Construction and Building Materials xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Onsite assessment of structural timber members by means of hierarchical models and probabilistic methods

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ARTICLE INFO

Article history:
Received 2 May 2015
Accepted 28 May 2015
Available online xxxx

Keywords:
Bayesian methods
Hierarchical modeling
Timber reference properties
Updating

ABSTRACT

One of the main motivations for hierarchical modeling is to understand how properties, composition and structure at lower scale levels may influence and be used to predict the material properties at macroscopic and structural engineering scales. Structural timber is, in most cases, characterized by three parameters usually designated as reference properties: density, bending modulus of elasticity and bending strength.

The present paper addresses a review on different possibilities for obtaining reliable data about the mechanical behavior of timber elements by collecting information at different levels and by organizing that information into a hierarchy of sequential levels (from lowest to highest). The applicability and limitations of statistic and probabilistic methods on the prediction and inference of timber's reference material properties are discussed and exemplified.

1. Introduction

The quality (reliability) of a probabilistic structural analysis process is highly dependent on the quality of the information used for the input variables. Structural timber is, in general case, characterized by three parameters usually designated as reference properties: density, bending modulus of elasticity and bending strength.

The onsite assessment of these properties is being done following different approaches, which often consider the hierarchical structure of wood. This hierarchical structure can be seen at different scales, from nanostructure to macroscale, [1], similarly to other natural materials such as bone [2].

It is recognized that the structural performance of timber elements is dependent on variables that operate at different material's scale. This dependence influences the results obtained through the different tools and methods used for onsite assessment of structural timber elements. From the inclination of the microfibrils of cellulose inside the cells walls (micro) through the characteristics of the growth rings (meso) until the effect of gross defects (macroscale), different models have been built to deal with the requirement of more reliable models for the prediction of structural timber elements' performance.

Hierarchical or multilevel modeling is therefore suitable for this material, since it reflects the necessity of acquiring knowledge from timber's variables at different levels. The complexity of timber and the restrictions existing when performing onsite assessment make Bayesian statistics an excellent tool for combining information from multiple sources (non-destructive tests, NDT; semi-destructive tests, SDT; or even destructive tests, DT), to update information when new data is available and to include expert opinion (qualitative information).

Hierarchical Bayesian modeling requires the awareness and the distinction of different scales, such that a homogenization step may be taken to each of those scales as to define similar properties for each scale. The different hierarchical models applied to wood properties, such as density, strength or stiffness, are defined according to the study's purpose. If the adopted main unit is the growth ring then the levels can comprise a macrolevel (multilayer material with alternative layer of earlywood and latewood) and can end at a very low level as the nanostructure, where the layers of the cell's secondary wall are considered as unidirectional fiber-reinforced composites and middle lamella and primary wall are considered as random short-fiber/particle reinforced composites [1,3]. If the main unit is clear wood (macroscale), then growth ring (mesoscale) and cell level (microscale) can define the

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http://dx.doi.org/10.1016/j.conbuildmat.2015.05.127
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hierarchical model [4]. The main unit of analysis can also be the structural member with three levels defined as micro (timber board or beam), meso (local) and macro (global) [5]. In the present paper, focus is given to the models where the macrolevel is defined at the material level.

Several attempts were made to hierarchically model the stiffness and strength of timber elements, by considering the presence of weak sections separated by segments of clear wood [6–9]. In [10], Bayesian methods were used to update the mechanical properties of existing timber elements and the assessment was performed using First Order Reliability Methods (FORM). The results of that work evidenced that different degrees of belief in the new data may significantly influence the reliability level. Usually for in-service timber elements, new data are derived from NDT results obtained with ultrasound, resistance drilling and penetration resistance equipment. In [10], NDT were made to chestnut wood specimens and combined with results from compressive strength parallel to the grain tests. The uncertainty of the different NDT results was modeled by Maximum Likelihood estimates.

Hierarchical modeling has also been carried out using Bayesian Probabilistic Networks (BPN) for the analysis of variability of timber mechanical properties [11–13]. BPNs are used to represent knowledge based on Bayesian regression analysis describing the causal interrelationships and the logical arrangement of the network variables. In [11], a hierarchical model was used to determine the influence of the origins (different tree growth locations) and cross-sectional dimensions of new timber elements on the probability distribution of its material properties. On that work, BPNs using information of machine grading indicators were used to describe and infer on the dependence of different origins and dimensions of sawn structural timber on the relevant timber material properties. The parameters of the prior probability distribution functions, as well as the regression parameters, were estimated as random variables with mean values, standard deviations and correlations through the Maximum Likelihood method.

The present paper addresses different possibilities for obtaining reliable data about the reference properties of timber elements by collecting information at different levels and by organizing that information into a hierarchy of sequential levels (from lowest to highest).

2. Bayesian probabilistic methodology

Bayesian statistics is an inference method based in the Bayes' rule allowing to estimate the updated probability, given an additional evidence is provided. Bayesian probability, therefore belongs to the category of evidential probability analysis that is used to evaluate the probability of a new information or hypothesis. For that aim, Bayesian probabilistic methods first specifies a given prior probability, which is then updated when new relevant data are made available. The prior probability distribution expresses the uncertainty about a given parameter before evidence is taken into account. The posterior probability function, which is the conditional distribution of the uncertainty, may be obtained by considering the Bayes' theorem, multiplying the prior distribution by the likelihood function and then normalizing it.

As the prior distribution probability is often only the subjective assessment of an expert, in Bayesian methods probabilities are considered as the best possible expression of the degree of belief in the occurrence of a certain event, and thus not considered direct and unbiased predictors of occurrence frequencies that can be observed in practice. However, if the analysis is carried out carefully, the probabilities will be correct if averaged over a large number of decision situations [14]. Therefore, it is necessary that the subjective and purely intuitive part is neither systematically over conservative, nor over confident. Calibration to common practice and to empirical data may be considered as an adequate path to that aim.

The JCSS Probabilistic Model Code [15] concludes that, compared to the frequentistic interpretation the Bayesian interpretation is the only one that makes sense in the end, as it overcomes the difficulties of updating distributions when more statistical data is available.

When uncertainties are present, The Bayesian interpretation overcomes these difficulties and provides the most logical and useful framework for consistent decision making [14].

Bayesian methods are a suitable method for parameter estimation and model updating, as they allow quantifying an approximation about the statistical uncertainty related to the estimated parameters, regarding both the physical uncertainty of the considered variable, as well as the statistical uncertainty related to the model parameters. However, for making this possible, it is necessary to take into account the measurement and the model uncertainties in the probabilistic model formulation. Since Bayesian methods grant the opportunity to incorporate different considerations about the uncertainty of models in the updated probabilistic model, the comparison between different assessment experts' results may be regarded as a problem, as consensus about a comparison basis has not yet been established.

2.1. Maximum Likelihood method

In a probability paper, the vertical scale is changed by means of a non-linear transformation such that the cumulative distribution curve plotted in that graph is represented by a straight line. Attending to the configuration of that line (location and slope) it is possible to assess the parameters of the inherent distribution. This method is useful for normality tests [16] and to determine if a given data sample is well defined by a specific type of probability distribution. However, a more efficient and accurate method is the Maximum Likelihood method, which is based on finding the set of parameters of an assumed probability distribution function which most likely characterizes the underlying data sample. Although the Maximum Likelihood method is not a full Bayesian approach and it can also be used in a frequentistic approach, it is commonly used to find the distribution parameters of the prior information in a Bayesian methodology, and thus it will be briefly described here. In general, for a fixed set of data and an underlying statistical model, the Maximum Likelihood method allows to select the set of values of the model parameters that maximizes the likelihood function. The general procedure on how to implement the Maximum Likelihood method can be found in [5,17] and in [18], where a parameter that describes the model uncertainty is also implemented.

In Bayesian statistics, the Maximum Likelihood estimator coincides with the most probable Bayesian estimator, given that the parameters of the prior distribution are uniformly distributed, meaning that the maximum posterior estimate is the parameter that maximizes the probability of that parameter given the analyzed data. Therefore, the Bayesian estimator coincides with the Maximum Likelihood estimator for a uniform prior distribution.

In probabilistic analysis, as the inference on characteristic values is of special interest in the field of structural safety assessment, it is also recommended that special focus is given to the extreme values of the distributions. Therefore, a scheme for estimating the parameters of probability distributions focusing on the tail behavior should also be addressed, as considered in [19] where a censored Maximum Likelihood estimation technique was used.

Please cite this article in press as: Sousa HS et al. Onsite assessment of structural timber members by means of hierarchical models and probabilistic methods. Constr Build Mater (2015), http://dx.doi.org/10.1016/j.conbuildmat.2015.05.127