Assessment of Strength and Stiffness Properties of Reclaimed Structural Timber of Norway Spruce

Authors: Maarja Kauniste, Tõnu Saarelaan, Alar Just, Eero Tuhkanen

This paper assesses the mechanical properties of aged structural timber using both destructive and non-destructive testing methods. It evaluates the applicability of conventional grading approaches to reclaimed timber and examines the reliability of alternative assessment techniques.

This work was conducted part of Drastic's **Nordic Demonstrator**, which focuses on validating reclaimed timber for structural and load-bearing applications in temporary commercial buildings. It contributes directly to Demonstrator objectives by supporting the development of reliable assessment methods for reclaimed timber, contributing to safer and more effective circular construction practices.

The work was conducted by researchers from **TalTech (Tallinn University of Technology)**, a Drastic project partner.

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ASSESSMENT OF STRENGTH AND STIFFNESS PROPERTIES OF RECLAIMED STRUCTURAL TIMBER OF NORWAY SPRUCE

Maarja Kauniste[1], Tõnu Saarelaan[2], Alar Just[3], Eero Tuhkanen[4]

ABSTRACT: This study reports the outcomes of strength grading of 56 test specimens of reclaimed timber members with cross-sectional dimensions of 48x98 mm. Timber members were assessed through both destructive and non-destructive testing methods. The examined material consisted of previously utilized Norway spruce. To determine the dynamic modulus of elasticity, an oscilloscope and a waveform generator were used to measure the propagation velocity of sound waves within the test specimen. The study also compared the results of three visual strength grading standards (INSTA 142, UNI 11119, and NS 3691-3) and destructive tests. Innovatively, the test specimens where specifically graded locally near the breaking point of destructive tests (destructive zone). This method eliminates instances where the overall rating is lower than the visual assessment of the selected section, thus avoiding an underestimation of the precision of visual strength grading methods.

KEYWORDS: reclaimed timber, reuse, circular economy, material quality assessment

1 - INTRODUCTION

Timber is a renewable natural resource, that has been utilized in construction for centuries. In comparison to other construction materials such as reinforced concrete or steel, the structure of wood is more intricate. Despite its complex structure, the use of wood is on the rise and regaining its former prominence, which can largely be attributed to its ease of processing, low thermal conductivity compared to aforementioned materials and a high strength-to-weight ratio. Today, there is an increasing emphasis on climate neutrality, mindful consumption of materials and recycling. While the use of natural and renewable materials was recently deemed sufficient, it no lunger fully aligns with the objectives of sustainable development. The focus has shifted towards how materials, including timber, can be repurposed for new applications at the end of their life cycle, minimizing the need for complete recycling. In the context of reusing timber in various structures, it is essential to accurately assess the material's condition and, when necessary, dismantle the elements without causing considerable damage.

The evaluation of timber's condition in terms of mechanical properties can be conducted using various methods, such as visual inspection, machine sorting, and destructive testing. However, the latter is not suitable keeping in mind material reuse. Due to wood's heterogeneous composition, visual grading remains a particularly complex and challenging task and while standards such as the Italian UNI 11119 [1] and the Norwegian NS 3691 [2] exist for assessing wood in historic or heritage buildings, their applicability is limited. Although measurement techniques for various defects can be transferred, the corresponding strength parameters must be tailored to regional conditions. The mechanical properties of wood are significantly influenced by factors such as growth environment and service conditions, meaning that for example timber from Mediterranean region cannot be evaluated using the same criteria as timber from Nordic region. Therefore, to ensure an accurate assessment of the strength properties of aged wood and to mitigate material waste due to over-dimensioning, it is essential to conduct research that

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accounts for the limited climatic conditions and their long-term variations.

The objective of this research was to investigate the mechanical and physical properties of previously used timber using both non-destructive and destructive testing methods. Additionally, the study aimed to compare the variations in existing visual strength grading standards and evaluate the reliability of the results derived from these methods. Although several previous studies have explored this subject, the conclusions generally indicate that the correlations observed require further investigation, necessitating additional testing. The material under investigation was previously machine-graded Norway spruce (*Picea Abies*) sourced from Norway, where it had been utilized in concrete applications. This timber was brought to Tallinn University of Technology for testing through the Drastic project, in collaboration with project partner OmTre AS, an organization focused on the reuse of reclaimed construction wood and the development of the first temporary building constructed from recycled wood as part of this initiative. A total of 56 test specimens, each with a cross-sectional dimension of 98x48 mm, were used in the study.

Visual sorting was carried out in accordance with three established standards: INSTA 142:2009 [3] for the assessment of new timber used in Scandinavia, UNI 11119 [1] from Italy specifically for evaluation of reclaimed timber, and prNS 3691-3 [4], a Norwegian standard also for assessing the condition of old timber. Both non-destructive and destructive bending tests were executed using an electromechanical testing machine in compliance with EN 408:2010 [5]. In addition, modulus of elasticity was assessed using an oscilloscope and wave signal generator to measure the velocity of sound wave propagation in the specimens.

2 - BACKGROUND

Previous research on the mechanical properties of aged wood utilizing various methods has been conducted both in Estonia and internationally. In Estonia, several theses have been written on this subject at the Estonian University of Life Sciences and Tallinn University of Technology (TalTech). The strength classes for new timber are defined in EN 338 [6], specify the mechanical properties and density for structural design. The grades are assigned based on destructive testing according to EN 408. For old timber, while no standardized procedure exists, a similar approach can be applied.

At TalTech Martin Püssa [7] investigated the strength properties of new sawn timber through visual grading based on the BS4978 standard and an acoustic-based method utilizing the Timber Grader MTG 920 device. A total of 12 different cross-sectional properties of Norway Spruce beams were assessed and the results concluded that acoustic strength grading presents a credible alternative to visual grading, as it was possible to sort 11,5% of the material into a higher strength class than C24 in one setup, and up to 22,4% more material was classified into the C24 class compared to visual sorting in another setup.

Arriaga et al. [8] investigated the challenges of grading in-situ timber using standards designed for new timber. They found that these standards resulted in high rejection rates, as defects like distortion and fissures, which are more common in larger, older cross-sections, were not allowed in new timber grading. However, these defects had minimal impact on the timber's mechanical properties. Additionally, the limited access to existing structures, often preventing examination from all four faces, further complicated the assessment. The study also highlighted the lack of specific characteristics in historic structures, making predictions unreliable. Using the Spanish visual strength grading standard UNE 56544, the researchers found that applying all requirements led to an 84% rejection rate. They concluded that existing standards for grading new timber are ineffective for assessing in-situ structures.

MSc thesis by Kauniste [9] focused on the visual assessment of approximately 120-year-old Norway spruce beams by destructive and non-destructive testing methods. A total of 19 test specimens were studied for their physical and mechanical properties. Visual strength sorting was done according to three different standards: UNI 11119, UNI 11035, and INSTA 142. In conclusion, it was revealed that all the aforementioned standards underestimate the strength of the wood by 47.6-53.6%, with the best results obtained based on the Scandinavian standard INSTA 142, which is intended for assessing new wood. Kauniste also pointed out that knot locations determined the strength class of the material in 86.7% of cases. The relationship between static modulus of elasticity and bending strength in this study was found to be 0.67, indicating a moderate correlation.

Piazza et al. [10] studied the strength and stiffness of timber in in-situ structures using non-destructive testing and visual grading. The research compared results from two Italian grading standards, UNI 11119 and UNI 11035, and highlighted that knots are the most severe natural defects in timber, significantly affecting strength and stiffness. However, the study also found that knots alone are not reliable indicators of strength, as their impact varies by species and depends on how their impact

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on strength is assessed. As such, the knots in tension reduce strength, while those in compression can improve both modulus of elasticity (MoE) and modulus of rupture (MoR). Furthermore, visual grading often underestimated the material's stiffness. Among all the testing methods in this research, ultrasound had the highest correlation (R=0.6), while others had a lower correlation (R<0.3). The research also revealed that UNI 11119 consistently underestimated strength more than UNI 11035, showing a weaker correlation between predicted and actual strength.

3 - PROJECT DESCRIPTION

The timber used in this study was Norway spruce (*Picea abies*), that had previously been utilized as formwork for concrete on a construction site, classified to a strength class C24. A total of 56 specimens were used, with cross-sectional dimensions of 48x98mm. Since the aim was also to conduct non-destructive tests on a single specimen from three different sections, cross-sectional measurements were taken at the centre of each section, providing more accurate results when calculating bending stiffness. The measurement points are shown in *Figure 1*. The lengths of the beams varied between 1.9 and 2.85 meters, except for two beams that were damaged at the ends, requiring shortening to remove the defective sections.

The material was initially analysed in Sweden by computerized tomography (CT) scanning. After that the specimens were transported to Estonia. All the tests were conducted at the Ehituse Mäemaja laboratory of TalTech. All specimens were photographed from all four sides, assigned a unique identification number, and labelled with letters A through D to distinguish the faces, as seen in Figure 2. This labelling was essential in order to visually grade each face, enabling conclusions about the overall strength of the specimen or the analysis of parameters on a specific face for comparison with the results from destructive or non-destructive tests. For the bending tests, it was necessary to mark the locations of the support and load points, as well as the centre of the span.

Visual assessments were conducted in two ways: a general evaluation of the entire specimen and a targeted assessment of the destructive zone identified through destructive tests. The primary focus of visual grading was on the measurement of knots, as this parameter has been shown in numerous studies to significantly influence the strength grading results of most specimens. Additionally, all specimens were visually sorted according to established grading criteria. Non-destructive bending tests were performed to determine both global and local bending stiffness moduli, along with moisture content measurements and destructive testing on selected specimens. In order to determine the dynamic modulus of elasticity, an oscilloscope and a wave signal generator were used to measure the propagation speed of the acoustic wave in the test specimen.

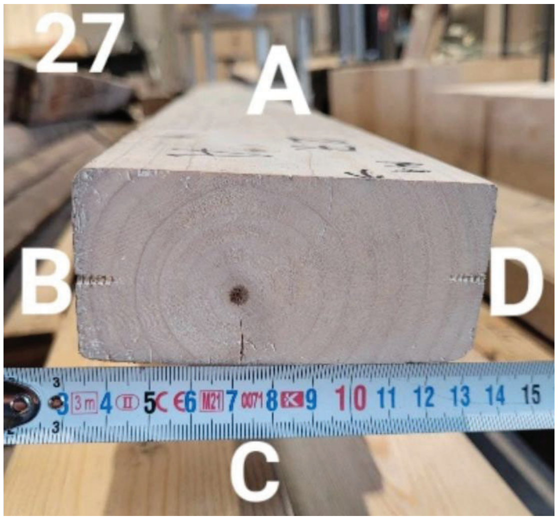

Figure 2 Photograph of specimen's 27 cross-section.

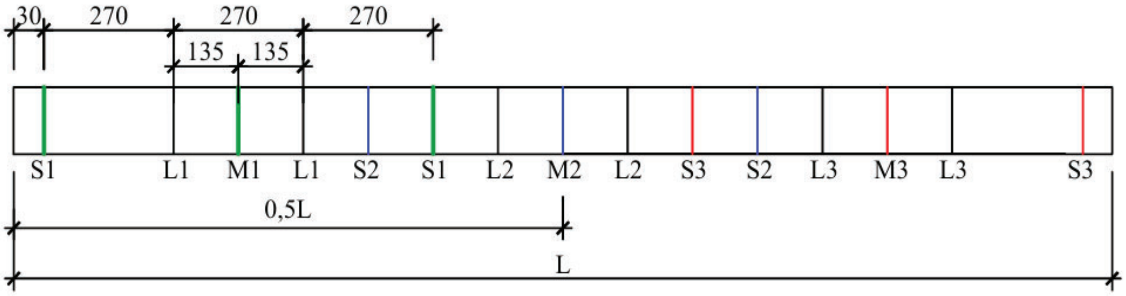

Figure 1 Markings on specimens for bending tests. M indicates the centre of the span, L marks the load positions, and S represents the support. The number refers to the test section.

4 - EXPERIMENTAL SETUP

4.1 General

In this study, a total of 56 specimens were used, with cross-sectional dimensions ranging from 45-48 mm in width and 95-98 mm in height. The lengths varied between 1.9 and 2.85 meters. All specimen dimensions were determined according to -EN 408:2010+A1:2012. [5] As the width and height varied across the specimens, measurements were taken at three different points, ensuring that they were not closer than 150 mm to the ends. A tape measure was used to determine the length with sufficient accuracy, while a digital calliper with a precision of 0.01 mm was used to measure the cross-sectional dimensions. Since the aim was also to conduct non-destructive tests on a single specimen from three different sections, cross-sectional measurements were taken at the centre of each section, providing more accurate results when calculating bending stiffness. The measurement points were located at the centre of the specimen, approximately 44 cm from the ends (as indicated by the marking method *Figure 1*). The moisture content was measured for half of the test specimens according to EN 13183-1:2002. All the calculations are presented at 12% moisture content. During the tests, the laboratory's average relative humidity was (25±5) % and the temperature was (22±2) ˚C. [11]

4.2 Visual grading

The specimens were then visually assessed according to three standards: INSTA 142 (Scandinavian standard), prNS-3691-3 (a new Norwegian standard), and UNI 11119 (Italian standard). The aim of using different standards was to determine which one provided the most accurate assessment and to compare the new Norwegian prNS-3691-3 standard with the Scandinavian INSTA 142. The evaluation of the test specimens was performed using two methods. In the first approach, all sides of the specimens were assessed, and the strength class was assigned based on the worst-case scenario for the entire specimen. In the second method, specimens that underwent destructive testing were visually evaluated, and the strength class was determined solely for the zone affected by the destructive test.

The INSTA 142 standard allows for the assignment of the highest strength class, T3 (C30), while the Norwegian standard sets the maximum at C24. The Nordic standard includes four strength categories: T3 (C30), T2 (C24), T1 (C18), and T0 (C14). If the assessed element does not meet the T0 requirements, the specimen is considered defective and gets rejected. [3] According to the Norwegian standard, timber cannot be visually graded above C24, and if previous documentation indicates a strength class of T3 (C30) according to INSTA 142, it must be revised to C24. The remaining categories in the prNS-3691-3 standard are the same as in INSTA 142 but marked with the letter "R" to indicate reclaimed wood, e.g., R24 (equivalent to C24 strength class). [2] The UNI 11119 standard does not assign strength classes but defines the maximum allowable stresses based on the wood species. According to the aforementioned allowable stresses the standard strength classes from EN 338 [6], can be derived using the following formula [10]:

$$\sigma_A = f_k \frac{k_{mod}}{1{,}5\gamma_M} \tag{1}$$

where:

σ_A	allowable stress, in newtons per square millimetres
f_k	5- percentile characteristic value of strength, in newtons per square millimetres
k_{mod}	modification factor used in Eurocode 5
γ_M	partial factor for the material property (1,3 as proposed in Eurocode 5)

4.3 Global modulus of elasticity

The determination of global bending modulus of elasticity was performed and calculated in accordance with the EN 408:2010+A1:2012, which stipulates that the minimum length of the specimen must be (19±3) times the cross-sectional height, and the span should be (18±3) times the cross-sectional height. The span was set at 810 mm, and all tests from three different segments were conducted exclusively on the flat side of the specimens. The test setup is described in *Figure 3*. Additionally, 50 mm wide steel plates were used under the load heads to reduce local crushing.

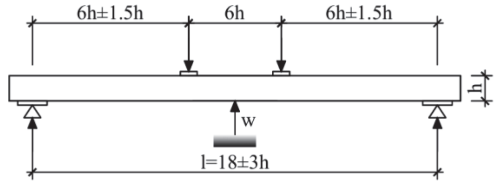

Figure 3 Test setup for determining the global modulus of elasticity.

The maximum load that can be applied during the test is $0.4F_{max,\ est.}$ The loading rate must be 0.003h (mm/s), where h represents the cross-sectional height. 30 specimens were tested with the assumption that $0.4F_{max,\ est} = 3$ kN. The remaining 26 specimens were tested after the destructive tests, so applicable force was adjusted to 5 kN, which more closely corresponded to 40% of the maximum force.

The bending tests were conducted using a universal electromechanical testing machine, LFM-600 kN, equipped with parallel grippers and connected to the Dion 7 software (walter+bai ag). The load (kN) and the corresponding displacement (mm) at a specific time (s), were provided by Catmaneasy. Displacements were measured using LVDT sensors. To transfer the data from the devices to the software, they were connected to data acquisition systems QuantumX MX840B or MX1615B (HBM).

4.4 Dynamic modulus of elasticity using ultrasonic waves

Ultrasonic wave measurements were conducted based on the test schemes outlined in EN 12504-4:2021. [12] The results were measured in the transverse direction, and the tests were performed following the same system as the bending tests, i.e., with measurements taken at three locations on a single specimen (at the centre of the span), except for a few cases where the specimens were too short or damaged to allow for measurements at all three positions.

The testing procedure utilized two sensors, one emitting and the other receiving. The emitting sensor generated a vibration pulse, which, after passing through the specimen's thickness, was converted into an electrical signal by the receiving sensor. The time taken for the pulse to traverse the specimen was measured using an oscilloscope. The resonance frequencies of the sensors generally fall within the range of 20-150 kHz, with a frequency of 50 kHz used for these tests. The sensors were positioned at a right angle to the specimen, in direct contact with each other, as shown in Figure 4 (i. e. direct transmission). More precise distances are described in *Figure 1*. The MoE_{dyn} was calculated using the following formula (2). [13]:

$$E_{dyn} = \rho(\frac{3V_l^2V_t^2 - 4V_t^4}{V_l^2 - V_l^2}) \quad (2)$$

where:

E_{dyn}	dynamic Young's modulus, (N/m^2) or (Pa)
ρ	bulk density, (kg/m^3)
V_l	Velocity of the longitudinal sound pulse, (m/s), determined by dividing the test piece thickness by the corrected pulse transit time
V_t	Velocity of the transverse sound pulse, (m/s), determined by the corrected pulse transit time, being the average value of determinations in two orthogonal orientations

The tests were conducted using the following equipment: the Keysight DSOS204A Digital Storage Oscilloscope, which has a bandwidth of 2 GHz, a sampling rate of 20 GSa/s, and a 10-bit ADC, to measure the acoustic waves. The wave signal generator was a Tektronix AFG3252 Dual Channel Arbitrary Function Generator with a sampling rate of 2 GSa/s and a frequency range of up to 240 MHz. Longitudinal wave sensors, specifically the Olympos Panametrics M1036 with a frequency of 2.25 MHz and a 0.5'' probe, along with shear wave sensors, the Olympos Panametrics V151, operating at 0.5 MHz with a 1.0'' Videoscan probe.

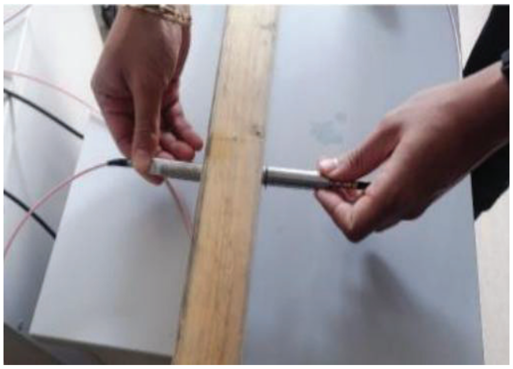

Figure 4 Measurement of wave velocities through the thinner section of the test specimen.

5 - RESULTS

5.1 Visual grading - UNI 11119

Table 1 Visual grading results of the entire specimen according to the UNI 11119 standard

Number of specimens	Category	UNI11119	
		Maximum allowable stresses (N/mm²)	
		Modulus of rupture (MoR)	Modulus of elasticity (MoE)
5	I	11	12500
15	II	9	11500
26	III	7	10500
10	Rejected	-	-

Table 2 Visual grading results of the test specimens in the destructive zone according to the UNI 11119 standard

Number of specimens	Category	UNI11119	
		Maximum allowable stresses (N/mm²)	
		Modulus of rupture (MoR)	Modulus of elasticity (MoE)
9	I	11	12500
7	II	9	11500
1	III	7	10500

The results are divided into two categories: evaluations of full-length specimens and results from the destructive zone. Table 1 describes the visual strength grading of test specimens according to UNI 11119. A total of 56 test specimens were evaluated, of which 10 (18%) were sorted as defective and were therefore rejected. Five specimens (9%) were graded to I category, 16 specimens (27%) to II, and 26 specimens (46%) to III. The normative bending strength for category I, calculated using equation (1), is $f_{m,k}$= 26.8 N/mm^2 (C24 strength class), for category II, the value is 21.9 N/mm² (greater than C18), and for category III, the bending strength is 17.1 N/mm² (C16).

Table ***2*** describes the results of the specimens graded in the destructive zone (approximately 80-90 cm length section). In contrast to the results for the entire specimens, no specimens were classified as defective, and the majority received an evaluation to category I. Results exceeding the C24 strength class accounted for 53% of the total, and 94% of the results were better than the C18 strength class, whereas for the entire specimens, this percentage was 36%. This indicates that significant differences can exist in the local and global visual assessment of the specimens.

5.2 Visual grading - INSTA 142

In the results described in *Table* ***3***, all test specimens achieved at least a C18 strength class result, whereas according to the UNI 11119, this proportion was only 36%. Nearly half (48%) of the specimens were assigned to the C24 strength class, and the distribution between C18 and C30 strength classes was also quite even (27% and 25%, respectively).

The data in *Table* ***4*** characterizes the strength grading results obtained in the destructive zone according to the INSTA 142. In comparison with UNI 11119 in *Table* ***2***, the results are similar, but when comparing the destructive zone results with those with the full-length specimens, the results obtained using INSTA 142 (*Table* ***3*** and *Table* ***4***) are more consistent than those obtained using the UNI 11119 (*Table* ***1*** and *Table* ***2***). For example, results exceeding the C24 strength class accounted for 94% of the specimens in *Table 4*, whereas for full-length specimen evaluations, this number was 73%. In the UNI 11119, the corresponding results were 94% and 36% (for the C18 strength class).

Table 3 Evaluation results of the full-length specimens according to the INSTA 142 standard

INSTA 142		
Number of specimens	**Category**	**Strength class**
14	T3	C30
27	T2	C24
15	T1	C18
0	T0	C14

Table 4 Visual grading results of the test specimens in the destructive zone according to the INSTA 142 standard

INSTA 142		
Number of specimens	**Category**	**Strength class**
6	T3	C30
10	T2	C24
1	T1	C18
0	T0	C14

5.3 Visual grading - prNS 3691-3

The primary difference between the Norwegian standard and the Scandinavian standard (INSTA 142) is the absence of the C30 strength class, consideration of previous documentation if such exists, evaluation of cuts and holes, as well as the determination of the cross-sectional structural zone. [4] The material under study was most influenced by knots and the restriction to a maximum assessment of the C24 class. The measuring of knots was carried out according to the requirements of INSTA 142, and under this standard, all specimen categories corresponded similarly to the *Table* ***3*** and *Table* ***4***. Results for the T3 category (C30 strength class) were classified under the R24 category. The remaining aforementioned factors did not affect the categories.

Table 5 Evaluation results of the full-length specimens according to the PRns-3691-3 standard

prNS3691-3		
Number of specimens	**Category**	**Strength class**
41	R24	C24
15	R18	C18
0	R14	C14

Table 6 Visual grading results of the test specimens in the destructive zone according to the prNS3691-3 standard

prNS3691-3		
Number of specimens	**Category**	**Strength class**
16	O24	C24
1	O18	C18
0	O14	C14

The visual assessment results in Table 5 and *Table* ***6*** according to prNS-3691-3 are almost identical to the INSTA 142 results when the C30 strength class is combined with C24. According to the author's assessment, the similarity arises from the nature of the test specimens. The specimens used in this research were 48x98 mm beams used in concrete work as part of formwork. Differences compared to the Scandinavian standard possibly arise when the test specimens are more structural in nature and include notches (e.g., tenon joints), holes (e.g., dowels, bolts) that are located in the structurally more important zone in terms of cross-section. In such cases, these assessment criteria begin to have a greater impact on strength grading.

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5.4 Static modulus of elasticity

To determine the MoE, three non-destructive bending tests were conducted on each test specimen, all on one side but at three different sections (*Figure 1*). The maximum variation within a single specimen was 3900 N/mm² (specimen nr 4). The average variation within a single specimen was approximately 1760 N/mm², accounting for 16.5% of the mean value obtained from 28 test specimens. This level of variability suggests that local factors exert significant influence on the material, and it is challenging to accurately predict the overall strength properties of the material based on a single section. *Figure 5* illustrates the MoE for the five test specimens with the greatest variation, measured from three sections.

The MoE was also determined through visual inspection of the destructive zone and overall assessment of the entire specimen. *Figure 6* and *Figure 7* show the results of the visual grading for the entire specimen (WHOLE) and the destructive zone (DZ). The static modulus of elasticity values is presented for the DZ as average results. The numbers 1-3 following the specimen number indicate the position of the destructive zone, see further details in *Figure 1*. Empty bars in the graph indicate specimens that do not meet the criteria, i.e., defective

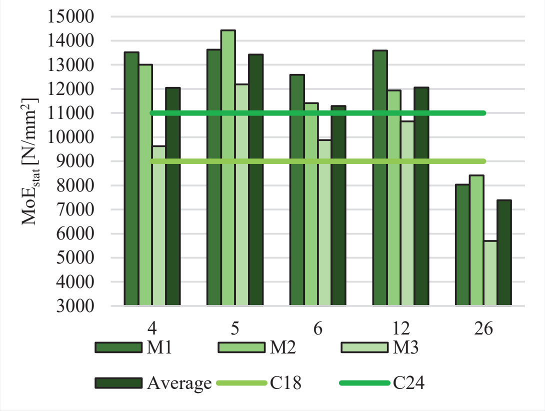

Figure 7 MoE measured from 3 sections of the specimen.

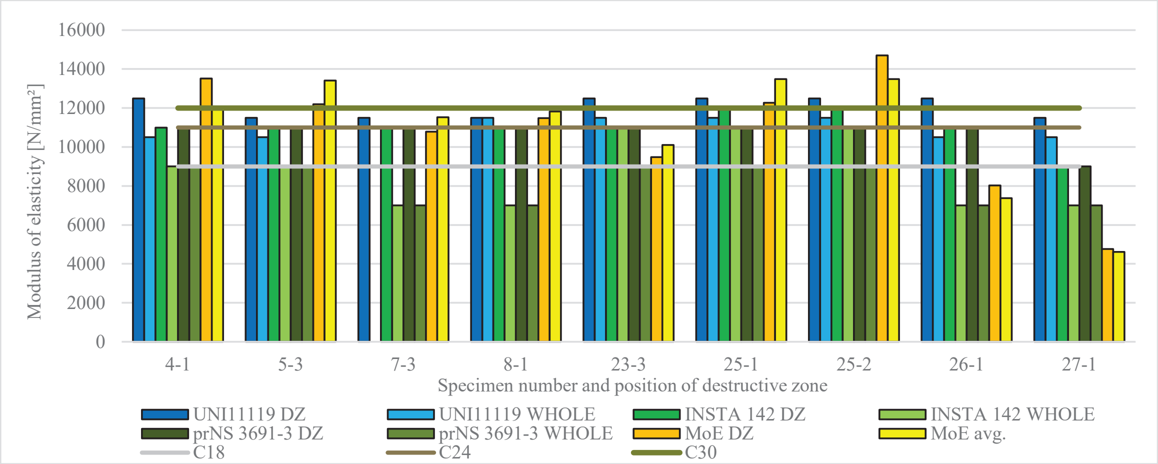

Figure 5 Comparison of visual grading results with bending test outcomes for the first half of specimens.

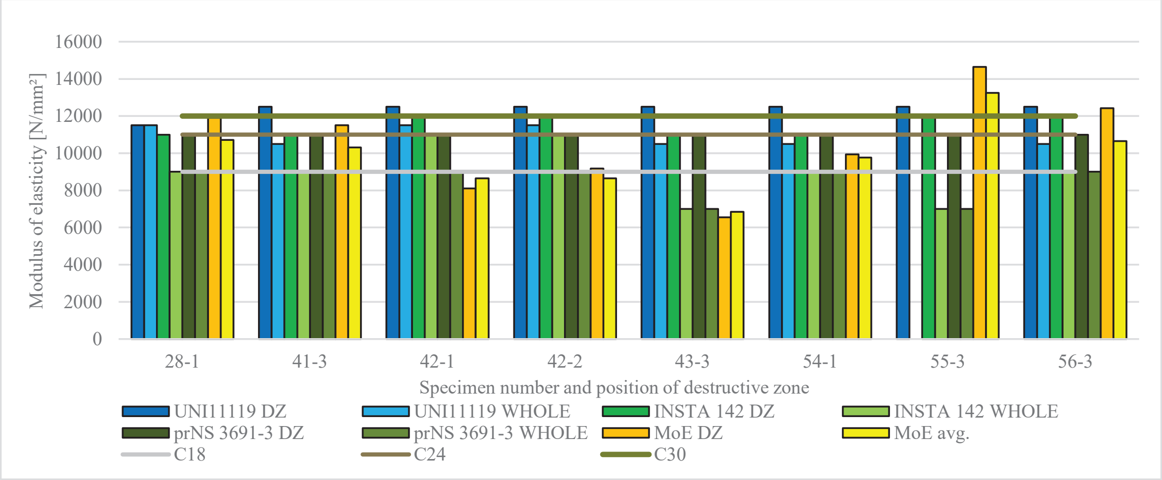

Figure 6 Comparison of visual grading results with bending test outcomes for the latter half of specimens.

specimens. Local visual grading results are better or equivalent for all specimens compared to the grading the entire specimen and bending test results are occasionally lower than the results from visual strength sorting. The UNI 11119, on average, overestimates the results the most (24% in the destructive zone and 14.3% for the entire specimen). These results are consistent with the research by M. Nocetti et al [14], where the UNI 11119 was found to yield excessively high values for the MoE. The INSTA 142 and prNS 3691-3 standards tend to evaluate the MoE for the entire specimen in favour of underestimation (11.3% and 17% lower than the bending test results, respectively). Results observed in the destructive zone are less overestimated compared to the UNI 11119, with discrepancies of 12.6% and 9.5%, respectively. Some extreme cases are present in the results, such as specimens 27 and 43, where the standards have overestimated the modulus of elasticity by 68-140%. Of the three standards, the INSTA 142 provides the most accurate results, while the Norwegian standard exhibits the least overestimation error.

5.5 Dynamic modulus of elasticity

Figure 8 illustrates the relationship between the longitudinal static MoE and the transverse dynamic MoE. It is evident that the compared characteristics exhibit high variability, and the correlation is weak, with a coefficient of r = 0.15. This suggests that the method in question cannot be used for assessing the longitudinal strength parameters of wood. Additionally, a limitation of this method is its highly localized measurement approach. This means that, at a given measurement point, the results may be influenced by wood defects, while in another case, no defects may be present. Consequently, significant differences in values can arise for the same specimen. In this study, localized ultrasonic wave measurements were conducted at the centre of the span used in the bending test, where the local effect is expected to be the most pronounced.

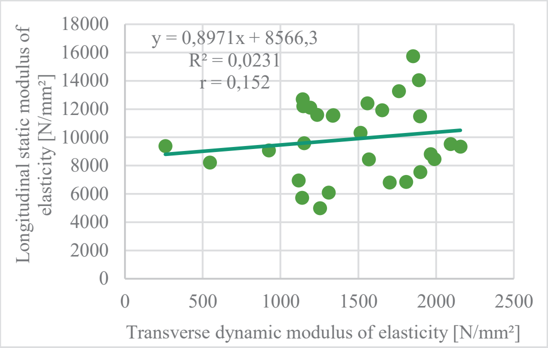

Figure 8 Comparison of the longitudinal static and transverse dynamic modulus of elasticity.

5.6 Bending strength in comparison to visual grading results

Figure 9 compares the strength classes of specimens obtained through visual sorting with the bending strength determined in the destructive bending test and the bending strength corrected using formulas outlined in EVS-EN 384. [15] To ensure comparability, the visual assessment results were used that were determined in the same zone where the bending strength test was performed. This approach eliminates situations where the overall assessment is lower than the visual evaluation of the tested segment, thus preventing the visual strength sorting method from being presented as less accurate than it is.

A total of 17 tests were compared, with all bending test results exceeding the values obtained through visual assessment. When the bending tests were corrected using formulas from EVS-EN 384, the corrected bending strengths in two cases were lower than the visual assessment values (14.7 MPa and 23.8 MPa). Although specimen 27-1 was quite exceptional due to the presence of knots, low density, wide growth rings, and the fracture image, it is justified that visual strength sorting standards are conservative in such cases. For example, in L. Ütsik's research [16], out of 48 specimens, 8 showed results

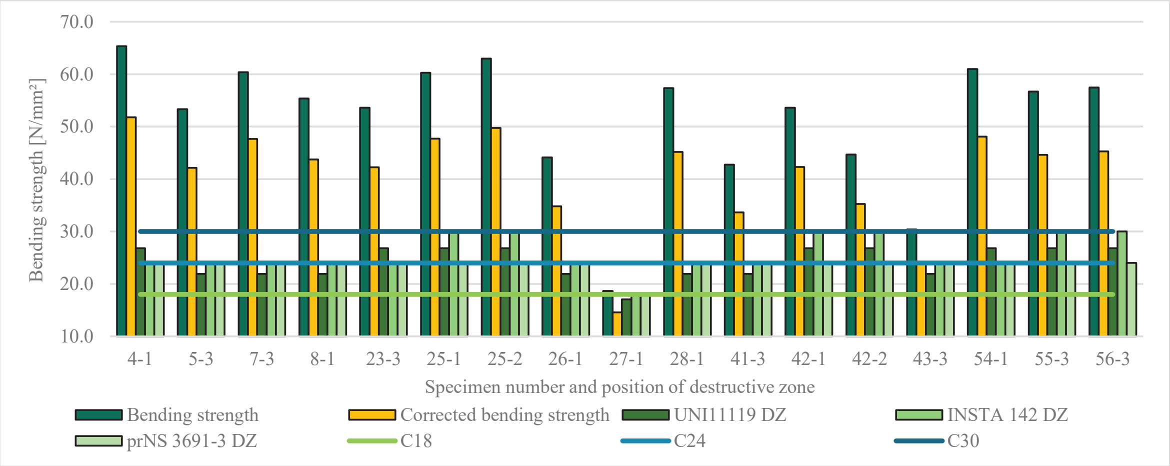

Figure 9 Comparison of visually assessed bending strengths in the destructive zone according to different standards and the bending test results.

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where the material was visually rated stronger than the bending test revealed (17% of the total sample, compared to 11.8% in this study), and in one case, the visual assessment matched the bending test result (2% of the total sample). The results remain in a similar range, and it can be concluded that such discrepancies between visual assessments and bending strengths obtained through testing are to be expected.

Looking at the overall picture, *Figure 9* shows that in most cases, the maximum bending strengths are significantly higher than the values from visual strength sorting. Nearly 70% of the specimens had maximum bending strengths greater than the values of strength class C50, but after correction, they fell into strength class C40. Visual sorting standards tend to underestimate the strengths of specimens by an average of 50-54%. The prNS 3691-3 underestimates the strengths the most, while the INSTA 142 provides the most accurate results among the three. M. Piazza and M. Riggio [10] found in their study that the UNI 11119 underestimated bending strengths by 61%, meanwhile in this research the number was 53%.

5.7 Semi-destructive bending in comparison to destructive bending

The relationship between MoR and MoE is presented in *Figure 10*. The comparison involves the bending strength obtained through testing and the corrected MoE$_{stat}$, which accounts for shear deformation effects. In order to determine the maximum bending strength, the MoE$_{stat}$ of the same span of the destructive testing was used. The correlation coefficient is r = 0.81, indicating a strong positive correlation. Based on this data, it can be concluded that the MoE$_{stat}$ is a good strength indicator for estimating the bending strength of timber. In M. Hani's study [17] the same indicator was 0.76 (strong correlation, 50 specimens of Norway spruce), and in M. Kauniste's thesis, it was 0.67 (moderate correlation, 11 tests). [9]

The difference in results between Hani's and Kauniste's may be due to the sample size, and the material used- unused timber compared to 120-year-old used timber. In conclusion, it can still be stated that the MoE$_{stat}$ can be used to predict the bending strength of timber. Approximately 65% of the bending strength results are described by the MoE$_{stat}$.

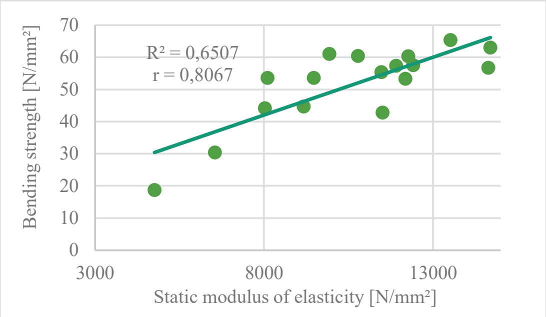

Figure 10 Scatter plot of the relationship between bending strength and static modulus of elasticity.

6 - CONCLUSIONS

The aim of using multiple visual strength grading standards was to identify the most reliable method and refine the new prNS 3691-3. Visual assessment was performed in two ways: a general evaluation of the entire specimen and local zone evaluation for destructive tests. The focus was on measuring knot locations, as prior research identified this parameter as a key factor in strength grading. In the comparison of methods, UNI 11119 was the simplest and clearest, while the other standards were more detailed and time-consuming. For bending strength, the best results were obtained using the INSTA 142, as it allowed for the highest strength class (up to C30), although the estimated values were still much lower than the actual test results. On average, the standards underestimated bending strength by 50-54%, with the prNS 3691-3 underestimating results the most. The average bending strength for specimens with corrected average values was 40.6 N/mm². In two cases, the corrected bending strength values were lower than the visual grading strength classes. For MoE$_{stat}$, the most accurate results were obtained using the prNS 3691-3 in the destructive zone, with values 9.5% higher than actual tests. INSTA 142 overestimated the MoE by 12.6%, and UNI 11119 by 24%. For general evaluation, both Norwegian and Scandinavian standards underestimated the MoE (17% and 11.3%, respectively), while UNI 11119 was the only one to overestimate it by 14.3%, consistent with findings from other studies that suggest UNI 11119 tends to overestimate MoE values.

A strong correlation was found between the experimentally determined MoE and MoR, with a correlation coefficient of r = 0.81. Although the sample size was small (17 tests), the correlation value remained within a similar range compared to other studies ([9], [17]). Therefore, it can be concluded that determining the MoE through non-destructive bending tests allows for relatively accurate strength predictions for timber. The limitation of this method is that it cannot be used for on-site assessment of structures. A correlation between dynamic MoE in the transverse direction and static MoE in longitudinal direction obtained was r = 0.15, indicating a weak relationship, and this approach was deemed not suitable for predicting wood strength properties.

Visual strength grading standards can reliably classify wood into strength classes up to C24 or C30. While this method is accurate and allows for a margin of error in favour of the grader, it may lead to over dimensioning of the structure from an optimization perspective. Machine grading, on the other hand, can assign wood to higher strength classes but requires investment in necessary equipment and is not always be feasible for on-site material assessment. A positive aspect of such studies is that they enhance the reliability of wood reuse in construction. The tests have demonstrated that timber previously used for other purposes can be successfully graded into strength classes suitable for construction. While the physical and mechanical properties of old wood have been studied extensively, the sample sizes are generally small, and further testing with similar experiments is needed to confirm the conclusions. Visual strength sorting standards tend to underestimate the material strength compared to the results from destructive bending tests, but the visual strength classes are generally guaranteed. A downside of this is the over dimensioning of structures and excess material usage. From a reuse perspective, this overuse is not necessarily a waste, as the material finds another purpose. Moreover, such an approach may increase user confidence, knowing that the strengths are generally overestimated. On the other hand, if studies show that overestimations are significant, consideration should be given to introducing additional criteria to visually classify wood into higher strength classes.

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