



Some elasto-mechanical properties of black locust laminated veneer lumber under dry and wet conditions

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Abstract

Black locust (*Robinia pseudoacacia* L.) has great potential for weathered exterior applications due to its natural durability and density. In particular, the narrow sapwood range and the crooked trunk areas with strong fiber inclination make the production of veneer lumber from shorter logs very interesting, except for logs with a tension back. This paper describes selected elasto-mechanical properties of robinia laminated veneer lumber, tested in a climate of 20 °C and 60% relative humidity and at the fiber saturation point. In particular the Young's modulus (E_L , E_R , E_T) in tension, the Poisson's ratios (μ_{LT} , μ_{TR} , μ_{LR}), and the strengths (σ_L , σ_R , σ_T) were determined experimentally by tensile tests, and the lateral strain coefficients μ_{TL} , μ_{RT} , and μ_{RL} were calculated from these values. The results show a significant decrease in Young's modulus and modulus of rupture with increasing wood moisture content in the longitudinal, radial, and tangential directions. There was no notable dependence of the lateral strain coefficients on moisture content. Additionally, no significant correlations were observed between the investigated properties and gross density, nor between Young's modulus and tensile strength. Unlike Young's modulus and tensile strength, the lateral strain coefficients showed no clear trend with increasing wood moisture content. The strain coefficients are in good agreement with literature values, but further research with larger samples and different material sources is needed to complete the engineering constants. In addition, characteristic values of component size and material durability are of interest for future development.

1 Introduction

Robinia (*Robinia pseudoacacia* L.), also known as black locust, has long been recognized for its impressive mechanical properties and durability. Robinia has been cultivated for over 400 years in Europe. It has been limited in its utilization as construction wood due to its twisted trunk. Although the utilization of robinia in constructional and load-bearing use was first observed in predominantly agricultural buildings in the early 80's of the past century (Keresztesi 1981, 1988; Molnar 1995), research on the elasto-mechanical properties of robinia wood is rather scarce. Researchers, particularly

in Eastern Europe, report superior material properties since the 1950's (Göhre 1952; Barrett et al. 1988; Kopitović et al. 1989). Several research studies (Adamopoulos 2002; Adamopoulos et al. 2007; Pollet et al. 2012; Bijak and Lachowicz 2021) determined the flexural and strength properties of small and clear wood specimens conditioned at 20 °C and 65% relative humidity depending on specified wood anatomical features. Values for the modulus of rupture and the modulus of elasticity of green black locust and at a moisture content of 12% are also given in USDA Forest Service (2010). Sikora et al. (2022) and Varga and van der Zee (2008) investigated the change of mechanical properties due to thermal modification and steaming, respectively. Schickhofer and Hasewend (1999) investigated the bending strength of glulam beams of varying dimensions and additionally performed tensile tests on finger-jointed robinia lamellae. Becker et al. (2003) concentrated on assessing the suitability of native hardwoods such as oak, ash, robinia, beech and poplar for the production of glulam elements by testing the surface bonding performance and the flexural properties of glulam beams. The studies by Rug and Eichbaum (2012) are the first to deal with the grading of robinia lumber and its standardized grading

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into strength classes. The impact of moisture on the strength and elastic stiffness of wood has been well documented (Kufner 1978; Hoffmeyer 1990). However, there is a lack of clear correlations in the literature regarding the relationship between wood moisture and lateral strain coefficients. Green and Kretschmann (1994) observed a reduction in both μ_{LT} and μ_{LR} in compression tests on southern pine when the moisture content was 4.4% up to the fiber saturation point (FSP). Hering et al. (2012) noted a slight decrease in μ_{LT} and μ_{LR} during compression tests on beech. This study also experimentally determined the full set of Poisson's ratios. All six transverse strain coefficients, except μ_{TR} , decreased within a moisture range of 8.7–17.9%, although the effect was minor. Conversely, using the ultrasonic method, Ozyhar et al. (2013) reported an increase in both μ_{LT} and μ_{LR} for beech at moisture levels between 9.6% and 18.7%. Additional research by Ozyhar et al. (2012) on beech under tension revealed an increase in μ_{LT} and a slight decrease in μ_{LR} at moisture contents ranging from 5.9 to 16.3%. Overall, the influence of moisture content was found to be minimal within the range of 0–16.3% for both tensile and compressive loading.

Carrington (1922) investigated the Poisson's ratios of small and defect-free spruce beams in four-point bending tests at moisture contents between approx. 5 and 110%. He found an increase in lateral strain coefficients with increasing moisture content up to FSP for all lateral strain coefficients except for loading in the longitudinal-radial plane where opposite results were obtained. At moisture contents above the fiber saturation point, there were no significant changes in the Poisson ratios. Mizutani and Ando (2015) investigated a wider range of wood moisture contents ($u=0$ –170%) and its influence on the transverse strain coefficients in the longitudinal-radial and longitudinal-tangential plane using compression tests on Japanese cypress and magnolia wood. A significant decrease in both transverse strain coefficients was observed with increasing moisture content under the FSP. The study observed the opposite effect at moisture contents above the FSP.

There is very little literature on the elastic constants and mechanical properties of robinia LVL, and the authors are not aware of any studies that have been carried out. The only reports available concern the durability of robinia LVL (Nzokou et al. 2005; Reinprecht and Zubkova 2010). Dittrich (2017) investigated the potential of peeling black locust logs to produce veneers with desirable properties. He focused on the impact of boiling temperature and duration on parameters such as roughness, cracks, cutting resistance, moisture, density, and color, but did not include elasto-mechanical properties. This study investigates the elasto-mechanical properties of robinia Laminated Veneer Lumber (LVL) under various moisture conditions to assess its suitability for structural

applications. The primary objective is to provide a comprehensive analysis of small and clear robinia LVL specimens, bridging the gap between the promising properties of robinia wood and its practical use in construction. This includes evaluating strength and stiffness parameters, such as Young's modulus (E), transverse strain moduli (μ), and strengths (σ) in radial (R), tangential (T), and longitudinal (L) directions. Specifically, the properties E_L , E_R , E_T , μ_{LT} , μ_{TR} , μ_{LR} , and σ_L , σ_R , σ_T were experimentally determined. The transverse strain moduli μ_{TL} , μ_{RT} , and μ_{RL} were calculated retrospectively. The successful development of robinia LVL in combination with an adapted breeding program could revolutionize the use of this under-utilized wood species in structural applications. Its superior mechanical properties and natural durability make it a sustainable alternative to traditional building materials. Furthermore, promoting the use of robinia is in line with environmental conservation efforts by encouraging the use of fast-growing, resilient tree species.

2 Materials and methods

2.1 Basic mechanical assumptions

The anatomical structure of wood is described by a three-dimensional orthogonal coordinate system with three cutting planes: the cross-section (perpendicular to the longitudinal axis), the radial section (parallel to the longitudinal axis and in the direction of the wood rays), and the tangential section (perpendicular to the cross-section and to the wood rays). Due to the inhomogeneous and anisotropic structure of wood, it is considered an orthotropic material, where the elasto-mechanical properties vary according to the direction. This view allows the differentiation of wood and forms the basis for mathematical models of the material (Bodig and Jayne 1993). Within the proportional limit, there is a linear relationship between elastic strain and stress, known as Hooke's law. In the anisotropic case, this law relates the strain components to the stress components, indicating a linear relationship. Hooke's law can also be expressed in terms of compliance, the inverse of stiffness (Eq. 1).

$$\varepsilon_{ij} = S_{ijkl} \cdot \sigma_{kl}, \quad (1)$$

where, ε_{ij} = Strain components, σ_{kl} = Stress components (normal and shear stresses), S_{ijkl} = Compliance tensor.

Assuming normal stresses do not cause shear stresses and vice versa, and that shear stresses only cause shear deformations in the same plane, the compliance matrix can be reduced to nine independent components.

The first index indicates the direction of the deformation or the initiating force (cause), the second index indicates the direction of the stress or strain (effect). If the indices one, two and three are assigned the directional designations L, R and T commonly used in wood physics, the compliance matrix can be given as Eq. 2

$$\begin{pmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_T \\ \gamma_{RT} \\ \gamma_{LT} \\ \gamma_{LR} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{pmatrix} \begin{pmatrix} \sigma_L \\ \sigma_R \\ \sigma_T \\ \tau_{RT} \\ \tau_{LT} \\ \tau_{LR} \end{pmatrix} \quad (2)$$

where, γ_{ij} =Distortion components (shear angle), τ_{ij} =Shear stresses.

The compliance S_{ii} in the diagonal represents the reciprocal of Young's modulus or shear modulus and the Eq. 3 applies:

$$S_{11} = \frac{1}{E_L}; S_{22} = \frac{1}{E_R}; S_{33} = \frac{1}{E_T} \quad (3)$$

$$S_{44} = \frac{1}{G_{LR}}; S_{55} = \frac{1}{G_{LT}}; S_{66} = \frac{1}{G_{RT}};$$

where, $E_{(L;R;T)}$ =Young's modulus in longitudinal (L), radial (R) and tangential (T) direction, $G_{(LR;LT;RT)}$ =Shear modulus in longitudinal-radial (LR), longitudinal-tangential (LT), and radial-tangential (RT) plane.

For the components S_{ij} ($i \neq j$) next to the diagonal, the Eq. 4 applies:

$$S_{12} = \frac{-\mu_{RL}}{E_R}; S_{13} = \frac{-\mu_{TL}}{E_T}; S_{21} = \frac{-\mu_{LR}}{E_L} \quad (4)$$

$$S_{23} = \frac{-\mu_{TR}}{E_T}; S_{31} = \frac{-\mu_{LT}}{E_L}; S_{32} = \frac{-\mu_{RT}}{E_R}$$

where, $\mu_{(i;j)}$ =Poisson's ratio.

The Poisson's ratio $\mu_{(i;j)}$ describes the ratio of the passive transverse strain ϵ_j (transverse to the loading direction) and

the active longitudinal strain ϵ_i (in the loading direction) following Eq. 5:

$$\mu_{ij} = \frac{\epsilon_j}{\epsilon_i} \quad (5)$$

Assuming an orthotropic body and the symmetry relationships between the lateral strain coefficients it is sufficient to experimentally determine the properties E_L , E_R , E_T , μ_{LT} , μ_{TR} , μ_{LR} and to calculate the symmetry components from the determined properties (Bodig and Jayne 1993) as presented in Eq. 6.

$$\frac{\mu_{RL}}{E_R} = \frac{\mu_{LR}}{E_L}; \frac{\mu_{LT}}{E_L} = \frac{\mu_{TL}}{E_T}; \frac{\mu_{RT}}{E_R} = \frac{\mu_{TR}}{E_T} \quad (6)$$

2.2 Raw material processing

To produce the test material, three different sections of steamed robinia (*Robinia pseudoacacia* L.) logs were peeled into 1.7 mm thick veneer sheets by an Austrian producer. Although each of these parameters may have an important impact, the origin and age of the logs are unknown. Prior to peeling, the logs were steamed at 80 °C for a minimum of 36 h. Following the peeling process the veneers were dried in a roller dryer to a target wood moisture content of 8%, at a temperature of 110 °C. To ensure the production of flawless test specimens, the veneers were visually graded according to EN 635-2 (1995). Only class E veneer was accepted for further processing, and the maximum knot diameter was limited to 3 mm. In order to minimize grain deviation in the veneers, the peeled veneer sheets (Fig. 1A) were manually split into at least 40 mm wide strips (Fig. 1B), as the fracture zone perpendicular to the grain followed the direction of the grain. However, due to unavoidable inhomogeneities within the individual veneer strips, it was not possible to ensure a consistent grain direction parallel to the axis, so veneer strips with a grain deviation of more than 5°

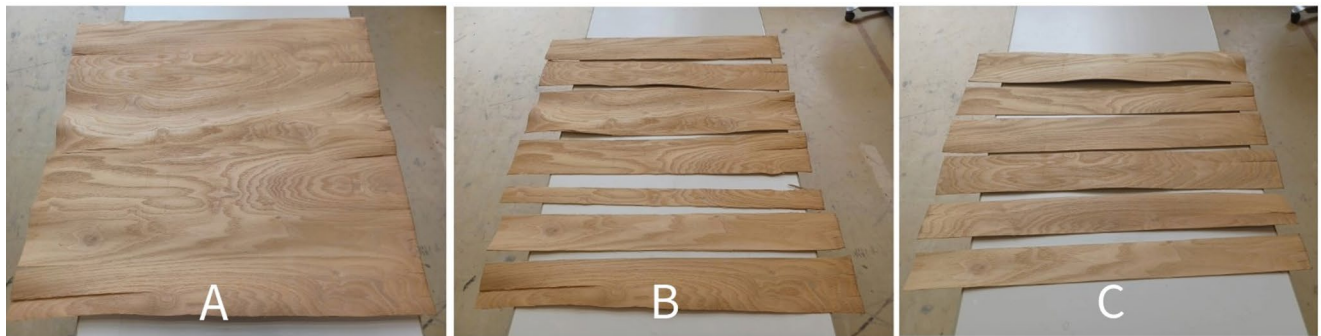


Fig. 1 Peeled veneer sheets (A), manually split veneer strips (B) and edge-straightened, reassembled strips before edge-gluing to veneer sheets (C)

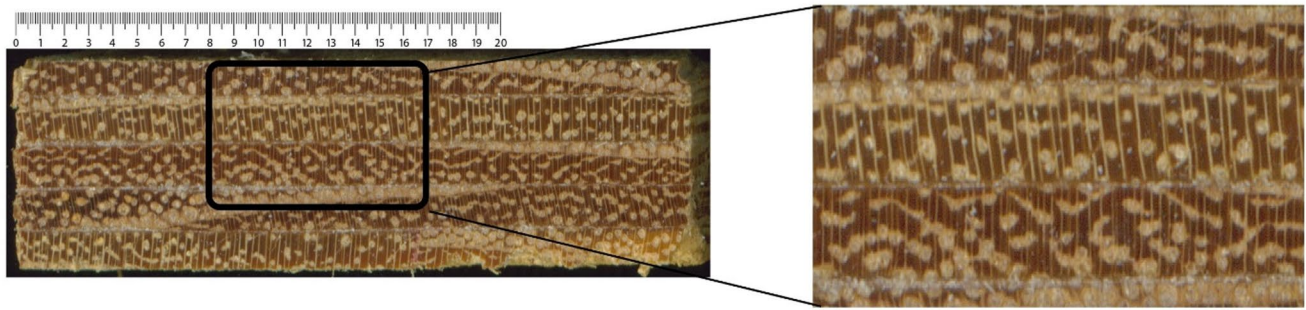


Fig. 2 Cross-section of a five-layered laminated veneer lumber with radial (R) and tangential (T) annual ring orientation; dimensions in mm

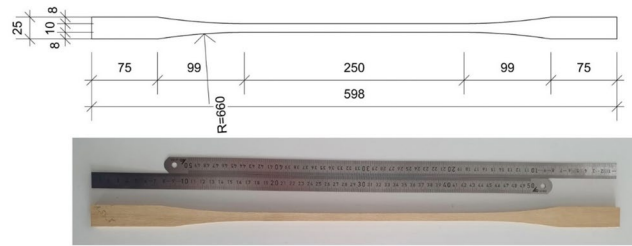


Fig. 3 Bone-shaped tensile test specimen for the determination of Young's modulus and strength in fiber direction (L); dimensions in mm (drawing) and cm (picture)

from the axis were discarded. The individual veneer strips were randomly mixed to avoid the non-random influence of wood-specific characteristics before the edge-straightened strips (Fig. 1C) were reassembled and laterally glued into veneer sheets using a veneer gluing machine with urea-formaldehyde adhesive (BASF Kaurit 106). The veneer sheets were then cut to a size of 700 mm x 700 mm and conditioned at 20 °C and 65% relative humidity (20/65). Laminated veneer panels consisting of five unidirectionally oriented veneer sheets were used to produce specimens for the determination of stiffness and strength parameters, while the panels for the determination of lateral strain coefficients (Poisson's ratios) consisted of three layers. This reduced the load applied to generate lateral strains and eliminated measurement errors due to clamping slippage.

All panels were bonded with an amount of 160 g/m² using a single-component polyurethane system suitable for bonding hardwood species such as beech, oak, ash, and robinia. After manufacture, all panels were conditioned at 20/65 for a minimum of seven days and then symmetrically calibrated to thicknesses of 8.5 mm and 5 mm, respectively, with subsequent storage at 20/65 until equilibrium moisture content (mass constancy). Unlike solid timber, circumferential peeling of logs that are as cylindrical as possible allows the cross-section of the laminated veneer lumber to be layered into radial (R) and tangential (T) main anatomical directions. This allowed the majority of the veneer sheets to be arranged with the radial direction of the annual growth rings

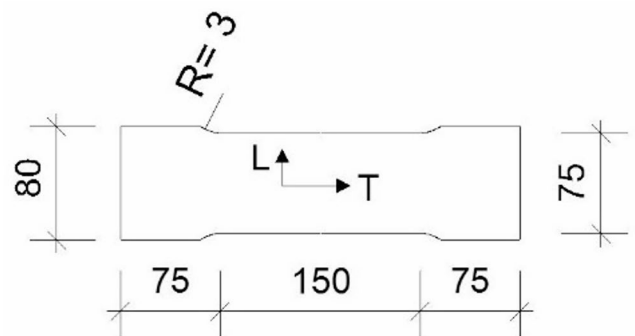


Fig. 4 Slightly bone-shaped tensile test specimen for the determination of Young's modulus and strength in tangential direction (T); dimensions in mm

perpendicular to the plane (radial direction) of the board and the tangential direction in the plane of the board (Fig. 2).

2.3 Sample production for material characteristics in longitudinal-tangential plane

To determine Young's modulus and tensile strength in fiber direction (L), a specimen geometry already successfully assessed by Hirschmüller et al. (2018) for laminated veneer lumber made of beech was used and manufactured from the five-layered LVL-boards using a CNC manufacturing system. The effective cross-section is 10 mm (T) x 8.5 (R) mm with a free test length of 250 mm in fiber direction L (Fig. 3).

The 300 mm long and slightly bone-shaped specimens for investigating the strength and Young's modulus in tangential direction were also produced from the five-layered LVL panels. They had an effective cross-section of 75 mm (L) x 8.5 mm (R) with a free clamping length of 150 mm in the tangential direction (T) (Fig. 4).

The specimens used to test the lateral strain coefficients were not bone-shaped, as loading to fracture was not desired and a sufficiently large area was required to apply the strain sensor instrumentation on the sample surface. Test specimens measuring 300 mm (L) x 75 mm (T) x 5 mm (R) were



Fig. 5 Three-ply LVL-board in longitudinal-tangential (LT-) plane for the determination of μ_{LT} ; dimensions in cm

fabricated from the three-layered LVL-boards to perform tensile tests to determine the transverse strain coefficients μ_{LT} (Fig. 5). Thus, the following effective cross-sections were applied:

- Strength and Young's modulus in L -direction: 10 mm (T) x 8.5 mm (R).
- Strength and Young's modulus in T -direction: 75 mm (L) x 8.5 mm (R).

Fig. 6 Radial view of multilayer LVL block with visualisation of cutting lines (dotted lines); dimensions in mm

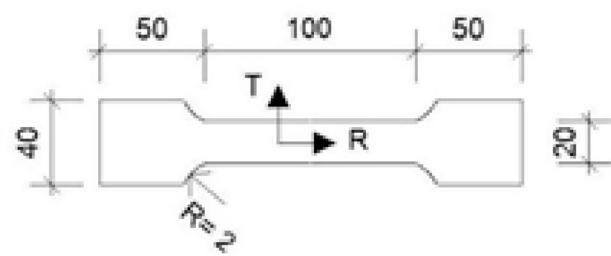
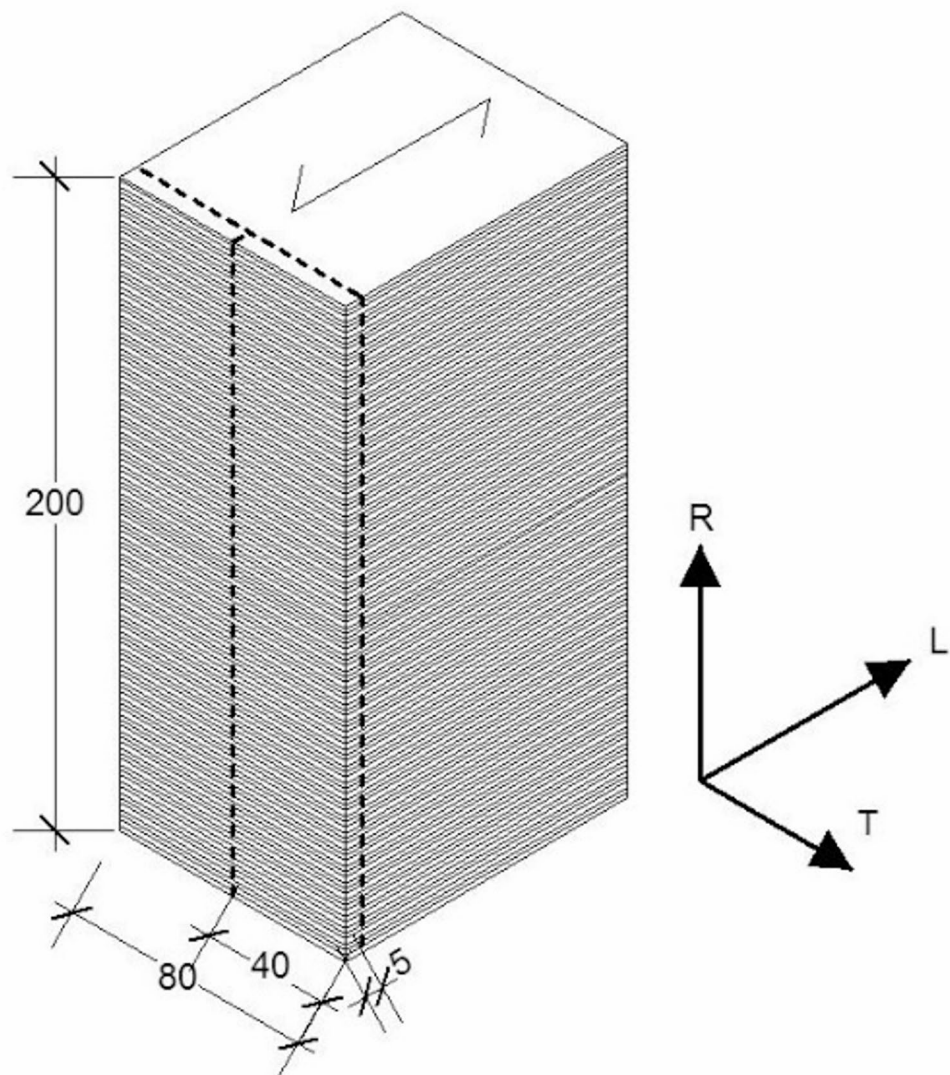


Fig. 7 Bone-shaped tensile test specimen for the determination of Young's modulus and strength in radial direction (R); dimensions in mm

- Transverse strain coefficients: 75 mm (T) x 5 mm (R).

2.4 Sample production for material characteristics in longitudinal-radial and tangential-radial plane

Due to the orientation of the radial direction (wood rays) in the thickness of the LVL panel (Fig. 2), it was necessary

to produce LVL blocks (Fig. 6) to obtain specimens in the *LR* and *TR* planes. The stiffness and strength of the material in the radial direction were investigated on 40 mm wide and 200 mm long bone-shaped specimens with an effective cross-section of 20 mm (*T*) x 8.5 (*L*) mm and 100 mm free test length (*R*), containing approximately 120 veneer layers in the radial direction (Fig. 7).

For the determination of the Poisson's ratios in the *TR* and *LR* planes, LVL blocks 80 mm wide, 100 mm high, and 350 mm long were produced, using the three-layered LVL panels as the base material (Fig. 8). The 5–6 mm thick samples were separated from the corresponding plane, cut to a size of 300 mm (length) x 75 mm (width) and then calibrated to a uniform thickness of 5 mm (Fig. 9).

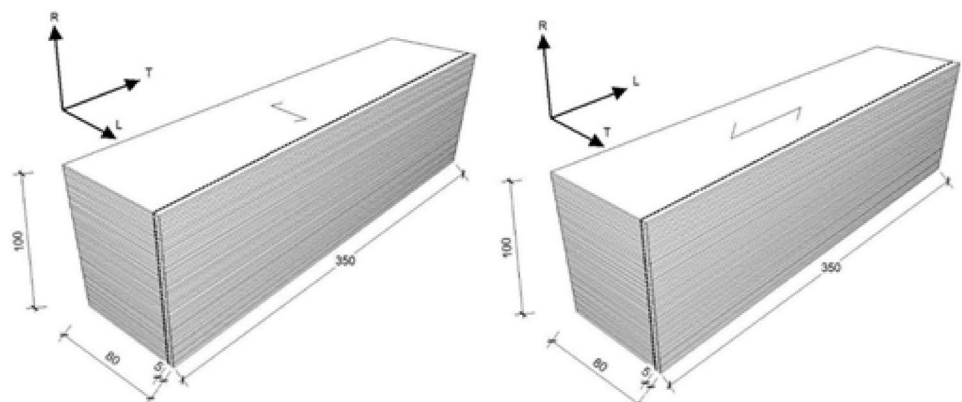
2.5 Sample conditioning, gross density determination, and test conditions

After cutting the specimens from the veneer sheets and veneer blocks, they were stored at 20 °C and 65% relative humidity until they reached equilibrium moisture content, a thickness calibration was performed, and the gross density ρ_N was determined. Once this had been determined, the individual samples were cut to their final size or milled to bone shape. Part of the samples were then stored in water under alternating negative and positive pressure (with pressure levels in accordance to EN 14080:2013) for 72 h until fiber saturation was reached (group *FSP*), while the other part for the determination of strength and stiffness parameters was conditioned at 20 °C and 65% relative humidity until the tensile tests were carried out (group *20/65*). To avoid any influence of moisture induced sample deformation on the results of the Poisson's ratio determination during the extended test period, the samples for measuring the position ratios were stored in the test laboratory room for four weeks and conditioned at an average room climate of 25 °C and 58% relative humidity. Thus, those values were taken at slightly different moisture conditions (group *25/58*). Care was taken to ensure that the samples were not removed from

conditioning until immediately before the test. Elastic properties and strengths were determined according to EN 789 (2005) using a Zwick/Roell Z100 universal testing machine with a 100 kN load cell to determine characteristic values acc. to EN 14358 (2016) in fiber direction and a 10 kN load cell to determine characteristic values under load in radial and tangential growth ring orientation. The load was applied at a controlled rate of 3 mm/min, using pneumatic clamping jaws 60 mm long. Strains were measured on both sides of the specimen using extensometers integrated into the system with a measuring length of 100 mm (Fig. 7). Strain determination for Poisson's ratio was carried out using orthogonally mounted displacement transducers on both sides of the specimens based on strain gauges (HBM DD1). The measurement length in the direction of the force was $l_{0,0^\circ} = 100$ mm and transverse to the direction of the force was $l_{0,90^\circ} = 60$ mm (Fig. 10). Extensive preliminary tests with a sample size of more than twelve specimens per plane were carried out to determine the maximum applicable load F_{max} (Table 1) and to estimate the measurement uncertainty of the measurement system, including the evaluation with an optical strain measurement system, which could not be used due to surface reflections from the water-stored samples. By repeating loading and unloading the samples in a displacement-controlled manner at a constant rate of 1.5 mm/min for several times, it was possible to achieve sufficient repeatability of the mechanical measurement system DD1. Thus, all samples were loaded and unloaded ten times to the maximum loads F_{max} according to Table 1. The strain (average strain of two DD1 sensors mounted opposite each other) of the last (tenth) measurement was then taken for further evaluation. The wood moisture content u was determined by kiln-drying after the tests according to EN 322 (1993).

Following the extensive preliminary tests, the elasto-mechanical parameters and transverse strain coefficients were analyzed as a function of wood moisture in the different major anatomical directions on an overall sample size of $n=70$. The effective cross-section of each specimen was measured at three points along the free test length just prior to testing and

Fig. 8 Multilayer LVL blocks for the manufacture of samples in radial-tangential *RT* (left) and radial-longitudinal *RL* (right) plane with visualisation of cutting lines (dotted lines); dimensions in mm



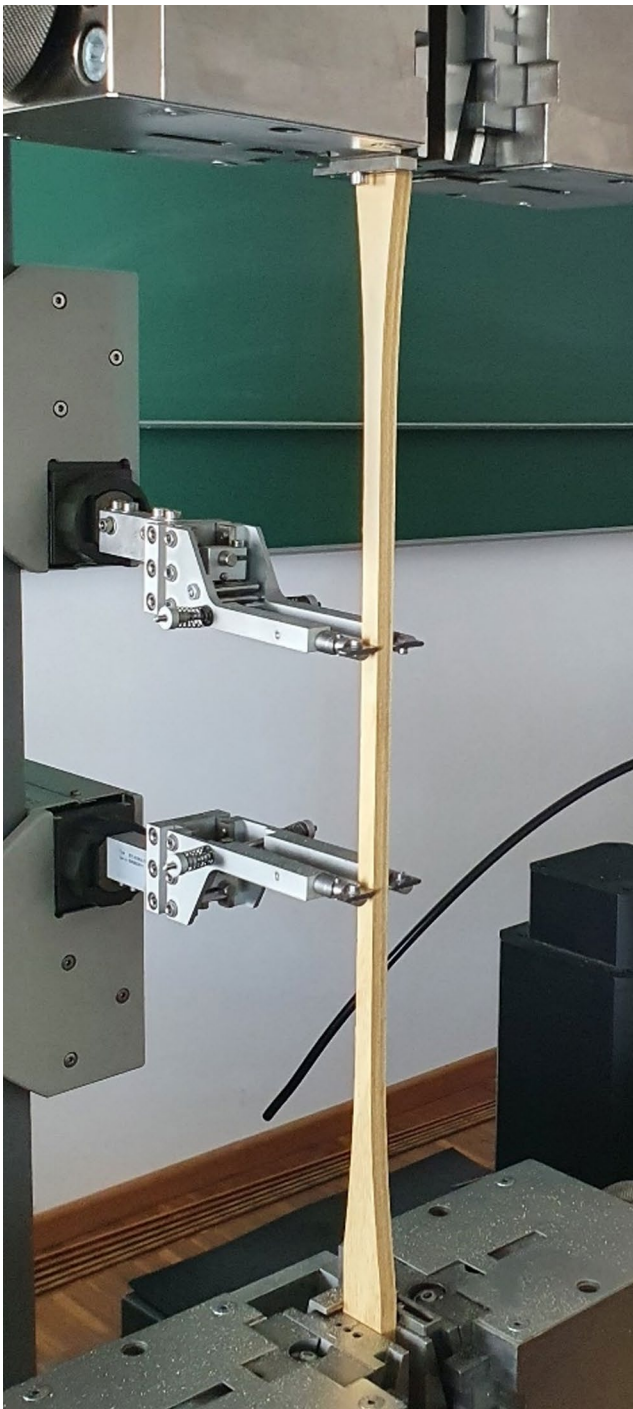


Fig. 9 Test setup for strength and stiffness parameters with bone-shaped specimens

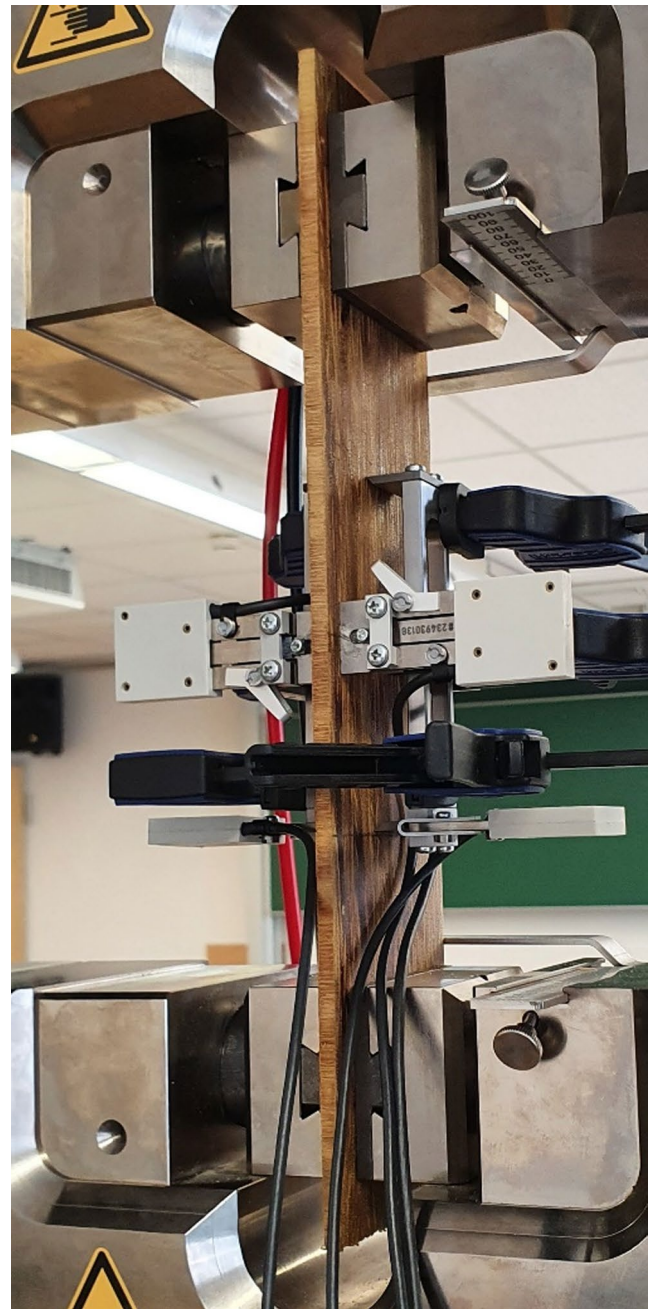


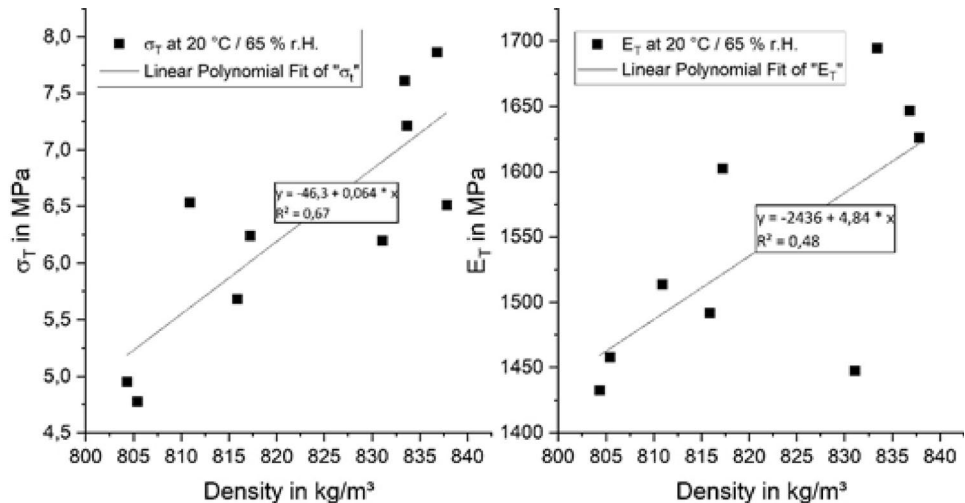
Fig. 10 Poisson's ratio test configuration

Table 1 To determine poisson's ratio maximum applied loads

	25 °C/58% rel. humidity conditioned			Wet stage ($u \geq \text{FSP}$)		
Poisson's ratio	μ_{LR}	μ_{LT}	μ_{TR}	μ_{LR}	μ_{LT}	μ_{TR}
F_{max} in kN	7	7	1	5	5	1

Table 2 Batches with number of prepared samples and effective cross-sections

Strength and stiffness parameters							Poisson's ratios					
Parameter	$E_{L,20/65}$	$E_{L,FSP}$	$E_{T,20/65}$	$E_{T,FSP}$	$E_{R,20/65}$	$E_{R,FSP}$	$\mu_{LR,25/58}$	$\mu_{LR,FSP}$	$\mu_{LT,25/58}$	$\mu_{LT,FSP}$	$\mu_{TR,25/58}$	$\mu_{TR,FSP}$
	$\sigma_{L,20/65}$	$\sigma_{L,FSP}$	$\sigma_{T,20/65}$	$\sigma_{T,FSP}$	$\sigma_{R,20/65}$	$\sigma_{R,FSP}$						
Number of produced samples n	10	10	10	10	10	10	3	3	3	3	3	3
Nominal cross-section in mm ²	8.5 × 10		8.5 × 75		8.5 × 20		5 × 75		5 × 75		5 × 75	

Fig. 11 Correlation between strength and density (left) and Young's modulus and density (right) of tangentially loaded specimens after conditioning at 20 °C and 65% relative humidity

averaged. The cross-section in Table 2 represents the nominal value of the cross-section; the actual value varied depending on the manufacturing process and the moisture content of the wood.

3 Results and discussion

The statistical analysis of the results was performed using a commercial software package for data evaluation and visualisation (Originlab-Origin Pro). In the first step, all data of the strength ($\sigma_{L,R,T}$) and stiffness parameters ($E_{L,R,T}$) including the gross density ρ_N within the batch (Table 2) were visually evaluated by boxplots, which provide an overview of statistical values and data distributions. The data were tested on goodness of fit to a normal distribution using a Kolmogorov–Smirnov test at a significance level of $\alpha=0.05$. The normal distribution of the parameters $E_{L,R,T}$, $\sigma_{L,R,T}$ and ρ_N within all batches could not be rejected. Therefore, the parameters of all batches significantly originated from a normally distributed population. The overall gross density ρ_N at equilibrium moisture content was determined to be (836 ± 17) kg/m³, with an outlier test according to Grubbs (1950) identifying no significant outliers at the 5% significance level.

3.1 Strength and young's moduli

For each major anatomical direction, 10 samples per wood moisture level were available. Samples that failed at the

clamping region were discarded. In addition, six of the radially laminated specimens (batches E_R/σ_R in Table 2, see Fig. 6) had to be removed after pressurized water storage due to poor adhesion, reducing the sample size of this series to $n=4$. The equilibrium moisture content of the specimens for strength and stiffness parameters, analyzed at a climate of 20 °C and 65% relative humidity, was on average $u = (8.6 \pm 0.2)$ % and showed a low scatter. Despite an alternating vacuum-pressure storage for 72 h under water, a uniform wood moisture content was not achieved in the wet samples; however, they exceeded the fiber saturation point (FSP) of solid robinia wood ($22\% \leq u \leq 24\%$) acc. to Wagenführ and Scholz (2018). The reason behind that phenomenon is not clear, but anyway, the authors assume a correlation between water uptake, gross density, growth ring spacing and Earlywood to latewood ratio. To evaluate the impact of ρ_N on strength σ and stiffness E properties, correlation analyses between gross density and strength/stiffness were conducted as an initial step (Fig. 11). A moderate correlation between σ and ρ_N , as well as E and ρ_N , was observed only in samples conditioned at 20 °C and 65% relative humidity (r.H.) when loaded in the tangential direction. In contrast, all other comparison series exhibited no or very weak correlations ($-0.3 < R^2 < +0.3$). Similarly, the correlation between σ and E showed a moderate positive correlation ($R^2 = 0.67$) exclusively for samples conditioned at 20 °C and 65% r.H. when loaded in the tangential direction. The other series demonstrated no or weak correlations. According to the authors, the parameters of machine grading that are suitable for softwoods cannot be applied to grading robinia LVL.

Table 3 Strength and stiffness parameters of 20 °C/65% RH conditioned and wet ($u \geq \text{FSP}$) robinia LVL

Conditioning	20 °C/65% r. H.			FSP		
Anatomical direction	<i>L</i>	<i>T</i>	<i>R</i>	<i>L</i>	<i>T</i>	<i>R</i>
Youngs modulus <i>E</i> in MPa	17,021 ± 1567	1548 ± 92	1999 ± 59	11,109 ± 1137	969 ± 58	833 ± 12
Mean strength σ in MPa	182.6 ± 17.6	6.4 ± 1.0	6.3 ± 1.1	134.5 ± 17.3	4.0 ± 0.6	2.7 ± 0.4
Characteristic strength f_k in MPa	148.3	4.4	4.3	103.0	2.9	1.8
ρ_N in kg/m ³	854 ± 11	822 ± 13	840 ± 6	833 ± 24	829 ± 10	842 ± 14
<i>u</i> in %	8.4 ± 0.2	8.7 ± 0.1	8.5 ± 0.1	40.7 ± 5.2	22.6 ± 0.2	39.9 ± 0.6
No. of tested samples	10	10	9	10	9	4

Values represent mean ± standard deviation

The difference in Young's modulus and strength between the two different conditioning levels (group 20/65 and group FSP) was analyzed in pairs for each anatomical direction using the Student *t* test (significance level $\alpha=0.05$). A significant decreasing trend in Young's modulus and strength with *u* above FSP was observed in all three anatomical directions. Comparing the mean values $\bar{x}$ of Young's modulus *E*, E_R decreased by 58%, E_T by 37%, and E_L by 35% with increasing wood moisture *u*. A similar trend was observed for the mean values $\bar{x}$ of strength, where a strength reduction factor k_{moist} of 0.69 (*L*), 0.65 (*T*) and 0.42(*R*) on characteristic level (characteristic strength values calculated acc. to EN 14358 (2016) could be observed (Table 3). The current timber engineering standard EN 1995-1-1 (2014) implicitly contains a moisture reduction factor for the material strength k_{moist} . The strength modification factor k_{mod} is composed of the duration of load factor k_{load} and the moisture reduction factor k_{moist} (Stapf and Aicher 2012; Hirschmüller et al. 2018).

$$k_{mod} = k_{load} * k_{moist} \quad (7)$$

The duration of load factor k_{load} for permanent loading can be directly derived from the strength modification factor $k_{mod} = 0.6$ given in EN 1995-1-1 (2014) for service class (SC) 1, where $k_{moist} = 0$. As in the case of SC 3 the strength modification factor is set to $k_{mod} = 0.5$, and the moisture reduction factor for SC 3 acc. to EN 1995-1-1 (2014) can be calculated as

$$k_{moist} = \frac{k_{mod,SC1}}{k_{mod,SC3}} = \frac{0.5}{0.6} = 0.83 \quad (8)$$

Therefore, this factor exceeds twice the k_{moist} value of 0.4 obtained in this investigation, which compared small-scale robinia LVL specimens in dry and water-saturated conditions.

3.2 Poisson's ratios

The average equilibrium moisture content of the samples at room climate (25 °C and 58% rel. humidity in average),

analyzed for Poisson's ratio determination, was $u = (8.0 \pm 0.3)$ %. As mentioned before, a uniform wood moisture content was not achieved in the water-soaked samples, but they are above the fiber saturation point (FSP) of robinia solid wood reported in the literature. The robinia LVL used to determine the Poisson's ratios has an average gross density of $\rho_N = (848 \pm 18)$ kg/m³ at equilibrium moisture content and is not significantly different to the basic population given in the previous section. The specimens revealed within all load steps (load step LS 1 to 10) a linear elastic behavior up to the defined load limits given in Table 1. Clearly visible is the large increase in elongation for the tangentially loaded saturated specimens (Fig. 12) compared to the dry specimens, which is consistent with the strong reduction in Young's modulus for the radially loaded saturated specimens as given in Table 3. Poisson's ratio was determined as the slope of the straight line from lateral to longitudinal strain of the tenth load cycle LS according to Eq. 5 (Fig. 13 left). The continuous approach of the strain line to a final value is clearly visible (Fig. 13, right). The significance of the Poisson ratios of the tenth load cycle in the dry and wet states was analyzed in pairs for each anatomical plane using the Mann-Whitney U test (significance level $\alpha=0.05$).

Although a slight increase in the lateral strain coefficients with increasing wood moisture can be observed in all variations tested, there is no statistically significant increase. Due to the very small number of samples, an outlier test was not performed. The results of selected Poisson ratios from the tensile tests are summarized in Table 4. As previously described, the remaining three lateral strain coefficients can be calculated using the symmetry condition according to Eq. 6. The results from Tables 3 and 4 were utilized for this calculation. Since the specimens used to determine the Young's moduli and Poisson ratios at $u \geq \text{FSP}$ have varying wood moisture contents, only the values determined at 20 °C and 65% relative humidity were calculated. The calculated Poisson ratios are:

$$\mu_{RL,kalk} = 0.05; \mu_{TL,kalk} = 0.05; \mu_{RT,kalk} = 0.41$$

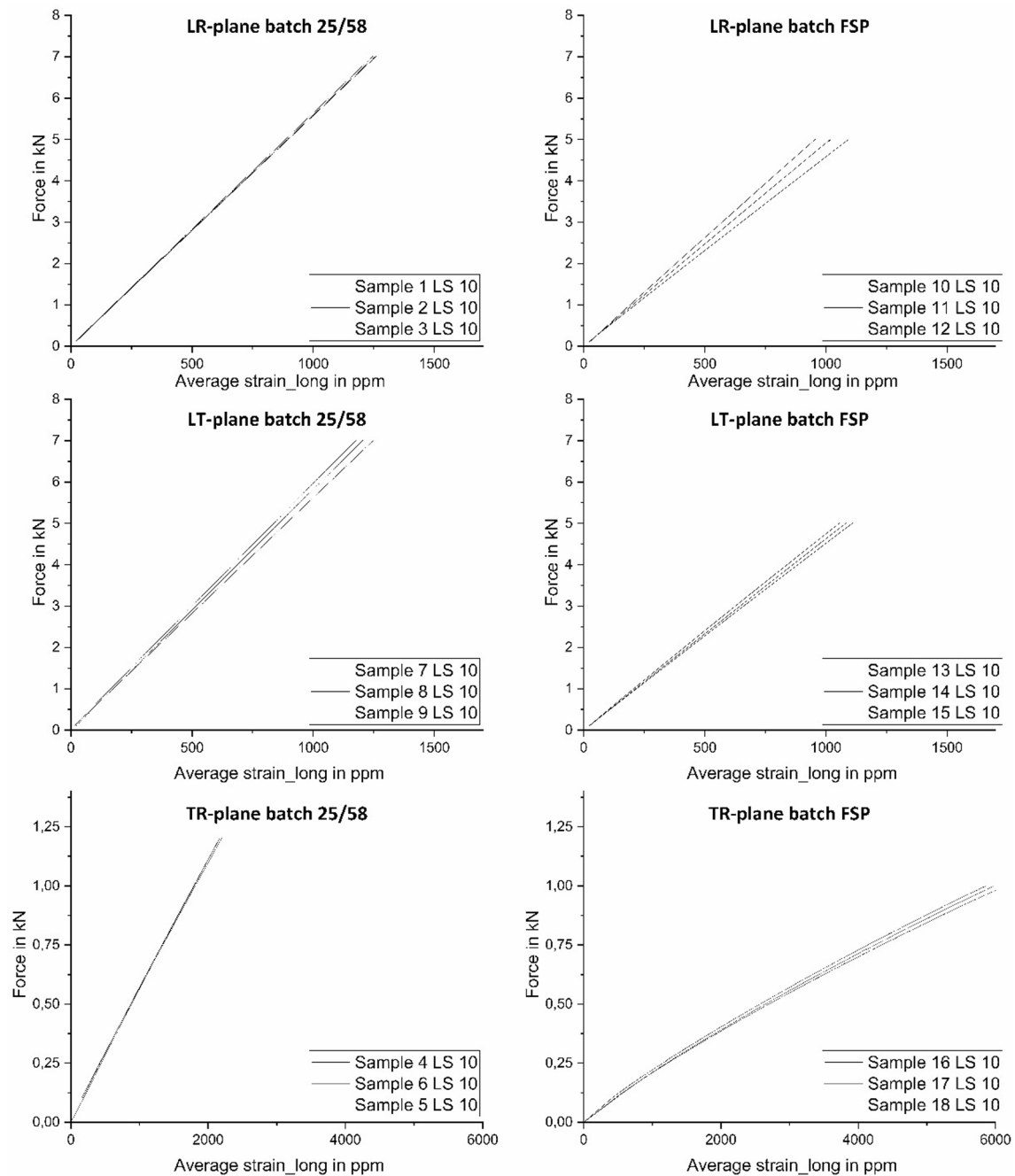


Fig. 12 Force (vertical axis)—Longitudinal strain (horizontal axis) relationship of tensile specimens for Poisson's ratio determination; loading in fibre (*LT* and *LR* planes) and tangential direction (*TR* plane) of dry (left graphs, Batch 25/58) and saturated (right graphs, Batch *FSP*) specimens

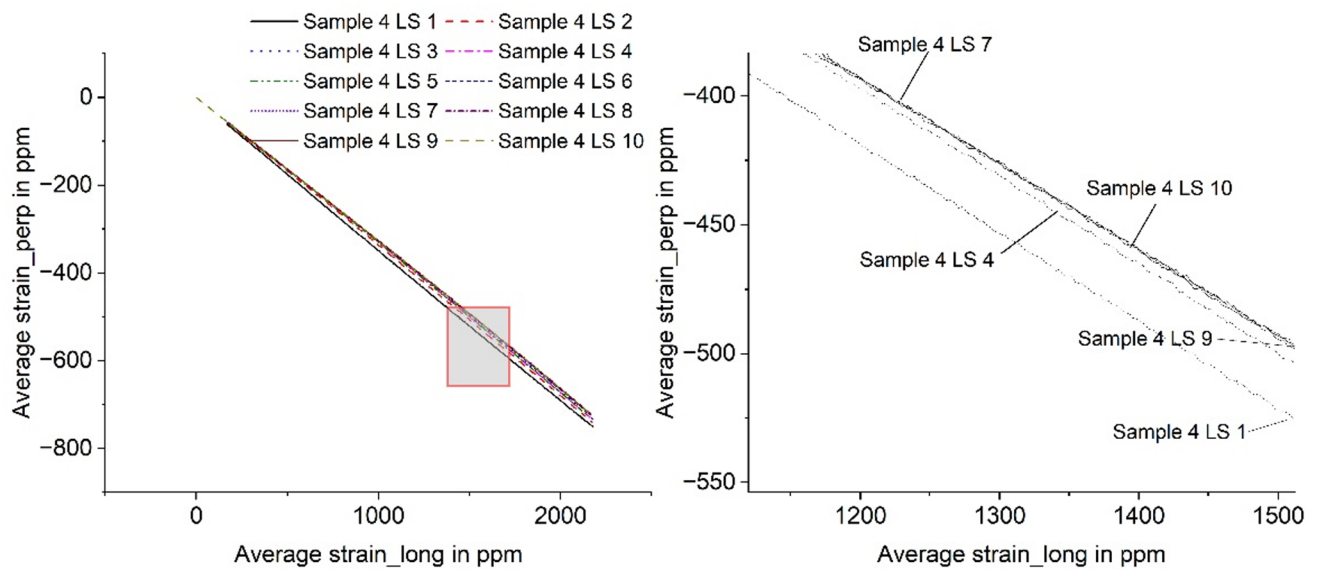


Fig. 13 Strain in the load direction (horizontal axis) as a function of strain perpendicular to the load direction (vertical axis) using the example of a batch $\mu_{TR,20/65}$ specimen from Table 2 (left) with mag-

nification area (grey box); magnified graphs with visualization of the individual load cycles LS (right)

Table 4 Poisson ratios of 20 °C/65% RH conditioned and wet ($u \geq FSP$) robinia LVL

Conditioning	20 °C/65% r. H.			FSP		
Anatomical plane	LR	LT	TR	LR	LT	TR
Mean of Poisson's ratio $\bar{\mu}$	0.42 ± 0.03	0.54 ± 0.03	0.32 ± 0.01	0.49 ± 0.11	0.54 ± 0.11	0.35 ± 0.01
ρ_N in kg/m ³	838 ± 18	829 ± 20	865 ± 7	838 ± 18	840 ± 16	868 ± 5
u in %	7.9 ± 0.3	7.9 ± 0.3	8.3 ± 0.1	26.6 ± 1.1	31.9 ± 2.4	38.0 ± 0.6
No. of tested samples	3	3	3	3	3	3

Values represent mean $\pm$ standard deviation

4 Conclusion

This study examined the elasto-mechanical properties and equilibrium moisture content of robinia laminated veneer lumber under dry and wet wood moisture conditions. The average equilibrium moisture content was $u = (8.6 \pm 0.2) \%$, which is lower than the literature values for solid robinia wood. For water stored samples, the wood moisture content reached $u \geq 22.6\%$, exceeding the fiber saturation point (FSP) of solid robinia wood given in the literature. The influence of the anatomical constitution, the manufacturing process (steaming and peeling of logs) as well as the subsequent veneer drying at elevated temperatures of 110 °C on the FSP of laminated veneer lumber remains unclear and could be part of future research. Tensile test results indicated that, beside the noticeable high characteristic tensile strength, both the modulus of elasticity and strength significantly decrease with increasing wood moisture content, which is consistent with common literature. Notably, the influence of wood moisture content was less pronounced in the longitudinal direction. Corresponding to already published literature, the ratio of elastic moduli for hardwood is $E_L/E_R/E_T \approx 20/1,6/1$. This study found values of $E_L/E_R/E_T \approx 11/1,3/1$ of 20 °C/65% relative humidity conditioned

samples. Specific comparable values for robinia wood are unknown. It was observed that the Poisson's ratios (μ_{LR} , μ_{LT} , μ_{TR}) slightly increased with increasing wood moisture content; however, no statistically significant increase was detected. Different wood moisture contents of the water-stored samples complicate the comparability. The Poisson's ratios are comparable with literature values for hardwood. Nevertheless, the elasto-mechanical properties of robinia laminated veneer lumber are highly influenced by wood moisture content, whereby the Poisson's ratios seem to be not that influenced by a change in wood moisture content. These results are consistent with those reported in the literature, but future investigations should aim for a larger sample size and consistent wood moisture content to further refine the results.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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