World Conference on
Timber Engineering
Oslo 2023

GREEN OAK BUILDING WITH HIGH-TECH METHODS, PART 1: CHARACTERISATION OF THE RAW MATERIAL

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ABSTRACT: In Germany, only half of the annual increment of oak stands is used. Especially small-diameter oaks are currently either not used or only used as firewood. This research project aims on making small-diameter oak logs available as structural timber members. For this purpose, the mechanical properties of the logs and factors influencing them must be determined.

In the experimental program, (oven-dry) wood density, moisture content, internal and external wood defects and round wood geometry properties were measured by non-destructive and destructive methods. Additionally, dynamic and static modulus of elasticity and modulus of rupture were determined for log characterisation. The test material (210 oak logs, *Quercus petraea* (Matt.) Liebl.) originated from one stand at age of 90 years in Rhineland-Palatinate which developed from stump sprouts.

The results show that the strength and stiffness of small-diameter oak logs are well sufficient for the use in load-bearing structures. Initial analysis on strength prediction of individual logs based on non-destructive methodologies reveal large heterogeneity at the small sample size and thus only restricted prediction strength. Among the investigated predictors, oven-dry wood density and log dynamic modulus of elasticity showed the best correlation with strength.

Improvement of the strength prediction, which could then allow strength grading, would be desirable for even more efficient utilization of small-diameter oak wood. This could possibly be achieved by finalizing the assessment of the internal knot features in this study and by increasing the sample size (number of oak logs) in a subsequent study.

KEYWORDS: structural timber, NDT, wood properties, wood density, external quality grading, *Quercus petraea*

1 INTRODUCTION

In Germany, only half of the annual increment is used in oak stands [1]. Especially small-diameter oaks are currently either not used or only used as firewood. The use of wood as a construction material has several advantages. On the one hand, the carbon is sequestered much longer compared to firewood, and on the other hand, energy-intensive materials such as steel or concrete are substituted. In addition, there is a higher added value for the forest owner.

In order to exploit these opportunities, our research project aims on making small-diameter oak logs available as structural timber members, e. g. for columns, frameworks and agricultural buildings, like barns. For this purpose, the mechanical properties of such logs and the factors influencing them must be determined, as these have only been insufficiently investigated so far. Most of the previous studies on strength properties have been conducted on softwoods, since softwoods have been used much more frequently for load-bearing structures than hardwoods in recent decades due to their straightness and better predictable mechanical properties. As a consequence, one goal of the project was to apply conventional NDT technology already in use for (board strength) grading, with which we can infer the strength of green oak logs.

The second part of this project deals with the implementation of log bending tests (strength and stiffness) to obtain reference values, the third part with the construction of a demonstration hall from a subset of the investigated oak logs. Part two was also presented at this conference and included in the proceedings [2].

2 MATERIAL AND METHODS

As test material, 210 oak logs (*Quercus petraea* (Matt.) Liebl.) with a length of 5 m and an average mid diameter of about 25 cm were cut from one stand at age of 90 years in Rhineland-Palatinate. The trees have developed from

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https://doi.org/10.52202/069179-0097

stump sprouts. The logs were divided into three subsamples (n = 70, each) to facilitate the measuring process. Subsample 3 was used for the construction of the demonstration hall [2] and underwent a shorter test program without destructive measurements. In this article, we only present the results from the subsamples 1 and 2 which underwent the complete measurement programme in non-destructive and destructive testing for characterisation. From these subsamples, 80 logs were debarked, 30 logs were edged on two sides and 30 logs were edged on four sides. Debarking was executed for faster drying, edging for a simplified construction geometry (Figure 1).

__Figure 1:__ Oak logs from subsample 1 (n = 70). Edged on two or four sides (left) and debarked (right).

In the experimental program, green density distribution and internal knot features of the logs were determined by computed tomography scans (MiCROTEC® CT.LOG, Figure 2).

__Figure 2:__ Measurement of natural frequency (Viscan), left, and of raw density and geometry (CT.LOG and DiShape), right.

The dry wood density distribution was measured on 2 × 1 cm small clear samples, which were taken in four spatial directions from a ~2 cm thick log slice from the top end of the log (Figure 3). The samples were dried to constant weight at 103 °C, followed by immersion weighing to determine sample volume. Moisture content of the logs (MC, moisture mass fraction on dry basis) was determined by sampling of seven slices per log at the end of the trial (Figure 3). In conjunction with the mass measurement of the log at all phases of the test programme, we were able to determine the moisture content of the logs at earlier points in time as well.

External wood defects, i.e. knots, were investigated by log quality grading following the German Framework Agreement for Timber Trade (RVR) [3]. Geometry properties were measured using a 3D laser scanner (MiCROTEC® DiShape, Figure 2).

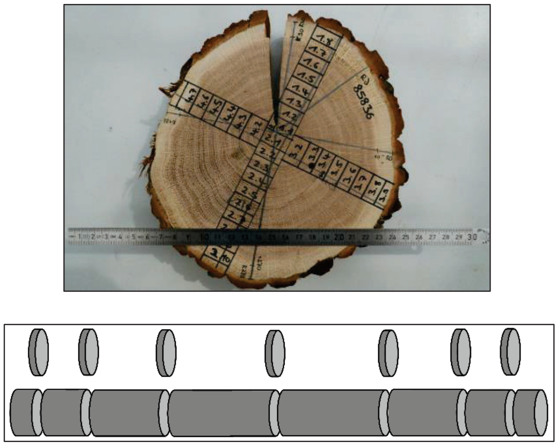

__Figure 3:__ Samples for determination of oven-dry density distribution (MC = 0 %) on a log slice from the top end of the log (top). Slice samples for determination of the final moisture content and dry mass of the log (bottom).

The curvature was calculated from the DiShape data as the maximum bow height divided by the log length, excluding the 50 cm butt end of the log, according to [4] to avoid buttresses.

The dynamic modulus of elasticity (MOE_{dyn}) of the logs has been calculated from measurements of the natural frequency (MiCROTEC® Viscan, Figure 2), the green density and length of the logs. The static modulus of elasticity (MOE_{stat}) and the bending strength (MOR) have been investigated by our project partners according to DIN EN 14251 [5] (see part 2 of this project) [2].

3 RESULTS AND DISCUSSION

Round wood grading according to RVR show that most logs were graded in quality class C, which represents intermediate quality logs characterised by a large number

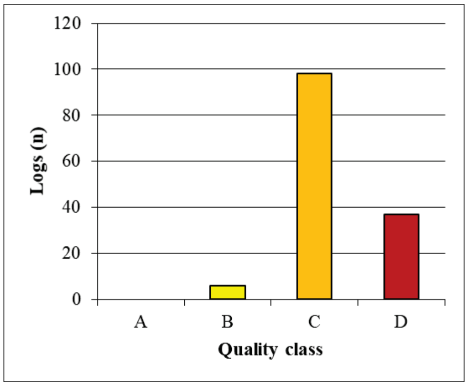

__Figure 4:__ Frequency distribution of the oak logs from subsample 1 and 2 (n = 140) in different quality classes (A = best quality, D = worst quality) according to the German Framework Agreement for Timber Trade [3].

of small to medium sized knots, the presence of curvature and other features (Figure 4). Mean number of externally visible knots and burls per log was 24.9 (± 17.9) and mean curvature was 1.7 % (± 0.8 %), with multiple curvatures occurring frequently.

Wood density in oven-dry condition (Figure 5) was within the range found for oak in the literature [6]. Heartwood showed a slightly higher dry density than sapwood, probably due to narrower annual rings in sapwood affected by increasing competition between the trees. Incorporation of chemical substances in heartwood seems to have a minor effect on dry wood density [6].

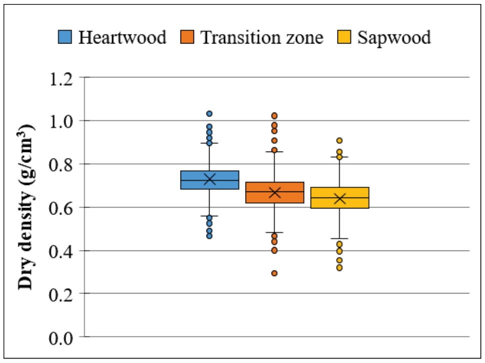

Figure 5: *Dry wood density distribution (MC = 0 %) of different wood compartments for the 140 oak logs from subsample 1 and 2, determined on 4720 wood samples.*

Moisture content in fresh condition was, compared to other studies [7], relatively low at 66.8 % (mean value for subsample 2, not measured for subsample 1), which is probably due to the very dry weather conditions over the last years. The logs dried to an average moisture content of 35.4 % within ~20 months (Figure 6) until the testing programme terminated with destructive testing. When the bending tests were performed, all but two logs from subsamples 1 & 2 were still above the fibre saturation point (FSP), which is at approx. 25 % MC for oak wood [8].

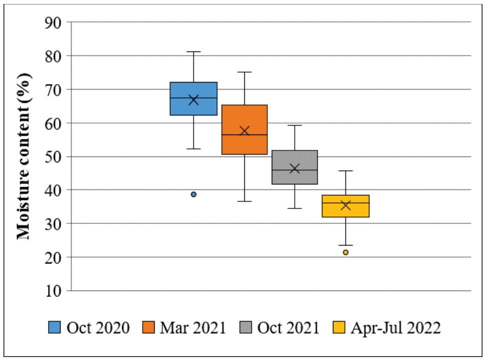

Figure 6: *Moisture content distribution of subsample 2 (n = 70 oak logs) over time, determined by regular weighing and measurement of the dry mass of the logs at the end of the trial. Felling was conducted in September 2020, bending tests from April to July 2022.*

Dynamic modulus of elasticity ranged from 5,481 MPa to 18,754 MPa (median 12,070 MPa) for all logs. Mean dynamic MOE was about 3.5 % higher than mean static MOE (see part 2 of this project [2]). Static MOE showed several extremely high values with a maximum of 32,956 MPa. Consequently, the median of $\mathrm{MOE_{stat}}$ was only 10,647 MPa, and therefore 13.4 % lower than the median of $\mathrm{MOE_{dyn}}$, which is in accordance with other studies comparing non-destructive and destructive methodologies for mechanical characterisation of timber [9]. Modulus of rupture (MOR) ranged from 27.4 MPa to 135.0 MPa (median 66.1 MPa) for all logs [2]. Conventional classification of stiffness and strength results to standard seemed not appropriate, as dimension/geometry and moisture content of our test specimens (logs) were not in line with common test standards. Literature values were mostly determined on small clear oak specimens at a moisture content of 12 %. For such specimens, a range of 9,200-13,500 MPa for $\mathrm{MOE_{stat}}$ and of 78-117 MPa for MOR is given by [10] and a mean of 12,300 MPa for $\mathrm{MOE_{stat}}$ and of 105 MPa for MOR were reported by [11]. In green condition, a mean $\mathrm{MOE_{stat}}$ of 8,600 MPa and a mean MOR of 57 MPa was specified [11]. Consequently, the strength and stiffness values measured in this study appear to be within the natural range for oak, or even slightly higher if the high moisture content of the logs is taken into account.

ANOVA and bivariate linear regression analysis to clarify the influence of the external and internal log structures and characteristics on the bending strength revealed the necessity to deal with the different geometric variants separately. Hereafter, only the results for the round logs are presented. In future, round logs will probably play a more important role in the processing of small-size oak construction timber than edged logs, since less material is wasted and no sawing is required. Bending tests were performed on 71 of the 80 round logs. Three round logs were used for compression tests, the six remaining logs had either too strong curvature or too large drying cracks to perform the bending tests safely.

Oven-dry wood density and dynamic modulus of elasticity of the logs contributed most to the variation in log MOR (Figure 7). Both variables were statistically significant positively correlated with the bending strength, oven-dry density even quite closely (Pearson test, $\alpha = 0.05$ with $r = 0.61$ and $p = 0.000$ for dry density and $r = 0.51$ and $p = 0.000$ for $\mathrm{MOE_{dyn}}$).

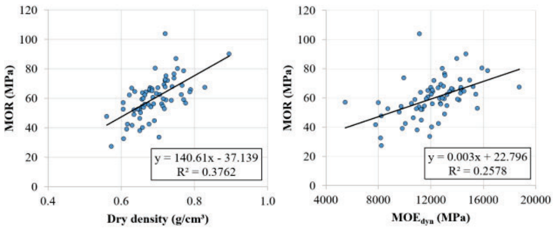

Figure 7: *Relation and linear regression between modulus of rupture and mean oven-dry wood density at MC = 0 % (left) and dynamic modulus of elasticity (right) for the debarked round wood (n = 71).*

https://doi.org/10.52202/069179-0097

In a study on a strength prediction model for pine wood, density and MOE_{dyn} were also the variables with the best explanatory power [12]. Compared to the present study, the coefficients of determination were slightly lower and the MOE_{dyn} had a slightly higher explanatory power than the wood density. In addition, study [12] did not investigate oven-dry density, but density at 12 % moisture content. However, this low and uniform MC is unlikely to have had a large effect on the strength of the correlation.

Considering a log grading procedure based on these characteristics, measurement of MOE_{dyn} can be described as non-destructive and relatively fast. The measurement of oven-dry density, on the other hand, is only possible based on destructive wood sampling. Since these samples originated from the very top end of the log, the log's subsequent use is hardly restricted. However, for an on-line work-flow, a disadvantage is the long time required for this measurement.

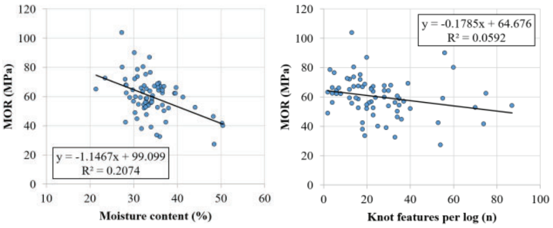

Figure 8: *Relation and linear regression between modulus of rupture and mean moisture content of the logs (left) and number of knot features per log according to [3] (right) for the debarked round wood (n = 71).*

In contrast to the literature, a statistically significant correlation (Pearson test, $\alpha = 0.05$ with $r = -0.46$ and $p = 0.000$) was also found between bending strength and moisture content of the logs (Figure 8, left). The literature states that the mechanical properties only change below the fibre saturation point (FSP) [13]. In this context, a mean log moisture measure over the whole cross section could be misleading as significantly drier areas below the FSP located in mechanical important peripheral stress zones might have a greater influence on the strength in a bending test than the core areas. An evaluation of additional moisture measurements by means of impact electrodes (resistance-based, Hydromette CH 17, GANN Mess- u. Regeltechnik GmbH) at peripheral log depths of 2 cm and 4 cm frequently showed values below the FSP, but explained the variation in strength distinctly worse instead of better. This indicates that we have a spurious negative correlation based on other, unknown causes in case of Figure 8 (left).

The number of externally visible knots and burls per log also showed a statistically significant, but very weak negative correlation (Pearson test, $\alpha = 0.05$ with $r = -0.24$ and $p = 0.045$) with bending strength (Figure 8, right). In a study on the effect of knots on the bending strength of boards from two different poplar clones, the correlation coefficients r range from -0.12 to -0.60, depending on the position and diameter ratio of the knots [14].

For a better interpretation of our results, a deeper analysis of the knot data is necessary. Above all, the internal knot structures of the logs must also be taken into account. For this purpose, all knot features in CT scans of five logs were manually annotated (over 10,000 polygons in total) and categorized (Figure 9). A machine learning algorithm was trained with these scans to develop an automated knot detection procedure for knot segmentation for further use on such CT scans (Figure 10). This process has not yet been completed, but due to the accuracy achieved so far stronger correlations between knot architecture of oak logs and their strength is expected.

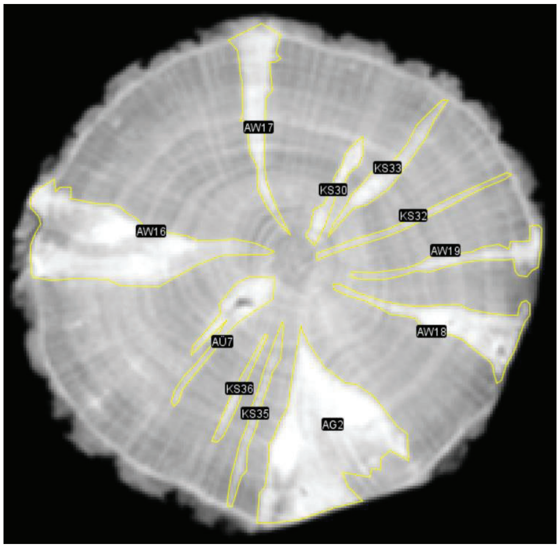

Figure 9: *Manually annotated and categorized knot features in a CT slice of an oak log. KS = bud trace, AW = burl, AG = sound knot, AÜ = overgrown knot; followed by the consecutive number of the feature within the log.*

Figure 10: *Comparison of manual (left) and machine learning based automated (right) segmentations of knot features in the same CT slice of an oak log.*

Mean curvature of the round logs was 1.9 % (± 0.8 %). Curvature showed no statistically significant correlation with bending strength. Strong stem deviation leads to stem eccentricity and severe tension wood formation in hardwoods which usually shows a lower strength. Obviously, the curvature recorded in the test material did not lead to the formation of tension wood with different mechanical properties. This assumption was visually confirmed during the sampling of numerous log slices after the bending test.

Measurement of knot features as defined in visual log grading regulations and CT scanning works non-

https://doi.org/10.52202/069179-0097

destructively. In contrast, measuring a precise moisture content is only possible by the collection of representative wood samples and their subsequent kiln-drying [15]. The disadvantage of this method is that it is time-consuming and destructive. Non-destructive rapid MC determination devices usually show high deviations in their measurement precision from the reference method [16].

Although small-diameter oak logs are well suited for construction purposes, grading procedures of individual logs similar to softwood board strength grading still requires further evaluation of our data. Furthermore, an increase in the sample number in additional studies could significantly improve this strength prediction.

4 CONCLUSIONS

The results of our collaborative research project indicate that small-diameter oak logs appear well suitable for load-bearing structures. This application seems to be the best option, since such logs cannot be used for the production of lumber or even veneer due to their knottiness, small diameter and strong curvature.

For even more efficient use, it would be beneficial to predict the strength of individual logs by non-destructive measurements. In this study, the best explanation for the variation in bending strength was obtained by the measurement of the oven-dry density at the top end of the logs, followed by the measurement of the global dynamic modulus of elasticity. Moisture content of the logs also showed a significant correlation with bending strength, but this relation appears to be coincidental since almost all logs were still above the fibre saturation point at the time of testing. Log curvature in the range found in the test material had no effect on bending strength, probably because it was not related to tension wood occurrence. Number of knots and burls quantified in course of external quality grading was weakly correlated with strength. However, the influence of knots is still under evaluation. In particular, innovative machine learning procedures applied to CT scans with respect to internal knot features could lead to a better strength prediction.

After completion of data evaluation, all measured parameters and log characteristics will be integrated into a strength prediction model for oak logs.

ACKNOWLEDGEMENT

This project (support code 2218WK18C3) was funded by the Federal Ministry of Food and Agriculture (BMEL) and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) through the Agency for Renewable Resources (FNR) from the Forest Climate Fund (WKF).

The authors would like to thank Oswald Keller, Heike Laux, Christoph Beilharz, Adrian Kölz, Elias Maurer, Jakob Fei and Nikolaj Markgrander for their great help with sampling and practical measurements, Werner Rützler for the CT/DiShape scanning and Martin Huber, Elisa Kammer, Omoyemi Edun, Hannah Staiger and Tushar Maske for the detailed processing of the CT scans.

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https://doi.org/10.52202/069179-0097