TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

ASSESSMENT OF STRENGTH AND STIFFNESS PROPERTIES OF AGED STRUCTURAL TIMBER

VANA KONSTRUKTSIOONIPUIDU TUGEVUS- JA JÄIKUSOMADUSTE HINDAMINE

MASTER THESIS

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Tallinn 2023

AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.
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THESIS TASK

Student: Maarja Kauniste, 182235EAEI
Study programme, EAEI02/17 Structural Engineering and Construction Management
main speciality: Structural Engineering
Supervisor(s): Professor Alar Just, Senior Lecturer Eero Tuhkanen

Thesis topic:
(in English) Assessment of Strength and Stiffness Properties of Aged Structural Timber
(in Estonian) Vana konstruktsioonipuidu tugevus- ja jäikusomaduste hindamine

Thesis main objectives:

1. Perform visual grading on the basis of 3 standards
2. Conduct destructive testing on the specimens
3. Compare and analyze the obtained results
4. Provide recommendations for enhancing visual assessment techniques

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Provide an overview of literature	
2.	Set up and conduct testing	
3.	Perform test data analysis	
4.	Formulate the research	

Language: English **Deadline for submission of thesis:** "22" May 2023a.

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PREFACE

The topic of this master's thesis was initiated by Alar Just, a tenured professor at Tallinn University of Technology. The thesis was prepared as part of the integrated study program in structural engineering and construction management at the Faculty of Engineering of Tallinn University of Technology with the aim of contributing to the reuse of aged timber as a valuable and versatile building material. Specifically, this thesis examined the ways in which old timber can be visually graded and the degree to which these assessments correspond to the actual condition of the wood.

I would like to express my gratitude to all those who contributed and guided me in the process of completing this master's thesis. I am especially grateful to my supervisor Alar Just for his encouraging and motivating advice and assistance at every step. Additionally, I express my gratitude to my co-supervisor Eero Tuhkanen and laboratory engineer Priit Peterson for their assistance in conducting experiments and providing insightful guidance throughout the process of writing this thesis. Furthermore, sincere thanks to Massimo Fragiacomo and Frank Hunger for their consultation on the specifics. Their contributions have been essential in bringing this thesis to completion.

Keywords: visual grading, in-situ assessment, MoE, MoR, Master’s thesis

List of symbols and terms

Latin upper case letters

A	cross-sectional area, in square millimetres;
$E_{m,g}$	global modulus of elasticity in bending, in newtons per square millimetres;
$E_{m,l}$	local modulus of elasticity in bending, in newtons per square millimetres;
F	load, in newtons;
F_{max}	maximum load, in newtons;
$F_{max,est}$	estimated maximum load, in newtons;
G	shear modulus, in newtons per square millimetres;
I	second moment of area, in millimetres to the fourth power;
W	section modulus, in millimetres to the third power;

Latin lower case letters

a	distance between a loading position and the nearest support in a bending test, in millimetres;
b	width of cross section in a bending test, or the smaller dimension of the cross section, in millimetres;
f_k	5- percentile characteristic value of strength, in newtons per square millimetres;
f_m	bending strength, in newtons per square millimetres;
h	depth of cross section in a bending test, or the larger dimension of the cross section, or the test piece height in perpendicular to grain and shear tests, in millimetres;
k_{mod}	modification factor used in Eurocode 5
m_1	mass of the test slice before drying, in grams;
m_0	mass of the oven dry test slice, in grams;

Greek lower case letters

γ_M	partial factor for material property;
ρ	density, in kg/m^3;
σ_A	allowable stress, in newtons per square millimetres;
ω	moisture content, in percent;
ω_{ref}	Reference moisture content, normally at 12%;

List of terms

Aged timber - wood that has been in use for a long period of time and has undergone natural changes as a result of exposure to the environment, such as changes in color, texture, hardness, and strength. This can include wood that has been used in construction for decades or even centuries, as well as wood that has been exposed to the elements in outdoor settings. It has undergone a natural aging process and has not been artificially treated or distressed in any way. This distinguishes it from wood that has been intentionally aged or distressed through techniques such as sandblasting, staining, or painting to give it a weathered or rustic appearance.

1 INTRODUCTION

Timber has been used for construction for centuries, making it an old but renewable natural resource. However, in light of increasing competition with other structural materials and strive for a eco-friendliness, it is crucial to have a comprehensive understanding of the varying structure and properties of wood, as well as their influence on performance expectations and long-term usage suitability. Timber, being a growing trend amongst architects, is a versatile and valuable material with a multitude of excellent properties that make it highly desirable for construction projects. Since wood is a heterogeneous mixture, visually grading it is a challenging task to be handled and although reusing materials, conserving existing buildings and overall footprint reduction, has been subject of debate for quite some time, we still don't have a joint comprehensive set of guidelines to help grade existing wood. The lack of these guidelines is also one of the reasons why the results obtained in numerous researches are often fluctuating and we are unable draw clear conclusions.

In order to determine the strength class of a fresh timber beam, it must undergo a grading process. Visual grading involves an assessment by a grader who examines the key characteristics that can potentially reduce the sample's strength and then designates the visual grade accordingly. The entire process is conducted in accordance with established standards and built on years of experience. However, when it comes to evaluating aged timber, we lack a standardized method to assess its quality. The matter is further complicated by the fact that there is often lack of data on old in-situ wood and its exploitation, which would help to evaluate its condition. Consequently, there is a real practical need to assess the condition of old timber to avoid the unnecessary demolition and loss of a structurally sound and valuable building material.

The easiest way to assess the quality of existing wood is, of course, by performing destructive tests (DT), but if the goal is to assess the condition of old timber and preserve it, it cannot be achieved by rendering the wood unusable, but it is necessary to conduct research using non-destructive testing (NDT) methods. Some of the possibilities for NDT-s are visual evaluation, different acoustic and ultrasonic methods and radiological methods. In this research the chosen methods were visual assessment, non-destructive and destructive bending tests.

The significance of this topic is amplified by the fact that, despite numerous studies, the findings are still inconclusive and additional testing is acquired to determine the most cost and time effective approach to assess the condition of existing wood. Moreover, the relevance of this subject matter is also illustrated by the fact that even the coalition agreement governing Estonia from 2023 to 2027 states the principle that new public buildings must preferably be built of wood. This approach supports climate-neutral construction practices to facilitate the storage of carbon. [1] It implores the question as to why previously utilized wood cannot also play a role in this strategy.

What sets this study apart from others is that, in addition to destructive testing, the 4-point non-destructive bending tests were conducted on all four faces of test specimens. This provides an opportunity to initially assess the wood visually and then to find connections to associate external characteristics with real properties. The goal of this methodology was to determine whether it is feasible to visually assess the most practical way in which to use of wooden elements in construction. Which face of the beam would be better suited for the tension side and which for the compression side, in the event that this question arises. Furthermore, this study compares the collected data with a Nordic standard for grading fresh sawn timber and two established Italian standards for visually assessing aged timber. This comparison provides an additional contribution towards the development of a standardized framework for future visual assessments.

All of the tests conducted in this research were performed in TalTech's Structural Hall (Ehituse Mäemaja), and the material used for the tests was Norway spruce (*Picea abies*) sourced from a wooden building that was at least 120 years old and had been deconstructed. The primary goals of this study were firstly to compare the results obtained from existing non-destructive methods with actual results, and secondly to provide guidelines for better visual grading of wood in the future, based on the aforementioned NS-INSTA 142:2009 and Italian standards UNI 11119 and UNI 11035. According to literature survey, Italian standards were considered as the most useful for grading of aged timber. To compare the results obtained from both destructive and non-destructive tests, various statistical analysis tools using MS Excel were employed.

This Master's thesis is divided into two main parts, theoretical and experimental, followed by analysis. The theoretical part provides an overview of the nature and properties of wood, with a focus on conifers, and discusses previous studies highlighting why methods for new timber are not suitable for evaluating old wood. It further elaborates on the physical and mechanical properties of wood, various NDT-s for determining wood properties, and the analysis of standards created in Italy for visually evaluating aged wood already existing in structures. The experimental part consists of various destructive and non-destructive tests conducted at TalTech, followed by a comparison of their results. Based on the tests and analysis, recommendations are proposed to make it easier for those involved to visually assess wood properties as accurately as possible in the future.

2 REVIEW OF THE LITERATURE

2.1 Structure of timber

Wood is a complex biological structure composed of various chemistries and cell types working together to support the needs of living plants. Cellulose, lignin, hemicelluloses, and small amounts of extraneous materials make up the cellular structure of all types of wood. Differences in the proportion and characteristics of these components, as well as variations in cellular structure, account for the varying weight, stiffness, flexibility, and hardness of different types of wood. Trees are broadly categorized into two classes - hardwoods and softwoods. Hardwoods are typically plants with broad leaves that shed their leaves during autumn or winter, and most imported tropical woods are hardwoods. Softwoods, on the other hand, are generally gymnosperms or conifers, which do not have enclosed seeds in the flower ovary and are nonporous in their anatomy. Softwoods typically bear cones and have needle- or scale-like evergreen leaves, and some, like larches, lose their needles in autumn or winter.[2]

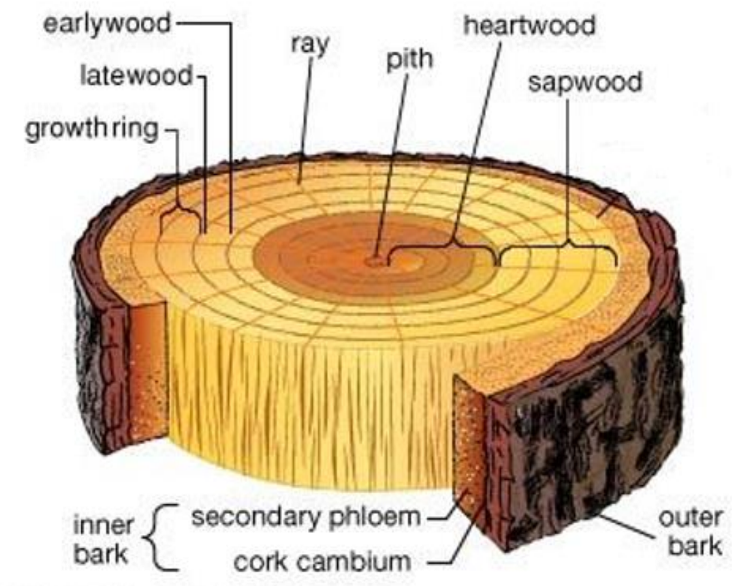


Figure 2.1-1 Transverse slice of tree trunk [3]

As shown in Figure 2.1-1, when examining a stump or a cross-section of a tree trunk, three distinct parts can be observed - the pith, wood, and bark. The cambium, a thin layer of tissue, can also be found between the wood and bark, although it is not easily discernible with the naked eye. The pith is typically small and located at the center of the cross-section. The central cylinder of wood in a tree is surrounded by bark, divided into two distinct parts. The inner bark is relatively light-colored and transports the synthesized food from the leaves to the rest of the plant. The outer bark is darker in color and dry, serving as an insulating layer. [3]

The wood is identified by the presence of ring growth, also referred as annual growth, that is a generalizing complex indicator which not only synthesizes the life activity of the tree, but also accumulates the effects of the surrounding environment on the tree. Spring wood, which is the lightest part of the annual ring, is formed during the first half of the vegetation period, specifically in the spring. Conversely, autumn wood, which is the darker part of the annual ring, is formed in the fall or autumn season and can be up to three times more dense than spring wood for conifers. To determine the age of a tree, it is common practice to count its annual rings. This can be done without harming the tree by using a growth drill, which drills a wood core out of the trunk perpendicular to the annual rings. The drill is screwed into the trunk until it reaches the core, and a chute-like pull-out rod is inserted into the drill pipe. By turning the drill back slightly, the core is released from the rod, and the number and width of the annual rings can be read from it. [3], [4]

2.2 Conifers

2.2.1 General

The Nordic softwood species contain cellulose, hemicellulose, and lignin in approximately the following proportions: 40-45% cellulose, 25-30% hemicellulose, and 25-35% lignin. [5] Unlike deciduous trees, whose growth takes longer than conifers and whose density increases with the growth of annual ring width, the situation is the opposite for conifers. Coniferous trees are considered mature and ready for harvesting when annual growth has started to decrease and narrower annual rings form in the peripheral part of the tree. However, under certain growing conditions, even trees with narrow annual rings may have low quality, this may be due to low-nutrient soil and also to the fact that the growing season has remained too short. Conifer wood is usually used for construction, one of the reasons for which is greater resistance to fungal damage and better corrosion resistance to chemical substances. In addition, conifer wood shrinks less when drying and thus has better processing properties. [4]

Coniferous wood is very uniform in structure and can be distinguished by the formation of heartwood. In the case of typical conifers growing in Estonia, different species of conifers can be easily identified using a quick identification method. If there is heartwood with resin ducts, the wood is either larch or pine, and if there are no resin ducts, it is juniper. Another way to differentiate is by the absence of heartwood. In this case, spruce has resin ducts while fir does not. However, differentiating between conifer species according to microscopic and macroscopic features is a much more involved process that includes the analysis of various main and auxiliary features in numerous ways. [4]

2.2.2 Norway spruce (*Picea abies*)

Spruce is a coniferous tree that is native to Europe (except southern Europe) and Russia; its mature outer region wood is of yellowish-white colour and is difficult to distinguish from younger sapwood. The annual rings of the spruce are clearly distinguishable and spruce is highly regarded for its technical properties when its presence of annual rings is 3-20 in 1cm. Spruce contains less resin than pine, which makes it easy to split, finish and process, but smaller dried branches can cause fiber tears. Although spruce is less resistant to rot and insect damage, it’s less sensitive to mold and mildew compared to pine. [4]

The composition of spruce contains 41% cellulose, 26% hemicellulose and 29% lignin. When freshly cut, spruce wood has a density ranging between 600-710 kg/m^3, 450-470 kg/m^3 in an air-dry state at 15% moisture and 420 kg/m^3 in an absolutely dry state. The compressive strength of spruce along the longitudinal fibers is about 45 N/mm^2, which is 5-6 times greater than its strength perpendicular to the grain. Additionally, its flexural strength ranges from 66-84 MPa and modulus of elasticity 8 300-13 000 MPa. In general, spruce has slightly inferior mechanical properties compared to pine, the decision between the two most commonly used conifers depends on the specific application and desired characteristics. [4]

2.3 Physical and mechanical properties of timber

2.3.1 Moisture

Water is a significant external factor that can significantly impact the characteristics of timber. The moisture content of wood is determined by the relative humidity of the surrounding air. As water enters a dry piece of timber, the molecules initially bind to the surface of the cellulose strands in the cell walls. Once all the available space in the cell walls is saturated, water molecules then occupy the cell cavity. The amount of water present in the wood is usually referred to as the moisture content or moisture ratio, expressed as a percentage of the weight of the wood. The higher the moisture content, the lower the strength and stiffness. Typically, it is observed that the strength and stiffness of timber increase linearly with decreasing moisture content below the fiber saturation point. However, above the fiber saturation point, there are no significant changes in strength and stiffness with increasing moisture content. [5]

Changes in the amount of moisture in wood can cause it to either shrink or expand, which can alter its overall size. Additionally, moisture content can greatly impact the wood's ability to resist decay and insects. Other important properties of wood, including its mechanical, thermal, and acoustic characteristics, are also influenced by its moisture content. Furthermore, processing methods such as drying, preservative treatment, and pulping can all be affected by changes in the moisture content of the wood. [3]

2.3.2 Density

Wood comprises of both large and small cavities within its total volume due to its porous nature, the less cavities wood has, the denser it is. The density of wood is a crucial physical property as it is strongly correlated with almost all the mechanical properties of wood. It affects strength, hardness, abrasion resistance, thermal conductivity, calorific value, shrinkage and expansion. The density of wood is in a strong correlation with moisture content because both the mass and volume of wood, that are used to calculate density, are affected by it and must be taken into consideration. In timber engineering, the most commonly used definition is the density ρ_{12}, which is based on the mass and volume of wood at 12% moisture content. The density of oven-dry wood, denoted by ρ_0, can vary greatly among different species. While most species have an oven-dry density within the range of 320 to 720 kg/m^3, there are notable variations beyond this range.[2], [4], [5]

2.3.3 Acoustics

The speed of sound in a structural material is determined by the product of its modulus of elasticity and density - the higher the elasticity of the wood and the lower the density, the higher the sound propagation. Therefore the sound conductivity is different for different species. In wood, the speed of sound varies based on the grain direction due to the significant difference between the transverse and longitudinal modulus of elasticity. If the material has cracks or cavities running perpendicular to the direction of sounds propagation, the sound waves will travel a longer distance, resulting in a lower measured speed of sound. This technique is based on the fact that the strength and stiffness of timber affect the speed of sound and attenuation.

In practice, compression waves are generated in a wood sample by tapping it with a hammer or using a sonic instrument to create a forced vibration. In fact, the velocity of ultrasound increases with increasing moisture and is documented to be three times faster along the grain than the across it, making it possible to detect defects such as knots or changes in cell structure. The ultrasonic technique is also useful for detecting biological degradation and the integrity of wood structure, particularly in the incipient range. [2], [4], [6]–[8]

2.3.4 Bending strength

When utilizing wood as a building material, it is essential to understand its mechanical properties for structural planning. Two fundamental properties that are employed in designing wooden structures to evaluate the stiffness and strength of wood are the bending modulus of elasticity (MoE) and the bending modulus of rupture (MoR). MoE is a measure of elasticity, or resistance to bending of the material. To put it simply- MoE indicates the pressure a material can take before being permanently deformed, while MoR is an indicator of its maximum load at failure, or bending strength, the pressure a material can take without breaking. Bending strength is a combination of tensile and compressive strength (also shear strength) and is subject to the greatest changes compared to other physical-mechanical properties of wood, even depending on, for example, wood fertilization. Its value in a non-defective wood sample lies numerically between the tensile and compressive strength values but decreases to a large extent as the specimen's dimensions increase. When bending a wooden beam, its deflection can be measured with special sensitive measuring instruments, and due to its elastic nature, the elongation disappears when the load is removed. Timber is a heterogenous material and the fact is well characterized by the MoE value: the MoE of timber is in the range of 7 000-12 000 N/mm^2 for the longitudinal fiber load, but only 200-500 N/mm^2 for the cross fiber, which means that timber works significantly better under tension than compression. The higher the modulus of elasticity, the smaller the deformations. [4], [9], [10]

2.3.5 Changes in volume

When the moisture content of wood falls below the fiber saturation point, it undergoes changes in size. Specifically, it shrinks when it loses moisture and swells when it gains moisture. These changes in size are not uniform in all directions but rather vary depending on the axial, radial, and tangential directions of the wood (see Figure 2.3.5-2). On average, the amount of shrinkage is about 0.4% in the longitudinal direction, 4% in the radial direction, and 8% in the tangential direction. In terms of volume, the average shrinkage is about 12%, although this can vary significantly between different species of wood. The difference between the shrinkage values of wood in its radial and tangential directions is known as shrinkage anisotropy. For example, when a beam with a squared or circular section is cut from a log and dried, as shown in Figure 2.3.5-1, its shape and form tend to change irregularly due to this property. Distortion in wood, which refers to the geometrical changes in the wood cross-section, can make the wood difficult to use. As a result of the dimensional changes caused by shrinkage and swelling, various forms of deformation can occur in wood. For example, joints can open or tighten, the cross-sectional shape can change, the wood can warp, cracks can form (known as checking), and there can be case-hardening (the release of stresses during machining, resulting in warping). Wood's greatest shrinkage or swelling occurs in the direction of the annual growth rings, or tangentially. In contrast, it shrinks or swells about half as much across the rings, or radially, and only slightly along the grain, or longitudinally. The combined effect of radial and tangential shrinkage can lead to distortion of wood pieces due to the difference in shrinkage and the curvature of annual rings. [2]–[5]

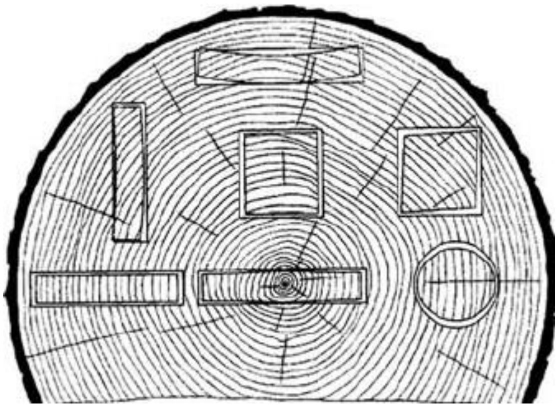


Figure 2.3.5-1 Shrinkage and distortion of wood upon drying [11]

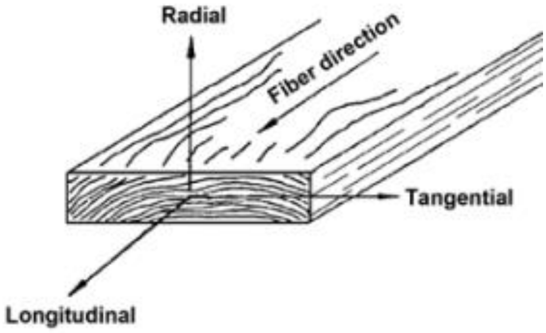


Figure 2.3.5-2 Three principal axes of wood [2]

2.3.6 Defects

Wood defects, such as knots, compression and tension wood and grain deviations, are the primary factors that lead to a reduction in strength. The degree of their negative impact is determined by the type and severity of the defects, their location within the wood, and the method in which the wood is subjected to load. Nevertheless, knots seem to influence the strength of the wood the most. A knot is a section of a branch that has become integrated into the trunk of a tree that interrupts the continuity and changes the direction of wood fibers. The impact of a knot on the mechanical properties of a wood member can be affected by various factors such as size, location, shape, and soundness, as well as the local slope of grain and the type of stress being applied. Another defects to influence wood are grain deviations that can take many forms, including slope of grain, which relates the fiber direction to the edges of a piece, and cross grain, which indicates the condition measured by slope of grain. Cross grain can be further divided into spiral grain, where fibers lie in the tangential plane instead of parallel to the longitudinal axis, and diagonal grain, which is caused by growth rings that are not parallel to one or both surfaces of the sawn piece. These two types can also occur in combination. Other types of grain deviations in wood include wavy, dipped, interlocked, and curly. Additionally, when trees have leaning boles or crooked limbs, they may develop an unusual type of wood called reaction wood. In softwoods, this abnormal tissue is referred to as compression wood and is located on the lower side of the inclined limb. In hardwoods, the abnormal tissue is called tension wood and is found on the upper side of the inclined member. Reaction wood is characterized by its distinct colour and higher density than normal wood, but can still be challenging to identify. One clear indicator of reaction wood is eccentric growth, which is more noticeable in softwoods than hardwoods. [2], [3]

2.3.7 Degradation

Bacteria, fungi, insects, marine borers, and various environmental factors such as climate, mechanical stress, chemicals, and temperature can cause degradation of wood. This degradation can occur in living trees, logs, or finished products, resulting in changes in the wood's appearance, structure, or chemical composition. The range of changes can vary from simple discoloration to severe alterations that render the wood unusable. Bacteria are known to cause darker discolorations, specifically heartwood, in living trees, they also can appear during prolonged storage in water, which can then cause significant structural changes in the wood, leading to its breakdown after being exposed to air. Bacteria, mold, and stain fungi can affect the appearance of wood, but they do not significantly weaken it by breaking down the cellulose fraction of the wood as decay fungi do. Decay fungi require specific environmental conditions, such as moisture, air, and temperature, to grow and thrive. When these conditions are met, fungal growth can occur, which can weaken and deteriorate the wood. However, decay does not occur naturally in wood and depends on external factors. Fungal growth can be prevented by maintaining a moisture content of less than 20%, keeping the temperature below 10°C or above 30°C, and avoiding submergence in water, which limits the availability of oxygen needed for fungal activity. Despite this, decay can still occur and significantly reduce the mechanical properties of the wood, even when it is not visibly detectable. Therefore, it is best to discard any wood that shows even slight signs of decay to ensure safety. [2], [3]

2.4 Previous research and legislation

Numerous research studies have examined the mechanical properties of wood over time, both on small-scale specimens and on larger structural timber, with a particular focus on the potential for reusing salvaged timber. However, the results of these studies are not always in agreement due to the complex nature of the influence of various factors to properties of wood such as load duration and the original condition of the wood. The investigation of mechanical properties in bending is of particular interest to researchers. While the majority of research works have agreed that the bending strength and stiffness of wood remains unchanged or only slightly decreases over time, some studies have produced conflicting results. This could be due to variations in the testing methods used, the condition of the wood being tested, or other factors. Despite these discrepancies, the importance of understanding the mechanical properties of wood over time cannot be understated. As our understanding of how wood behaves over time improves, we can develop better strategies for reusing salvaged timber and reducing waste in the construction industry. [12]

Arriaga et al. [13] conducted a research that studied the inadequacies of grading existing in-situ timber using standards designed for grading new timber. Their study discovered that utilizing such standards often led to high rejection rates. Specifically, the researchers observed that certain effects, such as distortion and fissures, were more prevalent in large, old cross-sections, but were prohibited in grading new timber. However, these effects had a relatively insignificant impact on the mechanical properties of the timber. Moreover, one requirement that cannot be met in most cases with old structures, is the accessibility, meaning that the structures already in place were often inaccessible from all four faces of the pieces further complicating the assessing process. Another trouble was the lack of specific characteristics of historic structures, that made predictions unreliable. As part of their study, the researchers measured the defects using the Spanish visual strength grading standard UNE 56544 and discovered that by applying all of the requirements envisaged, the grading resulted in an 84% rejection rate. As such, the researchers concluded that standards for grading new timber were completely ineffective for assessing in-situ structures.

Piazza et al. conducted research that focused on assessing the strength and stiffness of timber in in-situ structures using NDT and visual strength grading. One of the primary objectives of the study was to compare the visual assessment results obtained using two different standards, UNI 11119 and UNI 11035. The research highlighted that among all natural defects in timber, knots are considered to be the most severe. This is because knots can significantly impact the strength and stiffness of timber and affect the behaviour of the structure as a whole. However, the study also found that knots alone are not reliable predictors of strength, as the correlation between knot size and strength varies with species and the way in which their effect on strength was evaluated. The research further revealed that when assessing in-situ wood, compromises could be made as the position of defects along and across the element can be considered with reference to the acting stresses. For instance, knots that are located in the tension zone reduce the modulus of rupture (MoR) significantly, while in compression, the presence of sound, tight knots can increase the hardness and shear strength of the wood. In such cases, the knots behave like pegs, providing additional support. Furthermore, the study found that visual grading generally underestimates the actual stiffness of the material. The results showed that the ultrasound test had the highest correlation (R=0,6) among all the methods tested, while the other methods had a correlation of R<0,3. Moreover, the research revealed that the visual grading according to UNI 11119 was found to underestimate results more and had a lower coefficient of correlation between true strength and predicted than visual grading done according to UNI 11035. [14]

The aforementioned UNI 11119:2004 [15] is a an established Italian national grading standard that sets forth objectives, procedures, and requirements for the diagnosis of the state of conservation and estimation of the strength and stiffness of in-situ wooden elements in load-bearing structures of buildings included in cultural heritage. This standard involves performing on-site inspections and utilizing non-destructive techniques and methodologies. UNI 11119 applies to numerous wood species and specifies admissible exceptions to the procedures envisaged in EN 518 [16] to make it applicable to in-situ wooden elements. In order to classify the wooden elements, certain criteria and rules indicated in Table 2.3.7-1 and Table 2.3.7-2 are used to divide test specimens into categories based on certain characteristics. The main focus of the standard is on the examination of the following characteristics: single knots, groups of knots, wanes, inclination of the grain in both radial and tangential sections, and cracks resulting from shrinkage, scaling, lightning, frost, and other factors. After determining the class and species of the wooden element, Table 2.3.7-3 is used to determine the maximum allowable stresses and modulus of bending elasticity. The aforementioned tables provided in this chapter only pertain to spruce as it is the only species of wood that was tested in this particular study.

Table 2.3.7-1 Classification rules for wooden structural in-situ elements [15]

Characteristics		CATEGORY IN WORK		
		I	II	III
Wane		≤1/8	≤1/5	≤1/3
Various injuries Frost cracks Ring shake		Absent	Absent	Eligible, provided in limited extent
Single knots		≤1/5 ≤ 50 mm	≤1/3 ≤ 70 mm	≤1/2
Group of knots		≤2/5	≤2/3	≤3/4
Slope of grain (%)	In radial section	≤1/14	≤1/8	≤1/5
	In tangential section	≤1/10	≤1/5	≤1/3
Radial shrinkage cracks		Eligible, provided they do not pass		

Table 2.3.7-2 Method of measuring the characteristics of wooden structural in-situ elements [15]

Wane	The smaller of the two ratios between the dimensions of the chamfer legs and the dimension of the corresponding side of the effective section.
Single knots	The ratio between the minimum node diameter and the side dimension of the effective section on which they appear.
Group of knots	The ratio between the sum of the minimum diameters of the nodes included in a section of 150 mm and the dimension of the side of the effective section on which it appears.
Slope of grain	The inclination of the shrinkage cracks with respect to the longitudinal axis of the member, measured on the faces of the members, in areas distant from nodes or other features that may involve strong localized deviations of the grain (for example due to knots); the base minimum measurement for the determination of this parameter is equal to 150 mm, measured parallel to the largest dimension of the element.

Table 2.3.7-3 Maximum allowable stresses and mean modulus of bending elasticity for structural in-situ elements [15]

		Maximum allowable stresses (N/mm²)					
		Compression					
Species	**Category**	**Parallel to grain**	**Perpendicular to grain**	**Static bending**	**Tension parallel to the grain**	**Shear parallel to the grain**	**Bending MoE**
Spruce (Picea abies Karst.)	I	10	2,0	11	11	1,0	12 500
	II	8	2,0	9	9	0,9	11 500
	III	6	2,0	7	6	0,8	10 500

The maximum tensile stress perpendicular to grain is conventionally assumed equal to zero.

Another standard mentioned in the Piazza et al. study is also an Italian grading standard called UNI 11035 [17] that identifies the most common types of structural timber and indicates the rules to be adopted to carry out the visual classification in order to pertain srength and stiffness characteristics according EN 338. Its requirements apply to types of new timber for structural use. This standard can also be applied to old, in-situ wooden elements, provided all of the following conditions are met: the element must belong to one of the types of wood envisaged in this standard, the visibility and accessibility of the element must be extended to at least three longitudinal faces and one transversal face and it applies to wooden elements that do not fall within the scope of UNI 11119. It also states, that if the element cannot be graded according to UNI 11035, its load-bearing capacity has to be estimated otherwise. [17] The classification rules to be adopted are added to APPENDIX 6 and characteristic strength values used in this study are added to Table 2.3.7-1, rest of the characteristics are presented in APPENDIX 5. The tables only pertain values for spruce (group conifers 1) as it is the only species of wood that was tested in this particular research.

Table 2.3.7-4 Strength and stiffness characteristics from UNI 11035

Properties		**Spruce**		
Characteristic values for the types of wood considered in standard EN 338		-	C24	C18
Resistant categories		S1	S2	S3
Bending (5- percentile), N/mm^2	$f_{m,k}$		25	18
Modulus of elasticity parallel to grain (medium), kN/mm^2	$E_{0,mean}$		11,8	10,5
Modulus of elasticity parallel to grain (5-percentile), kN/mm^2	$E_{0,05}$		7,9	7,0
Density (average), kg/m^3	ρ_{mean}		450	450

The two aforementioned standards have several distinct differences. To begin with, UNI 11035 is primarily designed for evaluating new wood, but it can also be used for assessing old wood as long as it is not covered under the assessment of UNI 11119. This distinction arises from the fact that UNI 11119 is specifically created for evaluating old load-bearing structures of buildings that fall under the scope of cultural heritage. Consequently, UNI 11035 can be utilized for assessing old timber that is not considered a part of the heritage protection framework. Another notable difference is that UNI 11035 has more extensive set of criteria, requiring at least three longitudinal faces and one transversal face of the wooden element to be visible for grading. On the other hand, UNI 11119 also necessitates three longitudinal faces to be shown but with the possibility of having fewer faces displayed, as long as stated in the grading report, and it doesn't mandate the display of transversal faces. Additional difference between the two standards is that UNI 11035 provides characteristic strength, stiffness, and density values, which are fifth percentile values, whereas UNI 11119 offers allowable stress values. The grades referring to the two codes can be compared with the help of following equation: [14]

$$\sigma_A = f_k \frac{k_{mod}}{1{,}5\gamma_M} \tag{2.4}$$

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)

One of the main strength-reducing parameters are knots. They're caused by a branch embedded in the log. Knots are classified according to their shape, size and position in sawn timber. A knot cluster, characterized by lack of continuity of grain, is a group of two or more knots where the lines of continuous grain are deflected around the entire group. A group of knots where the grain does not deviate around the entire group, is not considered a knot cluster. [18]

Another European standard EN-17121:2019 [19] considers condition survey and diagnostic methods for assessing heritage load-bearing timber structures with a view to establish safe working loads or to determine the need for strengthening or repairing in order to ensure their continuing use. This standard doesn't provide specific numerical values but outlines the necessary steps for conducting a visual on-site assessment. The procedure required for the on-site examination and assessment of historic timber structure contains of two phases but not necessarily in the following order. To put it briefly, the first phase requires a desk study to provide information about structure's history and future intentions, a visual survey to obtain an overview and plan the next stage, a measured survey to locate main problems, a preliminary structural analysis to determine overall forces and a preliminary report that includes a description, concerning areas, service conditions etc. of the structure. The second phase contains of a detailed survey including detailed mapping of defects, assessment of timber grades and results of NDT. The final step of second phase is a diagnostic report on the condition of the structure with proposals for remedial measures. [19]

In addition to the information provided, there is a comprehensive COST Action E55 [20] report available that discusses the factors that must be taken into account while assessing and updating existing timber structures. The report outlines the necessary steps that need to be followed and the types of documents that can provide valuable insights. The mentioned documents, that highlight the crucial data in order to be prepared for the evaluation and renewal of structural wooden elements in the future, are proposed to be assembled in '’Building Book’’, which is discussed in more detail on report’s page 52. It is important to note that the report primarily focuses on buildings for which information about structures is available, rather than very old wooden buildings with incomplete documentation. Nonetheless, it is appropriate to consider the content of this report in the future perspective, so that past mistakes are not repeated. The report serves as a valuable resource to ensure that timber structures are properly maintained and updated, and that safety of occupants is not compromised. [20]

COST Action E55 initiative is to establish a foundational framework and best practices for the effective and sustainable utilization of timber as a structural material. This initiative is designed to address a range of issues related to timber construction and engineering, including the assessment of failures and malfunctions, the vulnerability of timber structures to various types of stress and damage, and the robustness of timber structures in a variety of different contexts. It is structured into three distinct working groups. The first group is focused on assessing failures and malfunctions in timber structures, with the aim of identifying common causes of failure and developing effective strategies for preventing and mitigating these issues. The second group is focused on examining the vulnerability of timber structures to various types of stressors, such as environmental factors, seismic activity, and other forms of physical stress. The aim of this group is to develop strategies for designing timber structures that are more resilient and less susceptible to damage. Finally, the third group is focused on the robustness of timber structures in a variety of different contexts, including fire resistance, impact resistance, and load-bearing capacity. [20]

While we’re on the subject of future it is only fitting to touch upon the innovative three-year project called InFutUReWood carried out in collaboration among researchers from seven countries. The InFutUReWood project introduced a novel concept: to design while considering the future deconstruction, recovery and reuse of timber in other (new) buildings and building products and doing so with the objective of incorporating the kind of reclaimed wood that is currently available. The research conducted under this project spanned seven distinct work packages (WP) ranging from planning for the most efficient primary design to facilitate deconstruction to estimating the volumes and quality of wood material that could be recovered and reused in Finland, Ireland and Spain. The project yielded surprising and promising results, particularly in WP2, which entailed the deconstruction, transportation and reassembly of five different building with two distinct goals. In three of these buildings, an impressive proportion of wood was saved and reused in its original design, ranging from 83% to 97% of material, while 86-100% was saved in order to reuse it in a modified manner. The other two buildings with a goals to be disassembled into discrete materials also had a proper saving proportions 41-67% and 67-96% respectively. The research even introduced a newly developed term, the ''ReBuilding Index'', which refers to a method for optimizing primary designs to ensure that structures can be easily deconstructed and reused. [21] Throughout the long-term InFutUReWood project, many questions were answered, but even more were left unanswered, demonstrating the need for continued testing and research. The project provided evidence that wood can be successfully recycled if desired, but much more work and testing is required to fully realize the potential of sustainable timber use in future construction projects and to do it in the most sensible manner.

3 MATERIAL AND METHODS

3.1 Material

The old timber used in testing originated from a building located on Vaksali street, Tartu, Estonia. The design of this building was based on standard architectural projects from St. Petersburg, which where then adapted to suit the specific location of the structure. The first mention of said building, on a smaller scale, has been recorded in Tartu's city plan since 1906. Although upon examination of the building's architectural details, it is highly likely that the structure was completed before 1900, as the facades of adjacent buildings built in the late 19th century exhibit common features with the given buildings architectural elements, especially the rafter ends, that are tested in current research. The building has served various purposes throughout its history, for example a cinema screening room and a library, but has remained unused since 1990. [22]

Unfortunately, due to the lack of available historical records before 1940, it is challenging to determine the precise construction date of this building with complete accuracy and it has not been possible to uncover more detailed information regarding its exploitation and state of structure. Nonetheless, the timber specimens used in this research seem to be about 120 years old. [22]

Photo 3.1-1 Vaksali 2e building before destruction [22]

3.2 Marking of pieces and dimensions

There were a total of 19 specimens tested in this research, which were divided into two groups: 15 with smaller CS (~100x100mm) and 4 with larger CS. This was done in order to build an appropriate support system for testing according to EVS-EN 408 [23]. Prior to performing visual assessments and non-destructive tests, two random specimens from each group were selected for destructive testing. The objective of this testing was to ascertain the amount of force equivalent to 40% of the maximum allowable limit when conducting ND tests. The distribution is shown below in Table 2.3.7-1.

Table 2.3.7-1 Distribution of specimens

	Smaller CS	**Larger CS**
Selected for destructive testing	9, 20	19, 24
Selected for visual grading and ND tests	1, 4, 5, 6, 7, 8, 10, 11, 14, 15, 16, 17, 21	22, 23

All of the specimens were photographed, given a number and each face was marked with a letter A...D (as shown in Photo 2.3.7-1 and APPENDIX 7). The letter given to the beam's face indicates its location being on compression side during the 4-point bending test. Every non-destructive (ND) bending test was carried out on all four sides of the specimen. The purpose of this approach was to establish a clear connection between the visual assessment of the specimen and its actual performance under stress. By conducting tests on each side, it was possible to gain a better understanding of the correlation between different deformations in addition to groups of knots, and the specimen's overall strength characteristics. This method allowed to identify patterns and trends in the data, which in addition to analysis of the bending behavior of the specimen, provide valuable insight into how various factors contribute to its strength and resilience.

Each specimen's length was measured with tape measure and cross-section (CS) dimensions were measured with Vernier caliper to 1 mm of accuracy. The caliper was used to measure parallel distance (A-C and B-D) by attaching one outer jaw on the flatter face and other jaw to where it makes contact with the specimen first. This method gives a marginally larger area than the actual CS area, but is a convenient practice to carry out on site. Since the width and thickness varied within a test piece, three separate dimensions were taken at different positions and final measurement was calculated as the arithmetic average of them.

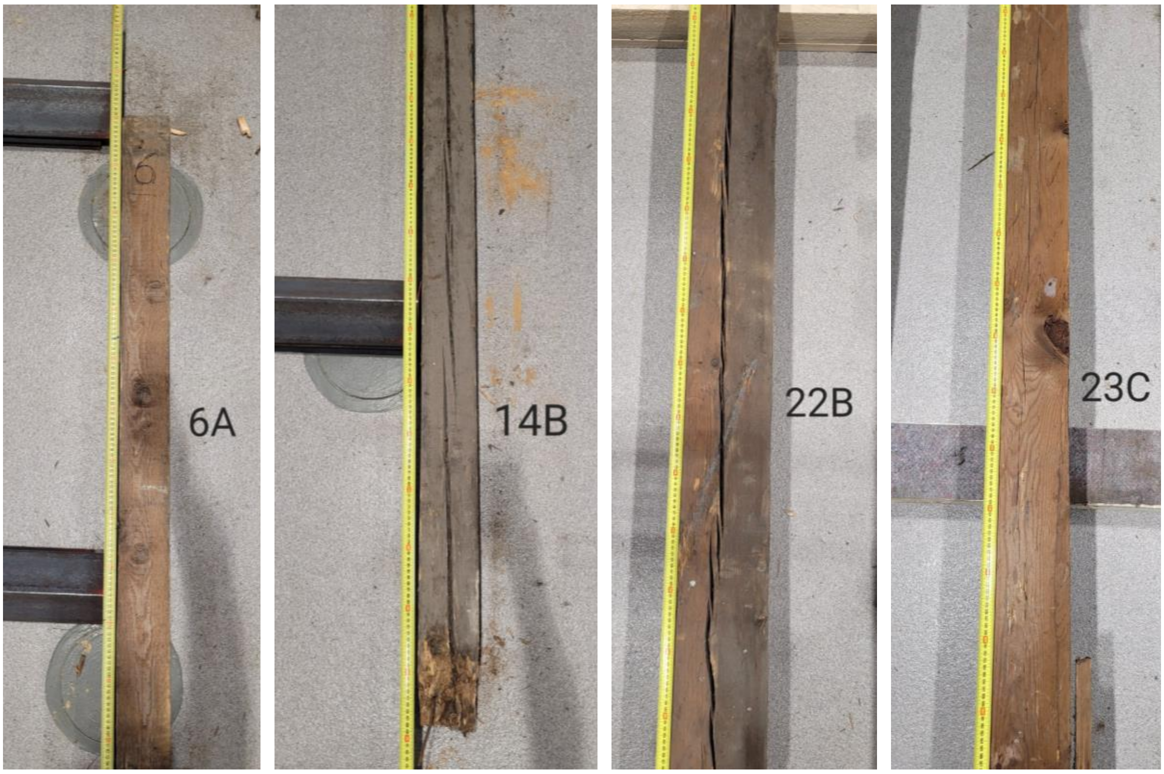


Photo 2.3.7-1 Example photos of marking of specimens

3.3 Moisture content and density

The timber specimens were kept in TalTech's Structural Hall (Ehituse Mäemaja) laboratory for one to two months before conducting tests, with an average temperature of (20±2)°C and a relative humidity of (45±5)%. Upon completion of the bending test a section free from resin bark and knots from the end of the beam was cut off in order to determine the moisture content and density of the whole beam. The moisture samples were then immediately weighted using an electronic scale with a resolution of ±0,1 g and placed into a ventilated oven at (103±2)°C until the mass remained constant within 0,1 % in 2 h according to EN408 [23] and EN 13183-1 [24]. The test slices were then removed from the oven and weighted again.

3.4 Procedure

3.4.1 Local modulus of elasticity in bending

The tests were carried out according to EVS-EN 408:2010+A1:2012 [23]. All of the beams had a minimum length of 19±3 times the depth of section. Small steel plates with the width of 50 mm and 100 mm were inserted between the beam and the loading heads and also between the beam and the supports for beams for smaller CS-s and for larger CS beams, respecitvely. They were placed in order to minimize local indentation.

The maximum load applied, as stated in the standard, is 0,4 $F_{max,est}$. The inital $F_{max,est}$ was determined for the beams with smaller CS by testing the maximum bending strength of two randomly selected beams from the patch, on the basis of which 8kN was taken as the maximum force to use for further NDT-s. For large CS beams the aforementioned maximum force received with the same method was 30 kN. The non-destructive bending tests were conducted with Enerpac P80 Hydraulic Hand Pump and Enerpac Hydraulic Silinder RC506 with capacity of 50 t.

The additional weight from steel beam (19,7 kg) and plate (6,7 kg) as seen in Photo 3.4.1-2 has been taken into account in calculations.

Photo 3.4.1-1 Enerpac P80 Hydraulic Hand Pump

Photo 3.4.1-2 Enerpac Hydraulic Silinder RC506

Using data obtained from the bending NDT-s, the load-deformation graphs were plotted. Section between 0,1 $F_{max,est}$ and 0,4 $F_{max,est}$ was used for a regression analysis.

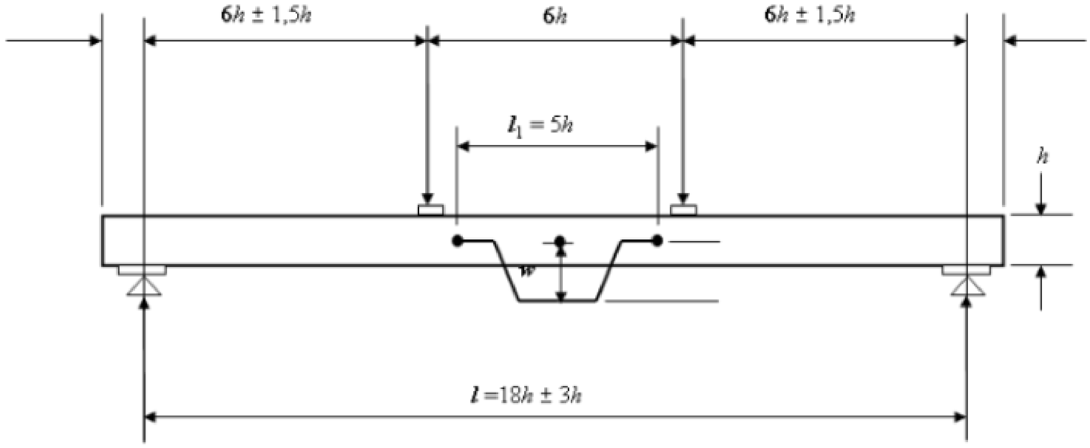
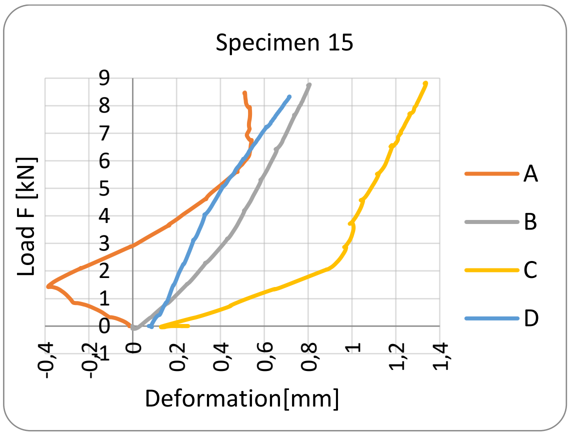
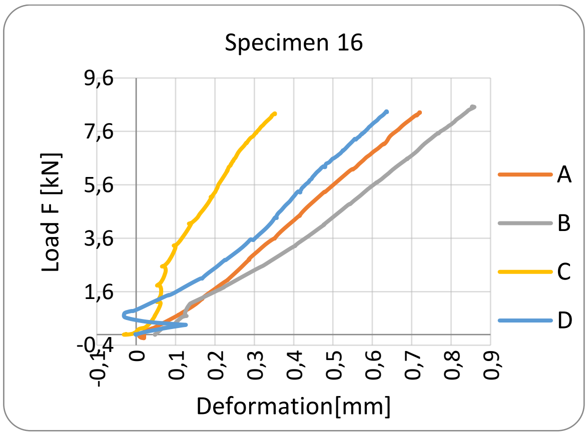


Figure 3.4.1-1 Test arrangement for measuring local modulus of elasticity in bending [23]

Initially, three gauges were installed to measure deformation and calculate the local modulus of elasticity. However, upon analyzing the data, it was determined that only the middle gauge would be used moving forward. This decision was based on the fact that the old timber used was twisted, causing the gauges to shift during application of the load, but without bend actually occurring. This movement made it challenging to plot the load-deformation graphs accurately, as the beam would bear the load even if its loaded sides were not yet parallel to the supports, resulting in illogical deformations, as seen in Graph 3.4.1-1 and Graph 3.4.1-2.



Graph 3.4.1-1 Specimen 15. Failed load-deformation graph for local modulus of elasticity



Graph 3.4.1-2 Specimen 16. Failed load-deformation graph for local modulus of elasticity

3.4.2 Global modulus of elasticity in bending

The tests were carried out according to EVS-EN 408:2010+A1:2012 [23]. All of the beams had a minimum length of 19±3 times the depth of section. The test specimens with smaller CS-s were placed symmetrically on supports that were 1,8 m apart and for beams with larger CS-s the distance between supports was 2,6 m. Small steel plates with the width of 50 mm and 100 mm were inserted between the beam and the loading heads and also between the beam and the supports for beams for smaller CS-s and for larger CS beams, respecitvely. They were placed in order to minimize local indentation.

The maximum load applied, as stated in the standard, is 0,4 $F_{max,est}$. The inital $F_{max,est}$ was determined for the beams with smaller CS by testing the maximum bending strength of two randomly selected beams from the patch, on the basis of which 8kN was taken as the maximum force to use for further NDT-s. For large CS beams the aforementioned maximum force received with the same method was 30 kN. The non-destructive bending tests were conducted with Enerpac P80 Hydraulic Hand Pump and Enerpac Hydraulic Silinder RC506 with capacity of 50 t.

The deformation w was measured at the centre of the span and from the centre of the tenison edge.

Using data obtained from the bending NDT-s, the load-deformation graphs were plotted. Section between 0,1 $F_{max,est}$ and 0,4 $F_{max,est}$ was used for a regression analysis.

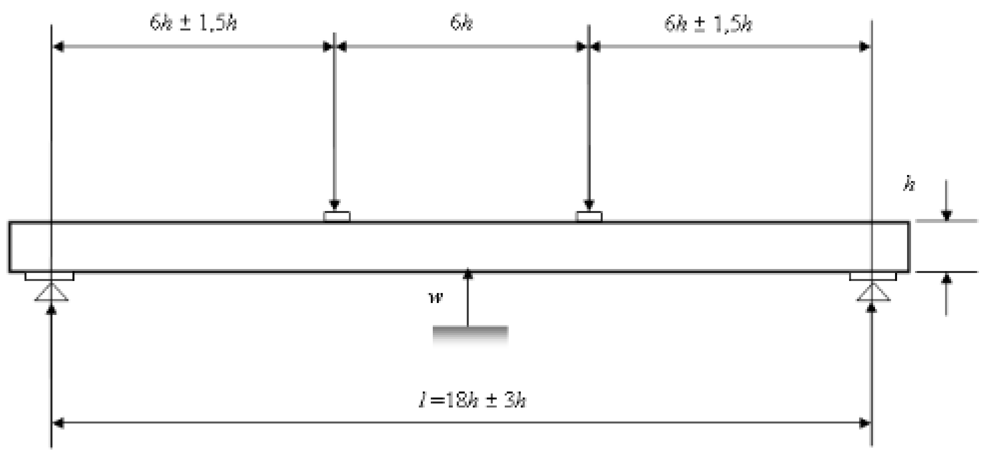


Figure 3.4.2-1 Test arrangement for measuring global modulus of elasticity in bending [23]

3.4.3 Bending strength parallel to the grain

The tests were carried out according to EVS-EN 408:2010+A1:2012 [23]. All of the beams had a minimum length of 19±3 times the depth of section. The test specimens with smaller CS-s were placed symmetrically on supports that were 1,8 m apart and for beams with larger CS-s the distance between supports was 2,6 m. Small steel plates with the width of 50 mm and 100 mm were inserted between the beam and the loading heads and also between the beam and the supports for beams for smaller CS-s and for larger CS beams, respecitvely. They were placed in order to minimize local indentation. The destructive bending tests were conducted with Enerpac P80 Hydraulic Hand Pump and Enerpac Hydraulic Silinder RC506 with capacity of 50 t. The maximum load (F_{max}) of the bending test was recorded.

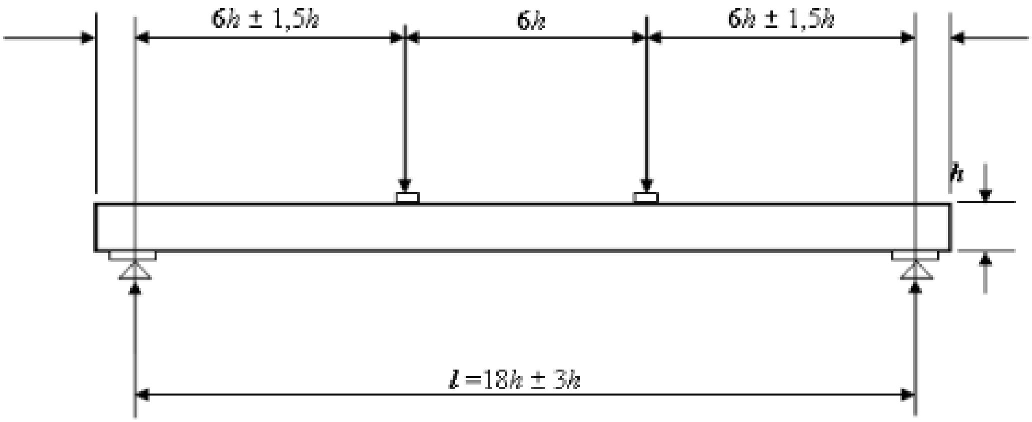


Figure 3.4.3-1 Test arrangement for measuring bending strength [23]

3.4.4 Slope of grain

The slope of grain (SoG) refers to the deviation of wood fibers from a line that runs parallel to one edge of sawn timber. When considering the overall characteristics of wood, the primary factors contributing to mechanical properties variation are typically SoG and wood density. [25]

Measuring SoG can be a challenging task as it requires careful evaluation. This characteristic can be assessed visually during the grading process or studied in a laboratory setting. There are various methods available for determining SoG, such as the use of a scribe as outlined in EVS-EN 1309 [26].

The scribe (see Figure 3.4.4-1) is a tool that consists of a cranked rod with a swivel handle at one end and a needle set to a slight trailing angle at the other. By drawing the scribe along the piece of timber in the apparent direction of the grain and applying sufficient but not excessive pressure, a line will be scribed that accurately represents the direction of the grain. To verify the accuracy of the scribed line, it is recommended to draw several adjacent lines with the direction of pull diverging slightly to the left and right, while ensuring that the scribe continues to follow the correct direction, as shown in Figure 3.4.4-2.

Figure 3.4.4-1 Sribe

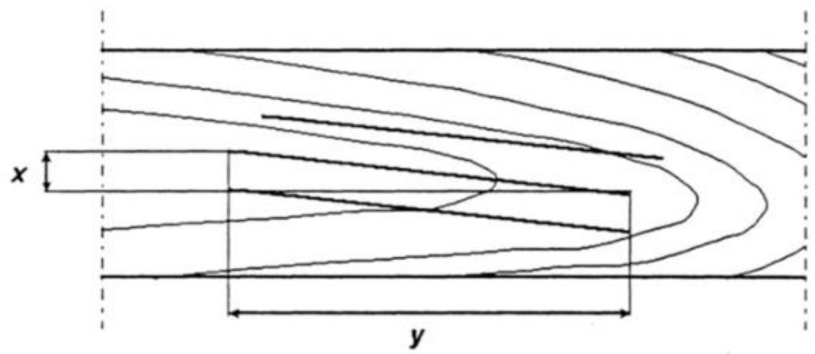
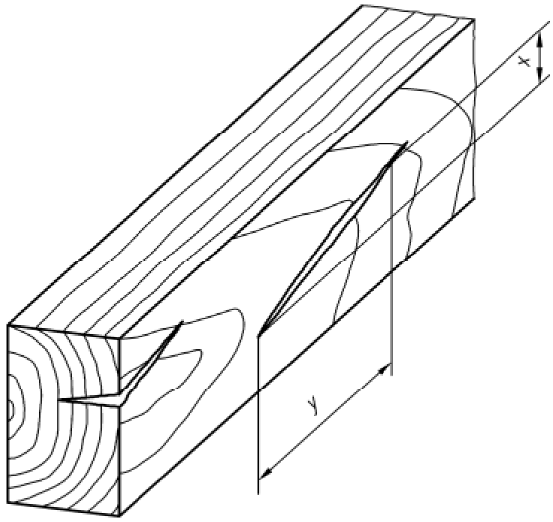


Figure 3.4.4-2 Use of scribe

Another way to measure the SoG of softwoods is according to DIN 4074-1 [27]. This standard states that the SoG *F* is calculated as the deviation *x* of the fibers in relation to the measuring length *y* and given as a percentage. Meanwhile, the local fiber deviations caused by branches are not taken into account. The fiber inclination is then measured according to the shrinkage cracks as in Figure 3.4.4-3, where *x* is the deviation of the shrinkage crack [mm] and *y* is the crack projection length [mm].



$$F = \frac{x}{y} \cdot 100$$

Figure 3.4.4-3 Determination of SoG according to shrinkage cracks

In addition to using the DIN 4074-1 and EN 1309 methods for determining SoG, there are other techniques available as well. For instance, resin ducts, small checks (which refer to the separation of fibers), and streaks of differently colored wood can also be indicative of grain inclination. However, none of these characteristics were present in the specimens used for this particular study, so they were not considered.

Another method involves placing small drops of pen ink on the surface of timber, which is expected to spread along the fibers and indicate the grain direction. A line can then be drawn through these indicators to determine and measure the grain direction. Yet, since this study focuses on visual grading, particularly the assessment of existing wood, this technique was not considered feasible. It is unlikely that in-situ timber elements would be stained with ink, making this method impractical for the purposes of the research.

Overall, while there are various methods available for determining SoG, the suitability of each approach depends on the specific circumstances and objectives of the study. This research utilized the DIN 4074-1 method as the primary approach for determining the SoG of the wood specimens. As the wood used in this study was aged, finding specimens without shrinkage cracks was challenging, so implementing this method was an ease. In instances where no visible cracks were apparent, the angle of inclination was checked after the destructive test by analyzing the fracture image (see Photo 3.4.4-1 and Photo 3.4.4-2), where the SoG could be determined in the same manner as described in DIN 4074-1.

Photo 3.4.4-1 Example 1 of fracture image

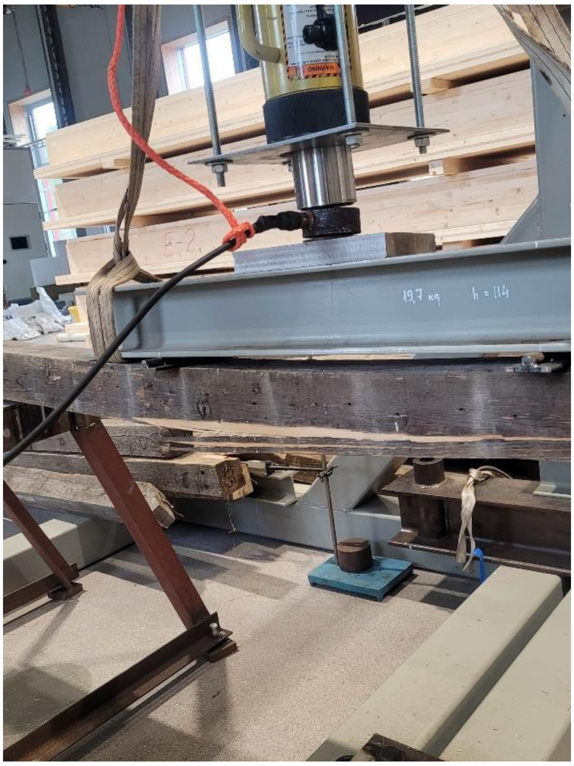


Photo 3.4.4-2 Example 2 of fracture image

3.4.5 Distortion

The varying shrinkage within a piece of wood can cause geometrical changes of the wood cross-section that can make them difficult to use. Distortion can be divided into four different forms (see Figure 3.4.5-1):

- Bow is the curvature along the length of the wide face of the board.
- Cup is the curvature across the width of the wide face of the board.
- Crook is curvature along the length of the narrow face or edge of the board.
- Twist is a deviation from parallelism of the end edges of the board. A twisted board is curved along its own axis. [5]

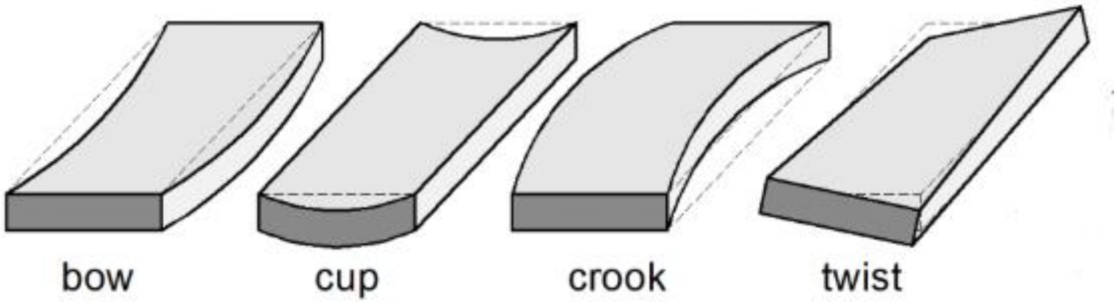


Figure 3.4.5-1 Definition of distortion modes

The study aimed to measure three types of distortions shown in Figure 3.4.5-1- bow, crook and twist. However, the cup deformation could not be measured nor was it necessary because the standards (INSTA 142, UNI 11119 and UNI 11035) used in the study did not provide any limitations to cup size, and the test specimens were square in shape rather than board-shaped so cupping wasn't prevalent.

In order to measure bow and crook, sides A-C and B-D of the specimen were chosen, respectively. The distortions were measured according to EN 1309-3:2018. [26] Firstly, the specimen was placed on a flat, even surface and with the help of a staple gun a fishing line was attached to the specimen at one end, pulled taut, and then fastened at the other end. The presence of a gap between the line and the center of the test piece was visually checked, and if present, it was measured using a caliper and documented. Visually, the method is quite well pictured in Figure 3.4.5-1 imagining the dashed lines are the fishing line, but instead connecting corners, the fishing line was drawn from the middle of the edge of the specimen to the middle of the opposing edge.

In order to measure twisting, the specimen were again placed on a flat, even surface with one end of the beam held tightly against the surface, and the distance of raised end from the plane was measured. Although this method may not give the most accurate results, it provides a more conservative result in favor of backup. However, it is not possible to measure the raise of only one corner when dealing with old timber anyway, as both bow and twist occur simultaneously in such cases.

3.4.6 Visual grading

In order to visually evaluate the wood specimens, this research relied on the Nordic Standard INSTA 142 meant for new timber and for comparison also the Italian national standards UNI 11119 and UNI 11035, which both provide guidelines for visual grading and sorting of old wood. One may add, that in addition to assessing aged in-situ timber, UNI 11035 is even suitable for sorting new wood. To assess the visual characterisics of the specimens, the research inspected all the methods described in chapter 3.4, as well as factors listed in Table 2.3.7-1 and APPENDIX 5 such as the absence and extent of (group of) knots, fungal degradation, compression wood and insect attacks. By taking these anomalies into account, the test specimens were categorized into different groups according to the standards, either by maximum allowed stress or strength class.

The standard UNI 11119 specified certain allowed stresses and the expected modulus of elasticity for the tested specimens, while the more comprehensive standard UNI 11035 specified a strength class based on many different aforementioned defects. The INSTA 142 meant for grading new sawn timber takes into account all the defects mentioned in the Italian standards while applying slightly stricter requirements and adding some additional parameters such as separating single knots by their location in the specimen (edge or flat side). By comparing the difference between the three standards, it was possible to determine which standard provided a more accurate result and which could be more appropriate to use for further research. It is important to note that the use of standardized methods for evaluating wood specimens is crucial for ensuring reliable and consistent results, as well as for facilitating comparisons between different studies.

3.4.7 Data analysis

The aim of the present research was to determine the results of visual assessment of wood and their relationship with actual strength indicators. To achieve this, ND bending tests and destructive tests were used in addition to visual grading. The data analysis of the test results was conducted using MS Excel computer program, where the data was entered and various descriptive statistical analyses were performed:

- Correlation coefficient r – measures the strength of a linear relationship between two variables.
- Coefficient of determination R^2 - provides a measure of how well observed outcomes are replicated by the model.
- Scatter plot – is a set of points plotted on a horizontal and vertical axes that shows the extent of correlation, if any, between the values of observed variables.
- Box plot (box and whisker plot) – is a graph, that uses boxes and lines to depict the distributions of one or more groups of numeric data.
- Distribution histogram – is a chart that plots the distribution of a numberic variable's values as a series of bars.

To characterize the strength of the relationships, following criterion was used:

$r=0$	No correlation
$\|r\|<0,3$	Weak correlation
$0,3\leq\|r\|\leq0,7$	Moderate correlation
$\|r\|>0,7$	Strong correlation
$r=1$	Perfectly positive correlation

It is worth noting that the statistical analysis yields estimated values for r and R^2, which cannot be interpreted as definitive results. The accuracy of these estimates is contingent on both the sample size and the replication of measurements. Due to the small sample size employed in this study, the predictive models cannot be widely applied, but the results do confirm the efficacy of the methods in practical applications. [28]

4 CALCULATIONS

Moisture content ω [%], calculated according to EN 13183-1:2002 [24] as a percentage by mass, using the formula:

$$w = \frac{m_1 - m_0}{m_0} * 100 \quad (4.1)$$

where

m_1 is the mass of the test slice before drying, in grams;

m_1 is the mass of the oven dry test slice, in grams;

Density ρ_w [kg/m^3] was calculated according to following formula:

$$\rho_w = \frac{m}{V} \quad (4.2)$$

where

m is the mass of the test slice before drying, in kilograms;

V is the volume of the test slice, in cubic meters;

Adjusted values for density ρ [kg/m^3] were calculated according to formula from EVS-EN 384:2016 [29]. If the moisture content u is lower than 8%, special consideration is required for the adjustment of strength properties, modulus of elasticity and density.

$$\rho = \rho_w(1 - 0{,}005(w - w_{ref})) \quad (4.3)$$

where

ρ is the density, kg/m^3;

ω is the moisture content at testing (8%≤ω≤18%)

ω_{ref} is the reference moisture content, normally ω_{ref}=12%.

In order to find the local modulus of elasticity $E_{m,l}$ [N/mm^2] calculated according to EVS-EN 408:2010+A1:2012 [23] it is necessary to find the longest portion on load-deformation graphs that gave the correlation coefficent of ≥0,99. Provided that this portion also covers at least the range 0,2 $F_{max,est}$ to 0,3 $F_{max,est}$. Then the local modulus of elasticity could be calculated from the following expression:

$$E_{m,l} = \frac{al_1^2(F_2 - F_1)}{16I(w_2 - w_1)} \quad (4.4)$$

where

F_2 -F_1 is an increment of load in newtons on the regression line with a correlation coefficient of 0,99 or better;

w_2-w_1 is the increment of deformation in millimetres corresponding to F_2 -F_1 (see Figure 3.4.7-1)

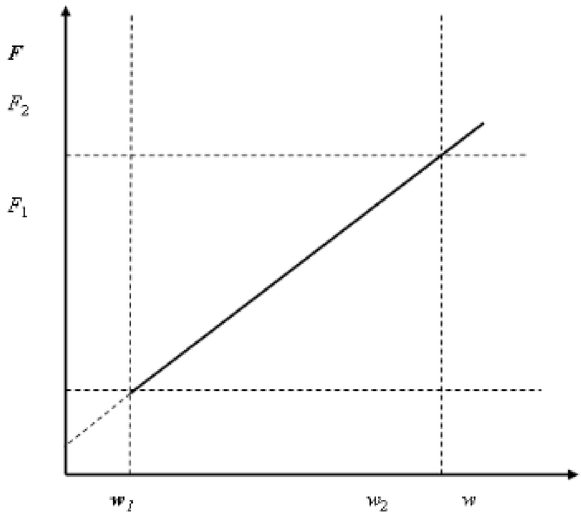


Figure 3.4.7-1 Load-deformation graph within the range of elastic deformation [23]

In order to find the global modulus of elasticity $E_{m,g}$ [N/mm²] calculated according to EVS-EN 408:2010+A1:2012 [23] it is necessary to find the longest portion on load-deformation graphs that gave the correlation coefficent of ≥0,99. Provided that this portion also covers at least the range 0,2 $F_{max,est}$ to 0,3 $F_{max,est}$. Then the global modulus of elasticity could be calculated from the following expression:

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh})} \quad (4.5)$$

where

F_2 -F_1 is an increment of load in newtons on the regression line with a correlation coefficient of 0,99 or better;

w_2-w_1 is the increment of deformation in millimetres corresponding to F_2 -F_1 (see Figure 3.4.7-1)

G is the shear modulus taken as 650 N/mm^2 (for coniferous wood species).

In order to find the adjusted modulus of elasticity parallel to the grain E_0 from the global modulus of elasticity $E_{m,g}$ for bending, the formula for softwoods according to EVS-EN 384:2016 [29] shall be used:

$$E_{0,u} = E_{m,g(uref)} * 1{,}3 - 2690 \quad (4.6)$$

where

$E_{m,g(uref)}$ is global modulus of elasticity at reference moisture content (normally u_{ref}=12%)

In order to find the modulus of elasticity parallel to the grain E_0 taking into account test values the formula according to EVS-EN 384:2016 [29] shall be used:

$$E_0 = E_{0,u}(1 + 0{,}01(u - u_{ref})) \quad (4.7)$$

where

$E_{0,u}$ is global modulus of elasticity parallel to the grain

u Is the moisture content at testing (8%≤u≤18%)

u_{ref} Is the reference moisture content, normally u_{ref}=12%

Bending strength parallel to the grain f_m [kN] is determined according to EVS-EN 408:2010+A1:2012 [23]:

$$f_m = \frac{3Fa}{bh^2} \quad (4.8)$$

where

F is load, in newtons;

a is distance between a loading position and the nearest support in a bending test, in millimetres

b is width of cross section, in millimetres;

h is depth of cross section, in millimetres.

5 RESULTS AND DISCUSSION

5.1 Visual grading results

5.1.1 According to UNI 11119

Table 5.1.1-1 displays how the specimens have been categorized according to the UNI 11119 standard. The results have been obtained by analyzing knots, groups of knots, SoG, wanes and cracks. The standard also includes rules for classifying wood specimens based on various damages like ring shakes and radial shrinkage cracks. However, since the test specimens in this study did not exhibit these limitations, it is assumed that they belong to the first category for the absent aforementioned parameters.

Table 5.1.1-1 Results of visual assessment according to the UNI 11119 standard

Category	Number of specimens	Maximum allowable stresses (N/mm^2)					
		Compression		Bending static (MoR)	Tension parallel to grain	Shear parallel to grain	Bending MoE
		Parallel to grain	Perpen-dicular to grain				
I	5	10	2,0	11	11	1,0	12 500
II	7	8	2,0	9	9	0,9	11 500
III	1	6	2,0	7	6	0,8	10 500
Not graded	2			-			

A total of 15 specimens were analyzed, but specimens number 1 and 21 were deemed unsuitable for further analysis due to exceeding wane proportions, insect damage (see Photo 5.1.1-1) and curly grain (see Photo 5.1.1-2). While UNI 11119 allows for specimens with localized insect damage to be considered if degraded areas are excluded from the effective section, this was not possible in the current situation.

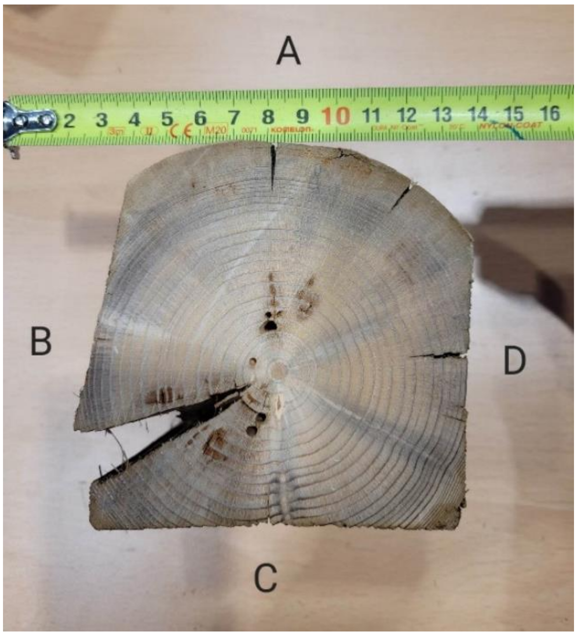


Photo 5.1.1-1 Specimen 1 CS with visible insect damage

Photo 5.1.1-2 Specimen 21B with visible curly grain

Based on the data presented in the Table 5.1.1-1, it can be inferred that the test specimens have been visually assessed to be in relatively good condition. The table reflects design values, which before applying partial safety factors, common for sawn wood, using the formula 2.4 given in chapter 2.4 on page 23, allows specimens to be graded to strength classes according to EVS-EN 338 [30]. The majority of the specimens fall under the first or second category, indicating that their bending strength should be at least f_d=9 N/mm^2. This classification places more than half of the specimens in the strength class C18, while the remainder are in the C24 class or above. Only one test specimen (nr 6) has been rated in the third category, which is still within an acceptable range for strength, leading to its classification as belonging to the C16 class. Such a high percentage of test specimens belonging to the C18 and higher strength classes suggests that the reusing of the material is a favourable option, given that higher strength classes are indicative of higher quality materials. However, it is important to note that visual grading is only one factor in assessing the quality of wood and any conclusion drawn from such a small sample size may not be reliable and could be considered premature.

5.1.2 According to UNI 11035

Table 5.1.2-1 displays how the specimens have been categorized according to the UNI 11035 standard. The results have been obtained by analyzing wanes, knots, group of knots, ring width, SoG, cracks, fungal degradation, insect attacks and distortion. The standard also includes rules for classifying wood specimens based on parameters such as compression wood and parasitic plants. However, since the test specimens in this study did not exhibit any of these limitations, it is assumed that they belong to the first category for the absent aforementioned anomalies.

Table 5.1.2-1 Results of visual assessment according to the UNI 11035 standard

Category	Number of specimens	Class
S1	5	-
S2	7	C24
S3	1	C18
Not graded	2	-

Analogously to the visual grading according to the previous standard, 15 specimens were analyzed, and specimens 1 and 21 were rejected for insect damage, wanes and curly grain (see Photo 5.1.1-1 and Photo 5.1.1-2). Compared to UNI 11119, several additional parameters were included for analysis, but still, following the guidelines of UNI 11035, the results remained very similar to the former one. In the UNI 11035 grading system, the strength classes distributed according to the EVS-EN 338 [30] are already given, so they do not need to be calculated from design values. In terms of categorization, the results are closely resembling those obtained from UNI 11119, with 5 specimens appointed to the highest category, 7 to the second and 1 to third. It is worth mentioning that since UNI 11119 has fewer requirements for categorizing test specimens, the results obtained are also more conservative. Although, in terms of characteristics, the grading by UNI 11035 goes a step further, by placing more than half of the specimens in the strength class C24, while the remainder have at least C24 or better properties. Only one test specimen (nr 6) has been rated in the third category, which leads to its classification as belonging to the C18 class.

5.1.3 According to INSTA 142

To ascertain the validity of the statements in the literature suggesting that the assessment standards designed for new wood may not be applicable to evaluate old wood, it becomes relevant to compare the obtained results with one of the standards specifically devised for new wood.

The Nordic visual strength grading rules for timber, also known as INSTA 142, is a standardized grading system used in Denmark, Finland, Iceland, Norway, and Sweden for coniferous woods including Norway spruce tested in this research. The grading rules are specifically designed for timber sourced from northern and northeastern Europe. The main purpose of INSTA 142 is to provide a systematic method for assessing the strength and quality of timber based on three major types of observations. These include identifying strength-reducing features such as knots, size and shape of the timber, and any biological attack present on the wood. [31] The sorting classes are named according to decreasing strength T3, T2, T1 and T0, and are varying between coniferous species. [32] Table 5.1.3-1 shows the results of visual grading according to the INSTA 142 standard.

Table 5.1.3-1 Results of visual assessment according to the INSTA 142 standard

Category	Number of specimens	Class
T3	5	C30
T2	7	C24
T1	1	C18
T0	0	C14
Not graded	2	-

As seen from the table above, the results are once again very similar to the previous ones. One of the main differences with applying criteria given in the Nordic standard is that for instance knots are distinguished by their location on situating either on the flatter face or edge face of the sample and it also sets special criteria for squared CS timber. Additionally, group of knots is not measured the same way as in UNI 11035 and UNI 11119 but rather taken into account as largest knot dimension equal to the sum of the largest permitted flat side knot and the largest permitted edge side knot. For square timber, the same parameter is explained as largest knot size not greater than 4 times the size of the largest permitted single knot. This approach makes the assessment of group of knots more sparing than in the Italian standards. One additional difference, which was not drawn out in this work, but can likely happen in the case of a larger sample, is the categorization according to the width of annual rings, which is strictly more limited in INSTA 142.

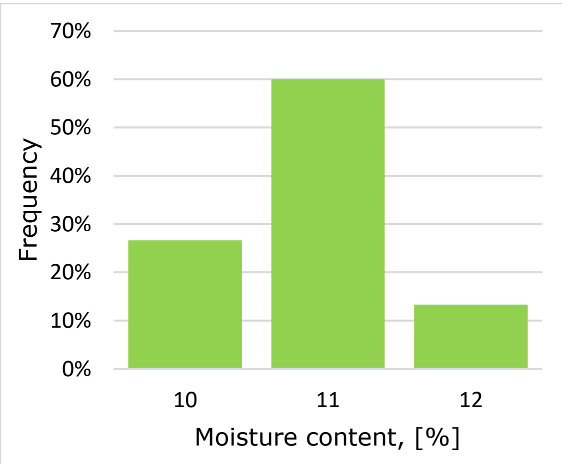
In general, INSTA 142 is very similar to the UNI 11035 standard in terms of evaluation criteria, it has stricter requirements in some areas and more lenient requirements in others, but while UNI 11035 ends the categorization at C24 strength class, INSTA 142 also allows test specimens to be assigned to strength classes from C14 up to C30.

5.2 Destructive and semi-destructive testing

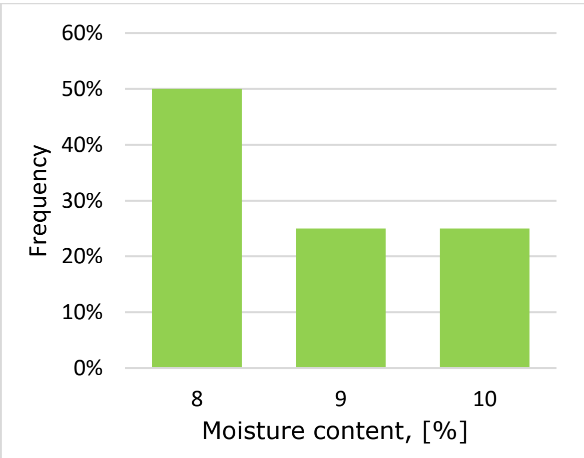
The CS dimensions given in APPENDIX 1 are calculated as the arithmetic average of measurements from three different places. The lengths reflected for specimens 19, 22, 23 and 24 had longer length originally, but were cut to 2,8 m for testing. Prior to analyzing the data from the study, it is important to examine the physical and mechanical characteristics of the test samples. To achieve this, frequency diagrams have been created for the test specimens to illustrate their MC, density, bending strength (determined by destructive testing), and static modulus of elasticity (determined through non-destructive testing). Histograms are used to compare test values separately for beams with smaller and larger cross-sections and box plot graphs for smaller corss-section beams to illustrate the visual summary of different statistical characteristics of the specimens.

5.2.1 Moisture content

The tests were conducted on test specimens that were at their equilibrium moisture content. To enable comparisons with values given in standards at a later stage, it was essential to determine the moisture content of the test objects during the testing process. The outcomes of these measurements are displayed in the graphs below.



Graph 5.2.1-1 Frequency diagram of MC for beams with smaller CS

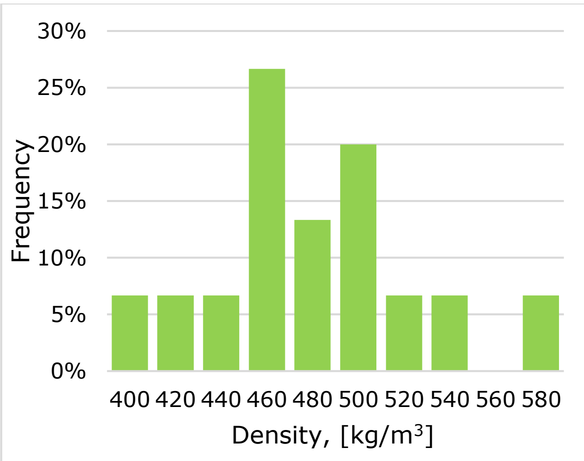


Graph 5.2.1-2 Frequency diagram of MC for beams with larger CS

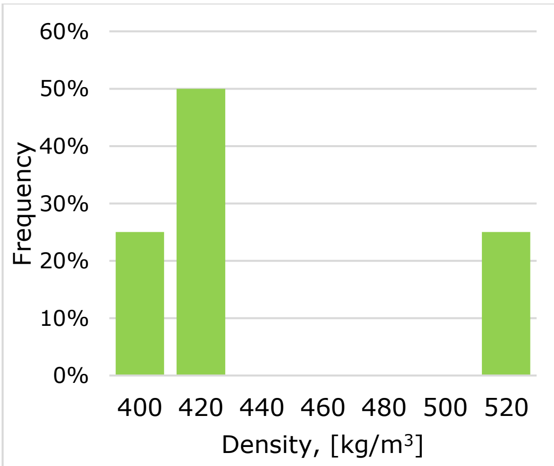
The test specimens with a smaller CS were kept in a laboratory with a temperature of (20±2)°C and a relative humidity of (45±5)% before testing. After carrying out the tests, small cubes were cut from the specimens and were then placed into a ventilated oven at (103±2)°C until the mass remained constant. The same process was conducted with specimens with larger CS with the exception, that they were kept in the said laboratory for two months before testing. It can be seen from the histograms (see Graph 5.2.1-1 and Graph 5.2.1-2) that at the moment of testing, the moisture content of samples with a smaller CS was slightly higher, varying between 10-12%, and the moisture content of samples with larger CS was lower, varying between 8-10%.

5.2.2 Density

The density of wood is typically determined at a specific moisture content. In this study, it was deemed significant to calculate the density of the test specimens at the same moisture content, which was set to 12% based on the EVS-EN 338:2016 [30]. Since the density was determined before testing to failure, the density of each specimen has been divided by 1,05 (for softwoods) according to EVS-EN 384. [29] The following histograms (Graph 5.2.2-1 and Graph 5.2.2-2) illustrate that the frequencies of the test specimens' densities vary significantly. The density of the spruce test pieces, for smaller CS beams for instance, ranges between 400 to 580 kg/m^3 and for larger CS beams from 400 to 520 kg/m^3.



Graph 5.2.2-1 Frequency diagram of density for beams with smaller CS



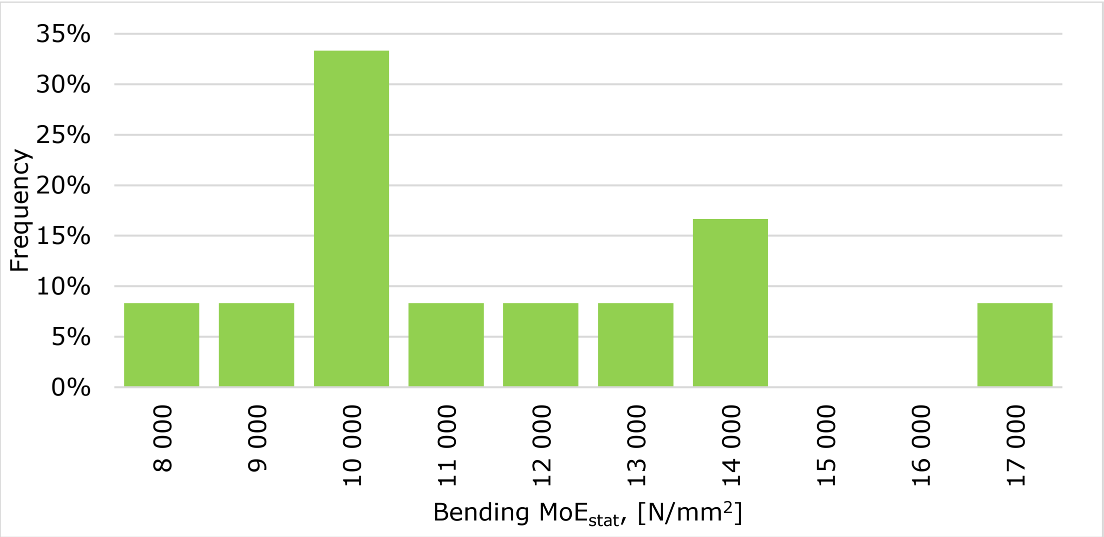
Graph 5.2.2-2 Frequency diagram of density for beams with larger CS

Norway spruce typically has an average density of 450-470 kg/m^3, which drops to 445 kg/m^3 at 12% MC. [33] However, the average densities of the specimens in this study are varying, with 42 % being slightly higher than average (480 kg/m^3) for smaller CS specimens and 25 % over average of 437 kg/m^3 for beams with bigger CS dimensions. Although the histograms (Graph 5.2.2-1 and Graph 5.2.2-2) clearly demonstrate that the densities of both smaller and larger CS-s beams' test specimens do not conform to a normal distribution. Even though the densities may vary, the overall trend suggests that they align with the average density of Norway spruce. Consequently, it is anticipated that other characteristics correlated to density will also match.

5.2.3 Static modulus of elasticity

As one of the objectives of this study was to analyze timber beams from all four faces of the specimens, it was crucial to conduct ND 4-point bending tests on each side. This was done to determine the side with the lowest MoE and to gain insights into whether there was any correlation between the properties of the timber obtained from visual assessments and the actual test results. By carrying out the NDT, the research aimed to identify the optimal side for conducting the DT, which would provide more detailed information about the timber's properties and behavior.

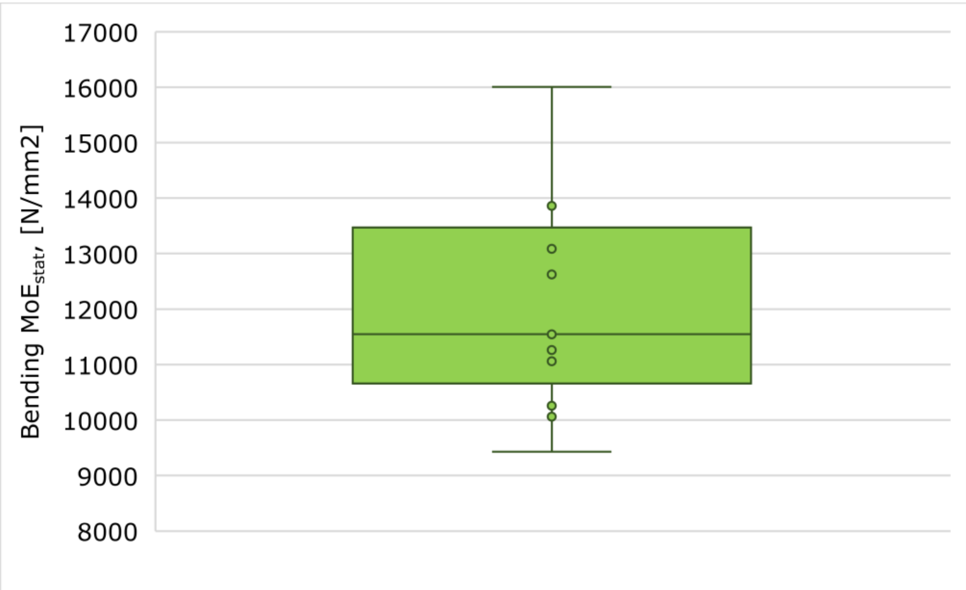
The global bending modulus of elasticity obtained from the ND bending test has been adjusted to the static modulus of elasticity corresponding to 12% moisture content according to the standard EVS-EN 384. [29] Graph 5.2.3-1 shows the values of the smallest MoE_{stat} value obtained from 4-point bending test carried out on beams with smaller CS dimensions. In the case of beams with a larger CS, the histogram of the static modulus of elasticity is not presented due to the small number of test specimens. The results for larger CS-s were MoE_{stat}=39 834 N/mm^2 for specimen 22, and MoE_{stat}=17 964 N/mm^2 for specimen 23.



Graph 5.2.3-1 Freguency diagram of static modulus of elasticity for beams with smaller CS

Again, the results are highly variable, ranging from 8 000 N/mm^2 up to 17 000 N/mm^2, making it difficult to draw conclusions. Only value of 10 000 N/mm^2 appears to be more prevalent than others, indicating that the distribution of modulus of elasticity values may be approaching a normal distribution. However, since the specimens cross-sectional dimensions and moisture contents were very similar, it suggests that the value of elastic modulus in addition to MC may be more influenced by factors such as the material composition, exploitiation and different types of defects such as knots, SoG and degradation.

The following Graph 5.2.3-2 provides a visual summary of the distribution, spread, and central tendency of the data gained from 4-point destructive bending tests for smaller CS specimens. The graph illustrates the median value as the horizontal line in the box, which is 11 548 N/mm^2. Secondly, the box represents the interquartile range, varying between 10 659-13 473 N/mm^2. The whiskers indicate the range of the data, excluding outliers, but there seem to be no outliers in this sample. The lack of outliers in the dataset indicates a relatively consistent distribution without unusual or extreme values that could distort the overall analysis. The data points are tightly clustered within a reasonable range, suggesting a more typical pattern. However, it's important to recognize that the absence of outliers doesn't imply a complete absence of variability. Variability can still be present within the dataset, as evident from the spread of the box. Therefore, it is essential to take into account the comprehensive range of information provided by the box plot as a whole.



Graph 5.2.3-2 Box plot graph of bending MoE_{stat} for smaller CS specimens

5.2.4 Semi-destructive bending on each face

The following Graph 5.2.4-1 illustrates the results of 4-point ND bending test on each face of the specimens with smaller CS dimensions, with addition of average value and the E_0 values of sawn coniferous wood which correspond to strength classes C18 and C24 from EVS-EN 338. [30] All of the specimens had a CS dimensions and MC roughly the same, so the variability of results has to lie elsewhere.

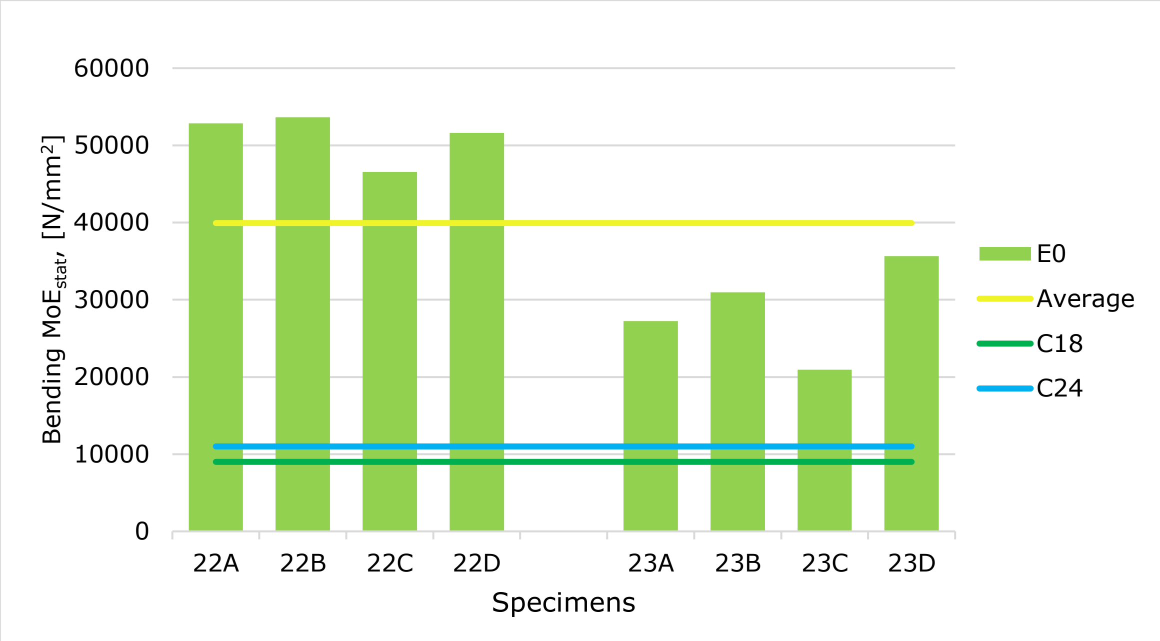
Based on the data provided in the Graph 5.2.4-1 it is evident that a prominent trend emerges in eight of the test specimens, representing 73% of the sample of smaller CS. This trend suggests that the position of the test specimen, specifically the location of the sides in relation to the tension and compression zone, is a critical factor in determining its strength characteristics. Although the graph displays noticeable fluctuations in the data, the variability is counterbalanced by test specimens that produce nearly identical results from all faces, resulting in a fluctuation averaging at only 5,3% across the entire sample. Still, it can be inferred that the orientation of the grain in the specimen can also influence its behavior under load.

It is essential to note that contrary to Graph 5.2.3-1, the Graph 5.2.3-1 does not illustrare the values of specimens 1 and 21. The reason being that specimens reached its maximum bending capacity during the initial ND bending test when a load of 7,3 kN and 7,7 kN was applied, respectively. As mentioned in the visual grading chapters 5.1.1 and 5.1.2, that upon visual inspection, specimen 21 had curly grain on the C and B sides of the test piece in the critical zone of the beam, which may have contributed to its failure. Understandably, test specimen 21 fractured when side A was under compression, while side C was in tension. The reason for specimen 1 fracturing prematurely was due to insect attacks throughout its entire length. Given the deformations present in the aforementioned test specimens, they would have been rejected during the visual sorting process anyway. Therefore, it is reasonable to exclude their results from the calculation of the average, as this would unnecessarily bring down the overall result.

Furthermore, in addition to E_0 values of every face Graph 5.2.4-1 additionally represents the average value of the whole sample, exceeding the prescribed strength values for both C18 and C24. However, this is primarily due to a few specimens that exhibit exceptional characteristics, resulting in a higher average value. Nonetheless, it can be argued that, all the test specimens meet the criteria for the C18 strength class.

Graph 5.2.4-1 Bending MoE_{stat} of smaller CS specimens of each face

The static modulus of elasticity is an important measure of a material's strength and stiffness, but it is not always sufficient to draw definitive conclusions about the specimen's overall strength. In the case of these two beams, as seen on Graph 5.2.4-2, the measured static modulus of elasticity can vary significantly, from 20 000 N/mm^2 to 50 000 N/mm^2, without providing a clear indication of the strength of the material. As demonstrated by the graph, the results for opposite sides of can again fluctuate significantly, but since these were rectangular not squared samples, it is rather easy to distinguish in which way the beam would work better.



Graph 5.2.4-2 Bending MoE_{stat} of larger CS specimens of each face

In order to analyze the relationship between bending test results and visual grading outcomes, comparisons were made for both smaller and larger CS specimens. An important point to consider in the visual evaluation process was the assignment of a distinct category to each face, which allowed for the examination of any characteristic that might indicate the weakest side among the four. The comparison was conducted based on the categories established by all three standards, yet no discernible correlation could be established. Notably, no evident pattern emerged between factors such as the presence of the largest diameter knot and the weakest side on the tension face, or the existence of the largest fiber inclination angle and the weakest face. Consequently, it can be inferred that the tested body should be regarded as a cohesive entity, with singular parameters such as individual knots, groups of knots, fiber inclination angle, and cracks proving inadequate as isolated indicators of strength determination. Rather than focusing on isolated factors, it is crucial to take a comprehensive approach and consider the broader context to arrive at reliable conclusions. This observation demonstrates that even if a specific side of the specimen meets the criteria for a higher class within the standard and should therefore conceptually have better strength properties, when the overall specimen is rated in a lower class, it is necessary to regard the entire specimen as belonging to the weaker category.

5.2.5 Bending strength

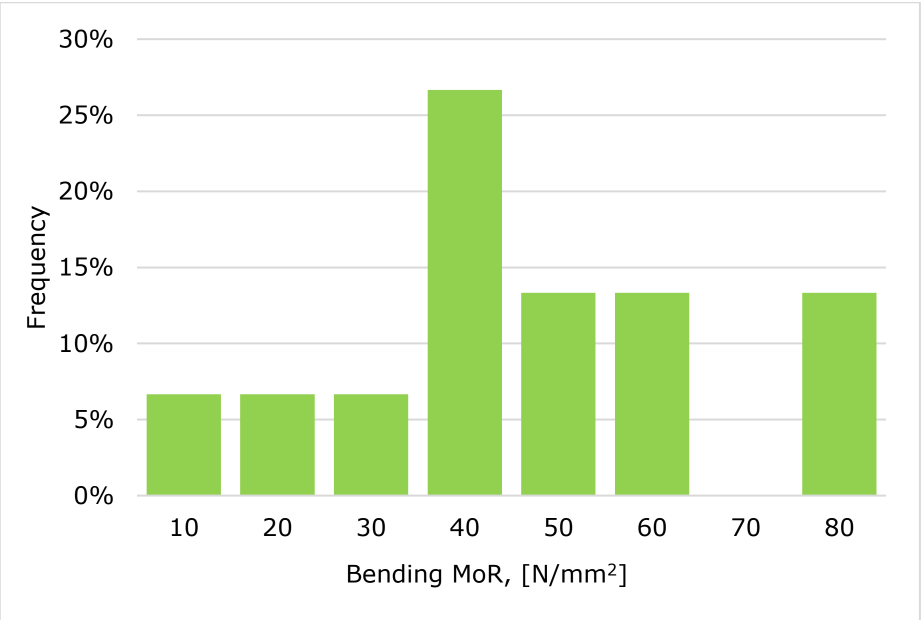
Bending strength values have been adjusted according to EVS-EN 384 [29] as follows: for depth less than 150 mm, and characteristic density less than or equal to 700 kg/m^3, bending strength shall be adjusted to 150 mm depth by dividing the values by the factor k_h from formula:

$$k_h = Min\begin{cases}\left(\frac{150}{h}\right)^{0,2} \\ 1,3\end{cases} \quad (5.2)$$

where

h is the depth, in mm.

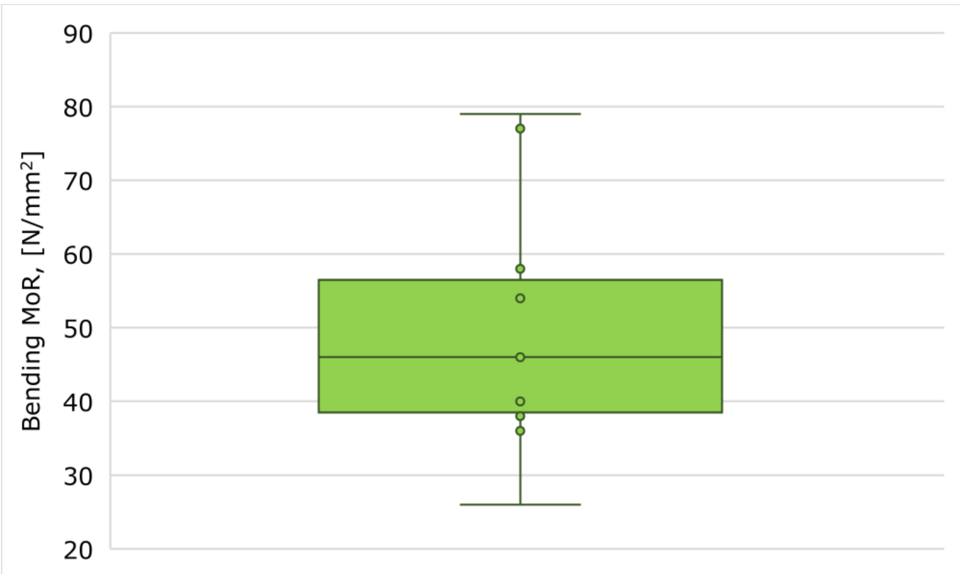
The histogram presented below displays the bending strength values obtained from the destructive bending test of the test specimens. These values were recorded at a moisture content of 10-12% for beams with smaller CS and 8-10% for beams with larger CS. The faces for DT were chosen according to the previous bending tests, on the basis of which the test pieces were fractured according to the face with the lowest stiffness. Upon comparing the test specimens with a smaller CS of ~100x100mm, it can be observed that the distributions of bending strength do not conform to a normal distribution.



Graph 5.2.5-1 Freguency diagram of bending MoR values for beams with smaller CS-s

The histogram (see Graph 5.2.5-1) reveals that the most frequent values of bending strength are slightly lower than the high average value of 50 N/mm^2. The reason for the high average value is attributed to two specific test specimens (5 and 10), which demonstrated exceptionally high bending strength values of 77 N/mm^2 and 79 N/mm^2, respectively. However, it should be noted that due to the significant variability in the results, it is challenging to draw definitive conclusions from this observation. Therefore, further investigation and analysis may be necessary to fully understand the factors contributing to the variability in bending strength values and their impact on the overall quality and reliability of the test results. The bending strength results of specimens with bigger CS-s were 55,3 N/mm^2 for specimen 22 and 28,2 N/mm^2 for specimen 23.

The following Graph 5.2.5-2 provides a visual summary of the distribution, spread, and central tendency of the data gained from ND 4-point bending tests for smaller CS specimens. The graph illustrates the median value as horizontal line inside the box, which is the middle value of data set when the minimum values of bending MoR-s of each specimen were arranged in ascending order, the median in this instance is 50. Secondly, the box represents the interquartile range, which encompasses the middle 50% of the data, varying between 38,5-56,5 N/mm^2. The lower edge of the box corresponds to the 25th percentile (Q1), and the upper edge represents the 75th percentile (Q3). The lines extending from the box are called whiskers, which indicate the range of the data, excluding outliers. Outliers are marked as the individual data points beyond the whiskers, representing extreme values that deviate significantly from the majority of the dataset. In this instance there are no outliers.

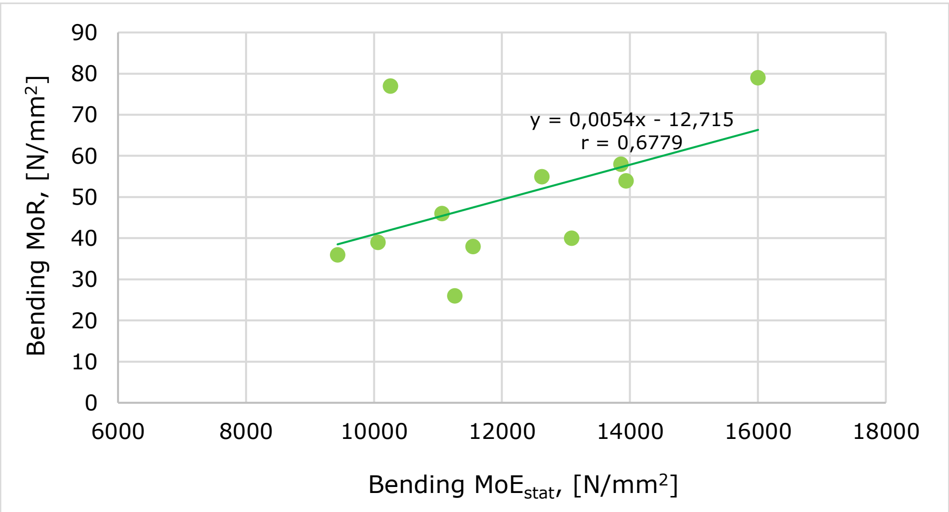


Graph 5.2.5-2 Box plot graph of bending MoR values for smaller CS specimens

5.3 Semi-destructive bending in comparison to destructive bending

MoE, also known as bending modulus of elasticity, holds significant importance in wood properties as it quantifies the wood member's resistance to bending when subjected to a load. A higher MoE value signifies increased stiffness, making it suitable for structural applications. On the other hand, MoR, or bending modulus of rupture, serves as an indicator of flexural strength. It measures how a test specimen of specified dimensions behaves during a bending test until it fractures at maximum stress.[34]

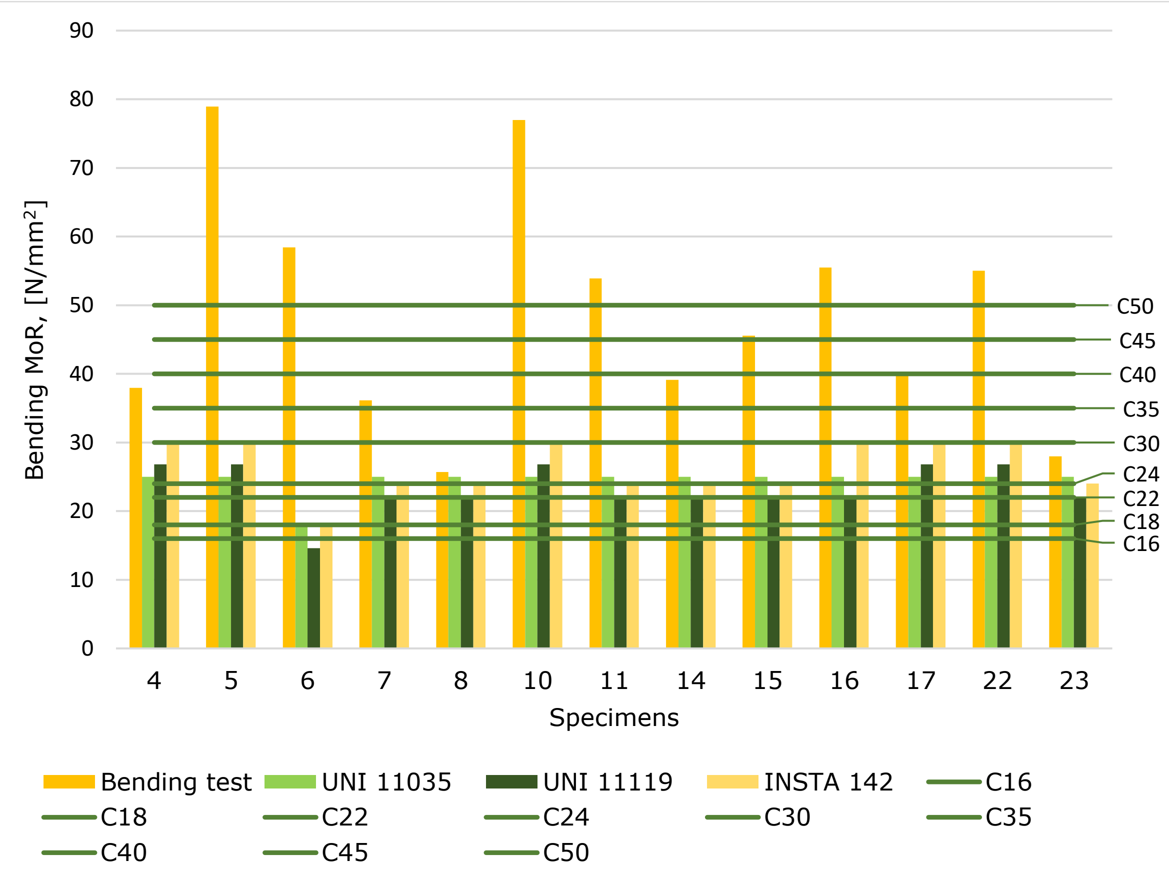
The scatter graph (see Graph 5.2.5-1) displays a positive relationship between the variables of static bending modulus of elasticity (MoE) and bending modulus of rupture (MoR) for smaller CS specimens being analyzed. With a correlation coefficient of 0,67, there is a moderately strong positive correlation between the the two variables. This means that as one variable increases, the other tends to increase as well, albeit not perfectly. Based on the observed positive upward trend, it can be inferred that an increase in MoE corresponds to an increase in the value of MoR. Although there is some variability in the data points, the general trend suggests a positive association between them. While a correlation coefficient of 0,67 between MoE and MoR suggests a moderate relationship, it doesn’t guarantee that the correlation will remain the same for other specimens or when developing predicition models, but rather measures the strength and direction of the linear relationship between two variables within the given sample. The correlation coefficient does not imply causation or provide information about the strength of the relationship in terms of prediction. No correlation coefficient was found for specimens with larger CS due to the small sample size.



Graph 5.2.5-1 Relationship between MoE and MoR for smaller CS specimens

5.4 Visual grading in comparison to destructive bending

The visual assessment process involved an examination of 15 specimens, with the intention of categorizing them based on visual characteristics. Notably, individual knots were found to have the most pronounced impact on the visual categorization, surpassing the influence of knot groups. It is important to note that knots are considered a group only if the surrounding grain is visibly disrupted. Consistent with the findings of numerous previous studies, it was apparent that knots held great significance in the categorization of the specimens, accounting for a substantial 86,7% of the cases, the other 13,3% encompassed different contributing factors, with 6,7% attributed to wanes and/or insect damage, while the remaining 6,7% was influenced by curly grain and exceeding the limitations set by the SoG. Interestingly, the occurrence of knot groups was observed in only 8% of the cases among the test specimens investigated in this research. While they did contribute to the categorization process, they never emerged as the determining factor due to the presence of a dominant single large knot on the same face of the test specimen, which invariably played the decisive role.



Graph 5.2.5-1 Comparison of test and visual grading results

The Graph 5.2.5-1 very effectively illustrates the notable variability between the results obtained from actual bending tests and those derived from visual evaluation using different standards. Notably, the dark yellow bars in the graph visibly surpass the other bars and even surpass the results of the C24 strength class outlined in the EN 338 standard. This observation further emphasizes the notable difference between the visual evaluation standards and the real strength of the wood being tested. When comparing the results of the visual strength sorting with the strength classes obtained through the bending test, a noticeable disparity becomes apparent. While the visual strength sorting categorizes the wood into the highest class of C30, the bending test reveals a significantly higher strength class for 46,2% of the sample- C50. This reveals a significant limitation of visual strength sorting, as it cannot classify wooden material into higher strength classes, resulting in the marketing of high-quality wood as lower grade material. It is evident for both small and bigger CS beams, that the majority of test specimens in the destructive bending test exhibit strength classes of C30 or higher. However, in the visual strength sorting, the number of test specimens categorized as C30 is significantly lower.

The graph serves as compelling evidence that the visual assessment standards significantly underestimate the true strength of old timber. In the specific context of this study, it is observed that UNI 11035 underestimates wood strength by an average of 49,6%, while UNI 11119 exhibits an underestimation of 53,6%. Intriguingly, the Nordic standard, originally designed for sorting new wood, displays the lowest error percentage, albeit still underestimating the strength of the tested old wood by 47,6%.

Although in previous studies visual assessment has not shown complete reliability, in the example of this work all the standards used underestimate the real strength, so in terms of idea there would have been minimal risk of using the current specimens again in a construction.

5.5 Discussion and propositions

One of the aims of this study was to determine the most effective visual assessment method for evaluating the strength properties of wooden elements. Three different standards were utilized: NS-INSTA 142:2009, UNI 11119, and UNI 11035. While the first standard is primarily intended for assessing the strength of new wood, the latter two are designed for evaluating aged wood already present in structures, with UNI 11119 especially focusing on historical structures. Previous research on similar topics has generally agreed that applying standards meant for new wood to the assessment of old wood is impractical. This is due to the high percentage of elements being rejected, as well as the incorrect classification of those that do pass the assessment, resulting in significant error rates.

Contrary to previous research, the results of this study demonstrated a different outcome, with the standard designed for grading new wood yielding the most accurate results. This standard, known as the Nordic standard INSTA 142, encompasses various visually assessed properties such as knots, knot clusters, wanes, cracks, annual ring widths, insect damage, and shape distortions. The limitations outlined in this standard closely resemble those specified in standards specifically developed for assessing old wood, albeit with some variations. For instance, INSTA 142 imposes stricter restrictions on annual ring width and knot sizes depending on their location within the cross-section compared to other standards. However, there are also instances where this standard exhibits more leniency in certain parameters when compared to the others.

The exceptionally positive outcomes achieved in this study can be partly attributed to the seemingly high quality of the initial material, which exhibited favorable results in visual evaluation, not to mention destructive tests. However, it is important to acknowledge that no broad generalizations can be derived solely from this single study with a limited sample size. Looking ahead, it remains reasonable to establish a distinct unified system for assessing old wood, particularly in cases where the condition of specimens significantly differs from those examined in this study, rendering the existing standard for new wood less applicable. In this regard, the author of this study believes that the Italian UNI 11119 standard provides the most suitable foundation for visually assessing old wood. This is for several reasons:

1) Out of the three standards considered, UNI 11119 stood out as the one with the least number of parameters to evaluate. This streamlined approach allowed for quicker assessment compared to the other standards.

2) This standard enables the evaluation of test specimens from three faces or less, if stated in the report. Additionally it does not necessitate visibility of transversal faces. As elements within a structure are frequently not accessible from all sides, this standard is the most practical for in-situ assessment.

3) By employing the minimal number of parameters, this standard focuses solely on factors that have the most significant impact. It omits measurements of deformations that, as demonstrated in this study, have no decisive influence on class determination or correlation with actual strength. In contrast to the INSTA 142 and UNI 11035 standards, which involve time-consuming measurements of

various distortions, this standard prioritizes practicality by disregarding non-essential criteria.

The author of the paper has proposed several improvements to address the shortcomings of the UNI 11119 standard to make visual evaluation more precise and user-friendly in the future. The suggested propositions are as follows:

1) Addition of exclusions

   Keep all the parameters reflected in UNI 11119 but add the possibility of excluding specimens according to different types of knot locations and fiber deformations. In the example of this work, the weakest specimen was the one with curly grain, the presence of which was not explicitly limited in the standard. In the future, it would be advisable to immediately exclude test specimens with such fiber deformations.

2) Convertment of results

   Instead of presenting allowable stresses as a result of categorization, in order to create more unified system, the standard should provide the strength classes stated in EN 338.

3) Addition of strength classes

   In order to improve the accuracy of the visual assessment process, it is essential to add more classification categories according to EN 338, enabling elements to be placed in a wider variety of strength classes. This approach would help prevent both over- and underestimation of element strength.

4) Specification of limitations

   Following the previous step, it is recommended to reduce the allowed values and narrow the range in order to minimize the variability among specimens assigned to the same class.

5) Graphic content

   In order for the descriptions of various defects to be unambiguous, it is necessary to add visual material in the form of photos and figures to the standard. This also has the potential to help speed up the grading process.

SUMMARY

Timber, a widely used renewable construction material, offers not only a ''sense of warmth'' and excellent workability but also possesses a multitude of other valuable properties. Apart from these mentioned qualities, wood exhibits a high strength to weight ratio, resistance to corrosion, and requires minimal energy for processing compared to competing construction materials. [35] Despite the growing popularity of wood and wood-based products in the construction industry, there has been insufficient focus on assessing the condition, preservation, and potential reuse of existing timber. While we have numerous standards for evaluating the quality of freshly sawn timber, there is currently no standardized system for assessing the strength properties of aged timber. Destructive testing provides a straightforward means to determine wood characteristics, but if the aim is to preserve and reuse the material, alternative approaches must be explored. Acoustic, radiological, and visual assessment methods offer potential solutions, with this research primarily focusing on the latter.

The objective of this Master's thesis was twofold: firstly, to examine the strength and stiffness properties of aged structural timber, and secondly, to establish a correlation between visual assessment and the actual properties of old wood. The aim was to identify the most accurate method for conducting visual grading that best aligns with the true conditions of the wood. Additionally, the bending behavior of each test specimen from four different faces was analyzed to, for example, determine if it was possible to visually assess which side of the element would take on the greatest tensile force. To achieve these goals, a combination of destructive and non-destructive tests was conducted on 15 spruce (*Picea abies*) test specimens 120 years of age.

The initial step included documenting the test specimens' data, such as length and cross-sectional measurements. Furthermore, photographs were taken from each face to provide visual record. Subsequently, a visual assessment was conducted using three standards: the Nordic NS-INSTA 142:2009 intended for visual grading of new wood, and the two Italian standards, UNI 11119 and UNI 11035, specifically designed for assessing the strength parameters of in-situ timber, with the former focusing on historical wood. After the visual evaluation, non-destructive bending tests were performed using a 4-point setup. The specimens were loaded from all four sides up to 40% of their expected maximum load capacity. Lastly, destructive bending tests were conducted based on the data gathered from the non-destructive tests. The specimens were loaded while their weakest face being on tension side, as determined by their static modulus of elasticity, until destruction. Through this process, the strength and stiffness properties of the test specimens were determined and compared to the results of the visual assessment.

The average bending strength of the sample, including values of the two specimens visually graded further unusable, was 44 N/mm^2. Excluding this data, the average bending strength increased to 50 N/mm^2. All of the beams given a grade through visual assessment, exceeded the thresholds for the C24 strength class, with 46,2% even surpassing the C50 class indicators. The static modulus of elasticity of the square test pieces varied between 0-10,6% depending on the face, with an average result of 5,3%. This implies that the slight advantage gained by placing the strongest side of the specimen in the tensile zone is relatively insignificant. Furthermore, upon comparing the static modulus of elasticity with the results obtained through visual inspection, no correlations could be established.

Contrary to previous research conclusions, the visual assessment results yielded unexpected outcomes. Previous studies suggested that using visual evaluation standards designed for new wood results in a high rejection rate for old wood, making it an impractical approach. However, the Nordic standard for new wood exhibited the lowest error percentage, underestimating the strength of the elements by an average of 47,6%. In contrast, the UNI 11035 and UNI 11119 standards had higher error percentages, underestimating the strength by 49,6% and 53,6%, respectively. It is also worth mentioning that none of the visual assessments overestimated the strength. When considering the most crucial defects, the findings of this study are consistent with the existing literature. Specifically, singular knots were identified as the determining factor in approximately 86,7% of cases when categorizing the specimens.

The study successfully fulfilled its purpose by demonstrating that both the standards for evaluating old and new wood yield unreliable results, on the example of current research, by underestimating the actual values. A significant drawback of these standards is their limitation in visually sorting timber beyond the C30 class (NS-INSTA 142) and up to the C24 class according to Italian standards. While this prevents structurally hazardous situations, it results in constant overdimensioning of elements, leading to economic repercussions and increased wood consumption, which hampers environmental sustainability. While this thesis shows promising findings for the reuse of old timber and extending its lifespan, drawing firm conclusions based on a small sample size would be premature. More research is needed to validate these results and assess the reliability of visual evaluation as the sole tool. For now, including additional evaluation methodologies is recommended to ensure more reliable conclusions. Furthermore, investigating the impact of different types of knots, wood fiber defects, and the position of wood pith within the cross-section on element characteristics is important for a better comprehensive understanding of the subject matter.

KOKKUVÕTE

Puit on üks enamlevinud taastuvatest ehitusmaterjalidest, mis omab lisaks ''soojustunde'' tekitamisele ja heale töödeldavusele arvukalt teisi väärt omadusi. Lisaks eelmainitule on puidul ka hea suhe omakaalu ja kandevõime vahel, korrosioonikindlus, ning võrreldes ehitusmaastikul konkureerivate materjalidega, on puidu töötlemine ka väikese energiakuluga. [35] Hoolimata viimase aja puidu ja puidupõhiste toodete konstruktsioonides kasutamise populaarsuse tõusust, ei ole küllaldaselt tähelepanu pööratud juba olemasoleva puidu olukorra hindamisele, säilitamisele ning ringkasutuspotentsiaalile. Meil on arvukalt standardeid hindamaks värske saepuidu kvaliteeti, kuid puudub ühtne süsteem olemasoleva vana puidu tugevusomaduste hindamiseks. Kõige lihtsam viis puidu karakteristikuid määrata on sooritada purustavad katsed, kuid kui eesmärgiks on materjali säilitamine ja taaskasutamine, tuleb leida teine lähenemine. Selleks on erinevaid võimalusi nagu näiteks akustilised, radioloogilised ning visuaalse hindamise meetodid. Antud magistritöö keskendub eelkõige eelmainitutest viimasele.

Käesoleva töö eesmärgiks oli uurida vana konstruktsioonipuidu tugevus- ja jäikusomadusi ning leida seejärel seos visuaalse hindamise ja vana puidu tegelike omaduste vahel. Sooviti leida parim viis visuaalse hindamise teostamiseks, mis annaks kõige lähedasemad tulemused reaalsele olukorrale. Lisaks sellele oli oma osa ka iga katsekeha neljast küljest painutamisel, et analüüsida, kas visuaalselt on võimalik hinnata näiteks seda, milline elemendi külg neljast võtaks vastu enim tõmbejõudu. Selleks teostati nii purustavad kui ka mittepurustavad katsed viieteistkümnele 120 aasta vanusele kuusepuidust (*Picea abies*) katsekehale.

Esmalt dokumenteeriti katsekehade andmed pikkuse ja ristlõikemõõtude näol ning igast katsekehast tehti neljast küljest fotod. Seejärel teostati visuaalne hindamine Põhjamaade NS-INSTA 142:2009 ning kahe Itaalia standardi UNI 11119 JA UNI 11035 baasil. Eelmainitutest esimene on mõeldud visuaalsel vaatlusel uue puidu tugevuse hindamiseks ning kaks järgmist on loodud vana, juba konstruktsioonis eksisteeriva puidu tugevusparameetrite hindamiseks. Järgmisena teostati 4-punkti mittepurustavad paindekatsed, millega koormati katsekehasid neljast küljest paindele 40% eeldatavast maksimaalsest koormusest. Katseprotsessist viimasena sooritati mittepurustava paindekatse andmete alusel purustavad paindekatsed, purustades proovikeha elastsusmooduli põhjal kõige nõrgemast küljest.

Purustavate katsete tulemusel saadud väärtused olid üllatavad. Kogu valimi keskmiseks paindetugevuseks saadi 44 N/mm^2, mille hulka on arvestatud ka kaks visuaalse hindamise protsessis kasutuskõlbmatuks hinnatud puidu katseandmed. Ilma nende tulemust arvestamata oli valimi keskmine paindetugevus 50 N/mm^2, kuid kõik visuaalsel vaatlusel taaskasutuskõlblikeks puitelementideks kategoriseeritud talad ületasid C24 tugevusklassi kuuluvuse piiri ning 46,2% suisa C50 klassi näitajad. Ruudukujuliste katsekehade elastsusmoodul kõikus olenevalt katsetamise küljest vahemikus 0-10,6%, keskmise tulemusega 5,3%. Seega on tugevaima külje tõmbetsooni paigutamisel võit marginaalne, seda enam, et võrreldes staatilisi elastsusmooduleid visuaalse vaatluse teel saadud tulemustega, ei leitud seoseid.

Visuaalsel teel saadud tulemused olid ootamatud. Analüüsides kirjandust järeldati, et kasutades uue puidu visuaalseks hindamiseks mõeldud standardeid, on vana puidu puhul elementide tagasilükkamise protsent liiga suur ning ettevõtmine ei tasu end ära. Antud magistritöö raames katsetatud puiduga aga olid tulemused vastupidised. Nimelt saavutas kõige väiksema veaprotsendi võrreldes reaalsete tulemustega just uue puidu hindamiseks loodud Põhjamaade standard, alahinnates elementide tugevust keskmiselt 47,6%. Teisele kohale jäi vanale puidule mõeldud, põhjalikumaid kriteeriume rakendav UNI 11035 ning kõige suurema veaprotsendiga oli veidi üldisem ajaloolisele puidule mõeldud UNI 11119 standard. Eelmainitud standardite visuaalsel teel saavutatud tulemused alahindasid reaalset tugevust vastavalt 49,6% ja 53,6%. Ükski visuaalsel teel saadud tulemus ei ülehinnanud reaalset tugevust. Analoogselt varasemate uuringutega, said ka antud töös katsekehade kategooria määramisel otsustavaks defektiks koguni 86,7% juhtudest üksikud oksakohad.

Magistritöö põhjal võib öelda, et see täitis oma eesmärgi kinnitades, et nii vana kui uue puidu hindamiseks mõeldud standardid annavad ebausaldusväärseid tulemusi ning antud töö näitel alahindavad reaalseid väärtuseid. Eelmainitud standardite suurim puudus hetkel seisneb selles, et need ei võimalda puitu visuaalsel teel sorteerida kõrgemale kui C30 klass (NS-INSTA 142) ning kuni C24 Itaalia standardite põhjal. See väldib küll konstruktiivselt ohtliku olukorra tekkimist, kuid pidev elementide üledimensioneerimine põhjustab majanduslikku kahju. Lisaks majanduslikule poolele omab see negatiivset mõju ka keskkonnasäästlikkuse vaatepunktist, suurendades vajamineva puidu kogust. Kuigi antud töös saadud tulemused on väga positiivsed puidu ringkasutamise ning pikema eluea võimaldamise seisukohast, on nii väikese valimi põhjal ennatlik põhjapanevaid järeldusi teha ning kindlasti oleks vaja sooritada rohkem katseid tulemuste kinnitamiseks. Visuaalne hindamine ainukese vahendina on võrdlemisi ebatäpne ning kindlamate järelduste tegemiseks oleks tarvilik lisaks kasutusele võtta mõni teine hindamise metoodika. Lisaks on oluline uurida veel erinevat tüüpi oksakohtade ja puidu kiu defektide ning puidu säsi positsiooni mõju ristlõikes elemendi karakteristikutele.

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APPENDIX 1 Preliminary data of each specimen

Specimen	Faces	CS measurements [cm]	Length [m]
1	A - C	9,7	3,1
	B - D	9,1	
4	A - C	9,7	3,0
	B - D	9,9	
5	A - C	9,5	3,8
	B - D	9,7	
6	A - C	9,7	3,7
	B - D	9,7	
7	A - C	9,7	3,0
	B - D	9,6	
8	A - C	9,7	3,7
	B - D	8,7	
9	A - C	7,1	4,3
	B - D	9,2	
10	A - C	9,8	2,9
	B - D	9,6	
11	A - C	10,0	2,8
	B - D	9,8	
14	A - C	9,5	3,5
	B - D	9,7	
15	A - C	9,7	3,7
	B - D	9,8	
16	A - C	9,6	2,1
	B - D	9,6	
17	A - C	9,5	2,9
	B - D	9,6	
19	A - C	13,4	2,8
	B - D	17,3	
20	A - C	9,7	3,1
	B - D	9,9	
21	A - C	9,6	2,2
	B - D	9,5	
22	A - C	14,2	2,8
	B - D	17,6	
23	A - C	13,4	2,8
	B - D	18,0	
24	A - C	13,9	2,8
	B - D	17,6	

APPENDIX 2 Grading of specimens according to INSTA 142

Specimen	Face of compression	Knots	Group of knots	Defor-mations	Slope of grain F	Ring width	Final category INSTA142
1	Not graded						
4	A	T3	T3	T3	T3	T3	T3
	B	T3	T3		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
5	A	T3	T3	T3	T3	T3	T3
	B	T3	T3		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
6	A	T2	T2	T2	T3	T2	T1
	B	T1	T1		T3		
	C	T2	T2		T3		
	D	T2	T2		T3		
7	A	T2	T2	T3	T3	T3	T2
	B	T2	T2		T3		
	C	T2	T2		T3		
	D	T3	T3		T3		
8	A	T2	T2	T2	T3	T2	T2
	B	T3	T3		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
10	A	T3	T3	T3	T3	T3	T3
	B	T3	T3		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
11	A	T3	T3	T3	T3	T3	T2
	B	T2	T2		T3		
	C	T2	T2		T3		
	D	T2	T2		T3		
14	A	T3	T3	T3	T3	T3	T2
	B	T3	T3		T3		
	C	T2	T2		T3		
	D	T2	T2		T3		
15	A	T3	T3	T3	T3	T3	T2
	B	T2	T2		T3		
	C	T2	T2		T3		
	D	T2	T2		T3		
16	A	T3	T3	T3	T3	T3	T3
	B	T2	T2		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
17	A	T3	T3	T3	T3	T3	T3
	B	T3	T3		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
21	Not graded						

Specimen	Face of compression	Knots	Group of knots	Defor-mations	Slope of grain F	Ring width	Final category INSTA142
22	A	T3	T3	T3	T3	**T3**	**T3**
	B	T3	T3		T3		
	C	T3	T3		T3		
	D	T3	T3		T3		
23	A	T2	T2	T3	T3	**T3**	**T2**
	B	T3	T3		T3		
	C	T2	T2		T2		
	D	T2	T2		T3		

APPENDIX 3 Grading of specimens according to UNI 11119

Specimen	Face of compression	Knots	Slope of grain F	Final category UNI11119
1	Not graded			
4	A	I	I	I
	B	I	I	
	C	I	I	
	D	I	I	
5	A	I	I	I
	B	I	I	
	C	I	I	
	D	I	I	
6	A	II	I	III
	B	III	I	
	C	II	I	
	D	III	I	
7	A	II	I	II
	B	II	I	
	C	II	I	
	D	II	I	
8	A	II	I	II
	B	I	I	
	C	I	I	
	D	I	I	
10	A	I	I	I
	B	I	I	
	C	I	I	
	D	I	I	
11	A	I	I	II
	B	II	I	
	C	II	I	
	D	II	I	
14	A	I	I	II
	B	I	I	
	C	II	I	
	D	II	I	
15	A	I	I	II
	B	II	I	
	C	II	I	
	D	II	I	
16	A	I	I	II
	B	II	I	
	C	I	I	
	D	I	I	
17	A	I	I	I
	B	I	I	
	C	I	I	
	D	I	I	
21	Not graded			

Specimen	Face of compression	Knots	Group of knots	Slope of grain F	Final category UNI11119
22	A	I	S1	I	I
	B	I	S1	I	
	C	I	S1	I	
	D	I	S1	I	
23	A	II	S1	I	II
	B	I	S1	I	
	C	II	S1	II	
	D	II	S1	I	

APPENDIX 4 Grading of specimens according to UNI 11035

<table>
<tr><th>Specimen</th><th>Face of compression</th><th>Knots</th><th>Group of knots</th><th>Deformations</th><th>Slope of grain F</th><th>Ring width</th><th>Final category UNI11035</th></tr>
<tr><td>1</td><td colspan="7">Not graded</td></tr>
<tr><td rowspan="4">4</td><td>A</td><td>S1</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S1</td></tr>
<tr><td>B</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">5</td><td>A</td><td>S1</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S1</td></tr>
<tr><td>B</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">6</td><td>A</td><td>S2</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S3</td></tr>
<tr><td>B</td><td>S3</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">7</td><td>A</td><td>S2</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S2</td></tr>
<tr><td>B</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S2</td><td>S2</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">8</td><td>A</td><td>S1</td><td>S2</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S2</td></tr>
<tr><td>B</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">10</td><td>A</td><td>S1</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S1</td></tr>
<tr><td>B</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">11</td><td>A</td><td>S1</td><td>S2</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S2</td></tr>
<tr><td>B</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S2</td><td>S2</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S2</td><td>S2</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">14</td><td>A</td><td>S1</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S2</td></tr>
<tr><td>B</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
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<tr><td>B</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">16</td><td>A</td><td>S1</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S2</td></tr>
<tr><td>B</td><td>S2</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td rowspan="4">17</td><td>A</td><td>S1</td><td>S1</td><td rowspan="4">S1</td><td>S1</td><td>S1</td><td rowspan="4">S1</td></tr>
<tr><td>B</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>C</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>D</td><td>S1</td><td>S1</td><td>S1</td><td>S1</td></tr>
<tr><td>21</td><td colspan="7">Not graded</td></tr>
</table>

Specimen	Face of compression	Knots	Group of knots	Deformations	Slope of grain F	Final category UNI11035
22	A	S1	S1	S1	S1	**S1**
	B	S1	S1		S1	
	C	S1	S1		S1	
	D	S1	S1		S1	
23	A	S2	S1	S1	S1	**S2**
	B	S1	S1		S1	
	C	S2	S1		S2	
	D	S2	S1		S1	

APPENDIX 5 Characteristic values according to strength classes from UNI 11035

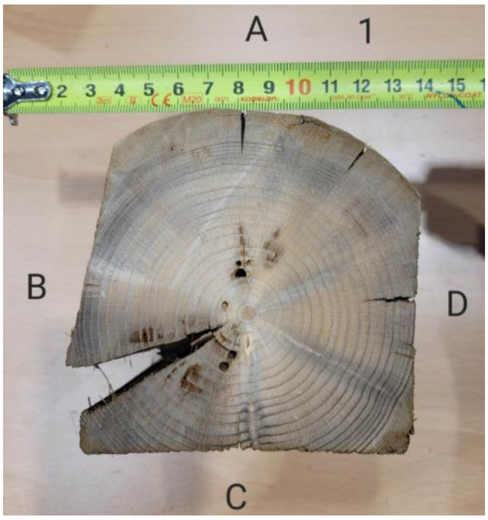
Properties		Spruce		
Characteristic values for the types of wood considered in standard EN 338		-	C24	C18
Resistant categories		S1	S2	S3
Deflection (5- percentile), N/mm^2	$f_{m,k}$		25	18
Traction parallel to grain (5- percentile), N/mm^2	$f_{t,0,k}$		15	11
Traction perpendicular to grain (5-percentile), N/mm^2	$f_{t,90,k}$		0,4	0,4
Compression parallel to the grain (5-percentile), N/mm	$f_{c,0,k}$		21	18
Compression perpendicular to grain (5-percentile), N/mm	$f_{c,90,k}$		2,6	2,6
Shear (5th percentile), N/mm^2	$f_{v,k}$		4,0	3,4
Modulus of elasticity parallel to grain (medium), kN/mm^2	$E_{0,mean}$		11,8	10,5
Modulus of elasticity parallel to grain (5-percentile), kN/mm^2	$E_{0,05}$		7,9	7,0
Perpendicular modulus of elasticity to grain (medium), kN/mm^2	$E_{90,mean}$		0,39	0,35
Shear modulus (average), kN/mm^2	G_{mean}		0,74	0,66
Density (5-percentile), kg/m^3	ρ_k		375	375
Density (average), kg/m^3	ρ_{mean}		450	450

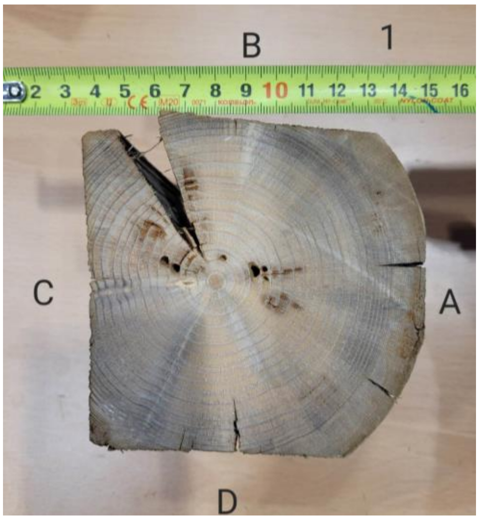
APPENDIX 6 Criteria of grading for Conifers 1 group from UNI 11035

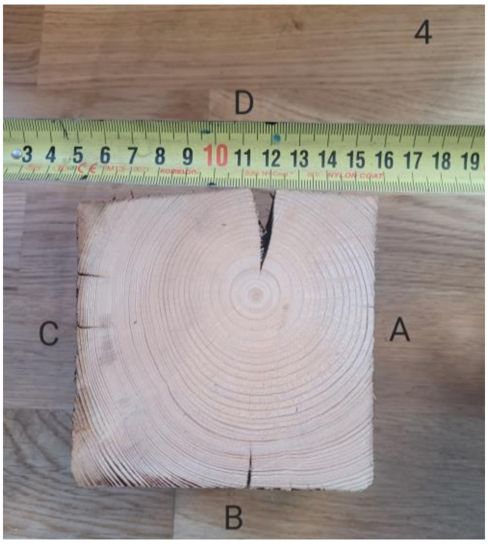
Criteria	Category		
	S1	S2	S3
Wanes[1]	s≤1/4	s≤1/3	s≤1/4
Single knots[2] Group of knots[3]	A≤1/5 (0,2) and in any case d <50 mm Ag≤2/5 (0,4)	A≤2/5 (0,4) and in any case d<70mm Ag≤2/3 (0,67)	A≤3/5 (0,6) Ag≤3/4 (0,75)
Ring width	≤6mm	≤15mm	
Slope of grain	≤1:14 (7,0%)	≤1:8 (12,5%)	≤1:6 (16,5%)
Cracks: - from withdrawal - ring shake - from lightning, frost, injuries	 Allowed, if not passing Not allowed Not allowed	 Allowed, with restrictions [6] Allowed with restrictions[4] Not allowed	
Fungal degradation: - Blue stains - brown and white caries	 Allowed Not allowed		
Compression wood	up to 1/5 of the perimeter on faces or section	up to 2/5 of the perimeter on faces or section	up to 3/5 of the perimeter on faces or section
Insect attacks	Not allowed	Allowed with restrictions[5]	
Parasitic plant	Not allowed		
Deformations: - bow - crook - twist - cup	 10mm for very 2m of length 8mm for every 2m of length 1mm for every 25mm of length no restrictions		 20mm for every 2m 12mm for every 2m 2mm for every 25mm no restrictions

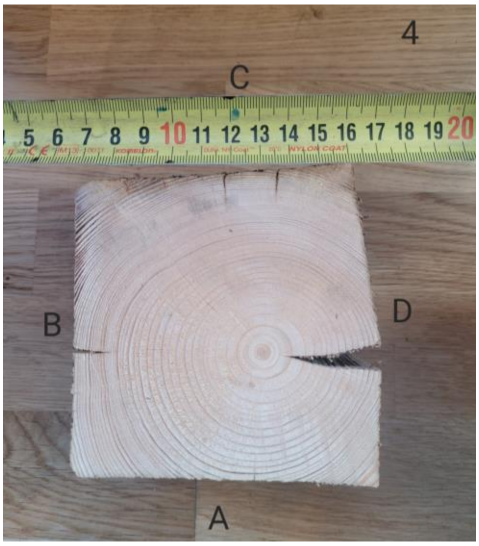
1. s is expressed as the ratio between the projection of the same wane on a surface and its total width on surface.
2. The largest knot of the sawn material is considered, and the ratio A between its minimum diameter d and the width of the face which this diameter is measured.
3. Do not consider this criterion for Fir and Larch/Northern Italy. For other species/origin combinations consider the Ag ratio between the sum of the minimum diameters of the nodes included in a 150 mm section and the width of the face on which they appear.
4. Generally not allowed; only for Larch/Northern Italy and Fir/Italy is the ring shake formation visible or probable admitted if rmax < b/3 and H < b/6,
   Where:
   a. r_{max} the maximum ring shake radius;
   b. b the longer side of the section;
5. ε the eccentricity, i.e. the maximum distance of the pith from the geometric center of the section. Only holes with a blackish halo are allowed, or round holes, without a blackish halo, with a diameter between 1.5 and 2.5 mm, as long as the attack is certainly stopped for a max. of 10 holes, evenly distributed, for meter of length (sum of all four faces).
6. Through cracks allowed only at the ends, for a length not greater than the width of the sawn timber.

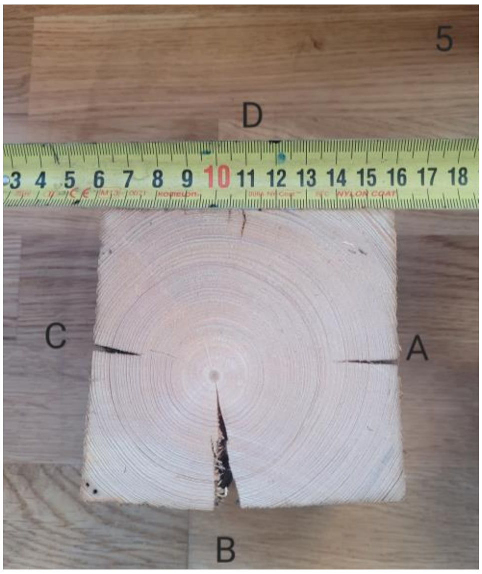
APPENDIX 7 Cross-section photos

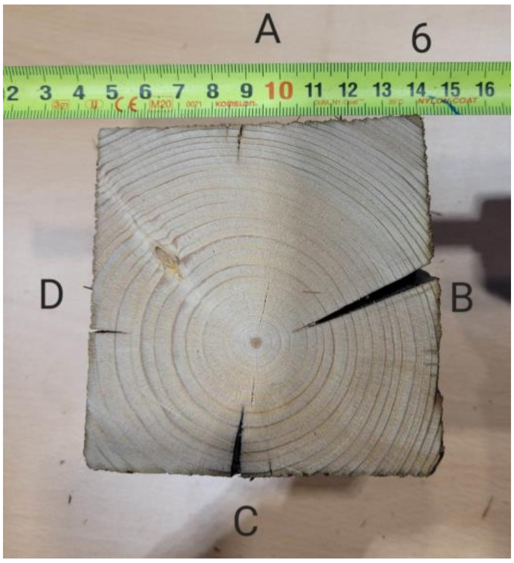











A
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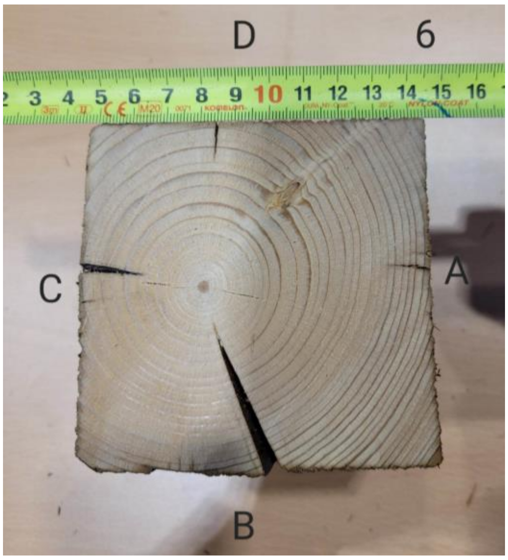
D
B
C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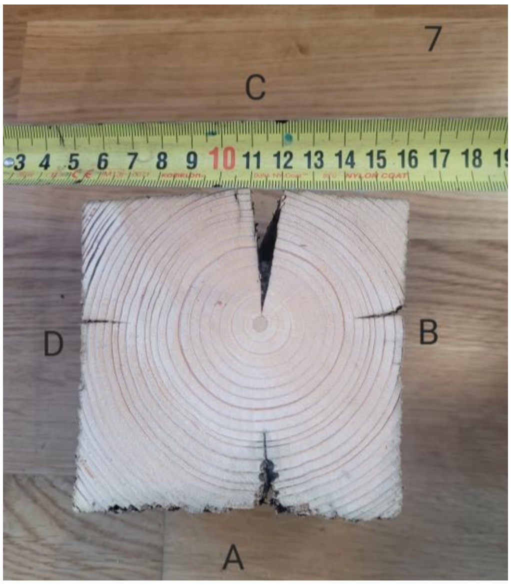
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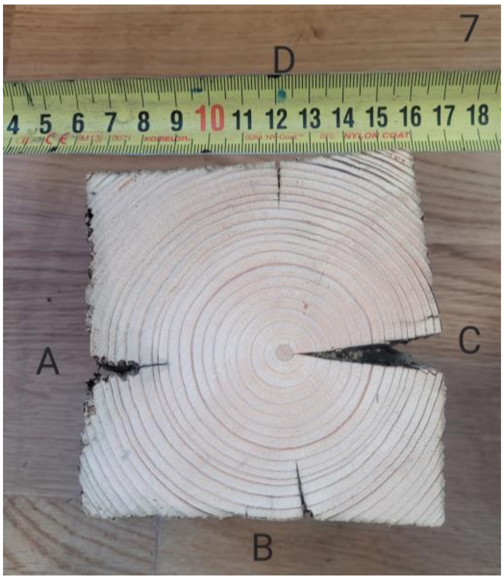
C
D
B
A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D
A
C
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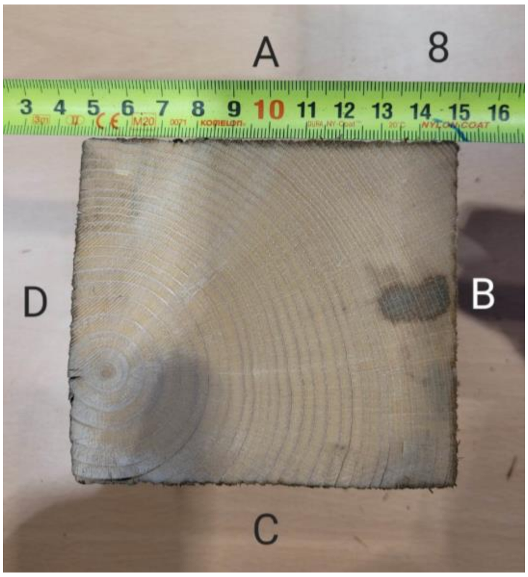
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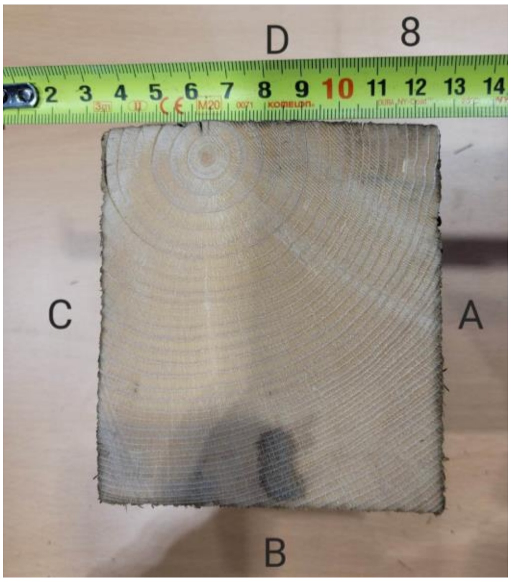
D
B
C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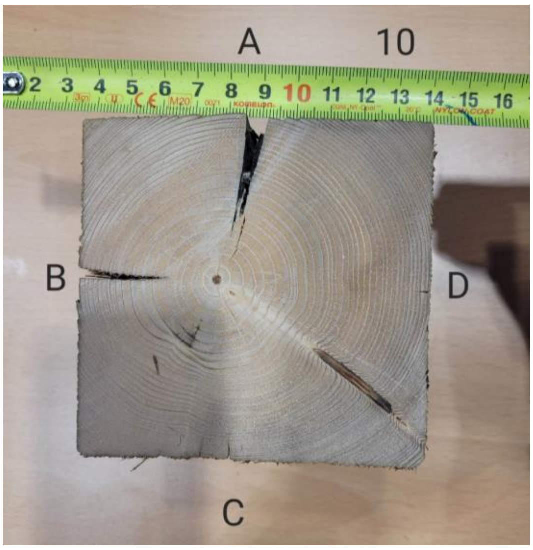
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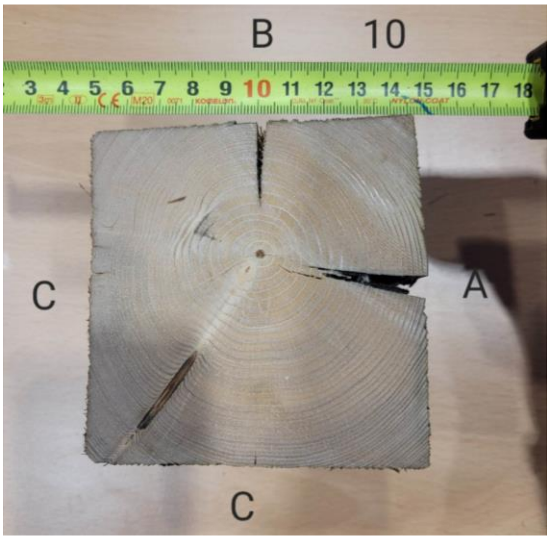
B
D
C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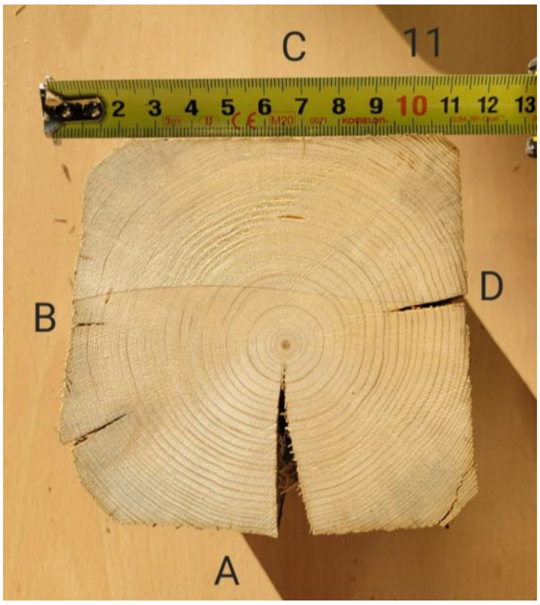
C
A
C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B
D
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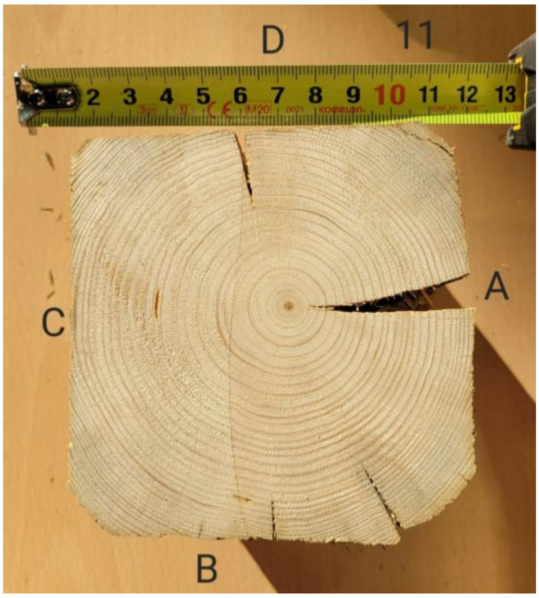
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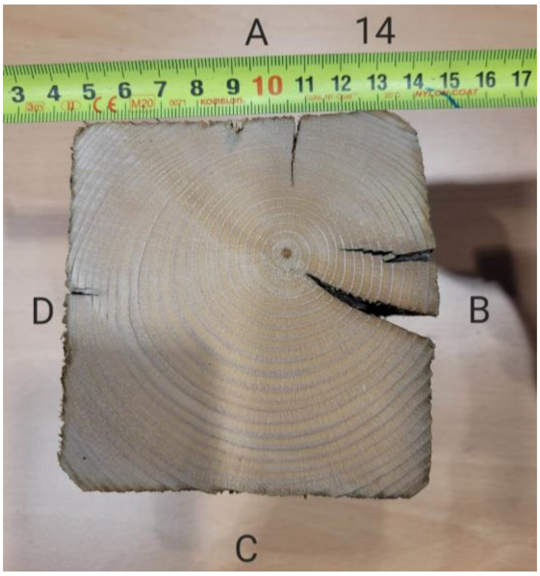
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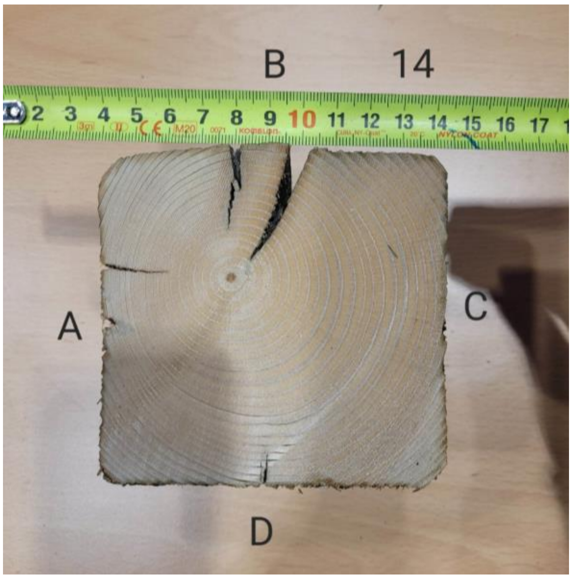
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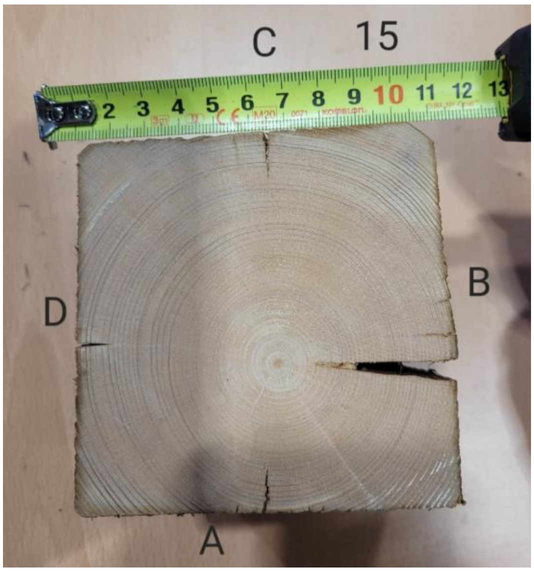
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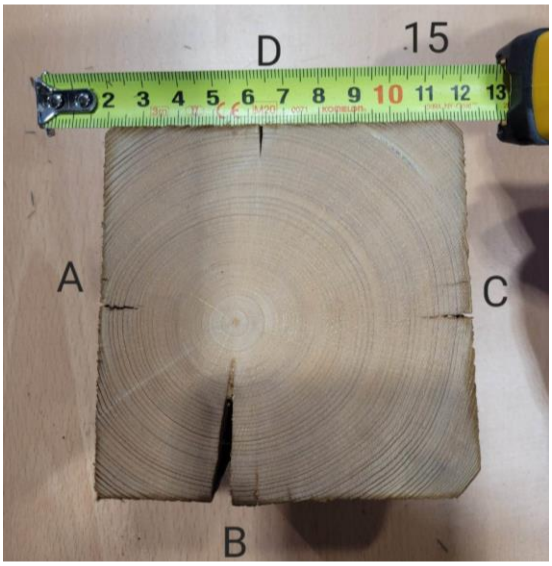
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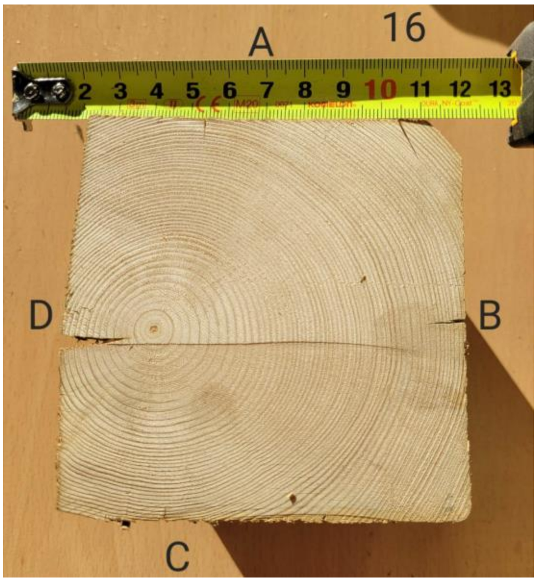
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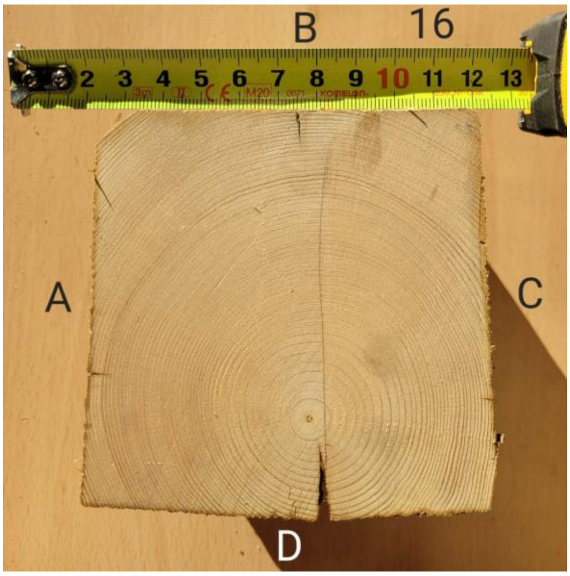
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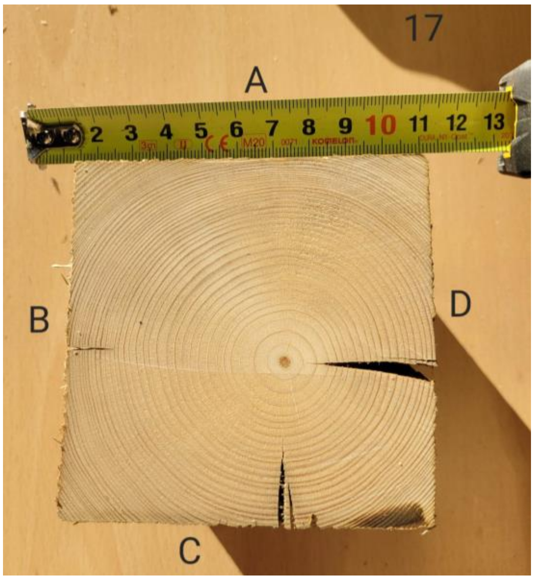
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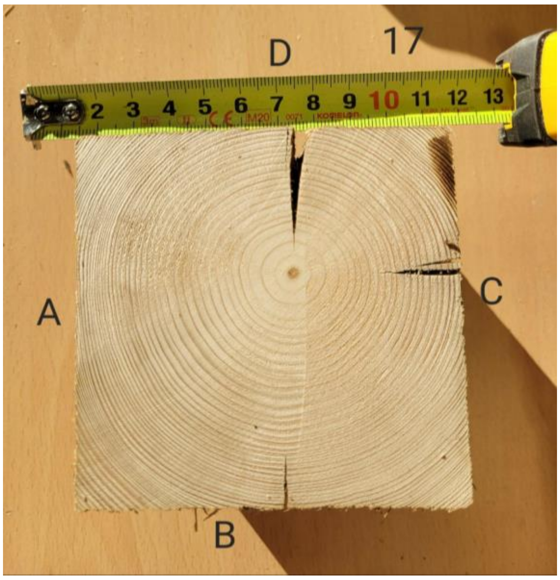
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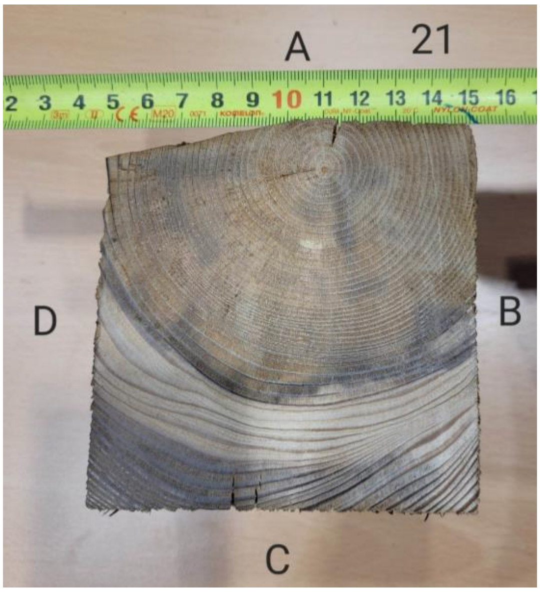
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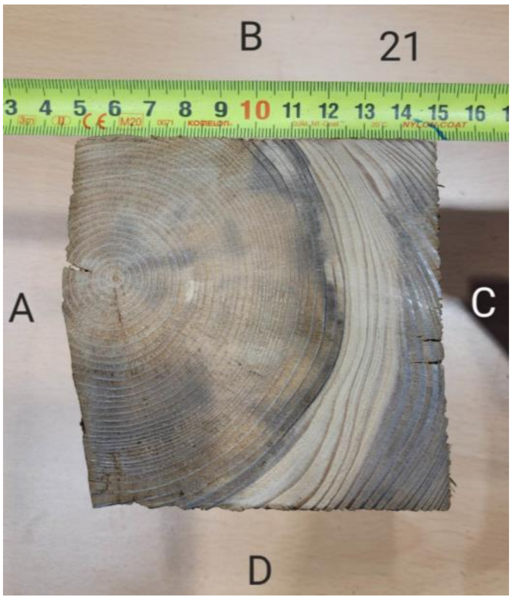
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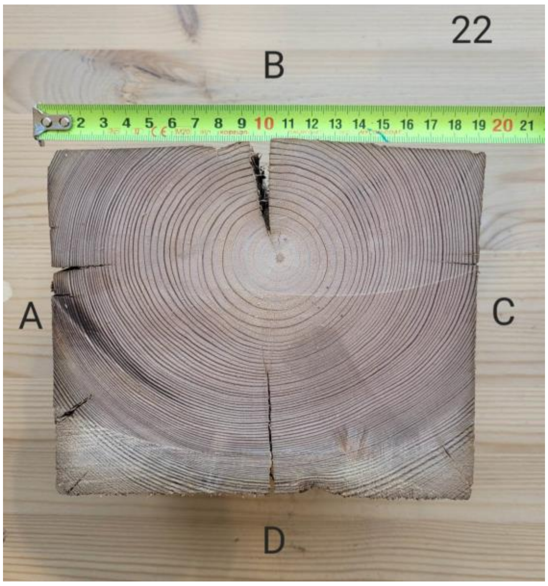
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A
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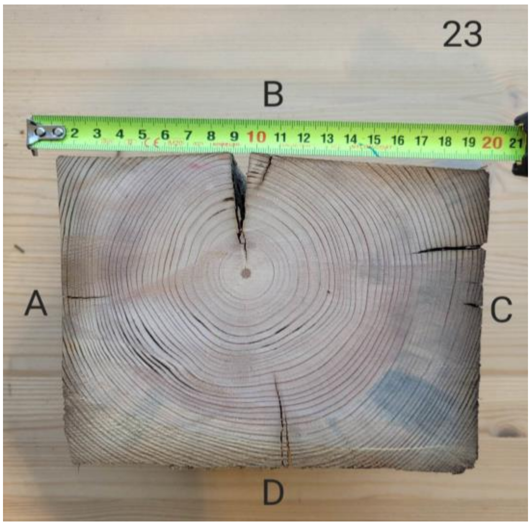
D


C
22
B
D
A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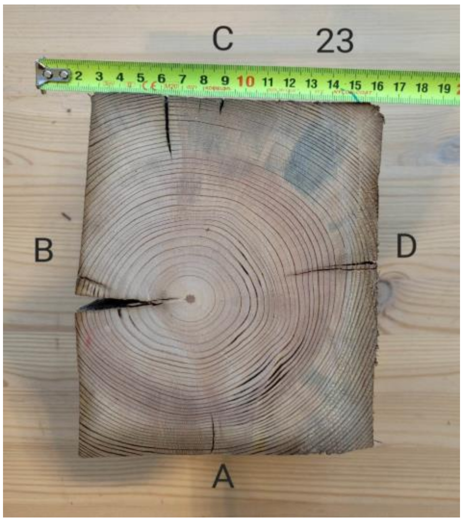
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