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THE INFLUENCE OF AN IMPROVED STRENGTH GRADING IN SITU ON MODELLING TIMBER STRENGTH PROPERTIES

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Abstract

The management and preservation of structures in our built environment are central and challenging tasks for practicing engineers. Various situations lead to the necessity to evaluate existing timber structures. Within the CEN member states, the so called Eurocodes form the basis of design and verification the of load-bearing capacity of structures. Current Eurocodes do not contain special recommendations for existing structures, the principles for new structures are applied. This can lead to an incorect estimation of the load-bearing capacity within the semi-probabilistic safety concept.

A central task within the investigation and evaluation of existing structures is strength grading of the material in situ using nd/sd technical devices. Studies show the potential of the ultrasonic time-of-flight measurement in combination with visual evaluation for an improved grading. This potential should be considered when modelling the material properties of a structural element. The information on the material from an improved grading can be used to update the distribution function of the material strength as a target variable using a measured reference variable. In this contribution test data from spruce, pine and oak is analysed applying the stochastic grading model of Pöhlmann & Rackwitz 1981.

It can be shown that different grading techniques influence the updated distribution function of the material strength within the grade. This can be considered for the development of an adjusted design concept for the evaluation of existing timber structures. What is more, perspectives to develop updated models dependent on the knowledge available are shown and discussed.

1 MOTIVATON

To estimate the material strength of a structural member made from timber, the material is graded into strength classes of EN 338:2016-07 [1] applying national grading standards and the assignment criteria of EN 1912:2013-10 [2]. This procedure results in a lower variability of the material properties within a class compared to the ungraded material. The variability of strength properties within a class depends on the quality of the grading procedure. The application of grading rules that have been developed for new structures on elements in existing structures is difficult, as elements are often not fully accessible and not all criteria can be investigated (see [3]). Nevertheless, a qualified grading on site enhances the amount knowledge of the specific element. Depending on the grading procedure, e.g. visual investigation or different nd/sd (non-destructive/ semi-destructive) technical devices, the amount of information changes and can be increased by combining different devices. An enhanced amount of knowledge helps to reduce uncertainties concerning the material quality and load-bearing capacity. An updated material model can be considered within a concept for the standardised verification of load-bearing capacity of existing timber structures. This is part of the work for Knowledge Level 2b as illustrated in

Figure 1. The proposed framework has been presented similarly in [4], here further developments are shown.

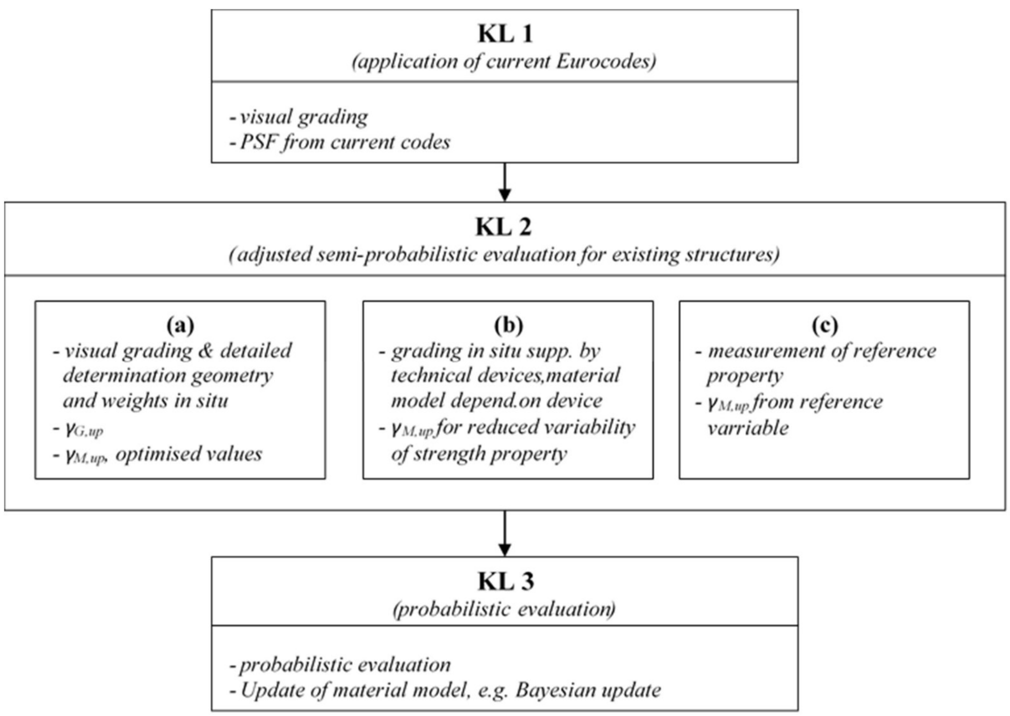

Figure 1: Framework for the evaluation of load-bearing capacity of existing structures.

A careful investigation is of utmost importance to avoid damage of a structure. Thus, results of calibration tests to analyse the potential of non-/semi-destructive grading by ultrasonic velocity measurement and extraction of core samples in combination with visual grading are presented. In this contribution the influence of grading procedures on the representation of the material model are studied. To obtain the material distribution function in a strength class, the stochastic grading model by Rackwitz & Pöhlmann is applied. These studies are based on the material tests presented in Linke, Rug & Pasternak [5]. What is more, Baesian Updating is performed to study the influence the grading techniques applied on the predictive model for a strength parameter.

2 THE STOCHASTIC GRADING MODEL BY PÖHLMANN & RACKWITZ

A stochastic model to consider the grading procedure for the derivation of a material model can be found in Rackwitz and Pöhlmann [6]. The basic assumptions of the model are explained shortly hereinafter, for details see [6] or [7].

The target variable may be *Y*. By a linear regression model it is connected to the reference variable *X*, which can be measured. Within these tests, errors can occur. A variable *Z* with an error term τ is measured, so that

$$Z = X + \tau \tag{1}$$

where X = reference variable, τ = normal distributed error term with $\tau \sim N(0,\sigma_\varepsilon^2)$

The target variable *Y* is not dependent on τ. It is assumed that the measured variable *X* is normal distributed with $N(0, \sigma_E^2)$. The probability density function (PDF) of the variable *Y* within a certain class is derived by Pöhlmann & Rackwitz [6]

$$f_y(y)\frac{1}{K}\frac{\sigma}{\sigma_\varepsilon\sigma_E}\varphi\left(\frac{y}{b}-\frac{a}{b}-\mu_E\right)/\sigma_M\left(\Phi\left(\frac{C_o}{\sqrt{1+C_I^2}}\right)-\Phi\left(\frac{C_u}{\sqrt{1+C_I^2}}\right)\right) \tag{2}$$

with

$$\sigma = \frac{\sigma_\varepsilon\sigma_E}{b\sigma_M} \quad (3) \qquad \sigma_M^2 = \left(\frac{\sigma_\varepsilon^2}{b^2}+\sigma_E^2\right) \quad (4) \qquad m = \frac{(y-a)/\sigma_E^2/b+\mu_E/\sigma_E^2}{1/\left(\sigma_E^2/b^2\right)+1/\sigma_E^2} \quad (5)$$

$$C_o = \frac{g_o - m}{\sigma_\tau} \quad (6) \qquad C_u = \frac{g_u - m}{\sigma_\tau} \quad (7) \qquad C_I = -\frac{\sigma}{\sigma_\tau} \quad (8)$$

$$y = a + bx + \varepsilon > 0 \tag{9}$$

where a and b = parameters of the linear regression, g_o and g_u = boundaries of the grading parameter for the classes. The normalising constant K can be calculated

$$K = \Phi\left(-\frac{C_o^{'}}{\sqrt{1+C_1^{'2}}}\right)-\Phi\left(-\frac{C_u^{'}}{\sqrt{1+C_1^{'2}}}\right) \tag{10}$$

with

$$C_o^{'} = \frac{g_o - \mu_E}{\sigma_\tau} \quad (11) \qquad C_u^{'} = \frac{g_u - \mu_E}{\sigma_\tau} \quad (12) \qquad C_1^{'} = -\frac{\sigma_E}{\sigma_\tau} \quad (13)$$

The cumulative distribution function (CDF) can be obtained from Eq. (2) by numeric integration [7]. Within this method, the correlation between grading parameter X and target variable Y is considered.

3 TEST DATA

3.1 Overview of analysed grading parameters and studied timber species

Detailed information on grading procedures and timber samples can be found in [5]. Table 1 summarizes the scope of the investigation.

Table 1: Grading parameters and studied timber species – overview.

Grading Techniques	Visual grading		
	Direct ultrasonic time-of-flight measurement (Steiger)	Indirect ultrasonic time-of-flight measurement (Steiger)	Density measurement by samples acc. to DIN EN 408:2012-10
Timber species	Oak (301 samples)		
	Spruce (303 samples)		
	Pine (300 samples)		

4 RESULTS

4.1 General remarks

Applying the stochastic grading model, the probability density function of the target property (bending strength) in a strength class by considering the correlation of reference and target variable is calculated. As the concept is based on a two-dimensional normal distribution, the probability density function within the strength class from Eq. (2) corresponds to a normal distribution. However, in reliability analyses strength properties are modelled by lognormal distributions to avoid negative values. The parameters of the corresponding lognormal distribution can be calculated from the parameters of a normal distribution.

Technical devices have been checked acc. to DIN 4074-3:2008-12 [8]. Based on this, the error term in the stochastic model can be assumed to be normal distributed with $\tau \sim N(0,20^2)$ [m/s] for ultrasonic measurements. For density measurements the error term consists of the weight and the geometry measurement, and can be taken $\tau \sim N(0,(10^{-9})^2)$ [kg/m³] for these very sensible devices. The values are mean values for all timber species investigated. The following sections show the results. Results are discussed in section 4.5.

4.2 Oak samples

The results for grading using the ultrasonic device are given in Table 2 and illustrated exemplary in Figure 2 for indirect ultrasonic time-of-flight measurement. As the correlation of density measurement and bending strength of oak samples was low, no results can be shown here.

Table 2: Results for oak samples and different grading techniques obtained from stochastic grading model.

Timber species	**Grading based on**					
	Direct US time-of-flight measurement		**Indirect US time-of-flight measurement**		**Density measurement by samples acc. to DIN EN 408:2001-12**	
Oak	**ungraded**					
	μ [N/mm²]			56.93		
	cov			0.35		
	D35					
	cov x_k [N/mm²] ρ	0.25 36.54 0.69	*cov* x_k [N/mm²] ρ	0.24 37.29 0.72	*cov* x_k [N/mm²] ρ	*Low correlation*
	D40					
	cov x_k [N/mm²] ρ	0.23 41.26 0.69	*cov* x_k [N/mm²] ρ	0.22 46.46 0.72	*cov* x_k [N/mm²] ρ	*Low correlation*
	Better than D40					
	cov x_k [N/mm²] ρ	0.21 49.54 0.69	*cov* x_k [N/mm²] ρ	0.17 61.53 0.72	*cov* x_k [N/mm²] ρ	*Low correlation*

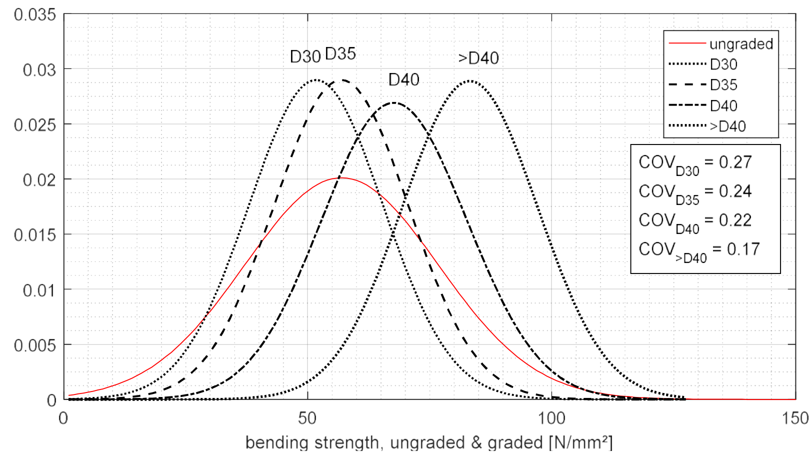

Figure 2: Probability density functions of graded and ungraded material from stochastic grading model exemplary for oak samples and strength grading based on indirect ultrasonic-time-of-flight measurement.

The results from oak samples show a low variability of the bending strength within the classes D40 and better than D40 when graded by ultrasonic time-of-flight measurements. Characteristic values are similar to the values in EN 338:2016-07 [1] or higher. Thus, this method seems to be well suitable to support grading procedures of oak members. The reason for the correlation coefficient of density and bending strength being low in these tests remains to be studied.

4.3 Spruce samples

The results for spruce samples are summarised in Table 3.

Table 3: Results for spruce samples and different grading techniques obtained from stochastic grading model.

Timber species	Grading based on					
	Direct US time-of-flight measurement		Indirect US time-of-flight measurement		Density measurement, samples acc. to DIN EN 408:2001-12	
Spruce	**ungraded**					
	μ [N/mm²]			45.67		
	cov			0.36		
	C24					
	cov	0.36	*cov*	0.37	*cov*	0.39
	x_k [N/mm²]	21.38	x_k [N/mm²]	20.34	x_k [N/mm²]	19.78
	ρ	0.42	ρ	0.44	ρ	0.30
	C30					
	cov	0.33	*cov*	0.33	*cov*	0.38
	x_k [N/mm²]	25.43	x_k [N/mm²]	24.53	x_k [N/mm²]	21.12
	ρ	0.42	ρ	0.44	ρ	0.30
	Better than C30					
	cov	0.29	*cov*	0.29	*cov*	0.34
	x_k [N/mm²]	31.16	x_k [N/mm²]	31.59	x_k [N/mm²]	26.14
	ρ	0.42	ρ	0.44	ρ	0.30

Figure 3 illustrates the probability density functions of the bending strength of the ungraded and graded material exemplary for direct ultrasonic time-of flight measurement. Table 3 and Figure 3 show higher coefficients of variation (cov) of the strength property compared to the studies on oak members. What is more, the correlation coefficient is in the middle range. Besides, the characteristic values (5%-quantile based on a lognormal distribution) are relatively low. However, similar to the studies on oak samples, the coefficient of variation of the strength property in the class is reduced for strength classes > C24 (>D35 for oak) compared to the ungraded material.

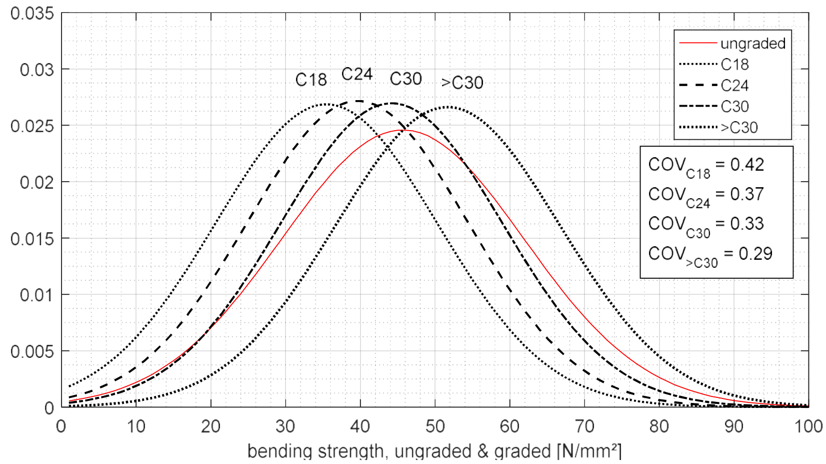

Figure 3: Probability density functions of graded and ungraded material from stochastic grading model exemplary for spruce samples and strength grading based on direct ultrasonic time-of-flight measurement.

4.4 Pine samples

Studies on pine samples showed correlations of $\rho_{US,dir} = 0.23$ for direct and $\rho_{US,indir} = 0.27$ for indirect ultrasonic time-of-flight measurements. For grading based on density measurements on small clear samples the correlation coefficient is $\rho_{dens} = 0.54$. As almost all the samples would be graded to strength class C40, no different results for strength classes can be shown. The coefficient of variation is $cov = 0.36$, the expected value is $\mu = 53.72$. Thus, solely visual grading seems to underestimate the load-bearing capacity.

4.5 Discussion of results

It can be concluded that the quality of the grading procedure based on different technical devices depend on the timber species. A great potential of the ultrasonic time-of-flight measurement as grading parameter can be shown for oak samples. The variability of strength parameters in the classes were low, characteristic values (5%-quantile) were high. For spruce and especially pine the correlation of USM with the strength properties as single grading parameter were low. This is probably due to timber species specific properties as e.g. a high KAR (knot area ratio) value.

At first sight these correlations seem to be low. However, it has to be emphasized that grading parameters have been analysed independently. The load-bearing capacity of timber as inhomogeneous material depend on a range of parameters which have to be considered jointly. Being focused on single parameters, the results are promising. For future work, multiple correlation of grading parameters has to be analysed. This leads to an accounted reduction of the variability of material properties within the classes.

5 BAYSIAN UPDATE OF THE MATERIAL MODEL

5.1 General idea

Based on Baysian estimation the material model can be updated by jointly consideration of prior and additional information. The posterior model $f_{\Theta}^{''}(\theta \mid \hat{x})$ is developed by

$$f_{\Theta}^{''}(\theta \mid \hat{x}) = \frac{f_{\Theta}^{'}(\theta) L(\theta \mid \hat{x})}{\int f_{\Theta}^{'}(\theta) L(\theta \mid \hat{x}) d\theta} \tag{14}$$

where $f_{\Theta}^{'}(\theta)$ = probability density function of a of a random variable based on prior information, $L(\theta \mid \hat{x})$ = likelihood and $\int f_{\Theta}^{'}(\theta) L(\theta \mid \hat{x}) d\theta$ = normalising factor. With the posterior probability density function the predictive function $f^{'''}(x)$ can be calculated [9]

$$f^{'''}(x) = \int fx(x \mid \theta) f_{\Theta}^{''}(\theta \mid \hat{x}) d\theta \tag{15}$$

with $f_{\Theta}^{''}(\theta \mid \hat{x})$ = posterior probability density and $fx(x \mid \theta)$ = probability density function of x dependant on ϑ The integrals can be solved numerically or by simulation. For normal distributions analytical solutions exist, see e.g. [9].

Considering grading procedures applicable for elements in existing structures, a new prior model that constitutes of a combination of visual grading and different technical devices can be developed. This model can be used as basis for an adjustment of partial safety factors depending on the amount of information collected in situ and for a Baysian update of the material model. Based on this information, the posterior and the predictive model can be developed using additional test data from a specific object. For an illustration of the procedure see

Figure 4, levels are explained shortly in Figure 1.

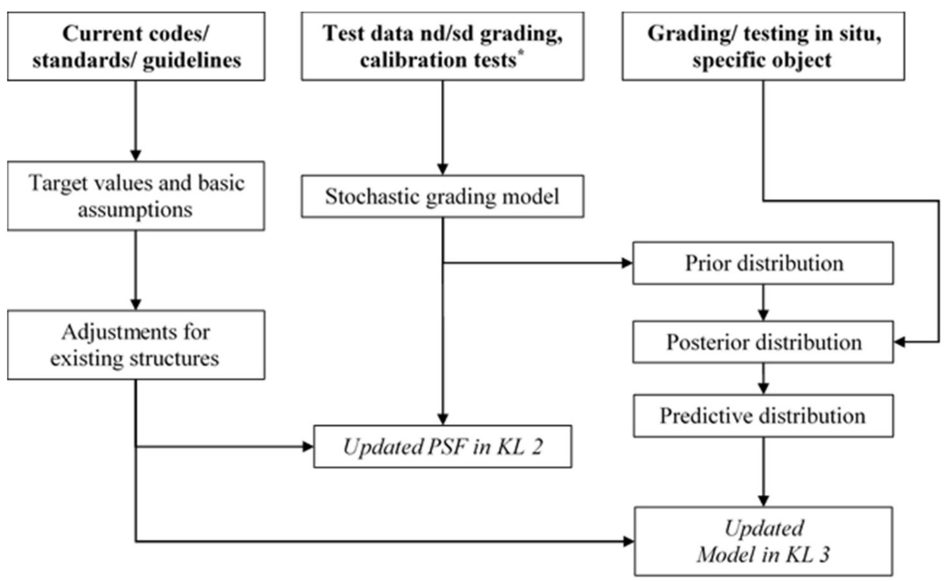

Figure 4: Schematic updating procedure (*Testing has been carried out at HNE Eberswalde, see [5]).

If the material is graded by visual inspection without measuring specific properties, the material model may be developed from EN 338 and the Probabilistic Model Code (PMC) by the Joint Committee on Structural Safety (JCSS) [10]. This model may be used as prior model for a Baysian update and as basis to derive a target safety level for structures designed by current regulations. For specific grading procedures the material model as prior distribution and for an adaption of safety factors may be adjusted. As mentioned above, a model including multiple correlation of grading parameters to reduce the variability of parameters has to be developed, work is still under progress. However, perspectives shall be shown and discussed.

5.2 Exemplary data

For exemplary purpose it is assumed that three measurements lead to estimated values for the bending strength of $f_{m,ex,n} = [61.8\ \ 80.5\ \ 79.5\ \ 55.1\ \ 85.1]\ N/mm^2$. For this example, five of the samples tested in [5] that have been graded by visual inspection and indirect ultrasonic time-of flight by one of both criteria to D40, the other one higher, have been chosen randomly (samples Ei-7-103, Ei-7-112, Ei-7-128, Ei-7-129, Ei-7-182).

Based on Table 2, a cov for the bending strength in class D40 of $cov_{m,D40} = 0.22$ is assumed, the characteristic value is taken from EN 338:2016-07 [1] $R_{k,D40} = 40 N/mm^2$.

5.3 Update of the partial safety factor based on testing (KL 2c)

The parameters of the predictive distribution function can be used to update the partial safety factor (PSF) for the evaluation of load the bearing capacity. A method as described in [4] is applied. The updated partial safety factor can be calculated with

$$\gamma_{m,up} = \exp\left(\frac{cov_{y,target} \cdot \sqrt{1-\rho_{x,y}^2}}{1+\rho_{x,y} \cdot cov_{y,target} \dfrac{x_{meas} - \mu_{x,ref}}{\mu_{x,ref} \cdot cov_{x,ref}}} \cdot \left(\alpha_R \cdot \beta + \Phi^{-1}(q) \right) \right) \tag{16}$$

$$\gamma_{M,up} = \gamma_{Rd} \cdot \gamma_{m,up} \tag{17}$$

with $cov_{y,target}$ the coefficient of variation of the target variable y, $cov_{x,ref}$ the coefficient of variation of the reference variable x, $\mu_{x,ref}$ the mean value of the reference variable x, $\rho_{x,y}$ the correlation coefficient of both variables, α_R the sensivity factor of the material resistance, β the target reliability, q the quantile for the definition of the characteristic value of the target variable used for design and γ_{Rd} the safety factor for model uncertainties.

Current work showed that β may be assumed $\beta = 3.2$ for a reference period of $T_{ref} = 50a$. With $\alpha_R = 0.8$ [11] and $q = 0.05$ the second part of Eq. (16) becomes 0.915. The correlation coefficient is taken from Table 2 as $\rho_{x,y} = 0.72$, the measured variable is $x_{meas} = 4.764 \cdot 10^3\ m/s$ (mean value of measured variables), $\mu_{x,ref}$ is taken as criteria of the grading procedure for D40 $\mu_{x,ref} = 4.602 \cdot 10^3\ m/s$, the coefficient of variation of the measured variable $cov_{x,ref}$ is taken from JCSS PMC [10] $cov_{x,ref} = 0.10$ and the coefficient of variation of the target variable $cov_{y,target}$ is taken from the predictive distribution (Table 4) $cov_{y,target} = 0.22$. The model factor is taken $\gamma_{Rd} = 1.08$ (see [4]). Applying these values the PSF becomes $\gamma_{M,up} = 1.24$.

Another approach is the update of the PSF for different design situation as optimisation problem. This work is at state still in progress and will be part for an evaluation in level KL 2a/2b (see

Figure **1**).

5.4 Bayesian update of the material model (KL 3)

For this contribution the analytical procedure to obtain the predictive model as described in [9] is applied. As prior and posterior distribution functions can be assumed belonging to the same distribution type, the prior distribution is a conjugate prior.

The predictive distribution function may be used to verify the load-bearing capacity of the member (KL 3).

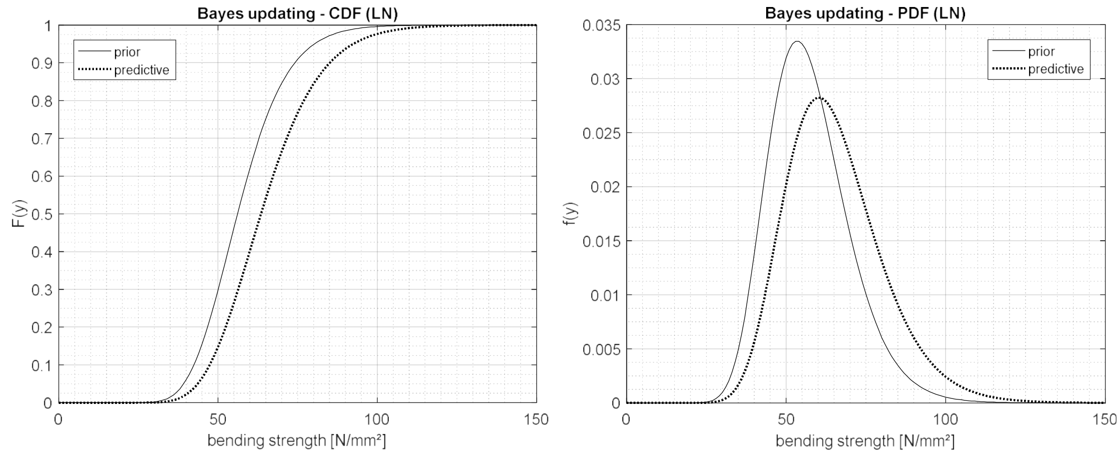

Figure 5: Bayes updating, left: cumulative distribution function, right: probability density function.

Table 4: Exemplary Bayes updating of bending strength based on oak samples.

	m [N/mm²]	cov	x_k [N/mm²]
Prior	57.44	0.22	40
Data	72.38	0.18	53.53
Predictive	65.17	0.23	44.61

The expected value of the predictive material model is higher than of the prior model. The coefficient of variation is a little higher, as within the updating procedure the uncertainties resulting from the original (prior) model and the test results are coupled.

The application of the procedures described in section 5.3 and 5.4 on a practical example is illustrated in [12].

6 DISCUSSION AND FUTURE WORK

Results show, that the correlation coefficients for ultrasonic time-of-flight measurement and bending strength depend on the timber species. Evaluated as single grading parameters, the correlation has found to be low for pine, moderate for spruce and very good for oak. The correlation of the bending strength with density measured on small clear samples as single grading parameter has been found to be moderate.

These values result from the numerous parameters that influence the load-bearing capacity of a member made from natural grown timber. It becomes clear that multiple regression coefficients of different grading parameters could help to consider more grading parameters simultaneously. Combining the information gained from visual inspection, ultrasonic measurements and extraction of core samples for density measurements increases knowledge and hence reduce uncertainties concerning load-bearing capacity. What is more, the influence of the prior distribution function on the updated model has to emphasized. Thus, a careful choice of this model is of great importance.

For hardwood the correlation of ultrasonic time-of-flight measurement and bending strength seems to be very good. However, including more grading parameters into a multiple regression model could improve the correlation and reduce the variability even more.

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