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A probabilistic approach for the linear behaviour of glued laminated timber

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ABSTRACT

A probabilistic model for glued laminated timber (GLT) is proposed, using a random process model for the random stiffness distribution within each lamination.

The random process model is derived on basis of stiffness profiles of 448 wooden Norway spruce boards obtained by non-destructive methods. Employing the Karhunen-Loève expansion, this model is used to represent the random nature of each lamination within the GLT setup. Different GLT setups are statistically analysed employing the conventional finite element framework within the so-called perturbation and polynomial chaos projection schemes.

The numerical results concur well with those obtained by Monte Carlo simulation and experimentally-obtained results.

1. Introduction

Timber is constantly gaining importance in the building sector and the number of structural elements made of wood increases continuously. Wood not only shows a high ecological value and sustainability, but also a great variety of wood products is available for manifold purposes. However, compared to other building materials, timber exhibits a high amount of inhomogeneities and thus, a high variation in mechanical properties. For knot-free wood (also referred to as clear wood scale), besides species dependent parameters, this variation is mainly influenced by the density, moisture content and microfibril angle [1]. At the macro scale, knots and the resulting fibre angle deviations in their vicinity strongly influence the mechanical behaviour. As a result, strong variations of mechanical properties can be observed within wooden boards, which are used as base material for a variety of wood-products. Since wood is not an artificial but a naturally-grown material subject to species, light exposure and other factors not necessarily within control, the above-mentioned phenomena are assumed to be random to a certain degree. As a consequence, also the resulting mechanical behaviour of wooden boards is assumed to be subject to randomness [2,3].

By glueing together wooden boards to wood-based products, such as glued laminated timber (GLT) or cross laminated timber (CLT), a homogenisation of the mechanical behaviour is reached and the natural variation is reduced. To reliably quantify the homogenisation effect, also known as lamination effect the random fluctuations of mechanical properties observed within individual timber boards need to be considered, thus raising the necessity for the application of probabilistic approaches [4]. For this, the reduction of mechanical properties to a one-dimensional profile along each timber board has proven to be an efficient method for describing the spatial variation of mechanical properties. This approach has been applied successfully in numerous works, which are devoted to the modelling of GLT by means of a probabilistic approach. In the following, the most relevant investigations are summarised (an extensive review of probabilistic approaches for GLT can be found in e.g. Brandner [5] and Kandler et al. [6]):

In Ehlbeck et al. [7–9], each timber board is virtually divided into cells of 150 mm length. A database, recording indicating properties (IP), in particular the knot-area-ratio and mass density of each cell, has been developed. Also, mechanical tests have been conducted on each cell, allowing for a regression model from IPs to experimentally obtained mechanical properties. This model is then used to predict the mechanical behaviour of other timber boards based on their measured IPs, or randomly generated IPs are applied within Monte Carlo simulations (MCS). These mechanically fully characterised timber boards then are virtually assembled to GLT beams and subsequently fed to a two-dimensional finite element (FE) code and analysed using MCS. This model has been further extended in Blaß et al. [10], where dry density and knot ratio are used as indicators for stiffness.

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Wang and Foschi [11] proposed a random process model characterised by the power spectral density [12] for the representation of the random timber board stiffness. The power spectral density was estimated from quasi-continuous three point bending tests along a sample of timber boards. Using these stiffness profiles, GLT beams were virtually assembled and analysed within a two-dimensional FE code. Besides MCS also the first and second order reliability method (FORM/SORM) were applied to evaluate the system response.

Riberholt and Madsen [13], on the other hand, proposed a so-called weak-zone approach, where each timber board is modelled by clear wood sections interrupted by weak sections representing e.g. knot clusters. Within this approach, the length of each clear wood section, as well as the stiffness/strength of each section is controlled by a random variable. This approach can also be described as hierarchical model, see e.g. Källsner et al. [14].

Fink [15] presented a weak-zone approach, where the underlying sample of timber boards was not only manually investigated but also a grading machine was used to automatically obtain a local knot indicator for the identification of weak-zones. The mechanical properties of each clear wood and weak-zone section are then determined by regression from an experimentally-obtained database [16,17]. Subsequently, a probabilistic analysis on virtually assembled GLT beams was performed using MCS.

Recently, García and Rosales [18] compared results from a Nataf transformation and a non-Gaussian Karhunen-Loève expansion for modelling the elastic modulus of timber boards. It was found that both representations yield similar results. For the marginal probability density function (PDF), the principle of maximum entropy [19,20] was used. Therein, it is stated that under given constraints (such as positivity), the PDF with the largest entropy is the one which represents the data best. Using this principle, García and Rosales [18] report that the gamma distribution serves best to model the longitudinal stiffness of individual boards.

In recent years, a promising alternative method for analysing wooden boards by means of laser scanning has become feasible for application within industrial environments [21]. The principle is based on the so-called tracheid effect, which describes the light propagation of laser light within wood, which is more pronounced parallel to the grain than in perpendicular direction [22–24]. This can be exploited by projecting a laser dot on the surface of a timber board and recording its transformation from an originally circular dot to an elliptical form with the major axis being oriented in longitudinal direction of the fibres. Within industrial timber engineering environments, laser scanners yielding dense fibre angle measurements for the 4 surfaces of each board have become common in recent years [21]. On basis of these measurements, approaches presented in Briggert et al. [25] and Kandler et al. [26] allow for automatically reconstructing the knot geometry, which in turn can be used for three-dimensional finite element analysis. The occurence of knots in combination with local deviations of the fibre course are closely related to the mechanical properties of wooden boards [27], as has been shown in numerous works [28–33].

Subsequently, in the work of Olsson et al. [34], laser scan-based fibre angle measurements were employed to obtain a stiffness profile for each board. Thereby, the orthotropic clear wood stiffness tensor was transformed according to the measured in-plane fibre angles on the timber boards' surface, resulting in stiffness estimates on the surface points in longitudinal direction of the board. Integration over each cross section resulted in a stiffness profile, which was calibrated by comparing dynamic FE simulations based on said stiffness profiles with experimental dynamic excitation tests of the corresponding boards. The efficiency of this approach has been shown recently in Olsson and Oscarsson [35], where a coefficient of determination as high as $R^2 = 0.70$ between predicted strength and experimentally observed strength is reported.

While the orientation of the major axis of the laser dot ellipse only gives insight on the in-plane fibre angle, the ratio of minor to major axis can be used to estimate the out-of-plane angle of the fibres [36]. In Olsson and Oscarsson [37] and Kandler et al. [38], this approach was adapted for Norway spruce.

The laser scan approach was also employed in Kandler et al. [38], where 448 boards of grading classes LS15 and LS22 were weighed, had their moisture content measured and were laser scanned to determine their mechanical properties by means of stiffness profiles. In addition to the in-plane angle measurements, out-of-plane angle estimations were used within this study to obtain a three-dimensional fibre angle. The fibre angles were obtained at a resolution of 1 mm in longitudinal direction and 4 mm in perpendicular direction on all four surfaces of the board. The obtained fibre angles on each point on the surface are used to transform the clear wood stiffness tensor obtained by a micromechanical model (MMM) [1], for which the determination of moisture content, mass density, and some species-specific parameters have been proven to be sufficient.

Subsequently, 5 different types of GLT beam configurations have been assembled from the investigated sample of timber boards. The setup geometry is shown in Fig. 1 with dimensions as indicated in Table 1. For each of the 5 types, 10 specimens were assembled and tested under static four-point bending as shown in Fig. 1. Also, during the GLT assembly process, the location and orientation of each board was documented, to allow for an accurate reconstruction of each GLT beam.

In order to verify the stiffness profiles, the experiments were reproduced numerically. Thereby, the stiffness profiles were virtually assembled to GLT beams using the same positioning as recorded for their real world counterparts. Subsequently, the same four point bending tests were simulated by means of a two-dimensional FE approach, which was programmed within the MATLAB programming environment [39]. The effective stiffness E_{GLT} computed from the numerical model was then compared with the experimental values, see Fig. 2. Employing the stiffness profiles, the numerical results concur well with the experimental results for a range of different configurations from 4 to 10 laminations and 2 grading classes LS15 and LS22.

While the discussed probabilistic approaches are capable of delivering satisfying results, the determination of the databases for the underlying random input models is often cumbersome and requires significant effort. The laser scan approach, on the other hand, lends itself to automation, and can easily be implemented in existing production chains, yielding a stiffness profile for each scanned timber board on the fly.

Therefore, the objective of this work was the extension of the deterministic study presented in Kandler et al. [38] by an appropriate probabilistic approach. In analogy to the previous probabilistic investigations of GLT, it was assumed that the 448 recorded stiffness profiles are realisations of an underlying random process, governing the population of stiffness profiles. Thereby, the sample of stiffness profiles served as basis for the development of an appropriate random process model, which was, after its verification, employed within a probabilistic analysis.

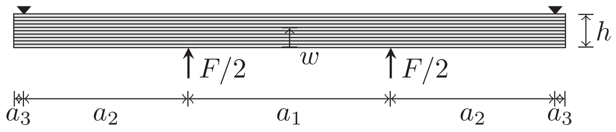

Fig. 1. Four point bending setup used for all GLT configurations. The measurements a_1, a_2, a_3 and h can be found in Table 1. The lamellas were planed to 33 mm thickness. After glueing, all GLT beams were planed to 90 mm width.