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ORIGINAL ARTICLE

Tensile strength prediction of Norway spruce boards processed from recovered wood: performance of visual and machine grading

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Abstract

Biotic and abiotic climate stressors jeopardize Norway spruce stands, necessitating the evaluation of alternative pathways for structural timber. One promising alternative is the utilization of recovered wood. Dimensional irregularities and design requirements often render reuse infeasible, underscoring the need for processing. Processing corrects dimensional discrepancies; however, prior grading becomes invalid due to cross-sectional changes. To date, there is no German standard for grading recovered wood. Due to additional features compared to new-sawn wood, the applicability of machine grading and the visual standard DIN 4074—1 requires an initial evaluation. This paper experimentally analyzes the general tensile strength of 146 boards (30×90 mm^2) processed from 22 salvaged rafters. The applicability of DIN 4074—1:2012 is evaluated by assessing visual features and correlating them with tensile properties. Machine grading is evaluated based on an automated scanning process. The findings highlight that visual and machine strength grading are both applicable to the processed recovered wood boards investigated. The graded boards exhibited tensile properties comparable to those of new-sawn wood. In the characterized extent, no impact from fastener holes was observed.

1 Introduction

Biobased resources for building construction are supported on both European (European Commission, 2025) and national (Bundesministerium für Bildung und Forschung & Bundesministerium für Ernährung und Landwirtschaft, 2020) levels. Their use conserves mineral resources by utilizing renewables, and biogenic carbon is stored throughout their lifespan. Germany is showing a positive trend in the use of biobased construction materials, with an increasing share of timber constructions in the residential buildings sector (Statistisches Bundesamt, 2025). However, Germany's longstanding tradition of using Norway spruce and fir as structural timber might face future supply limitations due to the declining health of spruce forests, caused by climate-related stressors such as storms and bark beetle infestations (Bundesministerium für Ernährung und Landwirtschaft, 2024). To anticipate potential resource shortages and supply conflicts, alternatives to new-sawn Norway spruce should be considered proactively. One such alternative is recovered wood, and several studies projected an increase in the future availability of recovered wood (Kalcher et al. 2017; Mahenthren et al. 2026; Szichta et al. 2022).

Research on the mechanical properties of recovered wood has primarily focused on two scales: small clear specimens and structural-size timber. Experimental tests on small clear specimens of spruce and fir revealed bending strength and stiffness comparable to new-sawn timber (Sonderegger et al. 2015). Specimens of Scots pine exhibited lower bending properties, with more brittle failures compared to new-sawn timber, and a positive correlation between mechanical properties and density (Moumakwa & Hughes 2025). Density correlations were even observed for larch recovered wood specimens (Xin et al. 2022). Tensile tests on specimens of the wood species Pinus indicated a reduction in tensile strength, but stiffness remained largely unaffected (Machado et al. 2019). These findings on small clear specimens offer insights into the potential effects of aging. However, predicting mechanical properties on the structural size level also requires the accurate consideration of natural features, as demonstrated by the grading method

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depending outcomes in Stapel and van de Kuilen (2013) and Stapel and van de Kuilen (2014a). Moreover, for recovered wood, additional criteria such as fastener holes (Fridley et al. 2001; Pasca et al. 2025; Scharpenack et al. 2026) need to be considered.

Conducting non-destructive bending tests on recovered structural size timber of Norway spruce (*Picea abies*), the study Branco et al. (2010) showed fulfillment with the bending stiffness requirement of C24, since all test specimens revealed a static stiffness value of at least 11.0 kN/mm^2. By means of destructive bending tests, rafters of the same wood species were investigated in the study Llana et al. (2023), and satisfied the requirements on all relevant grade-determining properties (GDP) for C24. The study Cavalli et al. (2016) reported, under both ungraded and graded conditions, high variability in the bending strength and stiffness of beams of both wood species, spruce and fir, often below the C24 threshold. Salzmann pine beams exhibited reduced properties relative to new-sawn timber (Arriaga et al. 2022). Aside from variations arising from natural features, a reduction in bending strength may also result from aging effects, as discussed for the small clear specimens, or from the presence of checks, as suggested by the findings in Lengyel and Saad (2025). Beyond strength-related considerations, practical challenges hinder direct reuse. Pronounced twist (Llana et al. 2023; Nasiri et al. 2025), and irregular cross-section dimensions (Arriaga et al. 2022; Böhm et al. 2025; Nocetti et al. 2021; Osuna-Sequera et al. 2020), complicate the integration of recovered wood into new assemblies. Frequent wane, as shown in Nasiri et al. (2025), may hinder flush contact with adjacent layers and may compromise load transfer or functionality (e.g., acoustics, fire safety). Consequently, dimensional and geometric imperfections can constrain the feasibility of reuse. While some case studies successfully integrated the irregular recovered wood dimensions into the design (Asa et al. 2024; Bergsagel and Heisel 2023), most scenarios require prior processing. Experimental approaches to equalize irregularities include manufacturing CLT (Dong et al. 2024; Llana et al. 2022; Rose et al. 2018; Uí Chúláin et al. 2023) and GLT (Privat 2019) from recovered wood, with generally promising but variable performance. Further studies focused on processed solid recovered wood (Böhm et al. 2025; Scharpenack et al. 2026). In the studies Böhm et al. (2025) and Irle et al. (2019), the manufacturing process and corresponding material losses at each step were outlined, concluding that processing recovered wood is feasible but labor-intensive and entails substantial material losses. For visually sorted boards and battens, suitability for structural application was investigated and, under certain conditions, proven in the studies Crews and MacKenzie (2009) and Scharpenack et al. (2026).

Besides the achieved mechanical property values, reliability in predicting those by grading is essential for structural applications. However, for now, the European standardization framework does not include provisions tailored to recovered wood, and existing standards are not generally suitable for the use on recovered wood. For new-sawn wood, EN 14081—1 (European committee for standardization 2019) provides the European regulatory framework for strength grading and, in particular, defines the requirements for national strength grading rules. For visual strength grading (VSG), DIN 4074—1 (Deutsches Institut für Normung 2012), the German VSG standard, is widely applied throughout Central Europe. However, DIN 4074—1 (Deutsches Institut für Normung 2012) was designed for natural features and lacks additional criteria for recovered wood, such as fastener holes, which may limit its applicability. However, in Scharpenack et al. (2026), the applicability of DIN 4074—1 to battens processed from Norway spruce rafters was demonstrated, even though adaptations depending on the fastener hole diameter were deemed necessary. In the Australian context, the study Crews and MacKenzie (2009) demonstrated the applicability of the national visual grading standard AS 2082 to defect-free boards processed from recovered wood. For unprocessed rafters, despite promising mechanical properties on a level of C24, the application of DIN 4074—1 was infeasible due to disproportionate rejections caused by pronounced twist and wane (Llana et al. 2023). To date, to the author's knowledge, the Norwegian standard NS 3691—3:2025 (Standard Norge 2025) is the only, by a standardization body published, visual grading standard for recovered wood, combining existing grading rules with additional sorting criteria, such as man-made defects. However, there are additional efforts across the globe to establish visual grading for recovered wood, such as the FWPA Standard G01 (Forest & Wood Products Australia Limited, 2025). These limitations underscore the need for VSG standards tailored to recovered wood and for research on processed material.

Manual VSG is a labor-intensive, slow process that, when added to the already demanding processing of recovered wood, makes the entire processing chain even more time-consuming. Machine strength grading (MSG), widely used for new-sawn timber, could accelerate the strength grading process. MSG primarily relies on the dynamic modulus of elasticity (Edyn), along with density and other parameters. As demonstrated by the previously discussed studies on mechanical testing of recovered wood, the modulus of elasticity can be a feasible predictor even for recovered wood. The study Nocetti et al. (2024) investigated the determination of Edyn for recovered wood based on MSG using both a time-of-flight and a natural frequency method. Nocetti et al. (2024) concluded that the natural frequency method

is better suited for predicting Edyn of recovered wood, as supported by validation by destructive testing. The investigations of Nocetti et al. (2024) align with those reported in Kovryga et al. (2020) for hardwoods, where natural frequency measurements achieved higher accuracy compared to ultrasound measurements.

Recovered wood is a promising alternative to new-sawn timber and can serve as a supplement to meet the increasing demand. However, notable research gaps regarding its strength behavior and prediction remain. Most studies have focused on unprocessed recovered wood, while little attention has been given to processed structural-size components. Furthermore, most studies have investigated bending properties, while tensile properties have remained widely uninvestigated. The present study contributes to addressing these research gaps by investigating the tensile properties of 146 boards processed from 22 salvaged Norway spruce rafters and evaluating the applicability of DIN 4074—1 and MSG. The present paper aims to answer the following research questions:

1. What are the characteristic tensile properties of Norway spruce boards processed from salvaged rafters?
2. Is DIN 4074—1:2012 and MSG applicable to these kinds of boards?
3. Can fastener holes be precisely detected using non-destructive methods of MSG?
4. Can a possible influence of the load history in bending be identified by differences in the mechanical properties of the material originating from the compression, neutral, or tension zone?

2 Materials and methods

2.1 General

The overall aim, conceptual framework, and methodologies of this study are illustrated in the flowchart presented in Fig. 1. To evaluate the mechanical properties of recovered wood boards, tensile testing was performed. Based on the obtained mechanical properties, the applicability of

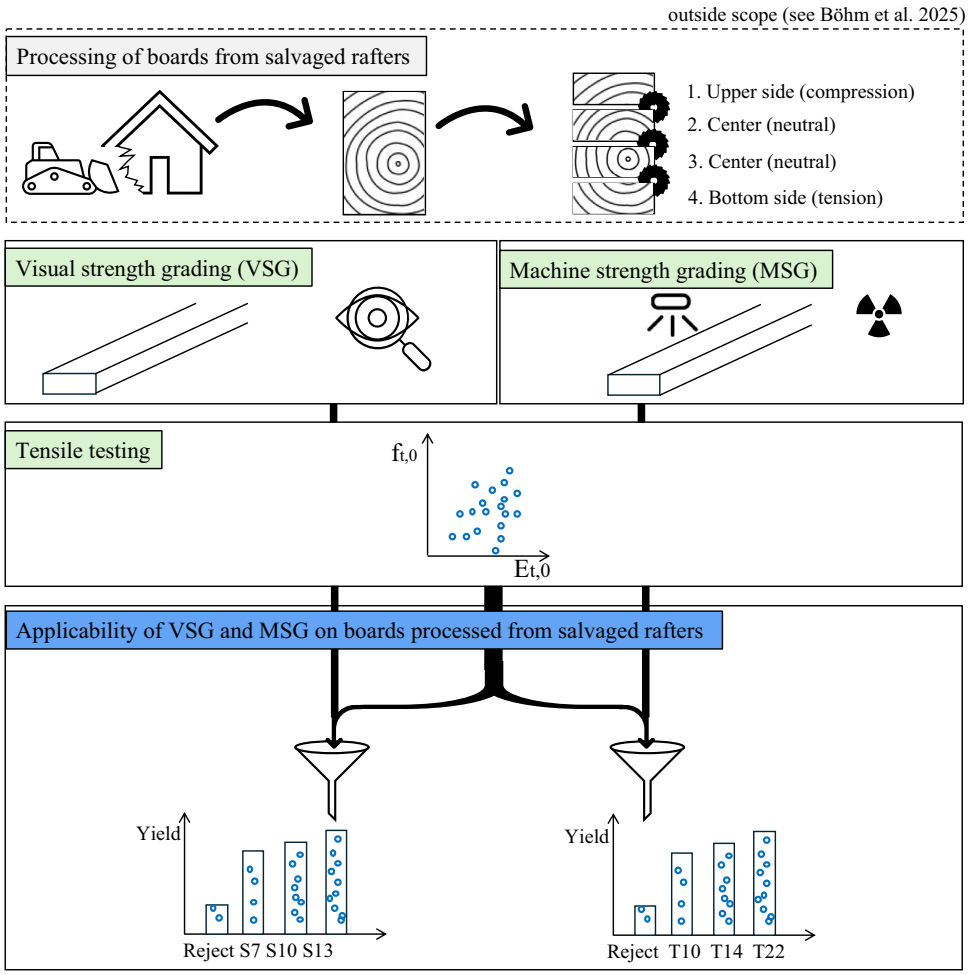


Fig. 1 Flowchart of the study illustrating the methodologies applied to evaluate boards processed from salvaged rafters for grade-determining properties (GDP), and to assess the applicability of visual (VSG) and machine (MSG) strength grading

Table 1 Overview of the number of salvaged rafters, including the corresponding roof structure erection year, and cross-section dimension as characterized in Böhm et al. (2025), as well as the number and cross-section dimensions of boards processed from these salvaged rafters

Site	Salvaged rafters			Processed boards	
	Year of erection	Cross-section	Number	Cross-section	Number
	[-]	[mm^2]	[-]	[mm^2]	[-]
1	1961	110 × 150	1	30 × 90	6
2	1992	115 × 155	5	30 × 90	40
3	1995	110 × 170	5	30 × 90	39
4	2000 (approx.)	110 × 170	6	30 × 90	46
5	2001	110 × 150	5	30 × 90	15
Total			22		146

standardized visual strength grading (VSG) and machine strength grading (MSG) was assessed.

2.2 Materials

A total of 146 unsorted boards with a cross-sectional dimension of 30 × 90 mm^2, processed from salvaged rafters, were investigated. Details on the board manufacturing process, processing yields, and rafter characterization are provided in Böhm et al. (2025). The key information concerning the material of the current study can be summarized as follows. For transportation, the original (full-length) rafters were cut into rafter sections of about 4 m in length. All subsequent processing steps were carried out on these rafter sections. Each rafter section was longitudinally sawn into board "slices", with cuts made parallel to the smaller face (width). Each board was labeled using a specific code. The in-process coding differentiated between boards cut from the in-situ rafter upper side, which were predominantly loaded in compression, the central neutral zone, with minimal stress, and the bottom side, predominantly loaded in tension. From each rafter section, mainly three to four 30 × 90 mm^2 boards were generated. Oddments with heights of less than 30 mm were discarded. Boards obtained from the upper and lower zones were categorized as from the compression and tension zones, respectively; boards obtained from the center were categorized as from the neutral zone. The salvaged rafters originated from the roof structures of five buildings in southern Germany, erected between 1961 and 2001. Of the 22 rafters investigated, 21 were Norway spruce (*Picea abies* (L.) Karst.), and one was fir (*Abies alba* Mill.). For simplicity, both species were treated as a mixed group in subsequent analyses, consistent with common trading practice. Due to the processing, the boards contained fastener holes, but no additional man-made cross-section reductions, such as those caused by carpentry joints or mechanical damage. Table 1 provides an overview of the key characteristics of the original rafters and the number of boards processed from each.

3 Methods

3.1 Specimen preparation

Specimen preparation followed the tensile testing requirements outlined in EN 408:2012 (European committee for standardization 2012). In the prior study of Böhm et al. (2025), the boards were manufactured to the maximum technical possible length. For the present study, the 30 × 90 mm^2 boards were further cut to the standardized specimen length. Each specimen consisted of a free testing length of 810 mm (nine times the board's height) with clamping areas at both ends (Fig. 2). The boards were cut to the specimen length so that the weakest point of the entire cross-section, mostly specific knot cluster configurations or fastener holes, was located at the center of the testing area.

3.2 Visual assessment

3.2.1 Visual grading according to DIN 4074—1:2012

Natural features were recorded and assessed according to the "grading rules for boards" in the German standard DIN 4074—1:2012 (Deutsches Institut für Normung 2012), focusing on the sorting criteria for knots (≥5 mm), presence of pith, and growth ring width. These natural features were recorded within the testing area shown in Fig. 2. The assessment of the sorting criterion global fiber deviation was omitted because the boards were sawn from the salvaged rafters in the axial direction, suggesting that the fiber deviation of the original rafters was likely transferred to the boards. Since the investigated rafters (1961—2001) originated from a period after DIN 4074—1 was introduced in 1939 (Deutsches Institut für Normung 2012), we assumed that their fiber deviation was within the required limits. Moreover, due to prior processing, sorting criteria wane, and warp were also omitted, as irregularities in the board's geometry, in general, were equalized during processing. Based on the applied sorting criteria, boards were assigned to one of the three visual grades (S13, S10, or S7) or categorized as rejects (R). Assignment to a grade was based

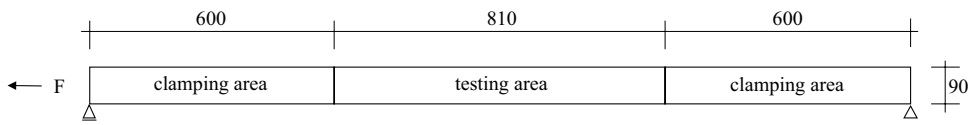


Fig. 2 Definition and dimensions of the clamping and testing area of the tensile specimen

Table 2 Overview of the thresholds for the applied sorting criteria for boards according to DIN 4074—1:2012 (Deutsches Institut für Normung 2012)

Sorting criterion	Visual grade		
	S7	S10	S13
Single knot knottiness (SK)	0.50	0.33	0.20
Knot cluster knottiness (KC)	0.67	0.50	0.33
Edge face knot (EFK)	-	0.67	0.33
Presence of pith	allowed	allowed	not allowed
Growth ring width	6 mm	6 mm	4 mm

Table 3 Characteristic values for the grade-determining properties (GDP) tensile strength parallel to the grain, ft,0,k (5th percentile), modulus of elasticity parallel to the grain, Et,0,mean (mean-value), and density ρk (5th percentile) according to EN 338:2016 (European committee for standardization, 2016b)

		T30	T22	T14	T10
ft,0,k	[N/mm^2]	30	22	14	10
ρk	[kg/m^3]	430	390	350	310
Et,0,mean	[kN/mm^2]	15.5	13.0	11.0	8.0
0.95*Et,0,mean	[kN/mm^2]	14.7	12.4	10.5	7.6

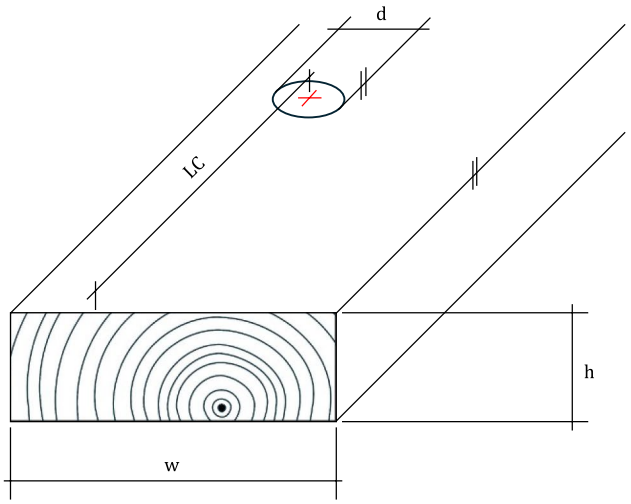


Fig. 3 Illustration of the methodology of the visual assessment of fastener holes, where w and h are the width and height of the board's cross-section, d is the perpendicular to the axial direction measured hole size, and LC is the axial position

on the criterion that resulted in the lowest grade or caused rejection. The sorting criteria were limited by the thresholds summarized in Table 2:

To validate the applicability of VSG and MSG, and to compare the results for boards of recovered wood to new-sawn wood, GDP values of T30, T22, T14, and T10 given in EN 338:2016 (European committee for standardization, 2016b) were referenced (Table 3). Based on EN 1912:2024 (European committee for standardization 2024), the strength classes were assigned to the corresponding visual grades as follows: S10 to T14, and S7 to T10. As shown for Central European spruce, S13 can be assigned to T22 (Kovryga and van de Kuilen 2018).

3.2.2 Visual assessment of fastener holes

Since this study focuses on boards processed from salvaged rafters, most man-made cross-section reductions have already been removed, and man-made defects were broken down to fastener holes. No insect infestation was found. Fastener holes were assessed in a manner analogous to natural features within the testing area, as shown in Fig. 2. As for the measurement of the knot size in DIN 4074—1:2012 (Deutsches Institut für Normung 2012), the diameter of each fastener hole was measured perpendicular to the axial direction on the face side. Fastener holes were categorized into two groups: G1 (2 mm≤d<5 mm) and G2 (d≥5 mm). G1 fastener holes were informally counted for characterization purposes, while for G2 holes, both the diameter (d) and the axial position were recorded (see Fig. 3). For holes appearing on both face sides, the larger diameter was considered.

3.3 Machine strength grading

All boards were machine graded at the facilities of *MiCROTEC* S.p.A. in Bressanone, Italy. A multi-sensor quality scanner (*Goldeneye*) performed X-ray scanning for the assessment of knottiness and laser-scattering measurements for the assessment of fiber angle. Using X-ray scanning, a density profile was generated for each board, with a scanning resolution of 2—4 mm along the length and 0.4—0.5 mm across the width of the boards. Furthermore, the dynamic MOE (Edyn) was measured using *ViSCAN*, which allows the natural frequency measurement with an optical laser interferometer. The dynamic MOE comprises natural frequency and density measurements.

For the machine grading, Edyn was selected as the indicating property (IP). The machine settings/grading thresholds were iteratively determined for grading to the set of preselected T-classes. To address the variety of structural applications and corresponding requirements, three target strength classes according to EN 338:2016 (European committee for standardization, 2016b) were considered for MSG: T30, T22, and T14. Further sub-classes included boards of strength class T10 and rejects, where rejects cannot be used structurally. In the combinations, changes in yield and grade-determining properties were examined. A detailed visual override according to Table 1 of EN 14081—1 (European committee for standardization 2019) was not carried out, as the requirements on warp and wane were expected to be met due to the prior processing. Moreover, insect infestation and biological degradation were generally not observed for the boards.

The grading machine settings were derived as follows. The dataset is first ranked in descending order based on the indicating property Edyn. For each IP value, the characteristic values of the GDPs (5th percentile of tensile strength (ft,0,k), mean tensile MOE (Et,0, mean), and 5th percentile of density (ρk)) for the specimens exceeding the boundary were calculated. The lowest IP value fulfilling all the requirements of the GDP was considered the grading threshold for the corresponding strength class. The procedure is applied recursively to the lower classes. Whereby the specimens not matching the requirements below the threshold of the higher class are taken to calculate the thresholds for the lower classes. The procedure for the settings derivation differs from that mentioned in EN 14081—2 (European committee for standardization 2022a). In particular, the verification procedure for the sub-sample was not considered due to the sample size, nor was the global cost matrix calculated. The k_s-factor according to EN 14358:2016 (European committee for standardization 2016a) was considered to make the calculation on the safe side.

3.4 Tensile testing

Tensile testing was performed in accordance with EN 408:2012 (European committee for standardization 2012). Figure 4 illustrates a labeled photograph of the tensile testing setup.

The grade-determining properties (GDP) were adjusted in accordance with EN 384:2022 (European committee for standardization 2022b) to a reference height of 150 mm in case of the tensile strength, and a reference moisture content of 12% for the density and tensile MOE. Density (ρ) was determined on a clear-wood and oven-dry (103 °C / 24 h) specimen taken near the failure point by relating its dry mass to its volume, measured by the buoyant method.

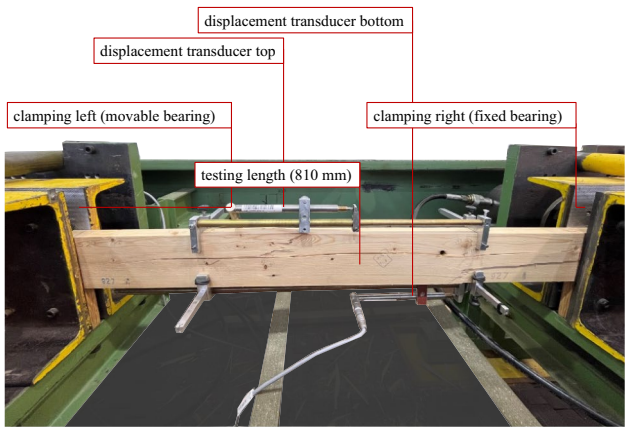


Fig. 4 Photograph of the tensile testing setup, with labels of the testing length, displacement transducers, and clamping arrangement

The moisture content at the time of testing was determined according to EN 13183—1:2002 (European committee for standardization 2002).

3.5 Statistical calculations

The characteristic values, as the 5th percentile for the tensile strength (ft,0,k) and density (ρk), were calculated parametrically as given in EN 14358:2016 (European committee for standardization 2016a). For ft,0,k, a lognormal distribution, and for ρk, a normal distribution served as the underlying distribution. The characteristic values of the static stiffness (Et,0,mean) and dynamic stiffness (Edyn) were calculated with confidence intervals (75%) in accordance with the standard. Basic statistics, besides the characteristic values, such as the mean, standard deviation (std), and coefficient of variation (COV), were calculated based on the corresponding functions in MATLAB R2024b (The MathWorks, Inc., 2024).

4 Results and discussion

4.1 Sample characterization

The characteristics of the ungraded material are summarized in Table 4 and include the grade-determining properties (ft,0,k, Et,0,k, ρk) obtained from the tension tests, dynamic stiffness (Edyn) obtained from MSG, as well as the knottiness obtained from VSG, along with their descriptive statistics. The characteristic tensile strength (ft,0,k) satisfies the threshold for T10, while the characteristic tensile stiffness (Et,0,k) and characteristic density (ρk) both meet the threshold for T14. As the weakest GDP determines classification, the unsorted batch corresponds to strength class T10. The results are consistent with values of new-sawn Norway spruce reported for Central Europe, such as those in the study Stapel and van de Kuilen (2014b), which determined characteristic values for unsorted new-sawn Norway spruce boards with a width of 126 mm to 150 mm: tensile strength of 12.3 N/mm^2, tensile stiffness of 11.2 kN/mm^2, and density of 363 kg/m^3.

Figure 5 illustrates the relationship between the modulus of elasticity, Et,0,12, and the tensile strength, ft,0,150. The coefficient of determination ($R^2 = 0.56$) indicates a good linear correlation between these properties.

Overall, the characterization reveals mechanical properties of the unsorted boards processed from salvaged rafters that are comparable to those of new-sawn spruce timber. Nevertheless, the substantial variability in the mechanical properties indicates that sorting would enhance reliability and enable higher-value utilization.

Table 4 Descriptive statistics of the to a height of 150 mm adjusted tensile strength parallel to the grain (ft,0,150), to a moisture content of 12% adjusted modulus of elasticity parallel to the grain (Et,0,12), and density (ρ12), as well as the dynamic modulus of elasticitiy (Edyn), and the visual knot criteria single knot knottiness (SK) and knot cluster knottiness (KC), where mean is the mean value, COV the coefficient of variation, and Q0.05, the 5th percentile

Site	N		ft,0,150	Et,0,12	Edyn	ρ12	SK	KC
			[N/mm^2]	[kN/mm^2]	[kN/mm^2]	[kg/m^3]	[-]	[-]
Total	146	mean	29.3	11.8	12.5	433	0.28	0.41
		COV	0.456	0.225	0.198	0.089	0.443	0.448
		Q0.05	12.6	-	-	366	-	-
1	6	mean	26.7	11.2	11.8	453	0.28	0.34
		COV	0.293	0.068	0.073	0.057	0.574	0.360
		Q0.05	12.7	-	-	392	-	-
2	40	mean	31.5	11.4	12.1	424	0.19	0.38
		COV	0.326	0.173	0.172	0.070	0.381	0.518
		Q0.05	17.0	-	-	370	-	-
3	39	mean	23.2	10.6	11.4	424	0.34	0.48
		COV	0.488	0.272	0.213	0.066	0.336	0.381
		Q0.05	9.1	-	-	372	-	-
4	46	mean	33.5	13.4	14.1	461	0.30	0.40
		COV	0.479	0.186	0.170	0.081	0.394	0.404
		Q0.05	14.5	-	-	393	-	-
5	15	mean	27.1	9.9	10.8	385	0.28	0.34
		COV	0.476	0.243	0.168	0.065	0.476	0.521
		Q0.05	9.4	-	-	335	-	-

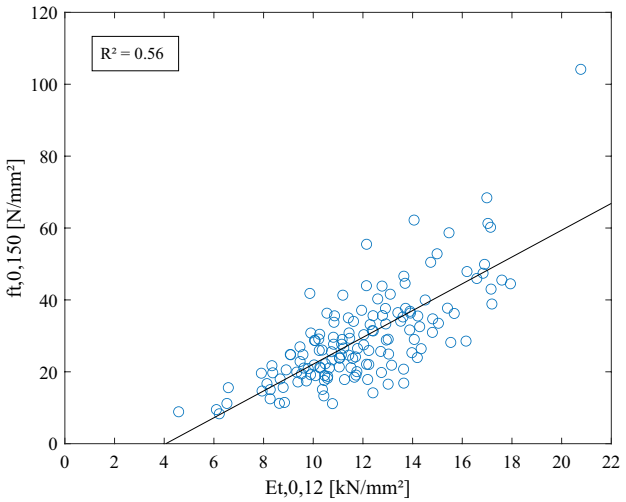


Fig. 5 Relationship between the modulus of elasticity (Et,0,12) measured for tensile testing parallel to the grain, adjusted to a moisture content of 12%, and the tensile strength (ft,0,150), in parallel to the grain, adjusted to a height of 150 mm, for the unsorted batch of spruce boards processed from salvaged rafters

4.2 Visual strength grading (VSG)

4.2.1 VSG yield

In total, 91% of the 146 boards (30 × 90 mm^2) were based on the "grading rules for boards" specified in DIN 4074—1:2012 (Deutsches Institut für Normung 2012) assigned to one of the visual grades S7 (38%), S10 (36%), or S13 (16%). 9% (13 boards) exceeded the threshold of 0.50 for the sorting criteria single knot knottiness (SK) or the threshold of 0.67 for the knot cluster knottiness (KC). The other sorting criteria investigated, edge face knot (EFK), presence of pith, and growth ring width, did not result in any rejections. The visual yield of 91% in this study demonstrates the efficient applicability of visual strength grading (VSG) according to DIN 4074—1:2012 (Deutsches Institut für Normung 2012) to processed recovered wood, whereas Llana et al. (2023) reported with a 5% yield for unprocessed recovered wood based on the same grading standard, the opposite. However, Llana et al. (2023) investigated a reuse scenario in which warp and wane primarily caused rejection. Since processing eliminates most difficulties associated with these criteria, processing recovered wood prior to visual grading is estimated as an essential step for an efficient visual grading process of recovered wood. Similar issues with these sorting criteria were reported in numerous other studies (e.g., Arriaga et al. 2022; Böhm et al. 2025; Nasiri et al. 2025).

Figure 6 shows the distribution of visual grades and rejection rates for each site. Variations in total yield per grade and site are evident, with maximum yields reaching 100% and minimum yields at 82%. No correlation was found between the year of initial roof structure erection and the yield.

The shown yields represent grading yields. For further economic assessments into the feasibility of recovered wood processing, a link to the total volumetric processing yield of recovered wood across the entire processing chain is needed. As shown in Böhm et al. (2025) a processing

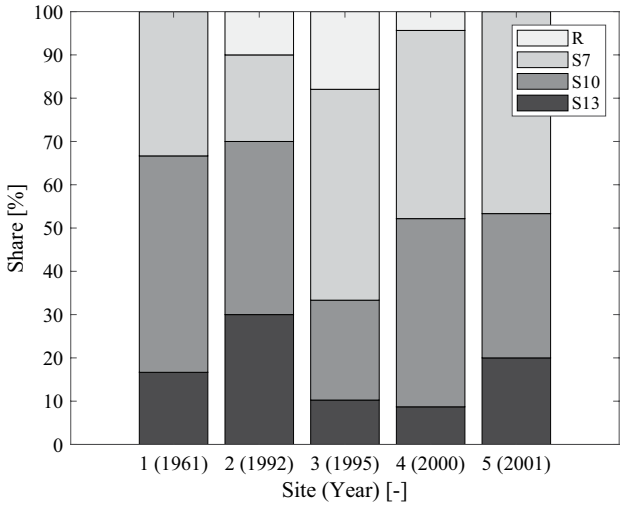


Fig. 6 Distribution of visual grades (S13, S10, S7) according to the assessment based on the "grading rules for boards" specified in DIN 4074—1:2012 (Deutsches Institut für Normung 2012) as well as rejects (R), categorized by site and sorted by year of initial roof structure erection

yield of about 42% can be achieved for manufacturing an ungraded batch of boards and battens of heterogeneous lengths from salvaged rafters. Based on the results of the present study, 91% of those ungraded boards with sufficient length can be used structurally as S7 or better. The complete economic feasibility assessments would, however, include the labor efforts for processing, which are outside the scope of this study.

The sorting criterion for growth ring width averaged 2.7 mm. Individual board values ranged from 1.0 mm to 5.7 mm, with site-specific means ranging from 2.1 mm to 3.4 mm. None of the boards exceeded the 6 mm threshold required for grades S7 and S10, but 15 boards exceeded the 4 mm threshold required for grade S13. In total, 34 boards showed pith, making them unassignable to grade S13.

4.2.2 Grade-determining properties (GDP) sorted by visual grade

The results for the grade-determining properties (GDP), sorted by visual grade, are summarized in Table 5.

Table 6 Ratios between values for grade-determining properties achieved by tensile testing and the corresponding requirements defined in EN 338 (ratio = tested value / standard requirements)

combination	Grade	ft,0,k	ρk	Et,0,mean
S13/S10/S7/R	S13	1.02	0.95	1.02
	S10	1.18	1.04	1.12
	S7	1.17	1.16	1.36
S10+/R	S10+	1.24	1.05	1.15

Comparing the experimentally tested GDPs to the requirements of the corresponding strength classes in EN 338:2016 (European committee for standardization, 2016b) shows, with one exception (ρk of S13), that the tested GDPs surpass the requirements (see Table 6).

Based on the results, it can be concluded that assigning the visual grades S10 and S7 to the tensile strength classes T14 and T10 can be effectively done for boards processed from salvaged rafters, as all grade-determining properties are met. However, an assignment of S13 to T22 is not possible, as the requirements are undershot for the GDP of the characteristic density. For this reason, the visual grade S10+, which is widely used in the trading practice, was additionally investigated. S10+ merges the visual grade S10 with all higher visual grades, as "S10 and better". Table 6 shows that in that case, the T14 thresholds are met.

4.2.3 Influence of initial strain zone

With a focus on the influence of previous load history, the tensile strength (ft,0,150) and tensile stiffness (Et,0,12) were grouped according to the rafter's strain zone from which the boards were cut. A differentiation was made between the compression zone (upper rafter side), the tension zone (bottom rafter side), and the neutral zone (center zone). As shown by the cumulative frequency distribution in Fig. 7, no differences between these zones are visible in the tensile stiffness or tensile strength for boards of grade S7. However, for boards of the visual grades S10 and S13, those cut from the rafter's tensile zone exhibit the highest tensile strength. Similar trends were found for the board's tensile stiffness in relation to the initial strain zone. Boards cut from the neutral or compression zones exhibit the lower properties.

Table 5 Grade-determining properties for the boards processed from salvaged rafters; with ft,0,150 is the tensile strength parallel to the grain, adjusted to a reference height of 150 mm, ρ12 is the density adjusted to a wood moisture content of 12%, and E0,12 is the modulus of elasticity parallel to the grain, adjusted to a moisture content of 12%; COV identifies the coeficient of variation, mean the mean value, and ft,0,k, ρk, and Et,0,mean the characteristic values

			ft,0,150 [N/mm^2]			ρ12 [kg/m^3]			E0,12 [kN/mm^2]	
combination	grade	N	ft,0,k	mean	COV	ρk	mean	COV	Et,0,mean	COV
S13/S10/S7/R	S13	24	22.4	45.1	0.388	369	445	0.090	13.3	0.203
	S10	53	16.5	31.4	0.317	365	434	0.089	12.3	0.187
	S7	56	11.7	23.1	0.332	360	431	0.091	10.9	0.226
S10+/R	S10+	77	17.4	35.7	0.397	368	438	0.089	12.7	0.196

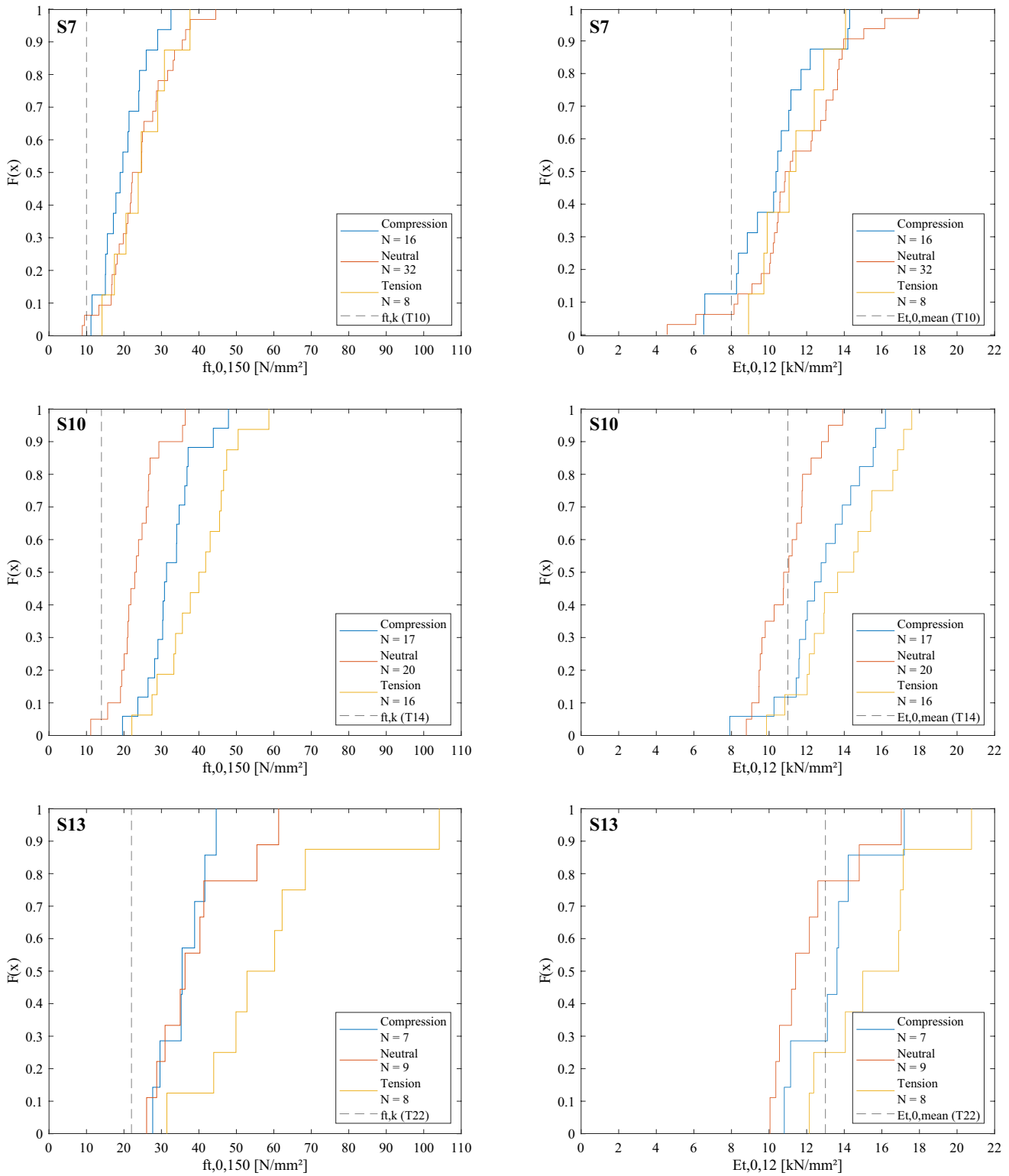


Fig. 7 Cumulative frequency distribution of the tensile strength (ft,0,150) and tensile stiffness (Et,0,12) by visual grades (S7, S10, S13), with a focus on strain zones: compression, neutral, and tension

Aside from scatters caused by natural features and the limited sample size, boards cut from the tensile zone were least affected by fastener holes. Fasteners were mainly found on the rafter's upper side (Böhm et al. 2025). Consequently, most fastener holes were located in the compression zone and, depending on the fastener length, sometimes penetrated the neutral zone. Boards cut from the tensile zone were less affected by fastener holes, which may cause the higher tensile properties within the same visual grade.

Another factor that may explain the lower tensile properties for S10 boards from the neutral zone is the presence of pith. Notably, for grade S10, boards originating from the neutral zone exhibit the lowest tensile performance. About half of these boards (45%) contain pith. According to DIN 4074—1:2012 (Deutsches Institut für Normung 2012) as a weakening criterion, pith is not permitted for boards of grade S13, but may have influenced the performance of boards in the neutral zone of grade S10. Even though no pith was observed in individual boards, a generally high proportion of juvenile wood may still be expected in lumber sawn from structurally recovered wood. Usually, new-sawn boards of that small dimensions (30×90 mm^2) are cut from the outer parts of logs, resulting in a higher share of mature wood. In contrast, lumber cut from structurally recovered wood, such as boards processed from salvaged rafters, originates from components that are likely to have originally been cut from the log's central part. Therefore, a high proportion of juvenile wood is probable due to the small distance to the pith, even when the pith itself is absent from the boards.

Whether the observed differences are also caused by variations in strain stresses within the load history needs to be further verified in a broader context using smaller specimen dimensions to eliminate the potential influence of natural features, such as knottiness values.

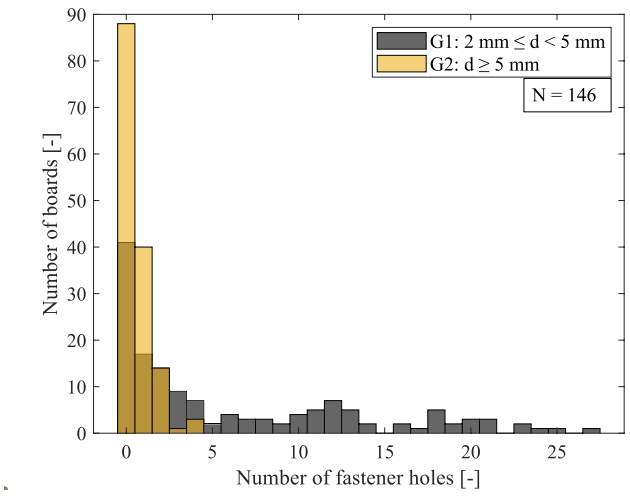


Fig. 8 Absolute frequency distribution of boards by number of fastener holes over an assessed board length of 810 mm, separated into G1 (2 mm≤d<5 mm) and G2 (d≥5 mm) fastener holes; bars of category G2 are displayed semi-transparent to allow illustrating overlapping bars

4.2.4 Fastener holes

The preceding sections demonstrated that the "grading rules for boards" specified in DIN 4074—1:2012 (Deutsches Institut für Normung 2012) are applicable to boards processed from salvaged rafters. The mechanical property requirements for ft,0,150 and Et,0,150 were satisfied, even though the boards were previously loaded and had fastener holes, which visually distinguish processed recovered wood from new-sawn wood. To better understand the negligible diameter and frequency of fastener holes in boards processed from recovered wood, their characteristics were subsequently assessed.

4.2.4.1 Visual characterization of fastener holes A total board length of 118.3 m was assessed for the presence of fastener holes, corresponding to the testing length of 810 mm per board across 146 boards. Within this length, 891 fastener holes classified as G1 (2 mm≤d<5 mm) and 83 classified as G2 (d≥5 mm) were identified. As illustrated in Fig. 8 for the absolute frequency, 60% of the boards contained no G2 holes (d≥5 mm), while 27% contained only a single G2 hole. In contrast, the distribution of G1 holes revealed a substantially broader scatter, indicating that boards were more frequently affected by small-diameter holes, in some cases with high penetration densities.

Given the threshold diameter for G2 fastener holes of 5 mm, the minimum diameter observed was 5 mm, while the maximum reached 14 mm. The mean diameter was 7.4 mm for G2 holes. An absolute frequency distribution of hole diameter is shown in Fig. 9, indicating that, for the sample analyzed in this manuscript, fastener holes predominantly fall within the range of 5 mm to 10 mm, with occasional outliers up to 14 mm.

However, it should be noted that the characterization of fastener holes refers exclusively to those located within the assessed center length of 810 mm for each board. During sample preparation, this section was chosen and cut to include the most crucial weakening criterion, defined by the knot or fastener holes. Consequently, the characterization focuses on these most prominent holes rather than on all fastener holes present over the entire board length.

4.2.4.2 Visual assessment of the fracture pattern The fracture patterns of the as S7 or better graded 133 boards were visually examined to identify the failure causes. The assessment focused on the origin and propagation of cracks. Failures caused by knots were categorized under the criterion

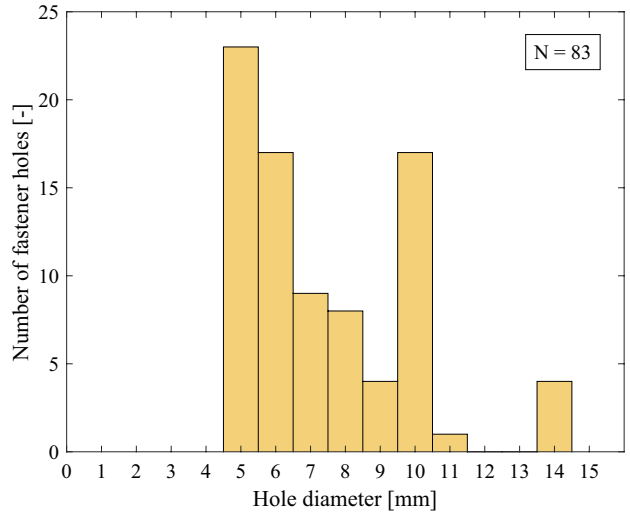


Fig. 9 Absolute frequency distribution of fastener holes by hole diameter for all G2 (d≥5mm) fastener holes

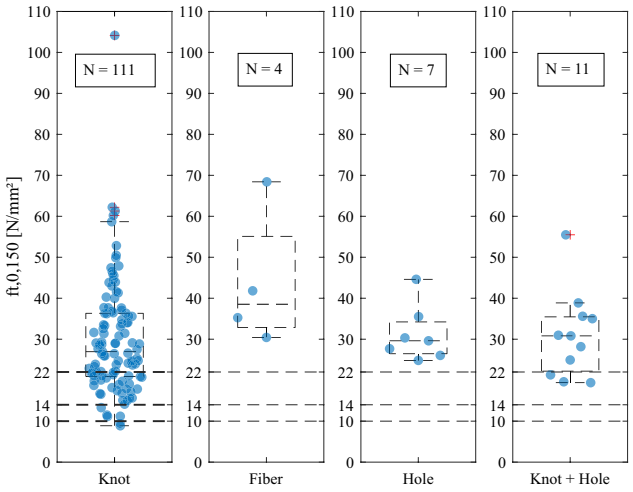


Fig. 10 Tensile strength of the boards categorized by their failure cause, with horizontal lines visualizing the thresholds for the tensile strength requirements of 22 N/mm^2, 14 N/mm^2, and 10 N/mm^2 for strength classes T22, T14, and T10, respectively, with individual datapoints for each specimen displayed in blue

"knots"; fiber failures without a direct impact of knots were classified as "fiber failure." Failures caused solely by fastener holes or in combination with knots were categorized as "hole" and "knot + hole," respectively.

A total of 86% of the boards failed primarily due to natural features, including knots (83%) and fiber failure (3%). In 5% of the boards, fastener holes were the main criterion for failure. An additional 8% failed due to a combination of fastener holes and knots. These results suggest that fastener holes can initiate or contribute to failure. At the same time, natural criteria, especially knots, remained the dominant factors in the failure of boards processed from recovered wood, similar to new-sawn wood.

Furthermore, the results show a relationship between visual grade and sensitivity to fastener holes, as expected, since the presence and severity of natural features decrease with higher grades, thereby expecting to increase the relative influence of fastener holes. In absolute numbers, out of 56 boards of grade S7, 1 (2%) failed due to a combination of knots and fastener holes; among the 53 boards of grade S10, 8 (15%) failed due to or with an impact of fastener holes; and out of 24 boards of grade S13, 9 (38%) failed due to or with an influence of fastener holes. So similar as shown for the results for the lumber type battens in Scharpenack et al. (2026) there are indications that also boards of lower grade fail primarily due to natural features, before man-made features, such as fastener holes, become governing.

To assess whether failures caused or influenced by fastener holes were critical, the tensile strength of these samples was compared with the thresholds for the corresponding reference strength classes T22, T14, and T10. As shown in Fig. 10, none of the seven boards that failed solely due to the presence of fastener holes exhibited tensile strength below the threshold of 22 N/mm^2. Among the 11 boards that failed due to a combination of holes and knots, three values fell below the 22 N/mm^2 threshold. However, their tensile strengths of 19.4 N/mm^2, 19.6 N/mm^2, and 21.3 N/mm^2 remained above the 14 N/mm^2 threshold for strength class T14.

4.2.4.3 Influence of fastener holes For the investigated batch, it can be summarized that fastener holes in the characterized frequency and diameter, do not crucially affect the tensile strength of boards processed from salvaged rafters. Since the characteristic values for the mechanical properties were achieved without a specific visual assessment of fastener holes (see Sect. 4.2.2), rejecting boards with fastener holes of the characterized diameter and frequency is not necessary. Moreover, failures associated with fastener holes occurred, with few exceptions, only after the threshold tensile strength had been reached. Based on the examined batch with cross section 30 × 90 mm^2, fastener holes up to 14 mm in diameter do not substantially affect the tensile strength. A direct comparison of our observations to other study results is not possible, since studies that reported an influence from fastener holes on the mechanical properties (e.g., Pasca et al. (2025) and Fridley et al. (2001)) investigated the bending performance and often examined a larger fastener hole diameter. However, since larger fastener hole diameters than those investigated in this study are expected

to also affect tensile strength, further research is required on fastener holes of larger diameters.

4.2.5 Applicability of DIN 4074—1:2012 on boards processed from salvaged rafters

The findings for VSG demonstrate that boards processed from salvaged rafters can be effectively visually graded based on the existing "grading rules for boards" in DIN 4074—1:2012 (Deutsches Institut für Normung 2012). Aside from the slight shortfall in meeting the density threshold for S13 boards, the thresholds of every correlated grade-determining property of the strength classes T22, T14, and T10 were met by the visual grades. Our observations indicate that the "grading rules for boards" in DIN 4074—1:2012 (Deutsches Institut für Normung 2012) remain applicable without requiring adjustments. Moreover, fastener holes with a diameter of up to 14 mm and their observed frequency (up to twice per board and a minimum spacing of 235 mm) did not substantially affect the tensile strength and can therefore be neglected. As only 4 of 146 boards had these larger fastener holes, a direct influence on the derived characteristic values of the sample could not be established. However, if larger holes occur more often, that could have changed the outcome.

4.3 Machine strength grading (MSG)

4.3.1 Development of machine settings for Edyn

The elaborated thresholds for machine settings based on Edyn for three targeted strength classes combinations and their corresponding yields and grade-determining properties are summarized in Table 7. In all three combinations, yields of similar magnitude, ranging from 138 to 141 boards (95% to 97%), were achieved. The results demonstrate that the boards can be effectively machine graded into the different target strength classes. The requirements for the sub-class T10 were not met in any case, which can mainly be attributed to the low sample size. The low sample size was also expected to be the reason that strength class combination A does not include T22 boards. A greater differentiation into strength classes could likely be achieved with larger sample sizes. Overall, machine grading of boards proved effective and appears to be a promising and accelerating method. However, further validation with a larger sample size is needed, since the minimum requirement of 20 pieces per strength class and combination, as specified in EN 14081—2:2022 (European committee for standardization, 2022a), was not met for the higher grades T22 and T30 in combinations A and B. Therefore, the elaborated machine settings should be interpreted with caution and as an initial indication that needs to be confirmed with larger datasets when aiming for certification to avoid the risk of overfitting.

4.3.2 Comparison between MSG and VSG—yield and characteristic values

To assess whether VSG or MSG yields superior outcomes in assigning boards to higher strength classes, the distributions of these classes were compared for both methods (Fig. 11). The strength class T30 could not be assigned under VSG because there is no corresponding visual grade within the VSG framework. VSG effectively subdivided the boards into the three visual grades (S13, S10, and S7), which could then be assigned to the corresponding three strength classes (T22, T14, and T10). MSG did not grade boards to the strength class T10, and these boards were likely graded to the higher class, T14, instead. Consequently, more boards were allocated to the higher strength class T14 under MSG, which is preferable in terms of applicability.

Overall, the findings demonstrate that the MSG of recovered wood boards is more effective than VSG, as this is the case for new-sawn timber (e.g., Glos and Schulz (1980), Sauter and Diebold (1997)). Additionally, boards can be classified in the strength class T30, which is not possible under the current VSG framework.

Table 7 Threshold machine settings for the indicating property (IP) dynamic modulus of elasticity (Edyn) for machine grading of boards processed from salvaged rafters for three strength class combinations

Combination	Strength class	Edyn threshold	N	Yield	ft,0,k	Et,0,mean	ρk
		[kN/mm^2]	[-]	[%]	[N/mm^2]	[kN/mm^2]	[kg/m^3]
-	unsorted	-	146	-	12.6	11.8	366
A	T30	16.2	13	9	31.4	17.0	447
	T14	8.6	128	88	14.2	11.5	369
	Reject	-	5	3	5.6	5.7	304
B	T22	15.6	17	12	29.5	16.4	443
	T14	8.9	123	84	14.1	11.4	369
	Reject	-	6	4	5.2	6.0	310
C	T14	9.2	138	95	14.2	12.1	369
	Reject	-	8	5	6.1	6.5	312

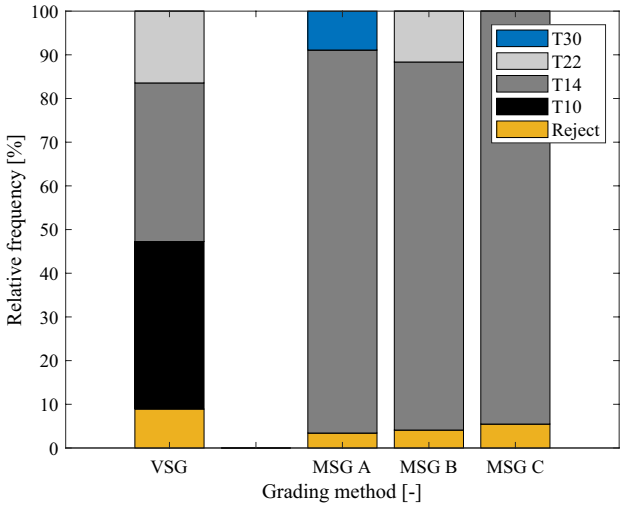


Fig. 11 Comparison of the yield indicated by the relative frequencies of each strength class separated by the grading method, where VSG refers to visual grading and MSG to machine strength grading, for combinations A to B (MSG A—MSG B) as detailed in Table 7

4.3.3 Recognizability of fastener holes with X-ray

The results in Sect. 4.2.4 demonstrate that for boards with a cross-section of 30×90 mm^2, processed from salvaged rafters, fastener holes within the characterized diameter and distribution range do not substantially affect the tensile strength. Based on the observed hole diameter and the findings from the previous study Böhm et al. (2025) on the characterization of the removed fasteners, the fastener holes are generally expected to occur mainly from screws, nails, or staples.

However, for decorative and premium appearance applications of processed recovered wood, fastener holes may not be desirable. In addition, for larger fastener hole diameters, comparable to the size of crucial knots, an impact on mechanical properties is expected. This can be, for instance, bolt holes, service penetrations, or carpentry connections. Although such holes are expected to occur only irregularly and rarely, they may should be taken into consideration in the grading process. Based on the provided machine data, the recognizability of fastener holes in the investigated boards is assessed, in order to apply these findings for cases with larger hole diameters.

4.3.3.1 Technical implementation in MATLAB The technical implementation was done with the software MATLAB R2024b (The MathWorks, Inc., 2024). The core of the technical implementation was done by the function *regionprops*. For the application of the function, the individual density matrices for each board were filtered and adjusted to the test length beforehand. Based on the setting of individual density thresholds, whose development is described in the following paragraph in more detail, binary images were generated, and connected components labeled with boundary boxes (using the function bwlabel) were illustrated to indicate regions with irregularly low density as indicators of fastener holes. Using the function *regionprops,* the height, length, and coordinates of the boundary boxes were measured. Figure 12 examplified illustrates the methodology

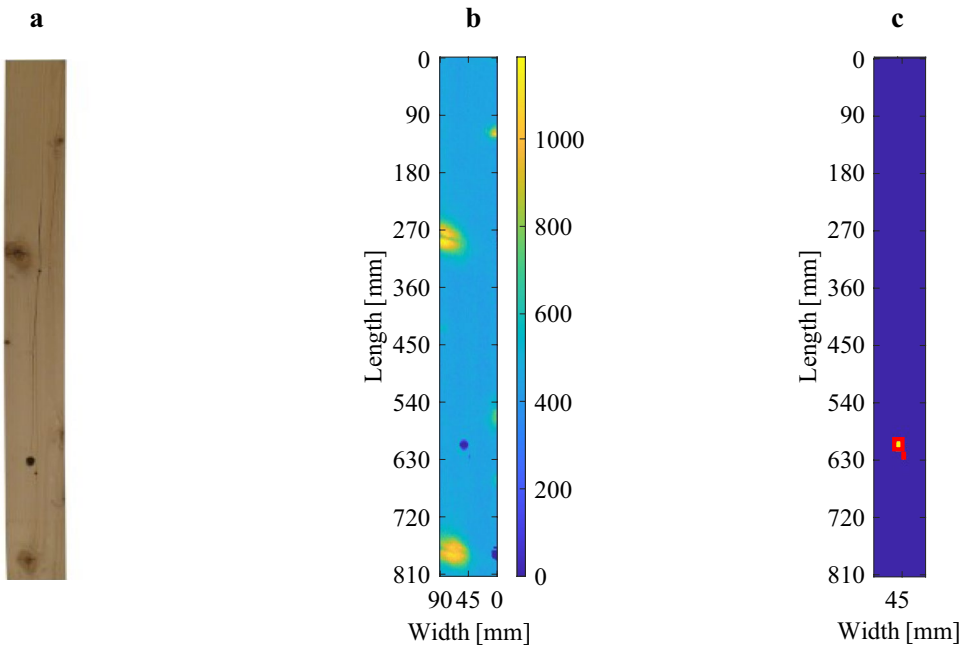


Fig. 12 Exemplified illustration of the methodology for the technical implementation of identifying and characterizing fastener holes based on the density profile; (a) is a photograph, (b) a density profile, and (c) a labeled binary image of one face side of a specimen along the testing length

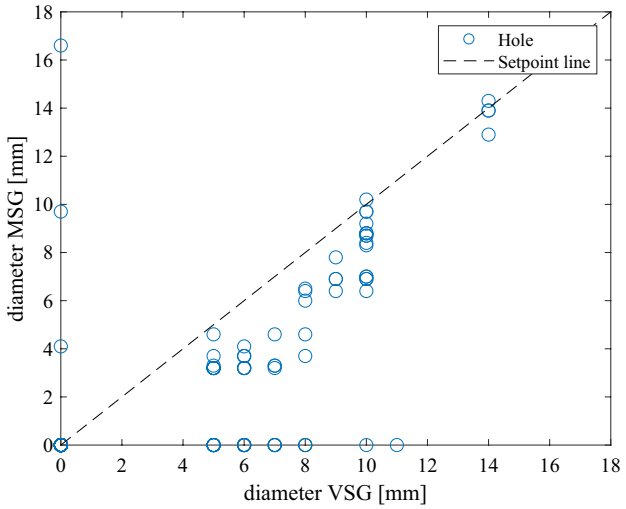


Fig. 13 Relationship between visual and machine-assessed fastener hole diameter

by showing a photograph (12a), density profile (12b), and labeled binary image (12c) for one specimen.

To ensure comparability with the VSG results, the MSG dataset was adjusted by excluding MSG-detected fastener holes with a diameter below 3 mm, because VSG did not capture numerous small fastener holes identified by MSG due to its 5 mm threshold. The 3 mm threshold for MSG, which differs from the 5 mm threshold for VSG, was chosen because the measurement-accuracy evaluation indicated that MSG underestimates fastener hole diameters relative to VSG (see Fig. 13). By excluding all MSG-assessed fastener holes smaller than 3 mm, all fastener holes not detected by VSG were effectively removed from the MSG dataset.

4.3.3.2 Threshold setting for irregular densities For knots, wood fibers flow around these high-density areas, causing local fiber deviation; for holes, fasteners displace or drill out fibers, leading to lower local densities. In theory, the local densities for fastener holes should be zero. However, as the fastener holes do not necessarily propagate vertically, and wood residues may protrude into the hole, the local densities are mostly just lowered, but not completely zero. This results in an irregular, low-range local density, for which thresholds need to be set, for which the following procedure is proposed.

The global densities of each specimen vary, as do the local densities within each specimen. An application of a static threshold for irregular low densities (e.g., 0, 100, 200, 300) was therefore proven inappropriate, as several settings testing runs revealed. As a result, a dynamic threshold was established. To identify a threshold for irregular low densities, Eq. (1) was applied. Equation (1) is based on the two-sigma interval, which describes in the present application the threshold for the lower 2.275th percentile of a normal distribution (Hartung et al. 2009).

$$irregulardensities = mean - 2 * std \quad (1)$$

, where *mean* is the mean value of the density profile, and *std* is the standard deviation. As exploratory test runs revealed, this threshold was the most robust among those considered: *mean*, *mean* -3*std, or the 5th percentile. The threshold enabled the sensitive identification of irregular densities while still allowing for differentiation between natural local density inhomogeneities.

4.3.3.3 Performance review and limitations Figure 13 illustrates the relationship between the fastener hole diameters, measured using visual (VSG) and machine (MSG) strength grading. As shown by the undershooting of the setpoint line, MSG tends to underestimate the diameter compared to VSG. To better understand the correspondence between the methods of VSG and MSG of fastener holes, a ratio was calculated by dividing the MSG recorded diameter by the VSG recorded diameter. As shown in Table 8, for diameters of 9 mm, 10 mm, and 14 mm, both measurement methods exhibit good correspondence. However, for diameters between 5 and 8 mm, there is a high discrepancy between the diameters assessed by VSG and MSG. With a correspondence of 0.97, no fastener holes were assessed either. The three observations that resulted in this discrepancy (observations on the y-axis) were found to be due to human measurement error in one case and knot holes in two cases. To enhance the accuracy of MSG measurements of

Table 8 Ratio calculated by dividing the MSG measured diameter by the VSG measured diameter for the same fastener hole (ratio = MSG / VSG); N is the number of fastener holes, mean is the mean value of the ratio, and std is the standard deviation

Diameter (VSG)	[mm]	None	5	6	7	8	9	10	11	12	13	14
N	[-]	89	23	17	9	8	4	17	1	0	0	4
mean	[-]	0.97	0.30	0.31	0.23	0.43	0.78	0.79	0.00	-	-	0.98
std	[-]	0.18	0.35	0.30	0.28	0.37	0.06	0.23	-	-	-	0.04

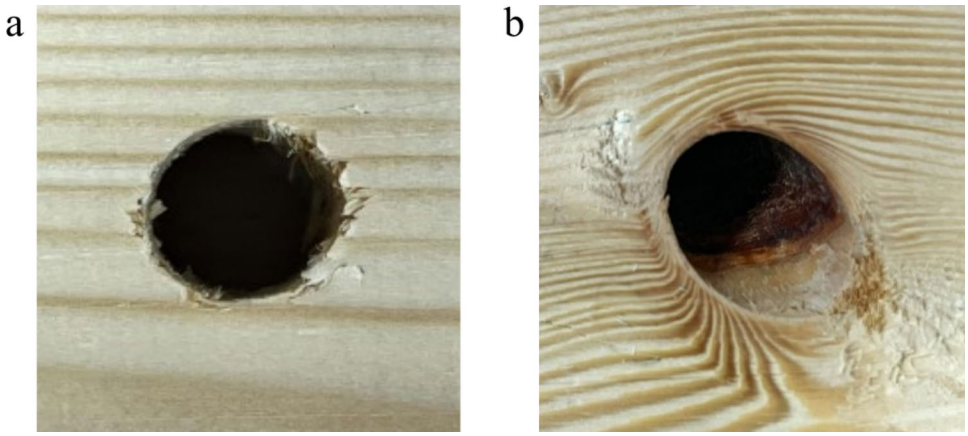


Fig. 14 Exemplified difference in the fiber propagation between fastener hole (a) and knot hole (b)

fastener holes, further development is needed to differentiate between fastener holes and knot holes.

4.3.3.4 Differentiation between knot hole and fastener hole In the current state of technical implementation, the machine detection and characterization of fastener holes based on local density irregularities can lead to misinterpretation between fastener holes and knot holes (see outliers on the y-axis in Fig. 13). Both result in an irregularly low local density. Therefore, a further criterion needs to be combined with the local density criterion to differentiate between the two.

One approach is to additionally consider the local fiber deviation around fastener holes. Fastener holes interrupt the continuous fiber propagation (Fig. 14a), whereas knot holes cause local fiber deviation as the fibers are diverted around it (Fig. 14b). To technically implement this idea in MSG, based on the scattering laser data, the local fiber propagation around the suspected hole area can be checked. Scattering laser data around knots have a high correlation with the actual presence of knots (Rais et al. 2021). So scattering laser data, indicating a continuous (straight) fiber direction at an area with very low or zero density, is consequently a strong indicator for the presence of fastener holes, see also Fig. 14a.

4.3.4 Applicability of MSG on boards processed from salvaged rafters

The MSG results showed that boards processed from salvaged rafters can be effectively classified into strength classes T30, T22, and T14 by setting specific thresholds in Edyn. Furthermore, it has been demonstrated that fastener holes can be accurately detected and characterized through density profile analysis, as they manifest as irregular, low-density regions. Their diameter can be precisely measured thanks to high machine resolution. To distinguish these holes from knots, it is advisable to perform further checks on local fiber deviations by analyzing laser scattering data around the holes. However, as shown by the study results in Khaloian Sarnaghi & van de Kuilen (2019), where the tensile strength was predicted based on 3D-modeled spruce boards and knots were modeled as holes, a differentiation between knots and fastener holes may be redundant, as revealed by a strong linear ($R^2 = 0.72$) and non-linear ($R^2 = 0.75$) relationship between predicted and experimental tensile strength of spruce. More relevant may be that the weakening spot in general, whether a knot or a fastener hole, is detected and considered in the strength prediction.

5 Conclusion

A total of 146 unsorted boards processed from 22 salvaged rafters exhibited tensile properties comparable to those of new-sawn timber of strength class T10. Based on the "grading rules for boards" specified in DIN 4074—1:2012 for new-sawn timber, with a yield of 91%, the recovered wood boards were assigned to one of the visual grades S13, S10, or S7. Although numerous fastener holes, predominantly of small diameter (2 mm $\leq$ d $<$ 5 mm), were characterized, standardized visual grading based solely on natural features ensured compliance with the tensile strength and stiffness required for the corresponding strength classes T22, T14, and T10 in EN 338. Effective sorting was also achieved by machine grading based on dynamic stiffness. By machine grading, fastener holes could be detected and measured from the density profile, although their diameters were underestimated compared with the assessment by visual strength grading.

The findings demonstrate that the established "grading rules for boards" in DIN 4074—1:2012 are also applicable to boards processed from salvaged rafters. Fastener holes within the characterized diameter range can be neglected, as

compliance with corresponding strength classes is achieved despite their presence. Our findings indicate that natural features, especially knots, remain the primary weakening criteria, even for recovered wood. Furthermore, the applicability of the unmodified method to recovered wood is also demonstrated for machine strength grading based on dynamic stiffness. Although it was possible to detect fastener holes with sufficient accuracy based on their density profile, considering them was not necessary in the machine grading process. Consequently, boards processed from salvaged rafters can substitute new-sawn timber in structural applications, offering a promising alternative for circular construction and resource efficiency.

As a contribution to extending standardization in response to evolving needs, this paper advances the scientific understanding of the structural performance of processed recovered wood at the material level. The study provides knowledge for the high-value utilization of the Norway spruce in a cascading context. Furthermore, determining grading criteria, in particular, the characteristics of fastener holes and their potential impact on tensile strength, was examined. Beyond providing fundamental knowledge of the mechanical properties of today's recovered wood and its compatibility with existing grading methods, the study offers structural designers and timber merchants practical insights that small-diameter fastener holes may not compromise structural applicability in a second use phase.

Due to the limited sample size of 146 boards, their uniform cross-section dimensions (30×90 mm^2), and their prior use as rafters, the generalizability of our conclusion to broader contexts needs to be tested. Further research is required on fastener hole diameters as related to the cross-section beyond those studied here, to identify the critical diameters that may affect board strength. As the findings reflect short-term performance, future studies related to long-term performance are needed.

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Data availability Data will be made available on request.

Declarations

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