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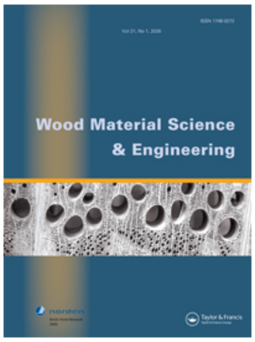

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The visual strength grading of Norway spruce battens processed from recovered wood: mechanical properties and modified grading rules in DIN 4074-1

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ABSTRACT
Strength grading is essential to ensure standardized and reliable design processes in timber construction. Current visual strength grading (VSG) standards, such as DIN 4074-1, focus on regulating natural features and grading new sawn timber. Sorting criteria for man-made defects resulting from prior use are lacking. This study examines the potential of VSG for battens processed from salvaged rafters for structural applications and proposes modifications to DIN 4074-1:2012 to make it applicable to battens processed from recovered wood. Battens were visually graded based on natural features, and fastener holes were characterized. Bending strength was tested against EN 338 classes, and the impact of fastener holes was assessed. The results indicate that grades S10 and S13 together account for a total yield of 57%. Clusters of fastener holes reduced bending strength in S10 battens, whereas larger holes affected S13 battens. Modification options for DIN 4074-1:2012 were identified, and their effectiveness was validated. As a result, a new sorting criterion, SRC (strength reducing criteria), was introduced to address the interaction between natural features and fastener holes. Battens processed from recovered wood can serve as an alternative to new timber if classified under the proposed grade W10+.

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1. Introduction

The wood species Norway spruce is the predominant resource in structural timber construction in Central Europe. However, the future availability of Norway spruce timber faces serious challenges due to the impacts of climate change. The most recent German National Forest Inventory (Bundesministerium für Ernährung und Landwirtschaft 2024) revealed that the Norway spruce stands are regressive due to biotic and abiotic stresses. The primary stressors identified were drought, bark beetle infestation, and storms. In the mid-term to long-term, the construction sector may face the associated consequences related to the availability of Norway spruce. Therefore, a shift may occur, and conventional construction practices in structural design and resource utilization must be rethought.

Besides the utilization of new sawn timber from tree species that are more tolerant to climatic stresses, the extension of the lifespan and circular utilization of existing timber components should be aimed at. The last two approaches can be implemented in various hierarchical strategies, such as the 9R framework (Potting *et al.* 2017). In the case of extending the lifespan of recovered wood, the additional terms of cascading or cascade, respectively, are used in academia (*e.g.* Szichta *et al.* 2024, Risse *et al.* 2017, Höglmeier *et al.* 2017, Brownell *et al.* 2023, Budzinski *et al.* 2020). Cascade utilization of recovered wood was shown to have environmental benefits (Höglmeier *et al.* 2014, Risse *et al.* 2017, Suter *et al.* 2017, Budzinski *et al.* 2020). Furthermore, its quantitative availability was demonstrated through several regional and national studies addressing the material flow of current and anticipated recovered wood streams (Höglmeier *et al.* 2017, Kalcher *et al.* 2017, Nasiri *et al.* 2021, Szichta *et al.* 2022, Gedde *et al.* 2025).

However, to cascade wooden components in a structural application, both the unprocessed and processed wooden components need to be strength graded first. The initial strength class assignment of the recovered structural components is often unknown, and even if known, it can easily lose validity when processing involves changing cross-sectional dimensions. Processing the structural components, particularly sawing and planing them, results in altered or reduced cross-section dimensions and, as a consequence, may lead to an increased impact of natural features. In this context, especially the knottiness increases, or the knot configuration changes, which may lead to a new strength class assignment. In the case of Germany, the first edition of the national grading standard DIN 4074-1 was published in 1939 (Deutsches Institut für Normung n.d.). Because of this, it can be expected that structural components used after 1939 were assigned to visual grades and feature specific mechanical property values. Before 1939, construction relied on best practices and the experience of carpenters, as a unified standard was not available.

For new sawn timber, two main strength grading approaches exist: machine strength grading (MSG) and visual strength grading (VSG). The European framework for timber

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strength grading is formed by the EN 14081-1 standard (European Committee for Standardization n.d.-a), and supporting standards. Visual strength grading is regulated at a national level. The German standard DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) specifies thresholds against which visual sorting criteria for natural features need to be checked. Based on the thresholds, new sawn timber gets assigned to the visual grades S7, S10, and S13. Special attention is given to knots and their diameter, frequency, and progression.

A harmonized European standard for grading recovered wood, covering the common European wood species and the grading methods (VSG or MSG), does not exist. A general and broad overview of the criteria essential for a reliable and standardized assessment of recovered wood is given in the research article (Ranttila *et al.* 2025). For recovered wood components, the existing visual grading standards for new sawn timber are less suitable, as they are not specifically designed or adapted for this application. On the one hand, they do not cover man-made defects, such as fastener holes and carpentry connections. On the other hand, studies have shown that existing visual grading standards for new sawn timber are inadequate due to low yield and are unsuitable for reuse scenarios (Arriaga *et al.* 2022, Llana *et al.* 2023, Nasiri *et al.* 2025). The most crucial visual sorting criteria that lowered the yield for reuse in the studies Arriaga *et al.* (2022), Llana *et al.* (2023), and Nasiri *et al.* (2025) were fissures, wane, and warp. In contrast, the study Crews and MacKenzie (2008) describes the suitability of an existing VSG standard (AS 2082-2000) for assessing recovered wood. However, unlike the other studies, the study Crews and MacKenzie (2008) investigated processed recovered wood, which is expected to have no distinct warp or wane due to its prior processing.

On a national level, as of now, the national Norwegian standard NS 3691-3:2025 (Standard Norge 2025) is the first standard applicable to recovered wood. The standard provides an initial outlook on a possible approach for VSG of recovered wood by assessing its man-made defects from previous utilization. The standard regulates the examination of recovered wood of Norway spruce and Scots pine with a minimal cross-sectional dimension of $36 \times 50\ \text{mm}^2$. NS 3691-3:2025 (Standard Norge 2025) proposes for the evaluation of natural features in the recovered wood, that reference should be made to existing documentation, or a re-assessment should be performed following the Nordic standard for visual strength grading (NS-INSTA 142). As the assessed recovered wood must either be cut or planed before evaluation, the NS 3691-3:2025 (Standard Norge 2025) standard eliminates most problems associated with wane and warp, which were faced in the studies Arriaga *et al.* (2022), Llana *et al.* (2023), Böhm *et al.* (2025), and Nasiri *et al.* (2025). The effectiveness of visual strength grading of processed recovered wood has already been proven by the study Crews and MacKenzie(2008).

Visual grading standards have a long history and are well established. Recovered wood grading should build on these established grading frameworks to ensure acceptance and applicability. To do so, and to build the basic framework for German standardization, the performance of the DIN 4074-1:2012 standard (Deutsches Institut für Normung n.d.) for grading of battens processed from recovered wood needs to be assessed, specifically considering the mechanical property values and grading yields. Additionally, a sorting criterion and an assessment method for parameters not covered by the grading standard, particularly fastener holes, need to be elaborated. This step requires knowledge about the influence of fastener holes on the bending strength of recovered wood, as well as their geometric and distributional characteristics for timber cross-sections used in practice.

The effect of man-made defects on bending strength has been the focus of several studies. Taking up the thoughts of Fridley *et al.* (2001) similarities in the impact on strength can be expected between knots and fastener holes. However, knots cause a deviation of the fibers, while fastener holes create a cut through them. Which of the two has the greater impact is unclear and is currently the subject of much debate. A complex interplay exists between the natural features and fastener holes on the strength behavior and fracture propagation. A study on modeled and experimentally tested generated hole configurations (diameter: 3-26 mm) in beams investigated that for some configurations, drilled holes were the primary cause of failure, while for others, natural features remained the leading cause of failure (Pasca *et al.* 2025). The study Fridley *et al.* (2001) examined fastener holes with diameters of 25.4 mm and 44.5 mm in beams with cross-sections measuring $102 \times 303\ \text{mm}^2$. Both hole sizes showed similar effects on the strength of the beams. However, their axial proximity to the area of maximum bending stress was more decisive. The significance of evaluating hole locations through visual grading is even a key finding in the study of Crews and MacKenzie (2008) and is even implemented in NS 3691-3:2025 (Standard Norge 2025) by assessing fastener holes inside or outside of edge zones. However, both studies (Fridley *et al.* 2001, Pasca *et al.* 2025) as well as NS 3691-3:2025 (Standard Norge 2025) focus on, compared to battens, cross-sectional large-format recovered wood. A direct transfer of the findings to the grading of battens is doubtful, as the fastener hole size to cross-section ratio highly differs for battens and beams. The study Rose *et al.* (2018) concluded, based on finite element modelling, that minor degradations in compression and bending stiffness occur due to small defects. Besides the lack of knowledge of the influence of fastener holes on the bending strength of battens, their expected geometric and distributional characteristics in recovered wood are also unknown. As Pasca *et al.* (2025) investigated randomly generated hole configurations (subsequently drilled) in new-sawn wood, no characterization of fastener holes was done. In general, just a few studies characterized fastener holes (Rose *et al.* 2018) and remaining fasteners (Böhm *et al.* 2025) in recovered wood by their geometry and distribution. More comprehensive datasets are essential, as understanding the characteristics and combinations of natural features and fastener holes in recovered wood will enable the modification or design of appropriate standards.

In conclusion, it can be stated that knowledge of the mechanical properties of battens processed from recovered wood, as well as the corresponding influence of fastener holes and their characterization, is missing. Filling this research gap is highly important to enable the extrapolation of recovered wood standardization to the adapted needs. Furthermore, conclusions can be drawn from components with a small cross-section to those with a larger one, whereas the reverse is impossible.

This study investigated the visual grading potential of 302 battens processed from salvaged rafters. The basic framework of the grading is built on the DIN 4074-1:2012 standard (Deutsches Institut für Normung n.d.). The German standard DIN 4074-1 was selected due to the national context of the study and because it covers the examined species, Norway spruce and fir. The success of conventional VSG, and the modification needs to DIN 4074-1:2012 for the grading of recovered wood will be validated by four-point bending tests according to EN 408:2012 (European Committee for Standardization n.d.-b). The study will act on the macroscopic material level.

Based on these objectives, the research questions of this study were:

(1) What are the characteristic values of Norway spruce battens processed from salvaged rafters based on four-point bending tests?
(2) What are the geometric and distribution characteristics of natural features and fastener holes in battens processed from salvaged rafters sourced from deconstruction and demolition sites in Southern Germany?
(3) What impact do natural features have on the total visual grading yield of battens processed from salvaged rafters?
(4) How do fastener holes influence the bending strength of battens?
(5) Specifically for battens processed from salvaged rafters: How can the “grading rules for battens” in DIN 4074-1:2012 be extended to include a sorting criterion for fastener holes to be applicable to recovered wood?

2. Materials and method

2.1. Design of the study

We conceptualized the study as shown in Figure 1. Our suggestion for visual strength grading of battens processed from recovered wood builds upon the existing framework of DIN 4074-1:2012 (Deutsches Institut für Normung n.d.). We suggest modifications, including an additional sorting criterion for fastener holes, as well as an initial approach for regulating insect infestations. Natural features were assessed according to the standard’s “grading rules for battens”. Fastener holes were characterized by their geometry and distribution. Afterwards, the battens were tested in four-point bending according to EN 408:2012 [40]) in edgewise (EW) or flatwise (FW) direction until failure. Based on the bending test results and the batten’s visual grade assignment, the general suitability of the original visual sorting criteria in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) were checked. Beyond that, the bending strength values grouped by visual grade were correlated with the geometrical and distributional characteristics of the fastener holes. Modifications to DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) for limiting fastener holes were iteratively developed and validated by determining their impact on the characteristic bending strength (fm,k).

2.2. Material

The battens investigated in the present study originated from 31 rafters of the roof truss constructions of six residential buildings erected or retrofitted between the years 1956 and 1987 in Southern Germany. The detailed description of sampling is provided in Böhm *et al.* (2025). The observed environmental conditions indicate that the structures can be assigned as service class 1 according to EN 1995-1-1 (European Committee for Standardization n.d.-c). A total of 302 specimens with cross-section dimensions of 30×50 mm^2 (N = 132) and 40×60 mm^2 (N = 170) were examined (Table 1). The battens were processed from characterized salvaged rafters, as detailed in Böhm *et al.*(2025) and briefly summarized as follows. During the processing of the rafters, the cross-section reductions from carpentry connections were cut out. However, fastener holes remained. Each batten was stamped with a unique specimen code containing information about the originating site, the rafter number, and the position of the batten within the rafter (bottom, central, and upper side). The rafters were cut parallel to their edge sides (narrower cross-section dimension). Depending on the dimension of the face side (larger cross-section dimension) of the rafters, the individual sawing patterns for each site resulted in two to four batten layers for each cross-section. Wood species identification was performed by examining the anatomical structure of microtome-prepared sections (radial, tangential, and longitudinal) under light microscopy. All rafters, except for two made of fir (*Abies alba Mill.*), were found to be from the wood species Norway spruce (*Picea abies (L.) Karst.*). As is common for processing and utilization of new sawn wood, both species were considered as a mix.

2.3. Method

2.3.1. Specimen preparation

The battens were initially cross-cut to the minimum length specified in EN 408:2012 (European Committee for Standardization n.d.-b), which corresponds to eighteen times the height, plus an additional length of 40 mm on each side (Figure 2). The initial length of the battens ranged between 689 and 3684 mm, so up to two test pieces – one for the flatwise and one for the edgewise bending test – were cut out of a single batten. As the assignment of a specimen to a strength class of EN 338:2016 (European Committee for Standardization n.d.-d) is based on the results of the edgewise testing, the preparation of the edgewise test pieces was preferred over the preparation of the flatwise test pieces. However, fastener holes primarily penetrated the face side of the battens. To examine the influence of fastener holes on bending strength with respect to different loading directions, the battens were tested in edgewise and flatwise orientations. The test pieces were cut in a way that the weakest section, regarding natural features such as knot size or fastener holes with the largest diameter or most clustered distribution, was always placed between the loading points. After preparation, the specimens were conditioned in a climate chamber at reference conditions of 20°C and 65% relative humidity until right before conducting the bending tests.

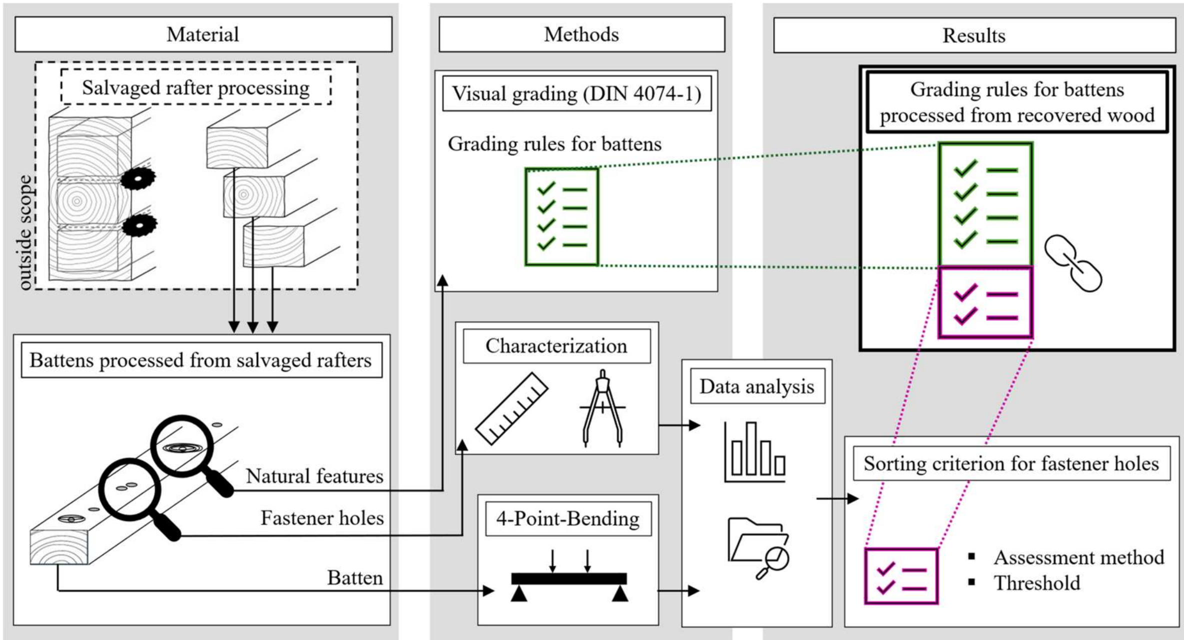

Figure 1. Flowchart summarizing the methodological steps taken in this study to develop a sorting criterion for fastener holes, extending the "grading rules for battens" in the existing DIN 4074-1:2012.

2.3.2. Visual assessment

The visual assessment of the battens was carried out in two stages. The first stage involved standardized VSG for natural features. In the second stage, we categorized the fastener holes. Man-made defects other than fastener holes, such as carpentry connections, were already cut out or equalized by planing during the processing of the salvaged rafters explained in Böhm *et al.* (2025).

2.3.2.1. Visual grading of natural features according to DIN 4074-1. First, the specimens were graded into S10 and S13 following the "grading rules for battens" in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) for new sawn timber. Unlike the "grading rules for boards" and the "grading rules for joists", the "grading rules for battens" do not include the lowest grade S7. The grading criteria applied are knots, presence of pith, and growth ring width. Global fiber deviation was not considered as a relevant criterion because the salvaged rafters were assumed to be sorted since their installation date (1956-1987) followed the introduction of DIN 4074-1 in 1939 (Deutsches Institut für Normung n.d.). As the salvaged rafters were cut parallel to the axial direction, the criterion of global fiber deviation of the initial rafters is maintained for the processed battens, making reassessment redundant. For each batten, knots with a diameter greater than 5 mm were recorded in the length between both loading heads, plus an additional buffer of two times the batten's width outwards (Figure 2). Table 2 summarizes the applied sorting criteria and their thresholds. To receive a grade, all thresholds must be met.

Table 1. Overview of the number of battens per flatwise (FW) and edgewise (EW) bending test, split by the site (origin of the rafters), cross-section, and year of construction / retrofitting; testing length: 620 mm (30 × 50 mm^2 FW), 800 mm (40 × 60 mm^2 FW), 980 mm (30 × 50 mm^2 EW), and 1160 mm (40 × 60 mm^2 EW).

Site [–]	Cross-section area [mm^2]	Year [–]	Number FW [–]	Number EW [–]
1	30 × 50	1956	22	22
2	40 × 60	1957	8	11
	40 × 60	1986	4	10
3	30 × 50	1961	13	10
	40 × 60	1961	10	7
4	40 × 60	1967	21	26
5	30 × 50	1968	33	32
6	40 × 60	1987	33	40
Total			144	158

2.3.2.2. Assessment of fastener holes. The method outlined in DIN 4074-1 for measuring knots was applied to fastener holes with a diameter larger than 5 mm (Group 2). Therefore, the diameter (d) of fastener holes was measured perpendicular to the axial direction of the batten (Figure 3). In contrast to NS 3691-3:2025 (Standard Norge 2025), we did not distinguish between the appearances of fastener holes within edge zones. To prioritize the consistent and familiar measurement in DIN 4074-1 in practice, we adopted the existing framework that overlooks these zones.

For the fastener holes G2, a perforation factor P was calculated. The calculation of P is methodologically similar to the calculation of the knottiness KCB for battens in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.). P describes the ratio of a single fastener hole (d3 in Figure 3) to the batten's width. When two fastener holes appear in a window of 50 mm (d1 + d2 in Figure 3), their diameters are added. If more than one single fastener hole or fastener hole cluster occurs, the maximum ratio is decisive. Equation (1) shows the calculation of the perforation factor P:

$$P = Max\left(\frac{d1 + d2}{b}; \frac{d3}{b}\right) \quad (1)$$

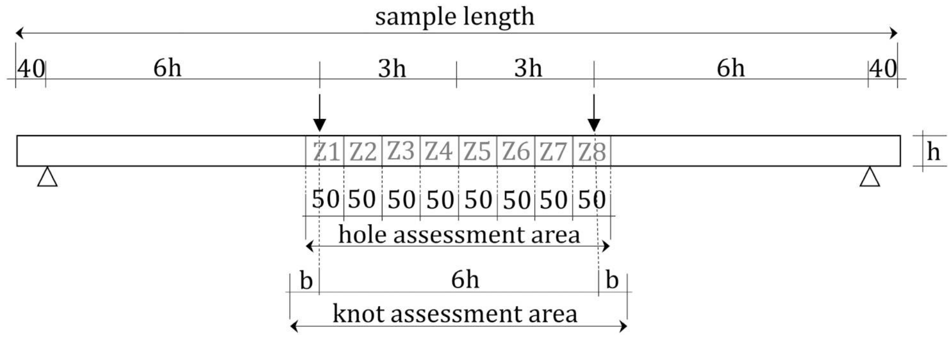

Figure 2. Graphical representation of the test pieces with indication of the four-point-bending test arrangement, the assessment areas for the knots and the perforation factor P, and static windows for the frequency assessment of the fastener holes (see Section 2.3.2.2), with h is the height of the specimen in a test setup, and b is the width.

where d is the diameter of the fastener hole, and b is the width of the batten.

In contrast to the assessment threshold of 5 mm for knots in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.), fastener holes with a diameter of at least 2 mm but less than 5 mm (Group 1) were also assessed within this study. G1 holes appeared frequently, prompting us to investigate whether their occurrence influences bending strength. Fastener holes smaller than 2 mm, which can be based on the results of Böhm *et al.* (2025) mostly be expected to occur from staples, were neglected. They were not anticipated to impact either the mechanical properties or further utilization. To assess the effect of holes in small-cross-section timber more precisely, such a detailed differentiation of fastener holes has been chosen.

As shown in Figure 2, the number of fastener holes of both groups, G1 and G2, was counted along a length of 400 mm, divided into eight static windows (Z1–Z8) of 50 mm each. The window length was oriented on the assessment length for knot clusters in DIN 4074-1:2012. By assessing the fastener holes in static windows, it was aimed to investigate whether high frequencies of fastener holes (e.g. from truss connector plates) affect the bending strength more than single holes. Fastener holes visible on two sides were counted once, with the reference side being one of the specimen's face sides.

2.3.2.3. Assessment of insect infestation. Three battens out of 302 were affected by insect infestation. In these cases, insect infestations were present throughout the entire cross-section of the batten. The three affected battens were processed from the same salvaged rafters. Although the insect species was not identified, termite infestation can be excluded due to the regional context (Southern Germany). Due to the limited number of battens affected by insect infestation, the development of a quantitative threshold for a sorting criterion for insect infestation, which restricts hole size and radial and axial extension, was not possible. Instead, the presence of the insect infestation was considered as a qualitative criterion (present/not present).

Table 2. Overview of the applied sorting criteria and thresholds based on "grading rules for battens" in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.).

Sorting criterion	Visual grade	
	S10	S13
Knottiness KCB	≤ 0.50	≤ 0.33
Edge knot	not allowed[a]	not allowed[a]
Presence of pith	allowed[b]	not allowed
Growth ring width	≤ 6 mm	≤ 6 mm

[a]allowed for battens with a cross-section of 40 × 60 mm^2 up to an on the edge side measured knottiness of 0.33, except for edge knots visible on both face sides.
[b]for spruce

2.3.3. Four-point bending test

The battens were mechanically tested till failure in four-point bending according to EN 408:2012 (European Committee for Standardization n.d.-b). The mechanical tests were conducted within the framework of a master's thesis (Jubair 2025) at Holzforschung München. The deflection across the entire specimen length was measured at the midpoint of the battens, within the neutral axis, using fixed displacement transducers on both sides.

The bending strength, fm, was adjusted to a reference height of 150 mm (fm,150) as given in EN 384:2022 (European Committee for Standardization n.d.-e). The characteristic

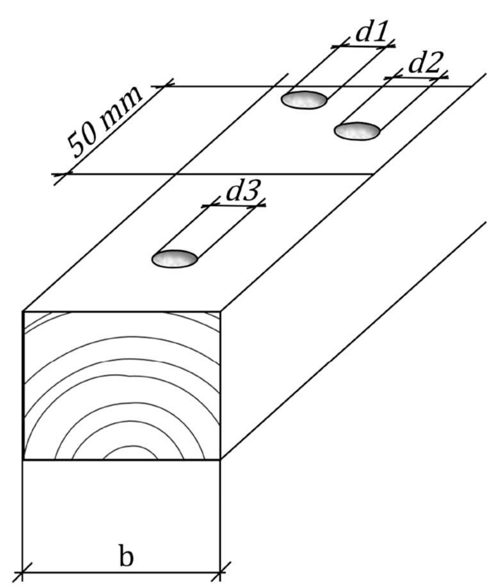

Figure 3. Measurement of the diameters (d) of fastener holes and the batten width (b) as a basis for the calculation of the perforation factor P.

bending strength, $f_{m,k}$, as the 5th percentile, was calculated for $f_{m,150}$, for each grade S10 and S13, and for rejects R, separated by test orientations, EW and FW. The calculation was performed based on the quantile-function in MATLAB (R2024b) (The MathWorks, Inc n.d.-a), which relies on a sorting-based algorithm and applies linear interpolation (The MathWorks, Inc. n.d.-b).

The global Modulus of Elasticity ($E_{m,global}$) was measured during the four-point bending tests. The density and moisture content were measured in oven-dry state on clear wood section cuts near the failure point. The sample was dried at 103 °C till reaching mass constancy as required by EN 13183-1:2002 (European Committee for Standardization 2002). The density was measured using buoyant measurement. Modulus of Elasticity and density were then normalized to a reference wood moisture content of 12% in accordance with EN 384:202 (European Committee for Standardization n.d.-e).

The local MOE ($E_{m,local,12}$) was calculated from the in EN 384:2022 (European Committee for Standardization n.d.-e) given relationship between the global MOE and local MOE for softwoods and is described in Equation (2). Studies have shown that the Modulus of Elasticity (MOE) for recovered wood is comparable to that of new sawn wood (Cavalli *et al.* 2016, Llana *et al.* 2023, Nocetti *et al.* 2024). Therefore, applying Equation (2) designed for new sawn softwood to recovered softwood is, to the author's understanding, considered valid.

$$Em, local, 12 = Em, global, 12*1.3 - 2,690 \quad (2)$$

In EN 1912:2013 (European Committee for Standardization n.d.-f), for new sawn Norway spruce, joists, or boards and planks (not battens), mainly loaded in bending in edgewise (EW) orientation, S10 is assigned to C24, and S13 to C30. An analogous assignment was checked for the battens within this study. The requirements for the grade-determining properties (GDP) of the strength classes C24 and C30 are specified in Table 3.

Table 3. Requirements on the characteristic values of the grade determining properties (GDP) for strength classes C24 and C30 in EN 338:2016 (European Committee for Standardization n.d.-d), with the following characteristic property values: $f_{m,k}$ is the 5th percentile of the bending strength, $E_{m,0,mean}$ is the mean bending MOE parallel to the fiber direction, and ρ_k is the 5th percentile of density.

		C24	C30
$f_{m,k}$	[N/mm^2]	24	30
$E_{m,0,mean}$	[kN/mm^2]	11.0	12.0
0.95*$E_{m,0,mean}$	[kN/mm^2]	10.5	11.4
ρ_k	[kg/m^3]	350	380

3. Results and discussion

3.1. Visual grading based on natural features

The VSG of 302 battens resulted in a total yield of 57%, with 33% yield of S13, and 24% of S10. The rest (43%) of the battens were rejected for exceeding the threshold of one or more sorting criteria. For the assignment, fastener holes were not considered. The sorting criteria for the knots, KCB and edge knot, were the sole decisive criteria for rejection. Out of 130 rejects, 70 (54%) were rejected due to the knottiness exceeding the allowable threshold of 0.50, and 36 rejects (28%) were rejected due to edge knots. In 24 cases (18%), the battens were rejected because they exceeded the thresholds of both sorting criteria. The growth ring width did not influence the grade of any batten. On average, the growth ring width of all battens across all sites was 2.9 mm, which is less than the threshold value of 6 mm. The average growth ring width of the individual rafters over all sites was between 1.0 and 4.6 mm. Each rafter's average growth ring width was calculated based on the growth ring width of all corresponding battens processed from it. The average growth ring width per site ranged from 1.9 mm to 3.3 mm. Therefore, the growth ring width can be described as homogeneous and without impactful outliers across rafters and sites. An influence of the year of construction or retrofitting was not observed. Of the 302 battens, 39 (13%) showed the presence of pith. 11 battens (4%) were downgraded from S13 to S10 solely due to the presence of pith. Due to the low impact of downgrading, it can be considered a less meaningful sorting criterion within this study.

A rejection rate of 43% shows that further optimization of the sawing pattern is recommended. All rafters were processed using the same approach in the sawing pattern orientation. However, by applying an individual optimized sawing pattern to each rafter, the total yield in S10 and S13 battens could be further increased. 28% of the rejects were solely due to edge knots. Analyzing the pith position when optimizing the sawing pattern can help reduce the number of battens with edge knots and related rejects. It is preferable to orient the sawing pattern so that the face sides of the battens face the pith, rather than the edge sides. This ensures that knots pass through the face side rather than the edge side, reducing the occurrence of edge knots. However, both knot criteria, knottiness KCB and edge knots, must be weighed against each other, as the value for KCB will also change. As exemplified in Figure 4, individualizing the sawing pattern with consideration of the pith location could effectively reduce rejections caused by edge knots. Furthermore, the cross-section could be used more effectively with its full capacity by generating more battens. It should be noted that this discussion is valid for the VSG according to DIN 4074-1 conducted in this study, and for MSG or other national VSG standards, the total yield and the requirements on an optimized sawing pattern would differ, since edge knots can be, in these cases, less significant or not significant at all.

3.2. Characterization of fastener holes

3.2.1. Diameter distribution

Within the total assessment area of 120.8 m (equating to 302 battens with each 400 mm hole assessment area) for all test pieces, 1025 fastener holes were recorded. This corresponds to 8.5 fastener holes in each running meter. About 96% of the fastener holes were assigned to Group 1 (2 mm $\le d <$ 5 mm) and 4% to Group 2 ($d \ge 5$ mm). 94.5% of the fastener holes were recorded on the face sides of the battens and 5.5% on the edge sides. However, the weakest section, placed in the middle third of the batten, was selected by the major natural features and/or the major fastener hole. Therefore, the counted distribution of fastener holes only represents

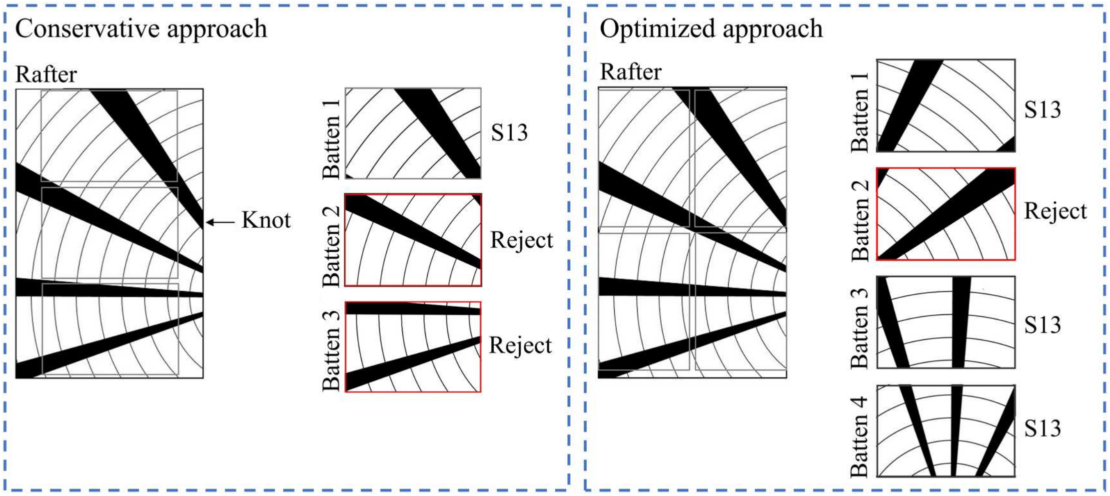

Figure 4. Exemplified sawing pattern optimization by considering the pith location, resulting in a reduction of the rejections caused by edge knots.

the middle third of the specimen and does not reflect the distribution across the entire board.

3.2.2. Fastener hole frequencies

A total of 2416 static windows were assessed, with a maximum of five fastener holes per static window. 70% and 98% of the static windows were unaffected by G1 or G2 fastener holes. For G1, fastener holes appeared in 20% of the cases once, in 8% twice, and in 2% of the cases three times per window. For two windows, the maximal frequency of five G1 holes was recorded. In 2% of the static windows, G2 holes appeared. A maximum of two G2 holes per window was recorded in two cases. The results reveal, particularly for G2 holes, a high share of windows unaffected by holes. Furthermore, larger holes (G2) appear occasionally, while smaller holes (G1) tend to appear in clusters.

3.2.3. Perforation factor P

The value for a perforation factor (P) was 0.0 for about 92% of the batten, as no G2 fastener holes appeared on the face sides or solely on the edge sides. For the remaining affected battens, P showed the following distribution: 4.6% of battens were within the range $0.10 \leq P < 0.20$, 1.7% within $0.20 \leq P < 0.30$, and 1.3% within $0.30 \leq P < 0.40$. Additionally, a perforation factor of $P = 1.00$ was observed in one batten, caused by a fastener hole that extended superficially between the two edge sides.

3.3. Mechanical properties from four-point bending test

3.3.1. Descriptive statistics

The bending test results are summarized in Table 4. In general, the achieved bending strength of S10 and S13 battens remained at the level of C24, with S10 battens slightly underperforming the requirements of C24. The bending strengths of both grades, S10 and S13, are similar for the EW and FW testing orientation. The characteristic value for the density (ρ_{12}), as the 5th percentile, of 350 kg/m^3 for C24 was achieved for the S10 battens of both grades. The characteristic MOE of 11 kN/mm^2 for C24 and 12 kN/mm^2 for C30 was met, except for one slight underperformance (S10 FW). Therefore, it can be agreed on the findings in the studies Cavalli *et al.* (2016), Llana *et al.* (2023), and Nocetti *et al.*(2024) that the MOE of recovered wood is comparable to the MOE of new-sawn wood. Results of rejected battens (R) are shown for reference only. In the following, to analyze the effect of fastener holes on the mechanical properties of timbers, only the battens graded to S10 and S13 are observed.

3.3.2. Influence of fastener holes on fm,k

With the aim of enhancing fm,k and matching the requirements of EN 338 for C24 (fm,k = 24 N/mm^2) and C30 (fm,k = 30 N/mm^2), the possibility of applying thresholds to the fastener hole diameter or frequencies needs to be checked. Therefore, Figures 5 and 6 show the relationship between the knottiness KCB according to DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) and the bending strength fm,150, with different criteria for fastener holes highlighted. Figure 5 shows the relationship highlighting the data for grouped perforation factors P for G2 holes, and Figure 6 highlights the specimens with different maximum frequencies of G1 holes in each static window. To investigate the influence of fastener holes on bending strength, the interaction between natural features, fastener characteristics, and bending strength was analyzed. In particular, for fastener holes larger than 5 mm (G2), the characterization step indicated that just a few battens contain those fastener holes of that group. Therefore, due to the small sample size affected, a statistical interpretation of the results was considered inconclusive.

3.3.2.1. Influence on fm,k highlighted by the perforation factor P (G2). The relationship shown in the scatter plots in Figure 5 follows a broad scatter with a coefficient of determination (R^2) of 0.159 for FW and 0.139 for EW across all grades. Figure 5 demonstrates that the knottiness (KCB) in general defines the grade classification: S13 for KCB values below 0.33, S10 for values between 0.33 and 0.50, and rejects for values above 0.50. However, there are some exceptions, as across the entire scatter, some specimens do not exceed the KCB knottiness threshold but are still graded as S10 or even

Table 4. Descriptive statistics (mean, SD, and 5th percentile (Q0.05) for the bending strength adjusted to 150 mm cross-section height (fm,150), density adjusted to 12% wood moisture content (ρ12), and local Modulus of Elasticity in fiber direction (Em,local,12), adjusted to 12% wood moisture content. Data is categorized by testing orientation and visual grade.

Orientation	Visual grade	fm,150 [N/mm^2]				ρ12 [kg/m^3]				Em,local,12 [kN/mm^2]			
		Number	mean	SD	$Q_{0.05}$	Number	mean	SD	$Q_{0.05}$	Number	mean	SD	$Q_{0.05}$
EW	S13	47	47.1	11.4	25.8	45	456	55	365	46	13.3	3.1	8.5
	S10	35	38.7	9.4	22.4	34	437	43	381	33	11.4	2.1	8.4
	R	76	34.2	10.0	18.6	76	438	44	367	75	10.7	2.4	7.3
FW	S13	52	45.3	12.0	25.0	51	459	54	375	50	12.9	2.8	9.0
	S10	38	37.5	9.7	23.5	37	437	52	364	35	10.6	2.5	7.5
	R	54	32.6	12.1	12.6	54	446	49	386	52	9.7	2.9	4.7

rejected. This is due to the presence of edge knots or pith. The edge knots are generally excluded from KCB knottiness calculations, as they typically do not appear on the face side. This exclusion contributes to the broader scatter observed, in addition to the already high variation for the KCB and bending strength.

Considering the color-coded interaction between a higher perforation factor P and the bending strength (Figure 5), for the EW testing, two affected S13 battens and no S10 battens show a reduced bending strength below 30 N/mm^2 and 24 N/mm^2, respectively. However, both S13 specimens were additionally weakened by distinct insect infestations. For the

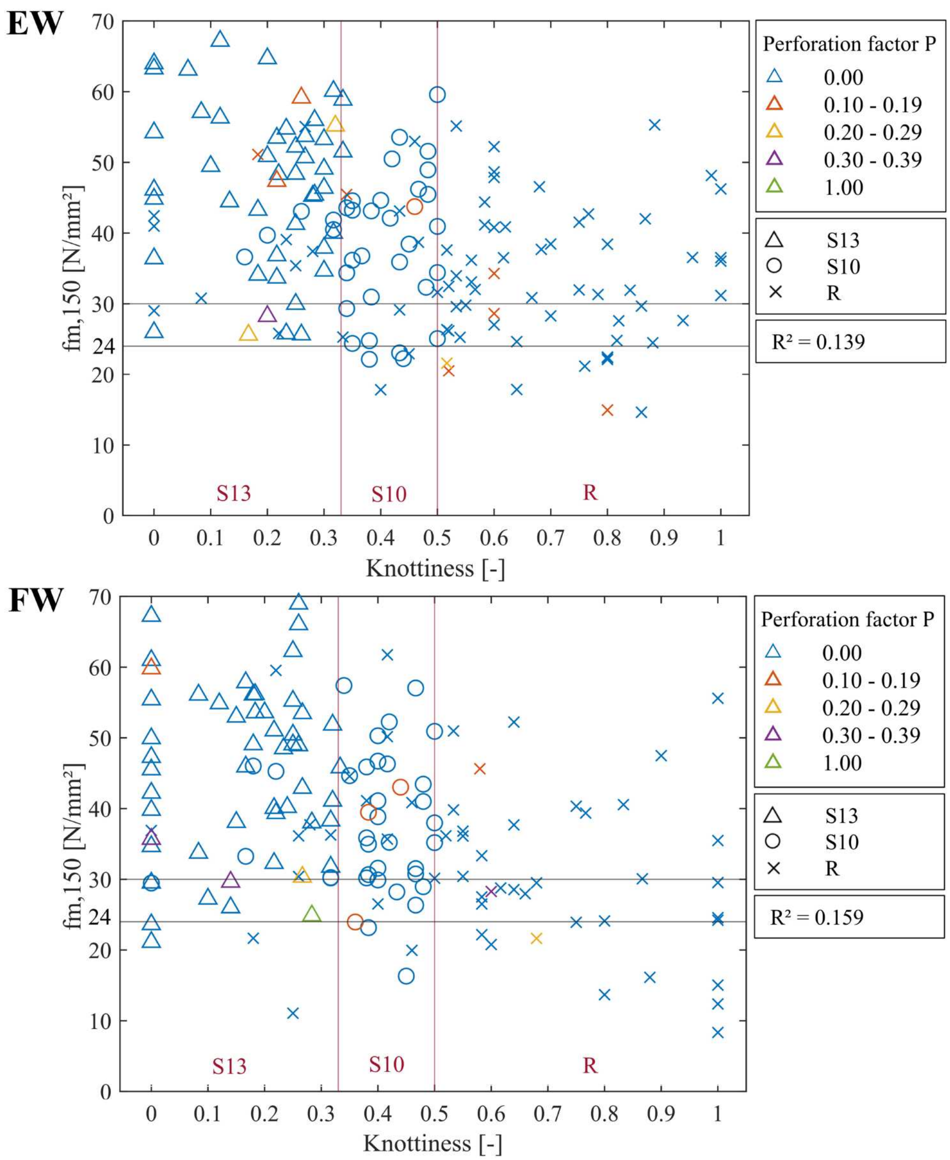

Figure 5. Relationship between fm,150, and the knottiness KCB for the edgewise (EW) and flatwise (FW) bending tests on 158 and 144 test pieces of Norway spruce, respectively. The results are grouped by their visual grade by markers, and by a grouped perforation factor P by color-coding. Vertical lines show the thresholds 0.33 and 0.50 for the knottiness KCB for S13 and S10, respectively. The horizontal lines show the reference bending strengths of 24 and 30 N/mm^2.

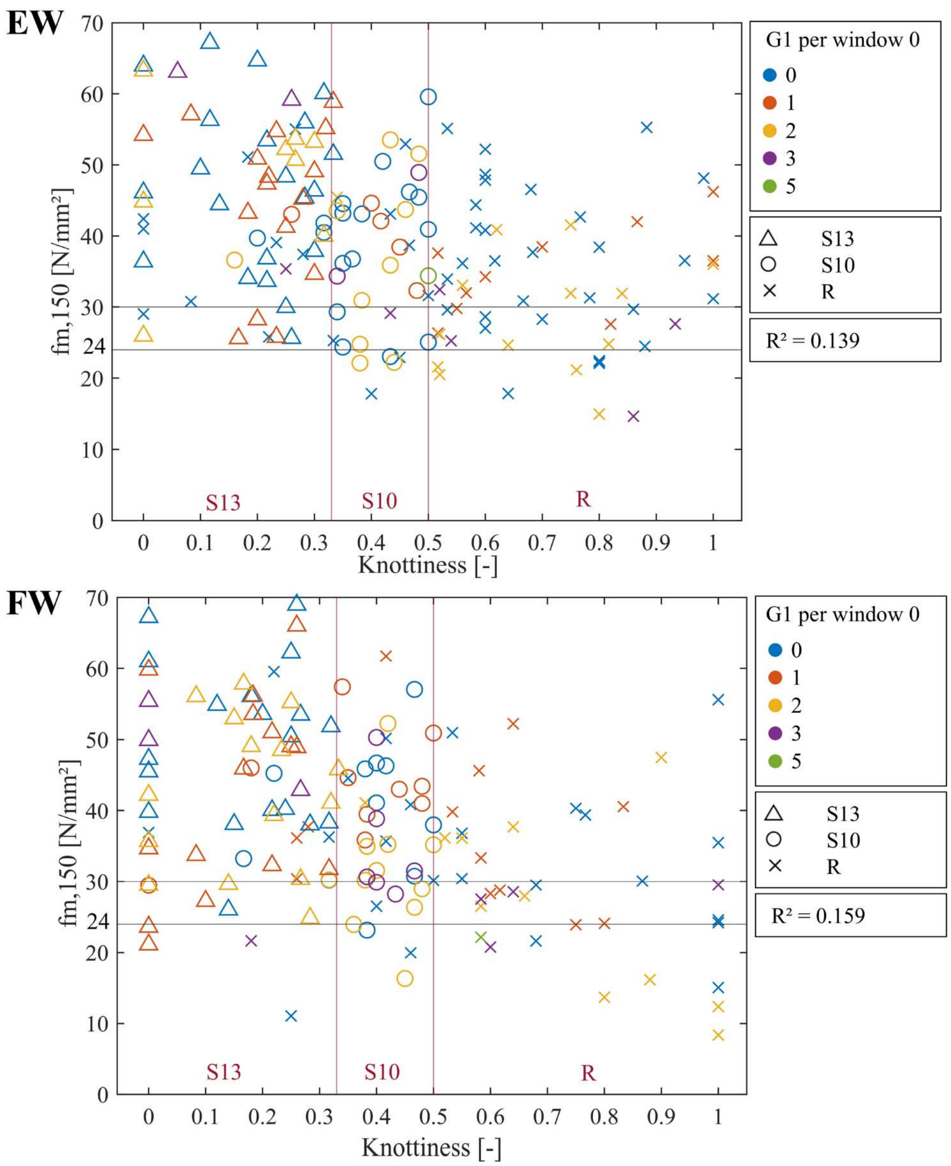

Figure 6. Relationship between fm,150, and the knottiness KCB for the edgewise (EW) and flatwise (FW) tests on 158 and 144 test pieces of Norway spruce, respectively. The results are grouped by their visual grade, as determined by markers, and by the maximum frequency of G1 holes per window, using color-coding. Vertical lines indicate the thresholds of 0.33 and 0.50 for the knottiness KCB of S13 and S10, respectively. The horizontal lines show the reference bending strengths of 24 and 30 N/mm^2.

FW testing, the strength-reducing effects, in correlation with the perforation factor P, are slightly more pronounced compared to EW testing, as indicated by the more affected S13 specimens, which surround the reference value of 30 N/mm^2, and one affected S10 specimen, with a strength corresponding to the reference value of 24 N/mm^2. Although an interaction and a lowering effect of the perforation factor P on bending strength is visible for some specimens, the bending strength of 24 N/mm^2 is never undershot.

3.3.2.2. Influence on fm,k highlighted by fastener hole frequencies (G1). Considering the color-coded relationship between the maximal frequency of G1 holes in each window and the bending strength (Figure 6), no or slight impacts are visible for the S13 battens in both testing orientations. However, the presence of G1 holes in clusters appears to affect the bending strength of grade S10 battens. The appearance arises from the observation that for a similar range of knottiness, KCB, S10 battens with higher G1 frequencies have a lower bending strength, fm,150, compared to those with low G1 frequencies. The observations can be made for the S10 battens of both testing orientations, whereby the observation is more pronounced for FW testing.

The effect of G1 hole frequency on bending strength varies by visual grade (S10 vs. S13) and testing orientation (EW vs. FW). In S10 battens, knots already weaken the test area through fiber deviations and density differences. Frequent perforations from small holes further reduce strength, favoring fracture. In S13 battens, with fewer knots, this influence is less pronounced. While perforations rarely cause failure alone, they contribute to the overall failure. Additionally, many G1 holes occur near the face side's neutral axis, making them less impactful in EW tests.

3.3.2.3. Summary of results for the influence of fastener holes on fm,k.

- Perforation factor P – Five battens of grade S13 were affected by fastener holes with a minimum diameter of 5 mm (G2), and which affected the characteristic bending strength of the sample, as it did not or slightly match the 30 N/mm^2 for C30. Their corresponding perforation factor were between 0.20 and 1.00, indicating for 30×50 mm^2 and 40×60 mm^2 cross-sectioned battens, a crucial fastener hole diameter of 10 mm and 12 mm, respectively. It is important to note again that the sample size of battens with G2 fastener holes affected was small (N = 24), and the battens were partly additionally affected by insect holes.
- Fastener frequency – Battens of grade S10 were weakened by the higher frequencies of G1 fastener holes; battens of grade S13 were slightly weakened for FW or not weakened at all for the EW bending orientation. Further investigations are needed to validate the weakening effect.

3.3.3. Evaluation of the fracture pattern

The visual evaluation of the fracture pattern over the entire batten length revealed that natural features were more often identified as the cause of failure than fastener holes or insect infestations. 82% of the battens failed due to natural features, especially knots. For 12%, fastener holes were taken as the sole criterion for failure. 5% failed due to the supportive impact of fastener holes in combination with knots. 1% of the battens (3 specimens) failed due to insect infestation or a combination of insect infestation and fastener holes, all originating from the same rafter.

The share of specimens with fastener holes as a failure cause increases with higher grades. For EW testing, 8% of the battens in grade R failed due to fastener holes, 20% of the battens in grade S10, and 26% of the battens in grade S13. For FW testing, 11% of the battens in grade R failed due to fastener holes, 16% in S10, and 31% in S13. Lower-grade battens may fail prematurely due to more pronounced natural features. For battens of higher grade, the fracture is attributed to fastener holes more frequently, as they contain fewer or no visible natural features.

Although some tests showed that the battens ultimately failed due to fastener holes, they exhibited high bending strength values exceeding 24 N/mm^2 or 30 N/mm^2. Since the holes were partly the only visible defects, they became the weakest link in the failure chain.

Table 5. Summary of the grading options for recovered wood, with the reference is built by DIN 4074-1:2012, which got added by rejection of battens with insect infestation (option 1) or rejection of battens exceeding the SRC threshold (option 2) or a combination of both step (option 1 and 2); results are sorted by tesing orientation and the visual grade, and are validated by remaining battens after each grading option and achieved characteristic bending strength (fm,k).

Orientation [–]	Visual grade [–]	Grading options		N [–]	fm,k [N/mm^2]
EW	S13	Reference	DIN 4074-1:2012	47	25.8
		+ option 1	Insect infestation	46	25.9
		+ option 2	SRC > 0.33	42	25.9
		+ option 1 and 2	Insect infestation and SRC > 0.33	42	25.9
	S10	Reference	DIN 4074-1:2012	35	22.4
		+ option 1	Insect infestation	35	22.4
		+ option 2	SRC > 0.50	38	22.6
		+ option 1 and 2	Insect infestation and SRC > 0.50	37	22.5
FW	S13	Reference	DIN 4074-1:2012	52	25.0
		+ option 1	Insect infestation	50	26.0
		+ option 2	SRC > 0.33	48	25.8
		+ option 1 and 2	Insect infestation and SRC > 0.33	46	28.8
	S10	Reference	DIN 4074-1:2012	38	23.5
		+ option 1	Insect infestation	38	23.5
		+ option 2	SRC > 0.50	38	24.4
		+ option 1 and 2	Insect infestation and SRC > 0.50	38	24.4

3.4. Proposed "grading rules for battens processed from recovered wood"

3.4.1. Insect infestation

Since DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) regulates new sawn timber, the standard covers exclusively insect holes from fresh-wood insects that infest standing trees and fresh roundwood. In the "grading rules for battens" within the standard, insect holes with a diameter of up to 2 mm are permitted for grades S10 and S13. An impact on the strength properties is, to the extent known, not expected by the standard. However, for recovered wood, our observations indicate that insect holes, which arose during the use phase, affect the bending strength. Due to the axial and radial extension found for the insect holes, an unrestricted rejection of affected battens is proposed for the "grading rules for batten processed from recovered wood", in line with the proposed regulations in NS 3691-3:2025 (Standard Norge 2025).

3.4.2. Fastener holes

3.4.2.1. Strength reducing criteria – SRC. Figure 5 indicates a reduction in the bending strength of S13 battens for perforation factors exceeding 0.2. For values greater than 0.2, S13 battens tend to fall below the threshold of 30 kN/mm^2. Based on these observations, a limitation of the perforation factor to 0.2 seems reasonable. The approach would cause a rejection of 30×50 mm^2 and 40×60 mm^2 battens containing fastener holes with diameters of 10 and 12 mm, respectively. The advantage of this approach is its simplicity of practical application. Furthermore, the approach creates an individual threshold for allowable hole diameters based on the specimen's width. The approach would allow larger holes for larger cross-sections, and vice versa. However, a major disadvantage of this approach is the neglect of the interaction with knots, which is of high importance, as shown by the results of Section 3.3.3. Battens without knots would be rejected due to the threshold exceeding holes, which may serve as a single sorting criterion, and therefore, without interaction with knots, as a minor influence on the bending strength. Given this disadvantage, we suggest incorporating a sorting criterion – strength reducing criteria SRC – that adds the knottiness KCB to the perforation factor P calculated for fastener holes with a diameter of at least 5 mm – see Equation (3):

$$SRC = KCB + P \, [-] \tag{3}$$

where KCB is the knottiness for Knot Cluster Battens, and P is the perforation factor (section 2.3.2). Both are the maximum within the assessment area. The threshold in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) of 0.33 for achieving S13 and 0.50 for S10, respectively, are retained and applied to the combined factor SRC. The maximum values for KCB and P are added within this study, independent of the actual axial position and relative proximity of both. This approach is suitable for the small cross-sectional specimens in this study, as the short testing and assessment length is similar to or even smaller than the free span of the underlying use scenarios of battens for substructure or roof battens. However, for larger cross-sections with greater free spans, the actual axial position and relative proximity of KCB and P need to be considered. An advantage of the general approach is that S13 battens shift, under consideration of the factor SRC, to the grade S10, without being completely rejected. A rejection would still occur if a single hole or its combination with the knottiness exceeds the threshold of 0.50.

As indicated in Table 5, fm,k increases slightly by considering SRC and the thresholds 0.33 and 0.50. For the EW testing, the modification steps appear less impactful than for FW testing, where the holes have more impact on the bending strength (Section 3.3.2). Regarding the number of specimens, a shift from S13 to S10 is visible, which is advisable in the context of efficient resource utilization and maximizing economic yield. The shift occurs when battens that first per DIN 4074-1:2012 to class S13 graded battens exceed in the subsequent step the sorting criterion SRC of 0.33, which disqualifies them from remaining in the S13 class. As long as the SRC does not surpass 0.50, the battens can still be classified as S10. However, if SRC exceeds 0.50, the battens are classified as rejects. The slight level of increase in fm,k is assumed to originate from the low share in battens, which contained G2 fastener holes, and were therefore considered for the calculation of P and SRC, respectively.

3.4.2.2. Fastener hole frequencies. Our suggestions for modification, limiting insect infestation and SRC, do not account for rejecting battens that exceed a certain threshold for G1 clusters. Table 6 illustrates the effect on fm,k and the number of specimens impacted by rejecting battens that contain clusters of more than two or three holes within a 50 mm window. For battens of grade S13, a rejection of battens with fastener hole clusters resulted in performance deterioration for fm,k rather than the intended optimization. In contrast, for the battens of grade S10, effective improvements in fm,k were achieved by removing battens with clusters of at least two G1 fasteners each window. The rejection of S10 battens with clusters of at least three holes in each window was ineffective. A slight improvement was indicated for rejecting battens with at least 2 holes in each window, and a slight negative impact was indicated for rejecting battens with at least 3 holes in each window for the grade S10 + . Grade S10 + is a common grade in trading visually graded timber and merges grades S10 and S13 to a grade "S10 and better", and the assignment of S10 + to C24 is being established. However, due to the, in general, low performance of rejecting battens with G1 clusters, an implementation in a standard for recovered wood is not proposed. Moreover, as shown by the results of grade S10+ is the threshold of 24 N/mm^2 even reached without the rejection of battens with specific G1 cluster frequencies.

Table 6. Characteristic bending strength (fm,k) of Norway spruce battens (S10, S13 and S10+) graded using different grading options: (0.) according to DIN 4074-1:2012, (1.) rejecting battens containing at least 2 fastener holes each window of 50 mm, and (2.) rejecting battens containing at least 3 fastener holes each window of 50 mm.

Testing mode [–]	Visual grade [–]	N [–]	Grading Options	fm,k [N/mm^2]
EW	S13	47	0. DIN 4074-1:2012	25.8
		37	1. G1 per window ≥ 2	25.7
		45	2. G1 per window ≥ 3	25.8
	S10	35	0. DIN 4074-1:2012	22.4
		22	1. G1 per window ≥ 2	23,9
		32	2. G1 per window ≥ 3	22.3
	S10+	82	0. DIN 4074-1:2012	24.6
		59	1. G1 per window ≥ 2	25.3
		77	2. G1 per window ≥ 3	24.5
FW	S13	52	0. DIN 4074-1:2012	25.0
		34	1. G1 per window ≥ 2	24.1
		49	2. G1 per window ≥ 3	24.8
	S10	38	0. DIN 4074-1:2012	23.5
		21	1. G1 per window ≥ 2	26.6
		32	2. G1 per window ≥ 3	23.2
	S10+	90	0. DIN 4074-1:2012	24.0
		55	1. G1 per window ≥ 2	24.2
		81	2. G1 per window ≥ 3	23.8

3.4.3. Recovered wood grade W10+

Table 5 showed a slight improvement in fm,k for each grade and testing orientation due to the suggested modification steps, including the introduction of a sorting criterion, SRC. However, except for the FW tested battens of grade S10, neither the reference threshold of 24 N/mm^2 nor 30 N/mm^2 was met, and therefore, the requirements for C24 and C30 were missed. To note again, the minor impact of the suggested modifications is assumed to be partly attributed to the small sample size affected by the G2 holes. However, to enhance practical relevance, further improvement is needed.

Since the requirements for C24 and C30 were not met despite the improvements from the suggested modifications, it is recommended to introduce a new, merged grade for recovered wood, W10+, alongside the suggested modifications regarding the sorting criteria. W10 + merges, similar to S10+, the visual grades S10 and S13, and is proven against a threshold of 24 N/mm^2. Furthermore, the introduction of the new class label W for visually graded recovered wood (where "Weiterverwendung", represented by the letter "W", is the German word for "continued use"), within the German national visual strength grading standard, is recommended. This label will help to differentiate recovered wood from new sawn timber in terms of strength values and emphasize the environmental benefits of cascade use within the context of the bioeconomy. A differentiation between new sawn and recovered wood also takes place in NS 3691-3:2025 (Standard Norge 2025), where, in contrast to the here proposed differentiation of the visual grade, a differentiation at the strength class level by the letter R is conducted (e.g. R24 instead of C24/T2). The use of existing strength classes for recovered wood should be checked and discussed in a broader context, considering the structural design.

Characteristic bending strength values of 24.6 and 26.3 N/mm^2 for EW and FW, respectively, were achieved for W10 + . 54% of the battens could be used for structural applications, which is just 3% less compared to the total yield of 57%, which was achieved after applying the existing "grading rules for battens" of new sawn timber of DIN 4074-1:2012 (Deutsches Institut für Normung n.d.).

3.4.4. Summary and conclusion for the visual grading of battens processed from recovered wood

The results show that battens processed from salvaged rafters can effectively be visually graded based on a combination of the existing sorting criteria (DIN 4074-1:2012), a new sorting criterion for fastener holes, and an, albeit non-conclusive, approach for insect infestation. By conventional visual grading, the processed battens were sorted to a strength (fm,150) and a stiffness (Em,local,12) level comparable to those of new sawn wood. However, merging the S10 and S13 of recovered wood battens into one grade, W10+, is proposed to match the requirements of C24 and improve the yields. Fastener holes and insect infestations should be considered for recovered wood, in addition to the established criteria for natural features outlined in DIN 4074-1. Fastener holes with a diameter below 5 mm (G1) can be neglected, despite their high frequency of occurrence. Fastener holes with a minimum diameter of 5 mm (G2) must be restricted in relation to the knottiness (SRC). Insect-infested battens are to be rejected alone due to their presence. Although the results showed only a slight increase in the characteristic bending strength, fm,k, using the proposed grading routine, which can be attributed to the small sample size affected by G2 holes and insect infestation, the grading framework shows promising results for the given sample. The grading routines proposed in the current study, as outlined in Table 7, can be viewed as an initial step towards extending DIN 4074-1 for the grading of battens processed from recovered wood. To prove itself, the SRC and the threshold need further validation on a larger sample size.

3.5. Limitations and outlook

The observations and the study design of this paper reflect the sawn wood type batten and the corresponding "grading rules for battens" of DIN 4074-1:2012 (Deutsches Institut für Normung n.d.). Further research is needed to investigate the applicability of the suggested grading routines on the recovered wood to the other sawn wood types with different applications, particularly to the "grading rules for boards" and the "grading rules for joists". It can be expected that the impact of the characterized fastener holes on the bending strength of the investigated small-dimensional timber will be less in larger cross-sectional lumber types.

Furthermore, the investigations are based on the processing of battens from salvaged rafters originating from Southern Germany, and thus cover the common fasteners used in this context. However, similar fastener holes are expected for other construction types (e.g. timber panel construction) and for geographical origins. Depending on the processing level, other man-made defects, such as mortise, must be expected.

Moreover, this study investigated a batch of recovered wood that was processed into battens through sawing and planing. The sorting criterion warp, which can be expected to be the main criterion for rejection for unprocessed recovered wood (Llana *et al.* 2023), was neglected since, through previous processing, warp would not have caused rejection in any case. However, in terms of the holistic applicability of the proposed grading rules to both processed and unprocessed battens, further investigations are needed for unprocessed battens.

Additionally, the results and conclusions of this study are limited to short-term strength and stiffness behavior. The long-term mechanical behavior of recovered wood needs to be addressed by taking into account the load history from the first service life. For new structural timber design, safety factors in combination with the duration-of-load factor kmod govern this for new sawn wood (European Committee for Standardization n.d.-c), but this needs to be modified for the design with recovered wood, as this material already has a load history from its first service life, which can only be estimated, see, e.g. (van de Kuilen 2007, van de Kuilen and Gard 2013).

To account for the load history and possible (non-visible) mechanical, physical, or biological degradation in a design process with recovered wood, strength-reducing safety factors must be applied, such as those on the load duration depending ones proposed by (Crews and MacKenzie 2008).

Finally, the CE-marking system to distinguish recovered structural timber from new structural timber is needed. For that, it is proposed that new sawn wood be marked as C24, in-situ graded wood as C24-IS, and recovered wood as C24-R.

Table 7. Proposed sorting criteria for battens processed from recovered wood of the wood species Norway spruce, which were previously sorted to visual grade S10 or S13 based on the "grading rules for battens" in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.).

Sorting criterion	Visual grade W10+
Fastener hole, d < 5 mm	allowed
Fastener hole, d ≥ 5 mm	SRC ≤ 0.50
Insect infestation	not allowed

4. Conclusion

The "grading rules for battens" of DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) can be modified for an application on battens processed from recovered wood, particularly salvaged rafters, and meet the requirements of C24 as done for new-sawn battens of Norway spruce, and as proposed in the present paper.

The natural features in 302 battens processed from salvaged rafters were characterized by high knottiness and the presence of edge knots, and resulted for the conventional grading procedure according to DIN 4074-1:2012 (Deutsches Institut für

Normung n.d.) in a total yield of 57% for battens of grades S10 and S13 (S10+).

The man-made defects were due to the prior processing level within the present study, and thereby the cutting out of carpentry connections and mechanical defects, limited to fastener holes. 2416 windows of each 50 mm were assessed, for which in 70% no G1 holes (2 mm ≤ d < 5 mm) and for 98% no G2 (d ≥ 5 mm) holes occurred. In general, 39% of the battens were recorded as having no fastener holes. However, small holes were recorded at a high frequency on battens cut from the built-in upper side of the salvaged rafters. Furthermore, small holes tend to appear in clusters, while larger holes appear occasionally.

Small (G1) but frequently occurring fastener holes weakened the bending strength of grade S10 battens processed from recovered wood; however, just to such an extent that they are negligible, as the threshold for the characteristic bending strength of 24 N/mm^2 is achieved despite their limitation. Larger fastener holes (G2) weakened the bending strength of the higher-grade battens, S13. For the lower-grade battens, S10, no crucial weakening influence was observed.

The "grading rules for battens" in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) are proposed to be modified for their applicability on battens processed from recovered wood by introducing a sorting criterion for fastener holes. Fastener holes smaller than 5 mm will be neglected. Fastener holes of at least 5 mm will be assessed by their diameter, similar to the assessment of knots in DIN 4074-1:2012 (Deutsches Institut für Normung n.d.). A limitation is proposed by setting a threshold for a newly introduced sorting criterion, SRC, which considers the interaction between knottiness and a hole-to-batten-width ratio, described by a perforation factor P, by adding both. A threshold for SRC of 0.50 is proposed to align with the requirements of the strength class C24. Additionally, a general rejection of battens, affected by insect infestation during the built-in phase, is proposed. Moreover, a notation for visually graded recovered wood with the letter "W" is proposed within the German standardization framework. The modification to DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) has proven itself based on the sample size within this study. 54% of the battens yield grade W10 and better (W10+) with an average characteristic bending strength of 24.6 N/mm^2 (EW) and 26.3 N/mm^2 (FW). However, due to the low sample size, in battens containing fastener holes of at least 5 mm or battens infested by insects, further validation of the proposed modifications to DIN 4074-1:2012 (Deutsches Institut für Normung n.d.) by larger sample size is needed.

Author contributions

CRediT: **Florian Scharpenack:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft; **Andriy Kovryga:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing; **Jan-Willem van de Kuilen:** Project administration, Supervision, Writing – review & editing.

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Data availability statement

Data will be made available on request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Grammarly and DeepL Write in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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