Strength grading of structural timber in existing structures – Study on the apparatus supported grading with the ultrasonic time-of-flight measurement

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Abstract The material properties of timber are determined by growth characetristics of this natural material what results in a significant variability of its parameters. Their limitation is required for its application as construction material. This is achieved by strength grading. The grading methods developed for new timber can only be applied on timber members in existing historic buildings with major restrictions. Therefore, a strength grading of timber members in existing structures is rarely carried out nowadays. Though, exact evaluation of the structural state and the planning of a substance careful, professional redevelopment is only possible when the present material quality is determined. Here, non- and semi-destructive test methods – e.g. ultrasonic time-of-flight measurement – can be used. This contribution describes comparative material studies on the applicability of this test method for the on-site strength grading. Two alternatives are investigated to determine how the ultrasonic time-of-flight measurement can be integrated in the present grading standards. The results show a significant improvement of the grading yield and the accuracy of the grading process can be achieved by the combined use of visual grading and ultrasonic measurements.

Keywords: historic timber structures, strength grading, ultrasonic time-of-flight measurement

1 Introduction

The material properties of structural timber show significant variation which result mainly from the wood structure itself. Additional variation is caused by local growth

conditions. Their limitation is an unconditional requirement for its application as regulated construction material. This is achieved by a strength grading.
The requirements of strength grading of structural timber are regulated on European level by EN 14081-1, which are met by the German grading standards DIN 4074-1/-5. In general, strength grading is divided into visual and mechanical grading procedures.
The visual grading concentrates on superficial visible and visually determinable growth properties. The timber is classified into three grades (coniferous wood: “S”-classes, deciduous wood: “LS”-classes). Hereby, the timber is divided into structural timber with low (S7, LS7), average (S10, LS 10) and high load-bearing capacity (S1, LS13). If the visual strength grading is combined with non-/semi-destructive test methods, the timber can also be classified into grade S15/LS15 (see DIN 4074-1 & DIN 4074-5, chapter 7.3.1). The assignment of the visually determined classes to the strength classes according EN 338 is accomplished according to EN 1912 based on the provenance, the wood species and the applied grading standard.
This assignment process is not necessary if the timber is machine graded. The results of the applied nondestructive measurements are used to directly assign the timber to strength classes according to EN 338. Besides deflection measurements, optical methods and radiography/microwaves dynamic measurements are applied for mechanical grading (see Sandomeer and Steiger, 2009).
The grading methods which have been developed for new structural timber can only be applied with great limitations on timber members in existing structures. This concerns basically the limited accessibility and visibility of the timber elements, the non-existing personnel qualification as well as the lack of in-situ flexible manageable and certified grading apparatuses (see Lißner and Rug, 2018). Therefore, a strength grading of timber members in existing structures is rarely carried out. The present load-bearing capacity of the structural timber is at most intuitively estimated. Static calculations are then performed under the consideration that the structural timber belongs to the grades S10 and LS10 according to DIN 4074-1/-5 respectively C24 and D30 according EN 338. In doing so, load-bearing capacity reserves and deficits cannot be revealed. This can lead to a less substance-carefully and unprofessional redevelopment. Nevertheless, the determination of the present material properties by a reliable on-site grading enables a more reliable assessment of the structural stability and functional capability. This enables substance-careful and efficient redevelopment measures.

2 Strength grading of timber in existing structures

The strength grading of structural timber members in existing structures in combination with the application of non-/semi-destructive test methods allows the exact and reliable determination of material properties. This would not be possible with the visual strength grading alone.

The visually observable and measurable grading criteria show only a weak correlation to the strength properties of structural timber (see Glos, 1995; Sandomeer and Steiger, 2009; Denzler and Glos, 2009). This leads to a low degree of distinctiveness, efficiency and significance. The combination of the visual grading with non-/semi-destructive measurements and test methods enables a significant enhancement of the efficiency, as shown in Table 1.

Table 1 Relation between non-destructive measurable indicating properties (IP) of the strength and the actual, destructive measurable strength properties (taken from Sandomeer und Steiger, 2009)

Indicating Properties (IP)	Coefficient of determination (R^2)
annual ring width	0,15 … 0,35
knots	0,15 … 0,35
density	0,20 … 0,40
natural frequency, ultrasonic velocity	0,30 … 0,55
static modulus of elasticity	0,40 … 0,65
dynamic modulus of elasticity	0,30 … 0,55
knots & density	0,40 … 0,60
knots & modulus of elasticity	0,55 … 0,75
knots, density & modulus of elasticity	0,55 … 0,80

In the last decades many non-/semi destructive test methods for the in-situ evaluation of structural timber have been developed, investigated and tested (see Lißner and Rug, 2018). Although this is rarely possible, the laboratory testing of samples taken semi-destructively certainly enables the exact determination of material properties (see Rug und Seemann, 1988) - especially in structures which are listed as national heritage. In such cases the non-destructive determination of material properties is only possible with sclerometers and dynamic test methods. The dynamic test methods include the measurement of the natural frequency (see Görlacher, 1984) and the ultrasonic measurement (see Steiger, 1996; Sandoz, 1989; Augustin, 2004). Both methods are nowadays state of the art and are used e.g. for the grading of timber in sawmills.

3 The ultrasonic test method

The ultrasonic test method is based on the strong correlation between the velocity of an ultra-sonic pulse and the stiffness and density of the material. It is divided into the ultrasonic echo method and the time-of-flight measurement. The ultrasonic echo method uses the reflection of an ultrasonic pulse induced perpendicular to the grain on surfaces (i.e. surfaces or imperfections). This method is mainly used for the detection of imperfection and damage (see Linke et al., 2017). The time-of-flight measurement uses the time which is required to send an ultrasonic pulse from transmitter to receiver and is subdivided according to the application of the direction of measurement (see Fig. 1). This method suitable for the determination of material properties (see Linke et al., 2017).

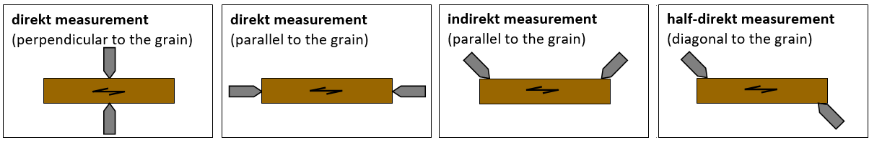

Fig. 1 Measurement methods for ultrasonic test (taken from Linke et al., 2017)

Besides the investigation of the basic applicability and crucial influences – e.g. moisture content, temperature – the strength grading of timber with the ultrasonic time-of-flight measurement has been studied. This includes the relation between the ultrasonic velocity and the material properties which are relevant for strength grading – i.e. density, bending strength, modulus of elasticity. A detailed summary of the ultrasonic time-of-flight measurement's state of the art is given in Linke et al., (2017).

The predominant part of the previous studies focused on the application on new structural timber. However, single studies showed, that there is no significant difference between new and old timber (see Kranitz et al., 2010). Therefore, the application on old timber is possible. This has been the case in the last decade, although these studies focused mainly on single structures with a relatively small extent. Extensive systematic studies on old timber are missing hitherto.

4 Comparative material tests

4.1 Aim & subject

The material tests described hereinafter are part of a systematical studies on new and old timber concerning the applicability of the ultrasonic time-of-flight measurement as a non-destructive method for the determination of the material properties of structural timber in existing structures. The aim of the study is the evaluation of the efficiency and reliability of the ultrasonic time-of-flight measurement as a grading tool. The subject of this sub study were specimen from spruce (Picea abies), pine (Pinus sylvestris) and oak (Quercus robur/petraea) with approximately 300 specimens of each species. The sample sizes and specimen dimensions are listed in Table 2.

Table 2 Sample sizes and specimen dimensions

Species	sample size n	specimen dimensions b/h/ℓ
Spruce (Picea abies)	303	
Pine (Pinus sylvestris)	300	50/80/1520 mm
Oak (Quercus robur/petraea)	301	

4.2 Methods

The comparative material tests are divided into three parts:

1. Visual grading according to EN 14081-1:2016 and DIN 4074-1:2012/-5:2008
2. Ultrasonic time-of-flight measurements
3. Destructive bending test according to EN 408:2012

Additionally, the density was determined according to EN 408:2012 and the moisture content was measured according to EN 13183-1/-2:2002.

4.3 Visual strength grading

The visual strength grading of the specimen was carried out according to DIN 4074-1:2012 and DIN 4074-5:2008. Herein, the criteria listed in chapter 5 of the respective standards were applied.
Several further features of the specimen, which do not account for one of the criteria listed above (e.g. finger joints, smaller damages due to production/transportation) were documented but not taken into consideration for the classification according to DIN 4074-1:2012/-5:2008.

4.4 ultrasonic time-of-flight measurements

After the specimen were graded visually the time-of-flight and the ultrasonic velocity were measured with the apparatus Sylvatest Trio (CBT CBS Lausanne, CH, see Fig. 2).
The measurements were carried out as direct (probes are placed end to end) and indirect (probes are placed sideways in an angle of approx. 30°) measurement parallel to the grain. On each specimen, the measurement was performed on the upper and lower third of the specimen's height (direct measurement) and on the top and bottom side of the specimen respectively (see Figure 2). For each measurement the time-of-flight as well as the velocity of the ultrasonic impulse was documented.

Fig. 2 Direct (top) and indirect (bottom) ultrasonic time-of-flight measurements (1 … transmitter/receiver probe, 2 … test apparatus Sylvatest Trio, Fa. CBT CBS, Lausanne/CH)

Additionally, the climatie conditions (GANN Hydromette BlueLine Compact) and the moisture content (GANN Hydromette HT 85 with insulated electrodes, depth of measurement t = 15mm) was measured. The test results were adjusted to a moisture content of ω = 12% and a temperature of υ = 20°C for better comparability. For this, the adjustment equations according to Sandoz (1993) were applied (see Eqs. (1) and (2)).

$$v_{12} = v_{\omega} + 29 \cdot (\omega - 12) \quad for\ \omega \leq 32\,\% \tag{1}$$

where v_{12} is the velocity at ω = 12 %, v_{ω} is the velocity at ω ≠ 12 % and ω is the moisture content.

$$v_{20} = v_{\upsilon} - 3{,}9 \cdot (\upsilon - 20) \quad for\ \omega = 12\,\% \tag{2}$$

where v_{20} is the velocity at υ = 20°C, v_{υ} is the velocity at υ ≠ 20°C and υ is the temperature.

4.5 Destructive bending tests

The global modulus of elasticity and the modulus of rupture (i.e. bending strength) were determined in bending tests according to EN 408:2012, chapters 10 & 19. The used test setup is depicted in Fig. 3.

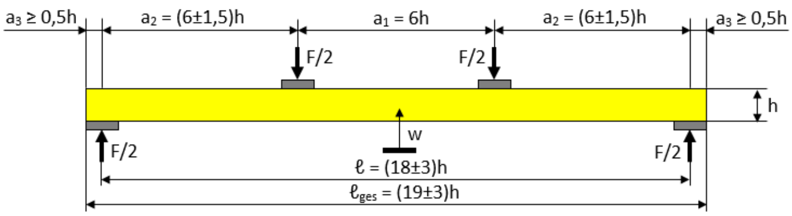

Fig. 3 Bending test setup (ℓ = 1440mm, ℓges = 1520mm, a1 = a2 = 480mm, a3 = 40mm)

The test load was applicated with a hydraulic press (max. load: 500 kN). The deflection was measured over the crosshead travel (with stiffness correction) with an external sensor (ASM position sensor WS11-2000).
The density was determined according to EN 408:2012 on samples which were cut out of the bending specimen (8 samples for each specimen). Additionally, the moisture content was determined on the same samples according to EN 13183-1:2002.

5 Results and discussion

5.1 Visual strength grading

The results of the visual strength grading of the tested specimen is depicted in Figure 4. The predominant part of the sample material was assigned to the grading classes S7/LS7 (low load-bearing capacity) and S10/LS10 (average load-bearing capacity). Only 11 % (spruce and pine timber) and 19 % (oak timber) met the requirements for the classification in the highest visual grading class S13/LS13 (high load-bearing capacity). What is more, 13-23 % (spruce and pine timber) and 21 % (oak timber) could not be assigned to any grading classes according to DIN 4074-1/-5. The main decisive grading criteria for all specimen (coniferous and deciduous wood) were knots, slope of grain and cracks.

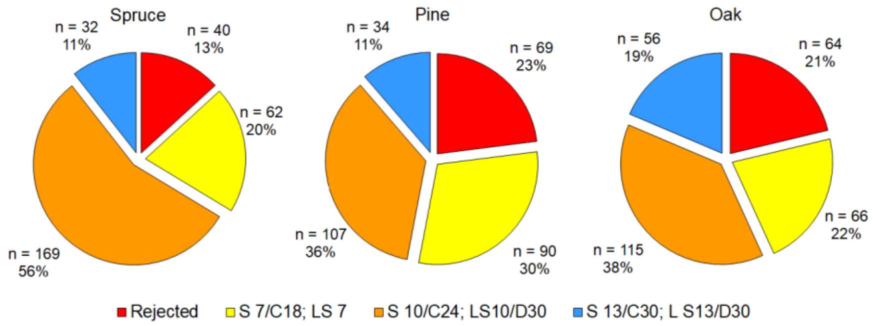

Fig. 4 Results of the visual strength grading according DIN 4074-1:2012/-5:2008 (n = sample size)

The relatively large amount of timber with low and average load-bearing capacity (grading classes S7/LS7 and S10/LS10) as well as the quite high rate of rejected specimen is a common result for a visual strength grading of structural timber. The observed grading yield is mainly caused by the relatively week correlation between the visual determinable and measurable grading criteria and the actual strength and stiffness properties of timber (compare Table 1). These results prove the fact, that

timber with a high load bearing capacity (i.e. S13/LS13 acc. DIN 4074-1/-5 respectively >C30/D30 acc. EN 338) cannot be graded visually in a reliable manner.
A significant improvement of the grading yield can be achieved by the additional application of non- and semi-destructive test methods. For example, the additional determination of the modulus of elasticity with the help of dynamic test methods leads to a significantly higher correlation (compare Table 1 & Fig. 5).

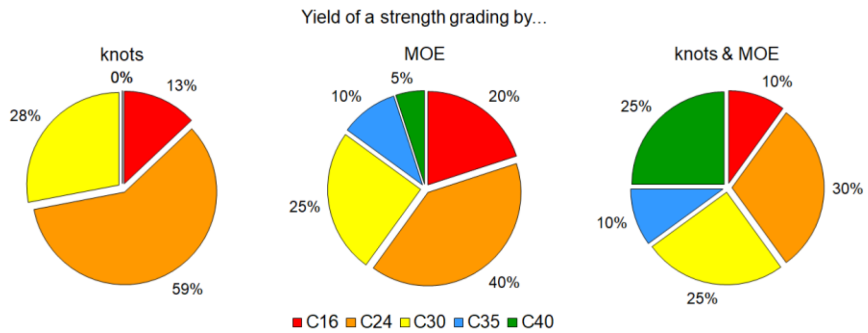

Fig. 5 Improvement of the grading yield by application of different grading criteria (taken from Blaß and Görlacher, 1996)

The applicability of an apparatus-supported strength grading is proven amongst others by the studies of Blaß and Frese (2002). The proposed grading procedure includes the determination of the dynamic modulus of elasticity with the natural frequency measurement according to Görlacher (1984) and the density as well as a visual grading according to the requirements of grading class S10 according to DIN 4074-1. Interestingly, a grading solely based on non-destructive measurements - i.e. the waiver of the visual grading – led to a decrease of the characteristic values. The grading procedure proposed by Blaß/Frese was introduced into the German grading standard in 2008.

5.2 Grading with the ultrasonic time-of-flight method

The ultrasonic time-of-flight measurement gives the opportunity to determine the material values of timber with relatively low effort. The applicability of this test method for the non-destructive testing and strength grading of structural timber was partially investigated in the past. In particular, the studies on Swiss and Austrian spruce timber presented in Steiger (1996), Sandoz (1989) and Augustin (2004) must be mentioned. In order to use the ultrasonic velocity as a grading criterion, limiting values were derived from the test results. They have been determined with the regression equations and the normative values of the modulus of elasticity from EN 338 (e.g. Augustin, 1998).

In analogy to the approach of Augustin (1998) several regression equations have been calculated from the results of the own ultrasonic time-of-flight measurements and the destructive bending tests. Herein, the relation between the ultrasonic velocity and the bending strength as well as the static modulus of elasticity was observed. The results are shown in Table 3.

Table 3 Relation between the ultrasonic velocity and the bending strength as well as the static modulus of elasticity of spruce, pine and oak (v_{dir} – direct measurement, v_{ind} – indirect measurement, r – coefficient of correlation, r^2 - coefficient of determination)

relation	spruce	pine	oak
$v_{dir} \leftrightarrow f_m$	$f_m = 0{,}02v_{dir} – 84$ (r = 0,425; r^2 = 0,181)	$f_m = 0{,}02v_{dir} - 26$ (r = 0,227; r^2 = 0,052)	$f_m = 0{,}03v_{dir} – 81$ (r = 0,686; r^2 = 0,470)
$v_{ind} \leftrightarrow f_m$	$f_m = 0{,}02v_{ind} - 76$ (r = 0,445; r^2 = 0,198)	$f_m = 0{,}02v_{ind} - 34$ (r = 0,274; r^2 = 0,075)	$f_m = 0{,}03v_{ind} – 86$ (r = 0,717; r^2 = 0,514)
$v_{dir} \leftrightarrow E_m$	$E_m = 4{,}6v_{dir} – 14267$ (r = 0,543; r^2 = 0,295)	$E_m = 2{,}8{*}v_{dir} – 1688$ (r = 0,284; r^2 = 0,081)	$E_m = 6{,}04v_{dir} – 15374$ (r = 0,829; r^2 = 0,687)
$v_{ind} \leftrightarrow E_m$	$E_m = 4{,}4v_{ind} – 12467$ (r = 0,564; r^2 = 0,318)	$E_m = 2{,}9v_{ind} – 2026$ (r = 0,317; r^2 = 0,100)	$E_m = 6{,}2v_{ind} – 15629$ (r = 0,844; r^2 = 0,712)

Table 3 shows, that there is no significant difference between the direct and indirect measuring method. Nevertheless, the relations to the modulus of elasticity are significantly stronger than the relations to the bending strength. In general, the observed relations differ significantly. While the observed coefficients of correlation for spruce and oak have an average to high value, the relations for pine are relatively weak.
The determined regression equations were used to calculate limiting values for the ultrasonic velocity. These were based on the characteristic bending strength and the mean value of the modulus of elasticity for coniferous and deciduous timber according to EN 338. The reliability and applicability of the derived limiting values was verified by comparing the classification according to the ultrasonic velocity with the classification according to the determined material properties density, bending strength and modulus of elasticity. In order to reach a high level of accordance the limiting values have been adjusted empirically. The results of this approach are shown in Table 4.

Table 4 Accordance between the grading results by grading according the ultrasonic velocity and the material properties density, bending strength and static modulus of elasticity (v_{dir} – direct measurement, v_{ind} – indirect measurement)

relation	spruce	pine	oak
$v_{dir} \leftrightarrow f_m$	57 %	48 %	54 %
$v_{ind} \leftrightarrow f_m$	53 %	50 %	42 %
$v_{dir} \leftrightarrow E_m$	84 %	79 %	94 %
$v_{ind} \leftrightarrow E_m$	74 %	55 %	65 %

The grading with the limiting values which were calculated on basis of the static modulus of elasticity shows a higher level of accordance than the approach based on the characteristic bending strength. Furthermore, the accordance based on the direct measurement is higher than on basis of the indirect measurement. This observation applies on all the three investigated species.
Secondly, the grading yield of the ultrasonic grading is improved when compared to the visual grading. The rate of timber with a high load-bearing capacity (> C30/D30 acc. EN 338) is significantly higher (see for example Figure 6).

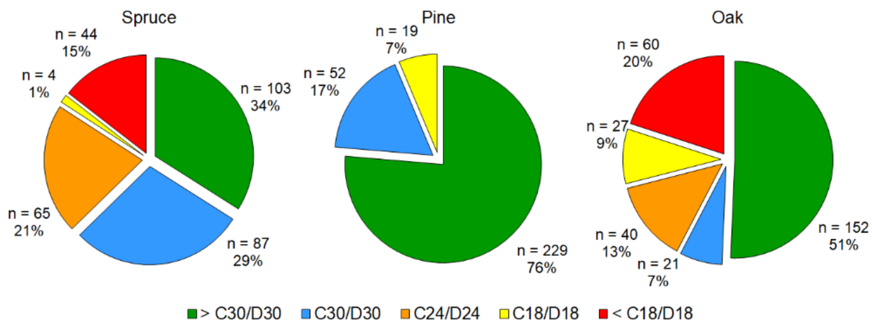

Fig. 6 Results of the grading based on the directly measured ultrasonic velocity and the static modulus of elasticity (n = sample size)

These results show that the ultrasonic velocity can principally be used as an additional grading criterion. To achieve a high level of accordance, the limiting values based on the relation between the ultrasonic velocity and the static modulus of elasticity should be applied. The limiting values, which were derived from the results of this study are shown in Table 5.

Table 5 Proposal for limiting values for the grading criterion "ultrasonic velocity" (v_{dir} – direct measurement, v_{ind} – indirect measurement)

Strength class	spruce		pine		Strength class	oak	
	v_{dir}	v_{ind}	v_{dir}	v_{ind}		v_{dir}	v_{ind}
C18	5100	4900	3900	3900	D24	4300	4200
C24	5500	5350	4600	4600	D30	4500	4400
C30	5750	5550	5000	4900	D35	4600	4600
C35	5950	5800	5300	5200	D40	4800	4700
C40	6150	6050	5700	5600	D50	5000	4900

5.3 Grading based on indicating properties

The results of the grading based on the ultrasonic velocity show, that thereliability must be enhanced since the observed accordance is partially low (see Table 4). Therefore, an alternative approach was investigated.
The machine grading uses a so-called grading parameter or indicating property. This parameter is derived from multivariate regression models and is used as an estimated value for the target values (i.e. strength and stiffness properties). Hereby, different test methods can be applied and considered in the grading decision.
According to this approach the results of the comparative material test were used to set up several multivariate linear regression models. In order to take the particularities of existing structures and the possible implementation of adjusted analysis methods into account the regression models were set up in a multi-level system.
The basis of this consideration are the so-called knowledge levels for the structural analysis proposed by Loebjinski, et al. (2018). The proposal differentiates four levels which range from extremely limited (knowledge level KL 0) to high (knowledge level KL 3). Depending on the level of investigation and the gathered information on the respective structure the application of adjusted analysis methods is possible. Nevertheless, the determination of the present material quality with non- and semi-destructive test methods is a strict requirement for their application. Table 6 shows the knowledge level as well as the corresponding minimum strength grading levels.

Table 6 Strength grading level (SGL) and the corresponding knowledge level (KL) according to Loebjinski, et al. (2018)

strength grading level	required strength grading procedure	corresponding Knowledge Level
SGL 0	no strength grading required	KL 0
SGL 1	visual grading according EN 14081-1	KL 1
SGL 2	apparatus supported visual grading *(visual grading and non-destructive test methods)*	KL 2
SGL 3	apparatus supported visual grading *(visual grading and non-/semi-destructive test methods)*	KL 2/3

The strength grading procedure required in the knowledge level KL 1 is comprehensively regulated in the present grading standards (EN 14081-1 & DIN 4074-1/-5). For the knowledge levels 2 & 3 the regulations of the DIN 4074-1/-5 concerning the apparatus supported visual grading can be considered. However, these normative regulations do not contain any concrete provisions on how the test methods are to be applied together with the visual grading regulations. Therefore, for further considerations the approach normatively regulated for machine grading is used.
The multivariate linear regression models were set up separately for the strength grading level SGL 2 & 3. Visual grading criteria as well as non- and semi-destructively measurable material properties were considered. The visual grading was taken into account by the criteria knots, slope of grain and cracks. The other visual

grading criteria were not considered since they are often not measurable on-site (e.g. pith and annual ring width), can be taken into account in the structural analysis (e.g. wane as reduced cross section, deformation as eccentricity) or can be eliminated in the course of redevelopment (e.g. decay, insects). The ultrasonic velocity as well as the transferred signal voltage were used as non-destructive criteria in the strength grading level SGL 2. Additionally, the dynamic modulus of elasticity and the density were considered in strength grading level SGL 3.
The relation between the grading criteria and the target property were investigated in different combinations. As a preliminary target property, the static modulus of elasticity was used. This was considered due to the generally high correlation between the static modulus of elasticity and the other material properties of timber. Furthermore, the investigated apparatus supported grading method is based on the dynamic properties of timber. For each species a total of 103 regression models were set up. The coefficients of correlation and determination of the strongest regressions of each species are listed in Table 7 for the strength grading levels SGL 1-3.

Table 7 Coefficients of correlation and determination of the investigated regressions

Strength grading level	Grading criteria	coefficients of correlation r & determination r^2		
		Spruce	Pine	Oak
SGL 1	knots/slope of grain/cracks	$r = 0{,}294$ $r^2 = 0{,}086$	$r = 0{,}535$ $r^2 = 0{,}286$	$r = 0{,}310$ $r^2 = 0{,}096$
SGL 2	knots /slope of grain/cracks/ ultrasonic velocity/transferred voltage (direct measurement)	$r = 0{,}790$ $r^2 = 0{,}624$	$r = 0{,}817$ $r^2 = 0{,}667$	$r = 0{,}869$ $r^2 = 0{,}755$
	knots /slope of grain/cracks/ ultrasonic velocity/transferred voltage (indirect measurement)	$r = 0{,}799$ $r^2 = 0{,}638$	$r = 0{,}816$ $r^2 = 0{,}666$	$r = 0{,}878$ $r^2 = 0{,}771$
SGL 3	knots /slope of grain/cracks/ dynamic MOE/ density (direct measurement)	$r = 0{,}803$ $r^2 = 0{,}645$	$r = 0{,}931$ $r^2 = 0{,}867$	$r = 0{,}885$ $r^2 = 0{,}783$
	knots /slope of grain/cracks/ dynamic MOE/ density (indirect measurement)	$r = 0{,}815$ $r^2 = 0{,}664$	$r = 0{,}916$ $r^2 = 0{,}839$	$r = 0{,}899$ $r^2 = 0{,}808$

Table 7 shows, that the relations of strength grading level SGL 1 are relatively weak. The implementation of non-destructively measurable material properties (e.g. ultrasonic velocity) improves the relation significantly. The additional implementation of semi-destructively measurable properties (e.g. density determined on small core drill samples) raises the coefficients of correlation and determination further. Though, depending on the species only a minor improvement was found.
In order to use the investigated relations for the apparatus supported visual grading method appropriate limiting values must be determined for the indicating property. This was done following the regulations of the EN 14081-2:2018, Annex B.

Therefore, one-dimensional linear regressions must be set up between the indication property (IP) and the target property (MOE) as shown in Eq. (3).

$$MOE = a_{MOE} \cdot IP + b_{MOE} \tag{3}$$

where MOE is the target value (here: static modulus of elasticity), IP is the indicating property, a_{MOE} is the regression coefficient of the target value and b_{MOE} is the intercept of the target value

The limiting values of the indication property can then be calculated by converting the regression equation and using the characteristic values of the modulus of elasticity according to EN 338 as required target value as shown in Eq. (4).

$$S_{MOE} = \frac{MOE_{req} - b_{MOE}}{a_{MOE}} \tag{4}$$

where S_{MOE} is the limiting value of the indicating property and MOE_{req} is the required value of the target value (here: characteristic value according to EN 338)

The calculated limiting values must be verified. According to the regulations of EN 14081-3:2016 for output-controlled grading systems this must be done with the help of the characteristic values. They must be determined according to EN 384 based on material test according to EN 408. The limiting values are verified if the characteristic values of the sample are at least equal to the characteristic values given in EN 338. Otherwise the limiting values must be modified and verified again.

The determination of the limiting values for the indicating property for the investigated apparatus supported grading method was only necessary for the strength grading level 2 & 3. For the strength grading level SGL 1 the limiting values are not required since the classification must be done based on the limiting values given in DIN 4074-1/-5. The regression equations which were used for the determination of the limiting values are listed in Table 8.

Table 8 Regression equations for the determination of limiting values for the indicating property

Strength grading level	species	Regression equation	coefficients of correlation r & determination r²
SGL 2	Spruce	$E_m = IP - 2{,}18 \cdot 10^{-11}$	$r = 0{,}790$; $r^2 = 0{,}624$
	Pine	$E_m = IP - 2{,}91 \cdot 10^{-11}$	$r = 0{,}799$; $r^2 = 0{,}638$
	Oak	$E_m = IP - 2{,}55 \cdot 10^{-11}$	$r = 0{,}817$; $r^2 = 0{,}667$
	Spruce	$E_m = IP - 2{,}55 \cdot 10^{-11}$	$r = 0{,}816$; $r^2 = 0{,}666$
	Pine	$E_m = IP - 1{,}64 \cdot 10^{-11}$	$r = 0{,}869$; $r^2 = 0{,}755$
		$E_m = IP - 3{,}64 \cdot 10^{-12}$	$r = 0{,}878$; $r^2 = 0{,}771$
SGL 3	Spruce	$E_m = IP + 7{,}26 \cdot 10^{-12}$	$r = 0{,}803$; $r^2 = 0{,}645$
	Pine	$E_m = IP - 1{,}27 \cdot 10^{-12}$	$r = 0{,}815$; $r^2 = 0{,}664$
	Oak	$E_m = IP + 3{,}64 \cdot 10^{-12}$	$r = 0{,}931$; $r^2 = 0{,}867$
	Spruce	$E_m = IP - 3{,}64 \cdot 10^{-11}$	$r = 0{,}916$; $r^2 = 0{,}839$
	Pine	$E_m = IP + 5{,}46 \cdot 10^{-12}$	$r = 0{,}885$; $r^2 = 0{,}783$
		$E_m = IP - 3{,}64 \cdot 10^{-11}$	$r = 0{,}899$; $r^2 = 0{,}808$

The limiting values of the indicating property were only calculated for selected strength classes according EN 338:2016, as listed below:

- Coniferous timber (Spruce/Pine): C18, C24, C30, C35, C40
- Decidious timber (Oak): D18, D24, D30, D35, D40

The determination of limiting values for the strength classes higher than C40/D40 was waived, since experience has shown that these values do not produce any significant improvements in the verification procedure or any improvements that can be used in reality.

The verification as well as a potentially necessary empirical modification of the limiting values was carried out in two steps. Firstly, the characteristic values of the static modulus of elasticity $E_{0,mean}$ were calculated for each class. Secondly, the classification based on the indicating property as well as based on the static modulus of elasticity determined in destructive bending test were compared.

The characteristic values for the static modulus of elasticity were calculated according to EN 384:2019, chapter 5.5.2.1 and EN 14358:2016, chapter 3.3. The classification based on the static modulus of elasticity which was determined in destructive bending tests was carried out under consideration of a measurement correction of 3 %. Furthermore, a limiting value undercut of 5 % was considered acceptable for the classification based on the indicating property following the regulations of EN 384:2019, equation (10).

Table 9 shows the derived limiting values. It can be seen that - due to the relatively strong relation (see Table 8) - the characteristic values of the static modulus of elasticity which are given in EN 338:2016 can be applied as limiting values for the indicating properties without modification.

Table 9 Limiting values for the indicating property for strength grading level SGL 2 & 3

Strength class acc. EN 338	Spruce [N/mm²]	Pine [N/mm²]	Strength class acc. EN 338	Oak [N/mm²]
<C18	<9000	<9000	<D18	<9500
C18	9000	9000	D18	9500
C24	11000	11000	D24	10000
C30	12000	12000	D30	11000
C35	13000	13000	D35	12000
C40	14000	14000	D40	13000

The comparison between the classification based on the indicating property and the classification based on the static modulus of elasticity determined in destructive bending test shows relatively high level of correspondence of approximately 85-95 % depending on the species (see also Table 10). The empirical modification of the limiting values did not lead to a significant improvement of the level of correspondence.

Table 10 Level of Correspondence between the classification based on Table 8 and the results of the destructive material tests

Strength grading level	Grading criteria	Level of correspondence		
		Spruce	Pine	Oak
SGL 2	knots /slope of grain/cracks/ ultrasonic velocity/transferred voltage (direct measurement)	85,1 %	91,3 %	91,3 %
	knots /slope of grain/cracks/ ultrasonic velocity/transferred voltage (indirect measurement)	84,8 %	92,3 %	91,3 %
SGL 3	knots /slope of grain/cracks/ dynamic MOE/ density (direct measurement)	85,1 %	94,0 %	91,6 %
	knots /slope of grain/cracks/ dynamic MOE/ density (indirect measurement)	84,5 %	94,0 %	90,6 %

The resulting grading yield is shown in Figure 7. In General, there is a significant increase of timber with a very high load-bearing capacity (> C30/D30 according EN 338) compared to the visual grading as well as to the grading based exclusively on the ultrasonic time-of-flight measurement.

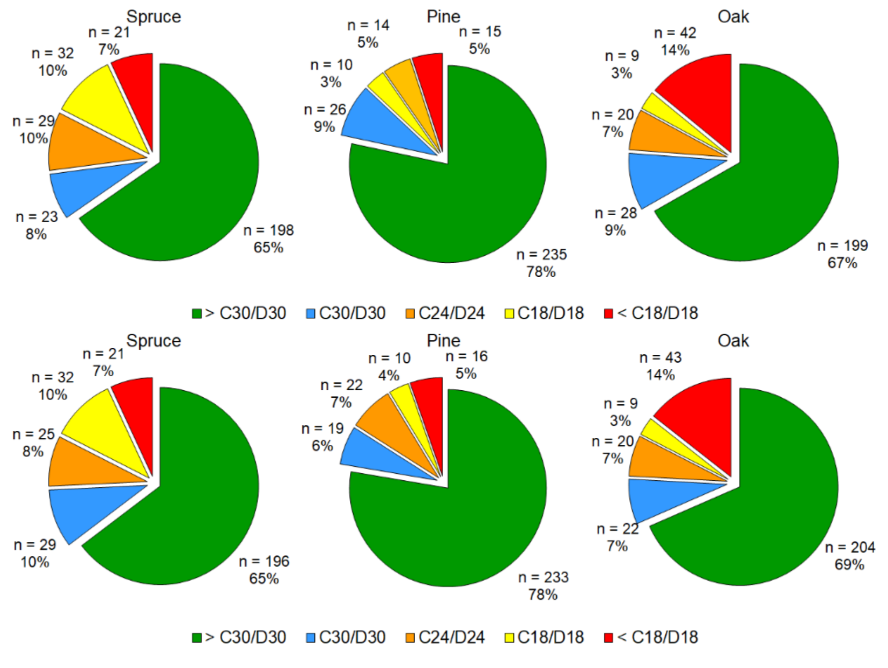

Fig. 7 Grading yield for the strength grading level – top: SGL 2; bottom: SGL 3 (indirect measurement; n = sample size)

6 Conclusion

The results of the study show that the application of the ultrasonic time-of-flight measurement for the on-site strength grading of timber members in existing structures in general is possible. The grading should not be carried out exclusively with non-destructive methods due to the partially weak correlation. The additional implementation of non- and semi-destructively measurable material properties – e.g. knots, slope of grain, cracks, density – leads to a significant improvement of the correlation. At the same time a higher level of correspondence with the destructive material tests was reached. The proposed grading method must be tested and verified in material tests on old timber on-site as well as in the laboratory. This will be the subject of future studies.

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