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STRENGTH GRADING OF STRUCTURAL TIMBER IN EXISTING STRUCTURES WITH THE ULTRASONIC TIME-OF-FLIGHT MEASUREMENT

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Abstract

The material properties of structural timber have significant variation. These result in the wood structure itself and are additionally influenced by environmental and growth conditions. 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 in Germany at the moment. To enable a detailed assessment of the structural state and a substance-carefully and professional redevelopment an in-situ strength grading of the timber members with reliable methods is required. Here, non- and semi-destructive test methods – e.g. ultrasonic time-of-flight measurement – can be used. The predominant part of the present studies was focused on its application on new structural timber with a statistically small extent.

Therefore, the applicability of the ultrasonic time-of-flight measurement for the determination of material properties of timber members in existing structures was investigated in comparative material test. The aim is the evaluation of its efficiency and reliability. The subject was 900 specimens in structural dimension cut from new spruce, pine and oak timber. The material tests included a visual grading, ultrasonic time-of-flight measurements and destructive bending test. The results of the comparative test show a significantly improved grading yield by combining visual grading and ultrasonic measurements. These results are proven by the bending tests. Therefore, this method can be used to determine the properties of timber members in existing structures. Further investigations are planned to improve and validate the proposed grading method on existing structures and in the laboratory.

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 the strength grading of structural timber are regulated on European level by the EN 14081-1 [1], which are met by the German grading standards [2, 3]. In general, the strength grading is divided in the visual and mechanical grading procedure.

The visual grading concentrates on superficial visible and visually determinable growth properties. The timber is sorted in three classes (coniferous wood: “S”-classes, deciduous wood: “LS”-classes). Hereby, the timber is divides in 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 are used, the timber can be sorted in the class S15/LS15. The assignment of the visually determined classes to the strength classes according DIN EN 338 [4] is accomplished according the DIN EN 1912 [5] 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 results of the applied nondestructive measurements is used to directly assign the timber to the strength classes according DIN EN 338 [4]. Besides deflection measurements, optical methods and radiography/microwaves the dynamic measurements are applied for the mechanical grading (see [6]).

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 [7]). Therefore, a strength grading of timber members is 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 equals the grade S10 respectively LS10. In doing so, load-bearing capacity reserves and deficits cannot be revealed. This can lead to lesser 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 [8]).

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 [6, 9, 10]). 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 [7]).

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 has been developed, investigated and tested (see [7]). Although this is rarely possible, the laboratory testing of semi-destructive taken samples certainly enables the exact determination of material properties (see [11]) - 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 [12] and the ultrasonic measurement (see [13-15]). 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 [16]). The time-of-flight measurement uses the time which is required to send an ultrasonic pulse from transmitter to receiver and is subdivided according the application of the direction of measurement (see Figure 1). This method suitable for the determination of material properties (see [16]).

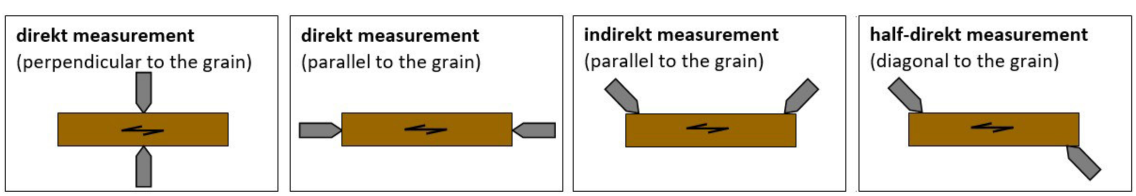

Figure 1: Measurement methods for the time-of-flight measurement (taken from [16]).

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. A detailed summary of the ultrasonic time-of-flight measurement's state of the art is given in [16].

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 [16]). 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 hereinafter described material test 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. The subject of this sub study was specimen from spruce (*Picea abies*), pine (*Pinus sylvestris*) and oak (*Quercus robur/petraea*) with around 300 specimens for each species.

4.2 Methods

The comparative material tests are divided in three part:

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

Additionally, the density was determined according EN 408. The moisture content was measured according EN 13183-1/-2.

4.3 Visual strength grading

The visual strength grading of the specimen was carried out according to DIN 4074-1:2012 [2] and DIN 4074-5:2008 [3]. Herein, the criteria listed in chapter 5 of the respective standards were applied.

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 classification according DIN 4074-1/-5 [2, 3].

4.4 ultrasonic time-of-flight measurements

After the specimen were visually graded the time-of-flight and the ultrasonic velocity were measured with the apparatus Sylvatest Trio (CBT CBS Lausanne, CH, see Figure 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) respectively on the top and bottom side of the specimen (see Figure 2). For each measurement the time-of-flight as well as the velocity of the ultrasonic impulse was documented.

Figure 2: Execution of the 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 climatically 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 [18] were applied (see (1) & (2)).

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

where: v_{12} = velocity at ω = 12%, v_{ω} = velocity at ω ≠ 12%, ω = moisture content.

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

where: v_{20} = velocity at υ = 20°C, v_{υ} = velocity at υ ≠ 20°C, υ = 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 [19], chapters 10 & 19. The used test setup is depicted in Figure 3.

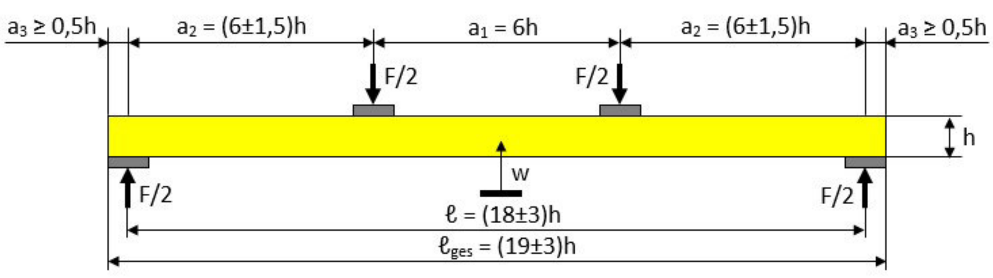

Figure 3: Bending test setup (measurements: ℓ = 1440mm, ℓ_{ges} = 1520mm, a_1 = a_2 = 480mm, a_3 = 40mm).

The test load was applicated 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 density was determined according EN 408:2012 [19] 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 EN 13183-1:2002 [20].

5 RESULTS & 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) respectively S10/LS10 (average load-bearing capacity). Only 11 % (spruce and pine timber) respectively 19 % (oak timber) met the requirements for the classification in the highest visual grading class S13/LS13 (high load-bearing capacity). Further 13-23 % (spruce and pine timber) respectively 21 % (oak timber) could not be assigned to any grading classes according DIN 4074-1/-5. The main decisive grading criteria for all specimen (coniferous and deciduous wood) were knots, slope of grain and cracks.

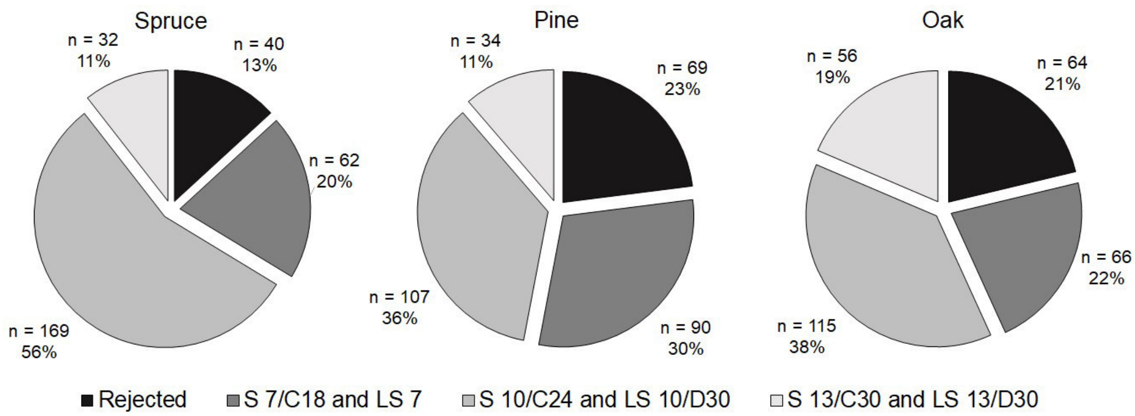

Figure 4: Results of the visual strength grading according DIN 4074-1/-5.

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 (see also [21]). 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 (see also [6, 9, 10] & Table 1). A large part of studies in the field of strength grading have proven 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 reliably graded visually.

A significant improvement of the grading yield – i.e. a reliable grading of timber with a high load-bearing capacity - can be achieved by the additional application of non- and semi-destructive test methods. For example, the results presented in [21] showed that the additional determination of the modulus of elasticity with the help of dynamic test methods leads to a significantly higher correlation (see Figure 5). The grading yield shown in Figure 5 was derived from studies which included visual grading, determination of the dynamic modulus of elasticity as well es destructive material tests.

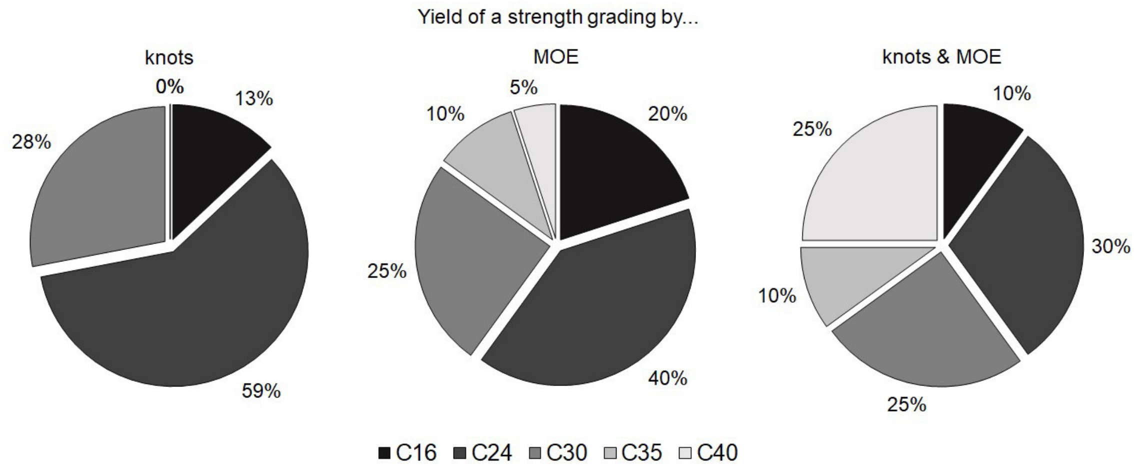

Figure 5: Improvement of the grading yield by application of different grading criteria (according to studies by Blaß/Görlacher, [21])

The applicability of an apparatus-supported strength grading is proven amongst others by the studies of Blaß/Frese. The grading procedure proposed in [22] includes the determination of the dynamic modulus of elasticity and the density as well as a visual grading according the requirements of grading class S10 according 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 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 [13, 14, 23] have to 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.

In analogy to this approach in [13, 14, 23] several regression equations have been calculated from the results of the 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 2.

Table 2: 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).

relation	spruce	pine	oak
$v_{dir} \leftrightarrow f_m$	$f_m = 0.02v_{dir} - 84$ (r = 0.425)	$f_m = 0.02v_{dir} - 26$ (r = 0.227)	$f_m = 0.03v_{dir} - 81$ (r = 0.686)
$v_{ind} \leftrightarrow f_m$	$f_m = 0.02v_{ind} - 76$ (r = 0.445)	$f_m = 0.02v_{ind} - 34$ (r = 0.274)	$f_m = 0.03v_{ind} - 86$ (r = 0.717)
$v_{dir} \leftrightarrow E_m$	$E_m = 4.6v_{dir} - 14267$ (r = 0.543)	$E_m = 2.8v_{dir} - 1688$ (r = 0.284)	$E_m = 6.04v_{dir} - 15374$ (r = 0.829)
$v_{ind} \leftrightarrow E_m$	$E_m = 4.4v_{ind} - 12467$ (r = 0.564)	$E_m = 2.9v_{ind} - 2026$ (r = 0.317)	$E_m = 6.2v_{ind} - 15629$ (r = 0.844)

The regression equations listed in Table 2 are showing the following:

1. There are only small differences between the relations based on the direct and indirect method.
2. The relations between the ultrasonic velocity and the bending strength are weaker as the relations to the static modulus of elasticity. This was observed on all three wood species.
3. The relations observed on spruce timber are showing an average correlation, whereas the relations determined for pine timber are relatively week. On contrary, the relations for oak timber show a strong correlation.

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 [4]. The reliability and applicability of the derived limiting values was verified by comparing the classification according the ultrasonic velocity with the classification according 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 3.

Table 3: Accordance between the grading results by grading according the ultrasonic velocity and the material properties density, bending strength and static modulus of elasticity.

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 with on basis of the static modulus of elasticity shows a higher level of accordance than the approach on basis of 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 of 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).

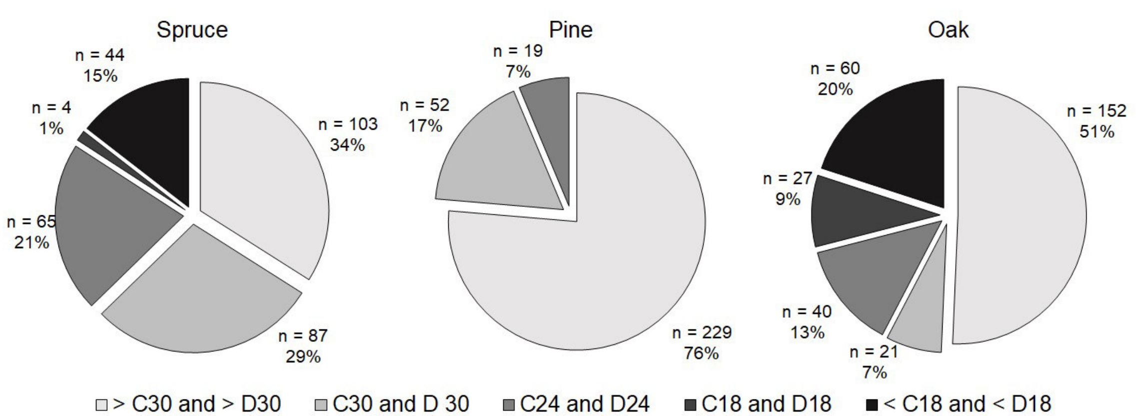

Figure 6: Grading yield based on the direct measured ultrasonic velocity and the static modulus of elasticity.

The described investigations show that the ultrasonic velocity can be used as a 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 4.

Table 4: Proposal for limiting values for the grading criterion "ultrasonic velocity".

Strength class	spruce		pine		Strength class	oak	
	directly measured	indirectly measured	directly measured	indirectly measured		directly measured	indirectly measured
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
C45	6350	6250	6100	5900	D60	5500	5300
C50	6600	6450	6400	6200	D70	6000	5800

6 CONCLUSIONS

The results of the described investigations are showing that the ultrasonic time-of-flight measurement can be used for the strength grading of structural timber. Due to the partially weak correlations between the ultrasonic velocity and the material properties the ultrasonic time-of-flight method should not be applied solely. It can be assumed that the correlation increases significantly when additional non- and semi-destructively measurable criteria are included. These investigations as well as the validation on old timber members in-situ and in the laboratory will be the subject of future studies.

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