Strength appraisal of wooden members in service by combining new and old technology

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Abstract

Structural safety analysis of old timber structures is based on gathering step-by-step information about the characteristics of the wooden structural elements leading to allocation of residual strength values. Although this task is often supported on a probabilistic basis (strength Probability Distribution Function of a certain visual strength grade) turns out quite deterministic when strength values allocation is carried out in an global (structure) or local (member) manner by assignment of the same strength value to different structural timber members (showing different defects and/or the same defect but with different levels of magnitude) based on the 5th percentile corresponding to a certain visual strength grade population.

This simple approach leads in most cases to over conservative values resulting in recommendations for the replacement of old timber structures after carrying out safety structural analysis following current design standards (Eurocode 5). This outcome was observed while performing safety analysis on different historical timber constructions in Portugal (roofs and flooring systems) which stayed in service for more than 100 years and showed incipient levels of deterioration.

Having in mind the need to maintain historical timber structures a new approach for allocating strength values to individual timber members is presented and discussed. This approach is based on the experience and data obtained during the development of visual grading standards and the use of new technologies available nowadays (for instance probing and ultrasounds). The possibility of combining information from new and old technology will be evaluated by testing pine timber beams and by application to a case study.
Keywords: timber, structures, survey, resistance, ultrasounds.

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1 Introduction

Wood as compared with other structural materials shows a significant variability of mechanical properties between wood species (hardwoods *versus* softwoods), within the same wood species (defects, density) or even within the same stem (effect of juvenile wood). In the case of structural timber members other sources of variability exist as for instance loss of strength due to the effect of load and environment history – creep, duration of load – and biological deterioration.

Strength appraisal of timber structures is thus a huge challenge which depends highly on the experience of the survey team. The following sequential steps are generally adopted: 1) identification of wood species involved; 2) establishment of visual strength (VS) grades (specific to a certain wood species) – allocation of reference characteristic values; 3) Identification of the type and degree of deterioration (biological or mechanical) – affecting characteristic values obtained in the second step.

This paper will be focus on the second step mentioned above. Allocation of a strength value to a timber member has always been conducted by considering the features (as density, knots and other defects) that the member shows. Visual strength grading standards were first based on tests on small clear wood specimens obtaining basic stresses which were afterwards multiplied by what was called the strength ratio (dependent on the nature and extend of defect permitted in a particular grade). This approach can be pictured as regarding the timber member as homogeneous (constituted only by clear wood - basic stresses dependent on density) and afterwards turning it heterogeneous by inserting the observed defects and considering their effect on clear wood strength-loss (resulting in allowable stresses used for design).

This procedure was later on modified by testing pieces of structural dimensions and analyzing the results obtained in order to establish relationships between mechanical properties and measured parameters (knots dimension, slope of grain, density, etc.). After settling basic grading rules, visual grades are defined and characteristic strength values (representing the 5º percentile of a non-parametric distribution of probability) allocated to each VS grade.

The predictive accuracy of visual grading is limited due to the general weak relationship between the grade parameters and mechanical properties and also due to grading decision reliance on the judgment of the grader which can never be totally objective (function of his experience).

The application of such visual grading procedures to timber members in service is even more difficult than at a sawmill or factory yard, since *in situ* it is frequently difficult or impossible to examine all timber surfaces. Considering the necessary caution taken during a survey for assessing the structural safety of a old timber structure, it is often assigned lower visual grades if doubts exist between two grades, which balanced with the procedure of making the allocation of strength values on a group basis (equalize strength values of different members showing different defects to the same 5^{th} percentile of the grade population) give a tendency for underestimation of the real strength and stiffness of timber members under inspection.

This practice can, and generally, results in recommendations for the replacement of old timber structures. Having in mind the need to maintain historical timber structures a new approach for allocating strength values to individual timber members is presented and discussed. This approach is based on the experience and data obtained during the development of a visual grading standard for maritime pine (*Pinus pinaster* Ait.) sawn timber either following principles of testing small clear wood, Mateus [1], or testing timber of structural dimensions, NP 4305 [2] (VS grades "Especial Estruturas" - EE and "Estruturas" - E). The approach proposed is also based on recent timber strength grading procedures developed using non-destructive techniques like ultrasounds.

2 Strength assessment of timber members

2.1 Constrains of the traditional approach

Assignment of strength and stiffness properties to timber members in service by allocation of visual strength grades (often revealing a strength probability distribution function with a high variability) can result on a significant misjudgement of the real strength capacity of timber members, Figure 1.

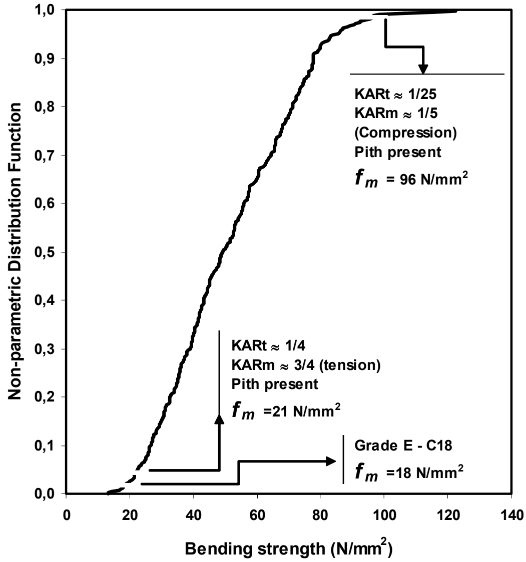

Figure 1: Disparities between strength of timber pieces belonging to the same visual grade - effect of grade E variability (40%) (Machado [3]).

The variability found in the visual grading process is mostly related with the weak capacity of strength and stiffness estimators (being the most common KAR, slope of grain, density).

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Also, this approach does not have in consideration that while evaluating a timber member in service information is often available which can be used for modifying the *a priori* strength probability distribution function (PDF) of a certain visual strength grade population. For instance whilst developing the visual standard all the possible sources of the raw material are considered together, yet *a posterior* knowledge can exist about the timber's source. Considering home-grown maritime pine timber two origins could be considered, corresponding to the centre and north of Portugal with different stand conditions leading to different PDFs, see figure 2.

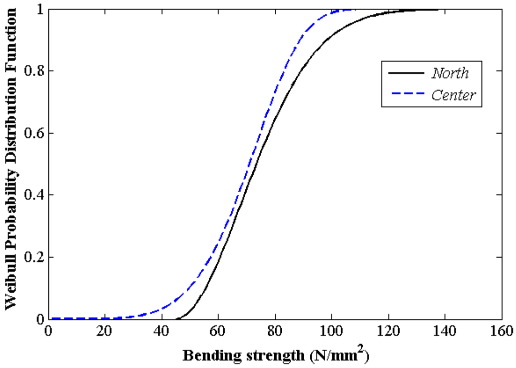

Figure 2: Weibull PDF fitted to Maritime pine timber strength from two regions in Portugal (EE VS grade).

Whereas VS grading of a timber beam is performed without any information about the final end-use (the way the beam is placed, location of defects as regards lengthwise stress distribution), survey observations make that information more clear (each member with its own defects and distribution of stresses and defects along the beam span can be known).

It should be remembered that frequently VS grade PDF is based on tests on timber beams where the unfavourable cross-section (containing the defect that determines allocation to a certain grade) is located on the more stressed zone which could be not the case when the timber beam is put in service.

2.2 Approach proposed

Having in mind the difficulties shown by VS grading on assessing with an acceptable level of accuracy the strength and stiffness of timber members in service, a novel proposal is therefore presented. The proposal considers timber structural elements as a composite material made from clear wood zones and defect wood zones, a concept similar to the general model proposed by Riberholt and Madsen [4] under the term weak-zone models. This model was applied by Machado *et al* [5] while characterizing maritime pine timber using acousto-ultrasonic readings along the length of a timber member, Figure 3.

In this paper a discussion is made about the possibilities of estimating strength values of the different zones and using that information to predict the mechanical behaviour of structural timber members. Strength is estimating using what can be called old (visual grading rules) and new (ultrasounds, probing) technologies.

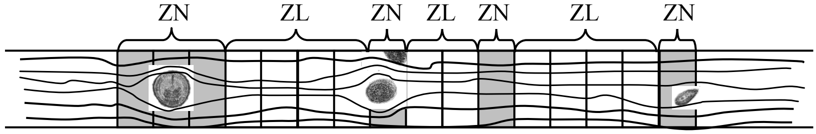

Figure 3: Representation of a timber element (ZN – Defect zone; ZL – Clear wood zone).

The separation between clear and defect zones has support for the evidence that no feature is able to act by itself as a good estimator of mechanical properties of timber (as clearly stated in visual grading). Knots, as regards maritime pine timber, are considered the main strength reducing parameter, Machado *et al* [5]. For this wood species the Knot Area Ratio (KAR) is an appropriate method for assessing its strength loss effect, figure 4, whereas for modulus of elasticity a significant loss of prediction capacity is clear.

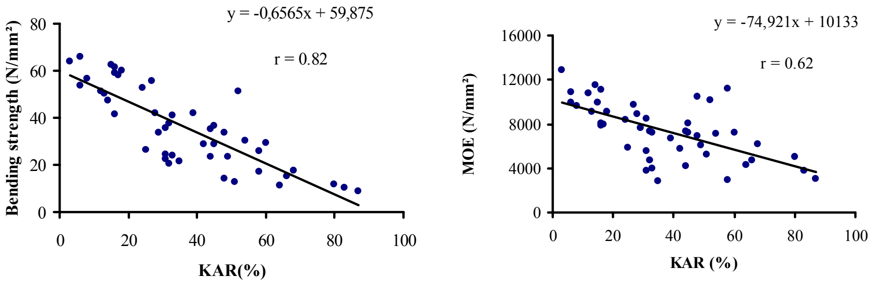

Figure 4: KAR effect on loss of strength and stiffness on medium-size test pieces (5x5x100cm).

In the old VS grading concept density was used as an estimator of clear wood strength. However the correlation between density and clear wood properties is in general weak (r inferior or equal to 0.60). In the present study density (ρ) is used along with ultrasound propagation velocity (c) for determination of dynamic modulus of elasticity (MOE_{dyn}) determined according to eqn. (1).

$$MOE_{dyn} = c^2 \rho \tag{1}$$

Ultrasound velocity was measured by inducing compressive ultrasound waves in the wood material. For this task PUNDITplus equipment and transducers of 150kHz were placed on the same surface (indirect method). MOE_{dyn} was determined for 26 maritime pine timber beams (visual strength grade E according with Portuguese standard NP 4305 [2]), and global modulus of elasticity (MOE_g) and bending strength were determined according to EN 408 [6]. Figure 5 shows that MOE_{dyn} gives a good prediction of MOE_g but no prediction is possible for bending strength (f_m).

These results expose the fact that while final strength capacity is mostly ruled by the worst defect (localized region), modulus of elasticity is a more global measurement of the quality of a beam and therefore gets a strong contribution from clear wood properties as well as those from defect zones.

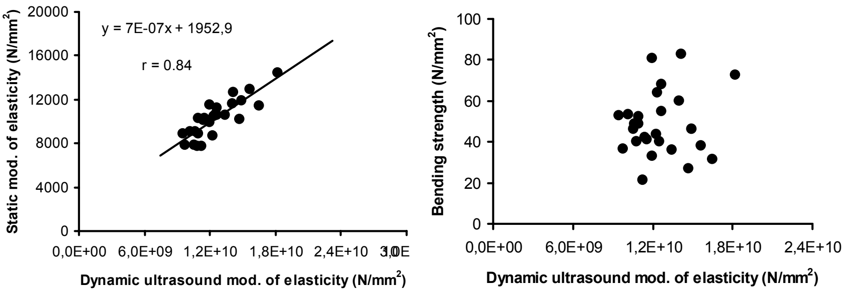

Figure 5: MOE_{dyn} versus static MOE for maritime pine structural timber beams (4x10x200cm).

Timber strength is therefore envisaged in this paper as a function of the general quality of the wood, ruled by clear wood strength, eqn. (1) and eqn. (2) (confidence interval of future values derived from the linear regression curve $f_m = a\ E_{dyn} + b$), and weakest point (ruled by the strength-loss effect of the knot, figure 6) influence on clear wood strength. This idea follows what was practiced on older VG standards. Strength-loss factor (K_{knot}) is based on the results obtained for maritime pine clear wood specimens by Mateus [1]

$$f_{m,MOE_{dyn}} = 2E-09 \cdot MOE_{dyn} + 21.32 \quad (2)$$

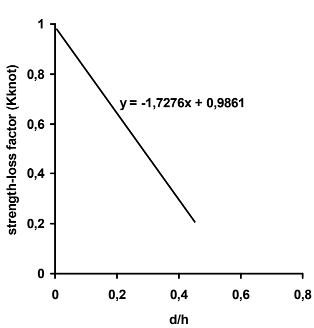

Figure 6: Strength-loss (K_{knot}) as function of knot diameter (d) and beam's depth (h).

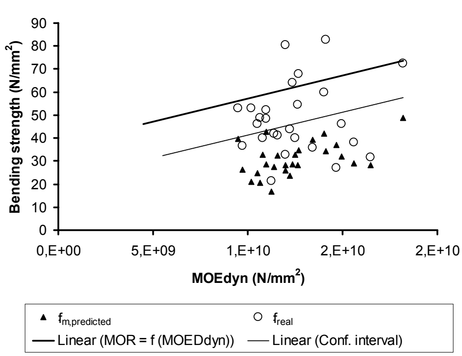

Figure 7: f_m predicted calculated from eqn (3) as compared with real f_m values.

The predicted beam strength, Figure 7, is then obtained from eqn. (2) multiplied by the K_{knot} value. In the following section the results of this approach and of two others will be applied to a case study situation (often found and analysed during timber structures surveys) and the results compared and discussed.

3 Discussion

Consider an old timber floor made from maritime pine timber beams, grade E according to NP 4305 [2], of cross section 150x40mm (depth x with) with a joist spacing of 400mm and a clear span of 3000mm. Some assumptions are made: permanent load of 1.2 kN/m^2 (weight of the beams and flooring boards); imposed load of 2.0 kN/m^2; k_{mod} equal to 0.8 (service class 1 and medium term action); k_{crit} = 1.0; k_{ls} = 1.1; k_h = 1.0. Factors: k_{mod} , k_{crit} , k_{ls} , k_h ; defined in Eurocode 5. The calculation made considered 26 timber beams.

Three approaches will be compared for assignment of bending strength values: 1) VS grading allocation (same strength value allocated to all timber members); 2) Monte Carlo simulation using PDF associated to a particular visual grade (different strength values allocated to different members); and 3) Non-destructive evaluation (NDE) - assignment based on ultrasounds, density and knots measurements (different strength values allocated to different members).

Regarding the second approach, strength values for each beam were estimated using a bootstrap method by taking a sample of 40 values by means of Monte Carlo and considering a Weibull three-parameter distribution (Weibull parameters taken from the fit of the distribution to the VS grade E population), eqn. (3).

$$f_{0.05,Weibull} = \beta + \theta[-\ln(1-0.05)]^{1/\eta} \qquad (3)$$

Table 1 shows the results obtained for the three approaches followed in terms of mean, minimum and 5th percentile strength value.

Taking as characteristic values for each approach the non-parametric 5th characteristic value obtained considering the range of values of the 26 beams tested, Table 2 shows the results comparing the design bending strength ($f_{m,d}$) and the design bending stress ($\sigma_{m,d}$).

Table 1: Reference strength values obtained following the different approaches.

Reference strength values (N/mm^2)	Approach			True value
	VS grading	Monte-Carlo	NDE	
Mean	18	23	31	49
Minimum	18	16	17	21
5th percentile	18	18	21	28

The results indicate a safety index clearly below one if taking the actual strength values of the beams, and under one even if using the approach proposed in the present paper. However if using more conservative approaches the safety

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index goes over one and a recommendation for replacement or reinforcement is foreseen, although looking at the actual strength values those actions seem unnecessary. It should not be forgotten that the analysis performed was simplified and that other aspects (shear stresses and bearing stresses at the supports, as well as at mid-span deflection should be checked against the requirements of EC5).

Table 2: Safety analysis results.

		Approach			True value
		VS grad.	Monte-Carlo	NDE	
Safety index	$\frac{design\ bending\ stress}{design\ bending\ strength}$	1.14	1.11	0.99	0.73

4 Conclusions

Truthful structural safety analysis of old timber structures will only be possible if an accurate tool for assessing strength and stiffness values for individual timber structural members is available.

A proposal is made to use information available about each member using tools as density determination (by probing) and ultrasound velocity as well as information collected in the past on the effect of different features on the strength capacity of timber members. Using these tools the results presented seem to indicate that it is possible to get a more reliable strength prediction of a timber member

However the approach proposed is only based on preliminary results and should be taken as a basis for more thoroughly research in order to validate the results now obtained. For that purpose a research project is ongoing that will bring information about the possibility of validating the results using micro-specimens extracted from timber beams, thermography and NIR.

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