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IMPROVING STRUCTURAL ROUNDWOOD CLASSIFICATION BY DIGITAL 3D-MEASUREMENT

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ABSTRACT: The paper addresses the use of small-diameter oak logs as a sustainable construction material. Knowledge of the mechanical properties is essential for structural applications. Therefore, the modulus of rupture has been investigated using geometrical data obtained by 3D-Lasertriangulation technology to provide one part of the missing knowledge to the construction industry. In the first step, the raw material was characterized by a quality assessment. Half of the logs were edged on either two or four sides for easier use in construction. Subsequently, the geometries of the logs were measured using 3D-Lasertriangulation technology, followed by destructive bending tests. A program developed in the Python programming language calculated the moment of inertia from these 3D-Lasertriangulation data. The results of the calculated modulus of rupture using this moment of inertia were compared with those received from calculation rules given in normative testing standards. The calculation method based on the 3D-Lasertriangulation data provides less scattering results in the not edged subsample. In general, both determination methods provide comparable results, but with the 3D-Lasertriangulation technology being automated, far quicker and less error-prone. This knowledge will contribute to the development of a grading system for the high-quality use of round hardwoods in construction.

KEYWORDS: small-diameter logs, roundwood, modulus of rupture, oak, *Quercus petraea* (Matt.) Liebl.

1 – INTRODUCTION

The current climate change leads to a shift in the available amount of wood and wood species for construction form softwood to hardwood. Unfortunately, European hardwoods like Sessile oak (*Quercus petraea* (Matt.) Liebl.) are not very suitable for sawing due to their specific growth characteristics, such as curvature and knot features. The utilisation of this resource in its natural round shape could provide a solution for that. Therefore, the modulus of rupture (MOR) has been determined on 113 oak logs from Rhineland-Palatinate, Germany. In previous studies on the same test specimen, the MOR was calculated according to normative requirements on test methods for structural round timber, assuming an elliptical cross-section on the test specimen. However, the natural shape and the growth characteristics of the roundwood logs result in varying section data along the length of the test specimen, which are not considered in test standards. Serving the development of a more accurate, far quicker and less error-prone determination method, the MOR has been calculated again using geometrical data obtained by 3D-Lasertriangulation technology. A comparison between both determination methods including a correlation analysis with non-destructive testing (NDT) results has been done to investigate the usability of the 3D-Lasertriangulation technology for this purpose.

2 – BACKGROUND

For centuries, hardwoods with round geometries have been used in construction and have been implemented into national standards in the United Kingdom, Italy and the USA [1]. Round logs edged on two or four sides, so called “Travi”, can be used in construction in Italy based

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on UNI 11035-3 [2], [3]. Based on the available testing standards ASTM D 2899 [4] and ASTM D 3957 [5], the use of round logs for homes and round timber piles is possible in the USA. The normative classification of round hardwood based on visual grading is currently not available in Germany. Round softwood can visually be graded according to the national standard DIN 4074-2 [6]. The visual grading of hardwood, on the other hand, is only available for sawn timber based on the national standard DIN 4074-5 [7]. The mechanical properties of round soft- and hardwoods can be tested in accordance with the testing standard DIN EN 14251 [8]. Therefore, finding parameters with NDT methods to predict the mechanical properties of round hardwood is of great importance for a sustainable high-quality application of round hardwood in construction.

A variety of studies has been carried out to investigate the usability of softwoods with round geometries in construction, for example [9], [10]. The former is focused on the use of small-diameter timber. For this purpose, 4-point bending tests were applied on 1400 samples to determine the MOR and the static modulus of elasticity (MOE) in bending of different softwoods. The 5%-quantile of the MOR of round timber was determined to be much higher than that of sawn timber in this study. In case of spruce, the value was even twice as high. Meanwhile, only a small number of studies investigated the use of hardwoods in construction [1], [11], [12], [13]. Accordingly, the number of studies dealing with oak wood and especially round logs in construction and their mechanical properties is scarce. A general overview of the use of acoustic wave methods and laser scanning as NDT methods in the sorting process of Hardwoods is provided in [1]. Ross et al. 2007 [14] looked into the usability of sawn green oak timber in construction. Nocetti et al. 2021 [13] investigated the moisture content, acoustic velocity and the dynamic MOE as NDT methods on 257 round oak logs prior to determining the mechanical properties with destructive 4-point bending tests. The best correlation between the mechanical properties and the results of the NDT methods was obtained between the dynamic MOE and the MOR as well as the static MOE.

A similar approach [15], [16] investigated the usability of green oak as a sustainable construction material. For this purpose, 140 round oak logs and oak logs edged on two or four sides were investigated. NDT methods like visual inspection, dynamic MOE and computed tomography were followed by destructive 4-point bending tests to determine the mechanical properties like the MOR in bending of the test specimen. Density and dynamic MOE were among the parameters with the strongest correlation with the mechanical properties. This paper is based on this research.

A method for the structural analysis of naturally shaped timber structures was developed by [17]. They investigated problems that occur when naturally shaped timber is calculated for construction using standard engineering models. Comparative studies between naturally shaped and straight timber construction elements were conducted to investigate the geometric influences. As a result, ways of improved modelling of these geometries were presented. A further step in this direction did [18] by modelling the geometric properties of naturally shaped wood for structural purposes. Calculation models were presented that consider the geometric properties of naturally shaped wood.

3 – EXPERIMENTAL SETUP

The mechanical properties of naturally shaped, small-diameter oak logs (*Quercus petraea* (Matt.) Liebl.) were investigated using 140 test specimens with a length of around five meters. The test-specimens were harvested in Rhineland-Palatinate, Germany, in two subsamples (Cut 1 and Cut 2). Both subsamples consist of 70 logs each. They were harvested in December 2019 (Cut 1) and in October 2020 (Cut 2). At the time of harvest, the trees were around 90 years old and had developed from stump sprouts. The logs had a mid-diameter between 20 cm and 29 cm and an average mid-diameter of about 25 cm. They were classified into the quality classes B ($n = 6$), C ($n = 88$) and D ($n = 35$) according to the RVR, the German Framework Agreement for Timber Trade (RVR) [19]. This classification is based on the log geometry and externally recognizable features like knots, rot, cracks and curvature. The focus of classification according to RVR is the usability of the raw wood in the sawmill and in the veneer industry. Because of the diameter and the classification, the test-specimen would currently either not be used or only be used as firewood and not for high-quality applications like constructions.

To improve the usability of these logs in existing construction concepts, a part of each subsample was edged on either two or four sides. They will be referred to as “Travi“ (Fig. 1, top, left). Whereas the other unedged logs will be referred to as “Round” (Fig. 1, top, right). The 80 “Round” logs were debarked to achieve a faster, natural drying and to protect them from wood pests. The 60 edged “Travi” logs were not debarked.

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Figure 1: Edged oak logs (top, left), debarked small-diameter oak logs (top, right), measurement of raw density and geometry using MiCROTEC® CT.LOG and DiShape (bottom, left), visualised 3D laser scan of a log (bottom, right).

To obtain a detailed 3D-scan of each log, a 3D-Lasertriangulation measurement was carried out using a “MiCROTEC® DiShape” (Fig. 1, bottom, left). It recorded the contour of a log’s cross-section every 5 mm measuring 360 points per cross-section (Fig. 1, bottom, right). This 3D-Lasertriangulation data was used to calculate the geometric properties of each log. Furthermore, the internal properties were documented using computed tomography. Both, the 3D-Lasertriangulation measurements and the computed tomography scans were carried out by the Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation in Freiburg, Germany. Subsequently, destructive four-point bending tests according to DIN EN 14251 [8] were conducted on the logs, with the test setups based on the dimensions of the test specimens (Fig. 2, left). After the test, a slice with a thickness of 50 mm was removed from each test-specimen close to the fracture point. This cross-section slice was digitally recorded and the oven-dry kiln density as well as the moisture content of the test specimen was determined on this slice. Besides the determination of the oven-dry kiln density and the moisture content, this was done by the Timber and Plastics Research Group at Mainz University of Applied Sciences.

The MOR result from the static moment at the fracture point divided by the moment of inertia (MOI) multiplied by the smaller of the two largest vertical distances of the outer contour to the centre of geometry. For this reason, the accurate determination of the MOI is essential for the calculation of (naturally shaped) beams. Inaccuracies in the determination of the MOI have a direct impact on the determination of the MOR. Therefore, different methods of determining the MOI for the calculation of the MOR were tested and compared. The resulting MOR values were evaluated and their correlation with parameters obtained using NDT methods was analysed.

The MOI can be calculated according to (1), based on an elliptic modelling approach. According to DIN EN 14251 [8], the MOR can be determined by (2) based on this modelling approach.

$$\mathrm{MOI} = \frac{\pi}{64}\, d_\mathrm{h}\, d_\mathrm{v}^3 \tag{1}$$

$$\mathrm{MOR} = f_{\mathrm{m},0} = \frac{16\, F_\mathrm{max}\, a}{\pi\, d_\mathrm{h}\, d_\mathrm{v}^{\,2}} \tag{2}$$

d_h	Diameter in the direction of load application at half span.
d_v	Diameter perpendicular to the direction of load application at half span.
F_max	Maximum load
a	Distance between the load head and the nearest support

As the log’s cross-sections are only approximately elliptical, the MOI was additionally determined using the 3D-Lasertriangulation data. In this case, the MOI was

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calculated based on the equally spaced 360 measuring points on the circumference of each recorded cross-section. For this purpose, a program was developed in the Python programming language. First, the program calculates the centre of gravity of each cross-section assuming a homogeneous mass distribution. The centre of the gravity of each cross-section is then shifted to the coordinate origin by a coordinate transformation. Finally, the MOI of the cross-section is calculated in relation to the coordinate origin. To do so, the cross-section between two measuring points was divided into a square and a triangle (Fig. 2, right). The sum of the calculated MOI for the partial areas of the cross-section (triangle and square) is the resulting MOI of the transformed cross-section. The calculation of the resulting MOI was done by adding the partial solution of the MOI resulting from the parallel axis theorem and the polar MOI. The MOI around the *x*-coordinate axes was calculated. This calculation method assumes a homogeneous mass distribution inside the cross-section.

The test-specimen's position during the bending test (0° position) was rotated compared to the position during the 3D-Lasertriangulation process. To calculate the MOI for the position of the test specimen during the bending test based on the 3D-Lasertriangulation data, the angle of rotation between both positions was measured. In a last step, the determined rotation angel was considered based on the transformation relationship.

Due to the considerable differences between the approximate elliptic geometry assumed in DIN EN 14251 [8] and the partially squared cross-section geometry of the subsample "Travi", the MOI was not calculated based on this DIN standard for this subsample. Instead, to provide a more precise determination of the MOI, it was determined in two different ways. On the one hand, it was calculated based on the digitally recorded cross-section slice taken close to the fracture point and on the other hand based on the 3D-Lasertriangulation data as described above.

Besides the determination according to DIN EN 14251 [8], the MOR for both subsamples were calculated using the different determination methods for the MOI for both subsamples. Based on the static model of a single-span beam with equal loads at the third points, (3) was used for the determination of the MOR.

$$\mathrm{MOR} = f_{\mathrm{m},0} = \frac{F_{\max}\, a\, z_{\max}}{2\, I} \tag{3}$$

$F_{\max}$	Failure load
a	Distance between the load head and the support
$z_{\max}$	Smallest of the two maximum vertical distances between the centre of gravity and the cross-section surface
I	MOI of the cross-section close to the fracture point

When using the 3D-Lasertriangulation data for the MOI calculation, the determination of the MOR was done using the average MOI of nine slices (approx. 4.5 mm) around the point of fracture. A statistical evaluation of the MOR results was done comparing the two different determination methods for the MOR of the "Round" and the "Travi" logs. Each statistical evaluation includes "Cut 1" as well as "Cut 2". Additionally, a correlation analysis to determine the accuracy and reliability of the MOR predictions based on potential indicating properties such as density and curvature was carried out.

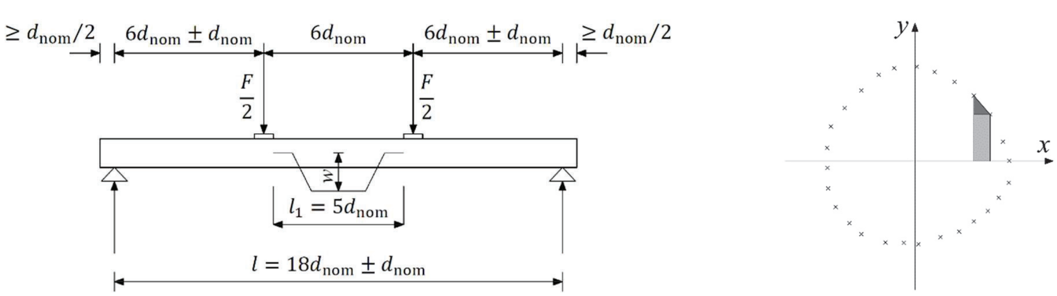

Figure 2: Test setup according to DIN EN 14251 [8] (own illustration) (left), Illustration of the calculated partial areas (right).

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For construction purposes, the characteristic 5 %-quantile value of the MOR is decisive. It was calculated according to the German standard DIN EN 1990 [20] (4 - 6).

$$V_{\mathrm{x}} = \frac{s_{\mathrm{x}}}{m_{\mathrm{x}}} \tag{4}$$

$$s_{\mathrm{x}}^2 = \frac{1}{n - 1} \sum_{1}^{\mathrm{n}} (x_i - m_{\mathrm{x}})^2 \tag{5}$$

$$X_{\mathrm{k}} = \eta \cdot m_{\mathrm{x}} \cdot (1 - k_{\mathrm{n}} \cdot V_{\mathrm{x}}) \tag{6}$$

V_{x}	Coefficient of variation (COV)
s_{x}	Standard deviation
s_{x}^2	Variance
m_{x}	Mean of the n sample results
n	Number of test results
x_i	Value of test result
X_{k}	Characteristic value
η	Factor for model uncertainties
k_{n}	Characteristic fractile factor (5 %-fractile)

4 – RESULTS

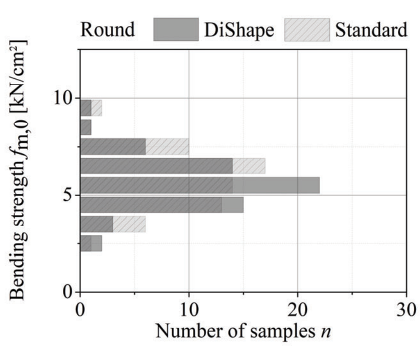
In the following, the results of the statistical evaluation and the correlation analysis are presented separately for the subsamples “Round” and “Travi”. The frequency distribution of both subsamples is illustrated in Figure 3. The results of the statistical evaluation of the MOR of the subsample “Round” are presented in Table 1. The calculated MOR results from the subsample “Round” with the calculation according to the standard DIN EN 14251 [8] range from 34.74 MPa to 97.97 MPa with an average of 63.17 MPa and a coefficient of variation of 22.2 %. The test results obtained by using the MOI determination from the 3D-Lasertriangulation data range from 30.81 MPa to 99.14 MPa with an average of 60.82 MPa and a lower coefficient of variation of 21.0 % compared to the results based on the standard DIN EN 14251 [8].

Table 1	**MOR “Round” [MPa].**	
	Standard	***DiShape***
n	64	64
mean	63.17	60.82
char.	38.90	38.77

The MOR results of the subsample “Round” calculated using the MOI determined from 3D measurement scatter less compared to those based on normative testing methods. The results of the statistical evaluation of the MOR of the subsample “Travi” are presented in Table 2.

Table 2	**MOR “Travi” [MPa].**	
	Slice	***DiShape***
n	49	49
mean	52.26	54.18
char.	27.17	25.57

The calculated MOR results from the subsample “Travi” using the calculation method based on the digital recorded cross-section slice range from 24.09 MPa to 89.57 MPa with an average of 52.26 MPa and a coefficient of variation of 27.8 %. The test results obtained by using the MOI determination from the 3D-Lasertriangulation data range from 19.74 MPa to 96.94 MPa with an average of 54.18 MPa and a higher coefficient of variation of 30.5 % compared to the results based on DIN EN 14251 [8].



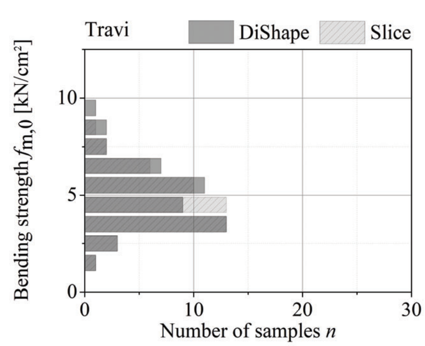


Figure 3: Statistical evaluation of the MOR Round (left), Travi (right).

The result of the determined characteristic MOR corresponds to the strength class D35 according to the German standard DIN EN 338 [21] for the debarked subsample "Round" and both methods. The results of the edged subsample "Travi" using the determination method based on the cross-section slice corresponds to the strength class D27 according to the DIN EN 338 [21] and to D24 using the determination method based on the 3D-Lasertriangulation data. The impact of the sawing process aligns with similar tests on softwood logs conducted by [9]. The comparable results of both MOI calculation methods for the subsample "Round" indicate that the approximation of naturally shaped cross-sections by ellipses is adequate in most cases. However, this method of determining the MOI seems to be more error-prone.

For the "Travi" subsample the results of the MOI calculation methods based on the digital recorded cross-section slices seems to be more error-prone. Main reason for that seems to be inaccuracies in scaling based on the measured cross-section diameter. Yet, the overall results for the "Travi" are still similar for both calculation methods. However, the differences in the MOI for some samples when using the different calculation methods indicate that the mentioned shortcomings of the digital recorded cross-section slice based MOI determination method should not be neglected.

The determination method using the 3D-Lasertriangultion data provides an automated, far quicker and less complex measuring process of the cross-sections at every point of the log. For this reason and based on the test results, this method is preferable for both subsamples. This research shows that integrating precise measurement methods improves material assessment. At the same time, these methods enable a faster and less error-prone determination of the MOI than existing methods. This contributes to an efficient use of this material, which is becoming increasingly important for the construction industry.

The development of a classification system for the small-diameter roundwood oak logs requires the possibility to assign the raw material to a strength class based on NDT results. For this purpose, a correlation analysis using the NDT results on the same test-specimen was carried out. The results for the subsamples "Round" and "Travi" are presented in Table 3 and illustrated in Figure 4.

Table 3	**MOR DiShape [MPa].**	
	Round	***Travi***
Knot features (RVR)	0.208	0.000
Curvature	0.088	0.190
Oven-dry density	0.486	0.223
Dynamic MOE	0.425	0.321

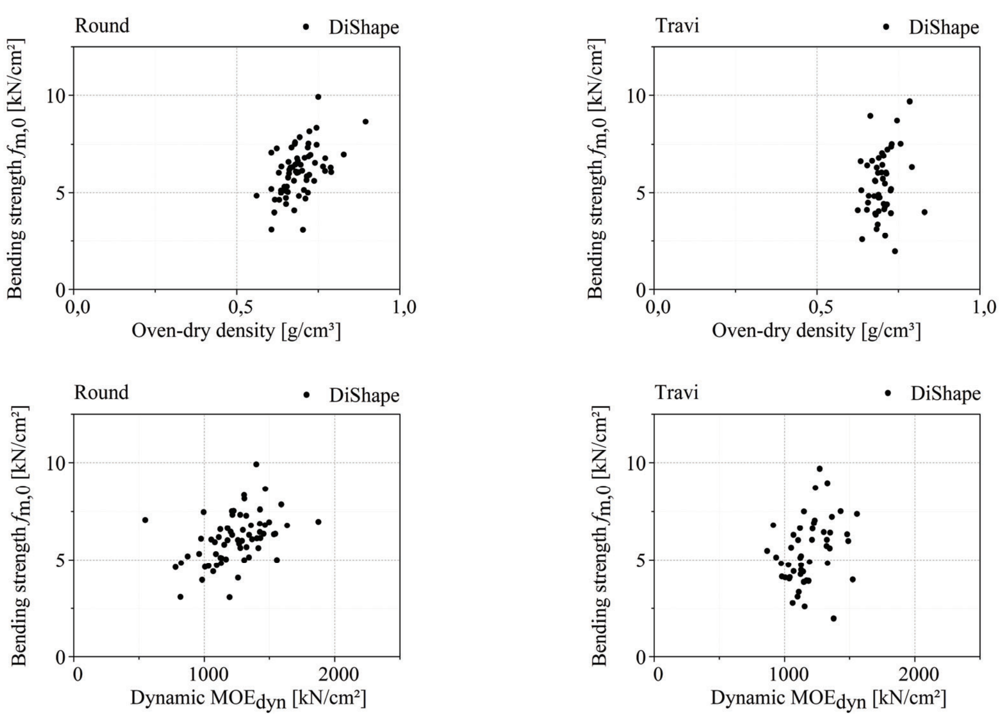


Figure 4: Correlation analysis of the subsamples Round (left), Travi (right)..

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Within the subsample “Round”, the curvature has the weakest correlation with all mechanical properties, which can be interpreted as very weak. The correlation with the knot features according to RVR is weak. The strongest correlation exists between the MOR and the oven-dry density, which is moderate, followed by the correlation of the MOR with the dynamic MOE, which is also moderate. Within the subsample “Travi”, the knot features according to RVR have the weakest correlation with all mechanical properties, which can be interpreted as no relationship. The correlation with the curvature is very weak. The correlation with the oven-dry density is weak. The correlation with the dynamic MOE provides the highest correlation coefficient, which can be interpreted as weak too.

The results of the correlation analysis of both subsamples “Round” and “Travi” differ from each other. All correlations with the curvature are very weak. All the relationships within the subsample “Travi” provide a weak, very weak or no correlation. Only the relationship with the oven-dry density and the dynamic MOE in the subsample “Round” provides a moderate correlation. Models that consider several correlations are currently being investigated.

5 – CONCLUSION

The results of this research indicate that the determined MOR of small-diameter oak logs is suitable for construction materials. This provides a necessary missing part of knowledge to the construction industry and brings significant improvements to the existing range of application of this material, due to its current limitation in consequence of the missing knowledge about the load bearing capacity and about the indicating properties necessary for the classification of the raw material. In general, both determination methods for the MOI lead to comparable results for the MOR in both subsamples. Therefore, the automated, far quicker and less error-prone method of calculating the MOI via the 3D-Lasertriangulation data seems preferable for further investigations.

Within the subsample “Travi”, the derived results of the characteristic MOR are smaller compared to the results of the subsample “Round” no matter which calculation method has been used. This obtained influence of the sawing process aligns with similar tests on softwood logs. Regarding the development of a grading system for the subsample “Round”, the best explanation for the variation in the bending strength is provided by the oven-dry density.

For the subsample “Travi”, the best explanation for the variation in the bending strength is provided by the dynamic MOE. These investigated indicating properties as well as the properties oven-dry density and dynamic MOE within the subsample “Round” could provide a suitable correlation for developing a grading system within this test series. Meanwhile, the log curvature and the number of knot-features according to RVR were found to be only weakly, very weakly or not correlated with the bending strength in this test series. 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.

In general, the MOR results are promising to go the next steps in the development of a grading system. Currently, a follow-up study is underway to investigate the MOE, using the same 3D-Lasertriangulation data for the investigated sample assortment. This knowledge should contribute to the development of a grading system and a better strength prediction for the high-quality use of round hardwoods in the future.

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