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In situ Evaluation of the Reference Properties of Structural Timber Members. Use of Available Tools and Information

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Abstract. Survey of existing timber structures often includes the need to allocate mechanical properties to structural timber members. This task has to take into account the huge variability of timber's properties (within and between species), characteristic that differentiates this material from other structural materials (e.g. concrete and steel). For many decades, and still now, the application of visual strength standards is the main or only procedure used for this task. Despite the large number of other non and semi-destructive technique developed their regular application to in situ assessment of timber's mechanical properties is still almost non-existent. The present paper discusses possible ways to use and combine information from visual grading standards and non and semi-destructive techniques to predict the reference properties of timber members in service.
The discussion has in mind studies conducted over the last years and the information provided by different guidelines, standards or papers recently published.

Introduction

The assessment of existing timber structures is required in different situations [1]: *rehabilitation of an existing constructed facility during which new structural members are added to the existing load-carrying system; to establish whether the existing structure can resist loads associated with the anticipated change in use, operational changes or its design working life; repair of existing structure which has deteriorated due to time-dependent environments effects or has suffered damage from accidental actions; where the reliability of the structure is in doubt (e.g. earthquakes)*.

This assessment comprehends different steps (according with different strategies, rules or standards) and the evaluation of multiple parameters (related to timber members, joints behaviour and deterioration). The high variability of timber properties and the extreme difficulty in assessing those parameters differentiates timber structures from other types of structures and turns complicated a reliable definition of the mechanical performance of structural members. Visual strength grading (VSG) standards are the most common methods used for predicting timber mechanical performance. Although the limitations of VSG the application of other non-destructive techniques (NDT) and semi-destructive techniques (SDT) is still scarce. Generally they are used to quantify the extension of a defect already detected by visual inspection or to assess timber members concealed by other members (e.g. drill resistance) but not to provide a prediction (quantitative value) of timber's resistance.

Recently several international committees (RILEM, COST E55, COST IE0601) provided some guidance documents for assisting while performing the assessment of existing timber structures [2, 3, 4]. These documents identify two different stages. A first stage referred as preliminary visual survey [3] or phase I [4] relies on VSG schemes, more or less adapted to on service conditions. In the second stage (detail survey of timbers or further inspection) the strategy to be followed is more dubious.

The present paper intends to discuss different types of approaches that can be followed in this second stage for the assessment of properties of structural timber members, the so-called reference properties. The discussion has in mind the possibility of merging data from different sources (methods) and in this way ensuring a cross-validation of that same data. This discussion will have in mind that assessment can be global (including system effects and joints) or local (timber member individually). In this last case, a timber member can be seen as a homogeneous element (properties ruled only by the worst defect) or as a heterogeneous element showing lengthwise variation of mechanical properties, Fig. 1a, according with the model proposed by [5]. Reference properties include bending strength, bending modulus of elasticity and density [6], Fig.1b. These properties are used for allocating strength classes to VSG standards in the European standardization [7].

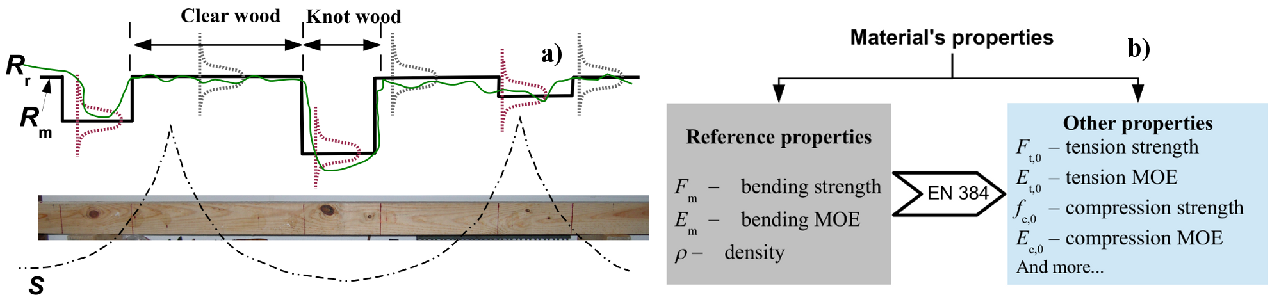

Figure 1. a) Model used as representation of a timber member (S – load; R_m – Simplified resistance profile; R_r – Real resistance profile); b) Reference and other properties of structural timber members

First stage – A preliminary survey of timber members

Visual inspection is the first step while assessing a timber structure, Fig. 2. This inspection intends to verify/determine: overall condition of the structure; moisture; geometric dimensions; damage; distortion; cracks; alterations to initial structure; general mechanical properties of timber members; joint's characteristics.

During this stage a first allocation of mechanical properties to timber members is made. This allocation is usually done using available data used for the design of the structure and/or VSG. Unfortunately in most cases no design values exist and only VSG can provide information about the general quality of timber members. Two documents provide guidelines to assist in applying visual grading in situ – [4, 8]. For this task it can be used VSG standards based on characteristic values (complying with [9]) or based on allowable stresses.

The application of VSG to timber members on service raises some concerns that should be taken into consideration:

- VSG standards are restricted to a wood species from a given provenance [7].
- VSG is prone to human error (generally acceptable as 10%).
- It is often impossible to inspect (totally or partially) all faces of the members. This condition turns difficult/impossible the full application of predictors as KAR for knots or rate of growth for density.

Regarding the first issue, it is assumed that timber member's properties are equal to those from another existing population (visual strength grade specific for the same wood species but probably from another origin). Recent results showed that application of VSG rules to species originated from another region can in some particular cases delivered non-conservative characteristic values [10]. Regarding the second concern, the survey process and decision about the properties of timber members depends of experts experience and availability of information and equipments.

The last concern and the fact that some features included in VSG standards do not have a direct impact on strength (e.g. warp) led to simplified VSG rules [3, 4, 11]. One example is the proposal for on service grading of Portuguese maritime pine that includes only one grade corresponding to strength class C14. The lower VSG (grade E) included in Portuguese standard for the same species corresponds to strength class C18. Considering the bending test results corresponding to 450 ungraded beams (100 x 40 x 2000 mm^3) of maritime pine only 5.1 % do not fulfil the conditions of C14. After removal of pieces rejected for structural applications (not fulfilling grade E) the number of pieces graded as C14 are 0%.

The different concerns mentioned and also graders precautions imply that application of VSG standards to timber members on service often delivers over conservative design values.

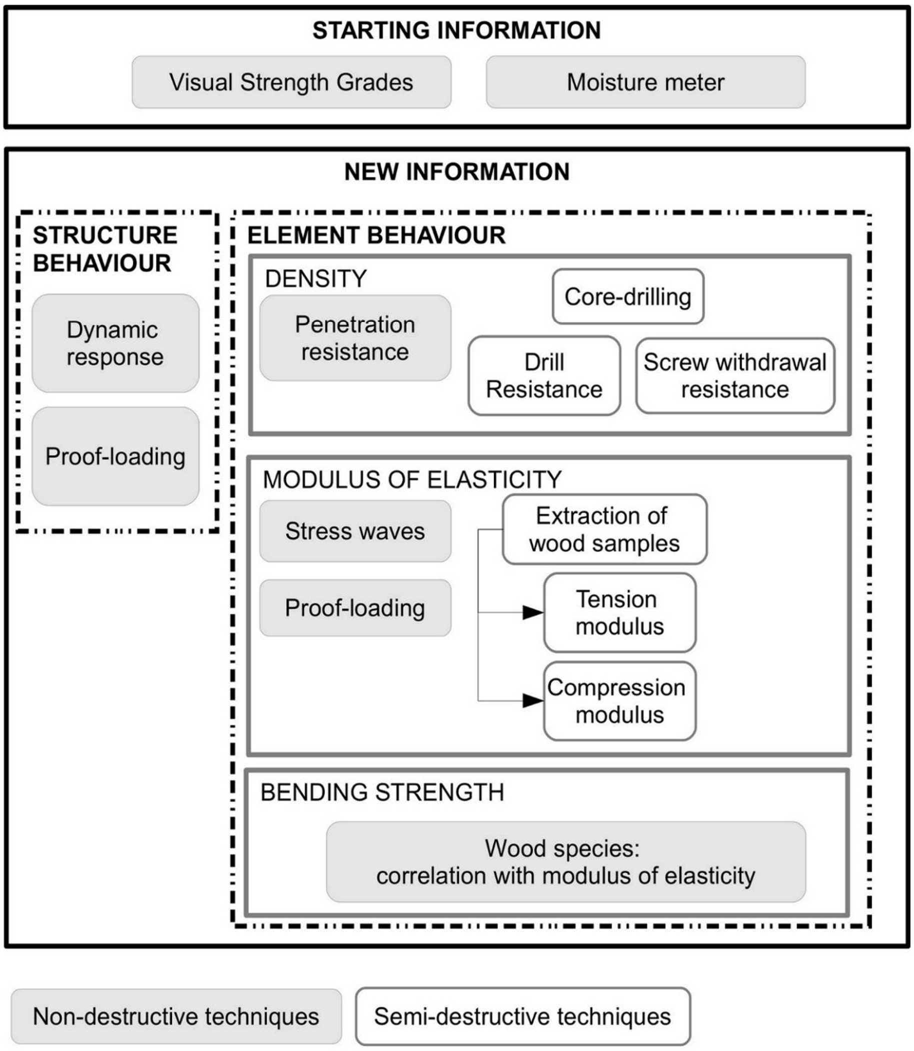

Figure 2. NDT/SDT for assessment of the reference properties of structural timber members.

At the end of this stage the reference properties is usually addressed to a particular strength class. At this stage also a moisture meter (NDT) is used since reference properties and biological deterioration is dependent on timber's moisture content. As summary, Fig. 3 shows the information that can be collected during the preliminary survey.

The information obtained allocates a general quality (visual grade) to all timber members and permits to carry out a preliminary safety and serviceability evaluation by application of semi-probabilistic codes as Eurocode 5 [12].

From this first stage two scenarios came out:

1. structure is considered fit for use and no more survey is needed to be carried out;
2. structure is considered not fit for use. In this case a decision has to be taken either to demolish (replacement by a new structure) or to carry out a more detail survey (possible considering reinforcement works).

In the majority of cases prediction of timber's mechanical characteristics based on VSG application led in general to over conservative predictions and so to the second scenario. The decision to carry out a detailed survey (2nd stage) is generally taken when: the structure is a heritage cultural asset or; the structure is in service for many years without showing a significant damage or deformations.

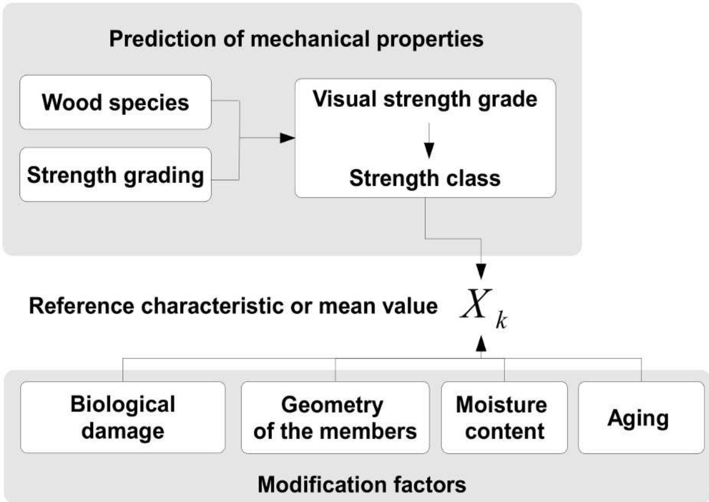

Figure 3. Factors used in a preliminary survey to assess the reference properties of timber members on service

Second stage – Detail survey of timbers

Detail survey is carried out on critical areas identified by structural analysis performed after the preliminary survey. A two steps procedure can be followed: first by improvement of visual grade by taking into consideration defects showed by each individual member and type and location of defects as regards stress and structural member type [4]. This procedure takes into account the low probability that the worst defect will be located in the highest load stress area, Fig. 1a). Also the possibility of load-sharing system effect can led to an increase of 10% on timber's mechanical properties [4]; second to apply other NDT/SDT to update the information obtained from VSG, Fig. 2.

Grading of timber members in an individual basis. VSG standards are based on independent variables (e.g. knot size, rate of growth, slope of the grain) showing a weak correlation with the different reference properties. Therefore in the case of VSG developed according with [9] there is no safe procedure to modify grade's characteristic values (except if raw data used for defined visual grades are available). Thus visual grading at this stage can only move a timber member to a higher strength grade if it exists in the standard. In the case of VSG developed under the principles of allowable stresses the improvement of characteristic values can be obtained in a more flexible way. However in this case the issue of conversion of strength values (from allowable stresses to characteristic values) has to be discussed.

The second stage can end after this second visual observation of timber members features. The new information can be used to perform a more reliable structural analysis.

However, as stated before, in some situations VSG cannot provide any additional information. Then the use NDT/SDT is the only option to confirm or adjust (update) the results obtained from visual grading and in this way deliver more reliable predictions about the reference properties of timber members. Existent reports [2, 3] present vast information about the NDT/SDT available but limited information about the way to combine information from NDT/SDT and visual grading.

In the next sections the combination of NDT/SDT in support of visual grading for assessing the reference properties of timber members will be discussed.

Density. For density the usual SDT available are core-drilling, resistance drilling, penetration resistance and screw resistance [2]. These techniques are classified as local test methods (LTM) [13] being necessary to consider the uncertainty of the measurement and the variability within timber member. Core-drilling is the only of these techniques that can provide a direct measurement of density but it shows as limitation a high level of destruction and aesthetical impact.

Resistance drilling presents in general a weak correlation with density showing a range of coefficients of determination between 0.21 and 0.69 [2]. Screw resistance is claimed to have a good correlation with density [14]. These two last techniques are strongly affected by operation factors (e.g. wood moisture content, equipment and testing procedure).

More accurate predictions can be obtained by merging information from a direct measurement of density (core-drilling) with an indirect measurement (through regression analysis) of density (screw and drill resistance).

As an example, core-drilling can be used to calibrate the indirect measurements obtained from drill resistance. After calibration (using a limited amount of samples) the lesser destructive technique (drill resistance) can be used in the same or other timber members assuming that all timber members are alike (e.g. moisture content and wood species). At this point as for VSG adjustments [4] it should be taken into account the type of structural members. In case of members subject to bending density prediction of the superficial layer of the member (≈ 1/4 of the thickness) is sufficient whereas for members subjected to compression or tension it is necessary to predict the density of overall cross-section. Therefore the type of structural members is a factor to consider when deciding the length of the wood core to be taken for calibration.

The calibration in situ avoids the use of pre-existent regression curves that most of the times are linked to operation conditions not possible to replicate in situ. However other source of uncertainty is affected since in situ calibration is associated with a limited sample size.

The use of core-drilling shows also as advantages the possibility to: determine moisture content (direct measurement); identify wood species; determine mechanical properties (direct measurement).

Modulus of elasticity. Different methods are used to determine or predict the modulus of elasticity of a timber member: Ultrasounds (NDT), proof-load test (NDT), dynamic response, tension test (SDT) and compression test (SDT).

Dynamic response and proof-loading are generally used to assess the behaviour of a structural system e.g. timber floors [15], though proof-loading can also be used to assess the behaviour of a structural member [16]. However, proof-load can only be used (for safety reasons) after previous information about the expected resistance of the structure, that means taking into account a preliminary structural analysis. Regarding dynamic response this technique can be used to confirmed or update the properties of timber members and joints predicted at the preliminary survey. Nonetheless, in the majority of situations proof-load and dynamic response techniques are not possible or are not used.

The mainstream involves the application of stress waves to obtain an indirect measurement of modulus of elasticity. For this purpose correlation between static modulus of elasticity and velocity of propagation of sound or dynamic modulus of elasticity is used. In situ often not all faces of the element will be available for inspection (condition that also affects VSG reliability) and therefore direct methods through propagation across the fibres or indirect methods (application of probes in the same wood surface) have to be used.

As for density it is important that a validation/support can be obtained from destructive tests (direct measurement). For that purpose it can be used small wood samples for performing tension or compression testing parallel to the grain [2, 17]. This wood samples are extracted from clear wood zones and so the modulus of elasticity can only be reported to these zones. Tension, compression and bending modulus of elasticity can be considered similar for clear wood zones. The extrapolation of the modulus of elasticity from clear wood zones to timber member, Fig. 1a, can be done assuming that elasticity is a global measurement of quality: where clear wood properties shows a significant higher contribution for this parameter than knot zones. However, when a low visual grade is allocated to the timber member it could be expected a significant influence of knots on the modulus of elasticity.

These destructive test results are LTM (variability within member has to be taken into account) and only represents the external layer of timber which can be sufficient in the case of timber members subject to bending but not so in other load cases (compression and tension).

Data analysis can be done by combination of information from two methods [10] or using destructive tests for local calibration of dynamic modulus of elasticity and then apply the same calibration curve to stress waves measurements done at other locations in the structure [2]. All these predictions are associated with a certain level of uncertainty which is in part linked to sample size, Fig. 4.

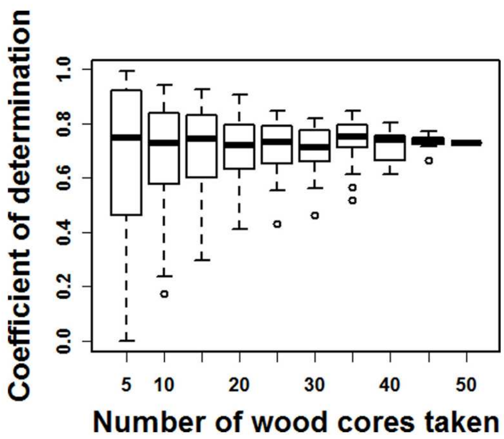

Figure 4. Influence of sample size on the variability explained by the regression curve (measured by the coef. of determination)

Bending strength:

Bending strength can be predicted through a global (all beam tested at the same time) or local approach (models as the one shown in Fig. 1a). Global evaluation can be done using the principle of machine strength grading, i.e. correlation between bending strength and modulus of elasticity (coefficient of correlation between 0.6 and 0.8 – medium correlation). This procedure can be adopted either from dynamic response or proof-loading tests or using the predicted modulus of elasticity for clear wood zones.

However, when a low visual grade is allocated to the timber member it could be expected a significant influence of knots on the modulus of elasticity. In this case the mean value provided by the regression curve should not be used but instead it should be used as prediction of bending strength the value correspondent to a lower alpha confidence interval curve. As in other situations the decision about using or not this kind of approaches (e.g. which alpha to apply) is an exclusive decision of the expert responsible for conducting the survey.

An alternative approach is based on models similar to the one in Fig. 1a. In this case a basic quality is defined by clear wood zones and ultimate load (f_{m}) is predicted based on strength-reduction factors (k_{knot}) dependant upon knot's dimension.

$$f_{\mathrm{m}} = f_{\mathrm{m,c}} \times k_{\mathrm{knot}} \,. \tag{1}$$

Bending strength of clear wood zones ($f_{m,c}$) can be predicted using the equation provided by EN 384 [17]) knowing the tension strength, Fig. 5. A medium correlation between tension parallel to the grain and bending strength of clear wood zones was obtained from the extraction of 109 tension specimens from forty maritime pine timber beams [18].

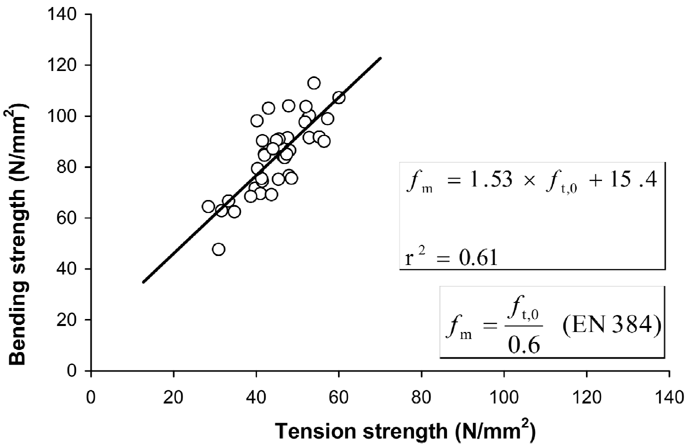

Figure 5. Prediction of bending strength from tension strength according with equation of EN 384

Other factors: In addition to the short-term evaluation it must be borne in mind that medium, long-term behaviour of timber structures is also dependent upon time variant defects (e.g. fissures and decay).Visual assessment can provide valuable information about fissures extension and possible effect upon reference properties. Also knowledge that large cross-section of boxed heart timber members were usually place in service at a green condition explains (drying process) gross checks usually found in historic timber structures. However some lack of information about how to assess fissures long-term stability seems to exist. Decay can evolve if the moisture conditions remains after survey. The loss of cross-section due to decay at the moment of the survey can be used by probabilistic models to foreseen the safety and serviceability in the short and medium-term [19].

Data analysis: Different types of uncertainties are involved in the process of predicting the reference properties of timber through NDT/SDT. For this reason a multiple approach is proposed (different techniques supplying the same property). This multiple approach aims to increase the accuracy and robustness of the prediction and to validate the values obtained. As a first step meta-analysis should be used to verify the consistency of the values obtained by two or more techniques. For merging the information different approaches can be followed (e.g. regression analysis, meta-analysis, bayesian analysis). Once established the validity of the new information bayesian inference can be used to joint this information with the one obtained by VSG (prior information) thus providing a posterior distribution of probability [3]. The update reference properties can then be used by probabilistic models [1]. These models show the advantage to cope more easily with inherent random variability or uncertainty, uncertainty due to inadequate knowledge and statistical uncertainty.

Summary

Recent publications [2, 3, 4] offers a systematic view about the assessment of timber structures covering aspects as: survey approach; state of the art regarding the different NDT/SDT techniques, including types of equipments available, applications and limitations; statistical tools that can be used for updating variables. However a gap still exists concerning gathering together all the information from survey (VSG along with NDT/SDT) and providing quantitative values that could be used by analytical and probabilistic structural models. This gap is acknowledged by COST Action FP1101 *Assessment, Reinforcement and Monitoring of Timber Structures*. In this paper some possible approaches are presented to combine information from visual grading and NDT/SDT for predicting timber's reference properties.

References

[1] ISO 2394:1998. General principles on reliability for structures. International Organization for Standardization.

[2] B. Kasal, T. Tannert (Eds), In situ assessment of structural timber, Springer, 2010.

[3] P. Dietsch, J. Köhler (Eds), Assessment of timber structures, Shaker Verlag, 2010.

[4] H. Cruz, D. Yeomans, E. Tsakanika, N. Macchioni, A. Jorissen, M. Touza, M. Mannucci, P.B. Lourenço, Guidelines for the on-site assessment of historic timber structures: accepted for publication in the International Journal of Architectural Heritage.

[5] H. Riberholt and P.H. Madsen. Strength distribution of timber structures. Measured variation of the cross sectional strength of structural lumber. Technical University of Denmark. Rapport nº R114. 1979.

[6] JCSS, Probabilistic Model Code, Joint Committee of Structural Safety. www.jcss.ethz.ch, 2001.

[7] EN 1912:2012, Structural Timber. Strength classes. Assignment of visual grades and species.

[8] UNI 11119: 2004. Cultural Heritage. Wooden artefacts. Load-bearing structures – On site inspections for the diagnosis of timber members. Nazionale Italiano di Unificazione.

[9] EN 14081-1:2011, Timber structures. Strength graded structural timber with rectangular cross section. Part 1: General requirements.

[10] J.S. Machado, P.B. Lourenço, P. Palma, Assessment of the structural properties of timber members in situ – a probabilistic approach, in: SHATIS'11 International Conference on Structural Health Assessment of Timber Structures, Lisboa, 2011.

[11] R.D. Anthony, K. D. Dugan and D. J. Anthony, A grading protocol for structural lumber and timber in historic structures, APT Bulletin: Journal of preservation technology 40 (2009) 2-9.

[12] EN 1995-1-1:2008, Eurocode 5: Design of timber structures. Part 1-1: General - Common rules and rules for buildings.

[13] P.B. Lourenço, A.O. Feio and J.S. Machado, Chestnut wood in compression perpendicular to the grain: Non-destructive correlations for test results in new and old wood, Construction and Building Materials 21 (2007) 1617-1627.

[14] Z. Cai, M.O. Hunt, R.J. Ross, L.A. Soltis, Screw withdrawal – A means to evaluate densities of in-situ wood members, in: 13th International Symposium on Nondestructive Testing of Wood. F.C. Beall (Ed.), University of California, 2002.

[15] R.J. Ross, M.O. Hunt, X. Wang and L.A. Soltis, Floor vibration: A possible assessment method for historic buildings, APT Bulletin: Journal of preservation technology 32 (2001) 23-25.

[16] M. Riggio, R. Tomasi, M. Piazza, Rufurbishment of a traditional timber floor with a reversible technique: the importance of the investigation campaign for the design and the control of the intervention, International Journal of Architectural Heritage: Conservation, Analysis, and Restoration (published online 23 April 2012).

[17] EN 384:2010, Structural timber. Determination of characteristic values of mechanical properties and density.

[18] J.S. Machado, P. Palma, Predicting the mechanical behaviour of solid pine timber elements through non and semi-destructive methods, in: 11th World Conference on Timber Engineering, Riva del Garda, Italy, 2010.

[19] R.D. Brites, L.C. Neves, J.S. Machado, P.B. Lourenço, H.S. Sousa, 2013, Reliabiliy analysis of a timber truss system subjected to decay, Engineering Structures 46 (2013) 184-192.