World Conference on
Timber Engineering
Oslo 2023

GREEN OAK BUILDING WITH HIGH-TECH METHODS, PART 2: LOG BENDING TESTS FOR DETERMINATION OF STRENGTH AND STIFFNESS

Kay-Uwe Schober[1], Beate Hörnel-Metzger[2], Maximilian Leonhard Müller[3]
Nicolas Hofmann[4], Franka Brüchert[5], Udo H. Sauter[6]

ABSTRACT: The green oak building research project deals with small-diameter oak logs as sustainable construction material for timber truss structures. The basis for structural use and design are the specific mechanical properties and the knowledge of performance influencing factors like wood defects, moisture content and density distribution. In a first step, the characterisation of the raw material itself has been done by quality assessment, followed by the determination of strength and stiffness parameters as input for the parametric design process and a prototype building as proof of concept. This paper summarises the experimental investigations on strength and stiffness of naturally dried green oak logs. The laboratory tests were supplemented by non-destructive data acquisition of the geometry, moisture, and density distribution along the full length and over the entire surface. The results show that strength and stiffness properties are affected by growth conditions, especially the moisture content and drying behaviour of green oak. The obtained results were in line with similar tests on softwood logs and other studies comparing destructive and non-destructive mechanical characterisation methods for roundwood. The preliminary results of the green oak research project indicate that small-diameter oak logs (≤ 250 mm) appear suitable for load-bearing timber structures.

KEYWORDS: small-diameter logs, roundwood, bending strength, visual grading, oak, *Quercus petraea* (Matt.) Liebl.

1 INTRODUCTION

In Germany, only half of the annual increment of oak wood from forests is used. Especially small-diameter oaks (≤ 250 mm) are currently either not used or only used as firewood. But they also sequester carbon dioxide and this much longer compared to firewood which is an added benefit for the forest owner. To exploit these opportunities, the green oak building research project aims on making small-diameter oak logs available as sustainable construction material, e.g., for columns and frameworks and in agricultural buildings, like barns. For this purpose, the mechanical properties of the logs need to be determined, due to insufficient knowledge and investigations, especially for small-diameter oak logs as natural resource in the building sector. This requires exploring the characteristics and factors influencing the structural performance and serviceability of green oak logs, like wood defects, moisture content (MC), density distribution and others, which are part of the subsequent presented investigations.

Part one of the Green Oak Building project deals with the characterisation of the raw material [1]. This topic was the main task of the forestry research partner FVA, located in Freiburg on the edge of the Black Forest, while the determination of strength and stiffness has been done in Mainz, Rhineland-Palatinate. The research results of both interdependent investigations on small-diameter oak logs (*Quercus petraea*) shall serve to upgrade the potential of this currently in Germany unemployed forestry resource as a local source building material for rural areas.

Based on the findings carried out in Freiburg and Mainz an approach was specified to derive the most suitable log as a structural member in wooden buildings dependent on its specific dimensions, actions, load scenarios, structural behaviour and design requirements. The buildings itself will be formed by the "perfect log" for its specified position in the structure by parametric analysis and design subject to the raw material database and the structural member database. Drawbacks of the idea to use the yet unpopular assortment of green small-diameter oak logs are their high moisture content, the low drying rate and the high distortion along the centreline, making any sort of standardized grading impossible. Additionally, the high moisture content is affecting the mechanical properties negative and can lead to additional crack development. It is questionable whether the visual grading and property assignment system for round timbers adequately assesses the potential quality of these logs for structural use.

---

[1] Kay-Uwe Schober, Mainz University of Applied Sciences, Timber and Plastics Research Group, Mainz, Germany, kay-uwe.schober@hs-mainz.de

[2] Beate Hörnel-Metzger, Timber and Plastics Research Group, Mainz, Germany, beate.hoernel-metzger@hs-mainz.de

[3] Maximilian Leonhard Müller, Timber and Plastics Research Group, Mainz, Germany, maximilian.mueller@hs-mainz.de

[4] Nicolas Hofmann, FVA Forest Research Institute of Baden-Württemberg, Germany, nicolas.hofmann@forst.bwl.de

[5] Franka Brüchert, FVA Forest Research Institute of Baden-Württemberg, Germany, franka.bruechert@forst.bwl.de

[6] Udo H. Sauter, FVA Forest Research Institute of Baden-Württemberg, Germany, udo.sauter@forst.bwl.de

https://doi.org/10.52202/069179-0016

2 BACKGROUND

Nowadays, logs used as round and sawn round timber beams are graded by visual examination with properties assigned by testing procedures defined in standards, e.g. [2]-[6] in the Americas or [7] in the European Union. Allowable properties for round timber beams and struts are derived using strength ratios for limiting defects as specified in grading rules and clear wood strength values. And the visual quality evaluation sort into categories for assignment of design properties. The characteristics of green oak (*Quercus petraea*) logs or in general unsawn hard woods prevented the further development of grading standards and industrial applications for round wood.

A major European study by RANTA-MAUNUS investigated the application of round wood in the building sector with experimental studies on round and sawn timber to compare both cross-section types with each other [8]. 1400 specimens, composed of different softwood species, such as Scots pine (*Pinus sylvestris)* and Norway spruce (*Picea abies)*, were tested in this study at an average MC of 16% to determine bending, compression and tension strength properties parallel to grain. The bending tests were conducted with the logs simply supported and loaded symmetrically at the 1/3-point of the span and tested at a span-to-depth ratio of 18:1. The modulus of elasticity (MOE) values were calculated using the average diameter of the log and the modulus of rupture (MOR) values were calculated using the diameter near failure. Furthermore, short column compression tests were conducted using an unsupported free span of six times the log diameter, with the compression MOE calculated using deformation measured over a span of four times the diameter. The research results have shown higher strength values for round wood compared to sawn timber made from the same logs. The bending strengths for roundwood have been observed with even double the value of sawn timber. Similar studies have been carried out and published in the following years mostly by American and European researchers, e.g. [9], [10], [11], [12] and others.

The studies confirmed the potential of round wood as building material while grading and design rules for round wood elements are still missing. In contrast to the above outlined research to determine material properties by testing under usual moisture conditions around 15% MC or to grade logs for design purposes, the impact of a much higher moisture content near or above fibre saturation in green and naturally dried logs along with a much lower drying rate played a significant role in this joint research.

Figure 1: *Debarked small-diameter oak logs for testing.*

3 MATERIAL AND METHODS

210 oak logs (*Quercus petraea* (Matt.) Liebl.) with a length of five meters and an average mid diameter of about 25 cm were cut from one 90 years old stand in Rhineland-Palatinate. The trees have developed from stump sprouts. The logs were divided into three subsamples ($n = 70$, each) to facilitate the measuring process. Subsample 1 (cut 1) and subsample 2 (cut 2) underwent the complete measurement programme in non-destructive and destructive testing for material characterisation [1]. From these subsamples, 80 logs were debarked (Figure 1), 30 logs were edged on two sides and 30 logs were edged on four sides. Debarking was executed for faster drying and edging for a simplified construction geometry. The remaining logs were assigned for construction of the demonstration hall and excluded from this characterization due to a shorter test program without destructive measurements.

At the test facility, each log was weighed and measured, and the slope of grain was recorded. The logs were oriented with the round side down for the sawn round logs and the load was applied to the flattened surface as they would typically occur. A similar handling has been implemented for the unsawn round wood (Figure 2). The experimental program consisted of 4-point-bending tests following DIN EN 14251 [7], which specifies the requirements to obtain mechanical properties of round timber from laboratory tests under controlled air conditions (20°C, 65% rH). Table 1 gives an overview of selected specimen dimensions. Due to different shape and diameters at tip and butt and distortions, special support devices for this test series have been custom made to address the irregular and for each specimen different geometries and shapes of the log sections.

Figure 2: *Natural and load-induced distortion of test specimen.*

To investigate the influence of wood defects, such as knots (Figure 3), different parameters have been investigated and recorded for each specimen: i) The position of the knot along the longitudinal axis of the log (x-axis), ii) the position of the knot along the height in loading direction (y-axis), defined in cylindrical coordinates by the radial distance and the azimuthal angle. To simplify the observation and speed up the lab test documentation, the azimuthal angle was recorded as knot position clockwise, defining ninety degrees or a quarter section to three hours like on a clock-face (Table 1) with later-on conversion in the cylindrical coordinate system.

iii) The knot radius (size), iv) the knot diving angle (inclination), and if possible, v) the knot length. The largest knot in the log (max knot) had some influence on both strength and stiffness prediction, but it was less correlated with these properties than was the sum of the knots in each cross section (knot sum). The correlation of the sum of the knots divided by the diameter of the cross section was like the correlation of the knot sum alone.

Table 1. *Exemplary summary of specimen span and sections.*

Log No.	vertical diameter d_v [cm] butt	mid-span	tip	knot position clockwise [h]	span [cm]
803	18.58	17.69	17.40	5:00	334.80
805	19.10	18.20	17.40	4:00	344.25
809	21.50	19.30	17.90	6:00	378.00
820	17.92	17.55	16.67	6:00	349.20
828	22.80	22.50	22.20	7:00	411.75
832	18.20	16.30	16.90	6:00	354.15
839	21.10	19.38	20.23	5:00	365.40
840	17.88	16.54	18.35	4:00	334.80
843	20.00	18.37	17.83	7:00	350.00
845	15.10	14.20	14.00	6:00	264.00
846	27.30	24.20	22.70	5:00	411.75
858	30.00	28.20	27.20	6:00	460.00

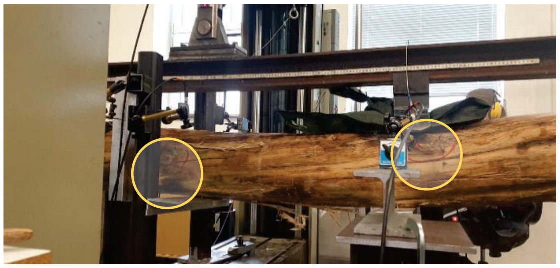

Figure 3: *Wood defects were recorded before flexural testing.*

Depending on the nominal diameter d_{nom}, the span was set-up as defined by the test standard [7] to $(18 \pm 1)\ d_{nom}$, including loading and measuring points (Figure 4), while d_{nom} has been calculated as an average value of the vertical and for bending tests more influencing diameter. The different values have been measured in vertical and horizontal direction separate for each log at the two supports (tip and butt side), near loading at $(6.5 \pm 1)\ d_{nom}$ from the specimen support and additional in the middle of the span. The 4-point-bending tests were derived by application of hysteresis with peaks of deflections at around 30% of the calculated average maximum stress level.

All tests were carried out by continuous measurements of time, deflections, and forces. First, non-destructive evaluation measurement was taken on each log while it was simply supported at the ends. The specimen (diameters vary from 20 cm to 30 cm, Table 1) were loaded up to a third of the failure load according to a preliminary design, then unloaded and the MOE was determined from measuring the incremental deformation 60 s after the first load level was applied. The deflections at midspan, near loading and at the supports were obtained with a linear variable displacement transducer (LVDT) to the nearest 0.0025 mm and the highest deflections in 100 mm to 200 mm range were recorded by laser sensors with different measuring ranges. The load-deflection plots were obtained for each specimen to calculate the MOR and static MOE depending on the wood defects, the species and overall quality.

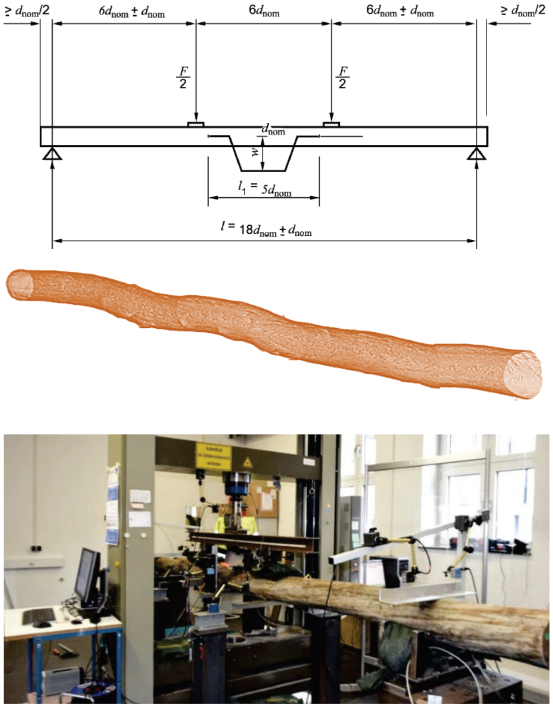

Figure 4: *Standard test arrangement with span-to-depth ratio 18:1 [7]; DiShape surface model of log no. 862 and lab view on log no. 862 waiting for action.*

After testing, a 50 mm thick section of each specimen has been removed from an area close to the location of failure to determine moisture content and the specific gravity (SG), as well as destructive investigations of geometry, oven-dry kiln density and moisture content in the defined section (failure location), [1]. The MC was measured in 2 cm and 4 cm depth at 0°/90°/180°/270° location (GANN Hydromette® CH 17). Then, the surface envelope of each log has been digital recorded from the images to calculate the cross-section data, e.g., diameter, section area, circumference, moment of inertia, etc. (Figure 5).

The lab tests were supplemented by non-destructive data acquisition of the geometry and raw wood density distribution along the full log length by MiCROTEC CT Log and DiShape, see Figure 4 middle and ref. [1]. The computed tomography scans and reconstructs the internal features of the log digitally and allow the assessment of the material in real time where size and position of internal wood defects can be accurately described in all three dimensions. The further use of the test outcome for design processes and material strength classification highly benefits from this technology and the accompanying research results and investigations.

Moment of inertia X: 292,666,326 mm⁴ *Area: 59,384.48 mm²*
Moment of inertia Y: 272,328,664 mm⁴ *Circumference: 883.73 mm*

Figure 5: *Section view of log no. 862 with special support construction (left) and digitalized cross-section (right) with corresponding section data.*

The MOR was calculated according to the round log testing standard [7], eq. (1), using the horizontal and vertical diameter (d_h ; d_v) at the point of failure, the maximum load (F_{max}), and the distance between the load head and nearest support (a).

$$\text{MOR} = f_{m,0} = \frac{16\, F_{\max}\, a}{\pi\, d_h\, d_v^{\,2}} \tag{1}$$

The MOE was determined from measuring the incremental deformation and applied load linear regression, eq. (2), in a specific load range (F_1 ; F_2) corresponding to the elastic range of structural response (0.1 F_{max} ; 0.4 F_{max}) and the corresponding deflections (w_1 ; w_2). The coefficient of determination was greater than 0.99 for all series. The moment of inertia I_{cal} has been calculated from the digital sections as described before (see also Figure 5) and the span ℓ is defined by the distance of the supports.

$$\text{MOE} = E_{m,0} = \frac{a\left(3\,\ell^2 - 4\,a^2\right)}{48\, I_{cal}} \cdot \frac{(F_2 - F_1)}{(w_2 - w_1)} \tag{2}$$

The green oaks had an average moisture content of ca. 70% after felling, drying within 20 months to 35% at the time of testing, which is still above the FSP of approximately 25% MC for oak wood [13]. The moisture content at the time of destructive testing has been determined from the 50 mm sawn-collected section where failure occurred by regular weighing and measurement of the dry mass. For better comparison of the different specimen and considered that the findings of this research shall serve for green oak log building application guidelines, the elastic properties were standardized by moisture for indoor climate.

Normative indoor climate in the Eurocode 5 service class system is characterized by a material moisture content corresponding to a temperature of 20°C and a relative humidity of 65% in the surrounding air exceeding it only a few weeks per year. The design code itself and the assumptions serve in general for timber buildings in softwood, where in service class 1 (SC 1) the average moisture content of 12% is reached quite fast and will be not exceeded in most cases. This process takes much longer for hardwoods, such as naturally dried oak. All test results have been evaluated, considering the moisture content at time of testing is above or near fibre saturation. The slow drying process is not affecting the material properties, respectively the MOE, until the FSP is reached. The changing behaviour and moisture dependency of the MOE below FSP until SC 1 conditions $T = 20°\text{C}$, $\text{rH} = 65\%$, $u = 12\%$, have been taken into account according to related research, e.g. [14], and eq. (3) with $u_1 \leq u_2 \leq$ FSP.

$$E_2 = E_1\left[1 - 0.016\left(u_2 - u_1\right)\right] \tag{3}$$

The test series of subsample 1 (cut 1) and subsample 2 (cut 2) have been evaluated statistically and design values have been derived for material properties, respective MOE, and MOR, to complete the characterisation of the raw material [1] done the forestry research partner FVA in Freiburg, Germany. The evaluation was following the "Design assisted by testing" guidelines of Eurocode – Basis of structural design, DIN EN 1990:2021-10 Annex D [15] with X_d as the design value of the specific property, s_x^2 the variance and V_x as the COV of X.

$$X_d = \eta_d / \gamma_m \cdot m_x \cdot \left(1 - k_n \cdot V_x\right) \tag{D.1}$$

$$s_x^2 = \frac{1}{n-1} \sum\nolimits_1^n \left(x_i - m_x\right)^2 \tag{D.2}$$

$$V_x = s_x / m_x \tag{D.3}$$

4 RESULTS AND DISCUSSION

The deflection of the log specimens was measured at mid-span and the positions of the loading rollers with two sensors under path-controlled loading. Figure 6 show the typical load-deflection behaviour including the observed local failure as small stepwise decreases in load before ultimate failure occurs.

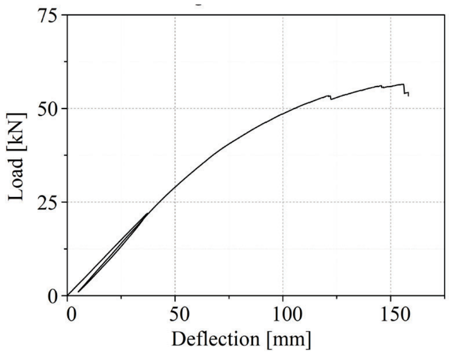

Figure 6: *Typical load-deflection relationship (hysteresis)*

The statistical evaluation has been done for cut 1 and cut 2 separately for the unsawn roundwood specimen, excluding the sawn roundwood in this stage of data interpretation. Table 2 show the results for all unsawn logs (cut 1 and 2) derived from testing as mean values of MOR and MOE, the characteristic and 5%-quantile values calculated from the statistical distribution over all samples and the influence of the moisture content when shifting the MC to normative indoor climate conditions.

The calculated MOE from testing ranged from 4,360 MPa to 32,956 MPa with an average of 11,026 MPa by scattering results and a coefficient of variation of 48.4%. The calculated MOR show a much better distribution in the range of 27.40 MPa to 103.77 MPa with an average value of 60.10 MPa, COV = 22.4% (Table 2).

Table 2. *Statistical evaluation of n = 71 log tests.*

	MOR (u_{test})		MOE (u_{test})	MOE (u_{12})
	[MPa]		[MPa]	[MPa]
mean	60.1	mean	11,026	13,500
char.	36.8	5%-Q	1,799	3,289

MOR(u_{test})	$f_{m,0,mean}$	MOR mean value at time of testing
	$f_{m,0,k}$	MOR characteristic value
MOE(u_{test})	$E_{m,0,mean}$	MOE mean value at time of testing
	$E_{m12,0}$	MOE mean value at calc. 12% MC
MOE(u_{12})	$E_{m,0,05}$	MOE 5%-Quantile from test series
	$E_{m12,0,05}$	MOE 5%-Quantile at calc. 12% MC

The statistical evaluation of all samples and subsamples shows that both, modulus of elasticity and modulus of rupture are normal distributed over the number of all samples. Figure 7 show the distribution of the MOR per example. The variation of around 22% for the fibre parallel bending strength is line with similar tests executed on softwood logs, [11], [12].

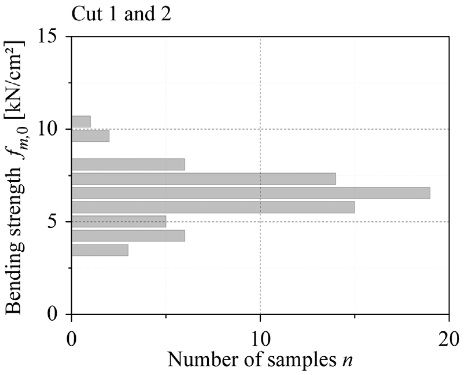

Figure 7: *Distribution of MOR for all samples.*

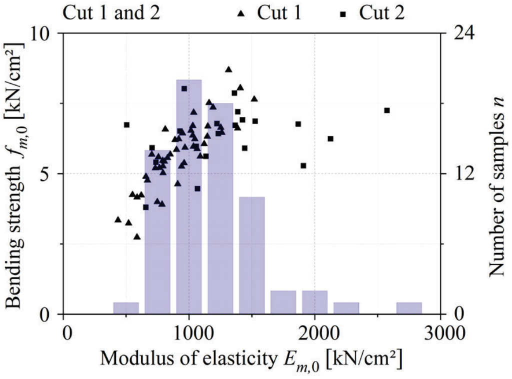

Figure 8. *Relation between MOE and MOR for all samples.*

Including the MOE in the evaluation, a linear regression dependency can be observed. Some specimens from cut 2 contribute a much higher MOE by medium strength in contrast to the rest of specimen (Figure 8). The mean MOE obtained by destructive tests appears 18% lower than the dynamic MOE measurement done in Freiburg [1]. This is also described in other research reports on comparison of destructive and non-destructive characterisation of material properties of wood.

Further investigations have been done relating the wood density and the moisture content to the mechanical properties tested. Fresh sawn or wet oak has a density of around 1,200 kg/m³ and a MC around 70%. To be in line with the test standards, the moisture content has been decreased over 18 months from the time of felling (December 2019 for cut 1) by natural drying. At the time of testing the MC was still over the FSP. To investigate further dependencies the MC have been reduced to 10-12% equilibrium humidity in service class 1 with the corresponding density ρ_{12} around 720 kg/m³. The kiln-dry density to the MOR relationship (Figure 9) and the kiln-dry density to the MOE relationship (Figure 10) could be confirmed as linear. The moisture content of the logs showed a good correlation with the modulus of elasticity and the bending strength. For further investigations, the relevant material properties have been also calculated for SC 1 conditions ($u = 12\%$), as the MC at the time of testing was above FSP for all specimens.

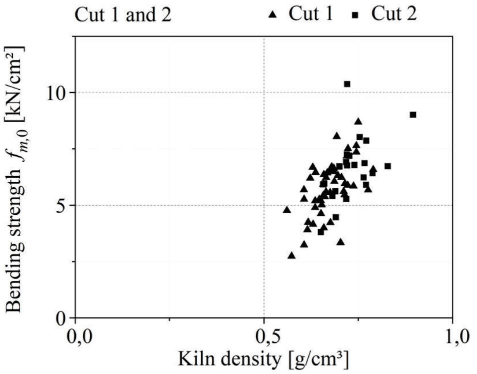

Figure 9. *Relation between MOR and kiln-dry density.*

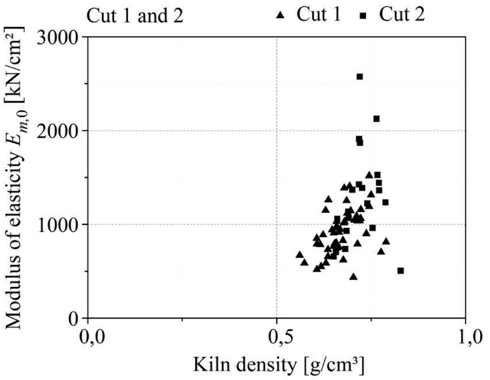

Figure 10. *Relation between MOE and kiln-dry density.*

5 CONCLUSIONS

The results of the research done show that small-diameter oak logs appear suitable for load-bearing structures. This could be a significant addition to the existing range of application, since those logs have no further use due to curvature, knot distribution or diameter. The work done is a first step towards sustainable applications of small-diameter oak as structural timber, using modern classification methods within the framework of forest management. The results are not perfect, but promising to go the next steps in roundwood classification to ensure a long-lasting and high-quality raw material for construction and the necessary increase in stocks of climate-resilient hardwood assortments in the coming decades.

A good correlation between flexural strength and stiffness could be observed in the first test series, basis for developing a grading system for round timbers. In the second batch only a few specimen delivered high stiffness values resulting in a high COV and scattering results. A follow-up study is needed in which logs of at least two nearby sites are sorted and then tested to confirm the flexural properties. Additional information is also needed on the compressive strength of lower diameter logs to quantify the relationship between compressive and bending material strength. These investigations have been started with destructive testing recently and will be expanded by studies of the effects of changing moisture content in logs on strength and stiffness as an aid for further classification and quality control issues.

The investigations done in Freiburg and Mainz have shown, that the more efficient team work and the use of digital and modern destructive and non-destructive applications and methods are beneficial to predict the material properties of irregular-shaped individual logs. Apart from shape and properties distribution along the trunk, the influence of knots is known and investigations on the sample assortment of this study have started already. Innovative machine learning procedures applied to computed tomography scans can help to reconstruct knots and other internal wood defects and shall serve for a better strength prediction of small-diameter hardwoods in the future.

ACKNOWLEDGEMENT

The project receives funding via the Waldklimafonds (WKF) funded by the German Federal Ministry of Food and Agriculture (BMEL) and Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) administrated by the Agency for Renewable Resources (FNR) under grant agreement No. 2218WK18D3. The authors would like to thank all employees of the National Material Testing Authority (MPA) in Mainz, going the extra mile for this project during the corona pandemic and Maximilian Leonhard Müller for his engagement and support in evaluating the experimental results.

REFERENCES

[1] Hofmann, N., Brüchert, F., Sauter, U.H., Schober, K.U., Hörnel-Metzger, B., and Müller, M.L. Green oak building with high-tech methods, Part 1: Characterisation of the raw material. *17th World Conference on Timber Engineering (WCTE 2023)*, Oslo, Norway, 2023.

[2] American Society for Testing and Materials (ASTM). Standard methods of static tests of lumber in structural sizes, D 198-02. *Annual Book of Standards*, Volume 04.10. Wood. ASTM, West Conshohocken, PA, USA, 2003.

[3] American Society for Testing and Materials (ASTM). Standard practices for establishing structural grades and related allowable properties for visually graded lumber, D 245-00. *Annual Book of Standards*, Volume 04.10. Wood. ASTM, West Conshohocken, PA, USA, 2003.

[4] American Society for Testing and Materials (ASTM). Standard test methods for establishing clear wood strength values, D 2555-98; Standard practice for establishing design stresses for round timber piles, D 2899-99. *Annual Book of Standards*, Volume 04.10. Wood. ASTM, West Conshohocken, PA, USA, 2003.

[5] American Society for Testing and Materials (ASTM). Standard practice for establishing stress grades for structural members used in log homes, D 3957-90. *Annual Book of Standards*, Volume 04.10. Wood. ASTM, West Conshohocken, PA, USA, 2003.

[6] American Society for Testing and Materials (ASTM). Standard practice for assigning allowable properties for mechanically graded lumber, D 6570-00. *Annual Book of Standards*, Volume 04.10. Wood. ASTM, West Conshohocken, PA, USA, 2003.

[7] DIN EN 14251:2004-04. Structural round timber - Test methods. German Version EN 14251:2003. DIN, Berlin, Germany.

[8] Ranta-Maunus, A. Round small-diameter timber for construction. *Final report of project FAIR CT 95-0091*, VTT Publication 383, Finnland, 1999.

[9] Kretschmann, D. E., and Green, D. W. Mechanical Grading of Oak Timbers. *Journal of Materials in Civil Engineering.* 11(2):91-97, 1999.

[10] Green, D. W., Gorman, T. M., Evans, J. W., and Murphy, J. F. Mechanical Grading of Round Timber Beams. *Journal of Materials in Civil Engineering.* 18(1):1-10, 2006.

[11] Zangiacomo, A.L. et *al.* Avaliação do módulo de elasticidade de peças estruturais roliças e de corpos-de-prova de Pinus elliottii (MOE evaluation for round timber and small wood specimens of Pinus elliottii). *Scientia Forestalis*, Piracicaba 41 (98): 283-291, 2013. (in Portuguese)

[12] Krajnc, L., Farrelly, N., and Harte, A. Mechanical characterization of green Sitka spruce logs. *Paper presented at Civil Engineering Research in Ireland 2016 (CERI2016)*, NUI Galway, 29-30 August, 2016.

https://doi.org/10.52202/069179-0016

[13] Krpan, J.: Untersuchungen über den Fasersättigungspunkt des Buchen-, Eichen-, Tannen- und Fichtenholzes. *Holz als Roh- und Werkstoff* 12 (3): 84-91, 1954.

[14] Hartnack, R. Langzeittragverhalten von druckbeanspruchten Bauteilen aus Holz (Long-time load-bearing performance of compressed wooden members), Doctoral Thesis, Bauhaus-Universität Weimar, Weimar, 2004. (in German)

[15] DIN EN 1990:2021-10. Eurocode: Basis of structural design; German version EN 1990:2002 + A1:2005 + A1:2005/AC:2010, DIN, Berlin, Germany.

https://doi.org/10.52202/069179-0016