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DOI
10.1515/hf-2021-0029

Publication date
2022

Document Version
Final published version

Published in
Holzforschung

Citation (APA)
Westermayr, M., Zeilhofer, M., Rais, A., Kovryga, A., & Van De Kuilen, J. W. G. (2022). Tensile strength grading of beech (Fagus sylvatica L.) lamellas from multiple origins, cross sections and qualities. *Holzforschung*, *76*(5), 397-407. https://doi.org/10.1515/hf-2021-0029

Original Article

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Tensile strength grading of beech (*Fagus sylvatica* L.) lamellas from multiple origins, cross sections and qualities

https://doi.org/10.1515/hf-2021-0029
Received February 19, 2021; accepted December 16, 2021;

Abstract: The market share of European beech (*Fagus sylvatica* L.) wood in the construction sector is low despite an increase in beech stock in Central European Forests in recent years. More efficient sawing techniques, higher lamella grading yields and solving of adhesion challenges may increase the competitiveness of beech glulam and promote its use. The aim of this paper is to revise the lamella grading system in the current German technical approval for beech glulam Z-9.1-679:2019 (DIBt (2019). *BS-Holz aus Buche und BS-Holz Buche Hybridträger und zugehörige Bauarten.* Allgemeine bauaufsichtliche Zulassung Z-9.1-679:2019. Deutsches Institut für Bautechnik) and to suggest modifications in the lamella grading rules for glulam production allowing higher yields and reliable tensile strength values at the same time. The unique dataset in this study combined different origins of lamellas and covered a wide range of visual, physical and mechanical wood characteristics including a high amount of low quality material. Indicating properties (IPs) for tensile strength, such as knot parameters and dynamic modulus of elasticity, were contrasted with tensile strength and static modulus of elasticity. Beech lamellas, graded by means of Z-9.1-679:2019 (DIBt (2019). *BS-Holz aus Buche und BS-Holz Buche Hybridträger und zugehörige Bauarten.* Allgemeine bauaufsichtliche Zulassung Z-9.1-679:2019. Deutsches Institut für Bautechnik), did not achieve the tensile strengths required for glulam production in many grading classes and the yield was low. A machine grading approach with dynamic modulus of elasticity as a single grading criterion gave higher yields than the current grading procedure and high reliability for tensile strength prediction with a prediction accuracy of $R^2 = 0.67$.

Keywords: grade determining properties (GDPs); grading classes; hardwood; indicating properties (IPs).

1 Introduction

The German technical approval for beech glulam Z-9.1-679:2019 (DIBt 2019) allows the production of six different glulam strength classes ranging from GL 28h to GL 48c. For beech glulam of a certain strength class, requirements for the lamella grades are defined in the approval, which are listed in Table 1. To produce for example beech glulam of strength class GL 32c, the outer lamellas need to fulfil the visual grade LS 13 and the inner lamellas must be of grade LS 10. The visual LS grades in Z-9.1-679:2019 (DIBt 2019) are defined in the German visual strength grading standard for hardwood DIN 4074-5:2008 (DIN 2008). For beech glulam of higher strength classes, additional requirements to the LS grades are given in terms of knot values and dynamic modulus of elasticity (MoE_{dyn}) (see “A” and “MoE_{dyn}” in Table 1). In DIN 4074-5:2008 (DIN 2008), knots are the main visual grading criterion indicating lamella tensile strength. In many hardwood species, such as beech, actual sizes of knots are hard to determine visually due to the low difference in colour compared to the surrounding wood (Kovryga et al. 2019a). Detecting knots by means of X-ray scanning also faces difficulties in beech wood due to the low density difference of knots to the surrounding clear wood (Giudiceandrea 2005). Recent studies (Ehrhart et al. 2016; Plos et al. 2018; Torno et al. 2013; Westermayr et al. 2018a) showed that

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Table 1: Grading rules from Z-9.1-679:2019 (DIBt 2019) and corresponding characteristic tensile strength estimated by Frese and Blaß (2005).

Grading class	Thresholds				$f_{t,0,k}$ (MPa)
	Grade acc. to DIN 4074-5	DEB/DAB acc. to DIN 4074-5	Additional knot criterion	MoE_{dyn} (GPa)	
LS10	LS10	≤0.33/ ≤0.5			22
LS10 + E13	LS10	≤0.33/ ≤0.5		>13	20
LS10 + E14	LS10	≤0.33/ ≤0.5		>14	30
LS13	LS13	≤0.2/ ≤0.33			27
LS13 + A	LS13	≤0.2/ ≤0.33	DEB ≤0.04		31
LS13 + E14	LS13	≤0.2/ ≤0.33		>14	30
LS13 + E15	LS13	≤0.2/ ≤0.33		>15	40
LS13 + A + E15	LS13	≤0.2/ ≤0.33	DEB ≤0.04	>15	48

grading in compliance with Z-9.1-679:2019 is not efficient in terms of yield as well as reliability of tensile strength class (T-class) allocation of the graded material. Low grading yields mean that in the production process from the log to the dried, graded and planed lamellas, only approximately 20% of the log can be used in the final glulam product (Torno et al. 2013). The German technical approval, for example, excludes lamellas with pith from lowest visual grade LS7. Another study showed, that beech lamellas, which are currently excluded from glulam production could be used for glulam manufacturing (Westermayr et al. 2018b).

The glulam strength classes in Z-9.1-679:2019 (DIBt 2019) originated from studies by Blaß et al. (2005) and Frese and Blaß (2005). Blaß et al. (2005) performed destructive and non-destructive investigations on beech lamellas from three different sawmills with visual grading class LS10 or higher. The lamellas were tested with a free testing length of 150 mm, which does not correspond to EN 408:2012 (CEN 2012a) regulations. They suggested a lamella grading approach with knot parameter thresholds from DIN 4074-5:2008 (DIN 2008) and with MoE_{dyn}. An assignment of characteristic tensile strength to lamella grading class can be found in the study by Frese and Blaß (2005). Blaß and Frese (2006) extended the model for hybrid glulam from beech and Norway spruce (*Picea abies*) and examined physical properties of beech lamellas. Frühwald and Schickhofer (2005) confirmed that knot parameters and MoE_{dyn} are good indicating properties (IPs) for tensile strength and *MoE*. Hübner (2009) defined more visual grading classes than DIN 4074-5:2008 (DIN 2008) and proposed stricter requirements for DEB value than DIN 4074-5:2008 (DIN 2008) after destructive tensile testing of 405 beech boards from German and Austrian forests. By means of a combined visual and machine strength grading approach with DEB and MoE_{dyn}, higher lamella strength classes than by means of visual grading alone could be achieved. Hübner (2009) did not exclude pith-containing lamellas in lower grades due to low influence of pith on the tensile strength of visually graded lamellas, which contrasts DIN 4074-5:2008 (DIN 2008). Ehrhart et al. (2016) defined new grading rules for Swiss beech lamellas of T-class T22 or higher based on a combined grading approach with knot parameter tKAR and MoE_{dyn}. Fortuna et al. (2018) observed tensile strength and *MoE* as well as non-destructive properties of a representative sample of Slovenian beech lamellas from mainly C and D log-quality according to EN 1316-1:2012 (CEN 2012b). The lamellas were graded into T-classes by means of MoE_{dyn}. Plos et al. (2018) graded the lamellas from Fortuna et al. (2018) visually according to DIN 4074-5:2008 (DIN 2008) and found high reject rates as well as inefficient strength class allocation. Schlotzhauer et al. (2018) observed visual and machine strength grading characteristics for beech lamellas cut from C and D quality logs. In contrast to other hardwood species, knots exhibited big diameters and the actual knot sizes were not always easy to determine. Brunetti et al. (2020) investigated the bending strength of beech boards from different stands representing the natural raw material of beech timber in Italy and collected physical properties of the raw material. The previous studies mentioned either low yield, inefficient strength class allocation or problems with reliability of the currently applicable grading procedure given in Z-9.1-679:2019 (DIBt 2019) and showed the need for a revision of currently applicable grading rules as well as for the proposal of new grading rules. The grading rules of Z-9.1-679:2019 have so far been reviewed on single datasets but not on a combined dataset with various origins of the lamellas as required by EN 14081-2:2018 (CEN 2018). This gap should be filled with the present study.

Efficient grading rules for the whole range of beech board qualities may increase lamella yield for glulam and CLT production, increase competitiveness of the product and promote the use of beech glulam in construction sector. Consequently, this research focuses on:

- Analysis of the influence of visual grading parameters and MoE_{dyn} on the tensile strength representing a large beech quality range.
- Derivation of effective grading rules combining high yields with reliable values for tensile strength of the lamellas.

2 Materials and methods

2.1 Material

Three different datasets of beech lamellas with non-destructively and destructively measured properties were available. The datasets differed regarding their origin, wood quality and cross section.

2.1.1 Dataset 1: beech lamellas from Creuzburg region (CB): The first dataset consisted of beech lamellas from Central Germany originating from a radius of 150 km around Creuzburg (Thuringia), the location of the sawmill *Pollmeier*. The beech lamellas were graded according to visual characteristics defined by the sawmill. These visual characteristics are not related to visual strength grading characteristics but to a grading for optical appearance, like colouration or cracks. The dataset contained lamellas from the producer's classes *Custom Shop, Common Shop, Cabinet* and *Superior*, which represent the full quality range of beech lamellas. The beech lamellas were part of a research project that aimed to use a high amount of low quality beech lamellas for glulam production in order to increase the yield and reduce the price of the product. One part of the lamellas was collected in 2017 with results published by Westermayr et al. (2018a), the other part was collected in 2019. Dataset Creuzburg region (CB) included 441 beech lamellas with cross sections of 24 × 100 and 24 × 150 mm^2 with 219 and 222 beech lamellas each and a length of approximately 3050 mm. The lamellas were stored at reference climate (20 °C/65% rh) before testing and had a mean moisture content of 9.1% with a COV of 0.16.

2.1.2 Dataset 2: beech lamellas from Kirchheim region (KH): The beech lamellas in the dataset Kirchheim region (KH) originated from the forestry office Kirchheim (Baden-Wuerttemberg) and were further described by Glos and Lederer (2000). The beech lamellas were cut from logs that could not be used for furniture production because of their quality according to the producer. An overall number of 104 and 115 beech lamellas with cross sections of 32 × 120 and 32 × 160 mm^2 were tested in tension. The beech lamellas had a length of 3083 mm for the smaller cross section and 3449 mm for the bigger cross section. Before testing, the lamellas were stored at reference climate (20 °C/65% rh). Mean moisture content before testing of the lamellas was 9.9% with a COV of 0.03.

2.1.3 Dataset 3: beech lamellas from Spessart region (SP): The beech lamellas in dataset Spessart region (SP) came from the SP in Central Germany. The research project dealt with the impact of both species mixture (Rais et al. 2020c) and climate (Rais et al. 2021b) on beech wood quality. Correlations between sawn timber stiffness and crown morphology (Rais et al. 2020a) as well as log properties (Rais et al. 2020b) were determined. More than 2000 boards of two different cross sections (50 × 150 and 40 × 80 mm^2) and a length of 4100 mm were analysed in the project. A representative sample of 396 beech lamellas was selected from these >2000 boards in a way that similar distribution of MoE_{dyn} was achieved in the sampled lamellas as represented in the original collective. The sampled lamellas were planed and shortened. The MoE_{dyn} was measured again on the final lamella dimensions of 38 × 130 × 2414 mm^3 and the lamellas were finally destructively tested in tension. The beech lamellas were stored at indoor climate in the laboratory before testing resulting in a mean wood moisture content of 9.1% with a COV of 0.08.

2.2 Methods

2.2.1 Measurement of grading characteristics: The MoE_{dyn} of the beech lamellas was determined by means of longitudinal eigenfrequency (*f*) measurements according to Equation (1). With a knock of a hammer on one end of the board, an acoustic impulse was generated and the first eigenfrequency *f* of the resulting longitudinal resonance wave was measured at the same end of the board. Board dimensions were measured with a tape, mass with a scale and density ρ was calculated from board dimensions and mass.

$$MoE_{\mathrm{dyn}} = 4{*}l^2{*}f^2{*}\rho \tag{1}$$

The locations and diameters of every knot within the testing length with a diameter larger than 5 mm were documented on all four faces of the boards. Knot parameters DEB (DIN Einzelast Brett) or single knot (SK) criterion and DAB (DIN Astansammlung Brett) or knot cluster (KC) criterion according to DIN 4074-5:2008 (DIN 2008) as well as tKAR according to BS 4978:2007 (BSI 2007) were calculated. The DEB value is the sum of the widths of a SK appearing on the flat and/or edge faces divided by two times the width of the board. The accumulation of knots is expressed by the value DAB regarding all DEB values within a 150 mm long section of a board. The knot area projected on the end grain over a length of 150 mm in ratio to the cross section describes tKAR. For tKAR and DAB, overlapping knots are only counted once. Knot parameters and MoE_{dyn} were used as IP for tensile strength prediction.

2.2.2 Destructive testing: The beech lamellas were destructively tested in tension according to European solid wood testing standard EN 408:2012 (CEN 2012a) with a testing length of nine times the width. The deformation was measured over a length of five times the width. During testing, the lamellas were clamped on both ends and load was applied in displacement control.

Moisture content of the lamellas was determined on small clear wood samples cut from each lamella as required by EN 408:2012 (CEN 2012a). The moisture content was measured with oven-dry method according to EN 13183-1:2002 (CEN 2002). The tensile modulus of elasticity and density were corrected to the reference moisture content of 12% according to EN 384:2016 (CEN 2016a).

2.2.3 Grading rules for beech lamellas for glulam production: Table 1 summarises the grading rules of lamellas for beech glulam according to Z-9.1-679:2019 (DIBt 2019). For beech glulam of a certain bending strength class, Z-9.1-679:2019 (DIBt 2019) defines the required lamella grading class. The lamella grading class from Z-9.1-679:2019 (DIBt 2019) is matched with the lamella T-class via the glulam strength class. To reach a specific glulam strength class, the required lamella T-class is thus calculated based on linear elastic stress distribution across the cross section combined with linear elastic material behaviour.

2.2.4 Assignment of lamellas to T-classes by means of machine grading: To assign graded lamellas to a certain T-class, the rules for derivation of machine settings according to EN 14081-2:2018 (CEN 2018) were applied. EN 14081-2:2018 (CEN 2018) requires a combined dataset with at least four subsamples. In this study, five subsamples were defined from the entire dataset representing five different tested lamella cross sections. IP thresholds for grading with DAB and/or MoE_{dyn} are defined in a way that:

1. The characteristic tensile strength of the graded entire sample reached at least 100% of the required characteristic tensile strength of the T-class.
2. The characteristic tensile strength in the graded subsamples achieved at least 90% of the required characteristic tensile strength of the T-class.

The characteristic material properties were calculated with the non-parametric approach given in section 3.2.3 b) of EN 14358:2016 (CEN 2016b). For calculation of T-class properties, no data of lamellas were cut off reaching higher T-classes as grading was performed into single T-classes.

The proposed grading rules by Frese and Blaß (2005) have not been assessed with multiple beech lamella datasets from different regions and cross sections yet. The datasets in this study offer the possibility to check the grading settings proposed by Frese and Blaß (2005) on a dataset with various origins and cross sections.

The lamellas from datasets CB, KH and SP were graded according to Frese and Blaß (2005) always into one single grade and lamella T-class was then determined by means of EN 14081-2:2018 (CEN 2018). The resulting lamella T-classes were compared with required lamella T-classes for glulam production that can be derived from EN 14080:2013 (CEN 2013).

Ehrhart (2019) suggested a different lamella grading approach based on tKAR value and MoE_{dyn} to grade Swiss beech lamellas in classes T22, T33, T42 and T50 for production of high-strength glulam. The grading approach is based on regression Equation (2).

$$\mathrm{IP}f_{t,0} = \begin{cases} e^{3.42+5.59*10^{-5}*MoE_{\text{dyn}}} & \text{for tKAR} \le 0.05 \\ e^{2.83+8.08*10^{-5}*MoE_{\text{dyn}}-2.34*tKAR} & \text{for tKAR} > 0.05 \end{cases} \tag{2}$$

The grading approach by Ehrhart (2019) was applied on the lamellas of beech datasets CB, KH and SP.

Kovrga et al. (2019b) showed that hardwoods have different ratios of strength to stiffness properties compared to softwoods and proposed DT strength classes for hardwood lamellas. The tensile strength and MoE properties as well as the density of the graded material from CB, KH and SP dataset are compared with DT class properties.

3 Results and discussion

3.1 Visual, physical and mechanical properties of beech lamellas

Table 2: Descriptive statistics (mean value and [COV]) for non-destructively and destructively measured parameters of ungraded boards split by the origin (CB – Creuzburg, KH – Kirchheim and SP – Spessart).

	CB	KH	SP	Total
DEB	0.19 (0.80)	0.15 (0.66)	0.15 (0.81)	0.17 (0.79)
DAB	0.22 (0.77)	0.18 (0.66)	0.18 (0.80)	0.19 (0.77)
KAR	0.14 (0.91)	0.13 (0.73)	0.12 (0.91)	0.14 (0.88)
tKAR	0.16 (0.87)	0.15 (0.73)	0.13 (0.88)	0.16 (0.85)
MoE_{dyn} (GPa)[a]	12.7 (0.18)	14.6 (0.14)	14.6 (0.15)	13.8 (0.17)
Density (kg/m^3)	767 (0.06)	703 (0.06)	748 (0.07)	746 (0.07)
Share pith (%)[a]	21.5	37.9	47	36.8
$f_{t,0}$ (MPa)	38.4 (0.63)	48.9 (0.46)	51.9 (0.54)	45.8 (0.57)
$E_{t,0}$ (GPa)	10.9 (0.25)	13.8 (0.18)	15.1 (0.42)	13.0 (0.25)

[a] Determined on entire board length.

The dataset CB exhibited the highest mean knot values, but datasets KH and SP did not show clear differences in any of the calculated knot parameters DEB, DAB, KAR and tKAR (see Table 2). More detailed, Figure 1 shows exemplarily the frequency distributions of the largest SK DEB within the testing length for the datasets CB, KH and SP. Although the dataset CB exhibited the highest mean knottiness, the distribution exhibited a higher scatter leading to a high number of knot-free specimens (DEB <0.05) as well as a higher share of specimens with larger knots (DEB >0.4) compared to datasets KH and SP.

Dataset SP was sampled representatively for German beech stands from different trees and was aimed at representing the natural spread of knot properties. A pre-grading did not take place at board level. Dataset KH showed a more uniform distribution of knot sizes

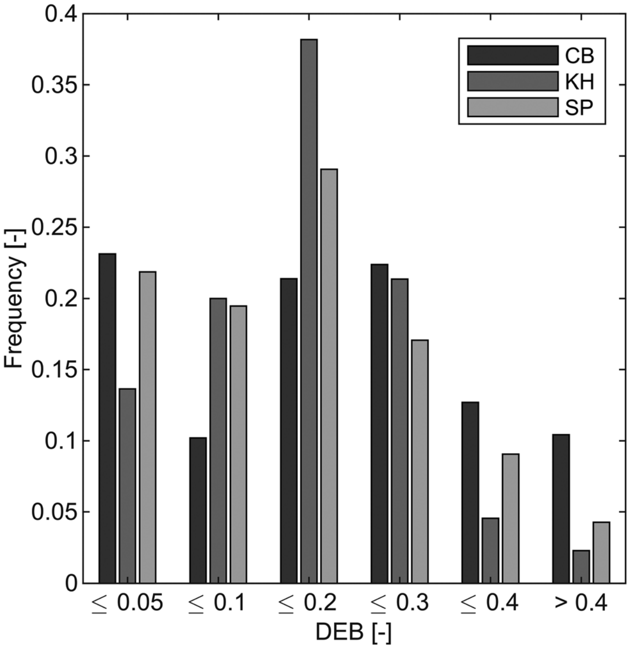

Figure 1: Histogram of DEB values in the three different datasets.

compared to dataset SP with a lower amount of knot-free lamellas and a lower amount of lamellas with big knots resulting in a lower COV of knot parameters.

In the studies by Blaß et al. (2005) and Ehrhart et al. (2016), the tested beech lamellas were already visually pre-graded and the samples contained a higher share of knot-free lamellas of 31% and 58% compared to datasets CB, KH and SP. In the study of Blaß et al. (2005), the lamellas had a minimum quality of visual grading class LS10 according to DIN 4074-5:2008 (DIN 2008) but high-quality lamellas for furniture production were excluded in order to achieve a low-cost material for glulam production. Despite the higher amount of knot-free lamellas than in datasets CB, KH and SP, a higher mean knot parameter DEB = 0.25 was found by Blaß et al. (2005). The study described that if knots were present they had big diameters. Schlotzhauer et al. (2018) observed shares of knot-free lamellas of 46% in beech lamellas from C/D log-quality coming from mixed forest stands. In case that knots were found in the lamellas they also had big diameters.

Ehrhart et al. (2016) found smaller mean tKAR = 0.10 than in the datasets CB, KH and SP probably resulting from pre-grading of the lamellas. Brunetti et al. (2020) found a similar mean knot value tKAR = 0.15 compared to the entire dataset consisting of all lamellas from datasets CB, KH and SP. The studies of Blaß et al. (2005), Ehrhart et al. (2016) and Schlotzhauer et al. (2018) did not contain lamellas with pith resulting either from pre-grading of the material or the cutting process of the lamellas.

Additionally to visual characteristics, the material quality can be described with MoE_{dyn}. The cumulative frequency distributions (CDF) of MoE_{dyn} of the lamellas (Figure 2a) showed that dataset CB exhibited a lower mean MoE_{dyn} than datasets KH and SP with no clear difference in mean MoE_{dyn} between dataset KH and SP. The low mean MoE_{dyn} of dataset CB corresponded with the highest mean knot parameters in dataset CB compared to datasets KH and SP. The MoE_{dyn} of the lamellas in all collectives were normally distributed as well as MoE_{dyn} of the entire dataset. The sample of Brunetti et al. (2020) was characterised with a mean MoE_{dyn} of 13.9 GPa similar to the entire dataset in this study. Even though Blaß et al. (2005) found higher mean DEB than in the datasets of this study, a mean MoE_{dyn} of 14.7 GPa was found, which is similar to MoE_{dyn} of the datasets KH and SP. One reason for the similar MoE_{dyn} despite higher knot values may be found in the length of the specimens by Blaß et al. (2005) with 3.5–5 m, which is higher than in datasets CB, KH and SP. The MoE_{dyn} describes the elastic properties of wood and is more affected by mean material quality than local defects, such as knots. Also, slope of grain and growth inhomogeneities in wood affect MoE_{dyn}. As shown by Ravenshorst (2015), the slope of grain can be recalculated from MoE_{dyn}. Schlotzhauer et al. (2018) also found a mean MoE_{dyn} of approximately 14 GPa for German beech lamellas of C/D log-quality similar to the entire dataset of this study despite higher mean knot values. Ehrhart et al. (2016) found higher mean MoE_{dyn} of 16.3 GPa for pre-graded material corresponding with low mean knot parameters.

Density showed variations regarding the three datasets. Ehrhart et al. (2016), Brunetti et al. (2020), Fortuna et al. (2018) and Schlotzhauer et al. (2018) found a similar mean density for beech lamellas compared to this study with 739, 716, 723 and 700 kg/m^3, respectively. Frühwald and Schickhofer (2005), Blaß et al. (2005) and Blaß and Frese (2006) declared lower mean densities between 660 and 676 kg/m^3.

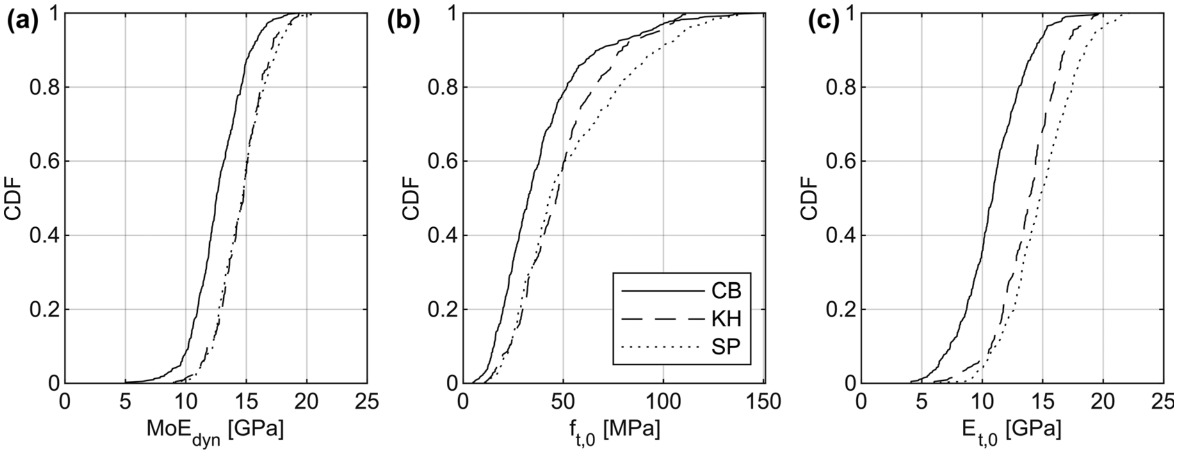

Figure 2: Cumulative distribution functions (CDF) of MoE_{dyn}, $f_{t,0}$ and $E_{t,0}$ of datasets CB, KH and SP.

Figure 2b shows that the CDF of the tensile strength of the dataset CB was shifted to the left compared to datasets KH and SP. The mean tensile strength of dataset CB was also considerably lower than the mean tensile strength of datasets KH and SP (Table 2). No clear difference in mean tensile strength between datasets KH and SP could be obtained. Only the tensile strength of the CB dataset exhibited a lognormal distribution proven by Kolmogorov–Smirnov and Shapiro–Wilk test performed on logarithmic strength values.

Blaß et al. (2006) found a higher mean tensile strength of 68.1 MPa than the mean tensile strengths of datasets CB, KH and SP. The higher mean tensile strength resulted most likely from the short free testing length of 150 mm. Ehrhart et al. (2016) described a mean tensile strength of 66.7 MPa, which can be explained by higher material quality than in dataset CB, KH and SP. Fortuna et al. (2018) found a mean tensile strength of 72.1 MPa that could not be compared with the tensile strengths of datasets CB, KH and SP as distributions of material parameters were not given in the study. The higher mean tensile strength in the study of Frühwald and Schickhofer (2005) of 62.2 MPa compared to datasets CB, KH and SP could not be clarified with the given data but may result from better material quality. The low mean tensile strengths in the datasets CB, KH and SP may also result from the high amount of pith-affected lamellas compared to the previous studies. Excluding lamellas with pith, the datasets CB, KH and SP show higher mean tensile strength of 40.0, 48.9 and 53.0 MPa as if lamellas with pith were included in the analysis (see values in Table 2).

The tensile *MoE* of the entire dataset as well as of datasets CB, KH and SP were normally distributed. The CB dataset exhibited the lowest mean tensile *MoE* of the datasets with 10.9 GPa (Table 2). Contrary to tensile strength, mean values of tensile *MoE* in datasets KH and SP differed considerably with a higher tensile *MoE* in the SP dataset (Figure 2c).

Blaß et al. (2005) reported a mean tensile *MoE* of around 13 GPa depending on the cross section, Frühwald and Schickhofer (2005) found a similar mean tensile *MoE* with 13.9 GPa. Both studies are thus in the range of the entire dataset with 13.0 GPa and dataset KH with 13.8 GPa. The study of Ehrhart et al. (2016) exhibited a tensile *MoE* of 14.5 GPa and Fortuna et al. (2018) observed a mean tensile *MoE* of 15.5 GPa, which is similar to dataset SP with 15.1 GPa.

An exponential regression yielded the highest coefficient of determination between tensile strength and *MoE* with $R^2 = 0.51$ (Figure 3). In the CB, KH and SP datasets, coefficients of determination between tensile strength and *MoE* of $R^2 = 0.52$, 0.59 and 0.68 were found.

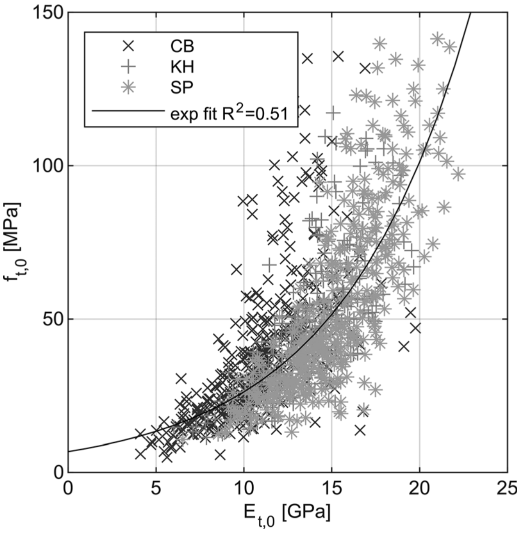

Figure 3: Correlation between $E_{t,0}$ and $f_{t,0}$ for the entire beech dataset ($N = 1014$).

The ratio between mean tensile strength and mean tensile *MoE* differs in datasets CB, KH and SP. The exponential correlation between tensile strength and *MoE* (Figure 3) may explain the different ratios as an increase in tensile strength exceeded the increase in tensile *MoE*.

3.2 Correlation of grade determining properties (GDPs) with IPs

In order to estimate tensile strength and *MoE* of lamellas, correlation analysis between IPs, such as knot or dynamic parameters, was performed.

Density exhibited a low correlation with tensile strength, confirming the results of previous studies on hardwood, including species such as ash and maple (Ehrhart et al. 2016; Frühwald and Schickhofer 2005; Kovryga et al. 2016a, 2019a,b; Westermayr et al. 2018b). The same effect is shown in Brunetti et al. (2020) for beech and in Nocetti et al. (2006) for chestnut both in bending. This indicates a generally weak correlation between density and tensile/bending strength for hardwoods.

For predicting tensile strength of the beech lamellas of the entire dataset, MoE_{dyn} was the IP with the highest coefficient of determination of $R^2 = 0.45$ using linear regression. An exponential regression exhibited a coefficient of determination of $R^2 = 0.51$. Results by Ehrhart et al. (2016) with $R^2 = 0.22$, by Fortuna et al. (2018) with $R^2 = 0.26$ and by Frühwald and Schickhofer (2005) with $R^2 = 0.26$ showed lower correlations of MoE_{dyn} with tensile strength. A reason for that can be found in the quality of the tested material.

The study contained a high amount of low quality beech lamellas with numerous growth defects. Characteristics like cracks, knots, pith and local fibre patterns influence the runtime of the longitudinal resonance wave, which makes the MoE_{dyn} sensitive especially for lower quality material. The higher the lamella quality and the lower the number of growth defects influencing the longitudinal resonance wave, the lower the correlation between tensile strength and MoE_{dyn} but the higher the importance of the global fibre deviation as shown by Ehrhart et al. (2018).

As density showed very low correlation with any IP, applying the individual density of each specimen according to Equation (1) may add scatter to the calculated MoE_{dyn}. This scatter could possibly be reduced by using simply the frequency and lamella length for strength prediction or by calculating MoE_{dyn} applying a constant density instead of the individual density of each specimen. In consequence, the MoE_{dyn} of each lamella was alternatively calculated with the mean density of the entire dataset instead of the individual density of each specimen. Calculating MoE_{dyn} with the mean density of the dataset showed similar correlation between MoE_{dyn} and tensile strength as if the individual density of each lamella was used.

The knot parameters DEB, DAB, KAR and tKAR all exhibited similar correlation with the tensile strength of the entire dataset with coefficients of determination between 0.37 and 0.43. Ehrhart et al. (2016) found higher coefficients of determination between tensile strength and knot parameters of $R^2 = 0.52$ (tKAR) and 0.53 (DEB/DAB). Frühwald and Schickhofer (2005) showed coefficients of determination between knot parameters and tensile strength of $R^2 = 0.34$ (DEB) and 0.36 (DAB), while Khaloian Sarnaghi and Van de Kuilen (2019) showed R^2-values in the range of 0.47–0.56 using surface knot information similar to that needed for the determination of tKAR. Correlations between IPs and grade determining properties (GDPs) appear to be influenced by the material quality used for testing. Studies like by Ehrhart et al. (2016) with high correlation of visual characteristics and tensile strength often showed low correlations between MoE_{dyn} and tensile strength.

The MoE_{dyn} exhibited a high correlation with the static MoE ($R^2 = 0.76$) of the entire dataset with coefficients of determination of $R^2 = 0.60$, 0.65 and 0.86 in the CB, KH and SP datasets. The coefficient of determination in the datasets was similar to the coefficients of determination found by Ehrhart et al. (2016) with $R^2 = 0.84$, Frühwald and Schickhofer (2005) with $R^2 = 0.5$ and Fortuna et al. (2018) with $R^2 = 0.66$ (laser vibrometer) and $R^2 = 0.64$ (STIG).

3.3 Grading of beech lamellas for glulam production according to German technical approval Z-9.1-679:2019 (DIBt 2019)

Beech lamellas for glulam production are strength graded according to the German technical approval Z-9.1-679:2019 (DIBt 2019) with visual grading criteria according to DIN 4074-5:2008 (DIN 2008). Tensile strength and yield of lamellas of the entire dataset are displayed in Table 3 after grading the material in classes according to Z-9.1-679:2019 (DIBt 2019). Tensile strength increased with visual grade of the lamellas and with further requirements concerning MoE_{dyn} and knot value "A" within one visual grade, especially on characteristic level.

DIN 4074-5:2008 (DIN 2008) excludes lamellas containing pith in all visual grading classes leading to low yields. For the lowest grading class LS7, allowing pith-affected lamellas did lead to a characteristic tensile strength of 15.6 MPa. A similar characteristic tensile strength of 16.0 MPa is reached when only pith-free lamellas are included in the analysis. This shows a negligible effect of pith on the characteristic tensile strength of grade LS7. The mean tensile strength including lamellas with pith in grading class LS7 was lower with 46.9 MPa compared to pith-free lamellas with 52.9 MPa. The similarity of tensile strength on characteristic level of pith-affected and pith-free lamellas encourages the presence of pith-affected lamellas in visual grading class LS7 in favour of higher yields.

Table 3: $f_{t,0}$ of the entire beech dataset ($N = 1014$) graded into one single grading class according the rules of Z-9.1-679:2019 (DIBt 2019) + DIN 4074-5:2008 and compared to the characteristic tensile strength estimated by Frese and Blaß (2005).

Grading class[a]	$f_{t,0,k}$ (MPa)[b]	$f_{t,0,k}$ (MPa)[c]	$f_{t,0,\mathrm{mean}}$ (MPa)[c]	Yield (%)[c]
LS7+	X	16.0	52.9	61.8
LS7 + pith	X	15.6	46.9	97.8
LS10+	22	20.6	57.5	53.5
LS10 + pith	X	17.6	49.9	86.7
LS10 + E13	20	25.7	57.6	56.5
LS10 + E14	30	29.4	62.0	44.0
LS13 +	27	26.7	65.2	40.0
LS13 + A	31	27.6	76.7	21.1
LS13 + E14	30	32.2	65.1	38.3
LS13 + E15	40	38.3	72.3	25.0
LS13 + A + E15	48	46.9	88.9	10.2

[a] Z-9.1-679:2019 (DIBt 2019). [b] EN 14080:2013 for $f_{t,0,k} \leq 30$ MPa + estimates based on characteristic values reported by Frese and Blaß (2005). [c] Test data.

Kovryga et al. (2019a) already suggested neglecting pith as grading criterion for lower lamella T-classes in ash and maple as board strength was not negatively influenced.

The additional grading criterion MoE_{dyn} as well as the additional knot criterion “A” (DEB <0.04) from Z-9.1-679:2019 (DIBt 2019) increased the mean and characteristic tensile strength of the lamellas in the different grading classes. While the increase of tensile strength by additional grading criterion MoE_{dyn} was pronounced equally on mean and characteristic level, knot criterion “A” mainly affected the mean tensile strength. Similar to visual grading, the material from dataset CB showed lower tensile strength in grading classes than material from dataset KH and SP on mean and characteristic level.

The lamellas of the combined dataset CB, KH and SP were graded into visual grading classes LS7, LS10 and LS13 according to DIN 4074-5:2008 (DIN 2008) and reached the requirements for lamella classes T14, T18 and T25, respectively. Frese and Blaß (2005) proposed lamella class T22 for LS10 and T27 for LS13. The achieved T-classes of the lamellas from the combined dataset CB, KH and SP contrast the proposed lamella T-classes according to Frese and Blaß (2005) for only visually graded material showing the need for revision of these grading rules. With the combined visual and machine strength grading approach by Frese and Blaß (2005), lamella T-classes could only be reached in grading classes LS10 + E13 and LS13 + E14 (Table 3).

The German technical approval for beech glulam Z-9.1-679:2019 (DIBt 2019) focuses on glulam of strength classes GL28 or higher. This restricts the use of low quality lamellas and the amount of lamellas that can be applied for glulam production. Allowing also lower glulam strength classes could result in a higher yield of beech lamellas. For an application of low quality lamellas for glulam production, new and efficient grading rules have to be defined (Kovryga et al. 2016b).

3.4 Proposal of a tensile strength grading approach for beech lamellas

Grading rules are based on IPs for strength and *MoE*. Thresholds for IPs were defined according to EN 14081-2:2018 (CEN 2018). For visual grading the DAB value was used as IP as it had the highest correlation of the knot parameters with tensile strength and *MoE*. By means of visual grading with the knot parameter DAB, only GDPs for strength class T25 could be achieved (Table 4). This contrasts the finding of Hübner (2009) who graded beech lamellas visually into class T30 with a threshold DEB <0.1. For grading into higher strength classes other IPs have to be applied. Machine strength grading could be a solution for reaching higher lamella T-classes.

For machine strength grading, the MoE_{dyn} was used as IP with an exponential regression equation between tensile strength and MoE_{dyn} resulting in a coefficient of determination of R^2 = 0.51. Lamella T-classes up to T40 were reached. Machine strength grading was more appropriate for grading into higher strength classes than visual grading. If lamella class T14 was graded, machine grading and visual grading had similar yields. For classes T18 and T25, machine strength grading exhibited much higher yields than visual grading.

An even more efficient way of grading might be found in combining visual and machine grading IPs using multivariate regression models. The highest prediction accuracy could be achieved with exponential models (Equation (3)) resulting in R^2 = 0.65. Substituting DAB by DEB leads only to a minor decrease in prediction accuracy. One knot parameter in combination with MoE_{dyn} allowed good model fit and DAB was chosen due to higher correlation with tensile strength than DEB resulting in Equation (3).

Table 4: Threshold, yield, $f_{t,0,k}$ and $E_{t,0,\mathrm{mean}}$ for visual (DAB), machine (MoE_{dyn}) and combined grading (IP $f_{\mathrm{t,combined}}$) into one single T-class.

	Visual grading (DAB)				Machine grading (MoE_{dyn})				Combined grading (IP $f_{t,\mathrm{combined}}$, Equation (3))			
Lamella T-class	Threshold (–)	Yield (%)	$f_{t,0,k}$ (MPa)	$E_{t,0,\mathrm{mean}}$ (GPa)	Threshold (GPa)	Yield (%)	$f_{t,0,k}$ (MPa)	$E_{t,0,\mathrm{mean}}$ (GPa)	Threshold (MPa)	Yield (%)	$f_{t,0,k}$ (MPa)	$E_{t,0,\mathrm{mean}}$ (GPa)
T14	0.49	94.3	16.2	13.2	9	95.1	15.9	13.0	15	94.3	16.0	13.1
T18	0.13	39.7	24.9	14.8	11.5	83.6	19.1	13.6	24	82.4	19.7	13.7
T25	0.06	22.0	27.6	14.7	14.0	50.1	25.2	15.1	37	54.3	26.7	14.9
T27		–	–		15.0	34.5	29.3	16.0	47	35.3	31.3	15.8
T30		–	–		15.1	33.3	30.7	16.0	49	32.6	34.4	15.9
T36		–	–		15.9	21.2	36.3	16.9	53	26.9	38.5	16.2
T40		–	–		17.0	11.1	41.3	17.8	66	12.4	46.6	16.5

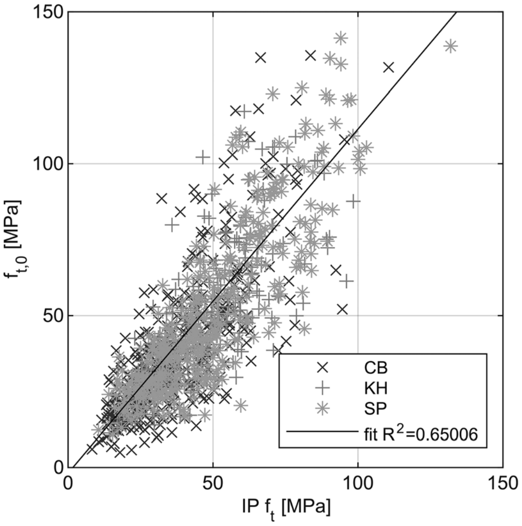

Figure 4: Scatter plot between IP f_t (Equation (3)) and $f_{t,0}$ for beech datasets CB, KH and SP.

$$\mathrm{IP}\, f_{t,0} = e^{2.27+0.122*MoE_{\mathrm{dyn}}-1.65*\mathrm{DAB}} \tag{3}$$

The correlation between IP from Equation (3) and tensile strength for the entire dataset and single data points for the different datasets is displayed in Figure 4.

The combined grading approach with MoE_{dyn} and the knot parameter DAB according to Equation (3) did not lead to considerably higher yields compared to machine strength grading with MoE_{dyn} as single IP. The combined grading approach resulted in slightly higher characteristic tensile strengths in all lamella T-classes compared to machine grading with MoE_{dyn} alone.

As proposed by Ehrhart (2019), regression equations between tensile strength and IPs were calculated separately for knot-free and knot-affected lamellas. Equation (4) led to a coefficient of determination of R^2 = 0.67 with no noticeable increase in yield in the tensile strength grading classes.

$$\mathrm{IP}\ f_{t,0} = \begin{cases} e^{1.985+0.134*MoE_{\mathrm{dyn}}-1.247*\mathrm{DAB}} & \text{for DEB} > 0 \\ e^{2.571+0.111*MoE_{\mathrm{dyn}}} & \text{for DEB} = 0 \end{cases} \tag{4}$$

Similarly to a differentiation of knot-free and knot-affected lamellas, regression equations were derived for pith-free and pith-affected lamellas with coefficient of determination of R^2 = 0.67 for Equation (5) with no clear increase in yield in the tensile strength grading classes.

$$\mathrm{IP}\ f_{t,0} = \begin{cases} e^{1.518+0.155*MoE_{\mathrm{dyn}}-0.674*\mathrm{DAB}} & \text{pith} - \text{affected} \\ e^{2.563+0.108*MoE_{\mathrm{dyn}}-1.953*\mathrm{DAB}} & \text{pith} - \text{free} \end{cases} \tag{5}$$

The coefficient of determination could only slightly be increased by calculating regression equations separately for pith- and knot-affected material compared to Equation (3).

Ehrhart et al. (2019) suggested a combined grading approach with MoE_{dyn} and tKAR knot parameter for glulam of strength classes GL40 to GL55 with lamellas from classes T22 to T50. Pith-affected lamellas were generally excluded. The lamellas of datasets CB, KH and SP graded by means of the approach by Ehrhart et al. (2019) reached the required GDPs for the proposed T-classes in all grading classes to at least 90% as required by EN 14081-2:2018. When applying the regression equation defined by Ehrhart (2019) on datasets CB, KH and SP, a coefficient of determination R^2 = 0.60 was achieved.

Ehrhart et al. (2019) also confirmed the different strength to stiffness ratio compared to softwoods that was found for hardwoods by Ravenshorst et al. (2004), Solli (2004) and Glos and Denzler (2006). Kovryga et al. (2019b) provided tensile strength classes for hardwood, called DT classes. After grading the beech lamellas from datasets CB, KH and SP by means of MoE_{dyn}, the mean *MoE* properties of the graded material were compared with the mean *MoE* properties suggested for the DT classes. The mean tensile *MoE* of the graded material exceeded the suggested the DT classes by far as the lamellas were always graded into one single grading class and not into grading class combinations like by Kovryga et al. (2019b). With the suggested tensile *MoE* in the DT classes by Kovryga et al. (2016a), beech lamella *MoE* is considered safely for construction purposes.

4 Conclusion and outlook

Three datasets containing beech lamellas of different qualities and origins were analysed regarding tensile strength and *MoE* properties. The dataset from Creuzburg contained a high amount of lamellas with high knot values and low MoE_{dyn}. The datasets from Kirchheim and Spessart showed similar qualities.

The lamellas were strength graded according to the current grading rules from Z-9.1-679:2019 (DIBt 2019). The graded lamellas mostly did not reach the required lamella T-classes. Additionally, low yields were found, especially because lamellas with pith or high knot parameters were excluded. Allowing lamellas containing pith and bigger knots for glulam production would increase the lamella yield. Challenges in the production process, especially during gluing of pith-affected lamellas, regularly accompanied by cracks, remain to be analysed though. A higher lamella yield could lead to a more competitive beech glulam and could increase the application of the product in the construction sector.

As sizes and shapes of knots are more difficult to determine in beech wood than in softwoods, MoE_{dyn} can be applied as effective grading parameter. The suggested grading approach based on MoE_{dyn} measurements achieved, especially for lower lamella T-classes, higher yields than the currently applied grading rules given in Z-9.1-679:2019 (DIBt 2019). Required GDPs for the T-classes were achieved reliably. Strength grading by means of MoE_{dyn} as single grading parameter exhibited similar results in terms of achieved T-classes and yield than a combined visual and machine strength grading approach.

More efficient grading rules could be provided by combining machine grading with MoE_{dyn} and detection of 3D fibre deviation with a laser dot using the tracheid effect (Briggert et al. 2020; Matthews and Soest 1986; Nyström 2003) as shown by Rais et al. (2021a). Fibre deviation could especially be a good predictor for tensile strength of knot-free lamellas in beech glulam as fibre deviation was, additionally to finger joints, often the reason for failure of beech glulam in the study of Ehrhart et al. (2018). Integrating virtual grading methods (Khaloian Sarnaghi and van de Kuilen 2019) into conventional grading models may further improve the yield in T-classes.

Acknowledgements: We would like to thank the staff and student assistants of the TU Munich for their support, specifically Heribert Bergmeier. We thank Martin Bacher from Microtec for his valuable recommendations and the anonymous reviewers whose comments helped improving the manuscript.

Author contributions: All authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: We thank the Bavarian State Institute of Forestry LWF, Grant No. G2/N/19/05 for funding the project “Easy Beech – Development of economic beech components with focus on medium-sized and local companies” during which this paper was developed. Thanks to the German Federal Ministry of Food and Agriculture, Grant No. FKZ 22025114 for funding the project “Impact of forest management on sawn timber quality of European beech (*Fagus sylvatica* L.) and optimising automatic log grading” during which dataset 3 was generated. Thanks to the Pollmeier Massivholz GmbH and Bayerische Staatsforsten as well as sawmill Försch/Bavaria for providing the material for the tests.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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