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Machine strength and stiffness prediction with focus on different acoustic measurement methods

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ABSTRACT

Strength grading is an important step for the production of homogenous and high-quality solid wood material. In particular, for hardwoods, the use of non-visible characteristics is indispensable. Dynamic MOE (MOE_{dyn}) is an important parameter widely used for grading of softwoods and applicable to hardwoods as well. There are two common ways to measure MOE_{dyn} – ultrasound (US) wave propagation and longitudinal stress wave (LSW) propagation. Both methods are used in practice, however, due to the different measurement techniques behind them, the results differ. Current paper analyses the stiffness and strength prediction accuracy for several temperate European hardwood specimens and stress the differences between the two measurement systems. The performance was analysed with regard to grading techniques, testing modes for the mechanical properties (tension and bending) and wood qualities. For more than 2861 pieces of European ash (Fraxinus excelsior), European beech (Fagus sylvatica), European oak (Quercus spp.) and maple (Acer spp), the MOE_{dyn} was measured using both techniques, and destructive tests (tension and edgewise bending) were applied. The results show that LSW has higher prediction accuracy compared to the US $MOE_{dyn.}$ The prediction accuracy for both methods and tensile application can be increased by calculating MOE_{dyn} with average density. Furthermore, the results support the species independent strength grading of hardwoods. Further research on the effect of different wood qualities and sawing pattern is required.

1. INTRODUCTION

Temperate hardwoods are very well known for excellent mechanical properties, which make them favourable for structural purposes. As a renewable material, wood shows high variation in mechanical properties. Strength grading is a crucial step for the production of homogenous and high-quality solid wood material with defined material properties. Whereas the research on softwoods has led to the high acceptance of the machine strength grading methods, the application of those methods to the hardwoods is less frequent. The research activities of the recent years in the field of strength grading and engineered wood products aimed to bridge knowledge gaps with regard to hardwoods.

The recent research activities have been focused on applying the established methods of machine strength grading for softwoods to hardwoods, as well as novel methods of non-destructive testing. In focus of the mechanical strength grading, the dynamic MOE (MOE_{dyn}) can be highlighted as a major criterion of interest. MOE_{dyn} is a mechanical property of the material and describes the elastic behaviour of wood under dynamic cyclic stress and has been used to characterize wood material for decades (Kollmann and Côté 1968). The MOE_{dyn} application for the strength grading of structural timber dates back to Goerlacher (1990) and is currently one of the most frequent methods for the machine strength grading of wood. Generally, there are two possibilities to determine MOE_{dyn}, which are: ultrasound (US) wave propagation and longitudinal stress wave (LSW) propagation. Both methods are related to the acoustic properties of wood. In the first case, the ultrasound wave signal is generated and the propagation in wood is measured, whereas in the other case, a stress wave is induced using a hammer and the eigenfrequency of wood is determined. Nowadays, the eigenfrequency has established itself as a very robust and is the most frequently used method. The characteristic vibrations in the board can be detected contact-free using laser vibrometer (Giudiceandrea 2005).

As a grading parameter, MOE_{dyn} shows a high correlation to static MOE, for both softwoods (Bacher 2008) and hardwoods (Frühwald und Schickhofer 2005). The prediction accuracy for the strength is high, especially for the softwoods. For the hardwoods, the prediction accuracy of both methods seems to be less high. The reported R^2 values for the strength prediction range from 0.18 to 0.36 for temperate hardwoods (Nocetti et al. 2016, Ravenshorst 2015).

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And are lower for the tensile strength prediction of temperate hardwoods shown for a variety of species ($R^2 < 0.25$) (Ehrhart et al. 2016, Glos and Lederer 2000, Green and McDonald 1993). For tensile strength, the prediction accuracy depends on the quality of the material, (Westermayr et al. 2018) reports of high R^2 value of 0.48 for low-quality beech lamella, compared to the value achieved for high quality with 0.22 (Ehrhart et al. 2016). This should imply that timber of rejectable quality shows higher grading accuracy. In most publications, the MOE_{dyn} is determined using the LSW. Therefore, the question arises regarding the performance of both methods and the differences between tension and bending strength prediction accuracy. Frühwald and Hasenstab (2010) mention that the accuracy of the method is higher for LSW.

The present study aims to investigate the differences in the prediction accuracy between US and LSW method on a large data pool of hardwood specimens tested at TU Munich in recent years. Both methods are compared regarding the prediction accuracy for the tensile strength and stiffness measurement. Special focus is given to the differences between the species, the ability to apply species independent strength grading, and the ability for the bending and tensile strength prediction. The species ash, beech, maple and oak that represent the hardwood species with different anatomical structure (ring-porous and diffuse porous) are investigated.

2. Materials

For the current study, in total 2681 specimens of European hardwoods – European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), oak (*Quercus spp.*) and maple (*Acer spp.*) were used. Table 1 gives an overview of the specimens and dimensions used. The length of the specimens varied between 3 and 5.5 m. The specimens originated from different projects run at TU Munich over two decades. Beech and oak were tested by Glos and Lederer (2000) within the hardwood strength grading project. Ash and maple tested in bending originate from the project on the assignment of those species to the bending strength classes (D-Classes) by Glos and Torno (2008a, 2008b). Tension test data of ash and maple were obtained by Kovryga et al. (2019) within the project on hardwood strength grading. For details, please refer to the publications.

Table 2 summarizes the mechanical properties of the tested hardwoods. The tested specimens are representative for the tested wood species and, particularly, for the growth region in Central Europe. The mechanical property values are comparable to the values given in publications. So for ash, the mean tensile strength values are comparable to the values reported by Frühwald and Schickhofer (2005). For beech, the values are lower compared to the ungraded tensile strength of beech ($f_{t,mean}$ = 62.2 MPa, Erhart et. al. 2016) and by Frühwald and Schickhofer. On the other side, the values considerably exceed the values reported by Westermayr et al. (2018) ($f_{t,mean}$ = 35,9 MPa) for low-quality beech lamella. The bending strength of oak is lower compared to beech and maple particularly due to the high moisture content, which was on average 31.9%. Therefore, the values are adjusted to the reference moisture content of 12% m.c. as described in section 3.

Table 1: Overview of specimens and dimensions

Species	Bending			Tension		
	Cross-section (*bxh*) [mm x mm]	*N*	Reference	Cross-section *(bxh)* [mm x mm]	*N*	Reference
Europeanash (Fraxinus excelsior)	50x100, 50x150	324	Glos and Torno (2008a)	50x100; 50x150	259	
				25x85; 35x160; 30x100; 30x125; 35x100; 35x125	481	Kovryga et al. (2019)
Europeanbeech (Fagus sylvatica)	35x70;60x120; 60x120 60x180	224	Glos and Lederer (2000)	30x120;30x160;30x165	217	Glos & Lederer (2000)
Maple (Acer spp.)	50x100;50x150; 50x175	459	Glos and Torno (2008b)	25x125;30x100; 30x125;	381	Kovryga et al. (2019)
				35x100; 35x125; 25x100		
Oak (Quercus spp.)	40x80;60x120; 60x180	336	Glos and Lederer (2000)			
TOTAL		1343			1338	

Table 2: Descriptive statistics of grading characteristics and mechanical properties from tension and bending test for European ash (Fraxinus excelsior), European beech (Fagus sylvatica), oak (Quercus spp.) and maple (Acer spp.) species

		Bending				Tension		
Species		ash	beech	maple	oak	ash	beech	maple
N		324	224	459	336	740	217	381
tKAR [-]	μ	0.055	0.102	0.075	0.175	0.067	0.146	0.119
	s	0.074	0.106	0.082	0.141	0.092	0.107	0.135
$E_{dyn,us,12}$ [GPa]	μ	16.1	18.1	15.1	13.4	16.5	17.7	16.7
	s	1.9	1.9	2.0	2.3	2.5	2.2	1.9
$E_{dyn,freq,12}$ [GPa]	μ	14.0	14.3	12.8	11.0	14.7	14.7	14.4
	s	1.8	2.8	1.7	2.1	2.4	2.0	1.7
m.c. [%]	μ	10.6	11.6	8.4	31.9	10.6	10.2	11.2
	s	0.9	0.6	0.9	9.5	1.0	0.4	0.6
ρ_{12} [kg/m³]	μ	678	742	635	714	685	723	664
	s	49	38	41	55	57	41	45
$E_{0,12}$ [GPa]	μ	12.7	14.6	12.0	10.9	14.1	13.8	13.8
	s	1.8	2.4	1.9	2.8	2.7	2.5	2.2
f [MPa]	μ	69.8	65.3	56.3	56.1	59.0	48.2	53.4
	s	16.1	20.7	18.7	17.2	28.2	22.1	26.2

3. METHODS

3.1 NON-DESTRUCTIVE MEASUREMENTS

For all the specimens, the grading characteristics and the mechanical properties from tension and bending test were determined. The MOE_{dyn} was measured in two ways - using the ultrasound wave and stress wave propagation. The longitudinal US measurement was done using sylvatest device with the frequency of 20 kHz. During the non-destructive measurement, the runtime of the wave is measured longitudinal to the grain direction between the transmitter and receiver transducer. The MOE_{dyn} is calculated as a product of density and ultrasound wave using Eq. 1:

$$E_{dyn,us} = v^2 \cdot \rho \tag{1}$$

For the longitudinal stress wave (LSW), measurement hammer is used to generate stress wave. The signal is recorded by means of a microphone or an accelerometer. Both measurements are done at the laboratory of the TU Munich for consistency check, as they provide similar results. In industrial facilities laser, vibrometer can be used to record vibrations contact-free. By applying the FFT-transformation, the eigenfrequency is calculated. The $E_{dyn,freq}$ is calculated by combining the eigenfrequency (f) with length (l) of the specimen and density (ρ) measurement using the following equation:

$$E_{dyn,freq} = 4 \cdot l^2 \cdot f^2 \cdot \rho \tag{2}$$

The density is measured by weighting the specimen.

For temperate hardwoods, density shows usually no correlation to the tensile and bending strength (Erhart et al. 2016, Westermayr et al. 2018, Frühwald & Schickhofer 2005). Therefore, the MOE_{dyn} was calculated using constant density value to study the effect of eigenfrequency and ultrasound velocity on the strength properties. For each wood species, the average density from Table 2 was taken into account. The difference between the MOE_{dyn} calculated with individual readings and MOE_{dyn} with an average density of the wood species are discussed in the paper.

To separate with low and high-quality specimens, the knottiness parameter *tKAR* (total knottiness area ratio) is used. *tKAR* is a parameter frequently used in scientific publications and is calculated as the area of knots appearing in 150mm large window, projected on the cross-sectional area. The overlapping areas are counted once.

3.2 DESTRUCTIVE TESTS

The hardwoods specimens were tested in tension and in bending according to the test specification of EN 408 (2010). The bending strength and local MOE were measured in four-point bending test. The test span between the two loading points was six times the depth of cross-section. For local MOE the deformation was measured over the length of five times the depth. The tension strength was determined with the free test length of nine times the height and the gauge length for the tensile MOE measurement was five times the height.

3.3. MOISTURE CONTENT ADJUSTMENT

The mechanical properties were adjusted to the reference conditions 20° and 65 relative humidity. For all species, the equation derived by Nocetti et al. (2015) on chestnut has been used to adjust dynamic and static MOE. The procedure in EN 384 does not specify any adjustment factors for m.c. above 18%. For MOE below FSP the eq. 3

$$E_{12} = \frac{E_u}{1-0.005\,(u-12)} \tag{3}$$

For changes in MC above fiber saturation point (FSP) the eq. 4 has been used:

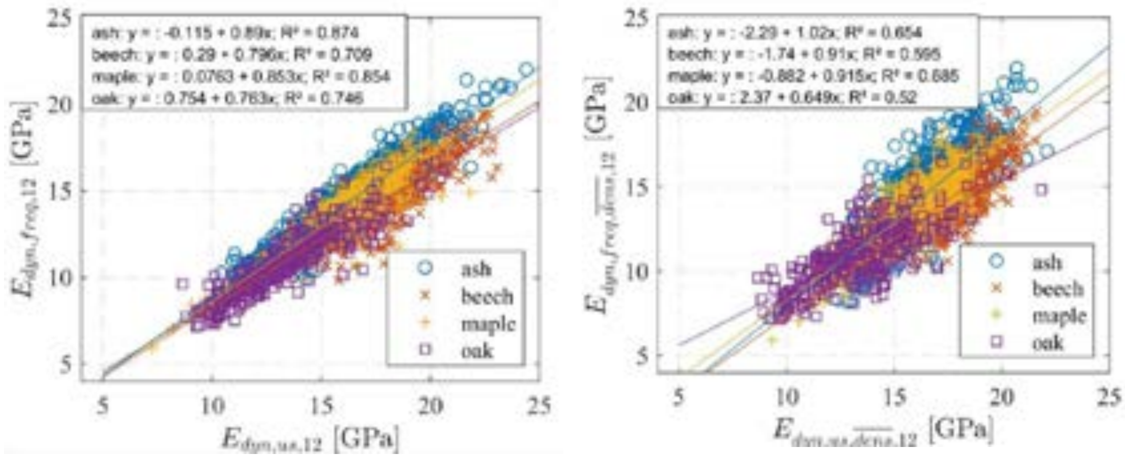
$$E_{12} = \frac{E_u}{0.9} \tag{4}$$

The equation assumes constant MOE value above FSP also shown by Unterwieser and Schickhofer (2011).

The bending strength (f_m) values are adjusted to the reference conditions by assuming a 1.4% increase in strength per 1% m.c. decrease up to the fiber saturation point (Hernández et al. 2014). The selected factor is supported by the findings of Glos and Lederer (2000) for the tested sample who found the difference in bending strength between green and dry specimens of about 21%. The selected factor is designated on the safe side, as in some publications higher change rate is reported. Wang and Wang (1999) report 3.9% per % m.c for red oak.

Table 3: Coefficient correlation (R^2) between the MOE_{dyn} determined using LSW and US method for both data sets tested in bending and tension for European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), oak (*Quercus spp.*) and maple (*Acer spp.*) species

	Bending				Tension			
	$E_{dyn,us,12}$	$E_{dyn,freq,12}$	$E_{dyn,us,\overline{dens},12}$	$E_{dyn,freq,\overline{dens},12}$	$E_{dyn,us,12}$	$E_{dyn,freq,12}$	$E_{dyn,us,\overline{dens},12}$	$E_{dyn,freq,\overline{dens},12}$
European ash								
ρ_{12}	0.450	0.346	0.005	0.001	0.476	0.414	0.057	0.042
$E_{dyn,us,12}$	1.000	0.866	0.617	0.469	1.000	0.878	0.749	0.594
$E_{dyn,freq,12}$		1.000	0.576	0.683		1.000	0.664	0.773
$E_{dyn,us,\overline{dens},12}$			1.000	0.796			1.000	0.807
$E_{dyn,freq,\overline{dens},12}$				1.000				1.000
European beech								
ρ_{12}	0.303	0.190	0.007	0.003	0.413	0.301	0.050	0.022
$E_{dyn,us,12}$	1.000	0.639	0.771	0.423	1.000	0.824	0.792	0.561
$E_{dyn,freq,12}$		1.000	0.491	0.849		1.000	0.689	0.824
$E_{dyn,us,\overline{dens},12}$			1.000	0.549			1.000	0.752
$E_{dyn,freq,\overline{dens},12}$				1.000				1.000
Maple								
ρ_{12}	0.187	0.138	0.003	0.007	0.366	0.189	0.005	0.008
$E_{dyn,us,12}$	1.000	0.877	0.768	0.634	1.000	0.768	0.693	0.391
$E_{dyn,freq,12}$		1.000	0.704	0.795		1.000	0.647	0.730
$E_{dyn,us,\overline{dens},12}$			1.000	0.864			1.000	0.739
$E_{dyn,freq,\overline{dens},12}$				1.000				1.000
Oak								
ρ_{12}	0.067	0.069	0.068	0.051				
$E_{dyn,us,12}$	1.000	0.746	0.743	0.561				
$E_{dyn,freq,12}$		1.000	0.520	0.770				
$E_{dyn,us,\overline{dens},12}$			1.000	0.750				
$E_{dyn,freq,\overline{dens},12}$				1.000				



(a) (b)

Figure 1: Relationship between MOE_{dyn} from US measurement and MOE_{dyn} measured using LSW method with MOE_{dyn} calculated (a) with individual density reading and (b) calculated with constant density value, grouped by the hardwood species

Table 4: Coefficient of determination (R^2) for the prediction of density, modulus of elasticity and strength from bending test and tension test for European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*), oak (*Quercus spp.*) and maple (*Acer spp.*) species

	Bending			Tension		
	ρ_{12}	$E_{0,12}$	f_m	ρ_{12}	$E_{0,12}$	f_t
European ash						
ρ_{12}	1	0.234	0.036	1	0.298	0.034
$E_{dyn,us,12}$	0.415	0.651	0.119	0.424	0.658	0.148
$E_{dyn,freq,12}$	0.312	0.778	0.282	0.386	0.749	0.270
$E_{dyn,us,\overline{dens},12}$	0.008	0.467	0.092	0.054	0.509	0.149
$E_{dyn,freq,\overline{dens},12}$	0.002	0.568	0.269	0.047	0.591	0.296
mc	0.116	0.009	0.009	0.012	0.059	0.009
European beech						
ρ_{12}	1	0.066	0.034	1	0.172	0.010
$E_{dyn,us,12}$	0.369	0.386	0.202	0.475	0.625	0.188
$E_{dyn,freq,12}$	0.287	0.699	0.407	0.351	0.847	0.386
$E_{dyn,us,\overline{dens},12}$	0.038	0.350	0.187	0.103	0.575	0.246
$E_{dyn,freq,\overline{dens},12}$	0.039	0.661	0.393	0.054	0.772	0.471
mc	0.191	0.053	0.070	0.020	0.025	0.002
Maple						
ρ_{12}	1	0.078	0.017	1	0.031	0.029
$E_{dyn,us,12}$	0.238	0.666	0.163	0.364	0.319	0.007
$E_{dyn,freq,12}$	0.201	0.792	0.312	0.207	0.598	0.142
$E_{dyn,us,\overline{dens},12}$	0.005	0.573	0.144	0.009	0.348	0.054
$E_{dyn,freq,\overline{dens},12}$	0.002	0.674	0.285	0.002	0.558	0.263
mc	0.000	0.077	0.085	0.067	0.002	0.000
Oak						
ρ_{12}	1	0.007	0.009			
$E_{dyn,us,12}$	0.209	0.554	0.312			
$E_{dyn,freq,12}$	0.192	0.572	0.398			
$E_{dyn,us,\overline{dens},12}$	0.022	0.482	0.252			
$E_{dyn,freq,\overline{dens},12}$	0.025	0.521	0.345			
mc	0.083	0.000	0.028			

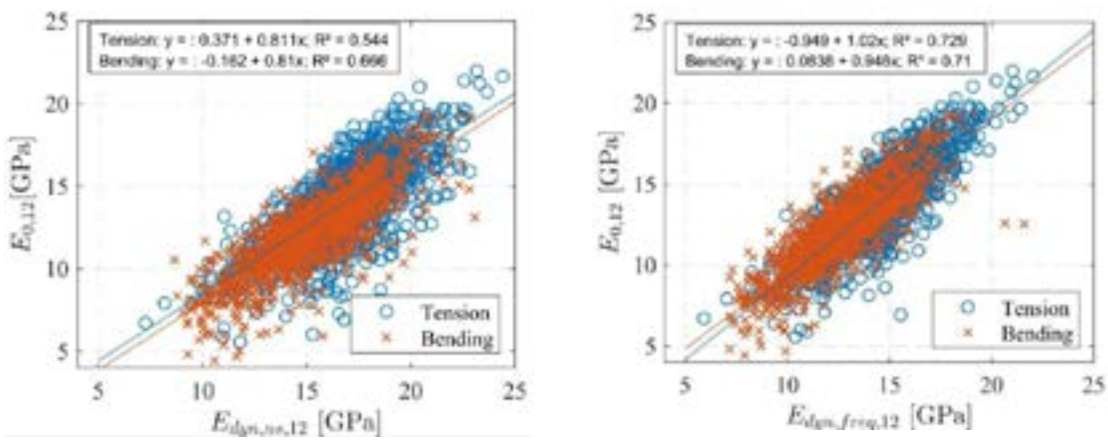
4. RESULTS

4.1. LONGITUDINAL STRESS WAVE METHOD VS. ULTRASOUND MEASUREMENT

Figure 1 shows the relationship between MOE_{dyn} from the US and LSW measurement. Generally, high consistency between both measurements across the wood species can be observed. The prediction accuracy between ultrasound MOE_{dyn} and eigenfrequency MOE_{dyn} ranges between 0.7 for beech and 0.87 for ash. If the MOE_{dyn} is calculated using average density (Figure 1b), the overall R^2 value drops and the scatter shows significantly higher variation. Therefore, individual density values provide a homogenizing effect on the relationship between the MOE_{dyn}. Major differences in the prediction of grade determining properties, like strength and stiffness, are, therefore, expected for the MOE_{dyn} without considering the density.

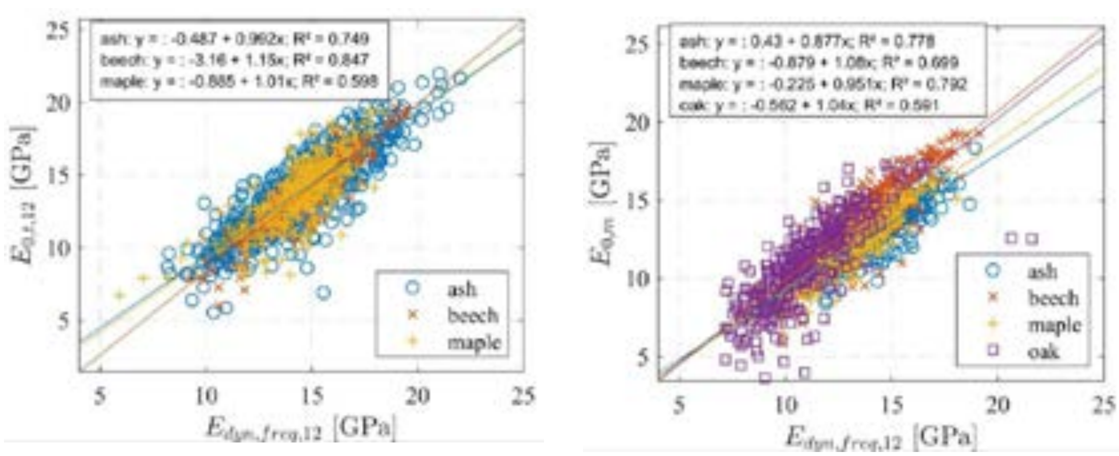
4.2. STIFFNESS PREDICTION

The prediction accuracy for the tensile and bending MOE is shown in Table 4. MOE_{dyn} from LSW measurement shows higher R^2 values compared to the US measurement. Whereas for ash the difference is less pronounced, the difference for oak and maple accounts approximately 0.3. The prediction strength of static MOE drops for both MOE_{dyn} ($E_{dyn,freq,\overline{dens},12}$ and $E_{dyn,us,\overline{dens},12}$) calculated with average density.



(a) (b)

Figure 2: Scatterplot between (a) MOE_{dyn} measured using US device and static MOE and (b) MOE_{dyn} measured using LSW method and static MOE for all investigated hardwood species, split by the testing mode (bending, tension)



(a) (b)

Figure 3: Relationship between (a) MOE_{dyn} measured using LSW method and tension MOE and (b) MOE_{dyn} measured using LSW method and bending MOE, grouped by the hardwood species (bending, tension)

The prediction accuracy between US MOE_{dyn} and LWS MOE_{dyn} is compared for a combined hardwood species data set in Figure 2 dependent on the testing mode. The LWS MOE_{dyn} scatters less compared to the US measurement. For both measurements, the regression equation seems to predict tensile and bending MOE equally well. Furthermore, no difference in scatter is observable between the two testing modes. For the specimens tested in tension, E_t shows larger scatter with values ranging up to 22 GPa.

The possibility of combining the wood species for the species independent strength grading is visualized in Figure 3. For both testing modes (bending and tension) the population of temperate European hardwoods show homogenous scatter. The values scatter within the same range. Furthermore, specimens show, especially for tension test specimens, almost parallel slope of the regression line. The observation supports the approach of Ravenshorst (2015) regarding the applicability of the species independent strength grading on the example of tensile data.

4.3. STRENGTH PREDICTION

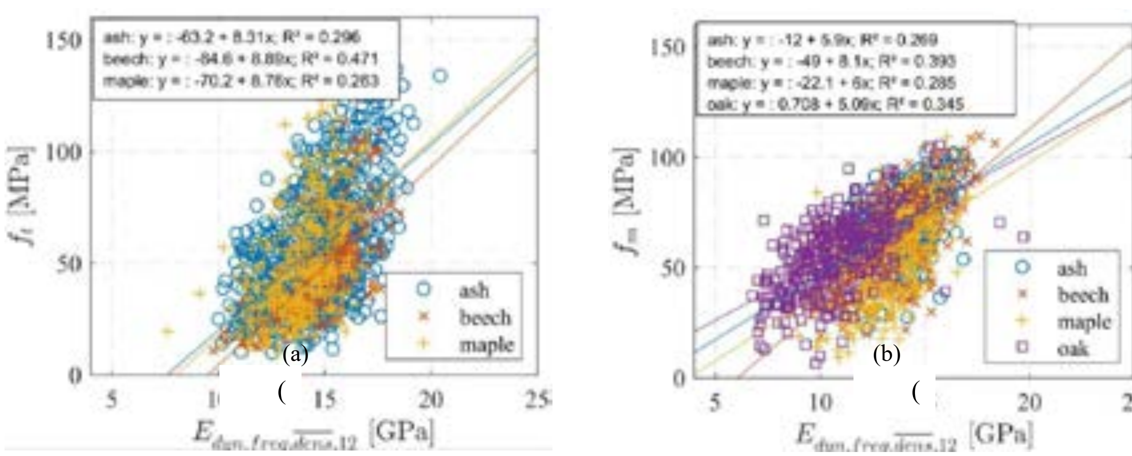
The bending and tensile strength are predicted with US ($E_{dyn,us,12}$) less accurately compared to the LSW. The accuracy ranges between 0.007 and 0.279 for US and 0.142 and 0.405 for the LSW. The R^2 values between $E_{dyn,freq,12}$ and strength (f_t and f_m) is approximately two times higher compared to the values between $E_{dyn,us,12}$ and strength. These findings support the results of Frühwald and Hasenstab (2010) who came to the conclusion that MOE_{dyn} from LSW is a better predictor for the tensile strength.

The scatter between MOE_{dyn} calculated with average density and tensile strength is visualized for the frequency measurement in Figure 4. The scatter for the US shows a similar pattern but higher variation (not shown here). The species range similar to the stiffness in the same values range. Especially, for the tensile strength, the scatter is uniform. The slopes of the regression lines are almost equal, allowing for a species-independent strength grading.

The use of ultrasound and eigenfrequency MOE_{dyn} depends on the density value used for the calculation of the MOE_{dyn} If the average density value of the wood species is used for the calculation of MOE_{dyn} and not the individual density value, the strength prediction accuracy increases for some samples. For specimens tested in tension, a clear increase in prediction accuracy is observable, for the specimens tested in bending, the exclusion of density value leads to a slight drop in R^2 values (0.015 on average). Same results have been shown by (Nocetti et al. 2016) on chestnut timber tested in bending. The prediction accuracy decreased from 0.24 to 0.15. This behaviour is attributed most likely not only to the testing mode but rather to specimens dimensions and sawing pattern used, as shown below.

Figure 5 visualizes exemplarily the difference in prediction accuracy of the tensile strength using MOE_{dyn} calculated with average and individual density. For the relationship between MOE_{dyn} calculated with average density and tensile strength, a scatter with less variation and steeper regression line can be observed. As a consequence, higher R^2 value can be achieved. By calculating with an average density, the variation in MOE_{dyn} is reduced. The density is a part of MOE_{dyn} calculation that show either low correlation or no correlation to the timber strength. In the case of maple, the correlation is even negative (r = -0.120).

Figure 4: Relationship between (a) MOE_{dyn} measured using LSW and tensile strength and (b) MOE_{dyn} measured using LSW and bending strength, grouped by hardwood species



(a) (b)

Figure 5: Relationship between tensile strength and MOE_{dyn} measured by using LSW and calculated with the individual (a) and average density (b) for ash sample tested by Kovryga et al. (2019) (N = 481)

The observable differences in strength prediction accuracy are attributed most likely to the cross-section size and the sawing pattern used. This can be observed clearly on the ash tested in tension. Ash specimens with cross-sections 50x100 and 50x150 were cut with “cutting all around” (without pith) and indicate no significant difference in prediction accuracy using $E_{dyn,freq,12}$ and $E_{dyn,freq,dens,12}$. Other tensile test samples, except beech, were sawn with pith. The juvenile wood is known for hardwoods for slightly higher density compared to the mature wood. Therefore, a higher share of pith specimens could affect the applicability of the density for strength prediction. Especially as between density and strength no or low correlation is present. So for the smaller ash dimensions, the prediction accuracy increased from 0.265 to 0.334. To make general conclusions and study the causes, the special testing program is required.

Additionally, the effect of the wood quality on the relationship between MOE_{dyn} and strength can be observed in Figure 6. The wood quality was defined as knot free specimens and specimens with $tKAR > 0.05$. For the tensile and bending strength prediction, the greater slope of the regression line is visible on the knot free specimens. In the case of tensile strength, the difference is much more pronounced. Although the R^2 value does not differ significantly between knot free ($tKAR < 0.05$) and specimens with knots, the variation of residuals in case of knot free specimens is greater. For bending strength the prediction accuracy is slightly higher.

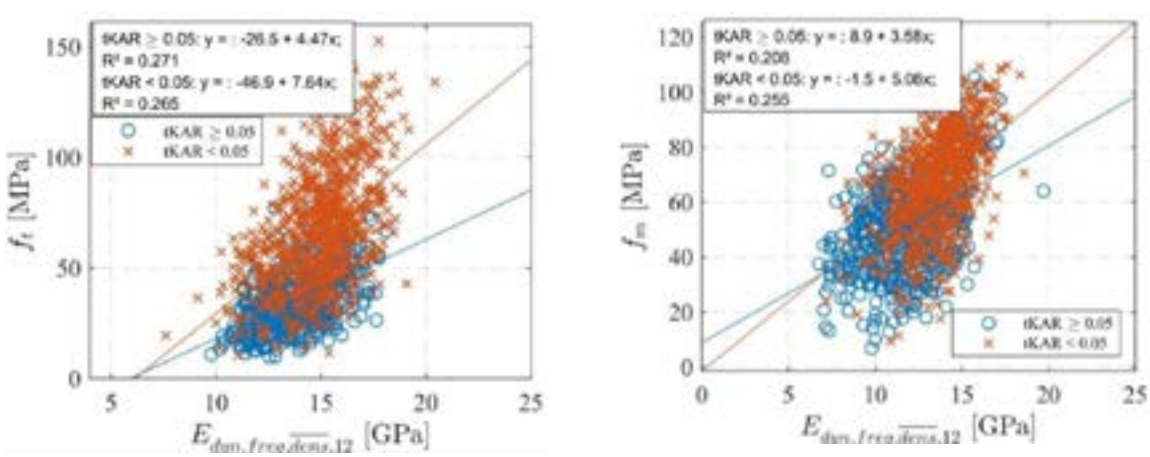
(a)

Figure 6: Relationship between (a) MOE_{dyn} measured using LSW and tensile strength and (b) MOE_{dyn} measured using LSW and bending strength, for a combination of hardwood species, grouped in knot free specimens ($tKAR < 0.05$) and specimens with knots ($tKAR > 0.05$)

6. Conclusions

In this paper, the differences between the prediction accuracy of the dynamic MOE measured by using US and LSW methods were studied. The MOE_{dyn} measured by using LSW allows higher prediction accuracy for the strength and stiffness. Nevertheless, the accuracy of the ultrasound (US) MOE is high as well, especially for the MOE measurements. The results also support the findings of Ravenhorst (2015) for the species independent strength grading for both bending strength and tensile strength. The same regression equation can be used to predict both tensile MOE and bending MOE with MOE_{dyn}. Furthermore, the effect of quality on the grading accuracy could be observed. Whereas for tensile specimens the prediction accuracy did not differ much, the slop of the regression line and the scatter differ significantly. The prediction accuracy of strength grading with LWS and US is dependent on the cross-section. For smaller cross-sections, the use of average density in MOE_{dyn} calculation is likely to reduce the variation and increase the prediction accuracy. Further research on these specimens is required.

(b)



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