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Variation and serial correlation of modulus of elasticity between and within European oak boards (*Quercus robur* and *Q. petraea*)

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Abstract: This research aimed at describing the tensile modulus of elasticity (MOE), density and knot variability between and within oak (*Quercus robur*, *Q. petraea*) boards, which is essential for the stochastic modeling of wooden composites, such as glulam. Longitudinal deformations for 100-mm long cells were measured. The local density variation along boards revealed a very low mean coefficient of variation (COV) of 3%. The global MOE was precisely predicted from local (cell) MOEs, which span from 2.6 to 22 GPa. The mean COV of local MOE along board length was 12%, with extremes of 3% and 28%. The cell-related relationships of MOE with either density or knot area ratio showed low *R*-values of 0.4 and 0.3, respectively. A multivariate linear regression with both variables increased the MOE prediction to *R*=0.6, which is below the literature results for beech and spruce wood. A serial correlation analysis of the local MOE was performed for board segments quasi-free of knots and for all cells, investigating different normalization approaches. Applying no MOE normalization delivered too high correlations due to pronounced inter-board MOE variations. A normalization based on an averaged maximum MOE per board delivered reasonable serial correlation results for the first four lags of the MOE knot-free variation (0.61; 0.38; 0.19 and 0.08). Considering also the knot-affected cells reduced the serial correlation roughly by a factor of 2.

Keywords: density, intra-board MOE variation, knot area ratio, oak (*Quercus robur*, *Q. petraea*) boards, serial correlations of local MOE, tensile loading

Introduction

Structural sized timber exhibits substantial fluctuation of stiffness and strength along the member length and width. This results from the growth-bound variation of knots, fiber deviation and density, which are the most important parameters. For the case of a single member subjected to bending or tension, the maximum deflection or elongation is bound to the global modulus of elasticity (MOE_{glob}) determined by all local contributions, MOE_{cell} , within the span (e.g. Corder 1965; Kass 1975; Showalter et al. 1987; Lam and Varoglu 1991; Lam et al. 1993; Isaksson 1999; Aicher et al. 2002; Fink 2014). For serviceability issues, local MOE values are irrelevant. However, owing to the strong correlation of strength and low stiffness sections or board segments, investigations on the variation and magnitude of the local MOE have been fundamental for the development of the first generation of stress/strength grading machines based on the bending principle (e.g. Senft et al. 1962; Sunley and Hudson 1964; Glos and Schulz 1980; Boughton 1994). Later research has proven that the determination of the local MOE based on local fiber deviation enhances the grade prediction significantly (Olsson et al. 2013; Oscarsson et al. 2014; Viguier et al. 2015).

Regarding glued laminated timber (GLT), the variation in the MOE along the lamination length is of prime importance. This results from the fact that a board segment with a low MOE is relieved from stress and potential fracture when bonded to adjacent laminations with stiffer cells, which attract a significant stress portion from the weak domain. This parallel-system load sharing, together with the hindrance of out-of-plane deformations of tension-loaded boards with knots closer to the edge, is generally referred to as the lamination effect (see, e.g. Serrano 1999; Frese 2006).

In their pioneering research on numerical simulation of glulam beams, which was related explicitly yet not methodologically to Douglas fir *Pseudotsuga menziesii* (Taylor and Bender 1991) timber, Foschi and Barrett (1980) addressed for the first time the fundamental importance of the local tensile MOE of closely adjacent cells of small lengths (150 mm) along the board length. The local MOE was described by a macroscopic clear wood base MOE, E_c ,

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described by a two-parameter Weibull equation, including factors to consider slope of the grain and the randomly attributed density. In a second step, the clear wood MOE of each cell was adjusted by means of a factor to an apparent MOE, E_{app} , by considering the knots according to the grade-dependent knot frequencies and size distributions. The adjustment factor considered the ratio between knot diameter and width of the board as the main variable.

A more straightforward simulation of local cell MOE values and their variations was then adopted by Ehlbeck (1985) and Ehlbeck and Colling (1987) in their research on GLT from Norway spruce *Picea abies* (Colling and Scherberger 1987; Colling 1990). In this case, a multivariate linear regression for E_{cell} depending on density, ρ , and local knot area ratio (KAR, defined as the ratio between the projection of a knot on the cross-section and the cross-section area – see below) was implemented. The data were derived from 640 board cells with lengths of 450 mm, cut from 100 boards (Colling and Scherberger 1987). E_{cell} was determined by the bending vibration method (Görlacher 1984). Owing to the low density variability along the board length, the cell density was assumed equal to the board density. The MOE (KAR, ρ) regression analysis yielded a very high correlation coefficient of $R=0.87$. In order to account for the scatter of E_{cell} between and within boards, each individual E_{cell} value was then modified stochastically based on the standard deviation (std.) of the residues.

An altered measurement of the local MOE values and their respective variations was introduced by Blaß et al. (2005) and Frese (2006) in their research on glulam made from beech (*Fagus sylvatica*) laminations. The tensile MOE were measured over a gauge (cell) length of 150 mm on test pieces with lengths of 800 mm. The between boards MOE scatter was evaluated from 300 boards, while the intra-board MOE variation was determined from 30 boards, each with four cells spaced at 800 mm. The evaluation, closely related to that of Colling (1990), revealed that the average intra-board std. of the local MOEs was significantly lower (–40%) than the std. of the MOE residues of all boards.

To summarize, the local MOE was, in all reported GLT models, derived from its relationship with the local KAR and density. The E_{cell} prediction equations are either obtained from tests with board segments, i.e. cells of considerable lengths (450–760 mm) or from short cells; however, these are non-consecutive owing to the clamping regions. The topic of the serial correlations of local MOEs has not yet been addressed in the GLT models. In fact, pronounced serial lag-1 and lag-2 correlations for the localized MOE, determined in flatwise bending, have been proven by Kline et al. (1986) for Southern pine lumber of various grades. The correlation coefficients obtained for the adjacent (lag-1) or second adjacent (lag-2) cells of considerable length (750 mm) were within the range of 0.78–0.92 and 0.68–0.90, respectively. Modeling of the serial correlations was then performed by a second-order Markov process. In an extension, Taylor and Bender (1991) modeled the localized MOE of Douglas fir lumber and their variations by means of serial correlations, this time also including cross-correlations with the localized tensile strength.

This paper addresses the variability along and between strength-graded laminations of oak (*Quercus robur*; *Q. petraea*) serving as input for an advanced oak GLT model (Tapia and Aicher 2018b). A new approach was adopted in the experimental campaign. The MOE results are evaluated regarding both, the discrete growth parameters and the serial MOE correlations.

Materials and methods

Material: Investigations into the variations of the MOE and density were performed using oak boards (*Q. robur/petraea*), originating from the mid-eastern part of France (region Bourgogne Franche Comté). The sample was obtained from the sawmill Scierie Mutelet, Rahon, France, and consisted of 52 boards (from which 47 were tested in tension) and contained a mixture of appearance grades QF2 and QF3, according to EN 975–1 (2009). The boards stemmed from second and third lengths, i.e. no butt logs, of larger diameter stems (breast diameter ≥ 55 cm). The nominal dimensions (length $\ell \times$ width

Table 1: Grading results for KAR and slope of grain for all investigated boards, and allocation to structural grades specified in DIN 4074-5 (2008).

Grade	Grading limits according to DIN 4074-5			Grading results (mean $\pm$ std.)			
	KAR-S (single)	KAR-G (group)	Slope of grain	% of boards ^a	KAR-S (single)	KAR-G (group)	Slope of grain
LS7	1/2	2/3	16%	8.5	0.21 $\pm$ 0.16	0.28 $\pm$ 0.18	14.12 $\pm$ 0.63
LS10	1/3	1/2	12%	36.2	0.14 $\pm$ 0.09	0.19 $\pm$ 0.11	7.30 $\pm$ 2.24
LS13	1/5	1/3	7%	46.8	0.10 $\pm$ 0.05	0.15 $\pm$ 0.09	3.52 $\pm$ 1.91

^aThe missing percentage (8.5%) corresponds to the rejected boards.

$b \times \text{thickness } t$) of the planed boards were $2500 \times 175 \times 24$ mm, respectively. The moisture content (MC) measured with a pin-type resistance meter was, on average, 10.2% [coefficient of variation (COV) = 4.6%]. The two QF appearance grades intentionally enabled a wide range of knottiness and grain deviation in the sample, presumably leading to high variation in the respective board properties. Thereafter, the boards were visually graded at the MPA, University of Stuttgart, in hardwood strength grades LS7, LS10 and LS13, as specified in the German structural hardwood grading standard DIN 4074-5 (2008), which conforms to EN 14081-1 (2016). The grading was performed according to the provisions and criteria specified for boards, as opposed to scantlings, which, according to definition (DIN 4074-5 2008), are characterized by thicknesses of $t < 40$ mm and widths of $b \geq 80$ mm.

Strength grading, together with an exact determination of size and position of the growth defects of each board, was performed as described below. The grade determining KAR and slope of grain values are summarized in Table 1. The portions of the obtained different hardwood strength grades (LS7, LS10 and LS13) were: 8.5%, 36.2% and 46.8%, respectively (8.5% were rejected).

Based on EN 1912 (2013), and disregarding (i) the non-compliant wood source (here mid-eastern France instead of Germany) and (ii) the board-related grading instead of scantling grading, the LS10+LS13 sample could be assigned to hardwood strength class D30 according to EN 338 (2016). The results given below for density and MOE conform to D30 [for the case of MOE without application of the single subsample penalization specified in EN 384 (2019)].

Concluding the considerations on material representativeness, it should be stated (Lanvin and Reuling 2012) that oak (*Q. robur/petraea*) shows a distinct reduction of MOE and strength (MOR) with increasing tree height throughout a wide range of (breast-height) diameters of approximately 25–70 cm. Furthermore, MOE and MOR decrease pronouncedly with larger stem diameters up to 60 cm, being very different from softwoods (e.g. Steffen et al. 1997). The positive effect of the latter on stiffness and strength in GLT made of oak boards from thinning trees (diameters up to about 50 cm) is reported by Faye et al. (2017).

Measurement of knot-related variables and grain deviation: The positions and dimensions of each knot larger than 5 mm were recorded using a digital caliper gauge. For each knot, three dimensions were measured: the minimum and maximum diameter of the assumed ellipse, and the width taken perpendicular to the board's length axis. These three variables allow for determination of the rotation angle of the knot, represented by an ellipse. The knot areas at different board faces, apparently belonging to the same knot volume, were marked with a unique number. This information was then used to digitally reconstruct the three-dimensional (3D) geometry of the knots in each board, for which the Python library pythonOCC (Paviot 2018) was used. Thereafter, the knot areas were numerically computed for each cell (see below). This was achieved by projecting the knot volumes onto the cross-section; the resulting areas were then used to compute the required ratios.

The KAR value for a simple knot and knot group according to DIN 4074-5 (2008) is defined as

$$\text{KAR} = \frac{\sum_{i=1}^n a_i}{2 \cdot b}, \quad (1)$$

to be computed in the most unfavorable section within a length of $L = 150$ mm. The clear wood area ratio (CWAR) is then simply

Figure 1: Determination of KAR in section of board with length L according to DIN 4074-5 (2008).

computed as $\text{CWAR} = 1 - \text{KAR}$. Figure 1 illustrates the definition of the KAR value for a typical situation with two knots ($n=4$) according to DIN 4074-5 (2008). In certain cases, computing the KAR value according to Eq. (1) yields different values to those obtained numerically, using the 3D model of the knots. For the studied case, the average differences are approximately 13% for both, single knots and groups of knots. However, the classification of the boards remained almost identical [only one board was classified in grade LS7 instead of LS10 when using Eq. (1)]. In this paper, the numerically computed KAR values are used for the grade allocation of the boards according to DIN 4074-5 (2008).

The maximum grain deviation along the board length, i.e. the global slope of grain ($\Delta y / \ell_g \cdot 100$), was determined manually according to DIN 4074-5 (2008), with a base length of $\ell_g = 300$ mm (Δy = offset of the fiber perpendicular to the board length direction) using a special scribe. The determination of the grain deviation stepwise or continuously along the board length, as a grade indicating parameter based on dot laser scanning using the tracheid effect (e.g. Oscarsson et al. 2014; Hu et al. 2018), was beyond the scope of the reported research, but should be incorporated in future studies (see below).

Local and global tensile MOE measurements and evaluations: The global tensile MOE parallel to the board length and nominal fiber direction, $E_{t,0,\text{glob}} = E_{t,0,\text{glob},\text{test}}$, was measured over a length of $\ell_{E,\text{glob}} = 8.6b = 1500$ mm. As this gauge length, selected with regard to the local MOE data sampling, significantly exceeds the requirement of $5b$ specified in EN 408 (2012) and EN 384 (2019), $E_{t,0,\text{glob},\text{test}}$ is slightly higher (see below) compared to the evaluation with a length of $5b$. For the measurement of the local MOE and their intra-board variations, $\ell_{E,\text{glob}}$ was virtually subdivided into 15 consecutive cells (observation windows) with equal lengths of $\ell_{i,\text{cell}} = 100$ mm. The tensile tests were performed with a servo-hydraulic universal testing machine (maximum load: 700 kN), equipped with special hydraulic-controlled grips. The free length between the grips was $\ell_s = \ell_{E,\text{glob}} + 2 \cdot 60$ mm = 1620 mm throughout, providing clamping lengths of approximately 350 to 450 mm (see Figure 2).

The loading protocol of the boards consisted of a series of loading-unloading cycles. Loading was performed in displacement control, at a stroke rate of 0.04 mm min^{-1} , while unloading to a zero load in each cycle was load controlled at a rate of 5 kN s^{-1} . In each cycle, the axial elongation of one cell of the board was measured by

Figure 2: Test set-up for determination of MOE variation along board length.

Figure 3: Extensometer device used for measurement of deformations in 100 mm-long cells: (a) rear-side view; (b) lateral view.

a special extensometer (Figure 3) in the linear elastic range, up to a nominal tensile stress of $\sigma_{t,0} = 7.1 \text{ N mm}^{-2}$ ($F_{t,0} = 30 \text{ kN}$). The extensometer device consists of two U-shaped steel frames, attached to the board by means of special screws. The frames are equipped with two linear variable displacement transducers (LVDTs), placed at diagonally opposite sides of the board cross-section (see Figure 3a and b).

Following each loading-unloading cycle, the extensometer was shifted to the next cell and the described loading and displacement measurement sequence was repeated (see Figure 2). In a subsequent step, the global MOE, $E_{\text{glob,test}}$, was measured over a gauge length of $\ell_{E, \text{glob}}$. The objectives of the $E_{t,0,\text{glob,test}}$ measurement were: (i) experimental determination of the global board stiffness, and (ii) verification of the overall quality of the measurements at the individual cells. For evaluation of the local and global MOE, the mean value of both diagonally opposite LVDT measurements was taken in the load range between 10 and 30 kN.

In order to verify the accuracy of both the local and global MOE measurements, the global MOE can be derived theoretically, hereinafter termed as $E_{t,0,\text{glob,cells}}$, from all locally measured MOEs within $\ell_{E, \text{glob}}$, by the well-known principle of springs arranged in series, as follows:

$$E_{t,0,\text{glob,cell}} = \ell_{E, \text{glob}} \left(\sum_{i=1}^N \frac{\ell_{i,\text{cell}}}{E_{t,0,i,\text{cell}}} \right)^{-1} \quad (2)$$

In the specific case where $\ell_{i,\text{cell}} = \text{const} = \ell_{\text{cell}}$, and hence $\ell_{E, \text{glob}} = N \cdot \ell_{\text{cell}}$, then

$$E_{t,0,\text{glob,cell}} = N \cdot \left(\sum_{i=1}^N \frac{1}{E_{t,0,i,\text{cell}}} \right)^{-1}. \quad (3)$$

Determination of global and local densities: Subsequent to the specially designed tensile fracture tests, which are not reported here (see Tapia and Aicher 2018a), the variation in the density along the length of each board was determined. For this purpose, each board was sawn into its individual cells. As the boards were generally broken into two or more pieces, the local densities, ρ_{cell} , could not be determined for each of the 15 cells, but on average for 11 ± 3 cells. The determination of the global and local densities was performed by weighing and measuring the dimensions of the whole board (before testing) and its individual cells, respectively. The MC measurement for the adjustment of ρ_{glob} and ρ_{cell} to the reference density at 12% MC according to EN 384 (2019) was performed by means of the oven-drying method with two cross-sectional slabs of dimensions $175 \times 50 \times 25 \text{ mm}^3$ cut from both ends of each board, and then taken as the average of both measurements.

Regression approaches for MOE: The simplest approach for describing the MOE relationship locally (and globally) with both independent variables KAR and density ρ , is doubtless a multivariate linear regression

$$E_{t,0} = \beta_0 + \beta_1 \cdot \text{KAR} + \beta_2 \cdot \rho + S_1(0; \sigma_1), \quad (4)$$

where $E_{t,0} = E_{t,0,\text{cell}}$ [N mm^{-2}] and $\rho = \rho_{0,\text{cell}}$ [kg m^{-3}]. Here, S_1 and σ_1 are the scatter and respective std. of the normally distributed residues. (Note: the selection of the oven-dry density instead of the density at MC = 12%, ρ_{12} , was made to enable improved comparison of the evaluated test results with the literature data.) The scatter $S_1(0; \sigma_1)$ of the residues, i.e. of the individual data points above and below the regression plane, is normally distributed in all cases, with a std. around a mean value of zero. As the scatter is independent of the quantities of

the KAR and ρ , an increase in the scatter with an increasing KAR and densities (a typical feature observed in softwoods) is not correctly captured. In order to overcome this deficiency of the linear regression (4), Ehlbeck et al. (1984) introduced a logarithmic relationship by replacing the dependent variable in Eq. (4) with its logarithm, as follows:

$$\ln(E_{t,0}) = \beta_0 + \beta_1 \cdot \text{KAR} + \beta_2 \cdot \rho + S_2(0; \sigma_2). \quad (5)$$

By means of Eq. (5), the same correlation coefficient R as in the case of Eq. (4) is obtained, but owing to the logarithmic nature of the equation, despite a constant std. σ_2 , the scatter S_2 increases with larger KAR and ρ values. In a slight modification of Eq. (5) in the context of describing beech wood results, Blaß et al. (2005) added a squared density term, leading to the following regression equation format:

$$\ln(E_{t,0}) = \beta_0 + \beta_1 \cdot \text{KAR} + \beta_2 \cdot \rho + \beta_3 \cdot \rho^2 + S_3(0; \sigma_3). \quad (6)$$

Strictly speaking, Eq. (6) was originally proposed using the maximum single knot area (DEB), as defined by DIN 4074-5 (2008), instead of the KAR, as almost no significant difference between the KAR and DEB was reported by Blaß et al. (2005).

Computation of serial correlations of local MOE: In general, the serial correlation (or autocorrelation) is the correlation between each element of a vector and the corresponding k -shifted element ($k = 1, 2, \dots$) of the same vector. In this case, the vector consists of the measured values for the local MOEs in each board. This statistical information can be used for simulating the mechanical properties of virtual boards by means of an autoregressive process, as conducted, for example, by Taylor and Bender (1991). Owing to the large amount of data gathered for each board compared to previous similar studies (almost 4 times more information per board), the serial correlations were computed for two different cases: (i) analysis exclusively of consecutive knot-free board segments (hereinafter referred to as the MOE base variation), and (ii) consideration of all cells in each board, irrespective of their KAR values.

The serial *lag-k* correlation coefficients were computed for the MOE variation of each board, similarly to the processes in Showalter et al. (1987), Taylor and Bender (1991) and Lam and Varoglu (1991). In order to capture the information concerning the MOE base variation, only sufficiently long clear wood segments were considered. These segments were defined to comprise a minimum of seven contiguous cells (i.e. 700 mm) each with a KAR value of <0.05 in a respective board. The accepted small KAR values (<0.05) allow for several extra boards to be selected for the computation of serial correlations.

For the computation of serial correlations, the MOE data of the different boards is analyzed in an aggregated manner, similar as done by Taylor and Bender (1991), or by Isaksson (1999) for bending strength. However, since the *aggregation* of different data sources (boards) into a single set for the computation of serial correlations is not a standard procedure when it comes to signal analysis (normally each signal is analyzed independently), the data of each board needs to be *normalized* with respect to all the other boards. This can be done by means of different approaches:

The first alternative (A) is to map the results of each board to a standard normal distribution and then compare them. This process uses the concept of mapping random variates belonging to an arbitrary distribution into another, as presented by Taylor and Bender (1988), and consists of the following steps:

- the MOE values belonging to the clear wood cells of each board are fitted to a normal distribution $\mathcal{N}(\mu, \sigma)$,

- then the fitted values are *mapped* into a $\mathcal{N}(0,1)$ distribution, according to

$$\tilde{E}_{t,0,\text{cell}} = \Phi^{-1} \left[F(E_{t,0,\text{cell}}) \right], \quad (7)$$

where F is the cumulative distribution function (CDF) of the fitted $\mathcal{N}(\mu, \sigma)$ distribution, and Φ^{-1} is the inverse CDF of $\mathcal{N}(0,1)$.

This process integrates the MOE data from different boards into a common base level, which allows for a unified analysis. The data used to fit the normal distribution for the MOE base variation correspond to those of all cells in each board, which satisfy the clear wood criterion ($\text{KAR} < 0.05$) defined above. Thus, assuming a board has two segments of clear wood, one with eight cells (>7) and another with five cells (<7), the data of both segments are used to fit the normal distribution of the MOE, although the segment with five cells is then not used to compute the lag correlations. The described normalization process has the disadvantage of cancelling the different variations levels caused by large changes in fiber orientation (due to knots) or other local defects.

A second alternative (B) regarded here, consists in the normalization of the data by considering the average of the three maximum MOE values of each board, $\bar{E}_{\text{max},3}$, and then dividing each set by this value, according to

$$\tilde{E}_{t,0,\text{cell}} = \frac{E_{t,0,\text{cell}}}{\bar{E}_{\text{max},3}}. \quad (8)$$

By doing so, the *base* value for the MOE variation can be assumed to be related to the regions with rather undisturbed fiber orientation.

A final case (C) considers the no-normalization of the data, as done by Taylor and Bender (1991). However, this approach potentially overestimates the computed serial correlations, as the large variation between different boards has a pronounced effect on the computed correlations.

Only the above specified first and second alternatives (A and B) compensate for the global differences between boards. It is also important to note that the data tuples (E_n, E_{n+k}) , used for the computation of each *lag-k* correlation, always belong to a specific board; i.e. the MOE values of the different boards are *not* concatenated into a single vector to perform the correlation analysis. Incorporating all data into a single vector would lead to erroneous results, as cells of different boards would be mixed when computing the serial correlations.

A final comment should be added with regard to the data handling. When computing the serial correlation of a vector X (in this case, the local MOE along a board), it is obvious that the same results will be obtained regardless of the direction along the board length in which the data are processed. This means, for example, that it is irrelevant for the lag-1 correlation, whether the sub-vectors $a_1 = [x_1 \dots x_{n-1}]$ and $a_2 = [x_2 \dots x_n]$ of a vector X are taken in one or the other order to compute the correlation (abscissa and ordinate in a graph). However, here, the (normalized) MOE values of all boards are considered together, which raises the question regarding the *direction* in which the data of each board are concatenated when computing the correlation. To illustrate this, suppose that, in addition to the single vector X , a second vector Y with sub-vectors $b_1 = [y_1 \dots y_{n-1}]$ and $b_2 = [y_2 \dots y_n]$ exists. Then, there are two possible manners in which they can be put together: either $[a_1, b_1]$ and $[a_2, b_2]$ or $[a_1, b_2]$ and $[a_2, b_1]$. Both of these options could be used to compute the lag-1 correlation, however, as the second halves of the vectors are interchanged, different values would be obtained.

Knowing this, different approaches can be applied to compute the serial correlations. In the method adopted here, the data of each board are taken in the order in which they were obtained, and concatenated together for the computation of the correlations. Another, more complex approach would be to perform an optimization to determine the direction of each board that maximizes the serial correlation. This approach, which corresponds to an integer non-linear problem, is not trivial and demands high computational power, even for the low number of boards used. To justify the chosen approach, it can be argued that the difference obtained between the described two options should only be significant for a small number of boards, but as the sample size increases, the difference should be negligible.

Results and discussion

KARs

The results of the global KAR determination per board are specified in Table 1. Figure 4 presents an example of one of the 3D models, in which the knots and respective clear wood area of each cell can be observed. Along with the maximum slope of grain, the global KAR results led to the specified grade allocation of the respective board. The mean KAR ratios varied from 0.10 (LS13) to 0.21 (LS7) for single knots (KAR-S), and were between 0.15 (LS13) and 0.28 (LS7) for groups of knots (KAR-G), as defined in DIN 4074-5 (2008). The scatter of the KAR values is very high almost throughout (except for KAR-S at grade LS13). The COV values are within the range of 60%–80%.

The KAR-G ratios are throughout all grades significantly higher by factors of approximately 1.5 compared to the KAR-S ratio. The KAR-S value is decisive for the grade

allocation of approximately 53% of the boards ($\approx 6\%$, as the only criterion and $\approx 47\%$ together with the fiber deviation and KAR-G value). This result is entirely different from the findings of Blaß et al. (2005) and Frese (2006) for beech wood laminations, in which, throughout various grades, almost no difference in the magnitude and scatter of the KAR-S and KAR-G values was found. This reflects presumably the growth-bound differences of the branch formation of the oak and beech species.

For any simulation of the mechanical properties of a lamination, either explicit KAR values have to be attributed to board segments (Colling 1990; Frese 2006), or this information enters implicitly by means of auto-correlated MOE values. Figure 5a reveals the discrete frequency distribution of the KAR values of the individual cells for both grades LS10 and LS13. The LS13 boards present a noticeable higher percentage of cells with KAR values in the lower ranges of $0 < \text{KAR} \leq 0.1$ and $0.1 < \text{KAR} \leq 0.2$, but for the higher KAR ranges the situation is reversed, giving the LS10 boards a longer tail, owed to the larger allowable knot areas.

For a realistic stochastic representation of a board, apart from the respective maximum KAR value, the

Figure 4: Post-processing of cell-related knot data, with exemplary image provided for board 50 (black areas correspond to CWAR).

Figure 5: (a) Discrete frequency distribution of KAR values in segments belonging to grades LS10 and LS13; (b) N-th largest KAR value relative to maximum KAR within each board.

Figure 6: Mean values and stds for distances between knots (or knot clusters) in boards belonging to grading classes LS10 and LS13.

information on the sizes of the next smaller knot or knot clusters, and their spacing is necessary. Both sets of information are strongly dependent on the regarded species. Figure 5b shows the ratio of the i -th highest KAR value of the board, relative to the board's maximum KAR value. In a rough average of all grades, the second and third largest knot size areas are approximately two-thirds and one half, respectively, of the grade-determining maximum knot size.

The distance between individual knots or knot clusters, termed inter-knot distance, representing the length of the clear wood segments in each board, is illustrated separately for the LS10 and LS13 samples in Figure 6. The inter-knot distances are regarded for different KAR thresholds. For example, the distances corresponding to the KAR threshold “0.05” comprise all of the distances between knots and knot clusters, considering all cells with KAR values >0.05 . Figure 6 indicates that the average distance between two adjacent knots is approximately 700 mm, for the case where very small KAR values (≤ 0.05) are disregarded. Furthermore, a steady increase in the inter-knot distance (clear wood length) can be observed

for both grades with an increasing KAR threshold. This is to be expected, as the probability of larger knots rapidly decreases (see Figure 5a). The COV of the inter-knot distance for the LS10 boards ranges between 50% and 70%, whilst for the LS13 sample the variation ranges between 30% and 85%. Finally, it should be pointed at the difference between both grades, regarding the rate at which the inter-knot distances get larger with an increasing KAR threshold. The steadily higher rate for LS13 boards compared to the LS10 grade is explained by the difference in knot sizes allowed in the respective grades.

Slope of grain

The results of the global slope of grain evaluation (maximum value per board) are presented in Table 1. A very pronounced difference can be observed. For the lower grades, LS10 and LS7, the mean values of the slope of grain are 2 and 4 times higher compared to the highest grade, LS13. The slope of grain value was in 40% of all boards the decisive parameter for the grade allocation. Although no local, namely cell-related, slope of grain data were sampled, it can be deduced from the results shown below that the local slope of grain should be an efficient indicating property for the variation in MOE and, hence, the tensile strength along the board length. The very promising potential of the local MOE prediction based on slope of grain, although denied by Schlotzhauer et al. (2018) for oak, has recently been revealed by Olsson et al. (2018) for narrow (100 mm) oak laminations, and will be investigated in a further study.

Global and local densities

Table 2 displays the statistical evaluation of the measured global and local densities, adjusted to MC=12%. It can be

Table 2: Global and local densities of investigated oak boards.

Grade	Density, ρ_{12} (kg m ⁻³)											
	Global						Local					
	n	Mean	COV	Min	Max	$x_{0.5}$	n	Mean	COV	Min	Max	$x_{0.5}$
Reject	4	725	4.6%	698	783	670	53	712	4.7%	640	812	657
LS7	4	709	9.7%	631	818	597	34	715	10.4%	606	825	592
LS10	17	701	6.8%	634	812	622	196	704	7.4%	609	843	618
LS13	22	691	5.8%	634	762	626	244	686	6.8%	595	826	609
LS10 + LS13	39	695	6.3%	634	812	623	440	694	7.2%	595	843	612
All	47	699	6.7%	631	818	623	527	697	7.3%	595	843	613

COV, Coefficient of variation.

observed that both, mean and minimum global densities, $\rho_{12, \text{glob}}$, of about 700 kg m^{-3} and 630 kg m^{-3} , respectively, almost coincide for grades LS7, LS10 and LS13. Similarly, the density scatter is very alike for grades LS10 and LS13, denoted by low COVs of about 7%. The results of the investigated sample indicate that the mean density of the boards is not related to the occurrence of knots and slope of grain for the investigated material and, hence, should not be a good predictor for strength class (see below, section MOE vs. KAR).

With regard to the representativity of the investigated oak material in terms of density, a very good agreement with the results of two comprehensive investigations (Glos and Lederer 2000; Faydi et al. 2017) on oak from different growth regions can be stated. The first mentioned study on bending of 340 unseasoned oak scantlings (growth region south-west Germany, forest district of Herrenberg), cut primarily from second and third length segments of logs harvested in thinning operations, was conducted with different cross-sections (in mm) from 40×80 to 60×180 . The second referenced work on French oak wood (source Bourgogne Franche Comté) focusing on vibrational MOE prediction, comprised 160 boards with cross-sections of about $24 \text{ mm} \times (80\text{--}170) \text{ mm}$. In both investigations, dealing similarly with a mixture of strength classes D18–D30 and reject, too, the average gross density, $\rho_{12, \text{glob}}$, was about 710 kg m^{-3} , which is very close to the material regarded here.

The local densities show a very similar scenario with regard to their indifference to strength grades. It is reasonable that the absolute differences between the minimum and maximum densities are more pronounced on the local level, where, on average, for grades LS7, LS10 and LS13, a value of $\Delta\rho_{\text{min/max}} = 226 \text{ kg m}^{-3}$ was determined. On the global level, the density span is 30% smaller.

The mean local density variation within a board, characterized by an average COV of 2.8%, is very small and similar throughout all strength grades (see Table 3). However, the spread of the local density variation (COV and extreme values) is somewhat larger for the strength

Table 3: COV of local densities of individual boards.

Grade	n	COV of density of individual boards (%)				
		Mean	Std.	COV	Min	Max
Reject	4	3.6	0.6	17.3	2.7	4.4
LS7	4	2.9	1.5	50.8	0.8	4.9
LS10	17	2.5	1.1	46.4	1.3	5.3
LS13	22	3.0	1.5	51.7	0.6	8.4
All	47	2.8	1.4	48.6	0.6	8.4

COV, Coefficient of variation; std., standard deviation.

grade LS13 (see Table 3). This is reasonable, as the difference between the clear wood and knot areas is more pronounced at higher strength grades.

The very low-density scatter between boards and along individual boards matches the results for the global and local beech lamination densities, as presented by Blaß et al. (2005). According to their findings, the density variation along the board length, measured for 20 boards with consecutive board segments with 200 mm lengths, was so small (specified exclusively graphically and ranging between 40 and 80 kg m^{-3} around the respective mean board density) that the density was then considered to be constant along the board length in all simulations. Similar findings and conclusions regarding the simulation in a glulam model have been presented by Colling (1990) for the case of spruce laminations.

Global and local MOE

Table 4 contains a condensed statistical evaluation of all global and local MOE results, separately for the three visual strength grades, the combined LS10 + LS13 sample, and for the entirety of specimens. Regarding the mean values of the global MOE, $E_{t,0, \text{mean, glob}}$, almost no difference can be observed between the LS10 and LS13 grades.

Table 4: Global and local MOE values for all investigated boards and cells.

MOE (GPa)	Global ($E_{t,0, \text{glob}}$)						Local ($E_{t,0, \text{cell}}$)					
	n	Mean	Std.	COV	Max	Min	n	Mean	Std.	COV	Min	Max
Reject	4	10.6	1.3	13%	9.2	12.3	60	11.6	2.6	22%	2.2	18.6
LS7	4	11.2	2.6	23%	8.1	15.0	60	11.7	3.1	26%	2.7	19.0
LS10	17	11.9	2.1	18%	8.8	16.0	255	12.2	2.7	22%	5.5	20.7
LS13	22	11.7	1.9	17%	9.1	16.6	330	12.2	2.7	22%	2.8	22.2
LS10 + LS13	39	11.8	2.0	17%	8.8	16.6	585	12.2	2.7	22%	2.8	22.2
All	47	11.6	2.1	18%	8.1	16.6	705	12.1	2.7	22%	2.2	22.2

MOE, Modulus of elasticity; std., standard deviation.

Figure 7: Cumulative distributions of all globally and locally measured MOE.

The normalized scatter, i.e. the COV, is very similar for grades LS10 and LS13 (L7 not discussed owing to the low number of specimens). The minimum and maximum values of $E_{t,0,\text{mean,glob}}$ are slightly (maximum 4%) higher for LS13. The mean and extreme values of LS7, irrespective of the very low number of specimens in the sample, are lower throughout, in line with the grading provisions.

Regarding the local MOE, $E_{t,0,\text{cell}}$, the mean values agree strongly with the global values within the respective strength grades, being maximally 4% higher in the case of LS10 and LS13. However, the spread of $E_{t,0,\text{cell}}$ is now considerably larger compared to $E_{t,0,\text{glob}}$ (Figure 7). This is highlighted by the substantially wider span of the extreme values of the $E_{t,0,\text{cell}}$ results, spreading from 2.2 to 22.2 GPa, while for $E_{t,0,\text{glob}}$, the range is significantly more narrow (8.1–16.6 GPa).

For all of the boards, excellent agreement is found between the measured global MOE ($E_{t,0,\text{glob, test}}$) and computed global MOE ($E_{t,0,\text{glob, cell}}$), derived from Eq. (3) based on the locally measured MOE values. On average, the ratio

of both results was $E_{t,0,\text{glob, test}}/E_{t,0,\text{glob, cell}} = 1.01 \pm 0.01$. When $E_{t,0,\text{glob, cell}}$ is calculated exclusively from the nine centrally placed cells in the board, i.e. for a gauge length of $5.1b$ (close to the gauge length specified in EN 408 2012), the resulting $E_{t,0,\text{glob, cell}}$ value is approximately 2% lower for all grades, compared to that obtained from the 15 cells.

Figure 8a–c illustrates three examples of different local MOE variations along the board length. Furthermore, CWAR of each cell and the global MOE (specified by the horizontal red line) are depicted. Figure 8a reveals a rather high $E_{t,0,\text{cell}}$ scatter, denoted by a COV of 21%. The position of a very weak cell (local MOE only 45% of global value) coincides with a pronounced CWAR drop-off. Board 76 (Figure 8b), with a very high global MOE of 16.6 GPa, also exhibits a high $E_{t,0,\text{cell}}$ fluctuation (COV = 16.8%), which, however, is only weakly related to the corresponding local CWAR variations. Figure 8c represents a board with very low $E_{t,0,\text{cell}}$ variability, together with an almost constant CWAR value of 100%.

The scatter of $E_{t,0,\text{cell}}$ within the boards of the different strength grades is specified in Table 5. The mean value of the COV of the intra-board MOE is slightly higher for the grade LS10 compared to LS13. However, the differences in the scatter among individual boards, determined by the COV of the COV of the intra-board MOE scatter is pronouncedly greater for the grade LS13 (50% vs. 38%).

Correlations

MOE relationship with density and KAR

Figure 9a presents the correlation between the global MOE ($E_{t,0,\text{glob}}$) and global density ($\rho_{12,\text{glob}}$), denoted by $R = 0.51$;

Figure 8: Examples of variation in local MOE and clear wood area ratios CWAR (dashed line) along lengths of different oak boards (horizontal red line: $E_{t,0,\text{glob, test}}$): (a) board 89: high COV of MOE; high correlation with CWAR fluctuations; (b) board 76: high COV of MOE; minor CWAR fluctuations; (c) board 91: small COV of MOE; constant CWAR = 100%.

Table 5: Coefficients of variation (COV) of local MOE within individual boards.

Grade	n	COV of $E_{t,0,cell}$ of individual boards (%)				
		Mean	Std.	COV	Min	Max
Reject	4	18.4	5.8	31.7	11.4	27.6
LS7	4	14.0	5.8	41.3	7.5	21.7
LS10	17	12.9	5.0	38.4	7.0	21.4
LS13	22	11.0	5.5	50.0	3.0	25.7
All	47	12.6	5.7	45.7	3.0	27.6

COV, Coefficient of variation; MOE, modulus of elasticity; std., standard deviation.

Figure 9: Correlations between MOE and density normalized to 12% MC.

The data are presented separately for the different strength grades LS7, LS10, LS13 and reject. (a) Global level; (b) local level.

the individual data points are differentiated with regard to the respective board grade.

The reported R -value is substantially lower than the correlations usually obtained for global MOE versus gross density of softwood laminations, where an R -range of 0.7–0.9 is typical (e.g. $R=0.88$ in Colling and Scherberger 1987). For hardwoods, limited literature data can be found on the relationship between $E_{t,0, glob}$ and ρ_{glob} . In a

recent study on French oak boards an R -value of 0.30 was obtained (Faydi et al. 2017), somewhat lower than in this study. For a mixed dataset of beech, oak, and ash laminations, an R -value of 0.40 was reported (Frühwald and Schickhofer 2005).

Figure 9b illustrates the correlation between the local MOE, $E_{t,0, cell}$, and corresponding local densities, $\rho_{12, cell}$. In this case, an even lower correlation ($R=0.42$) compared to the global level was obtained. It should be pointed out that the analyzed $E_{cell}-\rho_{cell}$ dataset is truncated ($n=527$) regarding the entirety of the cells ($n=705$), owing to the mentioned fracture-bound impossibility of measuring the density in each cell. The reported MOE- ρ correlation of the board segments is almost twice as high as the respective R -value of 0.23 obtained by Blaß et al. (2005) for a dataset of 330 beech board segments cut from a corresponding number of boards, with an average density $\rho_0=680 \text{ kg m}^{-3}$ and cross-sections in the range of $100 \times 25 \text{ mm}^2$ – $150 \times 35 \text{ mm}^2$. However, contrary to this investigation, in which the local densities are gross values obtained from weighing of the individual 100 mm segments, the density of the beech wood segments was then determined from 20 mm-wide knot-free segment slabs. Although global and, in particular, local MOE-density correlations found in this investigation are substantially higher than those reported for beech laminations, density has to be considered as a rather poor predictor for the MOE between and within oak boards for the material addressed in this study (see below). However, a generalization of this statement to oak species (*Q. robur*, *Q. petraea*) requires a significantly larger database.

The relationship of the global MOE with the grade-determining KAR_{max} value delivers a very low coefficient of correlation of 0.3. The removal of the two highest KAR_{max} ratios reduces the correlation to $R=0.16$, which highlights the unsuitability of this relatively small-sized database for establishing a reliable global MOE- KAR_{max} relationship. Furthermore, the adequateness of such a correlation can be questioned with regard to the theoretically small impact [e.g. Eqs. (2 and 3)] of a single weak, highly compliant local cell. The linear relationship between the cell-related KAR value, KAR_{cell} , and $E_{t,0, cell}$, based on a total of 527 cells, yielded, somewhat surprisingly, a similarly weak correlation coefficient of 0.31, being lower as the above reported R -value for the MOE-density relationship. The obtained low $E_{t,0, cell}-KAR_{cell}$ correlation deviates considerably from the result $R=0.70$ obtained by Blaß et al. (2005) for this relationship in the beech wood study. Whether the stated marked difference is species-dependent, or/and a result of the sample specifics of both, this and the referenced investigations, is of high interest and has to be investigated further.

Table 6: Parameters of Eqs. (4) and (6) for cell-related $E_{t,0} = f(KAR, \rho_0)$, obtained for investigated oak boards and literature data for beech and spruce.

Specie	Eq.	β_0	β_1	β_2	β_3	σ_i	R	n
Oak	(4)	-5200	-19 500	26.70	—	2050	0.59	527
Beech ^a		4066	-17 267	16.21	—	—	0.72	330
Spruce ^b		2695	-8756	38.96	—	1160	0.87	640
Oak	(6)	0.61×10^{-1}	-1.83	0.80×10^{-2}	-0.444×10^{-5}	0.178	0.58	527
Beech ^c		3.36×10^{-1}	-1.56	2.64×10^{-2}	-1.87×10^{-5}	0.182	0.76	482

^aBlaß et al. (2005, sample A, table 2.7); cross-sections (mm²): 100 × 25; 100 × 35; 150 × 25; 150 × 35.

^bColling and Scherberger (1987); cross-sections (mm²): 112 × 36; 195 × 36; 130 × 36; 170 × 32; 210 × 38.

^cBlaß et al. (2005, Eq. (4), table 4.1), all data ($n=482$).

KAR, Knot area ratio.

Local MOE versus the combined effect of KAR and density

The combined multivariate effect of the local KAR and density properties on the local MOE is investigated. [Note: In order to enable a direct comparison with the parameters specified in the literature for other species, the oven-dry density ρ_0 is used here, too. In order to achieve this, the previously specified density values ρ_{12} were converted into MC=0% by the MC equation provided in EN 384 (2019). This results in a minor bias, as the density-moisture adjustment equation specified in EN 384 does not fully apply to an MC-adjustment down to 0%.]

Table 6 presents the regression analysis results for the relationship of the local MOE, $E_{t,0,cell}$, with the cell-related KAR and density values using Eqs. (4) and (6). For comparison, the results reported by Blaß et al. (2005) for beech wood segments and Colling and Scherberger (1987) for spruce (*Picea abies*) segments are also provided (see Table 6 for cross-section dimensions). The gauge length in the referenced tension tests with beech wood was 150 mm, and for spruce, the local MOE was determined by the longitudinal vibration in segments, with a length of 400 mm (for further details, see Table 6).

Prior to a discussion of the oak results, it should be mentioned that a regression analysis by means of Eq. (5) produces almost identical β_i parameters, as obtained in the case of Eq. (6). Furthermore, the stds of the residues and R -values of both equations are alike, underlining the vanishing importance of the squared density term in Eq. (6).

It can be observed that the correlation coefficient $R=0.59$ for the oak $E_{t,0}$ relationship with the KAR and density is markedly lower than that of the beech material, and significantly smaller than that of the spruce segments. The strong difference in the obtained correlations for oak and spruce is further highlighted by the pronouncedly

larger std. σ_i of the residues for oak, although the absolute values of the MOE are comparable. The fact that the R -value from the multiple regression is significantly higher compared to the R -values 0.43 and 0.31, obtained for the MOE relationship with the single variables ρ and KAR, respectively, highlights the pronounced complementarity of both predictors for the investigated oak material. This is very different to the results of the referenced beech wood study, where MOE is almost entirely predicted by KAR, and the further inclusion of density delivers only a marginal increase of R . The notably lower $E_{t,0}$ prediction quality compared to beech wood, and even more so versus spruce, underlines the assumption of an obviously missing additional MOE predictor variable in the regression equations. A study presented by Olsson et al. (2018) delivered substantial evidence for the idea that, particularly in the case of the regarded species, the inclusion of the thus far neglected local fiber deviation should provide a significantly higher MOE prediction accuracy.

Serial correlations of local MOE

As demonstrated above, the local MOE exhibits pronounced fluctuations along the board length with respect to its global value. A large portion of the fluctuation can be directly attributed to the presence of knots (see e.g. Figure 8a). However, a high variation in the measured MOE throughout the board was also observed in the *knot-free* regions (see e.g. Figure 8b). For the purposes of this paper, this variation in the *knot-free* region is considered as the *base* variation in the MOE, which depends to a large degree on the variation in the density and presumably even more on the slope of grain.

Figure 10a and b illustrate the regression analysis plots of the first two serial correlations (lag-1 and lag-2) for the previously defined clear wood segments, after

Figure 10: Data and linear regressions of first two lags of serial correlation [(a) and (b)], and calculated serial correlations of lags 1–5 (c).

applying the normalization regarding the average of the three maximum MOEs per board, $\bar{E}_{\max,3}$, specified above as alternative B. Figure 10c reveals the decrease in the serial correlations for the first five lags. This decrease follows very closely the law $\text{lag}_n = \text{lag}_1^n$, which corresponds to an autoregressive process of first order.

Table 7 presents the serial correlation results of all three investigated evaluation alternatives A–C (see above). Not applying any normalization to the data (alternative C) results in very high serial correlations up to the lag-5. These are in the same order of magnitude (0.89–0.95) as the results presented by Taylor and Bender (1991), for investigations on Douglas fir (although different window lengths were used). The results for the evaluation alternative B, by applying the normalization based on $\bar{E}_{\max,3}$ show higher serial correlations ($R = 0.61$ for the first lag) as for the alternative A, and positive values for the first four autocorrelations (fifth lag is only slightly negative). Table 7 also specifies the serial correlation coefficients obtained for all board cells, irrespective of their KAR values after applying the $\mathcal{N}(0,1)$ and $\bar{E}_{\max,3}$ normalizations. It can be observed that the consideration of knot-affected cells leads to a marked decrease in the serial correlations, as the MOE of knot-affected cells differs notably from knot-free cells, which is expressed as large drop-offs in the MOE profile. However, this does not mean that knot-affected cells are entirely randomly located in relation to other cells, but occur usually at species-dependent intervals, and adjacent to cells with reduced MOE (due to fiber deviations in the vicinity of knots).

Conclusions

Based on the methodology of the repeated tensile loading of adjacent small board cells, combined with the measurement of local KARs and densities, different approaches for the local MOE prediction of the investigated oak board sample were analyzed, resulting in the following conclusions:

Table 7: First five serial correlation values according to different normalization procedures for clear wood segments (MOE base variation) and for all board cells.

Method	Procedure	Considered cells	Lag-1	Lag-2	Lag-3	Lag-4	Lag-5
A	$\mathcal{N}(0,1)$	Clear wood ^a	0.42	0.10	−0.05	−0.08	−0.24
B	$\bar{E}_{\max,3}$	Clear wood ^a	0.61	0.38	0.19	0.08	−0.07
C	No normalization	Clear wood ^a	0.89	0.84	0.81	0.78	0.75
A	$\mathcal{N}(0,1)$	All	0.32	−0.02	−0.09	−0.14	−0.20
B	$\bar{E}_{\max,3}$	All	0.34	0.08	0.05	0.00	0.00

^aConsidering a minimum of seven contiguous cells with KAR < 0.05.
MOE, Modulus of elasticity.

- The prediction accuracy of the local MOE exclusively by local or global density, or KAR, is low.
- The very low local MOE-KAR correlation differs pronouncedly from literature results for beech wood. This result, which might be widely species-dependent and further related to the investigated samples, deserves further investigation.
- A linear combination of both local quantities, density and KAR significantly increases the prediction quality. However, the correlation coefficient $R=0.6$ remains markedly lower than that reported in the literature for beech and spruce laminations. The use of an additional squared density term in the linear regression analysis, as proposed in the literature to improve the MOE or $\ln(\text{MOE})$ relationship, does not lead to any increase in the correlation.
- The reduced prediction accuracy for the local MOE compared to beech and spruce implies that a further MOE-explaining parameter is missing. It is assumed that the additional inclusion of the local slope of grain should lead to considerably improved correlations.
- Regarding the derivation of serial correlations for the local MOEs, the choice of an appropriate normalization is crucial. Applying no normalization delivers too high serial correlations, which is bound to the high inter-board MOE variation. A normalization with respect to the average of the three highest clear wood MOEs per board seems to be superior compared to the normalization using a standard normal distribution.
- The notably, roughly 50% lower serial (auto-) correlations of the local MOE obtained for all board cells, compared to the serial correlation for contiguous clear wood segments indicates that the presence of knots has a statistically quantifiable effect on the MOE variation, which can serve to model different levels of knottiness in boards.
- The study of the local MOE variation by means of autocorrelations, as opposed to the more classical approach regarding knot indicators, enables a representation of the observed MOE variability without requiring explicit consideration of knot-affected regions. This allows for the development of MOE simulation models that are independent of explicit knot indicators, focusing mainly on the stochastic characteristics of the material properties, which intrinsically considers the effects of knots. Whether this approach leads to *better* simulation models compared to models based on physical parameters was not considered in this paper, and remains a relevant question to be answered in future investigations.

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