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THE POTENTIAL OF PRODUCING HIGH ADDED VALUE STRUCTURAL TIMBER FROM LAMELLAE WASTE. TEST RESULTS AND ANALYSIS

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ABSTRACT

The research was based on the analysis of the density, bending strength and modulus of elasticity of 100 oak lamellae generated as small-sized production waste. In this part of the study series, the test results were presented in detail and analysed, in particularly the density distribution. Correlations between some test results have been shown. The dynamic and static test results were also compared. Despite the poor quality lamellae, the average density of the sample set corresponds to literary values and the distribution of density is normal. Specimens with low density are unsuitable for further use. But the density alone cannot be used for classification. Between static and dynamic modulus of elasticity can be found a good relationship. The relationships between density and both static and dynamic modulus of elasticity of the specimens can be considered as good, too. The best correlation is in bending tests between the deflection of the specimens in the elastic range and the bending strength.

KEYWORDS: Oak timber, yield, non-destructive, modulus of rupture, modulus of elasticity.

INTRODUCTION

The construction industry is presently responsible for 40% of global carbon-dioxide emissions. To reduce CO_2 emissions, the construction industry is increasing the use of renewable building materials, mainly wood, for which the demand has never been stronger (Adams et al. 2019). In the later decades, increasing amounts of deciduous logs, mainly beech, will be available on the European market, while the amount of conifers will decrease (Frühwald and Schickhofer 2004, Glavinić et al. 2020). In general, deciduous wood species have better mechanical properties compared to coniferous wood species, and they usually have better durability, fire resistance and aesthetics (Glavinić et al. 2020). Tension strength and tension modulus of elasticity of beech and oak wood are significantly higher than spruce (Linsenmann 2016). Based on the study of Frühwald and Schickhofer (2004), large deciduous wood lamellae are suitable for construction. As glued-laminated timber supports, they far exceed the strength specifications of current grading standards.

In the segment of the traditional log and timber processing industry that used deciduous woods, small sized products, especially small parquet lamellae were important. Today, their role has practically disappeared, since there is a very weak demand for, as an example, traditional parquets. For multi-layered products (e.g. engineered wood flooring), larger sized lamellae are typically used, produced usually directly for the purpose, not from residual materials. Accordingly, new uses for the small-sized and low-grade lamellae range need to be found. One possibility is the gluing of timber, which can be used for a variety of purposes. The largest user of coniferous and deciduous timber mass is the construction industry. Consequently, the construction industry may be the main area of interest for glued solid wood products made from low-quality deciduous wood raw materials. However, the preliminary machining processes required for gluing significantly increase the price of the product, which may then become unprofitable to produce. Therefore, a solution must be found which does not aim at removing the wood defects and then gluing the clear parts together, but at incorporating some of the wood defects into the product. In this way, the pre-processing work can be reduced and the yield can be increased, reducing the production cost. In agreement with Linsenmann (2016), in the future, the predominantly manufactured building products made of deciduous wood species will be most likely hybrid glued-laminated timber (glulam or GLT) or hybrid CLT consisting of smaller lamellae. CLT is typically made using larger sized lamellae, and there seems to be no willingness to change this practice. Thus, structural wood elements in the construction industry, especially GLT, may be the products for which these small boards (lamellae), judged currently to be defective, can be best used.

In the European Union, the rules for the engineering of timber structures are set in Eurocode 5. The stress values of structural timber required for the strength classification are described in standard EN 338. Both visual and mechanical test methods can be used for strength classification of structural timber. The main rules are described in the EN 14081 (2012-2019) standard series. For the most accurate classification, fracture tests are required and their detailed description is in standard EN 408. Finally, the standard EN 1912 (2012) establishes the link between national grading, e.g. German (DIN) or British (BS) and international strength classes (EN 338). It specifies the international strength classes to which a national grading can be assigned (Bejó et al. 2022).

In addition to visual grading, particularly bending strength tests are used today as the most important strength characteristic for the design of load-bearing timber structures (standard EN 408) and for the classification of structural timber (standard EN 338). Of course, non-destructive tests are also used to estimate strength properties. From the stress-strain ($\sigma - \varepsilon$) curve obtained during a bending strength test, a range of information can be extracted, especially the static bending strength (*MoR*) and the static bending modulus of elasticity (*MoE*).

Based on standard EN 408: 2010 + A1 (2012), the calculation of the global *MoE* (MoE_{global_2012}) is shown in Eq. 1:

$$MoE_{global\_2012} = \frac{3 \cdot a \cdot L^2 - 4 \cdot a^3}{2 \cdot b \cdot h^3 \cdot \left(2 \cdot \frac{\Delta w}{\Delta F} - \frac{6 \cdot a}{5 \cdot G \cdot b \cdot h}\right) \cdot 1000} \text{ [GPa]} \quad (1)$$

where: a – distance between a loading head and the support close to it (132 mm), b – width of the test piece, dimension perpendicular to the loading force (50 mm), h – thickness of the test piece, dimension parallel to the loading force (22 mm), L – support span (396 mm), ΔF – increment of load in the elastic phase of the bending test (800 N), Δw – increment of deflection corresponding to ΔF measured with an extensometer (mm), G – shear modulus (MPa).

Standard EN 408: 2010 + A1 (2012) allows the shear modulus to be assumed to be infinite if the test is conducted for a classification based on standard EN 384: 2016 + A1 (2019). In this case, Eq. 1 gives a much simpler relationship for global *MoE* (MoE_{global_2003}), which is the same as in the former standard EN 408 (2003) (Eq. 2).

$$MoE_{global\_2003} = \frac{\Delta F \cdot L^3}{\Delta w \cdot b \cdot h^3 \cdot 1000} \cdot \left[\frac{3 \cdot a}{4 \cdot L} - \left(\frac{a}{L}\right)^3\right] \text{ [GPa]} \quad (2)$$

For ease of implementation, the global *MoE* has been measured, which always gives a lower result than the local *MoE* (Ravenshorst et al. 2004). This is also true according to Tapia and Aicher (2020), and they have also shown that the results of the local *MoE* and global *MoE* are close to each other. The local *MoE* is given by the pure bending and this value is used in the design of structures. Therefore, it would be necessary to convert to the local *MoE* before classification. Unfortunately, the standard EN 384: 2016 + A1 (2019) specifies a conversion formula only for conifers to calculate the results on which the classification is based, and prescribes the definition of an individual formula for deciduous wood species. This requires a huge amount of measurement data, which is not available to us. We could not find a method of conversion specifically for oaks in the literature, so for the sake of certainty, the global *MoE* results will be used hereinafter. Based on standard EN 384: 2016 + A1 (2019), the adjusted *MoE* (MoE_{adj}) of the specimens has been calculated according to Eq. 3:

$$MoE_{adj} = \frac{MoE_{global\_2012}}{0.95} \text{ [GPa]} \quad (3)$$

The same procedure was used to prepare the values of MoE_{dyn} prior to classification for comparability, to get its adjusted value (MoE_{dyn_adj}). Eq. 4 shows the calculation of *MoR* using the maximum load (F; N).

$$MoR = \frac{3 \cdot F \cdot a}{b \cdot h^2} \text{ [MPa]} \quad (4)$$

Based on the requirements of standard EN 384: 2016 + A1 (2019), the results of *MoR* were converted to take into account the size effect, so that the bending strength of each specimen was obtained as an adjusted value (MoR_{adj}; Eq. 5). The modification factor shown in the denominator of Eq. 5 was in all cases greater than the minimum value 1.3, specified in the standard.

$$MoR_{adj} = \frac{MoR}{\left(\frac{150}{h}\right)^{0.2}} \text{ [MPa]} \qquad (5)$$

Strength properties can also be estimated by non-destructive tests, for example acoustic methods, where the spreading of vibrations is observed (Divós, 1993). From the behaviour of the vibration waves, mechanical properties, mostly *MoR* and *MoE* can be inferred. A uniform and dense structure provides a high spreading rate of waves, while knots, decay and high resin content have a negative effect. The mathematical relationship for the calculation of *MoE* is described as closely as possible by the theory of Timoshenko. Many other non-destructive methods have been developed worldwide in the last decades that give results more or less well correlated with *MoR*: optical scanning, laser profile scanning, laser fibre direction mapping, low wavelength X-ray or - less frequently - gamma radiation, and computed tomography, etc. The correlation coefficient rarely exceeds 0.80 between the results of these tests with the bending test of the timber, so it is advisable to use a combination of methods to improve the accuracy of the strength estimation (Bejó et al. 2022).

The reviewed studies deal mainly with the classification of timber and the test procedures used to provide data for classification. Studies dealing with the analysis of small sized lamellae or specimens of similar size and properties, such as the study of Frühwald and Schickhofer (2004), are scarce. However, large quantities of similar wood residues are generated in the wood industry, and we hypothesise that at least part of these residues could be used for further industrial purposes to achieve significant yield improvements. The aim of the first part of this study series is to investigate the properties of the small-sized wood lamellae, currently graded as unusable. For this purpose, some physical and mechanical properties of specimens from industrial production were tested under laboratory conditions: density, static bending strength, static bending modulus of elasticity and dynamic modulus of elasticity. In this paper the results of these tests and correlations between the results are presented. Moreover, the density and other properties are deeply analysed.

MATERIAL AND METHODS

Size and origin of specimens

These tests use 100 specimens of 22 × 50 × 425 mm (the latter is the direction of fibres) noble oak (*Quercus spp.*) with planed surfaces. The choice of these dimensions is to follow the industrial production, to study material with sizes used in everyday practice. 22 mm is the dried-planed size (thickness or cross-sectional height) of the sawmill's one-inch timber; 50 mm is an accepted lamella size, while the 425 mm length is more than 19 times the thickness size, making the specimens ideally suited for bending tests according to standard EN 408: 2010 + A1 (2012). The specimens were taken from the sawmill of Zalaerdő Zrt, Lenti, Hungary, they may be both pedunculate oak and sessile oak species, typical of the region (*Quercus robur* and *Quercus petraea*, respectively). According to Rellstab et al. (2016), the anatomy of these wood species cannot be clearly distinguished and they may hybridize with each other.

Quality description of specimens and their preparation for tests

The specimens, as residues of real industrial production (unusable or waste material), contained many wood defects. Low quality lamellae were selected, which meet at most the appearance grade QF3 and QF4 of standard EN 975-1 (2009). The lamellae in many cases are even inferior to grade III as defined in the former Hungarian lamella standard MSZ 08-0600 (1988). All specimens have been photographed (Fig. 1) and a detailed quality description has been obtained by a thorough visual inspection according to standard EN 1309-3 (2018), to be used later in the evaluation of the measurement results.

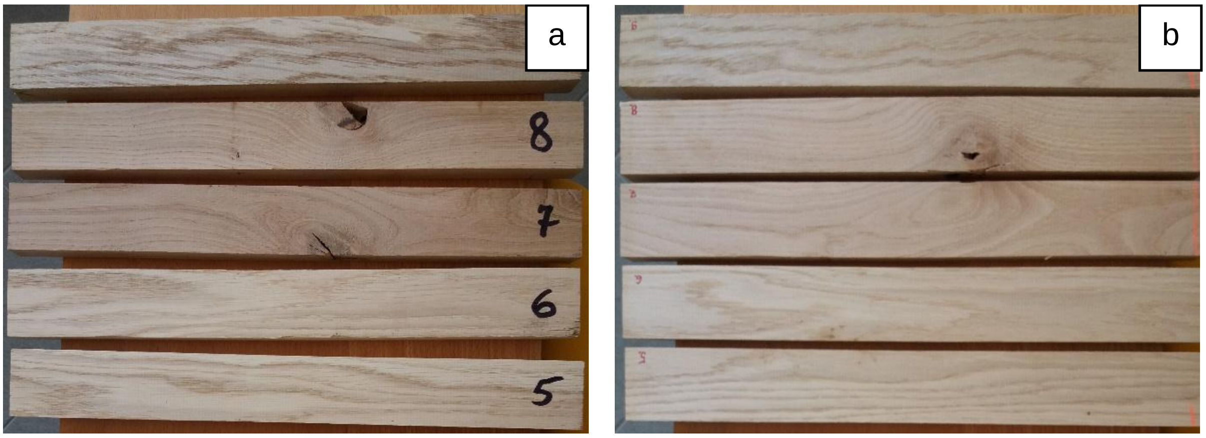

Fig. 1: An example of the specimen photographs. Both the top (a) and back (b) surfaces of the specimens can be observed, before the bending tests.

The test specimens were conditioned to an equilibrium moisture content at normal climate (20°C and 65% relative humidity) prior to the measurements. After the equilibrium moisture content was reached, the moisture content of the specimens, checked with a capacitive moisture meter, became 12% with very little variation due to prolonged conditioning, and therefore drying chamber tests were considered unnecessary.

Description of the tests

The specimens were first subjected to a non-destructive test and then to a static bending test. For the non-destructive test, the natural longitudinal vibration frequency was used, which gives a good estimation of *MoE* (Divós et al. 1994). The measurements were performed with a Portable Lumber Grader Plus (PLG+) timber classification equipment (Fakopp Bt, Hungary). It automatically determined both ρ and MoE_{dyn} (Sismándy-Kiss 2012, Bejó et al. 2022). The vibration was applied with a hammer at one end of the specimen, while the signal was detected with a microphone at the other end of the specimen. The specimen was supported at two points by scales with vibration damped pads to minimize vibration distortion. The exact length of the specimens was monitored by a laser distance meter and automatically transmitted to the computer, while the cross-section had to be specified manually. After sequential decoding of the recorded vibrations, the software determined the longitudinal wave propagation velocity, the vibration spectra and frequencies of the vibration modes and automatically selected the most relevant frequency peak. Based on the value of the peak, the software calculated MoE_{dyn} based on the Timosenko theory (Sismándy-Kiss 2012).

According to the standard EN 384: 2016 + A1 (2019), ρ should be determined on a clear section of the specimen close to the fracture after the bending test. However, the standard also allows for the calculation of ρ based on the mass and volume of the whole specimen, which was preferable because of its better comparability with non-destructive results. The requirements of standard EN 408: 2010 + A1 (2012) has been followed because it deals both with structural solid and glued-laminated timber and the end-use of small-size lamellae may be used in load-bearing structures. The bending tests were performed on an Instron 4208 (Instron Corporation, USA) universal material testing machine. The support span was 18 times the thickness of the specimen, 396 mm, while the distance between the 30 mm diameter rollers of the crosshead was 132 mm, symmetrically spaced between the supports. The load rate was 4.0 $mm \cdot min^{-1}$, which gave an average test duration of 3.94 min and meets the requirements of the standard. Prior to each measurement, an extensometer was fitted to the centre of the specimen (Fig. 2a), which provided the exact deflection data associated with the load in the elastic part of the bending test between 1000 N and 1800 N. Such low values were used compared to the standardized 40% of maximum bending force, because poor quality specimens have a high probability of breaking at low bending forces, which would damage the extensometer (Fig. 2). However, since the sampling was performed strictly in the elastic range, the values used to calculate *MoE* are correct in any case.

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) software. Statistical analysis included the normality test of ρ values and the correlation analysis of the tested properties using a significance level of $p < 0.05$.

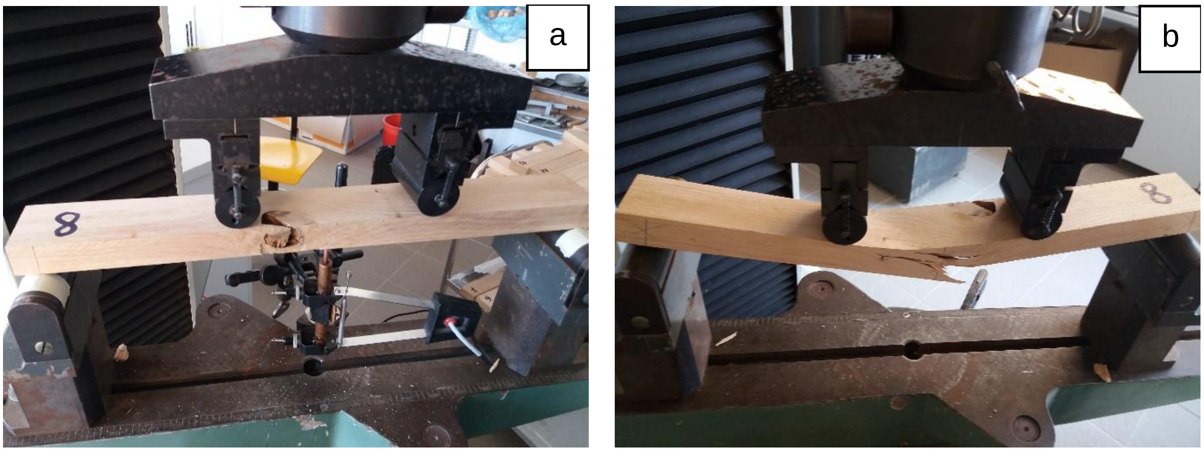

Fig. 2: Static bending test according to standard EN 408: 2010 + A1 (2012) at the beginning of the test (a) and after the failure of the specimen (b).

RESULTS AND DISCUSSION

Density of the specimens

Several studies have shown a strong correlation between ρ and physical-mechanical properties, while others have shown that this statement is not valid to higher density deciduous wood species (Frühwald and Schickhofer 2004, Munoz and Gete 2011, Ravenshorst 2015, Bejó et al. 2022; etc). In this research, the average ρ is 712.6 ± 72.5 $kg \cdot m^{-3}$ according to EN 384: 2016 + A1 (2019), minimally higher than the literature value 690 $kg \cdot m^{-3}$ (Molnár 1999, Wagenführ 2007) and can be considered as outstanding, taking into account the poorer material quality. The higher ρ of the knots and the slightly different tree-ring structure of some specimens may also play a role. The more significant, albeit acceptable standard deviation is mainly due to the occasional presence of sapwood and bark, fissures and other material imperfections. The coefficient of variations of all the tests are within an acceptable range, despite the poorer wood quality. This will be shown later. The results are therefore valid in this respect.

An extremely low ρ may occur due to the lack of material caused by large fissures, bark and knot holes, and an extremely high ρ due to a large amount of sound knots. Since the mechanical tests are designed for clear wood specimens (straight grain, free of wood defects), these extreme densities in the analysis, which do not actually belong to the statically functioning parts of the specimens, may lead to false conclusions. A nearly ideal bell curve is obtained by plotting the ρ values between 550 and 825 $kg \cdot m^{-3}$ on a bar chart of 90 specimens excluding the extreme values, based on the literature values of Molnár (1999) and Wagenführ (2007). To confirm this assumption, a normality test was performed (Fig. 3) which showed that the densities are considered to be statistically normally distributed (number of categories = 10; Kolmogorov-Smirnov d = 0.02878; Chi-Square test = 2.40231, df = 3 (adjusted), p = 0.49321). This result also confirms the proper quality of the tests from sampling to the extraction of the results.

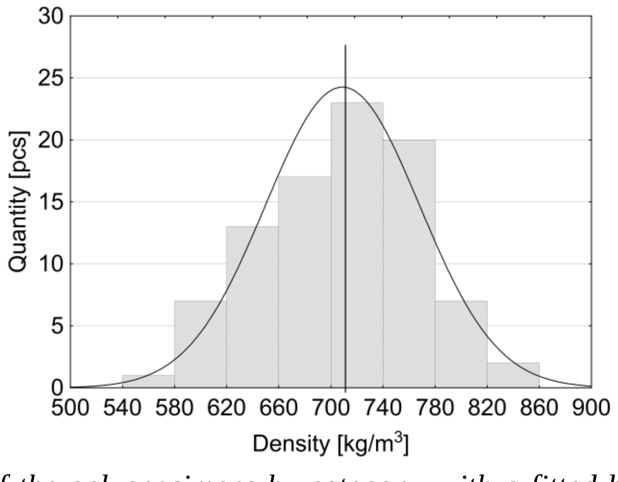

Fig. 3: Densities (ρ) of the oak specimens by category, with a fitted bell curve. The vertical black line represents the average ρ of the specimens between 550 and 825 $kg \cdot m^{-3}$.

On average, ρ obtained from the non-destructive test differs by 10.5% ± 7.1% from the standard test result, with a difference of 30.9% in the most extreme case. Presumably, the PLG+ timber classification equipment optimized for specimens several metres long (sawmill-sized) may have slightly biased the results due to the small specimen length used in the tests (425 mm). Consequently, all results of the non-destructive tests should be treated with caution and for information purposes only. These results will be presented in the following and will provide a good basis for analysing the reliability of the non-destructive test method.

Test results and correlations

After both density and the non-destructive tests, the same 100 specimens were subjected to a 4-point static bending test within a short time to ensure that the moisture content did not vary. Two specimens were subject to a measurement error when the data were not recorded. Despite the fact that many specimens were graded as unusable, as will be discussed in the second part of this study series, the average mechanical results of the 98 specimens have a coefficient of variation of only 22.0-24.8% (Fig. 4). Comparing the results, the average adjusted modulus of elasticity and the average adjusted dynamic modulus of elasticity are similar, even when the standard deviations are taken into account (Fig. 4). Since the bending test best simulates the stresses encountered in service, the results of the bending test are the most relevant.

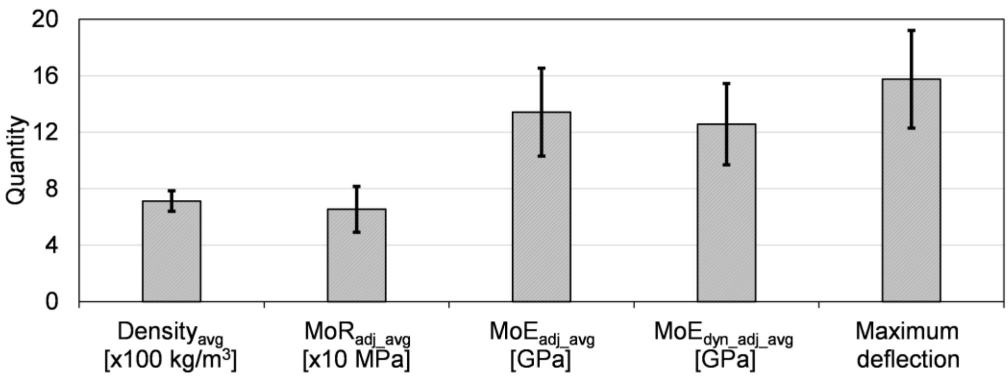

Fig. 4: Averages of the main results of the tests. Abbreviations: MoR_{adj_avg} – average adjusted bending strength; MoE_{adj_avg} – average adjusted modulus of elasticity; $MoE_{dyn\_adj\_avg}$ – average adjusted dynamic modulus of elasticity.

As a first step, we examined the effect on the trend lines, i.e. the relationship between the wood properties under study, considering all specimens and excluding specimens with extremely low and extremely high ρ values from the analysis, for the reasons explained before. The tests showed that at this sample size, the effect of excluding the data of the eight extreme ρ specimens from the analysis is insignificant. Accordingly, no specimens were subsequently excluded from the evaluation of the tests due to their extreme ρ. Tab. 1 shows the coefficients of determination (R^2) between all the properties tested on. The R^2 between ρ and MoR_{adj}; MoR_{adj} and MoE_{dyn_adj}; MoR_{adj} and maximum deflection; MoE_{adj} and maximum deflection; MoE_{dyn_adj} and maximum deflection; maximum deflection and deflection in the elastic range are considered weak or moderate, so these are not discussed below. The R^2 between MoR_{adj} and maximum deflection, as well as between MoE_{adj} and deflection in the elastic range stand out among similar relationships, as their measurements and computational methods are very closely related pairwise.

Tab. 1: Coefficients of determination (R^2) between the properties tested. Abbreviations: MoR_{adj} – adjusted bending strength; MoE_{adj} – adjusted modulus of elasticity; MoE_{dyn_adj} – adjusted dynamic modulus of elasticity.

	Density	**MoR_{adj}**	**MoE_{adj}**	**MoE_{dyn_adj}**	**Maximum deflection**	**Deflection between**
Density	100.0%					
MoR_{adj}	29.5%	100.0%				
MoE_{adj}	56.4%	75.5%	100.0%			
MoE_{dynadj}	51.3%	47.8%	57.5%	100.0%		
Maximum deflection	0.1%	39.7%	6.2%	4.2%	100.0%	
Deflection between 1000-1800 N	59.9%	62.8%	82.5%	52.0%	4.9%	100.0%

Fig. 5 shows the individual bending test results and the associated trend lines of 98 specimens from several aspects, selected from the best correlated results. These may be useful for subsequent non-destructive testing to predict strength values, e.g. the relationship between the deflection in the elastic range and MoR_{adj}.

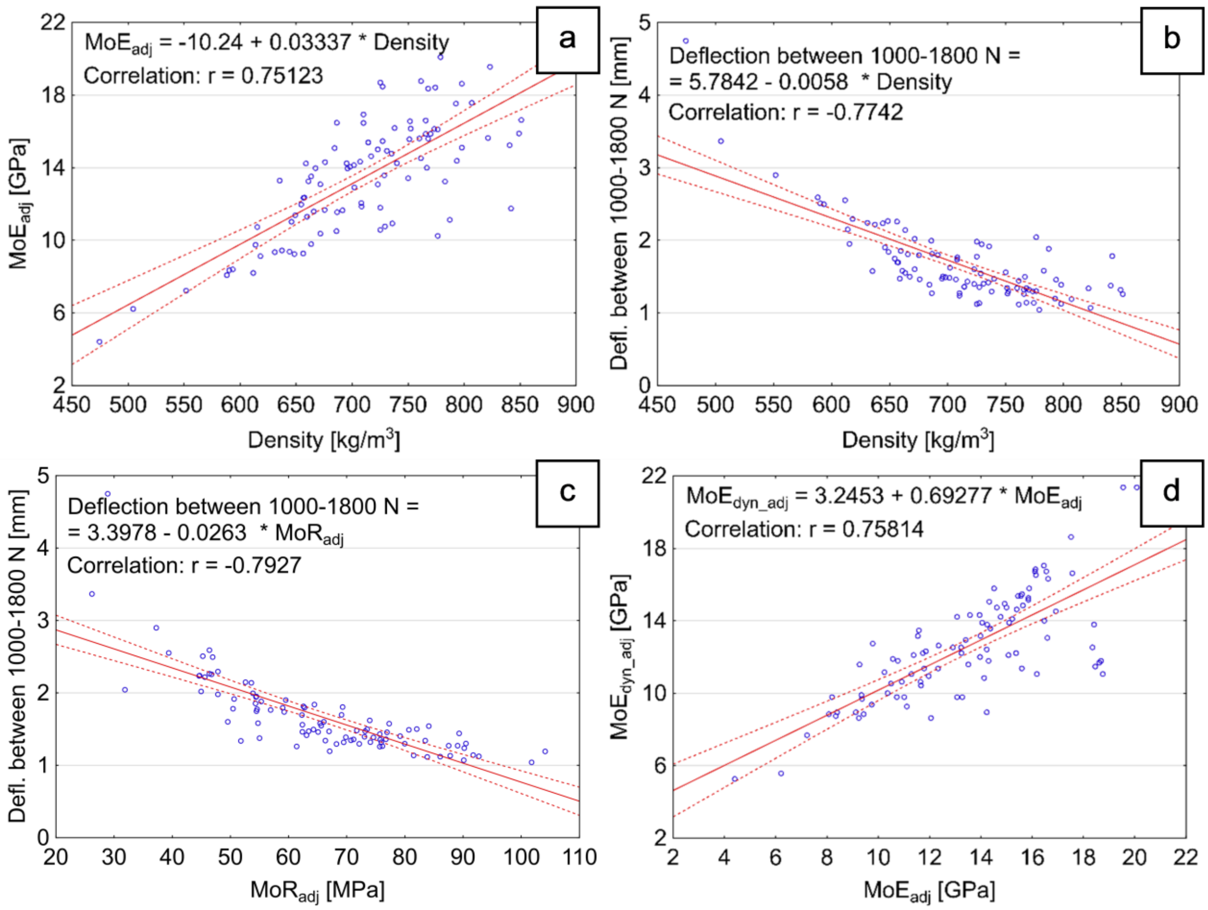

Fig. 5: Adjusted modulus of elasticity (MoE_{adj}) of the oak sample set as a function of density (ρ) (a), deflection in the elastic range as a function of ρ (b), deflection in the elastic range as a function of adjusted bending strength (MoR_{adj}) (c) and a comparison of static and dynamic modulus of elasticity (MoE_{adj} and MoE_{dynadj}) (d). The red trend lines represent all specimens with 95% confidence interval bands.

Due to the similarity of R^2 between ρ and both static and dynamic *MoE*, the relationship between ρ and MoE_{dyn_adj} is not shown separately in Fig. 5. The relationships between ρ and the elastic moduli are good, using linear trend lines (Fig. 5a), with R^2 = 56.4% for MoE_{adj} and R^2 = 51.3% for MoE_{dyn_adj}. Using more complex approaches, as a power trendline, even better R^2 can be achieved. This suggests that mechanical properties can be inferred from the value of ρ in tests of lower quality oak specimens. This is supported by the fact that all the properties tested have a high coefficient of variation (22.0% - 24.8%) except ρ (whose coefficient of variation is 10.2%). Outliers with low ρ occur due to high sapwood ratios, knot holes, fissures and other material imperfections due to lower specimen weight, which is consistent with the weakening of the material structure. In these cases, ρ can be used to clearly select specimens unsuitable for further use. As ρ increases, a higher bending strength and modulus of elasticity can be expected, as well as reduced bending capacity in the elastic range (Fig. 5a,b). Exceptionally high ρ is due to wide annual rings and high quality material, or the high ratio of knots. A significant proportion of the specimens with the highest ρ were below the trend line, i.e. provided poorer results than expected (MoR_{dyn}; MoE_{adj}; MoE_{dyn_adj}). In mass production, specimens with high ρ require individual testing because they are likely to contain many knots and thus have uncertain quality. Some specimens have poor strength results even at normal ρ. In these cases, the knots and/or the slope of grain weakened the material structure, while their ρ did not deteriorate. In other words, the ρ test alone cannot be used as a basis for the classification of the entire sample set.

Density shows a good correlation with the deflection measured in the elastic range (R^2 = 59.9%). This provides an easy-to-measure and reliable way to check whether the results of a ρ test are reliable under continuous operating conditions. The use of both methods improves the reliability of the grading of wood into strength classes. The best relationship between the deflection measured in the elastic range and MoR_{adj} is obtained (Fig. 5c). In this case, the R^2 is higher, showing an even better fit (R^2 = 62.8%). Using power trend line, this value increases up to 75.6%. In other words, they are not only closely related for clear wood, but also for the lower quality lamellae included in this study. Thus, we can directly infer the MoR_{adj} and the ρ from the deflection because of their good relationship. Unfortunately, the maximum deflection cannot be predicted from other data: its correlation with all the properties tested is very weak. But the maximum deflection is not relevant from a structural point of view.

Between MoE_{adj} and MoE_{dyn_adj} a good linear relationship can be found (R^2 = 57.5%; Fig. 5d). The dynamic test was carried out under partly inadequate test conditions because shorter specimens than the minimum required for the instrument were used. However, the good correlation between MoE_{adj} and MoE_{dyn_adj} demonstrates the suitability of the dynamic method. In addition, there are significant differences between MoE_{adj} and MoE_{dyn_adj}; MoE_{dyn_adj} gives the lower value by 6.8% on average. Thus, this difference in the use of non-destructive test results can be considered as a built-in safety factor, although it is not necessarily economical. High

MoR_{adj} in all cases means an above average MoE_{adj}. However, classification based on a below average MoE_{adj} is not safe, because our study has shown that an extremely low MoR_{adj} can also occur with a near average MoE_{adj}. The best solution to overcome these problems is to combine several methods to greatly refine the classification procedure (Bejó et al. 2022), thus developing a quick decision procedure that can be performed locally at a plant. The same is true for measurements in factories with continuous operation that can be integrated into a production line. On this basis, it would be useful to explore further relations, for example, between the bending test and hardness values that can be measured locally and quickly.

CONCLUSIONS

100 pieces of small oak specimens (22 × 50 × 424 mm) remaining as by-products of an industrial production were subjected to both non-destructive and bending tests. The analysis of the non-destructive tests showed that the method used does not provide reliable results due to the small specimen sizes and is therefore presented for information only.

The average density (712.6 ± 72.5 $kg \cdot m^{-3}$) of the specimens is well within the published values, despite the wood defects. The density distribution of the specimens is normal. Low density occurs due to serious wood defects, so it can be used to clearly select specimens unsuitable for further use. Specimens with extra high density require individual testing. Thus, a density test alone cannot be used for classification. Correlations were sought between all of the results of different tests. The relationships between density and both static and dynamic modulus of elasticity of the specimens are good (R^2 = 56.4% and 51.3%, respectively). The R^2 between density and deflection measured in the elastic range is 59.9%. Between static and dynamic modulus of elasticity there is also a good linear relationship (R^2 = 57.5%). Comparing the averages of the tests, the static and dynamic modulus of elasticity can be considered as similar. Considering the partially inadequate test conditions of the dynamic test, this good correlation is an excellent proof of the suitability of the dynamic method. The best correlation is between the deflection measured in the elastic range and bending strength (R^2 = 62.8%).

Currently, lower quality (including knots, sapwood, etc.) hardwood lamellae are rarely used for structural purposes. Their most common use is for energy purposes, although a reassessment of their use, which in many cases is based on habits and traditional practices, could allow their higher value recovery, improving plant performance and profits, partly reducing timber shortage and contributing to more environmentally friendly operations. Taking into account the results presented in this article, it is likely that a significant amount of the industrial timber residues could be used for lamellae, including for glued laminated structural applications. Of course, several other products could also be made by finger jointing, paneling, etc.

In the second part of this study series, the classification of the sample set according to the standard for structural timber EN 338 (2016) will be presented. Two different visual classifications, and a comparison with published values will also be introduced. These results will allow definitive conclusions to be drawn about the ratio of recovery of the low-quality lamellae that are currently waste products.

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REFERENCES

1. Adams, M., Burrows, V., Richardson, S., 2019: Bringing embodied carbon upfront. Coordinated action for the building and construction sector to tackle embodied carbon. World Green Building Council. London, UK, 67 pp.
2. Bejó, L., Sismándy-Kiss, F., Divós, F., 2022: A fűrészáru szilárdsági osztályozásának nemzetközi gyakorlata és hazai kutatási eredményei (International practice and Hungarian research regarding structural lumber grading). Anyagvizsgálók Lapja 2022(1): 27-37.
3. Divós, F., 1993: Fenyő faanyagok roncsolásmentes vizsgálata (Non-destructive testing of coniferous timber). CSc Dissertation, Erdészeti és Faipari Egyetem, Sopron, Hungary, 100 pp.
4. Divós, F., Dániel, I., Hodász, E., Járási, J., 1994: Experimental investigation of thirteen strength predictor parameters of coniferous wood. In: Proceedings of the First European symposium on nondestructive evaluation of wood. University of Sopron, Hungary, 86 pp.
5. EN 1309-3, 2018: Round and sawn timber. Methods of measurements. Part 3: Features and biological degradations.
6. EN 14081, 2012-2019: Timber structures. Strength graded structural timber with rectangular cross section.
7. EN 1912, 2012: Structural Timber. Strength classes. Assignment of visual grades and species.
8. EN 338, 2016: Structural timber. Strength classes.
9. EN 384:2016 + A1, 2019: Structural timber. Determination of characteristic values of mechanical properties and density.
10. EN 408, 2003: Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.
11. EN 408:2010 + A1, 2012: Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.
12. EN 975-1, 2009: Sawn timber. Appearance grading of hardwoods. Part 1: Oak and beech.
13. Frühwald, K., Schickhofer, G., 2004: Strength grading of hardwoods. Pp 675-679, Proceedings of the 8th world conference on timber engineering. WCTE, Helsinki.
14. Glavinić, I.U., Boko, I., Torić, N., Vranković, J.L., 2020: Application of hardwood for glued laminated timber in Europe. Journal of the Croatian Association of Civil Engineers 72(7): 607-616.

15. Linsenmann, P., 2016: European hardwoods for the building sector (EU Hardwoods). Holzforschung Austria, Wien, 57 pp.
16. Molnár, S., 1999: Faanyagismeret (Knowledge of wood). Mezőgazdasági Szaktudás Kiadó, Budapest, Hungary, 467 pp.
17. MSZ 08-0600, 1988: Szélezett fűrészáru (lamella alapanyag) rétegelt-ragasztott tartószerkezetek gyártásához (Edged timber (lamella raw material) for the manufacture of glued-laminated structures). Magyar Szabványügyi Hivatal, Budapest, Hungary.
18. Munoz, G.R., Gete, A.R., 2011: Relationships between mechanical properties of oak timber (*Quercus robur* L.). Holzforschung 65: 749-755.
19. Ravenshorst, G., van der Linden, M., Vrouwenvelder, T., van de Kuilen, J.W., 2004: An economic method to determine the strength class of wood species. HERON 49(4): 297-326.
20. Ravenshorst, G., 2015: Species independent strength grading of structural timber. PhD Dissertation, TU Delft: The Netherlands, 277 pp.
21. Rellstab, C., Bühler, A., Graf, R., Folly, C., Gugerli, F., 2016: Using joint multivariate analyses of leaf morphology and molecular-genetic markers for taxon identification in three hybridizing European white oak species (*Quercus* spp.). Annals of Forest Science 73: 669–679.
22. Sismándy-Kiss, F., 2012: Fűrészáru szilárdsága és fizikai tulajdonságainak kapcsolata (Strength of structural lumbers in relation to physical properties). PhD Dissertation, Nyugat-magyarországi Egyetem, Sopron, Hungary, 103 pp.
23. Tapia, C., Aicher, S., 2020: Variation and serial correlation of modulus of elasticity between and within European oak boards (*Quercus robur* and *Q. petraea*). Holzforschung 74(1): 33-46.
24. Wagenführ, R., 2007: Atlas of wood. 6. neu bearbeitete und erweiterte Auflage. Fachbuchverlag Leipzig im Hanser Verlag: Leipzig, Germany, 816 pp.

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