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PREDICTION OF BENDING PERFORMANCE OF OLD TIMBER BEAMS BY COMBINING INFORMATION FROM DIFFERENT METHODS

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ABSTRACT

An assessment procedure for bending performance of timber beams on-site by combining information from different non or semi-destructive methods is presented and discussed. Different methods were applied (core drilling, pilodyn, ultrasounds and stress waves) to old timber beams removed from a building given the fact after visual inspection it was decided that they will no longer be able to comply to the limit state requirements. The study comprised the visual grading of the beams and afterwards a proof-load test was applied to them for obtaining the modulus of elasticity. The information obtained from the different tests are combined using meta-analysis and probabilistic methods and the results obtained solely from visual grading or by the application of a proposed coherent procedure (combining all data) compared. The results showed that SDT/NDT methods can be useful for the confirmation of visual strength grading results. Thus a more reliable structural analysis can be performed and a more informed decision taken about the serviceability state of the structure.

Keywords: *Bending modulus of elasticity, non-destructive evaluation, visual strength grading; non-destructive testing methods*

1. INTRODUCTION

The assessment of timber structures involves the necessity to predict the mechanical quality (strength, stiffness and density) of timber members and the mechanical behaviour of joints as well as to carried out the geometric survey of the structure (2 or 3-dimensional drawings). This information allows a preliminary verification of the safety and serviceability of the structure. This verification has also to take into account time-dependent mechanical (creep and load-duration) and biological variables (deterioration).

Almost all documents addressing the assessment of timber structures propose a two-stage process. This process is presented in a general flowchart for assessment of existing structures recommended by the ISO 13822 standard [1]. In the case of timber members at a first stage the general quality of timber members are evaluated. This assessment results in the allocation of a general strength class or visual strength grade or as in the case of the UNI 11119 [2] allowable stresses.

However in general this first survey is non-conclusive and the final judgment about the fitness of a timber structure is solely based on the experience and feeling of the surveyor. The acknowledgment

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of the difficulties of this second stage assessment led recently this topic to be addressed by several committees and some publications are now available on the topic [3], [4].
These documents can be used to define a common survey procedure but the essential problem regarding how to proceed with the allocation of reliable mechanical properties to a particular timber member still remains. The Italian standard vaguely mentions the use of non-destructive methods as tools for getting more reliable results *In some cases, on site inspection can be completed by supplementary tests through the use of one or more non destructive methods with the aim of determining physical and/or mechanical parameters which can be clearly correlated with the strength of the critical section itself* [2]. The Swiss standard [5] makes reference to specific non or semi-destructive techniques (NDT or SDT) for the determination of specific properties but do not describe the way each technique should be used on-site, Table 1.

Table 1 NDT and SDT techniques mention in SIA 269/5 [5]

NDT/SDT technique	Purpose
Drilling resistance	Evaluation of deterioration due to fungi, insects and non-visible fissures as well as the loss of cross-section
Moisture meter	Moisture content of timber members
Dynamic hardness test	Evaluation of local density, and possible deterioration due to fungi and insects
Tear-out resistance (e.g. screw resistance)	Indicator of wood properties using the correlation with wood density
Ultrasound	Indicator of wood properties by using the correlation of the ultrasound velocity with strength/stiffness
Core drilling	Direct compression parallel to the grain test method allowing also to measure density and moisture content

Therefore it was clear the need of information for a support-decision about what type of non or semi-destructive technique to use on a particular timber structure and situation. The RILEM Technical committee TC 215-AST begin addressing this topic and published recently three papers that can help in defining a common approach for using NDT and SDT methods in the evaluation of timber structural members condition [6], [7], [8].
These papers present some relevant information regarding not only the limitations of each technique (e.g. drilling resistance, stress waves, penetration resistance) but moreover the definition of a testing method (including the number of samples/readings to be performed and where) and the external factors that can affect the readings and need to be taken into account.
Nevertheless the effort make in the aforementioned research areas it is necessary also to look in the way data should be analysed in order to ensure that the inspection work will provide useful and reliable information. Only then structural engineers can perform responsible safety and serviceability analysis of the timber structure.
The present paper presents and discusses a general procedure for predicting the bending modulus of elasticity of timber beams on-site by applying different SDT/NDT methods. The advantages of combining information from the different methods are discussed.

2. EXPERIMENTAL WORK

2.1. Material

Ten old timber floor beams were removed from a building in the city of Guimarães (North of Portugal). The building was under renovation works and it was decided (construction company decision) to replace the entire timber flooring. The beams showed a strong deterioration at the ends due to the close contact with the masonry walls (fungi and termites). By agreement with the company responsible for that work the beams were sent to LNEC for testing.

The beams were first visual inspected to detect biological deterioration, to select two clear wood zones for SDT/NDT testing and the possibility of a span/depth ration compatible to the testing requirements of EN 408 [9] for the determination of the global modulus of elasticity.
Since most of the beams showed a strong level of degradation at the ends it was decided to cut the ends of the beams showing biological damage. Afterwards the geometric dimensions of the beams were measured using a ruler. The moisture content of the beams was measured using equipment based on the electrical resistance method (GANN – Hydrometer T 85T). Table 2 presents the characteristics of the beams tested.

Table 2 Characteristics of the beams tested

Identification	**Geometric dimensions**				**Moisture content** (%)	**Visual strength grading** (grade / $E_{0,\mathrm{mean}}$)	
	Cross section (mm^2)			Length (mm)		UNI 11119	NP 4305
	End A	Center	End B				
3	105 × 155	105 × 160	105 × 155	2855	12.2	I (13 GPa)	E (9 GPa)
8	115 × 260	115 × 170	95 × 170	3040	15.8	I (13 GPa)	E (9 GPa)
9	115 × 160	115 × 165	115 × 160	2940	14.0	II (12 GPa)	E (9 GPa)
10	150 × 160	150 × 160	150 × 160	3040	16.4	II (12 GPa)	E (9 GPa)
11	143 × 157	144 × 155	143 × 153	2855	16.3	II (12 GPa)	E (9 GPa)
13	115 × 155	115 × 160	110 × 160	2953	17.6	I (13 GPa)	E (9 GPa)
15	130 × 160	130 × 160	125 × 160	3030	13.3	III (11 GPa)	E (9 GPa)
18	105 × 160	115 × 160	120 × 160	3050	15.5	II (12 GPa)	E (9 GPa)
20	150 × 160	140 × 160	140 × 150	1290	16.1	II (12 GPa)	E (9 GPa)
21	158 × 146	145 × 159	142 × 160	2660	12.7	I (13 GPa)	E (9 GPa)

Visual strength grading was conducted considering only the upper face and the lateral surfaces, therefore trying to mimic the possibilities of survey on-site where most of the times only three surfaces are free for direct observation and the ends are inaccessible.
The Portuguese standard NP4305 [10] for visual strength grading of maritime pine timber (*Pinus pinaster* Ait.) was applied since it is often use during the inspection of softwood structural members in Portugal. It was applied also the Italian standard UNI 11119 [2]. This standard was chosen since it is probably as much as the authors are aware the only standard specially addressing the strength grade of structural timber members on-site.
The application of the Portuguese standard (specific to maritime pine timber – *Pinus pinaster* Ait.) resulted always in allocation of grade E mostly because of the presence of the pith.

2.2. Test methods

The test program included different SDT/NDT methods. Some of them as sonic *vs* ultrasonic waves or core drilling *vs* penetration resistance were used since one of the objectives were the possible combination of data from different methods. Figure 1 shows a scheme of the test program.

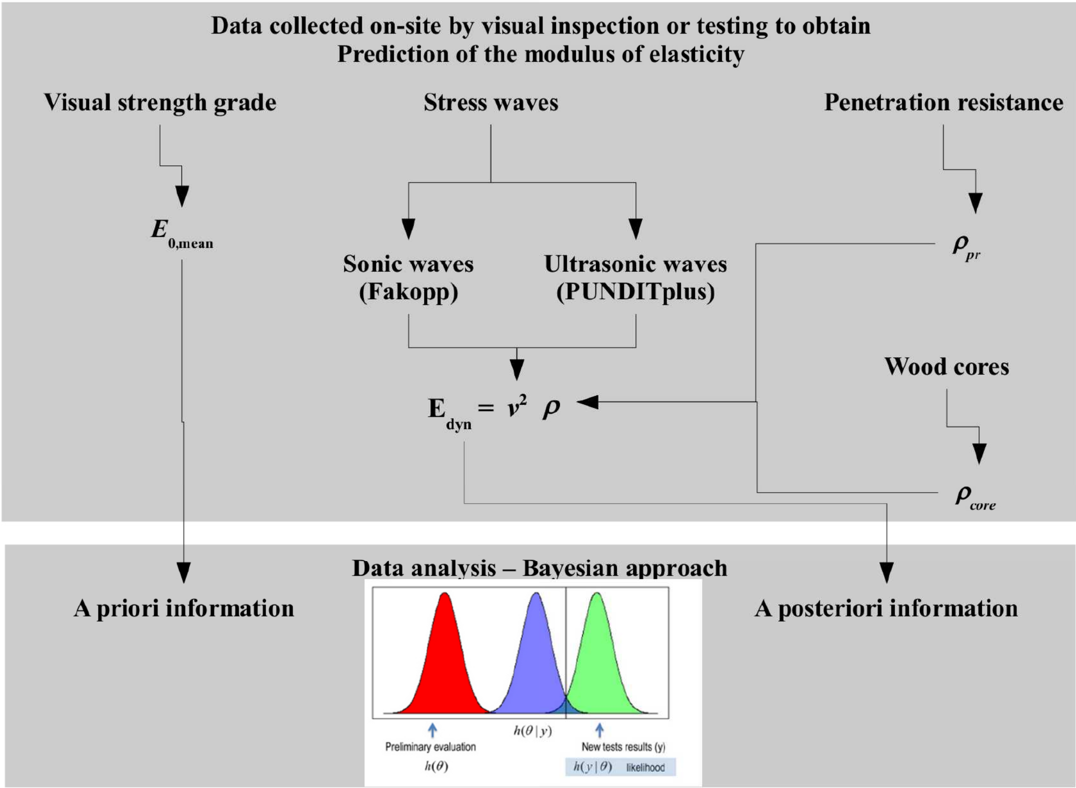

Fig. 1 Scheme regarding the procedure adopted in the present paper for predicting the global modulus of elasticity

2.2.1. *Bending proof-load test*

A proof-loading test was applied to obtain the global modulus of elasticity ($E_{m,g}$). The maximum proof-load applied was determined according with Eq. 1 (equation taken from [11]).

$$F_p = \frac{0.96 \cdot t \cdot h \cdot k_h \cdot f_{m,k}}{18} \qquad (1)$$

where F_p corresponds to the applied proof-load, t to the thickness of the beam, h is the depth of the beam, k_h is the size factors given in EN 384 [12]; and $f_{m,k}$ is the characteristic value of bending strength associated to a visual strength grade for a 150 mm depth. In the present case the wood species is unknown besides the fact that belongs to Genus *Pinus*. Therefore it was applied a low load level corresponding to the characteristic value associated to the rejection grade (13 N/mm^2) of NP 4305 [10].

Global modulus of elasticity values were adjusted to 12% moisture content according to EN 384 [12] and considering the values determined from the wood cores. This decision was taken bearing in mind that the precision of moisture meters (≈ ±2%) is significantly lower than the determination over wood cores. Nevertheless some discussion about this decision is still open and ongoing studies will consider the effect of moisture content over the predicting capacity of NDT/SDT methods (sensitivity analysis).

2.2.2. *Stress waves*

Stress waves comprised the use of sonic (Fakopp Microsecond Timer) and ultrasonic waves (PUNDITplus). The ultrasonic NDT method used a PUNDITplus equipment coupled to 150 kHz transducers. A mineral gel was used as coupling agent and the pressure was manual. In both techniques an indirect method was used (transducers placed on the same surface). Fakoop exponential transducers allows an easy coupling with wooden material being the readings more stable than using the PUNDITplus flat surface transducers. In this last case the more difficult coupling due to wood

surface inhomogeneities was clear. In some beams proper arrangement of PUNDITplus transducers was very difficult to obtain and more variable readings were obtained.
Two clear wood zones with at least 40 cm length were identified at each beam. In each of these zones readings were done at the top surface and at one of the vertical surfaces, Fig. 2.

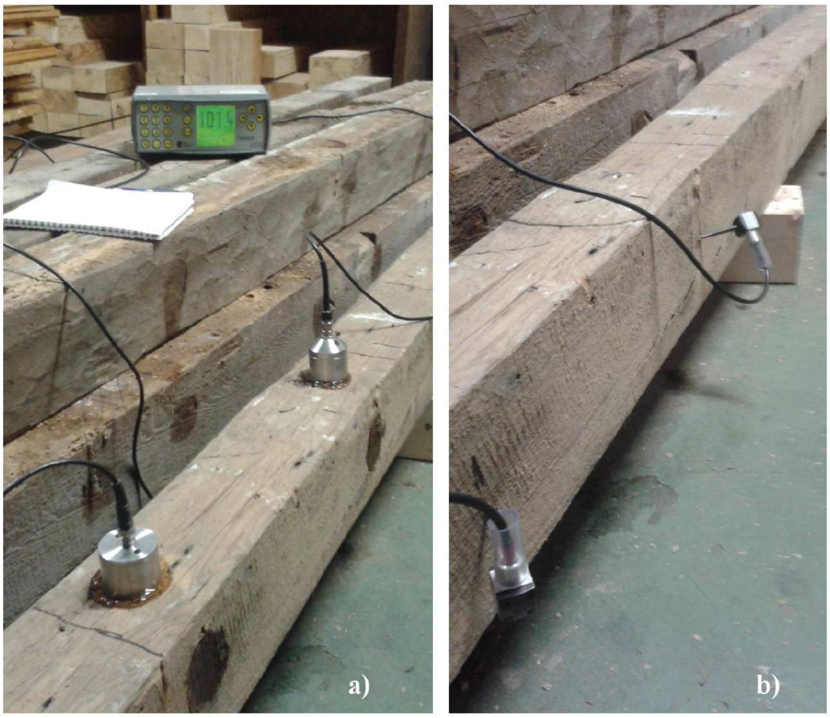

Fig. 2 PUNDITplus (left) and Fakopp (right) transducers applied on the top surface of a timber beam

For each test method and at each surface it was acquired five ultrasonic time-of-flight readings. The indirect ultrasonic wave velocity was adjusted given the regression curve obtain for maritime pine in [13].
Then for both methods the dynamic modulus of elasticity ($E_{0,\mathrm{dyn}}$) was determined using equation 2.

$$E_{m,dyn} = v^2 \times \rho \tag{2}$$

where v – wave velocity (m/s) and ρ – density (kg/m^3)

While wave velocity is directly determined from the time-of-flight measurement provided by the stress wave equipment divided by the distance between transducers, using a ruler, the problem is how to predict density.
Some alternatives are indicated in a recent paper [6]: using tabulated values for the wood species; correlation with drilling resistance; or, the determination of density from small specimens extracted in situ. Wherever the option followed lengthwise and cross-section variation of density should be taken into account. In the present study it was verify an alternative method based on a penetration resistance test described in section 2.2.3.
The mean value of the dynamic modulus of elasticity given by ultrasonic and sonic waves was obtained considering the combination between the density values (ρ_c) obtained from the three core drills and the five velocities (v) determined from the time-of-flight readings, Eq. 3.

$$E_{m,dyn} = \frac{\sum_{i=1}^{5} v_i^2 \cdot \left(\sum_{j=1}^{3z} \rho_{c,j} \right)}{15} \tag{3}$$

2.2.3. Penetration resistance

The penetration test was carried out using a pilodyn 6J Forest equipment. This test corresponds to a dynamic penetration test being measured the penetration of a metallic pin inside wood. In the present case this pin is shooted into the wood with energy of 6J.

This SDT method was used given the potential high correlation possible to be obtain ($r^2 = 0.66$ for 4) using only four measurements [8]. In the present study three measurements were carried out in each of the two clear zones used for the stress wave measurements (six reading in total).

The correlation between pilodyn penetration (mm) and density was determined for maritime pine and scots pine (*Pinus silvestris* L.) by [14]. This curve is compared with the one obtained by [15] for silver fir timber (*Abies alba* Mill.), Fig. 3. From this same figure it is possible to observe that although both equipments used identical impact energy (6J) (similar to the equipment used in the present study) the behaviour of the regression curves is significantly different.

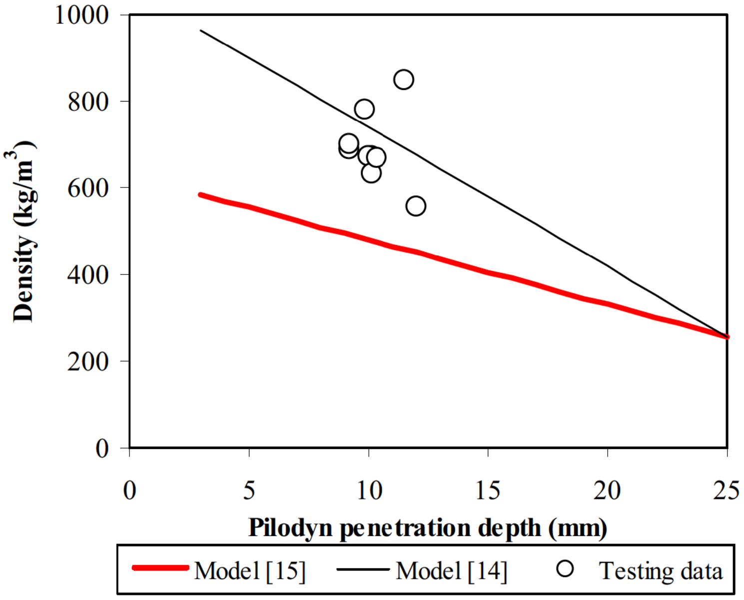

Fig. 3 Regression curves obtained from bibliographic references ([14], [15]) between penetration resistance and density for softwood species

Figure 3 highlights the problems associated with the use of pre-existing models. To counterbalance this issue a possibility of calibration of the readings using for instance wood cores or X-ray measurements should be checked. Once assumed that all timber structural members are from the same species and provenance (surveyor experience) the model permits that a less intrusive testing methods (as pilodyn) can be used for testing other structural member without the need to use more intrusive (destructive) methods (as core drilling).

2.2.4. Core drilling

Three wood cores were extracted along the length of the beam. These wood cores allowed the direct determination of density and moisture content. Each core showed a length (depth inside the element) around 40 mm which is about 1/4 of the beam's depth thus corresponding to the marginal volume of the beam. This procedure was carried out since the beam is subject to bending load in service. Therefore the length of the wood core permits to take into account the cross-section variation of density whereas the collection of cores in different places along the length of the beam allows to take into consideration the lengthwise variation of properties.

2.3 Data analysis

The prediction of the global modulus of elasticity was based on the application of a bayesian probabilistic model. This model assumes the existence of *a priori* information about the material which can be updated from new information collected by testing on-site. Bayesian model assumes that *Y* is a random variable representing the space of possible values for a certain property of the material and f_Y the probability density function that represents the distribution of the space of possible values of Y. The pdf f_Y is characterized by a vector of parameters θ – g_Θ. If a new data set is collected, $\widehat{Y}$ = {y_1, y_2, …, y_n}, a Bayesian updating of Θ distribution can be obtained, Eq. 4.

$$g''_\Theta\left(\theta\middle|\widehat{Y}\right)=\frac{g'_\Theta(\theta)\cdot L\left(\theta\middle|\widehat{Y}\right)}{\int_{-\infty}^{+\infty} g'_\Theta(\theta)\cdot L(\theta|\widehat{Y})dq} \tag{4}$$

where $g_\Theta(\theta)$ represents the pdf of the uncertain parameter Θ, $L\left(\theta\middle|\widehat{Y}\right)$ is the likelihood function of the results contained in $\widehat{Y}$, $''$means the *a posteriori* and $'$the *a priori* pdf of Θ.

In the present case a priori information was provided by considering the most reliable visual strength grade possible to be allocated to a structural member, Table 2. Posterior information was obtained from the NDT/SDT carried out in the different beams.
The bending modulus of elasticity for each beam was predicted using a combination of information from the sonic and ultrasonic test. The combine predicted modulus value was obtained using a parametric method. This equation considers two estimators of E (E_1 and E_2) with pdf defined as N~(E_1, σ_1^2) and N~(E_2, σ_1^2), respectively, being the combined unbiased estimator given by Eq. 5.

$$E=\omega_1\cdot E_1+\omega_2\cdot E_2 \tag{5}$$

with

$$\omega_1=\sigma_1^{-2}/\left(\sigma_1^{-2}+\sigma_2^{-2}\right) \text{ and } \omega_2=\sigma_2^{-2}/\left(\sigma_1^{-2}+\sigma_2^{-2}\right)$$

The location parameter (mean value) was considered as a random variable corresponding to the predicted modulus obtained from the dynamic modulus of elasticity. The scale variable was considered know (standard deviation). For the determination of this variable it was assumed a coefficient of variation of 13 % [16].

3. RESULTS AND DISCUSSION

For the majority of the beams tested the use of a priori information from visual strength grading resulted in conservative values of bending modulus of elasticity, Fig. 4. This result as expected is more evident by the application of NP 4305 [10] which was developed for grading of sawn timber and specifically to maritime pine. UNI 11119 [2] developed specifically for timber member in situ provides closer results to reality. However UNI1119 [2] provides for two beams E values above the result obtained from EN 408 testing.

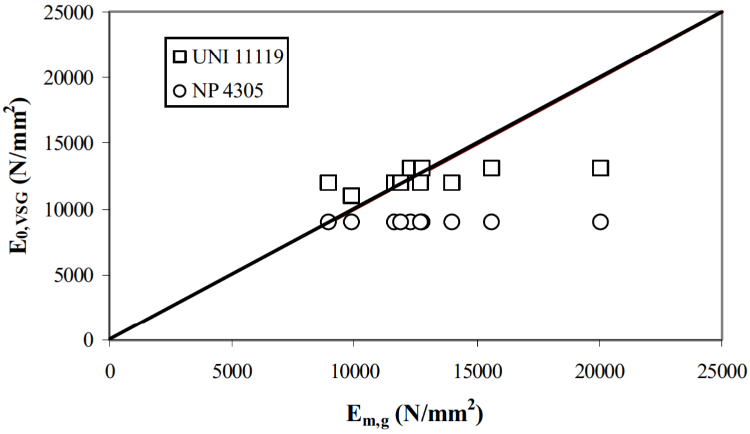

Fig. 4 Relation between E values obtained from EN 408 testing and those allocated after visual strength grading

Figure 5 compares the results obtained from the two stress waves methods applied in the present study. The results showed that both methods predicted values are clearly on the safe side. A high correlation was found using ultrasonic waves (r > 0.6) and medium correlation for sonic waves (r between 0.4 and 0.6). By observing this same figure it is evident that one beam is affecting significantly the correlation (beam 21). The reason for the high modulus of elasticity of this beam will be study with more details in the foreseen steps of the ongoing study. The removal of beam 21 in the case of sonic waves would produce a very high correlation (above 0.8) between the predicted value (dynamic modulus) and the measured property (global modulus).

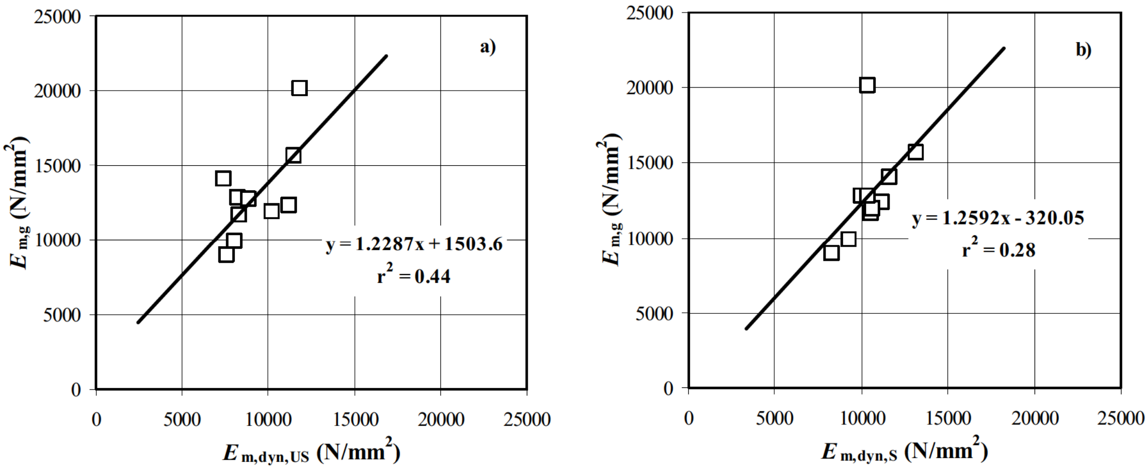

Fig. 5 Relation between E values obtained from ultrasonic (a) and sonic waves (b) methods and the global modulus of elasticity obtained from EN 408 [9] testing

The correlation using the combined predicted estimator (Eq. 5, Fig. 6) provided a correlation coefficient slightly inferior to the one obtained using the ultrasonic dynamic modulus of elasticity (Fig. 5a) but clearly superior to the one obtained from the sonic method (Fig. 5b).
The bayesian model showed an improvement of the prediction capacity, namely when using as background information the application of the UNI 11119 standard [2], Fig. 7. In this case the best prediction is obtained with a coefficient of determination of 0.47 (corresponding to a *r* value of 0.68 – high correlation).

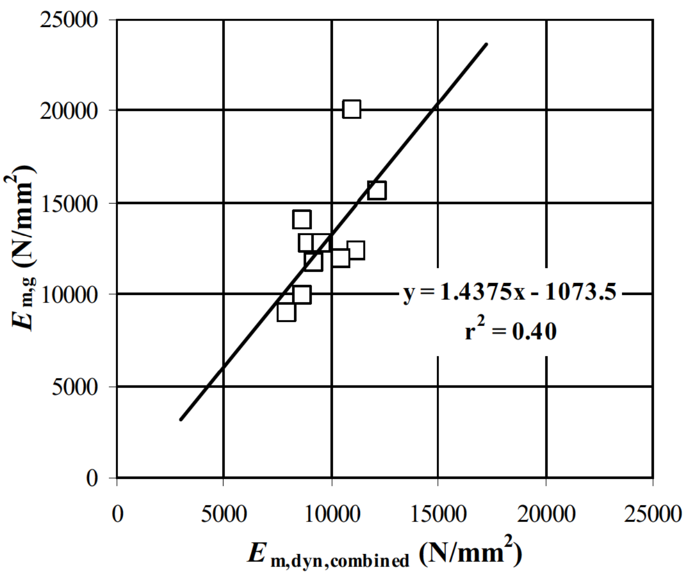

Fig. 6 Relation between *E* values obtained from the combination of ultrasonic and sonic waves methods and the global modulus of elasticity obtained from EN 408 [9] testing

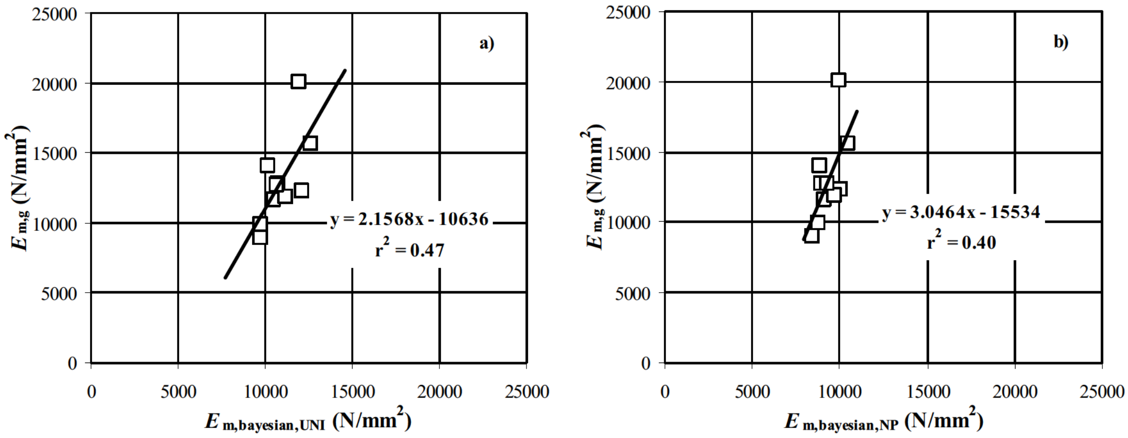

Fig. 7 Relation between *E* values obtained from bayesian model using UNI 11119 [2] E value (a) and NP 4305 [10] *E* value and the global modulus of elasticity obtained from EN 408 [9] testing

Comparing all the information collected from the beams, Fig. 8, it can be seen that using only the application of visual grading (NP4305 [10] or UNI11119 [2]) in general it is obtained conservative values. Non conservative predictions are only obtained in the case of UNI 11119 [2].
However only in one case the value is significantly lower than the global modulus of elasticity obtained from EN 408 [9] bending test (ratio = 0.8). The results also showed that the use of NDT/SDT methods alone or in combination with visual strength grade value provides a close result to the experimental bending data.

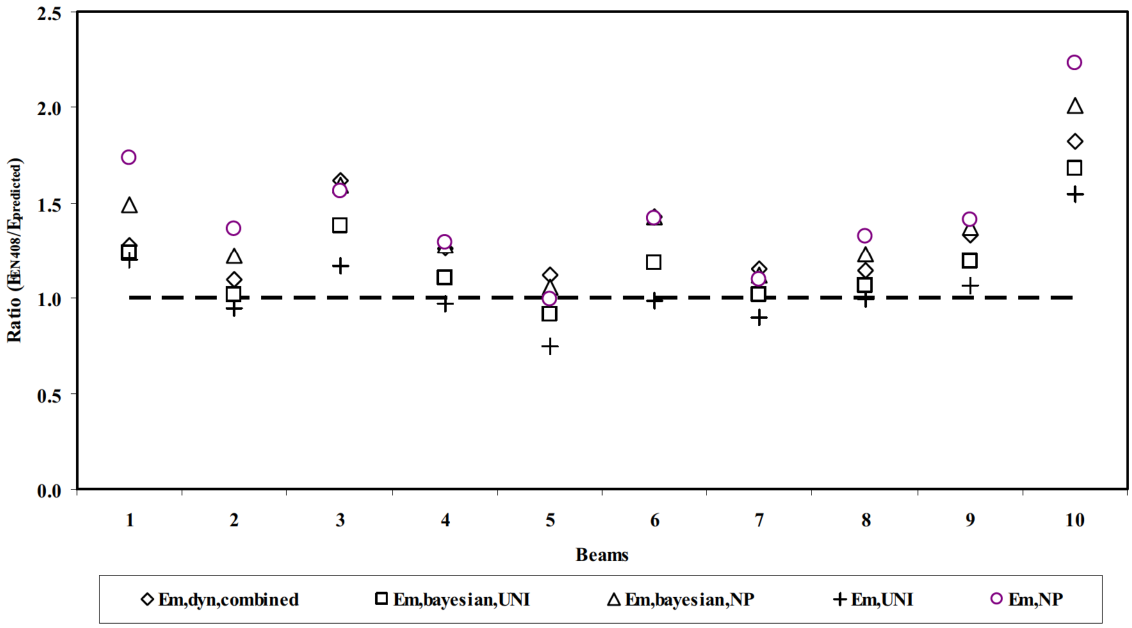

Fig. 8 Ratio between the modulus of elasticity obtained from EN 408 [9] and the one obtained using different approaches

3. CONCLUSIONS

The application of visual grading standards and NDT/SDT methods to assess the global modulus of elasticity of old timber beams showed that:

– the application of UNI 11119 provided reliable results;
– the combination of sonic and ultrasonic stress wave dynamic modulus of elasticity results can be used to cross-validate the visual grade values.
– bayesian model can correct some deviations from taking solely visual or NDT/SDT results.

ACKNOWLEDGEMENTS

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