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ORIGINAL

Determining moisture-dependent elastic characteristics of beech wood by means of ultrasonic waves

Tomasz Ozyhar · Stefan Hering · Sergio J. Sanabria · Peter Niemz

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Abstract The present study investigates the influence of moisture content on the elastic characteristics of beech wood (*Fagus sylvatica* L.) by means of ultrasonic waves. A set of elastic engineering parameters (i.e. three Young's moduli, three shear moduli and six Poisson's ratios) is determined at four specific moisture contents. The results reveal the significant influence of the moisture content on the elastic behaviour of beech wood. With the exception of some Poisson's ratios, the engineering parameters decrease with increasing moisture content, indicating a decline in stiffness at higher moisture contents. At the same time, wood anisotropy, displayed by the two-dimensional representation of the velocity surface, remains almost unchanged. The results prove that the ultrasonic technique is suitable for determining the elastic moduli. However, non-diagonal terms of the stiffness matrix must be considered when calculating the Young's moduli. This is shown experimentally by comparing the ultrasonic Young's moduli calculated without, and allowing for, the non-diagonal terms. While the ultrasonic technique is found to be reliable to measure the elastic moduli, based on the measured values, its eligibility to measure the Poisson's ratios remains uncertain.

Introduction

While elastic engineering parameters are present for a large majority of commercially used building materials, the availability of similar data for wood is often limited. However, engineering parameters are required as input parameters for

T. Ozyhar (✉) · S. Hering · P. Niemz
Institute for Building Materials (Wood Physics), ETH Zurich, 8093 Zurich, Switzerland
e-mail: ozyhart@ethz.ch

S. J. Sanabria
Electronics/Metrology/Reliability Laboratory, Swiss Federal Laboratories for Materials Science and Technology, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland

advanced computational models often used in modern civil engineering and material science, and their determination is therefore of considerable interest.

The main reason for the lack of engineering parameters for wood results from the complex nature of the material and the experimental effort associated with the determination of the parameters. Unlike the majority of building materials, wood is a material of biological origin, with pronounced anisotropic properties. Consequently, a set of twelve independent elastic engineering parameters (three Young's moduli, three shear moduli and six Poisson's ratios) is required in order to characterise the whole elastic behaviour of wood (Bodig and Jayne 1993). This implies a considerable experimental effort, especially as it is impossible to determine all elastic parameters within one measurement set-up using the commonly applied static experimental testing methods. Nonetheless, experimental work investigating the elastic behaviour of wood has been carried out by numerous researchers (e.g. Carrington 1923; Stamer and Sieglerschmidt 1933; Hörig 1935; Keylwerth 1951; Keunecke et al. 2008; Niemz and Caduff 2008), yet comprehensive data sets including the complete elastic behaviour are limited for most wood species. Still, less is known about the moisture-dependent elasticity of wood. Until now, few works have investigated the moisture-dependent elastic behaviour of wood (Tiemann 1906; Carrington 1922; McBurney and Drow 1962; Neuhaus 1983). Indeed, most investigations on the moisture-dependent elastic properties of wood are limited to the Young's moduli, and seldom present the shear moduli, while the moisture-dependent Poisson's ratios are almost unavailable for most wood species. Given the hygroscopic nature of wood, a complete characterisation of wood's elastic behaviour requires the knowledge of all twelve elastic parameters as related to wood moisture content.

The present study is an attempt to expand the knowledge of the moisture-dependent elasticity of wood. The main purpose of this study is to provide a consistent data set of moisture-dependent elastic engineering parameters, which can be used as input parameters for advanced modelling purposes, determined by applying the ultrasonic technique. While the use of ultrasonic waves to measure the elastic properties of solids is well known (Truell et al. 1969) and has been frequently applied to measure the moduli of wood (Bucur and Archer 1984; Keunecke et al. 2007; Hering et al. 2012), it has been rarely used to determine moisture-dependent elastic engineering parameters. Besides, in most research works, the ultrasonic technique was limited to the determination of the elastic moduli. However, in addition to the elastic moduli, Poisson's ratios may be determined from ultrasonic wave measurements on specimens cut at convenient angles to the planes of anisotropy (Bucur and Archer 1984; Gonçalves et al. 2011). Thus, it is possible to obtain all elastic engineering parameters in one measurement set-up using the ultrasonic technique.

Materials and methods

Ultrasonic technique

The most common degree of anisotropy accepted for wood is that of orthotropic material symmetry (Schniewind and Barrett 1972; Bodig and Jayne 1993).

Assuming symmetry of the non-diagonal terms of the stiffness matrix $\boldsymbol{C}$, an orthotropic material is characterised by nine independent elastic coefficients:

$$\boldsymbol{C} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} \tag{1}$$

Introducing the Christoffel's tensor Γ_{ik}

$$\Gamma_{ik} = c_{ijkm} n_j n_m, \tag{2}$$

where $\boldsymbol{n}$ is a unit vector in the direction of wave propagation with $i, j, k, m \in 1, 2, 3$, the phase velocity of an acoustic wave propagating in an elastically anisotropic solid can be expressed as a function of the stiffness tensor through Christoffel's equation:

$$[\Gamma_{ik} - \delta_{ik}\rho V^2] = 0, \tag{3}$$

where δ_{ik} is the Kronecker delta symbol, V the wave velocity and ρ the density of the solid. Calculating the eigenvalues and the eigenvectors of Christoffel's tensor, the elastic coefficients of the stiffness tensor can be written in the form of the general equation:

$$c_{ii} = \rho V_{ii}^2 \tag{4}$$

for the diagonal coefficients, and

$$c_{ij} = \frac{\Gamma_{ij}}{n_i n_j} - c_{ijij} \quad i \neq j \tag{5}$$

for the non-diagonal coefficients. Since the stiffness matrix $\boldsymbol{C}$ is the inverse of the compliance matrix $\boldsymbol{S}$,

$$\boldsymbol{C}^{-1} = \boldsymbol{S} \tag{6}$$

the coefficients of the stiffness matrix are directly related to the elastic engineering parameters expressed in terms of the compliance matrix:

$$S_{ij} = \begin{pmatrix} 1/E_1 & -v_{12}/E_2 & -v_{13}/E_3 & 0 & 0 & 0 \\ -v_{21}/E_1 & 1/E_2 & -v_{23}/E_3 & 0 & 0 & 0 \\ -v_{31}/E_1 & -v_{32}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{pmatrix}, \tag{7}$$

where E_i are the Young's moduli, G_{ij} are the shear moduli and v_{ij} are the Poisson's ratios. The conversion between the components of the compliance matrix and the components of the stiffness matrix is given in Bucur and Archer (1984).

Material selection and specimen preparation

All measurements were carried out on beech wood (*Fagus sylvatica* L.) grown in Switzerland. The average wood density, determined at a temperature of 20 °C and a relative humidity (RH) of 65 %, amounted to 689 kg/m^3. Wood used for specimen preparation did not contain any natural growth characteristics such as red heartwood, reaction wood or knots.

Four different cuboid specimen types with different orientations to the principal axes of anisotropy were used in the measurements (Fig. 1). Cubes with varying edge length of 8, 10 and 12 mm were prepared for each of the presented specimen types (I, II, III and IV). In order to achieve a precise surface area for ultrasonic testing, cubes were finished with fine sandpaper.

Prior to testing, specimens were divided into four groups and air-conditioned in climatic chambers at a temperature of 20 °C and different RH of 45, 65, 85 and 95 % until equilibrium moisture content (EMC) was reached. At least 15 specimens were prepared for every dimension and annual ring orientation. A total of 720 specimens with 15 specimens for each dimension, specimen type and moisture condition were available for testing.

Experimental procedure

At least three longitudinal and three shear wave velocities propagating along the principal axes of anisotropy, and additionally, three quasi-shear wave velocities measured at a suitable angle with respect to the principal axes of anisotropy are

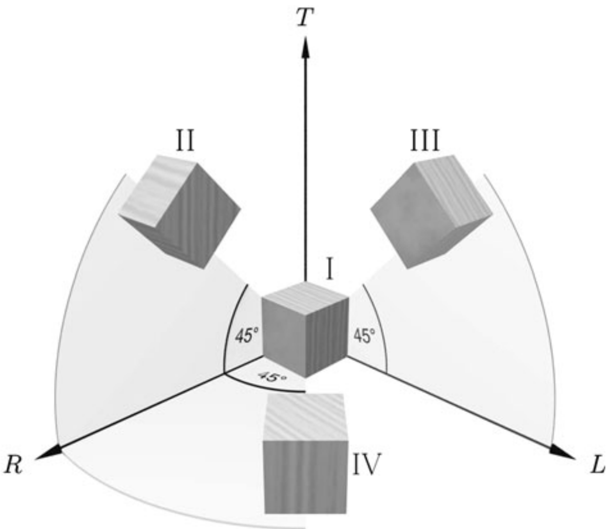

Fig. 1 Specimen types used for ultrasound velocity measurements and their orientation to the principal axes of anisotropy. Reference coordinate system relative to the axes of anisotropy: *L* longitudinal, *R* radial, *T* tangential

needed in order to determine all independent components of the stiffness matrix (Bucur 2006). In the present study, three longitudinal waves (V_{ii}), six shear waves (V_{ij}) and three quasi-shear waves ($V_{ij/ij}$) were measured according to the notation given in Table 1.

A direct pulse transmission ultrasonic technique was used to obtain the wave velocities. The ultrasonic waves were generated using an off-the-shelf Epoch XT ultrasonic flaw detector, which complies with EN12668-1:2010. The longitudinal wave frequency was 2.27 MHz, and the transversal (shear) wave frequency was 1 MHz. Two Olympus A133S transducers (TX and RX) with a diameter of 12 mm for longitudinal waves and two Staveley S-0104 transducers for transversal waves with a diameter of 12.7 mm were used to carry out the measurements. To ensure coupling between the specimen and the transducers during measurements, a gel-like coupling medium (Ultragel II) was used. Constant coupling pressure during the measurements was guaranteed by the use of a measuring spring. The Epoch XT recorded the received ultrasound waveforms with a sampling frequency of 100 MHz.

The resulting ultrasound wave velocities were determined by a simple linear regression from the measured time required for the ultrasound pulse to propagate through samples with various thicknesses (Fig. 2). For the worst-case timing uncertainty (10 ns), the highest measured sound velocity (5,029 m/s) and the smallest sample thickness (8 mm) the expected sound velocity error introduced by the flaw detector is <0.6 %. Having obtained the wave velocities, the elastic coefficients of the stiffness matrix $\boldsymbol{C}$ were calculated from the relationships listed in Table 2.

Results and discussion

Influence of moisture content

According to Bucur (2006), the propagation velocity of ultrasound waves is correlated with the presence of bound water in the wood structure. Studies have shown (Sakai et al. 1990; Sandoz 1993; Molinski and Fabisiak 2001; Oliveira et al. 2005; Saadat-Nia et al. 2011) that the ultrasound velocity decreases linearly with increasing wood moisture content (MC) up to the fibre saturation point (FSP). This is consistent with the measured wave velocities (i.e. longitudinal, shear and quasi-shear), which are observed to decrease with increasing wood MC (see Table 3).

Table 1 Notation used to keep track of the various ultrasound propagation velocities according to Ashman et al. (1984)

V_{ii}	Wave velocity of longitudinal wave propagating in the i direction
V_{ij}	Wave velocity of the shear wave with direction of propagation in the i direction and particle motion (direction of polarisation) in the j direction
$V_{ij/ij}$	Wave velocity of the quasi-shear wave with propagation direction in direction $\vec{n} = \left(\frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}}\right)^T$ and particle motion in the $i - j$ plane

$i, j \in L, R, T$

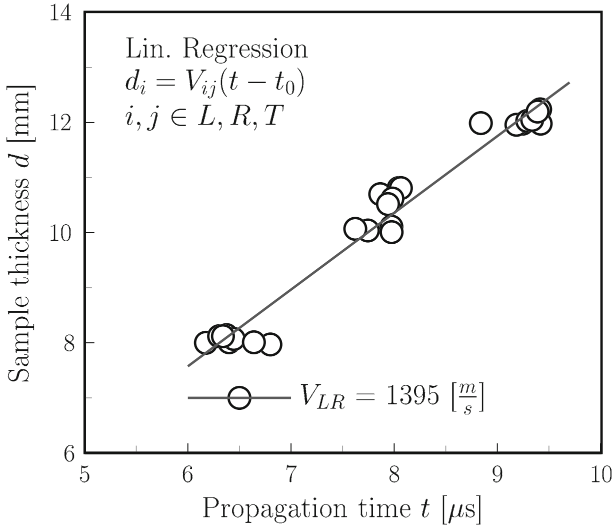

Fig. 2 Ultrasound wave velocity determination from the measured ultrasound propagation time and specific sample thicknesses

Table 2 Equations used to calculate the elastic coefficients from the wave velocities measured on specific specimen types

Specimen type[a]	Type of wave[b]	Equation[c]
I	V_{LL}	$c_{11} = \rho V_{LL}^2$
	V_{RR}	$c_{22} = \rho V_{RR}^2$
	V_{TT}	$c_{33} = \rho V_{TT}^2$
	V_{TR}/V_{RT}	$c_{44} = (\rho V_{TR}^2 + \rho V_{RT}^2)/2$
	V_{LT}/V_{TL}	$c_{55} = (\rho V_{LT}^2 + \rho V_{TL}^2)/2$
	V_{LR}/V_{RL}	$c_{66} = (\rho V_{LR}^2 + \rho V_{RL}^2)/2$
II	$V_{RT/RT}$	$c_{23} = \sqrt{\left(c_{22} + c_{44} - 2\rho V_{RT/RT}^2\right)\left(c_{33} + c_{44} - 2\rho V_{RT/RT}^2\right)} - c_{44}$
III	$V_{LT/LT}$	$c_{13} = \sqrt{\left(c_{11} + c_{55} - 2\rho V_{LT/LT}^2\right)\left(c_{33} + c_{55} - 2\rho V_{LT/LT}^2\right)} - c_{55}$
IV	$V_{LR/LR}$	$c_{12} = \sqrt{\left(c_{11} + c_{66} - 2\rho V_{LR/LR}^2\right)\left(c_{22} + c_{66} - 2\rho V_{LR/LR}^2\right)} - c_{66}$

[a] See Fig. 1

[b] See Table 1

[c] According to Kriz and Stinchcomb (1979)

Acoustic anisotropy

Consistent with the assumed orthogonal anisotropic symmetry, the longitudinal wave velocities V_{ii} are distinctively different for the principal directions of anisotropy. The measured velocity V_{LL} was two and four times larger than V_{RR} and V_{TT}, respectively. The anisotropy of beech wood is further apparent by the different values observed for the individual shear wave velocities propagating the three principal planes of anisotropy.

To visualise the influence of MC on the wave velocities, a two-dimensional representation of the moisture-dependent velocity surface is given in Fig. 3. Since the velocity surface shows the plane wave velocities for all three planes of anisotropy, it further provides a valuable insight into the acoustic anisotropy of beech wood. A surface of three sheets is obtained, consisting of a fast quasi-longitudinal sheet, and two slower quasi-shear and pure shear sheets. While the velocity surface reveals that an increase in MC leads to decreasing velocities, the acoustic anisotropy, given by the relationships between the individual waves is not significantly affected by the MC. The characteristic shape formed by the individual wave velocities remains almost unchanged for all moisture conditions.

Moisture-dependent elasticity

Elastic moduli

Two independent shear waves (V_{ij} and V_{ji}) with directions of propagation and polarisation in the same plane can be measured for each of the three principal planes of anisotropy. Given the observed relationship

$$V_{ij} \neq V_{ji}, \tag{8}$$

(see Table 3), six stiffness coefficients, two for each plane of anisotropy, can be calculated from V_{ij} and V_{ji}. Unequal shear waves with directions of propagation and polarisation in the same plane have also been reported by Bucur and Archer (1984) and Hering et al. (2012). According to Hering et al. (2012), the measured discrepancies are rather small compared with the variances obtained for the particular test series. Therefore, assuming the orthotropic material model presented in Eq. 1, the stiffness coefficients C_{44}, C_{55} and C_{66} were calculated from the averaged values of the shear wave velocities V_{ij} and V_{ji} (see Table 2).

The resulting moisture-dependent shear moduli are provided in Table 4. With the highest moduli measured at $\omega = 9.6$ % and the lowest at $\omega = 18.7$ %, shear moduli decrease with increasing MC (Fig. 4). Even though all three shear moduli are

Table 3 Moisture-dependent ultrasound wave velocities for beech wood

ω (%)	Longitudinal wave (m/s)			Shear wave (m/s)						Quasi-shear wave (m/s)		
	V_{LL}	V_{RR}	V_{TT}	V_{LR}	V_{RL}	V_{LT}	V_{TL}	V_{RT}	V_{TR}	$V_{LR/LR}$	$V_{LT/LT}$	$V_{RT/RT}$
9.6	5,029	2,350	1,331	1,485	1,335	1,133	1,281	786	785	1,654	1,005	730
12.7	4,681	2,207	1,204	1,413	1,269	1,084	1,239	754	731	1,557	935	704
16.8	4,524	2,057	1,159	1,395	1,130	1,038	1,256	727	689	1,458	879	697
18.7	4,480	1,960	1,059	1,166	1,219	1,042	1,216	733	659	1,398	875	677

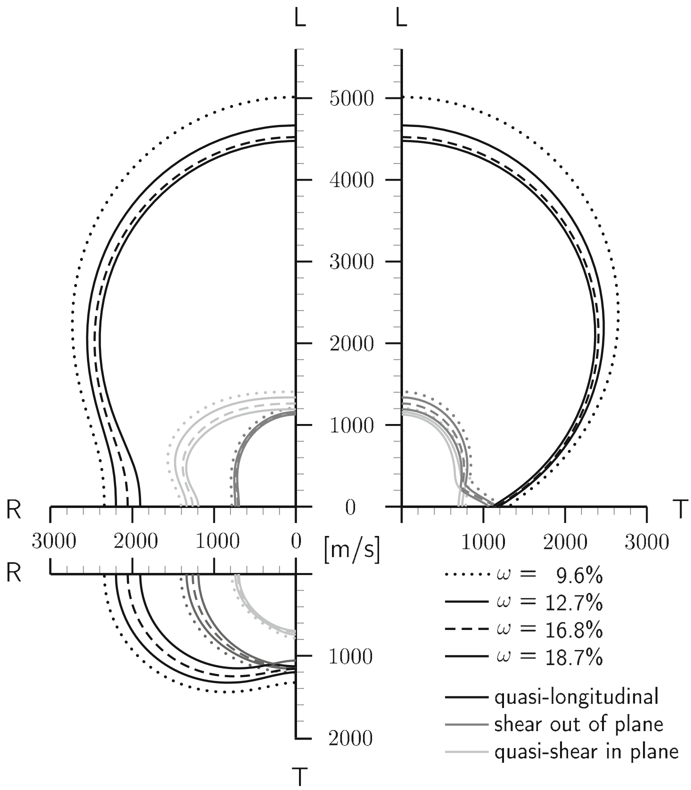

Fig. 3 Two-dimensional representation of the moisture-dependent velocity surface for beech wood. Calculated by solving Eq. 2 in the principal planes (*RT*, *RL* and *LT*)

affected by the MC, it should be noticed that the independent moduli are affected by the MC to a different degree. With a decrease of 28 % in the measured MC range, the decrease is most pronounced for the $G_{LR/RL}$ and almost twice as high as the 15.9 % decrease observed for $G_{LT/TL}$.

Moisture-dependent elastic moduli for European beech wood are almost unavailable in literature. Only few references cover the shear and Young's moduli for beech wood, and most data are limited to one MC. Further, since most of the available elastic moduli data presented in literature were measured in static tests, the comparison of the measurement results obtained in this study with literature data involves a comparison of different measurement techniques. However, the comparison with shear moduli values obtained in static tests at around 12 % wood MC (Stamer and Sieglerschmidt 1933; Hearmon and Barkas 1941) reveals reasonable similarity. Moreover, the values are in good agreement with shear moduli measured with the ultrasonic technique by Bucur and Archer (1984) and moisture-dependent shear moduli published recently by Hering et al. (2012).

Similar to the shear moduli, Young's moduli decrease from $\omega = 9.6$ % to $\omega = 18.7$ %. As opposed to the shear moduli, the influence of MC on the Young's moduli is more balanced. With a decrease of 25 % for E_T, 21 % for E_L and 18 % for E_R, Young's moduli are influenced by the MC to a similar degree.

No study is known to have investigated the moisture-dependent Young's moduli for European beech wood by means of the ultrasonic technique presented in this study. Therefore, the data presented here are compared with moisture-dependent Young's moduli measured in compression test presented by Hering et al. (2012) (as shown in Fig. 5).

Both, the Young's moduli determined by means of the ultrasonic method (denoted as Eq. 3) and in compression test (CT), decrease with increasing wood MC. However, values obtained from the two measurement techniques are essentially different. Compared with the CT Young's moduli presented by Hering et al. (2012), lower values are found for the ultrasonic Young's moduli in the longitudinal and tangential directions. In contrast, the ultrasonic Young's moduli in the radial direction are found to be slightly higher than the CT ones. While in the tangential and radial directions, the observed differences between the Young's moduli are rather small, in the longitudinal direction those differences are more pronounced. Overall, the ultrasonic longitudinal Young's moduli are found to be 20–30 % lower compared with the CT ones.

It is a known fact that Young's moduli for wood obtained by the ultrasonic technique tend to deliver higher values than comparable values obtained in static tests (Oliveira et al. 2002; Bucur 2006; Keunecke et al. 2007). This general trend is in disagreement with the lower ultrasonic Young's moduli obtained in this study.

It should be emphasised that in most investigations where higher ultrasound values are reported, a different ultrasound analysis is used. As opposed to the

Table 4 Moisture-dependent elastic engineering parameters for beech wood by means of ultrasonic waves

	ω (%)	Young's moduli (GPa)			Shear moduli (GPa)			Poisson's ratios (-)					
		E_L	E_R	E_T	$G_{LR/RL}$	$G_{LT/TL}$	$G_{RT/TR}$	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}
	9.6	11.18	2.31	0.56	1.37	1.01	0.43	0.01	0.04	0.11	2.21	0.26	1.09
	12.7	9.56	2.20	0.49	1.24	0.93	0.38	0.02	0.08	0.11	2.26	0.23	1.02
	16.8	8.20	2.04	0.44	1.11	0.91	0.35	0.03	0.11	0.13	2.43	0.20	0.90
	18.7	8.80	1.89	0.42	0.98	0.85	0.33	0.04	0.20	0.12	2.37	0.17	0.77
References													
1.	–[a]	9.16	1.85	1.03	1.39	0.97	0.35	1.24	0.25	0.90	0.10	0.26	0.14
2.	12.0	11.90	1.70	1.03	0.98	0.76	0.37	–	–	–	–	–	–
3.	10.5[b]	13.70	2.24	1.14	1.25	0.70	0.62	0.07	0.45	0.04	0.51	0.36	0.75

1. Bucur and Archer (1984), [a] MC unknown

2. Hearmon and Barkas (1941)

3. Stamer and Sieglerschmidt (1933), [b] shear moduli at $\omega = 12.5$ %

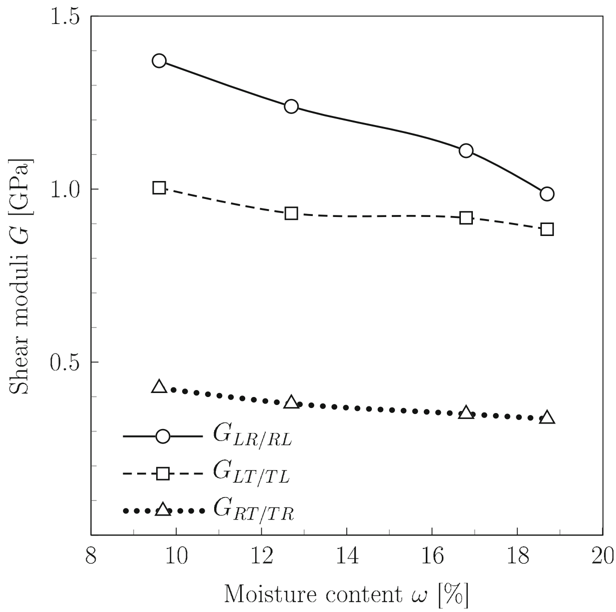

Fig. 4 Moisture-dependent shear moduli for beech wood determined by the ultrasonic method

technique presented in this study, in most investigations, a simplified equation is used to calculate the Young's moduli:

$$E = \rho V_{ii}^2. \tag{9}$$

A comparison of the ultrasonic Young's moduli calculated from Eq. 9 and Young's moduli calculated from the equations listed in Table 2 using the same input parameters (density and velocity), point out the significant difference (see Fig. 5). The results prove that a computation performed without taking the non-diagonal terms of the stiffness matrix into account (Eq. 9) results in highly overestimated values. It becomes visible that Young's moduli calculated from this equation do not coincide neither with the ultrasonic method used in this study nor with the Young's moduli obtained from the static compression test (Hering et al. 2012). In contrast, ultrasonic Young's moduli presented in this study are, overall, in good agreement with the Young's moduli from static compression test as presented by Hering et al. (2012), even if the values tend to underestimate the CT Young's moduli.

Poisson's ratios

Similar to the elastic moduli, the Poisson's ratios are affected by the MC. As opposed to the moduli, no uniform trend with MC is observed. While the ν_{RT} and ν_{TR} decrease, ν_{LR}, ν_{RL} and ν_{TL} increase with increasing wood MC. At the same time, ν_{LT} is found to be insensitive to MC. Those findings do not match the effect observed for European beech wood by Hering et al. (2012), who found decreasing ν_{LR}, ν_{LT}, ν_{RL} and ν_{RT}, ν_{TR}, ν_{TL}, which were insensitive to changes in MC. While the

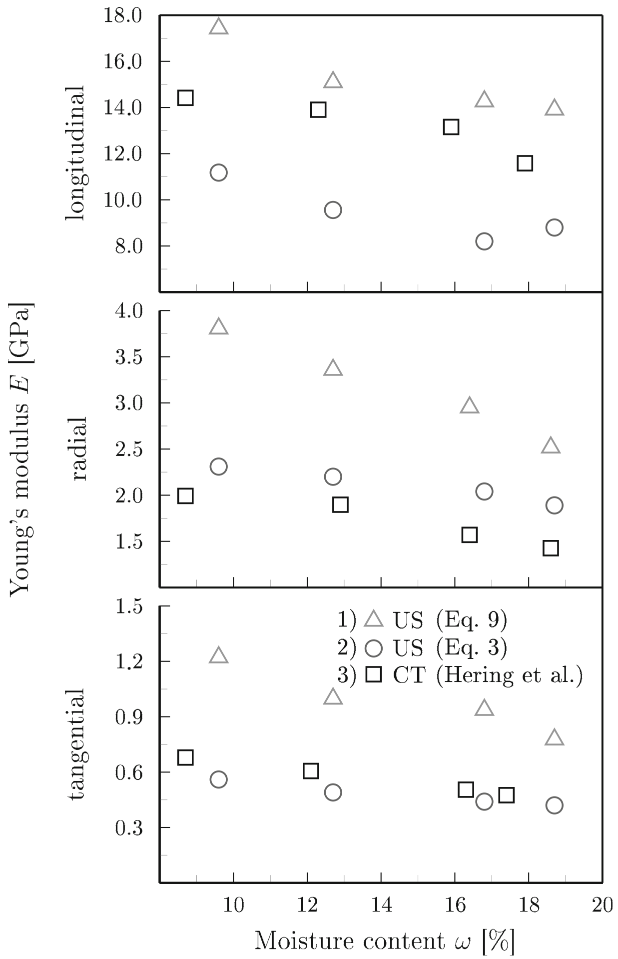

Fig. 5 Moisture-dependent Young's moduli obtained by: (*1*) means of ultrasonic technique from Eq. 9; (*2*) means of ultrasonic technique from Eq. 3; (*3*) in static compression test (Hering et al. 2012)

obtained ν_{RT}, ν_{LT}, ν_{LR} values are very similar with the Poisson's ratios cited in Hering et al. (2012), the comparison with the values measured for European beech wood in static tests by Stamer and Sieglerschmidt (1933) reveal discrepancies (see Table 4). Significant differences are also observed between the Poisson's ratios published here and the values measured using the ultrasonic technique by Bucur and Archer (1984). Furthermore, rather high values, exceeding a measure for ν_{TR} and two for ν_{TL}, were obtained.

While in theory, Poisson's ratios for anisotropic materials with orthotropic symmetry can have no bounds (Ting and Chen 2005), Poisson's ratios with values exceeding one are assumed to be unusual for wood. Indeed, Poisson's ratios with similar values have not been reported for wood in static tests. On the other hand, Poisson's ratios with values exceeding one, measured by means of ultrasonic waves have been published by other researchers (Bucur and Archer 1984; Gonçalves et al. 2011).

Taking into account that there is no reasonable explanation for the high Poisson's ratios, the results presented here seem doubtful. It has to be considered, however, that the Poisson's ratios presented in this study are calculated from complex relationships based on several assumptions. One should notice that even though the perfect elastic orthotropic symmetry is a reasonable assumption for wood, it is not fully satisfied, as demonstrated.

Conclusion

The elastic behaviour of beech wood is significantly influenced by the MC. With the exception of the increasing ν_{LR}, ν_{RL} and ν_{TL}, as well as the ν_{LT}, which seems to be insensitive to MC changes, the obtained elastic engineering parameters decrease with increasing MC. While the MC leads to a decline in wood stiffness, wood anisotropy, displayed by the two-dimensional representation of the velocity surface, does not change significantly with MC.

Based on the values measured for the elastic moduli, the ultrasonic technique is found to be suitable for determining the elastic moduli. However, when calculating the Young's moduli, non-diagonal terms of the stiffness matrix must be considered. A comparison of the Young's moduli calculated without, and allowing for the non-diagonal terms using the same input parameters, proves that a computation performed without taking the non-diagonal terms of the stiffness matrix into account will result in overestimated values.

While the ultrasonic technique is found to be reliable to measure the elastic moduli, Poisson's ratios with values exceeding one (and some exceeding two), as measured for ν_{TR} and ν_{TL}, are considered to be unusual for wood. Since similar values have not been reported in static tests, the applicability of the ultrasonic technique to measure the Poisson's ratios remains uncertain.

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