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THE POTENTIAL OF PRODUCING HIGH ADDED VALUE STRUCTURAL TIMBER FROM LAMELLAE WASTE. CLASSIFICATION AND VISUAL GRADING

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ABSTRACT

This study is the continuation of the first part (Horváth et al. 2023), in which density, bending strength and modulus of elasticity of 100 oak lamellae generated as small-sized production waste were investigated. In this part of the study series, the classification of our sample set is carried out according to the EN 338. A visual pre-grading is presented, to remove the worst specimens and achieve a better final result and a standardized visual grading is also shown. Our results are compared with literature values of clear specimens as well. Amount of 80% of the specimens were found to be suitable for further structural use. The total sample set is classified in strength class D35 (average density 712.6±72.5 kg/m^3; average MoR_{adj} 65.4±16.2 MPa; average MoE_{adj} 13.4±3.1 GPa), while the visually pre-graded part with better average test results is classified in strength class D45. Industrial wood residues contain a sufficiently high proportion of elements for further processing, so that after sorting it can be used as raw material for glued-laminated load-bearing timber.
KEYWORDS: Oak timber, yield, structural, classification, grading.

INTRODUCTION

In the first part of this study series, the literature on the topic of classification of timber and the test procedures used to provide data was presented in detail (Horváth et al. 2023). Some results were compared, and we found that studies dealing with the analysis of small-sized lamellae are scarce, although large quantities of similar wood residues are generated. The small boards (lamellae), currently judged to be defective would be best used in the construction industry, primarily as glued-laminated timber (GLT) to achieve a high income by using them as products, instead of waste. To explore this possibility, we examined by-products from industrial production. Bending strength is the most important strength characteristic for timber structures (Harte 2009, Gil-Moreno et al. 2022). Thus, we evaluated density (ρ), static bending strength (*MoR*) and static bending modulus of elasticity (*MoE*) tests on our sample set.

Moreover, we used a non-destructive method as well, and visual grading according to DIN 4074-5 (2008). We also performed individual visual grading to pick out the worst specimens of the sample set. This allowed us to leave the worst specimens out of the classification method and thus, achieve a better grade for the residue sample set.

Instrumental tests provide the most reliable and accurate results. However, visual strength assessment is still used in the wood industry, and there are many different versions of this method in different countries. For the strength of wood, visible inhomogeneities are important (Kovryga et al. 2020). When the timber is visually examined, only the surfaces are visible: different types of knots, knot surface areas and the widths of the annual rings on the end-grain surface. Other properties affecting its mechanical properties, such as density, some fissures and local fibre deviations, cannot be considered. Thus, the weakest (or second weakest) cross-section cannot be determined clearly in all cases by visual inspection of the timber surfaces. This is only an estimation of a human, and it is uncertain whether the cross-section declared as the weakest is really the weakest (Briggert 2020). For conifers, the most accurate strength prediction method is the machine strength classification. For deciduous wood species, the same characteristics are more difficult to detect and measure with the available technologies (Kovryga et al. 2020). Therefore, it is preferable to use non-destructive mechanical methods. The dynamic modulus of elasticity in bending (MoE_{dyn}), which can be determined, among other properties, by ultrasonic testing, is closely related to the "biggest knot parameter", the "knot cluster parameter", the distance from the pith and, for ring-porous species, the annular ring width (Frühwald and Schickhofer, 2004). The average strength of boards is increases with its MoE_{dyn} (Linsenmann 2016). Using MoE_{dyn}, values of R^2 between 0.18 and 0.36 can be achieved in wood classification. The predictive accuracy can be improved by combining it with a test for knots, but current technologies are not sufficiently accurate for deciduous wood species. Another way to estimate strength is the determination of fibre direction. Local deviations in fibre direction are caused by local inhomogeneities of wood (knots, included bark, etc.), whereas global fibre direction can be observed along the whole length of the wood (Kovryga et al. 2020). With a suitable test method, fibre deviation can also be an important parameter (Frühwald and Schickhofer 2004). Since the determination of surface fibre direction does not provide a good basis for strength estimation, non-destructive mechanical testing of fibre direction in the whole cross-section is currently being investigated, e.g., by ultrasonic waves perpendicular to the fibre direction (Kovryga et al. 2020). Despite this, authors did not find a correlation between strength and global fibre deviation (visually determined and using ultrasound), but they stated that the use of density may be one of the major characteristic properties for deciduous wood species. But density and mechanical properties are not as strongly correlated for deciduous woods as for conifers, and thus it is less suitable for strength classification (Frühwald and Schickhofer 2004, Tapia and Aicher 2020). Spatial assessment of density will be more useful for detecting wood defects. Unfortunately, this is also difficult, because the density of a lot of deciduous wood species differs only slightly from the density of the knots they contain. Kovryga et al. (2016) performed visual grading and combined visual and machine strength prediction tests to calculate the tensile modulus of elasticity and tensile strength. They found that if the tensile strength classes are used for deciduous woods, the tensile modulus of elasticity becomes a classification-limiting property. Several studies have reached similar conclusions. For example, Frühwald and Schickhofer (2004) found that although the timber they tested achieved excellent *MoR* and *MoE* values, the density results in a much lower strength class according to EN 338. Linsenmann (2016) proposed a modification of the EN 338 classification standard by reducing *MoE* and increasing both *MoR* and density for deciduous wood species. The European standards for wood structure (EN 14081 2016-2022, EN 1995-1-1: 2004 + A1 2008, EN 338 2016, etc.) contain requirements only for the design and properties of coniferous GLT. There is no appropriate standard for the design of deciduous GLT. Further, quality control of the structural deciduous wood product should be established and implemented as an essential prerequisite for placing it on the market. The timber classification standards for higher density deciduous wood species need significant refinement based on several independent studies (Frühwald 2004, Linsenmann 2016, etc), including, in addition to EN 338 (2016), visual timber grading according to EN 14081-1: 2016 + A1 (2019) and the former EN 518 (1998). With the introduction of newer standards in the future, non-destructive strength tests that have become more widely used in recent decades, are an excellent replacement for visual grading.

The aim of this part of the study series is to present the grading results of different classification methods of small-sized wood lamellae, currently graded as unusable, and to determine whether they could be suitable for further use, for example in structural glued-laminated beams. Furthermore, we have defined a simple visual pre-classification procedure to improve the grading results, as well as compared our results with data of clear specimens. A related study is also planned in the future to present the timber yield from low-quality logs based on the results of this study. Another study with test results of glued-laminated oak lamellae would be worthwhile to get a more complete view of the subject. Finally, the main objective of these studies is to find new potential uses of deciduous wood species and to provide information on their efficient and economical use in practice.

MATERIAL AND METHODS

We tested 100 oak (*Quercus* spp.) specimens of 22 × 50 × 425 mm, as described in the study of Horváth et al. (2023). The ρ of the specimens conditioned at 20°C and 65% relative humidity was measured by the mass and volume of the whole specimens. A modification factor was not required to determine the characteristic value (ρ_k) as specified in EN 384: 2016 + A1 (2019), which was thus given by the 5th percentile (Ravenshorst et al. 2004, EN 384: 2016 + A1 2019). A non-destructive test was also performed with a Portable Lumber Grader Plus timber classification equipment (Fakopp Bt, Hungary) to get the dynamic bending modulus of elasticity (MoE_{dyn}) of the specimens.

Static bending tests were then performed according to EN 408: 2010 + A1 (2012). Unfortunately, the measurement data of two specimens were lost, so we can analyse the results of 98 specimens. The values obtained were converted according to EN 384: 2016 + A1 (2019), from which the adjusted *MoE* (MoE_{adj}) of the specimens was obtained (Horváth et al. 2023). The characteristic value for classification (MoE_k) is the average of the MoE_{adj} values. For comparability, the adjusted value of MoE_{dyn} was also calculated the same way (MoE_{dyn_adj}) and the characteristic value (MoE_{dyn_k}), too. For *MoR*, the adjustment for each result was done to take into account the size effect (MoR_{adj}), described in detail by Horváth et al. (2023). According to EN 384:2 016 + A1 (2019), the MoR_{adj} values of the 98 specimens were ranked in ascending order, and the fifth weakest gave the value used for further calculation, the 5th percentile of the bending strength (MoR_{adj_05}). This was multiplied by the standard factor k_v to give the characteristic bending strength value (MoR_k). In our case $k_v = 1.0$, so $MoR_k = MoR_{adj\_05}$.

The calculation of the characteristic values and the classification based on these values was performed for all the specimens. We also made an individual visual pre-grading, where 20% of the specimens were considered to be of very poor quality. Omitting their results, we reran the classification using the recalculated characteristic values (ρ_{k_sel}, MoR_{k_sel}, MoE_{k_sel}, $MoE_{dyn\_k\_sel}$).

Results were analysed and presented using Microsoft Excel 365 (Microsoft Corporation, USA) and the TIBCO Statistica version 14.0.1.25 (TIBCO Software Inc, USA). Statistical analysis included normality test, correlation analysis using a significance level at $p < 0.05$ and one-way analysis of variance (ANOVA) Fisher LSD post-hoc tests with a significance level at $p < 0.05$, too.

RESULTS AND DISCUSSION

Classification of individual specimens

When designing load-bearing structures, the designer determines the quality and cross-section of the timber to be used according to strength classes. EN 338 (2016) provides detailed information in this topic; although the standard is intended to classify a sample, we have performed individual classification on our 98 specimens according to the requirements of the standard, shown in Tab. 1.

The ranking by MoR_{adj} is the most permissive for the classification per specimen, with the entire specimen set falling into outstandingly high strength classes (D45-80). This is why the study by Linsenmann (2016) recommends increasing the limits of MoR_{adj} in EN 338. But the weakest result should be used as a basis for classification, i.e., ρ_k (strength classes D40-50) and MoE_{adj} determine the final classification. In the latter case, a smaller peak is drawn at strength class D30, while a much more pronounced peak is drawn at strength classes D50-D55, covering the majority of the specimens (Tab. 1). There are also specimens classified as D60-D65, but these represent only 9% of the total mass as well as strength classes D18-27. MoE_{dyn_adj} is slightly more stringent but yields a similar amount of unclassifiable timber as MoE_{adj} (14% and 13%, respectively). However, based on our previous conclusions, the results of the non-destructive testing should be only treated as indicative (Horváth et al. 2023). The summary considers the ρ_k, MoR_{adj} and MoE_{adj}; the majority of our individually graded specimens were in strength classes D30-D50 (69%), while 13% were unclassifiable (Tab. 1).

Tab. 1: Results of strength classification carried out on specimens individually (EN 338: 2016, DIN 4074-5: 2008 and EN 1912: 2012). The colour transition from blue to red gives a visual indication of the significance of the strength class. Abbreviations: MoR_{adj} – adjusted bending strength; MoE_{adj} – adjusted modulus of elasticity; MoE_{dyn_adj} – adjusted dynamic modulus of elasticity.

Strength class	ρ_k	MoR_{adj}	MoE_{adj}	MoE_{dyn_adj}	Visual grading	Summary		
						ρ_k + MoR_{adj} + MoE_{adj}	ρ_k + MoR_{adj} + MoE_{adj} + visual	ρ_k + MoR_{adj} + MoE_{adj} + visual + MoE_{dyn_adj}
Unusable	3%	3%	13%	14%	24%	13%	30%	31%
D18	0%	0%	2%	8%	0%	2%	2%	5%
D24	3%	0%	2%	2%	0%	2%	1%	2%
D27	7%	0%	5%	5%	0%	6%	3%	5%
D30	3%	1%	13%	15%	76%	13%	64%	57%
D35	7%	3%	4%	14%	0%	5%	0%	0%
D40	17%	3%	7%	4%	0%	14%	0%	0%
D45	23%	9%	5%	5%	0%	16%	0%	0%
D50	22%	13%	20%	18%	0%	21%	0%	0%
D55	8%	6%	17%	9%	0%	6%	0%	0%
D60	5%	10%	5%	1%	0%	0%	0%	0%
D65	0%	12%	4%	1%	0%	0%	0%	0%
D70	0%	10%	1%	2%	0%	0%	0%	0%
D75	0%	10%	0%	0%	0%	0%	0%	0%
D80	0%	18%	0%	0%	0%	0%	0%	0%

Standards favour primarily instrumental testing. For visual grading, very large oversizes have to be used. Despite this, visual grading is still important in practice. A currently valid European standard is EN 975-1 (2009), which deals with visual timber grading, but it does not apply to the strength grading of structural timber. The European Union has left it up to the member states to define the visual grading procedures for structural timber, but there is no Hungarian standard on this subject. The Hungarian standard MSZ 08-0600 (1988), which dealt specifically with the grading of glued-laminated structural wood for load-bearing structures, has been withdrawn. For this reason, in this study the German standard DIN 4074-5 (2008) was used, which has been revised, improved and widely adopted by many countries. This standard clearly lays down the rules for visual grading of structural timber. Accordingly, we have visually graded our specimens based on both the German DIN 4074-5 (2008) and EN 1912 (2012) standards. The results of the strength classification of the 98 specimens based on the visual grading are also shown in Tab. 1. All specimens falling in the 5th percentile of ρ_k and MoR_k were unusable based on visual grading, so the results of visual grading of the weakest specimens are in agreement with the classification procedures. Nevertheless, some specimens that performed very poorly in the bending tests were ranked as strength class D30, mainly due to the occasional difficulty in visually detecting the slope of grain, as Koehler (1955) and Ravenshorst et al. (2020) found earlier. On the other hand, a number of specimens that scored well in the bending tests were ungradable. Visual grading showed a low yield of 76%, primarily due to the coarse grading system and secondarily to the difficult-to-detect slope of grain. By a coarse grading system, we mean that the grade LS7 of DIN 4074-5 (2008) can no longer be ranked as strength class D according to EN 1912 (2012), while both grades LS10 and LS13 correspond to strength class D30 for oak. Thus, combining the results of visual grading with the classification results of the other tests, the worst yield of 69% was obtained (Tab. 1). This represents a serious loss for manufacturers. In fact, the same can be said of many other visual grading systems, since our specimens are remnants of a real production process, once graded as unsuitable according to some industrial visual inspection guidelines and as other literature has concluded the same (Green et al. 1993, Riesco-Muñoz et al. 2011, Feio and Machado 2015, Trulli et al. 2017, etc). The results of standard visual grading and especially density and bending tests show that many specimens have been taken out of production unnecessarily.

Classification of the sample set

EN 338 (2016) was not composed for the classification of individual specimens, but to classify sample sets. According to the standard, the density and bending strength are to be classified based on the characteristic 5th percentile, while the modulus of elasticity is to be classified based on its characteristic mean value. ρ_k gave a strength class of D45, MoR_k D35, MoE_k D40 and MoE_{dyn_k} D35 for the 98 specimens, with an overall ranking of strength class D35 for the total sample set. So, Tab. 3 of EN338 (2016) gives a relatively consistent result for the classification of a larger sample set by ρ_k, MoR_k and MoE_k. When classifying individual specimens, MoR_{adj} is very permissive and it would be good to define specific values for individual classification in EN338 (2016), because possibility to classify individual samples would be useful in some cases (Moore et al. 2009, Feio and Machado 2015, Ravenshorst 2015). The classification by ρ_k in Tab. 1 is statistically normally distributed as shown by the normality test and can be seen in Fig. 1.

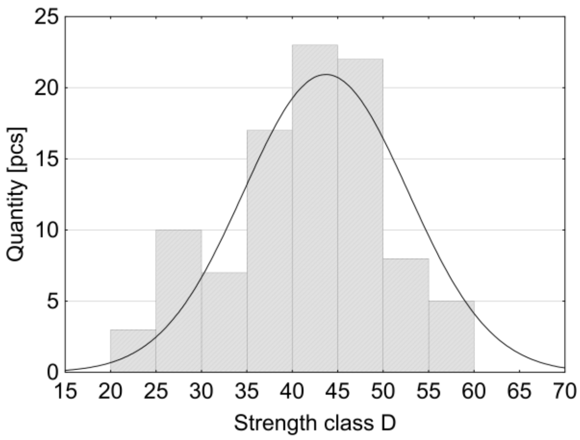

Fig. 1: Distribution of strength classes between D24 and D60 according to EN338 (2016), based on the density of oak specimens, with a fitted bell curve.

A bell curve can be drawn from the quantitative data of the individual classification with a maximum at strength class D45. The standardised classification according to EN338 (2016) gave the same result. In this case the individual classification is realistic and does not cause under-ranking or over-ranking. For MoR_{adj}, a significant over-ranking is seen for the individual classification, while for MoE_{adj} the classification is shifted more towards safety. The lowest rating for individual classification is given by MoE_{dyn_adj} for 64.3% of the specimens. Classifying according to the current standard EN 338 (2016) may have under-classified our sample set, as the next paragraph proves it.

Visual pre-grading followed by the standardized classification

We also created a unique visual pre-grading, to allow to pick out the worst specimens and thus improve the results of the following classification. After the pre-grading, the visual quality of all specimens was compared with the physical-mechanical test results. The typical characteristic description of some exemplary specimens is shown in Tab. 2, divided into three categories. This categorisation was able to pre-grade the specimens on the basis of their expected usability and then compare them with the other test results. The following three visual pre-grading categories were developed: *(1)* High quality lamellae: in addition to clear specimens, waviness in the fibre direction, slight slope of grain (1/5) and sapwood in 10% of the cross-section are allowed. *(2)* Lamellae with minor defects: the area of the knot or sapwood should not exceed 30% of the cross-section in any part of the timber and the slope of grain is up to ¼. *(3)* Lamellae with major defects (unusable): specimens not falling into the previous two categories.

Tab. 2: Examples of visual pre-grading categories of specimens and the averages by category. Abbreviations: MoR_{adj} – adjusted bending strength; MoE_{adj} – adjusted modulus of elasticity; MoE_{dyn_adj} – dynamic adjusted modulus of elasticity.

	No.	**Density [kg·m^{-3}]**	**MoR_{adj} [MPa]**	**MoE_{adj} [GPa]**	**MoE_{dyn_adj} [GPa]**	**List of comments, wood defects and observations**
High quality	79	797.9	92.7	18.6	11.7	wavy and diagonal grain on both sides, slope of grain
	80	701.6	71.7	14.1	10.8	wavy grain, slope of grain
	Total	**713±58**	**77±15**	**14±3**	**14±3**	**19 pieces**
Minor defects (usable)	89	793.6	76.9	14.4	13.6	slight wavy slope of grain on one side, wavy slope of grain on other side, 2 margin knots
	93	782.9	54.8	13.2	12.5	¼ of one side with frilly grain (due to a Ø2.5 cm dead knot on the other side), other side has slope of grain
	Total	**730±56**	**68±13**	**14±2**	**13±2**	**59 pieces**
Major defects (unusable)	8	835.7	38.5	11.8	4.0	at 40% of the length Ø1.5 cm margin knot, partly loose knot, slight local slope of grain
	34	656.4	46.8	9.3	11.6	on one side bark and discoloured sapwood, other side intact, slight slope of grain
	Total	**660±98**	**47±12**	**10±3**	**10±2**	**20 pieces**

In general, there shall be no fissure or warp in the sawn timber after drying, planning, length-cut and sanding, but pith as well as local slope of grain around the knots are allowed.

Insect holes and other biological damages, bark, wane and lack of material are not allowed. The maximum width of the annual ring is 5 mm.

Analysing all specimens individually, $MoE_{dyn\_adj\_avg}$ is on average 5.0%±14.0% lower than MoE_{adj_avg}. There is a statistically good linear relationship between MoE_{adj} and MoE_{dyn_adj}, with an R^2 of 57.5% (Horváth et al. 2023). Despite this statement, the difference is quite large, above 20% in 18 cases. This is probably the result of a measurement error, as the specimens were too short for the dynamic test equipment. In the category "high quality", where the correlation was 91.0% between MoE_{adj} and MoE_{dyn_adj}, 42% of the specimens had a difference of within 5%. Interestingly, in the category "minor defects" (54.7% correlation between MoE_{adj} and MoE_{dyn_adj}), 52% of the specimens showed values at least 5% lower in the dynamic test, while in the category "major defects" (86.8% correlation between MoE_{adj} and MoE_{dyn_adj}), 42% of the specimens had at least 5% higher values with dynamic testing. The latter is likely due to the higher average ρ of the specimens, as higher ρ of knots have a positive effect on the vibration transmission.

The middle category, "lamellae with minor defects", dominated (60.2% of all specimens). Although there are visible wood defects, their properties (MoR_{adj}, MoE_{adj} and MoE_{dyn_adj}) are statistically significantly higher and seems mostly good enough to use in wood structures (Fig. 2).

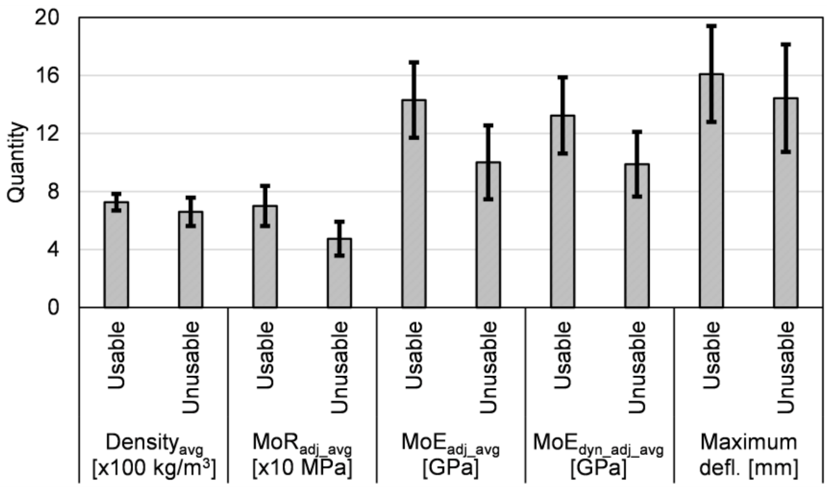

Fig. 2: Average key results of visually pre-graded specimens. 78 specimens were pre-graded as usable and 20 as unusable. Abbreviations: $Density_{avg}$ – average density; MoR_{adj_avg} – average adjusted bending strength; MoE_{adj_avg} – average adjusted modulus of elasticity; $MoE_{dyn\_adj\_avg}$ – average dynamic adjusted modulus of elasticity; Maximum defl. – maximum deflection.

Exceptionally low ρ values were found only in category "lamellae with major defects" for a few specimens, indicating a high percentage of sapwood or a lack of material, e.g., one edge of the specimen is missing. The lamellae with major wood defects are not suitable for further processing. For the sake of illustration, specimen No. 8, shown in Fig. 1 of the paper by Horváth et al. (2023), was visually pre-graded as unusable, as confirmed by the mechanical test results in Tab. 2. But it should be noted that visual grading cannot give accurate prediction, since specimen No. 8 did not break at the large, partly loose knot (Fig. 2b of the paper by Horváth et al. 2023) but a little further away due to the local slope of grain caused by the knot. This shows a relationship between the indicated wood defects, and the failure is due to the less spectacular defect, the local slope of grain. The properties of both categories "High quality" and "minor defects" in Tab. 2, allow some wood defects similar to the standards MSZ 55 (1978), MSZ 56 (1990) and EN 13228 (2011) for similar sized lamellae, because no material is completely clear in nature, even if it looks perfect at first sight. ANOVA tests of both ρ and MoE_{adj} show that groups of "high quality" and "lamellae with minor defects" are identical. Both the MoR_{adj} and MoE_{dyn_adj} statistical test results are also just below the significance level, so they are close to being considered identical. Based on the visual pre-grading of our specimens, the test results divided into the above three categories are illustrated in the bar chart in Fig. 2, similar to Fig. 4 in the paper of Horváth et al. (2023).

In Fig. 2, however, only two groups are distinguished, according to our objectives: a group of specimens may be suitable for structural use based on the pre-grading (high quality: 19 pieces + minor defects: 59 pieces = 78 pieces) and a group of specimens unusable for structural purposes (major defects, probably unusable: 20 pieces).

The average ρ of the total sample set was 712.6±72.5 kg/m^3, which is close to the value of 711±56 kg/m^3 found by Faydi et al. (2017), and 699±47 kg/m^3 found by Tapia and Aicher (2020), despite the fact that both of them examined exclusively graded wood. The average ρ of our visually pre-graded usable sample set was 726.1±57.2 kg/m^3, which can be considered as the same as the previous ones. Our average MoR_{adj} was 65.4±16.2 MPa, the average MoR_{adj_sel} was 70.1±13.8 MPa, while the MoR was 56±22 MPa for Faydi et al. (2017). In case of average MoE_{adj}, our tests resulted in 13.4±3.1 GPa, the average MoE_{adj_sel} was 14.3±2.6 MPa which are somewhat higher than the 10.3±2.2 GPa MoE test result of Faydi et al. (2017) and the 11.6±2.1 GPa test result of Tapia and Aicher (2020), similarly to the results of MoR. The differences may be due to different properties of the wood used in the tests and the different measurement settings. Both Faydi et al. (2017) and Tapia and Aicher (2020) tested samples classified as D18-D30 based on standardised visual grading.

In accordance with EN 338 (2016), the strength classification was carried out again on the 78 specimens that were found to be usable during the visual pre-grading. Based on the characteristic 5th percentile, ρ_{k_sel} gave a strength class of D50 and MoR_{k_sel} gave D45, while based on the characteristic averages, MoE_{k_sel} was classified into D50 and $MoE_{dyn\_k\_sel}$ into strength class D40. In sum, our sample set was graded as strength class D45 without dynamic test results and D40 including all test results. The MoR_{k_sel} and $MoE_{dyn\_k\_sel}$ dominated as well as the classification of the total sample set. Thus, by using visual pre-grading, very poor quality specimens can be filtered out. This clearly results in a better classification of the sample set, so it may be economically worthwhile to perform visual pre-grading. This is evidenced by the fact that all specimens below the 5th percentile of ρ_k and MoR_k were graded as unusable in the visual pre-grading, meaning the results of the two methods are in significant agreement. Since the two types of ranking (visual grading and machine classification) are based on different criteria, they complement each other well. It should be noted that visual pre-grading removes part of the timber from the sample, thus reducing the amount of graded structural timber that can be sold in higher price than the ungraded timber. Therefore, it is necessary to calculate in each case which will bring higher revenue, taking into account the current price of the different grades of structural timber: a larger quantity of structural timber classified in a lower grade, or a smaller quantity of structural timber classified in a higher grade due to pre-grading together with some ungraded timber. In addition, market needs must be taken into account.

Of the 20 specimens that were rated as unusable in our visual pre-grading, only 12 were found to be unacceptable according to the standardized visual grading. All specimens falling in the 5th percentile of ρ_k and MoR_k of the whole sample set were among them, so the visual grading according to DIN 4074-5 (2008) can also usefully complement the mechanical classification. However, the visual pre-grading system we developed provides a better yield because only 20% of the specimens are defective instead of 24% and it is in a better agreement with the mechanical tests results. Of course, our guidelines for oak lamellae only, cannot replace the complex specifications of the relevant standards, but they can be a useful aid to their development. Furthermore, our guidelines can contribute to a higher ranking of the sample set by the pre-grading of oak lamellae produced in a factory, with financial, environmental and marketing benefits. Based on our results, the structural use of most of our test specimens may be appropriate. The fundamental role of ρ in the test results is clearly visible. But it is important to pay attention, that the highest density specimens do not give the best mechanical values, because these results are strongly influenced by the knots.

Comparison of the test results

It is also interesting to compare our results with the test results of the best quality, clearest timber. In the PhD dissertation of Taschner (2013) sessile oak timber suitable for barrel stave production was investigated. Only selected clear timber (knot-free, straight-grained, dense annual ring structure) is used as a raw material for staves. The samples also originated from Hungary, and the measurement methods followed the specifications of the former Hungarian standard series MSZ 6786 (1976-1989), which were designed for testing small clear wood specimens. A modern, internationally well-known and very similar successor to this standard series is ISO 13061 (2014-2022). In our study, we have followed the specifications of standard EN 408: 2010 + A1 (2012), developed for testing structural timber, and thus the specimen size and measurement methods are somewhat different. Our aim is to compare our results with standardised results of clear wood, and therefore the study of Taschner (2013) provides a proper basis for further analysis (Tab. 3), because we know all the research details from his description. Other published values are also available, for example the book of Wagenführ (2007) with particularly advantageous data, as it includes both minimum and maximum values, not just averages. For comparability, Tab. 3 shows our results without the use of the modification factors required by EN 384: 2016 + A1 (2019), i.e., the raw values obtained during the test, similarly to the values of Wagenführ (2007) and Taschner (2013).

Tab. 3 shows that the average bending strength (MoR_{avg}) of oak came from the industrial production that we studied, are 13.7% lower than the average values for the defect-free specimens, but 36.9% above the published minimum. If we take into account the standard deviations, the average bending modulus of elasticity obtained in both the bending tests and in the non-destructive tests (MoE_{avg} and MoE_{dyn_avg}) are considered to be in agreement with the results of both Taschner (2013) and Wagenführ (2007). The 712.6 ± 72.5 $kg \cdot m^{-3}$ average density (Horváth et al. 2023) is also in agreement with the published average as well as the values of Taschner (2013) (692±44 $kg \cdot m^{-3}$). Consequently, if the standard deviations of our results shown in Fig. 4 in the paper of Horváth et al. (2023) are taken into account, we can find a large amount of additional wood suitable for further industrial use, even more so in the pre-graded sample set. If we exclude the specimens with major wood defects from our sample set (20% of the total quantity), the average values obtained are significantly improved (Tab. 3). For example, the average modulus of elasticity of pre-graded specimens obtained in the bending test (MoE_{sel_avg}) is higher than the results for the clear wood used for comparison.

Tab. 3: Comparison of the mechanical properties of our specimens with published values. Abbreviations: MoR_{avg} – average bending strength obtained in bending test; MoE_{avg} – average modulus of elasticity obtained in bending test; MoE_{dyn_avg} – average dynamic modulus of elasticity obtained in non-destructive test; MoR_{sel_avg} – average bending strength of pre-graded specimens obtained in bending test; MoE_{sel_avg} – average modulus of elasticity of pre-graded specimens obtained in bending test; $MoE_{dyn\_sel\_avg}$ – average dynamic modulus of elasticity of pre-graded specimens obtained non-destructive test; n.a. – not available

	All specimens (98 pcs)			**Pre-graded specimens (78 pcs)**			**Taschner (2013)**			**Wagenführ (2007)**	
	MoR_{avg} [MPa]	**MoE_{avg} [GPa]**	**MoE_{dyn_avg} [GPa]**	**MoR_{sel_avg} [MPa]**	**MoE_{sel_avg} [GPa]**	**$MoE_{dyn\_sel\_avg}$ [GPa]**	**MoR [MPa]**	**MoE [GPa]**	**MoE_{dyn} [GPa]**	**MoR [MPa]**	**MoE [GPa]**
Minimum	38.5	4.2	3.8	70.2	8.7	4.0	62.3	7.1	3.7	78.0	9.2
Maximum	152.9	19.1	20.3	152.9	19.1	20.3	223.6	17.4	22.8	117.0	13.5
Average	96.1	12.8	11.8	102.6	13.6	12.4	112.7	12.5	15.0	110.0	13.0
Std. dev.	23.8	3.0	2.9	19.4	2.4	2.6	15.9	1.9	2.4	n.a.	n.a.
Coeff. var.	24.8%	23.2%	24.9%	18.9%	17.3%	20.8%	14.1%	14.9%	16.0%	n.a.	n.a.

Based on our conclusion, it would be worthwhile to extend the quantity of structural timber manufactured according to EN 14081-1: 2016 + A1 (2019) with non-standard pieces that, although containing some serious wood defects, are free from the "Major wood defects" defined in our individual pre-grading. These small-sized lamellae may be suitable for use in glued-laminated timber structures, which requires further research. Considering the bending test results and ρ, 80% - 100% of the specimens tested and analysed in this study can be ranked in strength classes D35-D45, respectively, which is a very good result. The increased amount of raw material used for further products would have a positive impact on the profitability of the manufacturing. Glued-laminated timber with similar or better technical properties than sawn beams can be developed, using lower quality oak lamellae.

CONCLUSIONS

This study deals with a lower-quality oak lamellae sample set of 100 pieces. In the previous part of our study series, density, modulus of rupture and modulus of elasticity test results were introduced followed by their statistical analysis and showing correlations. In this second part we have classified the sample based on the results, compared them with the results of clear specimens, and developed a procedure for visual pre-grading to ensure better classification.

Bending strength and modulus of elasticity of our specimens are well within the literature values. Despite the wood defects they may meet the general industrial requirements. These lamellae may be used mainly to produce glued-laminated timber, which would allow part of the wood nowadays used as firewood to be sold as a very high value-added product. This idea is supported by the classification obtained according to standard for structural timber EN 338 (2016): this sample set belongs to strength class D35 and it is particularly suitable for further processing. Visual grading according to DIN 4074-5 (2008) did not give reliable and economic results. Visual grading criteria have also been defined to visually pre-grade our sample set currently being taken out of industrial production. By doing this, 20% of the specimens were declared as unusable and the classification of the remaining sample set is significantly improved as strength class D45. It is also possible to improve the classification by omitting specimens with a particularly low density, because low density indicates obvious strength problems. Comparing our average results with those of the clear samples, they are very similar, meaning that there is a large amount of additional wood available for further industrial use. A number of technical issues still need to be clarified before anything can be produced, which is a matter for further research studies. The objective of the study has been achieved, by demonstrating that the lamellae material base can be extended beyond the currently used materials by the use of lamellae which are free of major wood defects. In this way, a higher proportion of timber could be utilized in the wood industry, which creates the potential for more profitable management and better compliance with societal requirements.

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