

Mechanical properties of secondary lumber of Norway spruce

Böhm, Florian; Jubair, Sajjad; Kovryga, Andriy; van de Kuilen, Jan Willem

DOI

[10.52202/080513-0298](https://doi.org/10.52202/080513-0298)

Publication date

2025

Document Version

Final published version

Published in

Proceedings from the 14th World Conference on Timber Engineering

Citation (APA)

Böhm, F., Jubair, S., Kovryga, A., & van de Kuilen, J. W. (2025). Mechanical properties of secondary lumber of Norway spruce. In K. Rischmiller, M. A. Saleem, C. Downey, J. Gattas, D. Hossy, L. Ottenhaus, W. Wu, Y. Zhang, & Z. Yan (Eds.), *Proceedings from the 14th World Conference on Timber Engineering: Advancing Timber for the Future Built Environment, WCTE 2025* (pp. 2444-2453). World Conference on Timber Engineering (WCTE). <https://doi.org/10.52202/080513-0298>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

**Green Open Access added to [TU Delft Institutional Repository](#)
as part of the Taverne amendment.**

More information about this copyright law amendment
can be found at <https://www.openaccess.nl>.

Otherwise as indicated in the copyright section:
the publisher is the copyright holder of this work and the
author uses the Dutch legislation to make this work public.

Mechanical properties of secondary lumber of Norway spruce

Florian Böhm¹, Sajjad Jubair², Andriy Kovryga³, Jan-Willem van de Kuilen⁴

ABSTRACT:

Extending the service life of building components is essential for a circular economy. Wood, as a renewable raw material, plays due to its mechanical properties and ease of processing a crucial role in this process. Most studies focus on the reuse of building materials. However, it is essential to detect and investigate the use cases in which reuse is impossible due to changing dimensional requirements or damages. This study examines the bending properties of recovered wood, particularly battens with cross-sectional dimensions of 30x50 mm², which were processed from rafters originating from a roof truss deconstructed in southern Germany. The bending tests were performed and interpreted based on the damages of the prior use and the lumber pieces' background information. The visual observation resulted in many fastener holes, mainly derived for battens from the built-in upper layer of the rafters. Even though fastener holes contributed to or were the single cause for the failure of the battens, bending strength around the mean value or even higher was yet achieved for some battens. Developing unique sawing patterns for each rafter by taking into account the location of the pith and the arrangement of knots can enhance the yield. Additionally, introducing a third grade, S7, alongside the existing S10 and S13 grades - similar to the approach used for joists and boards in DIN 4074-1:2012 - could further optimize yield. Although it has been concluded that knots remain even for recovered wood the key sorting criteria, fastener holes, can additionally influence the mechanical properties and, therefore, need to be considered in a standardized strength grading.

KEYWORDS: recovered timber, waste wood, bending strength, circular economy, cascading

1 – INTRODUCTION

In Germany, about one-fifth of the load-bearing structures in residential buildings are predominantly made out of wood, and their share continuously increases [1]. Most of the structural components come from softwoods, primarily the Norway spruce. Disregarding the high availability, the predominant role of spruce is about to change, as spruce stands are highly affected by biotic and abiotic forest stresses, and more and more forestry areas are covered with more climate-tolerant wood species [2]. Utilizing alternative wood species and incorporating circular designs in construction, along with recovered building materials such as recovered wood, can effectively address potential bottlenecks in structural timber supply. Recovered wood will be available in large quantities in the future [3–5], and, moreover, its cascade

utilization will provide more environmental benefits than primary wood utilization [6, 7].

The primary approach in the waste hierarchy is to prevent waste [8]. However, when prevention is no longer possible, the recovered materials must be managed appropriately, for instance, at the end of a building's lifetime. According to the 9R framework proposed in [9], one main objective of a circular waste management approach is to extend the lifetime of materials by their reuse (R3). Reuse, in this case, refers to the unprocessed utilization of the components without changing the initial functionality [9]. For wood, extended material use leads to an increased carbon storage life, which is beneficial for reaching sustainability goals.

¹ Florian Böhm, School of Eng. and Design, Dept. Materials Eng., TU Munich, Munich, Germany, florian.boehm@tum.de

² Sajjad Jubair, School of Eng. and Design, Dept. Materials Eng., TU Munich, Munich, Germany, sajjad11.jubair@tum.de

³ Andriy Kovryga, School of Eng. and Design, Dept. Materials Eng., TU Munich, Munich, Germany, kovryga@hfm.tum.de

⁴ Jan-Willem van de Kuilen, School of Eng. and Design, Dept. Materials Eng., TU Munich, Munich, Germany / Biobased Structures and Materials, Delft University of Technology, Delft, the Netherlands, vandekuilen@hfm.tum.de

The idea of reusing recovered wood is widely discussed in research. In [10], 19 unprocessed recovered Norway spruce rafters were assessed with the aim of further application. Although the rafters, which have been used since 1949, could be assigned to the strength class C24 by destructive testing, the visual quality has led to a rejection rate of 95%, mainly due to twists. In [11], 45 recovered wood components from a roof truss of 1769 were assessed. The investigated components were mostly rafters made of Salzmann pine timber. The findings revealed that due to the deformation, a rejection rate for visual strength grading of about one-third significantly reduces the potential for reusing recovered wood. This confirms the findings in [12]. In [12], the further processing of recovered wood to sawn wood material and, therefore, in particular, the material yield was investigated. The study refers to the material - rafters - being processed after recovery to battens and boards. Also, in this study, deformation in the investigated rafters has led to a decrease in the reuse potential, categorized by a loss in the material yield of 11%. Additionally, cross-section reductions due to the wood joints, such as birdsmouth cuts at supporting points, reduced the reusable length of the material.

Besides the above-mentioned aspects, such as the deformation and, therefore, non-rectangular shape of cross-sections, variations in cross-section dimensions along the length [13, 14] and the presence of wane [15] are additional limitations for potential reuse. Furthermore, it is assumed that the dimensions of regionally available recovered wood often do not meet the requirements for subsequent use, as building designs are quite individual. These aspects make reusing recovered wood in structural application difficult or even sometimes impossible. Therefore, processing of recovered wood would enable the further utilization of the material in a solid reshaped form or as feedstock for wood-based panels or engineered wood products (EWP).

Several studies demonstrated that EWP from recovered wood, such as cross-laminated timber (CLT), represents a promising solution for high-quality wood cascading. In [16], recovered European oak beams with a cross-section of 146x164 mm² from a 200-year-old building demolished in Spain were processed into boards with a cross-section of 20x100 mm². The boards were used to produce CLTs, which were then tested for their mechanical properties and compared to reference CLTs made from fresh-sawn timber of the same wood species. Although the determined bending strength of CLTs made from recovered wood was lower than that made from primary wood, the values would still fulfill the

requirements for a structural application. In [17], recovered softwood timber alongside a later application in CLT was assessed. Since the requirements for bending properties were fulfilled, the suitability for utilizing recovered wood in CLT production for structural application was also demonstrated in this study. In [18], they included the deterioration from previous use (e.g., fastener holes) in their investigation of the utilization potential of recovered wood in CLT application. The results from finite element modeling (FEM) for compression stresses showed that minor defects, in frequencies to be found usually for recovered wood, have a minor influence on the MOE (< 6%), and several more minor defects degrade the MOE less than one large defect.

Besides the application of processed recovered wood in EWP, the possibility of using it as a final product without any further gluing should be considered as well. Therefore, this study investigates the properties of battens processed from recovered rafters of a roof truss of a residential building in southern Germany. The battens were processed during a broader study conducted [12]. This study aims to identify crucial visual sorting characteristics for battens processed from recovered wood. Therefore, the existing German visual strength grading standard DIN 4074-1:2012 [19] was applied and extended with the recording of fastener holes. The results of visual strength grading were validated by calculating the dynamic MOE of the battens by applying ultrasonic and longitudinal vibration measurements. Furthermore, edgewise and flatwise four-point bending tests were conducted. Taken together, the objectives of this study are as follows:

1. What is the frequency and size distribution of the fastener holes in recovered wood from rafters?
2. How do the fastener holes affect the mechanical properties of recovered wood battens, and how is it related to the effect of the knots?
3. Can the mechanical properties of recovered wood battens be reliably assessed by a visual strength grading?

2 – BACKGROUND

Visual strength grading (VSG) is Central Europe's most common and widespread method for assessing wood quality. The visual grades are assigned based on the visual criteria correlated to the strength, such as knots and fibre deviation. Within the European framework of the timber strength grading standards, EN 14081-1 [20], national visual grading standards cover the visual grading rules (e.g., DIN 4074-1, UNE 56544, NF B52001-1, BS

4978). These standards provide sorting characteristics for evaluating fresh-sawn structural timber and are not valid for the recovered wood.

The sorting characteristics in recovered wood are missing when assessing impurities and deterioration from previous use. Studies applied existing visual grading standards to unprocessed recovered wood [10, 11]. They resumed that existing standards are improper for grading recovered wood as the high rejection rate does not reflect the actual strength of the material. Therefore, [10] assumed that prior processing of recovered wood by four-sided planing would significantly reduce the rejection rate due to wane and warp. However, as [16] investigated, the processing of recovered wood, particularly re-sawing of the timber, may increase the value of the knottiness criteria and lead to the rejection of the recovered wood as the impact of a knot becomes more pronounced as the cross-section decreases. This observation heavily depends on the initial quality and knottiness of the recovered wood, suggesting that, in some cases, the material might be unsuitable for structural purposes even before processing.

Grading standards for recovered wood, including deterioration from previous use, are non-existent to the authors' knowledge. The only existing standard is a draft created by the Norwegian Standardisation Body [21] for the visual strength grading of recovered wood and, therefore, provides an initial outlook on assessing deterioration from previous use.

The definition of criteria that fit the recovered wood is within the scope of the current research activities. [22] identified crucial diameters and areas for fastener holes. They observed that there are not any deteriorations associated with the small diameter fasteners (less than 3 mm), which were comparable to the main diameter findings from [12] of about 3 mm.

To enable the successful VSG of recovered timber and in further steps to enable the harmonized grading practices, advanced grading characteristics that fit the specific nature of the recovered wood need to be further developed. Therefore, experimental testing on recovered wood specimens is required to better incorporate the influencing factors, such as damages (e.g., fastener holes) and deterioration due to environmental impacts (e.g., moisture and temperature fluctuations, load history).

3 - PROJECT DESCRIPTION

The current paper addresses the materials of a single site within a broader sampling conducted by [12]. 54 rafters

were recovered from five building demolition and five roof truss deconstruction sites. The building demolitions occurred as existing structures were replaced with new ones, while the roof truss deconstruction was primarily preparatory work for future building extensions. Building demolitions were executed using heavy machinery, such as excavators. Roof truss deconstruction was executed to preserve the existing building below. Different kinds of saws, crowbars, and (mainly) one crane were used for manual dismantling. Some structures were dismantled down to the rafters before deconstruction, while others had entire elements removed (Figure 1). The buildings observed were mainly residential, except for one hotel. The roof trusses in these buildings were either erected or retrofitted between 1956 and 2001. The initial cross-section dimensions of the rafters ranged from 75 mm to 115 mm in width and from 115 mm to 170 mm in height.



Figure 1. Recovered rafter fixed to deconstructed roof element initially erected in 1956. The cross-section of the rafter was 75x115 mm².

All fasteners and attachments were manually removed in a laboratory at the Technical University of Munich. Commercial standard tools, such as crowbars and pliers, were used for this process. The recovered rafters were then processed into battens and boards with cross-section dimensions of 30x50 mm², 40x60 mm², and 30x90 mm². A table saw, jointer, and thickness planer were utilized for wood processing. In the final processing step, reductions in cross-section were cut out from the battens. However, fastener holes and cracks remained in the samples. 447 battens and boards with a total length of 881.0 m remained after processing of the rafters (Figure 2). At this point, the sample length was not standardized. Most samples varied in length, with sample lengths ranging up to 4.0 meters. All battens were stamped with a unique code containing information about the dedicating site, rafter number, and

whether the batten was cut from the rafter's built-in upper (compression) or lower (tensile) site. Furthermore, the battens were stamped on the edge of one of the flat surfaces, indicating the reference surface for further investigations (Figure 3).



Figure 2. Final battens and boards after processing.

For each rafter, sections in all three anatomical directions were manufactured using a sliding microtome. The anatomical structures of the sections were then analyzed using light microscopy. Based on anatomical characteristics, a wood species was assigned to each rafter using an identification key for coniferous wood [23]. The wood species identification showed that 52 of the 54 investigated rafters were of the wood species spruce (*Picea abies*/spp.). Two more rafters were identified as fir (*Abies alba*/spp.). Further and more detailed information about the materials and their described processing can be found in [12].

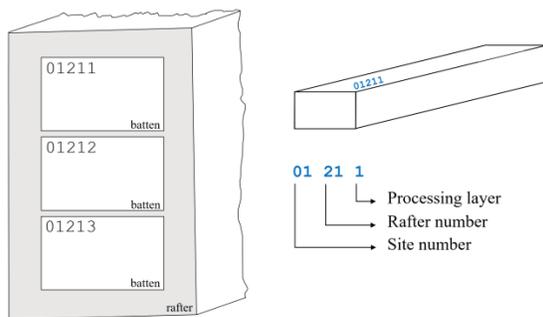


Figure 3. Representation of the systematic sample coding by stamping.

This conference paper investigates the visual, non-destructive, and bending properties of 44 battens

processed from a roof truss built in 1956. The cross-section dimensions of the battens were 30x50 mm². The battens were processed during an investigation in [12]. The data was collected at and with the help of the staff of Holzforschung München and within a Master's thesis [24].

4 - EXPERIMENTAL SETUP

4.1. GENERAL ON THE TEST PROGRAM

The experimental testing included the non-destructive testing of the material, such as the assessment of the visual and machine grading parameters, particularly the dynamic MOE. In addition to the existing standardized visual grading criteria, non-standardized sorting criteria for recovered wood (e.g., fastener holes) were recorded. Finally, the mechanical properties from edgewise and flatwise bending tests were determined in edgewise and flatwise four-point bending tests till failure.

4.2 VISUAL STRENGTH GRADING

The specimens were visually graded following the visual grading rules for battens of the German visual grading standard DIN 4074-1:2012 [19]. This includes the criteria for the three major properties correlated to the mechanical properties: knots, presence of pith, and growth ring width. The standard categorizes softwood battens into the grades S10 and S13. In contrast to categorizing boards, a grade S7 does not exist.

The regulations are as follows:

- Knots. To achieve grade S13, the knot width, measured parallel to the edge, must be smaller or equal to one-third of the batten's width; for grade S10, smaller equals half of the batten's width. Knots running from one edge surface to the opposite one are not permitted for battens with a diameter of 30x50 mm².
- Growth ring width. A growth ring width of less than 6 mm is necessary for both grades.
- Presence of pith. For the presence of pith, samples of spruce get graded into S10.

The battens were visually graded in the area between the loading heads and an additional length similar to the battens' width (Figure 4). The weakest point was placed inside the bending test specimen during the sample preparation.

All knots from a diameter of 5 mm were measured and recorded manually at the laboratory. Knot positions and dimensions were managed using knot assessment

software developed and hosted by Holzforschung München of the TUM. This software displays the cross-section of each knot in relation to the cross-section of the batten (Figure 5). Using this information, the proportion of the knot's width in relation to the width of the batten can be calculated. Additionally, the software can identify knots extending from one batten's edge to the opposite edge (Figure 6).

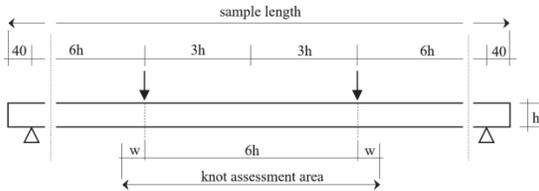


Figure 4. Graphical representation of the knot assessment area, where w is the width, and h is the height in millimetres.

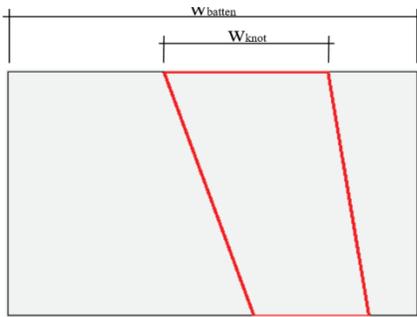


Figure 5: Visualisation of the knot cross-section (red) in relation to the batten's cross-section (grey/black) for a vertical running knot, where w is the width

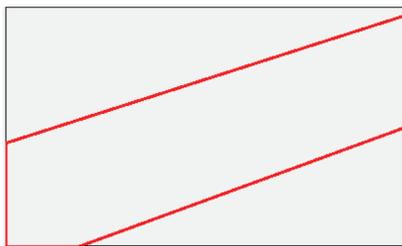


Figure 6: Visualisation of knot cross-section (red) in relation to the batten's cross-section (grey/black) for a knot, running from one edge to the opposite one

4.3 ASSESSMENT OF NON STANDARDIZED VISUAL CRITERIA

Since reductions in the cross-section (e.g., birdsmouth) were already cut off during processing, additional, non-standardized visual criteria could be constricted to fastener holes. The record and assessment of fastener holes were done two times. First, the fastener holes were recorded and assessed over the entire length of the battens

and not only over the standardized length of the bending test samples. Therefore, the number of fastener holes in each batten was counted. Second, the record and assessment of fastener holes were conducted over 400 mm in the middle of the sample. The recording and assessment length was divided into eight zones, each with a length of 50 mm (Figure 7). Fastener holes were categorized into the following two groups. Since no impact on the mechanical properties is expected from fastener holes smaller than 2 mm, this group of fastener holes was neglected. The first group (Group 1) contained fastener holes with a diameter between 2 mm and less than 5 mm. The second group (Group 2) contained all fastener holes with diameters larger than 5 mm. Fastener holes of Group 1 were assigned to one of the eight assessment zones (Z1-Z8). The exact position of the fastener holes of Group 2 was recorded, and an additional assignment to one of the zones was conducted. Fastener holes generally do not run vertically or horizontally through the battens. Therefore, the same fastener holes can appear on opposite or adjacent surfaces in different zones. Due to this, fastener holes were always allocated to the stamped top side of the batten (Figure 2).

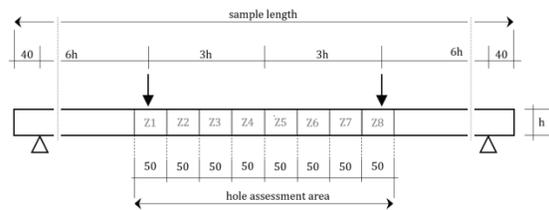


Figure 7. Graphical representation of the knot assessment area, where Z indicates the assessment zones, each with a width of 50 mm, and h represents the height in millimeters.

4.4 DYNAMIC MEASUREMENT

After processing, the full-length battens' dynamic Modulus of Elasticity (E_{dyn}) was determined based on ultrasonic (US) and longitudinal vibration (LV) measurements. The ultrasonic measurement of the E_{dyn} ($E_{dyn,US}$) is based on the insight that local grading characteristics in wood reduce the propagation speed of ultrasound traveling in the longitudinal direction [25]. According to the propagation speed (v) and the density (ρ), $E_{dyn,US}$ was calculated (Equation 1). The propagation speed was measured using a transmitter with a frequency of 30 kHz and a receiver at the face of the elastically on a foam-supported sample. Both transducers were connected to a *Sylvatest* device.

$$E_{dyn,us} = v^2 \cdot \rho \quad (Eq. 1)$$

The longitudinal vibration measurement of the E_{dyn} ($E_{dyn,LV}$) was induced by a hammer hit and recorded by a microphone. Fast Fourier-transform (FFT) transferred the recorded time-dependent signal to a frequency-dependent signal. Based on this signal, the first eigenfrequency was determined. The $E_{dyn,LV}$ was calculated according to Equation 2, where (l) is the length, (f) is the eigenfrequency, and (ρ) is the density.

$$E_{dyn,LV} = 4 \cdot l^2 \cdot f^2 \cdot \rho \quad (Eq. 2)$$

4.5. DESTRUCTIVE TEST

The bending properties of the battens, both edgewise and flatwise, were evaluated through four-point bending tests following the EN 408:2012 [26] standards. The samples were cut to the dimensions depicted in Figure 4. The distance between the supporting points was set at eighteen times the sample height (18h) plus an additional 40 mm on each side. Before the bending tests, the samples were conditioned at a temperature of 20°C and a relative humidity of 65%. After conducting the bending tests, a clear wood specimen was sliced across the entire cross-section near the point of failure. This wood slice was then oven-dried at 103°C until it reached a consistent mass. The wood's moisture content and density were calculated by weighing the samples and determining their volume through gravimetric measurements.

5 – RESULTS

5.1 VISUAL STRENGTH GRADING

The assignment of the 44 investigated battens according to the German standard DIN 4074-1:2012 [19] for visual strength grading of softwood resulted in a total yield of 41%. The yields to the individual visual grades are shown in Figure 8. The yields to S13 account for 16%, whereas 25% of battens were assigned to S10. The share of rejects is with 59% high, as one or more requirements on the sorting criteria were not met.

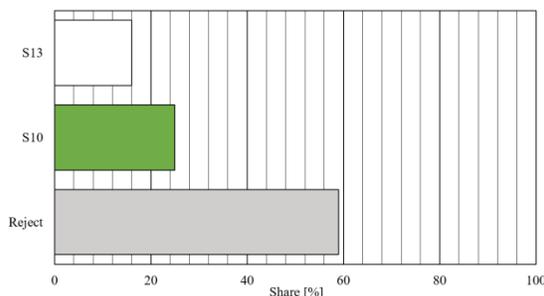


Figure 8. Share of the visual grades S10, S13, and Reject according to the visual grading of the battens according to DIN 4074-1:2012

The sorting criteria for knot holes, the presence of pith, and growth ring width were assessed. The major rejection criterion for the battens was the knottiness, as 54% of the rejected battens were discarded due to knot share exceeding half of the batten's width. On average, the knottiness of all battens was 0.52. Additionally, 23% of the rejected battens were discarded due to the non-allowable knot type – knot appearing on both narrow face sides. In contrast, another 23% of the rejected battens were discarded for exceeding the threshold for both knot size and type criteria. As for no case, the growth ring width exceeded the threshold of 6 mm, this sorting criteria did not influence the grading of the battens. On average, the growth ring width was 2.7 mm, which shows a high quality regarding this sorting criterion as it is for softwood correlated to the density.

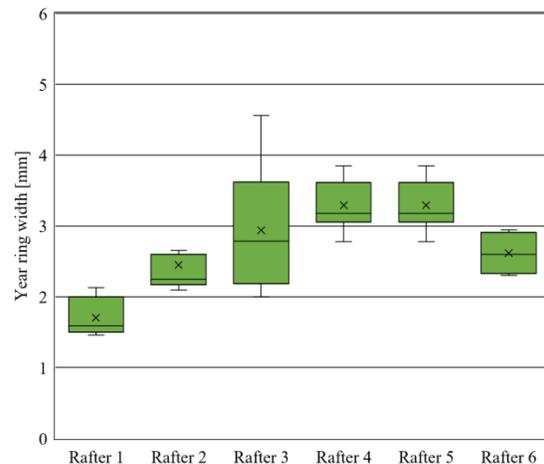


Figure 9. Boxplot of the growth ring width in millimeters for each rafter

The average growth ring width of each rafter shown in Figure 9 was between 1.7 mm (Rafter 1) and 3.4 mm (Rafter 4). The results indicate that the growth ring width of all rafters was quite similar, without significant outliers.

5.2 ASSESSMENT OF NON STANDARDIZED VISUAL CRITERIA

In the 44 investigated battens, totaling 69.3 running meters, we recorded 765 fastener holes with diameters ranging from 2 mm to less than 5 mm (Group 1). Additionally, we recorded 43 fastener holes with diameters of a minimum of 5 mm (Group 2). On average, there were 11.0 fastener holes per running meter for Group 1 and 0.6 fastener holes per running meter for Group 2.

However, as shown in Figure 10, the results indicate that the fastener holes of Group 1 fasteners highly impacted the battens cut from the build-in upper layer of the recovered rafter compared to battens cut from the built-in lower layers. On average, each rafter 113.0 fastener holes occurred in battens cut from the upper layer. In contrast, each rafter 14.5 fastener holes were found on average for battens cut from the lower layers.

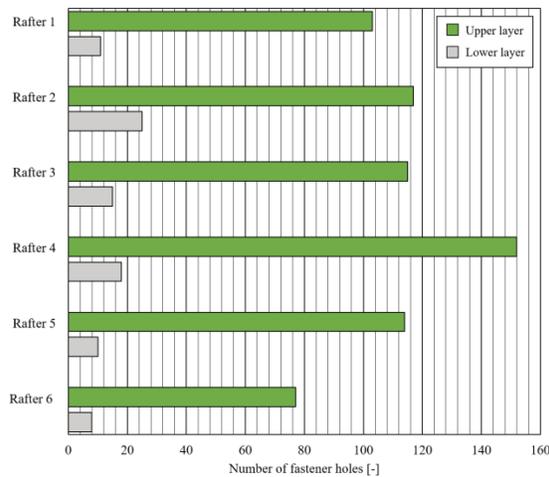


Figure 10. Number of fastener holes of Group 1 per rafter, displayed for battens cut from the built-in upper and lower layer of the rafter.

Based on the characterization of the fasteners removed from the recovered rafters by [12], it was shown that nails can be expected in recovered rafters especially. Nails were mainly used to fix the roof boarding on the rafters. The findings are reflected in this study as well. However, it was also shown by subdividing the number of fastener holes in upper and lower layer battens that the nail length and, therefore, the penetration depth influence the mechanical damage to the material.

5.3 NON-DESTRUCTIVE TESTING

The results of the non-destructive testing, which included longitudinal vibration (LV) and ultrasonic measurement (US), are displayed in Figure 11. For $E_{dyn,US}$, the average value across all battens was 14,505 N/mm², while for $E_{dyn,LV}$, the average was 12,230 N/mm². The coefficient of variation (COV) was 15% for $E_{dyn,US}$ and 17% for $E_{dyn,LV}$, indicating that these values are consistent with the ranges found in previously conducted tests. However, for each rafter's battens, the values for $E_{dyn,US}$ were about one-fifth (13-23%) higher than those achieved for $E_{dyn,LV}$. On average, the results for $E_{dyn,US}$ were 16% higher. This observation that the values of $E_{dyn,US}$ are higher than those of $E_{dyn,LV}$ is consistent with previous test results. When we compare the measured values to the data presented in

EN 338:2016 [27] Table 1, we find that the battens generally exceed the thresholds for the mean value of C24 (11,000 N/mm²). Additionally, the data in [28] indicates that the MOE for Norway Spruce is typically higher than the values specified in the standard.

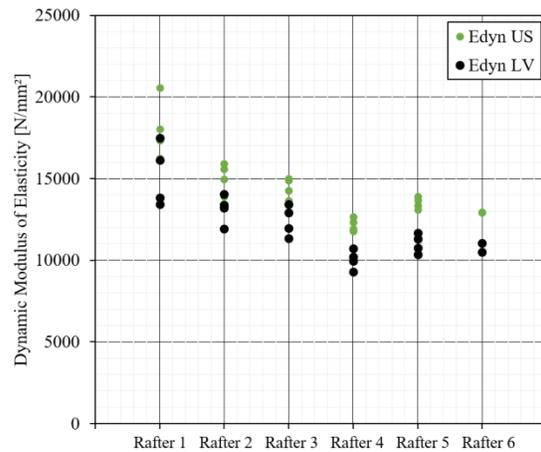


Figure 11. Dynamic Modulus of Elasticity (E_{dyn}) of the battens, measured through longitudinal vibration ($E_{dyn,LV}$) and ultrasonic measurement ($E_{dyn,US}$), grouped by the corresponding rafter.

5.1 FOUR-POINT BENDING TEST (EN408)

The results for the four-point bending test in a flatwise direction revealed for the 22 samples a mean bending strength of 44 N/mm² (COV 34%).

Figure 12 shows the cause of failure during flatwise bending. As for fresh-sawn wood, natural defects, especially knots, caused failure in most cases (82%). For 9% of the samples, fastener holes contributed together with natural defects to failure. In just 9% of the tests, fastener holes were the crucial single criteria for failure. As highlighted in Figure 12, although fastener holes caused the failure or contributed to the failure of the battens, high strength (31 N/mm², 38 N/mm², 45 N/mm², and 65 N/mm²) could be achieved.

Figure 13 shows the results of the edgewise four-point bending test and the corresponding cause of failure. A mean bending strength of 41 N/mm² (COV 31%) was achieved. Like the flatwise bending test results, 86% of the battens failed due to natural defects, especially knots. Two of the three battens where fastener holes were the crucial single cause of failure showed bending strength well above the mean value (54 N/mm² and 56 N/mm², respectively). However, one of these battens failed with a bending strength of about 19 N/mm². For this batten, fastener holes in the zone subjected to tension stresses

during the edgewise bending test caused the failure (Figure 14).

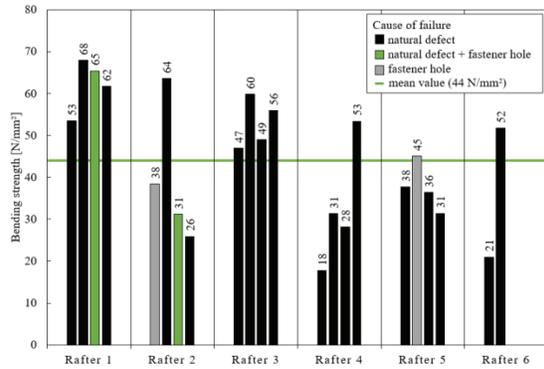


Figure 12. Bending strength for flatwise bending each batten, grouped by the corresponding rafter.

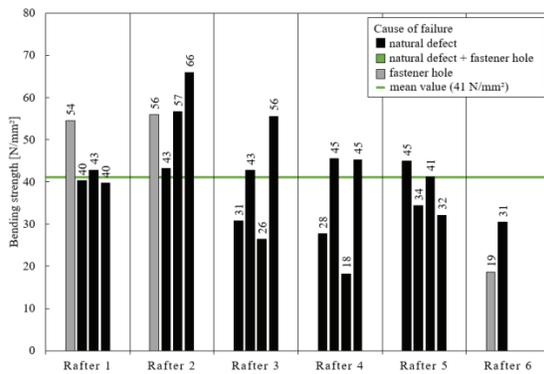


Figure 13. Bending strength for edgewise bending each batten, grouped by the corresponding rafter.



Figure 14. Picture of failure area of a batten that failed due to fastener holes subjected to tension during the edgewise bending test

Adjusting the edgewise bending test results to a reference height of 150 mm, as per EN 384:2022 [29], yields a parametric calculated 5%-quantile value ($f_{m,k}$) of 13.2 N/mm² for the ungraded battens (N=22).

6 – CONCLUSION

The visual assessment results from this study indicated that battens made from rafters recovered during the deconstruction of a roof truss contain many fastener holes. Battens, especially those cut from the upper layer of the rafters, were significantly impacted by these holes. Most of the fastener holes were created during the installation of the roof boarding, and the majority had, therefore, a diameter of less than 5 mm.

The visual strength grading of the battens from one deconstruction site, according to DIN 4074-1:2012 [19], revealed that natural defects, especially knots, caused a rejection rate of 59%. To address the high rejection rate, selecting an optimized sawing pattern tailored to every rafter, particularly to the pith location and knot configuration, could be a proper solution. Additionally, while there are only two grades for the standardized visual grading of battens - S10 and S13 - there is no equivalent grade, S7, which exists for the standardized visual grading of joists or boards. Introducing a grade S7 with reduced structural requirements could enhance yields and expand application possibilities. The high influence of knots on the visual strength grades is also reflected in the cause of failure. Natural defects, especially knots, were responsible for failures in 82% of flatwise bending tests and 86% of edgewise bending tests. In 18% of the flatwise bending tests and 14% of the edgewise bending tests, the presence of fastener holes contributed to failures, either in combination with knots or as the sole reason for the failure. Although it has been shown that fastener holes can affect the bending strength of battens, failures occur under high loads. The component failed at the fastener holes but would likely have failed soon after due to fiber failure. Thus, even when the impact of fastener holes on bending strength is evident, the presence of knots remains a key factor in determining overall strength.

In the example of battens coming from a single deconstruction site, the impact of fastener holes on bending strength can be observed. To assess the influence of fastener holes with the highest reliability, a larger number of samples and the correlation between various fastener hole diameters and batten cross-sections will be analyzed in future work. Furthermore, the influence of the load history and duration of load on the strength,

especially the long-term strength, needs to be incorporated.

7 – ACKNOWLEDGEMENT

This work was funded by the German Federal Ministry of Food and Agriculture (FKZ 2221HV037A)

8 – REFERENCES

- [1] N. Schmitz *et al.*, “Charta für Holz 2.0.: Kennzahlenbericht 2022/2023. Forst & Holz,” 2024.
- [2] BMEL, “Der Wald in Deutschland - Ausgewählte Ergebnisse der vierten Bundeswaldinventur,” 2024.
- [3] P. Szichta, M. Risse, G. Weber-Blaschke, and K. Richter, “Potentials for wood cascading: A model for the prediction of the recovery of timber in Germany,” *Resources, Conservation and Recycling*, vol. 178, p. 106101, 2022, doi: 10.1016/j.resconrec.2021.106101.
- [4] B. Nasiri, C. Piccardo, and M. Hughes, “Estimating the material stock in wooden residential houses in Finland,” *Waste management (New York, N.Y.)*, vol. 135, pp. 318–326, 2021, doi: 10.1016/j.wasman.2021.09.007.
- [5] J. Kalcher, G. Praxmarer, and A. Teischinger, “Quantification of future availabilities of recovered wood from Austrian residential buildings,” *Resources, Conservation and Recycling*, vol. 123, pp. 143–152, 2017, doi: 10.1016/j.resconrec.2016.09.001.
- [6] M. Risse, G. Weber-Blaschke, and K. Richter, “Resource efficiency of multifunctional wood cascade chains using LCA and exergy analysis, exemplified by a case study for Germany,” *Resources, Conservation and Recycling*, vol. 126, pp. 141–152, 2017, doi: 10.1016/j.resconrec.2017.07.045.
- [7] K. Höglmeier, G. Weber-Blaschke, and K. Richter, “Utilization of recovered wood in cascades versus utilization of primary wood—a comparison with life cycle assessment using system expansion,” *Int J Life Cycle Assess*, vol. 19, no. 10, pp. 1755–1766, 2014, doi: 10.1007/s11367-014-0774-6.
- [8] *Kreislaufwirtschaftsgesetz vom 24. Februar 2012 (BGBl. I S. 212), das zuletzt durch Artikel 5 des Gesetzes vom 2. März 2023 (BGBl. 2023 I Nr. 56) geändert worden ist: KrWG*, 2012.
- [9] J. Potting, M. Hekkert, E. Worrell, and A. Hanemaaijer, “Circular economy: Measuring innovation in the product chain: Policy Report,” The Hague, PBL publication number: 2544, 2017.
- [10] D. F. Llana, G. Íñiguez-González, M. Plos, and G. Turk, “Grading of recovered Norway spruce (*Picea abies*) timber for structural purposes,” *Construction and Building Materials*, vol. 398, p. 132440, 2023, doi: 10.1016/j.conbuildmat.2023.132440.
- [11] F. Arriaga, C. Osuna-Sequera, I. Bobadilla, and M. Esteban, “Prediction of the mechanical properties of timber members in existing structures using the dynamic modulus of elasticity and visual grading parameters,” *Construction and Building Materials*, vol. 322, p. 126512, 2022, doi: 10.1016/j.conbuildmat.2022.126512.
- [12] F. Böhm, K. Richter, and M. Risse, “Cascading potential of salvaged rafters from building demolition and deconstruction in southern Germany,” *Journal of Cleaner Production*, vol. 495, p. 144675, 2025, doi: 10.1016/j.jclepro.2025.144675.
- [13] C. Osuna-Sequera, D. F. Llana, G. Íñiguez-González, and F. Arriaga, “The influence of cross-section variation on bending stiffness assessment in existing timber structures,” *Engineering Structures*, vol. 204, p. 110082, 2020, doi: 10.1016/j.engstruct.2019.110082.
- [14] M. Nocetti, G. Aminti, M. Vicario, and M. Brunetti, “Mechanical properties of ancient wood structural elements assessed by visual and machine strength grading,” *Construction and Building Materials*, vol. 411, p. 134418, 2024, doi: 10.1016/j.conbuildmat.2023.134418.
- [15] M. Nocetti, G. Aminti, M. Degl’Innocenti, and M. Brunetti, “Geometric representation of the irregular cross-section of old timber elements: Comparison of different approaches for mechanical characterisation,” *Construction and*

- Building Materials*, vol. 304, p. 124579, 2021, doi: 10.1016/j.conbuildmat.2021.124579.
- [16] D. F. Llana, V. González-Alegre, M. Portela, and G. Íñiguez-González, "Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: Structural properties and non-destructive evaluation," *Construction and Building Materials*, vol. 339, p. 127635, 2022, doi: 10.1016/j.conbuildmat.2022.127635.
- [17] W. Dong, C. M. Rose, and J. A. Stegemann, "Cross-Laminated secondary timber: Validation of non-destructive Assessment of structural properties by full-scale bending tests," *Engineering Structures*, vol. 298, p. 117029, 2024, doi: 10.1016/j.engstruct.2023.117029.
- [18] C. M. Rose *et al.*, "Cross-Laminated Secondary Timber: Experimental Testing and Modelling the Effect of Defects and Reduced Feedstock Properties," *Sustainability*, vol. 10, no. 11, p. 4118, 2018, doi: 10.3390/su10114118.
- [19] *DIN 4074-1:2012-06: Sortierung von Holz nach der Tragfähigkeit - Teil 1: Nadelschnittholz*, Deutsches Institut für Normung, 2012.
- [20] *EN 14081-1:2016: Timber structures - Strength graded structural timber with rectangular cross section - Part 1: General requirements*, European Committee for Standardization, 2019.
- [21] *prNS 3691-1: Evaluation of recycled wood*, Standard Norway, 2024.
- [22] D. P. Pasca, A. Aloisio, Y. de Santis, H. Burkart, and A. Øvrum, "Visual-based classification models for grading reclaimed structural timber for reuse: A theoretical, numerical and experimental investigation," *Engineering Structures*, vol. 322, p. 119218, 2025, doi: 10.1016/j.engstruct.2024.119218.
- [23] D. Grosser, *Die Hölzer Mitteleuropas: Ein mikrophotographischer Lehratlas*. Reprint der Originalausgabe von 1977 (ehem. Springer-Verlag). Remagen: Verlag Dr. Kessel, 2003.
- [24] S. H. Jubair, "Cascading of recovered wood - Mechanical properties of secondary lumber and it's potential for a further utilization," [Unpublished Master' thesis], Professorship of Wood Technology, Technical University of Munich, Munich, 2025.
- [25] J.-L. Sandoz, "Grading of construction timber by ultrasound," *Wood Sci Technol*, vol. 23, no. 1, pp. 95-108, 1989.
- [26] *DIN EN 408:2012-10: Holzbauwerke - Bauholz für tragende Zwecke und Brettschichtholz - Bestimmung einiger physikalischer und mechanischer Eigenschaften; Deutsche Fassung EN 408:2010+A1:2012*, Deutsches Institut für Normung, 2012.
- [27] *DIN EN 338:2016-07: Bauholz für tragende Zwecke - Festigkeitsklassen; Feutsche Fassung EN 338:2016*, Deutsches Institut für Normung, 2016.
- [28] P. Stapel and J.-W. G. van de Kuilen, "Effects of grading procedures on the scatter of characteristic values of European grown sawn timber," *Mater Struct*, vol. 46, no. 9, pp. 1587-1598, 2013, doi: 10.1617/s11527-012-9999-7.
- [29] *EN 384:2022-08: Structural timber - Determination of characteristic values of mechanical properties and density*, Deutsches Institut für Normung, 2022.