were considered (sawn beams) [13]. These models, by use of random sampling selection, predicted the behaviour of full size scale elements accurately, with strong correlations to the experimental results (r^2 from 0.70 to 0.79) and a percentage error lower than 20%.

In this work, three floor beams, retrieved from the same building as the previous mentioned beams, were tested in bending as to verify the possibility of use of the prediction models for the analysis of existing timber elements with the same conservation conditions observed onsite.

Moreover, a BN is proposed also to infer about the $E_{m,g}$ with respect to the same sources of information.

3 METHODS

3.1 EXPERIMENTAL CAMPAIGN

3.1.1 Test samples and testing sequence

The tested elements correspond to three old chestnut (*Castanea sativa* Mill.) beams (Figure 2), designated further on as B1, B2 and B3, 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 remodelling of the building. 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.

Figure 2: Tested beams with detail of the traditional indentations for the floor support

In a first phase, the cross sections dimensions of the beams and its wane, were measured at each 40 cm segments. Visual inspection was made to each of the 40 cm segments in order to obtain a described grading of the element along its length as well as an overall grading of the structural element. To those same segments, NDTs were performed in order to assess the depth of decay. Both impact penetration tests and resistance drilling tests were considered for that purpose.

Following the initial geometric characterization and non-destructive testing, the beams were tested in 4-point bending tests, according to [11], obtaining both $E_{m,l}$ and $E_{m,g}$. Since the beams had different lengths, also different locations for the supports and consequently different spans were used for each beam. In the beams with bigger length (B1 and B2), also smaller span tests were performed in different segments of the beams, as to have a comparison basis with the smaller length beam (B3). With that procedure, for the B1 and B2 beams it was also possible to analyze the variation in MOE along their length, and compare it to the visual grading made by segments. Five bending tests were made for beams B1 and B2 each, and one test was made to beam B3, thus a total of eleven bending test results were obtained. Table 1 indicates the span between supports for each of the tests, and the

distance from the beginning of the beam. The length of the spans and test setup was defined according to [11] as it will be latter described.

Table 1: Beams' span for bending tests

Beam	Bending test	Span (mm)	1st support (mm)
B1	B1.1a	2511	328
	B1.1b	2511	1164
	B1.1c	2511	2001
	B1.2	3800	520
	B1.3	4184	328
B2	B2.1a	2511	338
	B2.1b	2511	1174
	B2.1c	2511	2011
	B2.2	3800	530
	B2.3	4184	338
B3	B3.1	2511	129

As no small size specimens were taken, the results obtained in the bending tests of small specimens in [10] were considered as a database of prior empirical data for the probabilistic analysis of this work.

3.1.2 Visual inspection

Visual inspection is one of the first and most important steps to be carried out in a structural diagnosis. During the inspection, data is gathered to define the general state of the structure and, thus, different evidences of structural pathologies are documented and classified according to its extent and severity.

In existing structural timber elements the most important aspects to be considered are the presence of natural growth defects, such as knots, slope of grain, cracks, moisture and / or water infiltrations and the presence of biological activity leading to decay (Figure 3). The presence of deformations and structural damages are also to be reported. In this work, due to the need to define indicative values for the mechanical properties of existing timber elements through visual grading and also due to the species of timber of the beams, the Italian norm UNI 1119:2004 [12] was considered. This norm establishes objectives, procedures and requirements for the diagnosis of the state of conservation and estimates the mechanical properties (resistance and stiffness) for structural wood elements present in cultural heritage buildings. Its methodological approach consists in the execution of a visual inspection and application of NDT. For strength grading of a single element, this norm considers three classes (I, II and III) regarding onsite diagnosis for a given timber specie (Table 2). The wood element is from a given class if it fulfills all the imposed requirements and considered as non-classifiable if it does not fit to neither class.

In this work for the three beams, 40 cm segments were considered for visual grading and the significant parameters were reported. Single knots were measured considering the ratio A of the minimal diameter d of the knot to the width of the element face, while knot clusters were evaluated through the ratio W of the sum of the minimal diameters t of all knots, in a 150 mm range (or until the fibers have not realigned to their normal direction), to the width of the element face. Wane was measured considering the ratio s of the oblique dimension and the height of the cross-section. Presence of biological attack was also identified and reported.
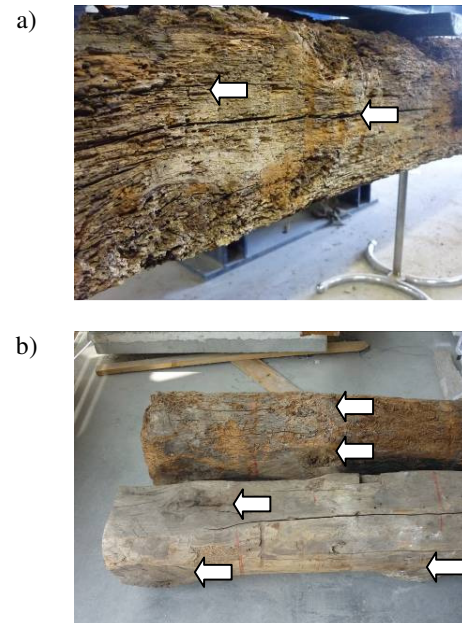

Figure 3: Example of defects found: a) decay and cracks; b) knots and slope of grain

Table 2: Mechanical properties for Chestnut (Castanea sativa Mill.) in a visual strength grading [12]

Class	compression // to grain	compression ⊥ to grain	static bending	tension // to grain [1]	shear // to grain	MoE in bending
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

3.1.3 Non-destructive methods

In this test campaign two NDTs, namely impact penetration tests and drilling resistance tests, were considered both for increasing the reliability of the visual inspection and to assess the depth of decay along the length of each beam. The equipments used were the impact

hammer Pilodyn® 6J and the controlled drilling device Resistograph® 3450.

The Pilodyn 6J® is a device that, through the release of a spring, transforms the elastic potential energy into impact energy. The penetration depth of a metallic needle with 2.5 mm of diameter can be measured and the depth is inversely proportional to the density of wood, which is rather interesting to measure surface fungi deterioration [14].

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 allow to characterize the full size of the specimen [15].

Initially, the impact penetration tests were made to all of the 40 cm segments of the beams and to all four faces, in order to obtain a qualitative comparison between segments and thus define the sections with presence of decay depth. For that purpose, the values of penetration depth made to reference specimens without defects or decay, from a prior database [16], were considered. The penetration impact tests were firstly considered as they are a fast and inexpensive method, providing straightforward results for an initial characterization of the surface layer of timber elements.

Then, drilling resistance tests were made on the sections that evidenced higher depths of superficial decay in the impact penetration tests previously made. The value of decay depth for those cross sections was obtained for each surface through the mean value of two measurements regarding the profiles obtained by the drilling resistance equipment (Figure 4). The profiles were analyzed, accounting to each initial measurement (needle entry) and last measurement (needle exiting) in the timber elements, as to minimize the effect of possible lateral friction. Measurements deviating more than 5% of the path length from the expected straight path were not considered, and the measurement was repeated. Measurements were made at a third of the cross section height or base.
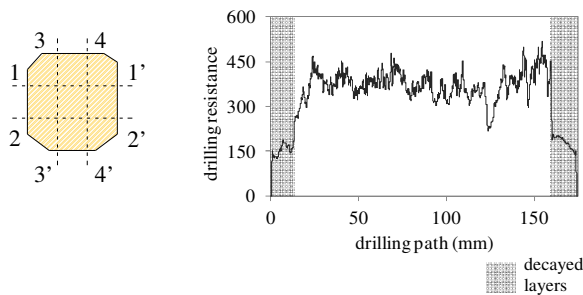

Figure 4: *Identification of drilling resistance tests on a cross section and example of a resultant profile*

The combination of the above techniques allowed the definition of the decay depth along the length of each beam, and consequently the residual cross section.

3.1.4 Bending tests

The timber elements were subjected to bending tests according to the test procedures given in norm EN 408 [11] which specifies laboratory methods for determination of physical and mechanical properties of timber in structural sizes. Although this norm is not intended for grading or quality control, it provides a standardized framework to obtain basic material properties that may be complemented with grade determining features, given for instance by visual inspection, for strength class grading.

The bending tests were made according to a 4-point bending configuration. The test specimen length, l, and the distance between the supports and the loading positions are proportional to the depth of the cross section, h. With respect to the properties of timber in bending, this norm suggests the determination of both a local modulus of elasticity, $E_{m,l}$, and a global modulus of elasticity, $E_{m,g}$. The difference between these moduli of elasticity depend on the gauge length of the measurement and also the stresses that the element is subjected within that range. The $E_{m,l}$ is measured in a distance of five times the height of the cross section, while the $E_{m,g}$ is measured along the full span of the beam between supports. The elastic moduli are calculated according to Equations (1) and (2):

$$E_{m,l} = \frac{a \cdot l_1^2 \cdot (F_2 - F_1)}{16 \cdot I \cdot (w_2 - w_1)} = \frac{a \cdot l_1^2 \cdot \Delta F}{16 \cdot I \cdot \Delta w} \quad (1)$$

$$E_{m,g} = \frac{3 \cdot a \cdot l^2 - 4 \cdot a^3}{2 \cdot b \cdot h^3 \cdot \left(2 \cdot \frac{\Delta w}{\Delta F} - \frac{6 \cdot a}{5 \cdot G \cdot b \cdot h}\right)} \quad (2)$$

where b is the width of the cross section (mm), h is the height of the cross section (mm), ΔF is an increment of load (N), Δw is the increment of deformation (mm) corresponding to ΔF, a is the distance between a loading position and the nearest support (mm), l is the span between supports (mm), l_1 is the gauge length (mm) for the determination of $E_{m,l}$, I is the inertia moment (mm⁴) and G is the shear modulus (N/mm²).

As the shear modulus was not obtained experimentally, its value was assumed to be unknown and taken as infinite as suggested in [11].

The tests were made with displacement control and the displacement rate was calculated such that the applied load necessary for calculation of MOE (40% of the estimated maximum load) was reached at 120 s. Due to the decayed surface and consequent predicted crushing of the timber fibers near the support and loading points, three loading cycles were considered (Figure 5).

The first cycle was used for adjustment and calibration of the loading machine to the specimen and to mitigate the effects of the possible crushing made by the loading process. Therefore, the results of the first cycle were disregarded and the final values of $E_{m,l}$ and $E_{m,g}$ were

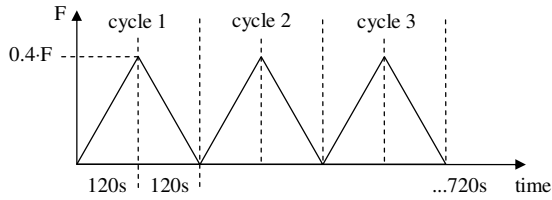obtained through the mean value of the results of the second and third loading cycles.

Figure 5: *Loading cycles for the 4-point bending tests*

For $E_{m,l}$ determination, two LVDTs were placed on each lateral face measuring the deflection at the expected neutral axis position, while $E_{m,g}$ was obtained through the LVDT deflection measurement at middle span between supports. Figure 6 shows an example of one of the 4-point bending tests.

Figure 6: *Beam B1 under a 4-point bending test*

3.2 RANDOM SAMPLING

After obtaining the visual grading per segment of each beam, the results of an existing database regarding small size specimen tests, taken from other beams from the same building, was used for prediction of the $E_{m,g}$ of the structural size beams.

The prediction model considers the computation of measurements of small size specimens' MOE, by modelling a reconstructed beam taking into account the visual grading of each segment. Therefore, for each segment of the reconstructed structural beam, it is attributed the value of MOE corresponding to a result, randomly selected, taken from the database of small specimens with the same visual grade. After, the displacements of each segment's nodes are calculated by the direct stiffness method and the calculation of $E_{m,g}$ of the reconstructed beam obtained by Equation (2).

In this work, only small size specimens with higher visual grading (class I) were considered for random sampling. Reduction coefficients were used for the segments of the

floor beams with lower classes (II, III, and non-classifiable, NC) based on the results of [13].

The random selection of specimens was repeated until a significant sample was obtained. A significant sample was considered to be reached when the coefficient of variation of the values of predicted $E_{m,g}$ stabilized. Following, the mean value of the sample was correlated to the experimental results.

The methodology used for obtaining the value of the predicted $E_{m,g}$ of the structural size beams, by use of random sampling of results from a prior database of small size specimens, and its comparison to the results of existing timber elements, is schematized in Figure 7.
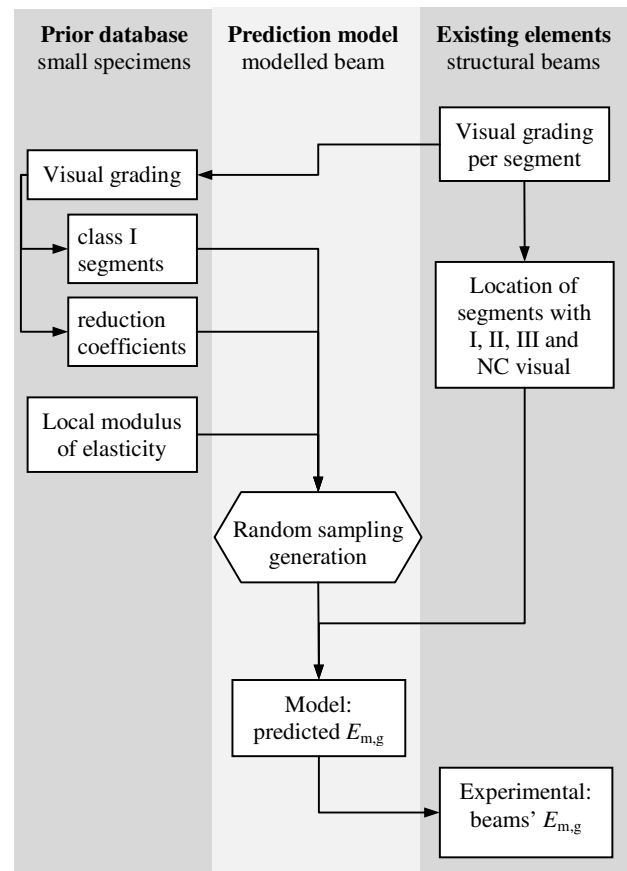

Figure 7: *Schematic process for the prediction models using random sampling*

3.3 BAYESIAN NETWORKS

BNs are used to represent knowledge based on Bayesian regression analysis describing the causal interrelationships and the logical arrangement of the network variables. BNs are represented by directed acyclic graphs (DAG), composed by a set of nodes, representing each system variable, connected by a set of directed edges, linking the variables according to their dependency or cause-effect relationship. Each variable node represents a random variable, either defined as a continuous random variable or as a finite set of mutually exclusive discrete intervals.

The main objective of a BN is to calculate the distribution probabilities regarding a certain target variable, by considering the factorization of the variables' joint distribution based on the conditional relations within the developed generic algorithm. In this light, the DAG is the qualitative part of a BN, whereas the conditional probability functions serve as the quantitative part.

In this case, a BN was developed in order to infer the influence of local data (smaller size specimens), both visual inspection and bending tests, on the results of $E_{m,g}$ of structural size elements (Figure 8).
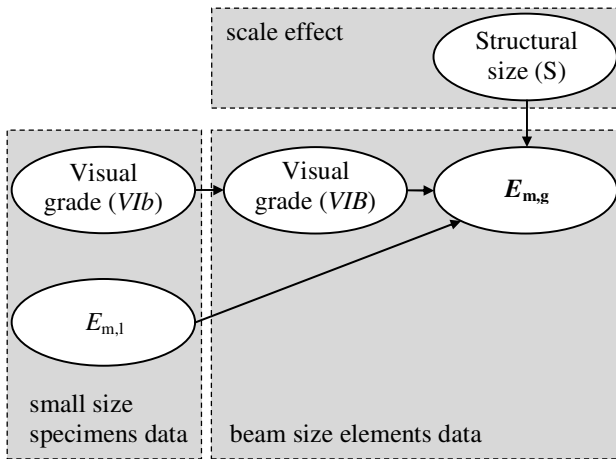
Figure 8: *Bayesian Network for inference of $E_{m,g}$*

The states in the nodes corresponding to visual inspection (both of smaller scale segments and structural size) are divided by the different visual grades (I, II, III and NC), whereas the states of the node corresponding to the information of bending MOE in small segments are considered by intervals of 2000 N/mm^2 up to 19000 N/mm^2, with an initial interval of [0,5000[N/mm^2 so as to prevent an interval without any event. The node corresponding to the selection of structural size takes into account the possibility to infer on properties of small size specimens or on structural size elements. In this node of the BN, it is possible to consider modification coefficients to take into account the scale, thus to calibrate the mechanical properties attending to the element's size. The child node corresponding to the $E_{m,g}$ of the beams is defined by discrete states with intervals of 2000 N/mm^2 up to a maximum value of 20000 N/mm^2.

The conditional probabilities within the parent nodes are based on the database results from [10], and evidence was given regarding the visual grading of the floor beams at the critical sections. Therefore, the updated information considers the visual grading of a specific segment to be comparable to the visual grading of a small size specimen, and information about its localized MOE may be given accordingly to that premise.

Taking into account the available results of visual grading, inference on $E_{m,g}$ of structural size beams was made upon information of the visual grading of beams critical section,

without prior information on small size bending tests. Therefore, probability for the result of $E_{m,g}$ is updated as considered in Equation (3):

$$P\big(E_{m,g},S|VIB_i\big) = \frac{P\big(VIB_i|E_{m,g},S\big)\cdot P\big(E_{m,g},S\big)}{P\big(VIB_i\big)} \qquad (3)$$

where $E_{m,g}$ is the global modulus of elasticity, S is the scale size of the element (imposed in this work as structural size beams), and VIB_i is the visual grade of the critical section with i being considered as class I, II, III or NC depending on the prior evidence.

Although not having the results of bending tests on small size specimens taken from the three analyzed beams, from the proposed BN and the database from [10], the probability of $E_{m,g}$ can also be updated if new information is after obtained by these tests on small size specimens extracted from the elements. In that case the updated results of $E_{m,g}$ would be given by Equation (4), as:

$$P\big(E_{m,g},S|VIb_i,E_{m,l\_j}\big) =$$
$$= \frac{P\big(VIb_i,E_{m,l\_j}|E_{m,g},S\big)\cdot P\big(E_{m,g},S\big)}{P\big(VIb_i,E_{m,l\_j}\big)} \qquad (4)$$

where VIb_i is the visual grade of the small size specimen taken from the structural beam with i being considered as class I, II, III or NC depending on the prior evidence, and E_{m,l_j} is the value of local modulus of elasticity in bending of the small size specimen with j being the interval class for that parent node depending on the prior evidence.

4 RESULTS

4.1 EXPERIMENTAL CAMPAIGN

4.1.1 Geometrical characterization
Although obtaining low coefficients of variation (CoV) on the exterior cross section sizes (respectively, 3.5% and 7.3% for height and width), due to wane a significant CoV was found for the cross section area and inertia (respectively, 11.9% and 20.1%), denoting a considerable geometric variation found along the beams' length. An example of the cross sections measured along the length of the timber elements is presented in Figure 9 for beam B1.
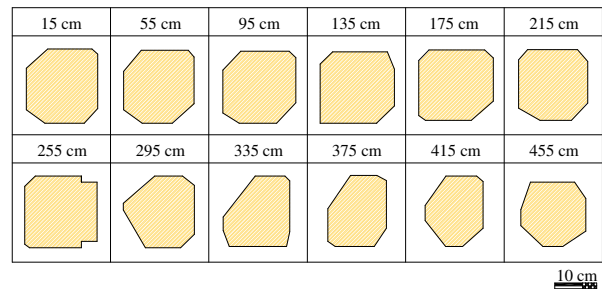

Figure 9: *Cross section measurements for beam B1*

4.1.2 Visual inspection

The most common defects found were the existence of knots and misalignment of grain direction. Along the length of the beams several segments presented signs of decay with the ends of the beams being the more affected. Also wane was found, more due to the initial sawing process, as the elements had still their round shape, rather than to loss of cross section integrity during the lifetime of the structure. Therefore, wane was not considered as a limiting parameter for visual grading in this study, but instead only the residual cross section without wane was considered. Furthermore, visual inspection also evidenced a large variation of defect concentration on different segments, being B1 the lower graded beam, while B3 was the higher graded (Figure 10).
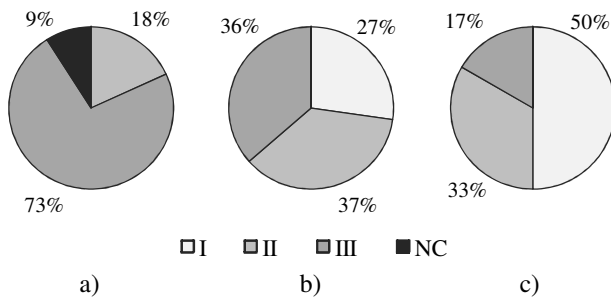
Figure 10: *Percentage of segments with a given visual grade in beams: a) B1; b) B2; c) B3*

4.1.3 Bending tests

The $E_{m,g}$ values obtained in the bending tests were calculated through Equation (2) considering the dimensions of the weakest critical section located within the measurement span. The dimensions of the cross section were decreased considering the mean value of decay depth obtained in the drilling resistance tests.

The results of the bending tests are presented in Figure 11, evidencing also the gauge length and visual grading by segments.

The influence of the decayed sections and round cross section geometry was found to be more significant in the lower span tests, evidencing lower modulus of elasticity values. Between spans with similar lengths, the values of $E_{m,g}$ was similar between the timber beams. Nevertheless, the values of $E_{m,g}$ also evidenced a decrease for segments with lower visual grading (III and NC) and an increase for segments with higher visual grades (I and II). In the larger span tests, and accounting the information presented in Figure 10, it visible that the beam with higher percentage of class I segments provided a higher $E_{m,g}$ (beam B3), whereas the beam with higher percentage of NC segments provided lower $E_{m,g}$ (beam B1).
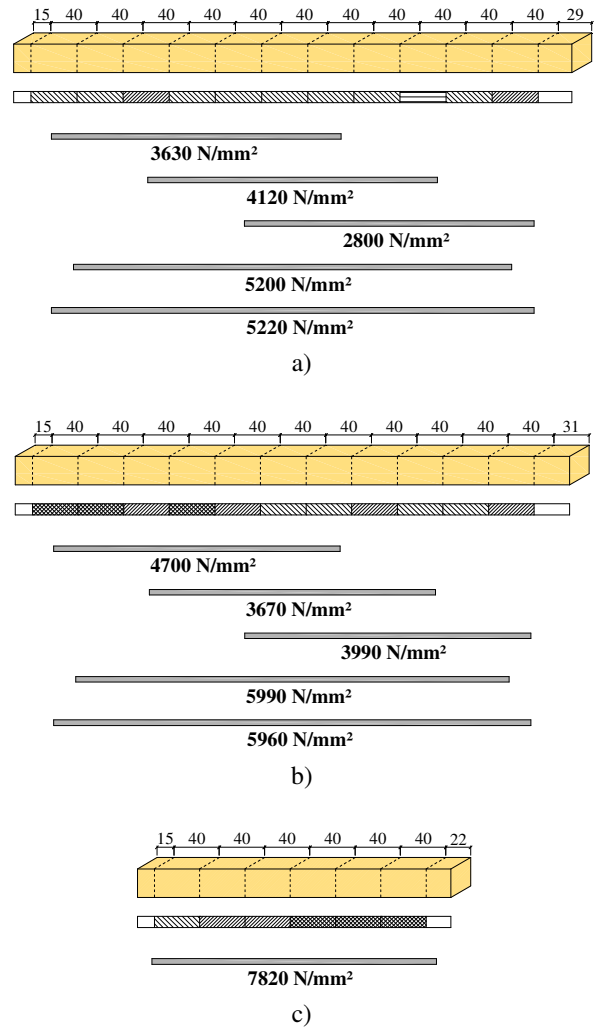

Figure 11: *Visual grading by segments (cm) and $E_{m,g}$ (N/mm^2) results (with indication of gauge length) for beams: a) B1; b) B2; c) B3*

4.2 PREDICTION OF BENDING STIFFNESS

The results of the predictive models by random sampling evidenced a r^2 of 0.36, being increased to 0.59 when considering only the lower span bending tests (Figure 12). Whereas, the BN obtained a r^2 of 0.61, being increased to 0.68 for lower span bending tests (Figure 13). However, in both cases a large mean percentage error was obtained, respectively of 152% and 174% for the random sampling models and the BN, both overestimating $E_{m,g}$.

The mean ratio between predicted and experimental values was similar for both prediction methods, being of 2.5 and 2.7 for random sampling models and for BN, respectively. To attend to this overestimation and to the scale effect, it is possible to consider reduction coefficients in each of the proposed methods. In the case of the random sampling method, the coefficients of reduction could be

implemented in the attribution of a reduced local modulus of elasticity, whereas for the BN method the reduction factors could be considered within the structural size node (*S*). With these coefficients of reduction, the mean percentage error would be minimized, however the r^2 would not be altered. In this work, these coefficients of reduction were considered since the prior database corresponded to elements of different scale sizes (sawn beams and sawn boards with rectangular cross section).

In Figures 12 and 13, the results from the prediction models with consideration of reduction coefficients are also presented for the smaller span lengths, evidencing that the results have a lower percentage error between experimental and predicted values. A mean percentage error of 21.3% is found for the random sampling model (with reduction coefficient, α = 2.5), similar to the obtained in [13], and a mean percentage error of 19.2% is found for the BN model (α = 2.7).
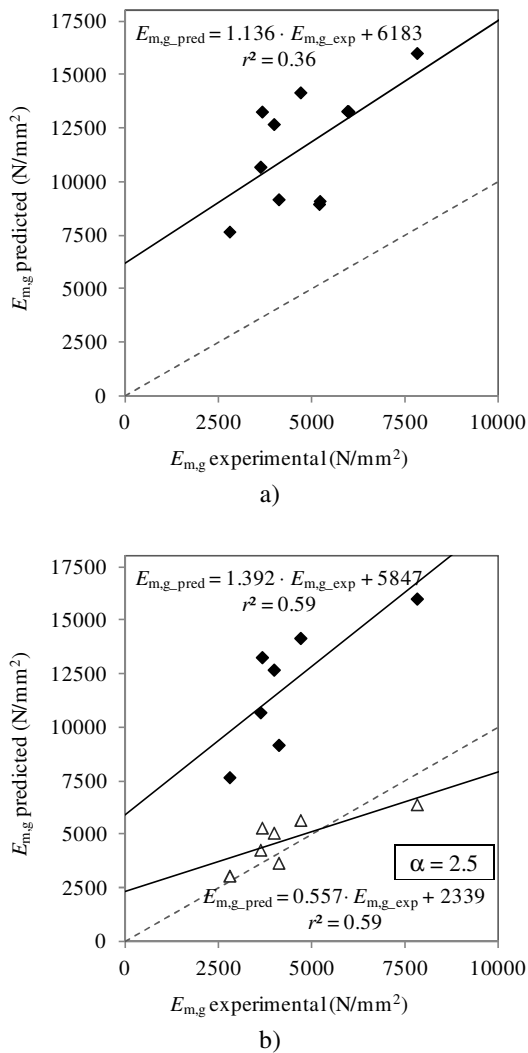

a)

b)

Figure 12: *Correlation of the experimental results with the random sampling prediction model results: a) all spans; b) smaller spans with reduction coefficient*
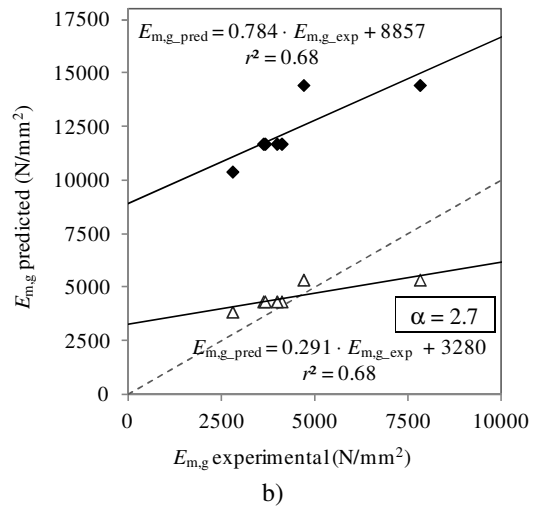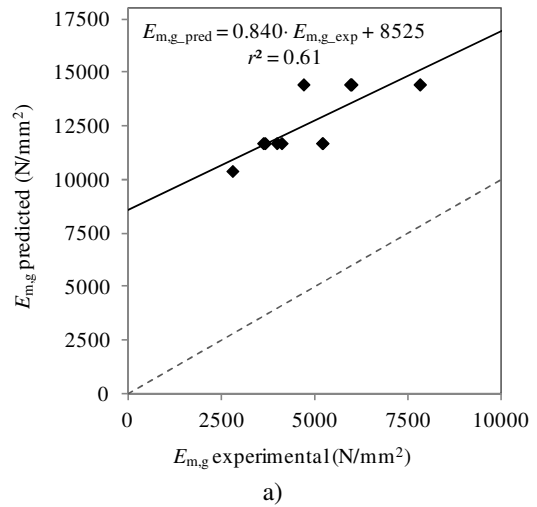

a)

b)

Figure 13: *Correlation of the experimental results with the BN model results: a) all spans; b) smaller spans with reduction coefficient*

5 CONCLUSIONS

Random sampling of data and use of Bayesian Networks were considered, in a probabilistic framework, to predict the global stiffness of three old chestnut beams, using information from visual grading and smaller size specimens taken from similar beams.

Although evidencing moderate correlations, also high mean percentage errors overestimating $E_{m,g}$ were found. The significant difference between predicted and experimental values derive, among other, from the large variability of cross section geometry (due to wane), the presence of decay and the increased probability of finding defects for members with higher volumes (scale effect). As the prior database of the prediction models corresponded to different size scales of the elements, also reduction coefficients of approximately 2.5 were considered for the prediction models, resulting in smaller mean percentage

errors between experimental and predicted values. These coefficients correspond to the scale effect relation between existing chestnut timber elements with round cross section and sawn beams of smaller dimensions with rectangular cross section.

Finally, for the random sampling model a coefficient of determination of $r^2 = 0.59$ and percentage error of 21.3% were obtained, whereas for the BN model a coefficient of determination of $r^2 = 0.68$ and percentage error of 19.2% were obtained.

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