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STRENGTH GRADING OF STRUCTURAL TIMBER IN HISTORIC BUILDINGS – STUDIES ON THE APPLICABILITY OF THE ULTRASONIC TIME-OF-FLIGHT MEASUREMENT

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ABSTRACT: The material properties of structural timber have a significant variation. Their limitation is an unconditional requirement for its application as regulated construction material. This is achieved by strength grading. Here, non- and semi-destructive test methods – e.g. ultrasonic time-of-flight measurement – can be used supportively.
Current grading rules are developed for new timber, their applicability on timber in historic structures is limited. Therefore, strength grading of timber members in historic structures is rarely performed. Thus, load-bearing capacity reserves and deficits cannot be revealed.
The applicability of the ultrasonic time-of-flight measurement for the strength grading of structural timber in historic buildings is studied in comparative material tests. The results of the first sub study have shown a significant improvement of the grading yield by the combined use of visual strength grading and ultrasonic time-of-flight measurement. These results will be validated in further material tests on other wood species as well as on existing structures.

KEYWORDS: strength grading, historic timber structures, non-/semi-destructive test methods, ultrasonic time-of-flight measurements

1 Introduction

The material properties of structural timber show significant variation which results mainly from the wood structure itself. Additional variation is caused by local growth conditions. Their limitation is a necessary requirement for its application as regulated construction material. This is achieved by a strength grading.
The accordance of structural timber to the DIN EN 14081-1 [1] is required as stated in the nowadays by the building authority in Germany introduced Eurocode 5 (DIN EN 1995-1-1:2010 [2], 3.2 (1)P). DIN EN 14081-1 [1] regulates the requirements of the strength grading process and methods as well as the identification and certification of strength graded timber. These Europe-wide requirements and regulations are met by the German grading standard DIN 4074-1 & -5 [3, 4] (see DIN 20000-5 [5], 4.2).
The strength grading is divided into visual grading and machine-based mechanical grading. The visual grading concentrates on visible and visually determinable growth properties – e.g. knots, annual rings, slope of grain, cracks. The timber is sorted in three classes (coniferous wood: “S”-classes, deciduous wood: “LS”-classes). Hereby, the timber is divided in structural timber with low load-bearing capacity (S7, LS7), normal load-bearing capacity (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 be sorted in the class S15 respectively LS15. This is possible by the combination of the limitation values of the grading criteria of the classes S10 and LS10 as well as method-specifically parameters of the used non-/semi-destructive test methods (see [2, 3], 7.3.1).
The assignment of the visually determined classes to the strength classes according DIN EN 338 [6] – i.e. the definition of the characteristic material properties for the design – is accomplished according to DIN EN 1912 [7] on basis of the provenance, the wood species and the applied grading standard.
This assignment process is not necessary if the timber is mechanical graded. The nowadays available stationary machinery uses optical measurements as well as non-destructive test methods. The result of these measurements is used to directly assign the timber to the strength classes according DIN EN 338 [6]. Besides, deflection measurements and radiography/microwaves dynamic measurements are applied for the mechanical grading (see [8]).
mechanical grading can only be carried out by companies which have qualified personnel and certified machinery (s. [9, 10]).
A third opportunity for the strength grading is the direct assignment of timber to the strength classes according

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DIN EN 338 [6] on basis of the characteristic material properties derived according DIN EN 384 [11].
The in Germany normatively regulated system of the strength grading is depicted in Figure 1.

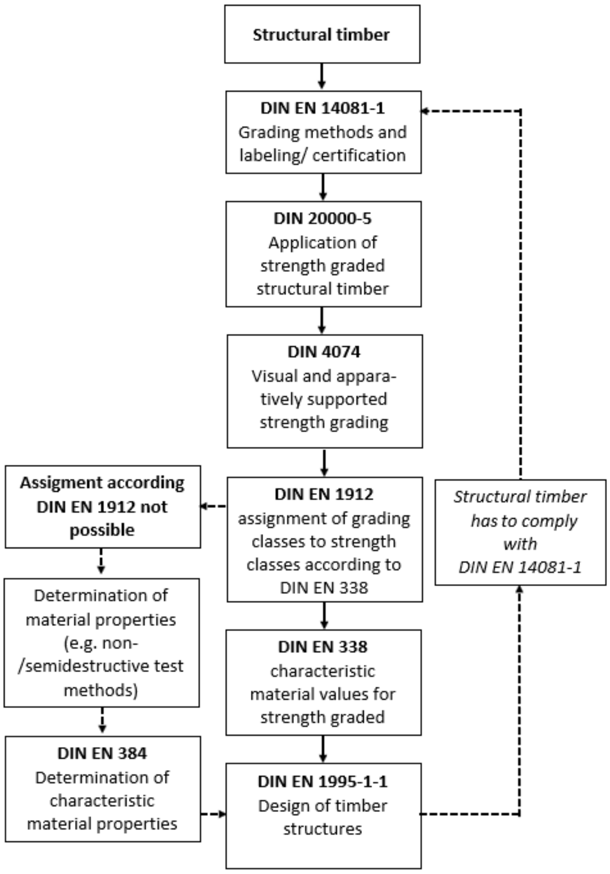

Figure 1: *normatively regulated strength grading system*

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 members, the non-existing personnel qualification as well as the lack of in-situ flexible manageable and certified grading apparatuses (see [12]).
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 performed under the consideration that the structural timber equals the grade S10 respectively LS10 according DIN 4074-1 & -5 [3, 4]. In doing so, load-bearing capacity reserves (members and connections with higher load-bearing capacity) and deficits (members and connections with lower load-bearing capacity) cannot be revealed. This can lead to less substance-carefully and unprofessional redevelopment.
With the help of reliability-theoretical methods the stability and load-bearing capacity of existing timber structures can be assessed exactly. This enables substance-careful and efficient redevelopment. To carry out such calculations the in-situ strength grading of the timber members with reliable methods is required (see [13]).

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 solely visual strength grading.

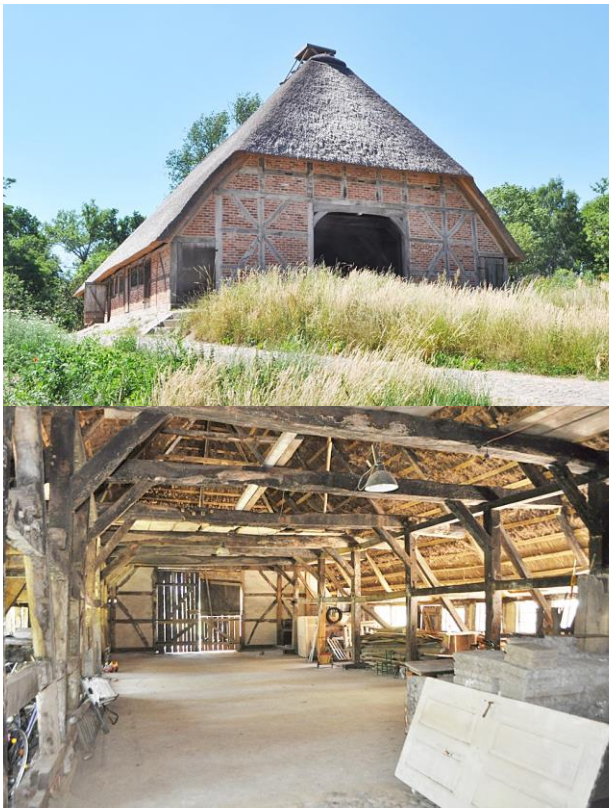

Figure 2: *half-timbered hall house, the redevelopment required the strength grading of the timber members – top: exterior view; bottom: interior view of the load-bearing structure*

The visually observable and measurable grading criteria show only a weak correlation to the strength properties of structural timber (see [8, 14]). 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 [8])

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 [15]). Although this is rarely possible, the laboratory testing of semi-destructive taken samples – e.g. core drill samples - certainly enables the exact determination of material properties (see [16-19]) - especially in structures which are listed as national heritage. In such cases the non-destructive determination of material properties is only possible with sclerometrical and dynamic test methods. The dynamic test methods include the measurement of the natural frequency [19] and the ultrasonic measurement (see [20-22]). 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 relation between the velocity of an ultrasonic 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 a perpendicular to the grain induced ultrasonic pulse on interfaces (i.e. surfaces or imperfections. This method is mainly used for the detection of imperfection and damage (see [23]. 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 Figure 3). This method is suitable for the determination of material properties (see [23]).

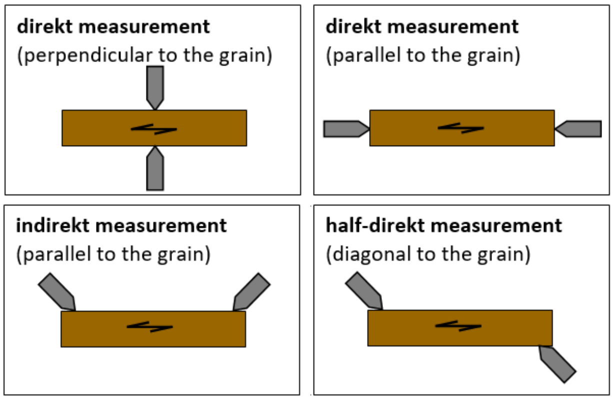

***Figure 3:** measurement methods for the time-of-flight measurement*

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 the strength grading – i.e. density, bending strength, modulus of elasticity. The results of previous studies show a moderate correlation to the density (r = 0,37 … 0,59) as well as a strong correlation to the bending strength and the modulus of elasticity (r = 0,58…0,76, see Figure 4p) respectively r = 0,67…0,95, see Figure 5). A detailed summary of the ultrasonic time-of-flight measurement's state of the art is given in [23].

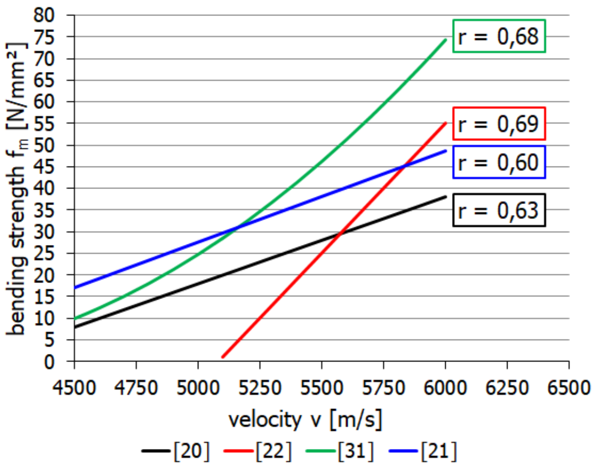

***Figure 4:** relation between velocity and bending strength according to literature (for spruce/pine)*

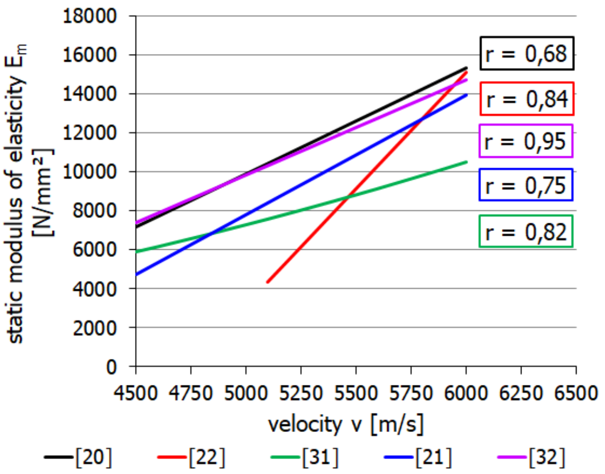

Figure 5: *relation between velocity and modulus of elasticity according to literature (for spruce/pine)*

Based on the observed relations limiting values for the ultrasonic velocity as grading parameter for structural timber have been proposed in [29] (see Table 2).

Table 2: *limiting values for the ultrasonic velocity as grading parameter for structural timber (taken from [29])*

Grading class according DIN 4074-1	Limiting value of the ultrasonic velocity (at ω = 12%) [m/s]
S13	v ≥ 5700
S10	5500 ≤ v < 5750
S7	5100 ≤ v < 5500
Rejected – not suitable for load-bearing purpose	v < 5100

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 [24]). Therefore, the application on old timber is possible. This has been the case in the last decade (see [25]), 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 hereinafter described material test are part of a systematic studie 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.
The subject of this sub-study were 190 specimens from spruce (*Picea abies*).

4.2 METHODS

The comparative material tests are divided in three parts:
1. Visual grading according DIN EN 14081-1 [1] and DIN 4074-1 [3]
2. Ultrasonic time-of-flight measurements
3. Destructive bending test according DIN EN 408 [26]

Additionally, the density was determined according to DIN EN 408 [26] and the moisture content was measured according to DIN EN 13183-1/-2 [27, 28].

4.2.1 Visual grading

The visual grading of the specimen was carried out according to DIN 4074-1:2012 [3]. The following criteria were measured and evaluated:
- Knots (DIN 4074-1:2012 [2], 5.1)
- Slop of grain (DIN 4074-1:2012 [2], 5.2)
- Pith (DIN 4074-1:2012 [2], 5.3)
- Width of annual rings (DIN 4074-1:2012 [2], 5.4)
- Cracks (DIN 4074-1:2012 [2], 5.5)
- Wane (DIN 4074-1:2012 [2], 5.6)
- Curvature (DIN 4074-1:2012 [2], 5.7)
- Discolouration, decay (DIN 4074-1:2012 [2], 5.8)
- Compression wood (DIN 4074-1:2012 [2], 5.9)
- Insect feeding (DIN 4074-1:2012 [2], 5.10)
- Further features (DIN 4074-1:2012 [2], 5.11)
- Moisture content (DIN 4074-1:2012 [2], 5.12)

Several further features of the specimen, which do not account as one of the criteria listed above (e.g. finger joints, smaller damages due to production/transportation) were documented but not taken in consideration for the assignment to the classes according DIN 4074-1:2012 [3].

4.2.2 Ultrasonic time-of-flight measurement

The time-of-flight and the ultrasonic velocity were measured with the apparatus Sylvatest Trio (CBT CBS Lausanne, CH, see Figure 6).

Figure 6: *Sylvatest Trio (Fa. CBT CBS, Lausanne/CH); left: test apparatus; right: transmitter/receiver*

The measurements were carried out as direct and indirect 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) respectively on the top and bottom side of the specimen (see Figure 7).

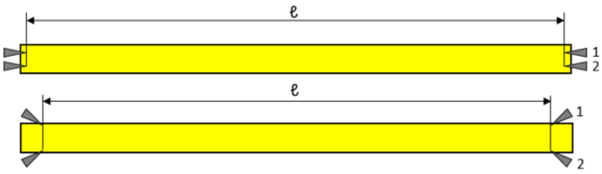

Figure 7: *Execution of the ultrasonic time-of-flight measurement – top: direct measurement; bottom: indirect measurement*

For each measurement the time-of-flight as well as the velocity of the ultrasonic impulse was documented. Additionally, the climatic conditions (GANN Hydromette BlueLine Compact) and the moisture content (GANN Hydromette HT 85 with insulated electrodes, t = 15mm) were measured.
The test results were adjusted to a moisture content of ω = 12% and a temperature of υ = 20°C for better comparability. The relations between the velocity and the moisture content respectively the temperature was investigated in [30]. The following adjustment equations were proposed:

$$v_{12} = v_{\omega} + 29 \cdot (\omega - 12) \text{ (für } \omega \leq 32\%) \quad (1)$$

v_{12} … velocity at ω = 12%; v_{ω} … velocity at ω ≠ 12%; ω … moisture content

$$v_{20} = v_{\vartheta} - 3{,}9 \cdot (\vartheta - 20) \text{ (für } \omega = 12\%) \quad (2)$$

v_{20} … velocity at ϑ = 20°C; v_{ϑ} … velocity at ϑ ≠ 20°C; ϑ … temperature

4.2.3 Destructive bending tests

The global modulus of elasticity and the modulus of rupture (i.e. bending strength) were determined in bending tests according to DIN EN 408:2012 [26], 10 & 19. The following procedure was applied:

- Support on two tilting supports
- Load application on the inner third of the specimen with a continuous velocity of v = 0,003h mm/s to ensure a rupture within t = (300±120) s
- Load application until rupture (i.e. 50% force reduction)

The used test setup is depicted in Figure 8.

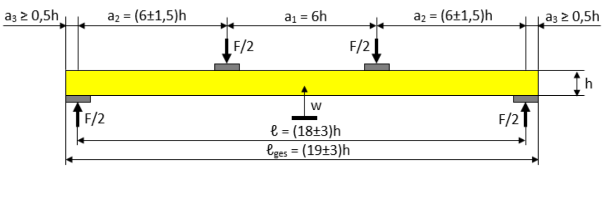

Figure 8: *Test setup for the bending tests (measurements: ℓ = 1440mm, ℓges = 1520mm, a1 = a2 = 480mm, a3 = 40mm)*

The test load was applied with a hydraulic press (max. load: 500 kN). The deflection was measured over the cross head travel (with stiffness correction) with an external sensor (ASM position sensor WS11-2000).
The modulus of elasticity and the modulus of rupture were calculated from the load-deflection-graph with the help of the following equations:

$$E_{m,g} = \frac{3a_2\ell^2 - 4a_2^3}{2bh^3 \cdot \left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a_2}{5Gbh}\right)} \quad (3)$$

$E_{m,g}$ … static global modulus of elasticity; a_2 … span between the support and the load application ; ℓ … span width between the supports; b … width of the specimen; h … height of the specimen; F_2-F_1 … increase in the load in the load-deflection-graph with a correlation coefficient of 0,99 or better; w_2-w_1 … deflection between F_2 - F_1; G … modulus of rigidity

$$f_m = \frac{3Fa_2}{bh^2} \quad (4)$$

f_m … bending strength (modulus of rupture); F … maximal test load; a_2 … span between the support and the load application; b … width of the specimen; h … height of the specimen

The density was determined according to DIN EN 408:2012 [26] on samples which were cut out of the bending specimen (8 samples for each specimen). The density was calculated with the following equation:

$$\rho_{\omega} = \frac{m_{\omega}}{V_{\omega}} \quad (5)$$

ρ_{ω} … density; m_{ω} … mass, V_{ω} … volume

The moisture content was determined with the electrical resistance measurement according DIN EN 13183-2:2002 [28] (GANN Hydromette HT 85 with insulated electrodes, t = 15mm).
Additionally, the samples for the determination of the density were dried. The moisture content was calculated according DIN EN 13183-1 [27] with the following equation:

$$\omega = \frac{m_1 - m_0}{m_0} \cdot 100 \quad (6)$$

ω … moisture content; m_1 … mass befor drying process; m_0 … mass after drying process

5 RESULTS

On basis of the visual grading the specimen could be assigned to the grading classes according DIN 4074-1 [3] as shown below:
- 41 specimens (≈ 22%) were assigned to the grading class S13
- 97 specimens (≈ 53%) were assigned to the grading class S10, mainly due to knots
- 27 specimens (≈ 14%) were assigned to the grading class S7, mainly due to knots and slope of grain

- 25 specimens (≈ 11%) could not be assigned to any grading class, mainly due to knots and cracks

These assigned grading classes were transferred to the strength classes of DIN EN 338 [6] according the specifications of DIN EN 1912:2013 [7] as shown in the following:
- grading class S13 equals strength class C30
- grading class S10 equals strength class C24
- grading class S7 equals strength class C18

The derived distribution of the specimen to the classes according DIN 4074-1:2012 [3] and DIN EN 338:2016 [6] is depicted in Figure 9.

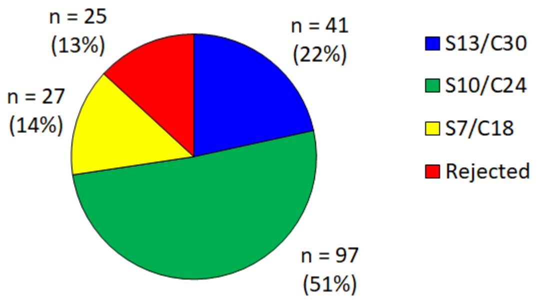

Figure 9: *Distribution of the specimen to the strength classes according DIN EN 338:2016 [6] on basis of the visual grading according DIN 4074-1:2012 [3]*

The results of the ultrasonic time-of-flight measurements show a clear increase of the measured velocity with the assignment of the specimen to a higher grading/strength class (see Figure 10). This was observed for the direct and indirect measurements as well as for the mean velocity and the minimal velocity.

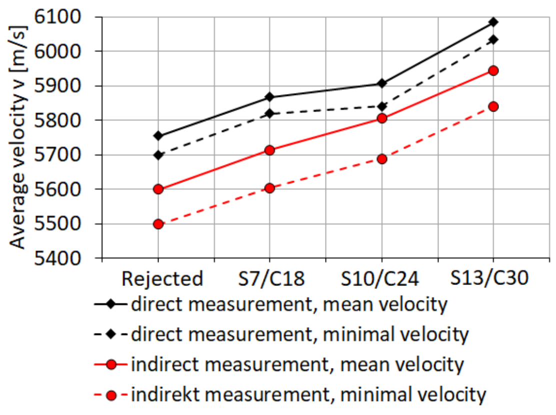

Figure 10: *Results of the ultrasonic time-of-flight measurement*

The specimens were additionally assigned to the grading classes according to DIN 4074-1:2012 [3]. Therefore, the mean ultrasonic velocity was solely used as grading criteria and compared to the limiting values according [29] (see Table 2). By doing so, the distribution shown in Table 3 and Figure 11 & 12 was derived.

Table 3: *Distribution of the specimen to the strength classes according DIN EN 338:2016 [6] on basis of the ultrasonic time of flight measurement*

Grading/ strength class	Distribution based on time-of-flight measure-ment (direct)	Distribution based on time-of-flight measure-ment (indirect)
S13/C30	72%	57%
S10/C24	19%	27%
S7/C18	17%	15%
Rejected	/	1%

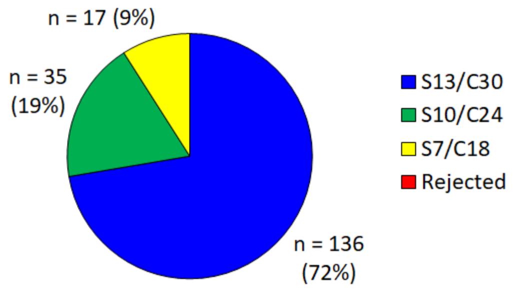

Figure 11: *Distribution of the specimen to the strength classes according DIN EN 338:2016 [6] on basis of the direct ultrasonic time-of-flight measurement*

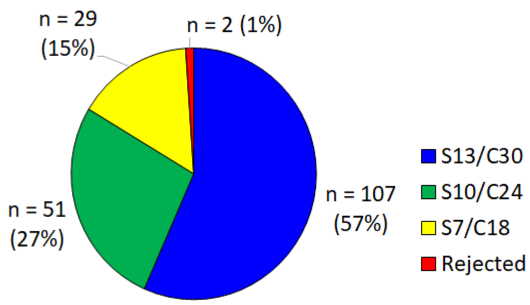

Figure 12: *Distribution of the specimen to the strength classes according DIN EN 338:2016 [6] on basis of the indirect ultrasonic time-of-flight measurement*

The results of the ultrasonic time-of-flight measurements show that the amount of structural timber with higher load-bearing capacity is significantly larger than derived from the visual grading. Furthermore, 150 specimens (direct measurement) respectively 138 specimens (indirect measurement) could be assigned to a higher grading/strength class than solely based on the visual grading. The assignment of 38 respectively 48 specimens could at least be confirmed.
These results could also be confirmed under consideration of the density as grading criteria. 146 specimens could be assigned to a higher class than based in the visual grading. The assignment of another 36 specimen was confirmed. Furthermore, the assignment of 87% of the specimens based on the density confirms

the assignment on basis of the ultrasonic time-of-flight measurements.
The assignment of the specimens to the strength classes on basis of the quasi-instrumental supported visual grading (visual grading, ultrasonic time-of-flight measurement and determination of density) is additionally compared with the strength grading based on the experimental determined bending strength and modulus of elasticity. The results show that 148 specimens (approximately 78%) are assigned to the same class by both methods of grading. Another 17 specimens (approximately 9%) show only a difference of <1%-10% to the limiting values of the next higher class. These differences can be explained by measurement deviation and therefore can be recognised as negligible.
In conclusion, the number of specimens for which the same class assignment could be derived from both grading methods (based on quasi-instrumental supported visual grading as well as on experimental tests) equals approximately 87%. This result gives evidence of the enhancement of the visual grading by combining it with non-/semi-destructive test methods. Furthermore, it indicates a high accuracy of the applied non-/semi-destructive test methods.
To investigate the relations between the results of the ultrasonic time-of-flight measurements and the material properties which required for the class assignment according DIN EN 338 [6] a regression analysis was carried out. According to the results in [21] the following relations have been investigated:

- average ultrasonic velocity & density
- minimal ultrasonic velocity & bending strength
- average ultrasonic velocity & static modulus of elasticity

The results of the regression analysis are show in Table 4 & 5.

Table 4: *results of the regression analysis – direct ultrasonic time-of-flight measurement*

relation	Coefficient of correlation & regression euqation
average ultrasonic velocity & density	$r = 0{,}313$ $\rho = 0{,}058 \cdot v_{mean} + 81{,}6$ $(R^2 = 0{,}098)$
minimal ultrasonic velocity & bending strength	$r = 0{,}595$ $f_m = 0{,}031 \cdot v_{min} - 134{,}6$ $(R^2 = 0{,}279)$
average ultrasonic velocity & static modulus of elasticity	$r = 0{,}753$ $E_m = 7{,}94 \cdot v_{mean} - 33507$ $(R^2 = 0{,}567)$

Table 5: *results of the regression analysis – indirect ultrasonic time-of-flight measurement*

relation	Coefficient of correlation & regression euqation
average ultrasonic velocity & density	$r = 0{,}241$ $\rho = 0{,}041 \cdot v_{mean} + 184{,}4$ $(R^2 = 0{,}058)$
minimal ultrasonic velocity & bending strength	$r = 0{,}543$ $f_m = 0{,}031 \cdot v_{min} - 127{,}9$ $(R^2 = 0{,}3145)$
average ultrasonic velocity & static modulus of elasticity	$r = 0{,}677$ $E_m = 6{,}61 \cdot v_{mean} - 24826$ $(R^2 = 0{,}459)$

The results in Table 4 & 5 show that the relation between the average velocity and the density is relatively weak. The correlation coefficient ranges from r = 0,241 (indirect measurement) to r = 0,313 (direct measurement). The relation between the average respectively minimal velocity and the modulus of elasticity respectively the bending strength shows a relatively high correlation (r = 0,677…0,753 & r = 0,543…0,595).
In conclusion, the ultrasonic time-of-flight measurement appears to be appropriate for the estimation of the bending strength and the modulus of elasticity of structural timber. The relations derived from the regression analysis are depicted in Figure 13 to 15.

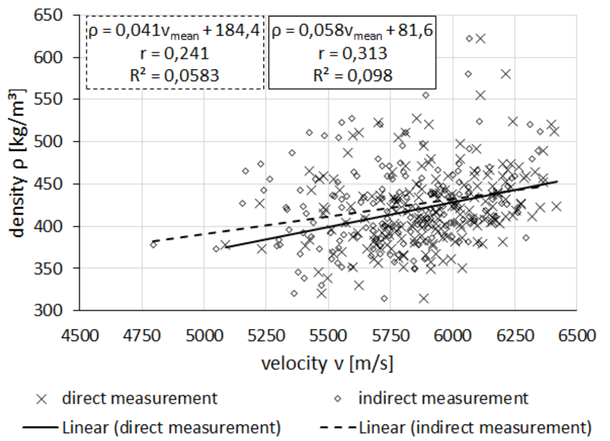

Figure 13: *regression between the average ultrasonic velocity and the density*

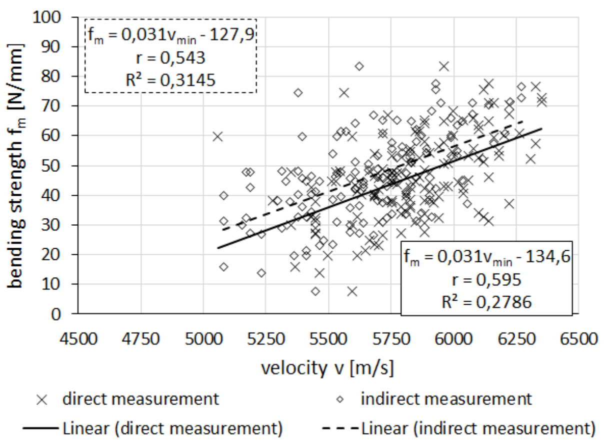

Figure 14: *regression between the minimal ultrasonic velocity and the bending strength*

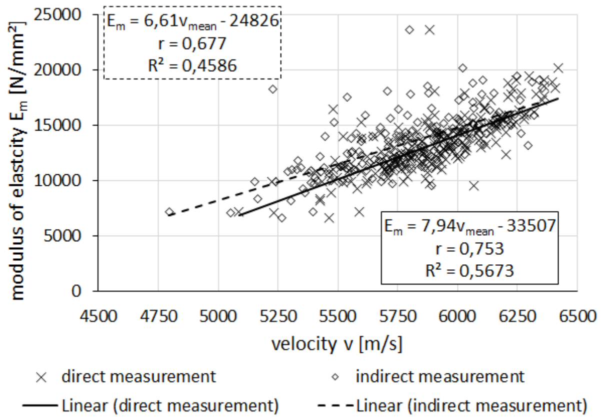

Figure 15: *regression between the average ultrasonic velocity and the static modulus of elasticity*

The comparison between the results of the regression analysis and literature data is shown in Table 6 as well as Figure 16 & 17.

Table 6: *comparison between the results of the regression analysis and literature data*

	velocity & bending strength	velocity & modulus of elasticity
direct measurement	r = 0,595	r = 0,753
indirect measurement	r = 0,543	r = 0,677
taken from [21]	r = 0,600	r = 0,750
taken from [31]	/	r = 0,950

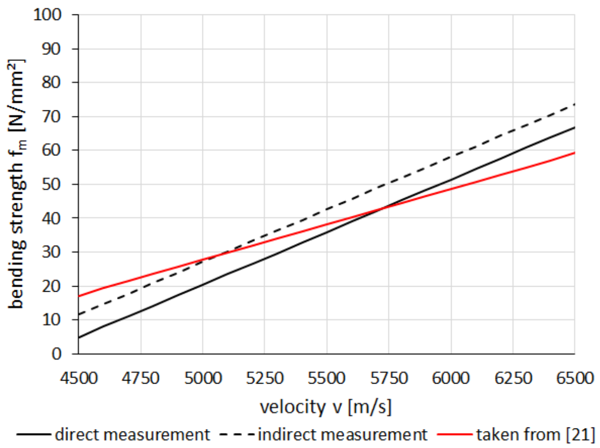

Figure 16: *comparison between the results of the regression analysis and literature data – ultrasonic velocity and bending strength*

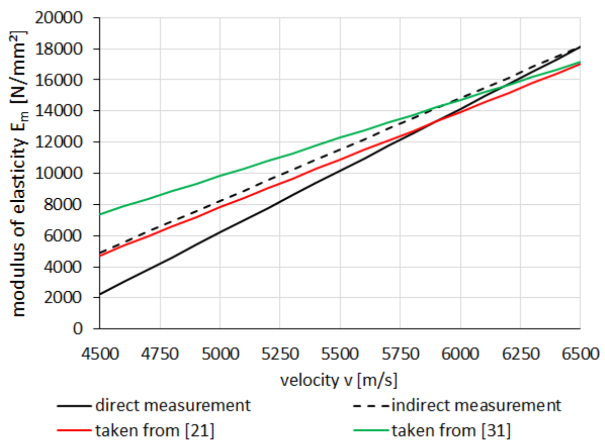

Figure 17: *comparison between the results of the regression analysis and literature data – ultrasonic velocity and static modulus of elasticity*

6 CONCLUSIONS

The results of the first sub study show that the combined use of the visual strength grading and the ultrasonic time-of-flight measurement leads to an enhancement of the grading results. Furthermore, the additional determination of the density gives the opportunity to further enhance the accuracy of the quasi-instrumental supported visual grading. The class assignment which was derived from this non-/semi-destructive grading method was proven by the experimental results of the bending tests.

The regression analysis shows a strong relation between the ultrasonic velocity and the bending strength respectively the static modulus of elasticity. Therefore, the ultrasonic time-of-flight measurement can be used as a non-destructive test method to determine the properties of timber members in existing structures. Concerning the density there is only a weak relation which leads to the conclusion that the density of structural timber in existing structures should be determined by other non-/semi-destructive methods – e.g. by taking core drilling samples.

These results will be validated in future sub-studies on other species as well as old timber. Furthermore, an application of the method on existing timber structures is planned.

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