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COMBINE USE OF NDT/SDT METHODS FOR ASSESSMENT OF STRUCTURAL TIMBER MEMBERS

Editors:

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Reliability of prediction by combining direct and indirect measurements

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Abstract

Several non and semi-destructive testing (NDT and SDT) methods have already been developed for in situ assessment of structural timber member's properties or deterioration level. The use of these methods as auxiliary tools to the traditional visual strength grading method can only be current if a fully comprehension of their limitations and reliable exploitation of their possibilities is achieved.

This chapter discusses the possibility of obtaining more reliable predictions by combining information from NDT and SDT methods taking into account possible sources of uncertainty. SDT methods can provide direct measurements of a desired wood's property (e.g. density or mechanical properties) and then be used to cross-validate the information obtained from indirect measurements (e.g. drilling resistance, stress wave velocity). The discussion is based on an example of prediction of bending modulus of elasticity through the combined information obtained from a stress wave NDT and a tension SDT method.

Introduction

Structural timber members present a high variability of properties (between and within members) being influenced by various variables. Among these variables wood species, density, defects and moisture content are the ones mostly taken into account during the survey of timber structures. Considering the large spectrum of variables involved and the difficulties in assessing their influence on the global mechanical behaviour of a structural timber member, several non and semi-destructive testing (NDT and SDT, respectively) methods have been developed. The description and limitations of these methods were already analyzed in recent reports [1, 2].

Visual strength grading (VSG) was the first NDT to be developed and is still the basic tool used in the assessment of timber structural members. VSG provides reliable results (meaning over conservative) and a long-term experience of its application in situ. However these over conservative values lead often to the demolition of structures showing no signs of damage or deformation after several years (in some cases centuries) in service. To support expert's decision other NDT and SDT methods were developed as auxiliary tools to VSG for the allocation of more reliable (meaning closest to the real value) mechanical characteristics to structural timber members in situ. However several shortcomings explains why their applications is limited and the final decision is still based solely on expert's opinion and application of a simplified set of visual rules.

NDT and SDT methods can be differentiated based on the type of information provided:

- Local (limited to a small volume of the element) or global (all volume of the element).
- Direct measurement or an indirect measurement of the desired property (density, strength, stiffness).
- Qualitative or quantitative measurements.

In the present chapter direct methods are the ones that provide a direct evidence of the mechanical or physical property of a wood member under examination. This definition includes methods that although providing a direct reading will require further information in order to extrapolate local to global behaviour. Other meaning is found in literature considering direct methods those not involving the need for empirical models (e.g. tension of micro-specimens) [3]. Direct methods can include the removal or not of wooden material. Proof-loading is an example of a NDT method capable of deliver a direct measurement of the global modulus of elasticity of timber beams in service [4]. However this method can only be applied in certain situations [5].

In some cases the removal and testing of structural members in the laboratory provides a direct information that can increase the reliability of NDT/SDT predictions. However this destructive procedure is dependent upon the possibility of removal of timber members (e.g. not suitable in historic structures) and results have again to take into account the gross wood's variability between members.

Direct assessment of physical and mechanical properties can be obtained by some SDT [6]. Indirect methods (NDT or SDT) are frequently applied in situ based on uni or multivariate empirical models (e.g. regression analysis) linking indirect measurements (e.g. ultrasonic modulus of elasticity, drilling resistance) to desired properties (e.g. static modulus of elasticity, density). Unfortunately on most cases the existent regression models are characterized only by its coefficient of determination and nothing is mentioned about the uncertainty of the different models.

Wood complexity and general difficulties associated to performing measurements in situ require a careful planning of the inspection works. This should begin always by settling on the property or properties to predict. Given a certain property the second step includes the choice regarding: NDT&SDT methods to apply; locations of testing; number of data to obtain from each method; and, suitable data analysis procedures.

Regarding data analysis it should be considered the restrictions regarding extraction of samples which only allows that only a few samples can be obtained and analyzed (small sample size). Also the majority of NDT and SDT methods provide local properties and only concern clear wood properties. For the prediction of the global behaviour of a timber member these information needs to be combined with information from defects (mostly knots and slope of grain).

The present chapter discuss the possible improvement of the reliability of predictions based on the combination of NDT and SDT methods.

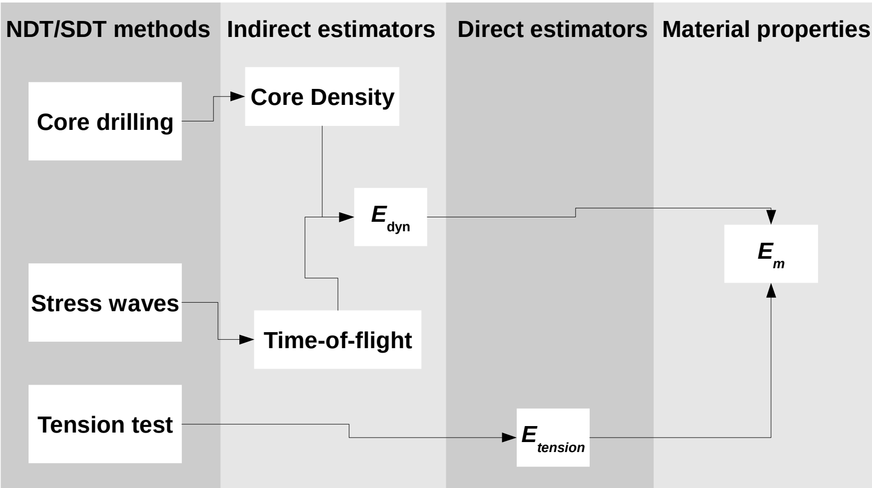

Fig. 1. NDT&SDT methods used for predicting the static modulus of elasticity. E_{dyn} – Dynamic modulus of elasticity; E_{m}– Bending modulus of elasticity

Core drilling (SDT), stress waves (NDT) and tension tests (SDT) are used as example for the discussion, Figure 1. The use of these methods for the prediction of two reference properties (density and modulus of elasticity) is analysed taking into account possible sources of errors, the effect of small sample size, the high spatial variation of properties inside a timber member and possible error propagation.

Joint use of direct and indirect measurements

As for other material a more precise and accurate assessment of timber members in situ can be achieved by joining information from different sources [7]. This combination of information can be done by:

- considering both as independent variables in a common empirical model (e.g. multiple regression analysis);
- using direct readings to calibrate the indirect readings made in situ. This calibration includes validation of prior regression models as well as to quantify adjustment factors (e.g. wood moisture);
- using both data as independent predictions of the property – possibility of cross-validation of the prediction.
- using first a fast technique as a preliminary screening of the structure followed by a second time-consuming technique in areas selected from the results of the first technique (e.g. thermography followed by drilling resistance for assessing presence and extension of decay).

Although considered above as autonomous paths they can in fact act together.

Uncertainties involving in situ evaluation

Whatever the path followed it must be bear in mind that predictions are always affected by errors, including aleatory (high spatial variability inside a timber member – within the cross section and length) and epistemic errors (lack of knowledge on the material or models, associated to the test method and human errors). These errors lead to a certain degree of uncertainty of the prediction made using NDT and SDT "…the estimate of even single parameters using established methods can be contaminated by significant errors and caution must be exercised in interpreting experimental data." [8]. The awareness of the type of error is only important as a mean to recognize what are the possibilities to diminish the amount of error. In the assessment of existing elements the uncertainty can be considered as epistemic (the errors are only due to our incapacity to get the necessary information, to deal with human errors or to apply the correct test methods) [9].

Wood's variability (aleatory error) can as a rule of thumb be considered known using the values provided in Table 1. These values should be regarded as start up values possible to be adapted to any particular situation (type or quality of wooden members, amount of information possible to be collected on site).

Table 1 Coefficients of variation for clear wood and structural timber

Property	Clear wood [10]	Structural timber [11] 1)
Density	10	10
Tension strength parallel to grain	25	30
Bending strength	16	25
Compression strength parallel to grain	18	20
Modulus of elasticity in bending	22	13

1) Values for European softwood and corresponding to a number of tests equal to 10

This uncertainty is always present since the number of samples or measurements possible to be made are limited and the extrapolation process (local to global assessment) is always complex given the nature of a timber member – heterogeneous, anisotropic and hygroscopic.

The limitations associated to the different NDT and SDT methods usually applied are described in a recent report [2].

Uncertainties associated to NDT/SDT methods

Density prediction using core drilling

Density is an important property given his positive direct impact in the strength and stiffness of wood. Some of issues involved in the determination of density in situ are discussed in [8]. It is also used to predict the modulus of elasticity through the determination of the dynamic modulus of elasticity. Density can be predicted using core drilling (SDT), drill resistance (SDT), penetration resistance (SDT) and pull-out resistance (SDT) [12]. The accuracy and precision of density's prediction model is strongly dependent on the variability showed by each individual timber member. Density's variation occurs along its length and within the cross-section (width and depth). The error of prediction can be partially dealt if the NDT or SDT method is applied taking into consideration important characteristics of the member (namely wood species, growth ring pattern and spatial variation inside the member) and if a sufficient number of readings are collected. Statistical models allow having an estimative of error as function of the number of readings collected, Figure 2. However this error is underestimated since it does not consider a possible spatial variation which usually occurs in wood. Consequently the sample size effect on error given by models as the one illustrated in Figure 2 only provides guidance for maintaining a certain level of precision and does not ensure the accuracy of our prediction.

Core drilling is a multifunction SDT method capable of providing information about wood species, moisture content, strength and density. The determination of density of core samples can be done according with standard procedures. Since the number of readings is limited (due namely to level of destruction made to the timber member) and considering the level of variability that can be found in a sole timber member the reliability of density's prediction is highly dependent on: the number of readings; and, the way they are carried out in order to ensure a proper representativeness of the material under observation. Therefore the accuracy of this SDT method depends strongly on expert decision about where to extract and the length of the cores whereas precision are more related with the number of cores extracted.

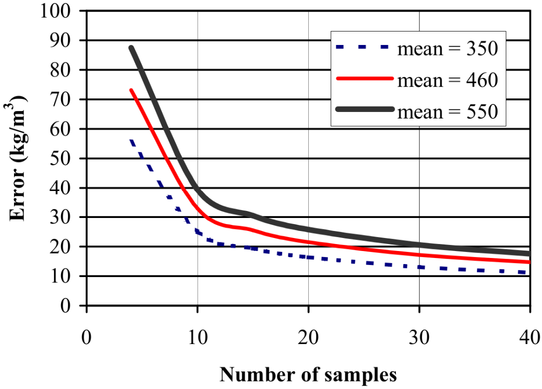

Fig. 2. Error as function of sample size and mean density (coefficient of variation of 10%) [13]

To illustrate consider a timber member with a cross-section 304 mm x 148 mm and two possible annual ring patterns (quarter-sawn and boxed heart). A quarter-sawn pattern (A) can be considered closest to a homogeneous section. In this example the density of each layer of latewood and earlywood is randomly generated assuming a normal density probability function using data taken from [14]. No lengthwise variation is assumed. A collection of four cores taken perpendicular to the grain and with different depths was simulated.

A boxed heart pattern (B) shows a cross-section variation of density was considered from the pith to the surface. Also no lengthwise variation was considered. In old timber structures large cross-section usually contains the pith inside showing an annual growth ring pattern similar to case B. For this case a comparison was made between taking four wood cores from the edges or taking two from the edges and two from the faces.

For all cases a bootstrap method was applied running 10000 iterations. Figure 3 shows the result of the different simulated cases. Figure 3 shows the importance to take into account the variation of properties inside a timber member in the prediction of density by a core drilling method. Depending on the type of growth ring pattern, cross-section variability and type of core samples (depth and extraction procedure) density prediction's error can vary in average from 0% to 15%. An estimation of the lengthwise and cross-section variability can be obtained by using another SDT method – drilling resistance. The variation of growth ring width is another source of variability not taken into account in the present simulation.

Density values are affected by moisture content and thus wooden cores they can be dried and moisture content determined for carried out the necessary corrections. The need to apply correction factors are always a difficult issue being address in another chapter of the present publication [15].

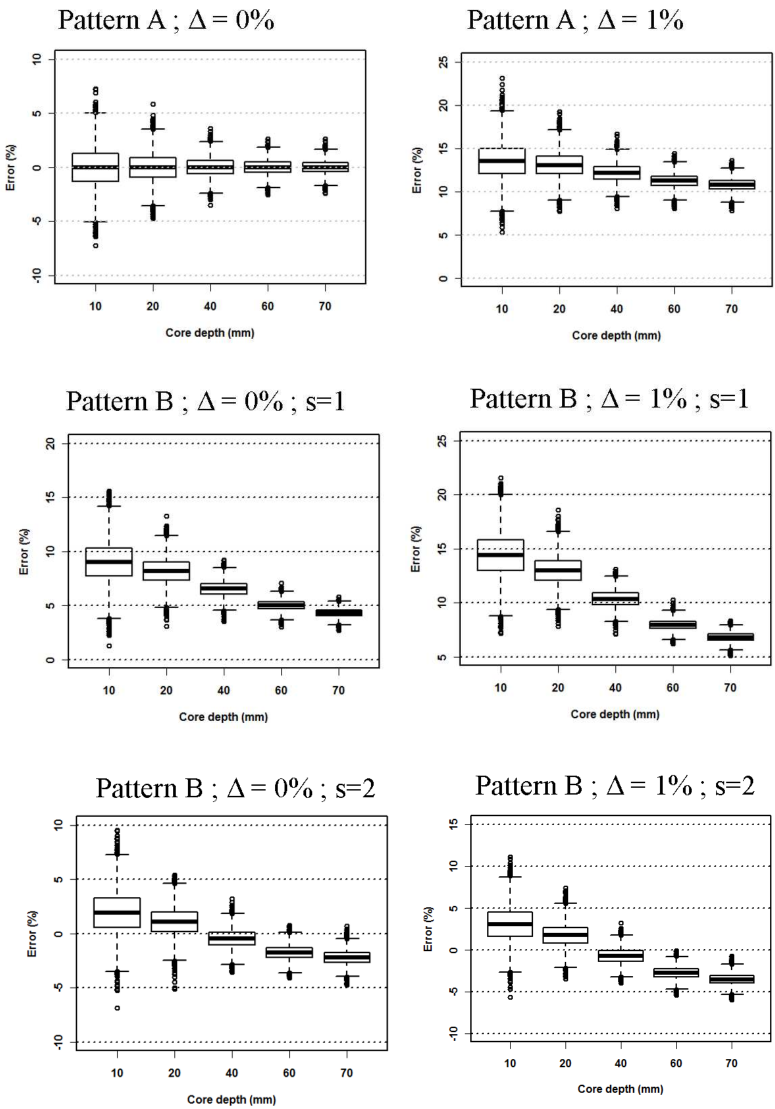

Fig. 3. Estimated error associated with density prediction through core drilling. Δ - cross-section variability; s – type of sampling (1 – all samples taken at the edge; 2 – two samples taken at the edge and other two on the faces)

The accuracy in density's prediction is important since this variable will be used for predicting the dynamic modulus of elasticity or directly the mechanical properties.

Other NDT/SDT methods for predicting density are available being some described in other chapters [16].

Modulus of elasticity prediction using stress waves

Static modulus of elasticity can be predicted by tension and/or compression tests (SDT) [17, 18], dynamic response (NDT) [19], stress waves (NDT) and load test (NDT) [12].

The prediction of the static bending modulus of elasticity (E_m) is usually obtained in situ using the correlation with the dynamic modulus of elasticity (E_{dyn}), regression equation below.

$$E_m = a + bE_{dyn} + \varepsilon$$

The dynamic modulus is obtained by applying stress waves NDT methods in situ. Information about the use of stress waves for in situ assessment of structural timber can be found in [12]. Wood is an orthotropic material being the equations of motion for bulk waves given by Christoffel's equation [13]. However considering the complexity of wood material and the experimental conditions on site a simplification is made and it is applied the equation for isotropic solids and obtaining a prediction of the dynamic modulus of elasticity (E_{dyn}) as showed above.

$$E_{dyn} = V^2 \rho \left(\frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} \right)$$

Considering the complexity of determining in situ the Poisson's ratio the above simplified equation is generally applied.

$$E_{dyn} = V^2 \rho K$$

Assuming $K = \left(\frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} \right) = 1$

The component of the equation regarding the coefficient of Poisson is considered a determinist value. The use of this equation is supported in different studies. Considering the values given in Table 2, for a stress applied along the grain a mean *k* value could probably be found between 0.39 and 0.57. Nevertheless since the uncertainties surrounding *k* factor (random) are merged with other uncertainties (density and TOF measurements) and taken into account by a final regression curve the real value of *k* is not significant.

Table 2 Average Poisson's ratio for Softwoods and Hardwoods [22]

Coefficient	Softwood	Hardwood
v_{LR}	0.37 (0.06)	0.37
v_{LT}	0.42 (0.07)	0.50

v_{ij} – ration for deformation along the j axis caused by stress along the i axis

TOF determination can be affected by: the lack of proper coupling between transducers and wood (wood surface roughness, lack of coupling agent); slope of grain or presence of other defects; uncertainty about wave path length [23, 24]. To minimize the error several readings (at least 5 [20]) should be carried out along the length of the beam.

Regarding density small samples can be taken from timber members for determination in the laboratory. This procedure can be done through core drilling as seen in the previous section and possible errors associated were already mentioned. Finally TOF should be corrected accordingly with the temperature and moisture content of the beam.

The combine information from stress waves and core drilling provide a prediction of the dynamic modulus of elasticity (E_{dyn}). Once obtained the dynamic modulus of elasticity a prediction of the static modulus of elasticity is generally done by applying empirical models (regression curves). The correlation between this two variables can varied from 0.58 to 0.96 depending upon the dimension (clear wood or structural wood), treatment and age of timber specimens [24].

Modulus of elasticity prediction using tension strength tests

Modulus of elasticity parallel to grain shows moderate dependence to type of loading being a common value used for design of timber structures. However the modulus of elasticity in compression is lower that in bending which in turn is lower than in tension [25] for structural timber elements. Nevertheless it can be considered independent of the load involved for clear wood specimens [25].

Information about the modulus of elasticity in bending of clear wood can then be obtained from tension tests carried out on small samples removed from timber members in situ [6]. This information although limited in terms of possible number of tests when compared with the possible readings obtained from stress waves can nevertheless provide us the possibility to: validate the values obtained from the indirect method; and, increase the reliability of our prediction.

Combining information from indirect and direct methods

To illustrate different options for combining information obtained from direct and indirect methods data from previous works will be used [26]. In these studies density and modulus of elasticity were obtained using the SDTs and NDT methods aforementioned.

However before trying to combine this information they should be careful analysed. A forest plot (Figure 6) can be used to evaluate if the results of both tests are consistent (values ranging in a similar interval).

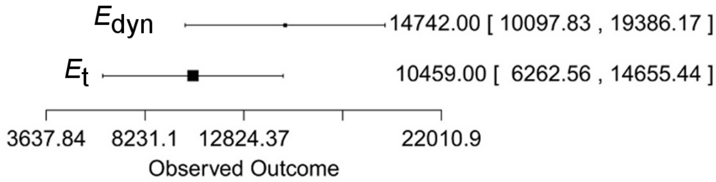

Fig. 6. Forest plot showing the mean and 95% confidence intervals for the results obtained from E_{dyn} and E_t (values in N/mm^2)

The result obtained allows us to consider that the data obtained from the two testing methods although not coincident can be accepted as being coherent. Unfortunately the values obtained from these two methods showed a high correlation coefficient (r^2 = 0.85) representing a possible conflict with one of the assumptions of regression analysis (independency of independent variables). The questions related with excessive multicollinearity does not have any standard metric and so it is a decision of the expert to make about using or not a multiple regression model in this circumstances.

In the present case a Meta-analyse technique is used and the combining of information is made trough an inverse variance method, see equation bellow.

$$E_{comb} = \omega_1 \times E_1 + \omega_2 \times E_2 + ... + \omega_n \times E_n \quad \text{and} \quad \omega_i = \sigma_i^{-2} \Big/ \sum_{k=1}^{n} \sigma_k^{n}$$

Where n estimators of the variable E are combined as a weighted average according with their variance (σ).

The combined predicted value can then be used as explanatory variable (E_{comb}) in a simple regression model. Two models are then available for predicting E_m: one as function of E_{dyn} (r^2 = 0.72); and, the other as function of a combined value E_{comb} (r^2 = 0.77). The two models are very close in terms of capacity of explained the E_m variability. These regression models assumed that independent variables are measured without errors and the error is only associated to the dependent variable [27]. However for the present analysis it will be taken into account also the uncertainty related with the independent variables (E_{dyn} and E_{comb}), scenario more close to reality. For that purpose a Bayesian analysis applying a Markov Chain Monte Carlo (MCMC) method is used to drawn inferences about the models and parameters. MCMC algorithms generate a Markov chain sequence of parameter values (the values at a given state of the chain depends only upon the previous state) being these parameters generated randomly (Monte Carlo). MCMC was carried out by running Winbugs inside R software trough R2WinBUGS package (1 chain, 1000 burn-in iterations, 9000 used iterations). Figure 7 shows the prediction for beam P20 and P21.

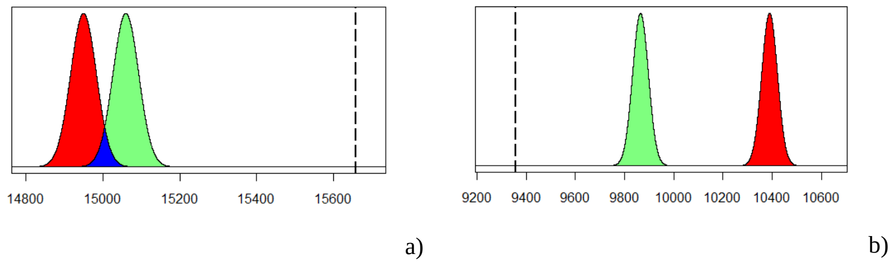

Fig. 7. Predicted E_m distribution for: a) beam P20 and b) beam P21, using model $E_m(E_{dyn})$ – red – and model E_m (E_{comb}). Real stiffness showed in the graphs by a dashed vertical line

For both beams considering the uncertainties of the variables it is clear that a closer approximation to the real stiffness is obtained using the combined information.

Final remarks

Assessment of timber structures is always done by crossing information from different sources. However this process is generally based on a series of individual results obtained from different NDT/SDT methods and that the expert uses to take an informative decision about the structural health of the structure. The possibility of combining in one single model the information provided by two independent methods, as for other materials (e.g. concrete), can lead to a more reliable prediction of that property. The need to consider the uncertainties associated to each test method, the need to understand the assumption behind a particular statistical model and finally the need to asses the robustness of the final model are also matters that should be considered.

The complexity of wood makes that any final decision relies heavily on the expert capability of extracting valuable information from the test methods applied, his/her experience and particular conditions regarding the structure under inspection. This heterogeneous information (qualitative and quantitative) makes bayesian methods a suitable data analysis method to be applied.

References

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

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

[3] Kasal, B (2013) Structural health assessment of in-situ timber – Am interface between service life planning and timber engineering. In 9th Meeting of Northern uropean Network for Wood Science and Engineering (WSE). Leibniz University of Hannover. Brischke, C. & Meyer, L. (eds). p. 157-164.

[4] Riggio M, Tomasi R, Piazza M (2014) Refurbishment of a traditional timber floor with a reversible technique: Importance of the investigation campaign for design and control of the intervention. International Journal of Architectural Heritage 8:74-93.

[5] Srpčič J (2010) Load tests (Proof Loading). In: Dietsch P and Köhler J (Eds) Assessment of timber structures, Shaker Verlag GmbH, Aachen, p 96-99.

[6] Kloiber M, Drdácký M (2014) Prediction of mechanical properties by means of semidestructive methods. In J S Machado, Mariapaola Riggio and Artur Feio (Eds) Combine use of ndt/sdt methods for assessment of structural timber members, p ….-,…..

[7] Verma S K, Bhadauria S S, Akhtar S (2013) Review of nondestructive testing methods for condition monitoring of concrete structures. Journal of Construction Engineering article ID 834572.

[8] Kasal B (2012) State-of-the-art in situ evaluation of structural timber – some critical observations. Revista Portuguesa de Estruturas 11:79-85.

[9] Kiureghian A D, Ditlevsen O (2009) Aleatory or epistemic? Does it matter?. Structural safety 31: 105-112.

[10] Forest Products Laboratory (2010). Wood Handbook – wood as a engineering material. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, 508 pp.

[11] JCSS (2006). Probabilistic model code. Part 3.5 – Timber. ISBN: 978-3-909386-79-6, Joint Committee on Structural Safety.

[12] Höls M, Dietsch P (2010) Assessment of timber structures. In: Dietsch P and Köhler J (Eds) Assessment of timber structures, Shaker Verlag GmbH, Aachen, p 14-21.

[13] Zar J H (1996) Biostatistical analysis. 3rd ed. Prentice-Hall International, Inc.

[14] Fries A, Ericsson T (2009) Genetic parameters for earlywood and latewood densities and development with increasing age in Scots pine. Ann. For. Sci. 66:404

[15] Iñiguez-González G, Arriaga F, Esteban M, Llana D F (2014) Adjustment factors for the homogenization of nondestructive techniques. In J S Machado, Mariapaola Riggio and Artur Feio (Eds) Combine use of ndt/sdt methods for assessment of structural timber members, p ….-,…..

[16] Faggiano B, Grippa M R, Marzo A (2014) A methodology for the determination of the timber density through the statistical assessment of ND measurements aimed at in situ mechanical identification. In J S Machado, Mariapaola Riggio and Artur Feio (Eds) Combine use of ndt/sdt methods for assessment of structural timber members, p ….-,…..

[17] Drdáchy M, Kloiber M (2013) In-situ compression stress-deformation measurements along the timber depth profile. Advanced Materials Research 778:209-216.

[18] Kasal B, Anthony R (2004) Advances in in situ evaluation of timber structures. Progress in Structural Engineering and Materials 6:94–103.

[19] Ilharco T, Lechner T (2014) Assessment of timber floors by means of non-destructive testing methods. In J S Machado, Mariapaola Riggio and Artur Feio (Eds) Combine use of ndt/sdt methods for assessment of structural timber members, p ….-,…..

[20] Dackermann U, Crews , Kasal B, Li J, Riggio M, Rinn F, Tannert T (2014) In situ assessment of structural timber using stress-wave measurements. Materials and Structures 47:787-803.

[21] Bucur V (1995) Acoustics of wood. RC Press, New York.

[22] Bodig J, Goodman R (1973) Prediction of elastic parameters for wood. Wood Science 5:249-264.
[23] Chapman M J, Norton B, Taylor J McA, Lavery D J (2006) The reduction in errors associated with ultrasonic non-destructive testing of timber arising from diferential pressure on and movement of transducers. Construction and Building Materials 20:841-848.
[24] Kasal B, Lear G, Tannert T (2010) Stress waves. In: B Kasal and T Tannert (Eds) In situ assessment of structural timber.
[25] Gehri E (1997) Timber as a natural composite: explanation of some pecularities in the mechanical behaviour. Case: Assessment of the modulus of elasticity of timber parallel to grain. In: Görlacher R (Ed) International Council for Building Research Studies and Documentation – Working Commission W18 – Timber Structures, Vancouver, Paper 30-6-3.
[26] Machado J S, Lourenço P B, Palma P (2011). 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.
[27] Gillard J (2010) An overview of linear structural models I errors in variables regression. REVSTAT – Statistical Journal 8:57-80.