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ORIGINAL

Moisture-dependent elastic characteristics of walnut and cherry wood by means of mechanical and ultrasonic test incorporating three different ultrasound data evaluation techniques

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Abstract Ultrasonic testing is a non-destructive testing method of choice for estimating the anisotropic elastic properties of wood materials. This method is reliable for estimating the Young's and shear moduli. However, its applicability to Poisson's ratios remains uncertain. On the other hand, despite their destructive nature, mechanical tests allow a direct measurement of all elastic properties including the Poisson's ratios. In some cases (e.g. when assessing cultural heritage objects), destructive testing may not be an option. In this work, two types of hardwood walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.), which often appear on cultural heritage objects, were tested using both ultrasonic and mechanical testing methods under four different moisture conditions below fibre saturation point. The results show that a higher moisture condition leads to a decrease in material elasticity. For walnut wood, their longitudinal Young's modulus (E_L) was reduced by 679 MPa under the compression load for a one per cent increase in moisture content. Moreover, three ultrasound data evaluation techniques, which differ in the way they incorporate the Poisson's ratios (full stiffness inversion, simplified uncorrected, and simplified corrected), were used to estimate the Young's moduli (E). The main goal is to obtain reliable material parameters using the ultrasound test. As a result, it is concluded that the chosen data evaluation method influences the accuracy of the calculated E. In a certain case, the simplified-corrected method, which requires only one specimen type, gave a closer agreement to mechanical tests (e.g. $\Delta E_T = 6\,\%$ deviation on mechanical results). In another case, the full-stiffness-inversion method, which requires four specimen types, gave the

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best estimation (e.g. $\Delta E_L = 2\,\%$). In this corresponding direction, the simplified-corrected method can only partially reduce the overestimation of the simplified uncorrected from $\Delta E_L = 47$ to 32 %. The variation of E produced by different evaluation procedures is due to the different correction factor values, which is a consequence of the variation in ν.

Introduction

In engineering, elastic material parameters are essential inputs to advanced material models. However, the availability of elastic material parameters in the case of wood is often very limited. It is mainly due to the enormous amount of species, each with own characteristics as well as due to its natural complexity. The material properties of wood are different in the three orthogonal material directions: longitudinal (L), radial (R) and tangential (T). Consequently, a considerable experimental effort is required to estimate the elastic parameters of only one particular wood species.

Various experimental methods have been developed to support the characterisation of wood properties using the mechanical test as the standard (Keunecke et al. 2008; Hörig 1935; Ozyhar et al. 2012). The mechanical test allows direct and accurate measurement of all elastic properties: Young's moduli (E), shear moduli (G) and Poisson's ratios (ν). However, the test is a destructive test, which limits its applicability. In a case of assessing standing constructions or cultural objects, the non-destructive tests are more suitable. The non-destructive testing of choice for wood elastic properties, which has been developed over the last decades, is ultrasonic testing (Bucur and Archer 1984; Gonçalves et al. 2011; Ozyhar et al. 2013). Despite its reliability of estimating E in the principal axes (L, R, and T) and G on the material planes (LR, LT and RT), its applicability to estimating ν is uncertain. Since the ultrasonic method is based on the inversion of the stiffness data, E and ν values are partially related. Therefore, the uncertainty of ν questioned the accuracy of E.

Both ultrasonic and mechanical testing methods of two types of hardwood walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.) were performed in this study. These species frequently appear in cultural heritage objects in museums. However, their elastic properties have only been scarcely investigated (e.g. Keylwerth (1951); Grosser and Jeske (2008)). For understanding the influence of moisture on the elastic strength of the material, the tests were carried out under four different moisture conditions: 50, 65, 80 and 95 % relative humidity (RH) at a temperature of 20 °C. The first goal of this study is to obtain a reliable set of moisture-dependent material properties for these two hardwood species (walnut and cherry wood) with a sufficient accuracy.

Moreover, alternative methods focusing mainly on improving the ultrasound testing were proposed in this study. E can only be accurately estimated from stiffness data if knowledge of ν is available (Ozyhar et al. 2013). Therefore, three data evaluation techniques, which differ in the way to incorporate ν, were used to estimate E from the ultrasonic data. The results were compared with the mechanical test results as the reference. The aim is to improve the accuracy of the ultrasonic method. Hence, a reliable set of elastic material properties (E, G and ν) can be obtained.

Material and methods

Material

The measurements in this study were taken for walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.) wood grown in the Caucasus region. The average wood densities (ρ) were 670 and 575 kg/m^3, respectively, and were measured in normal climatic conditions with a temperature of 20 °C and RH of 65 %. The specimens were small clear wood without any natural growth characteristics such as reaction wood or knots.

Wood is described as an orthotropic material on three material axes (L: longitudinal or fibre grain, R: perpendicular to growth rings, and T: tangential to growth rings) (Bodig and Jayne 1993). Based on Hooke's law, the relation between stress and strain for an orthotropic material presented under Voigt's notation is

$$[\varepsilon] = [S] \cdot [\sigma], \begin{bmatrix} \varepsilon_{LL} \\ \varepsilon_{RR} \\ \varepsilon_{TT} \\ 2\varepsilon_{RT} \\ 2\varepsilon_{TL} \\ 2\varepsilon_{LR} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_L} & \frac{-\nu_{LR}}{E_R} & \frac{-\nu_{LT}}{E_T} & 0 & 0 & 0 \\ \frac{-\nu_{RL}}{E_L} & \frac{1}{E_R} & \frac{-\nu_{RT}}{E_T} & 0 & 0 & 0 \\ \frac{-\nu_{TL}}{E_L} & \frac{-\nu_{TR}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{TL}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} \cdot \begin{bmatrix} \sigma_{LL} \\ \sigma_{RR} \\ \sigma_{TT} \\ \sigma_{RT} \\ \sigma_{TL} \\ \sigma_{LR} \end{bmatrix} \quad (1)$$

where $[S]$ is the compliance tensor, $[\sigma]$ and $[\varepsilon]$ are stress and strain tensor, respectively. Under Voigt's notation, they become matrix and vectors as shown in Eq. 1. E_i is the Young's modulus along axis i. G_{ij} is the average shear modulus in ij and ji direction, and the first and second indices represent the direction of vector normal to the shear surface and the loading direction. ν_{ij} is the Poisson's ratio that corresponds to a passive contraction in direction i when an extension is applied in direction j. Due to the material symmetry, the $[S]$ matrix is symmetric, which leads to $\frac{\nu_{LR}}{E_R} = \frac{\nu_{RL}}{E_L}$, $\frac{\nu_{LT}}{E_T} = \frac{\nu_{TL}}{E_L}$ and $\frac{\nu_{TR}}{E_R} = \frac{\nu_{RT}}{E_T}$. Therefore, the orthotropic constitutive equation incorporates nine independent elastic constants comprised of three Young's moduli, three Poisson's ratios and three shear moduli.

In the mechanical test, all elastic parameters are directly obtained as test results. In the ultrasonic test, however, ultrasound waves propagating through the material provide the stiffness matrix $[C]$, which needs to be inverted to calculate $[S] = [C]^{-1}$ and furthermore used to obtain the elastic parameters.

Mechanical test

Compression and tension tests

The specimens used for the compression and tension tests were dog-bone-shaped specimens. They were prepared for three different loading directions L, R and T (Fig. 1). Specimens with similar dimensions have been successfully tested to determine the E and ν of yew and spruce wood (Keunecke et al. 2008) and beech wood (Hering et al. 2012; Ozyhar et al. 2013). The specimens were acclimatised at 50, 65, 85 and 95 % RH and a constant temperature of 20 °C for at least two months before the tests. For each RH level, loading direction and wood species, 10–15 specimens were prepared.

Compression (CT) and tension (TT) tests were performed using a Universal Testing Machine (Zwick Roell Z100, Zwick Germany) equipped with a 100 kN load cell. A 50 N predefined initial force was set with a displacement rate of 5 mm/min and used as a starting point for the measurement. As soon as the initial load was reached, the tests were continued under a displacement-controlled rate of 1 mm/min to achieve failure within 90 (±30) s (Keunecke et al. 2008).

Before the test, three samples were tested for each load direction, humidity level and wood species to estimate the ultimate stress of the specimens. Fifty percent of the average ultimate strength obtained in this pretest was used as the upper-stress

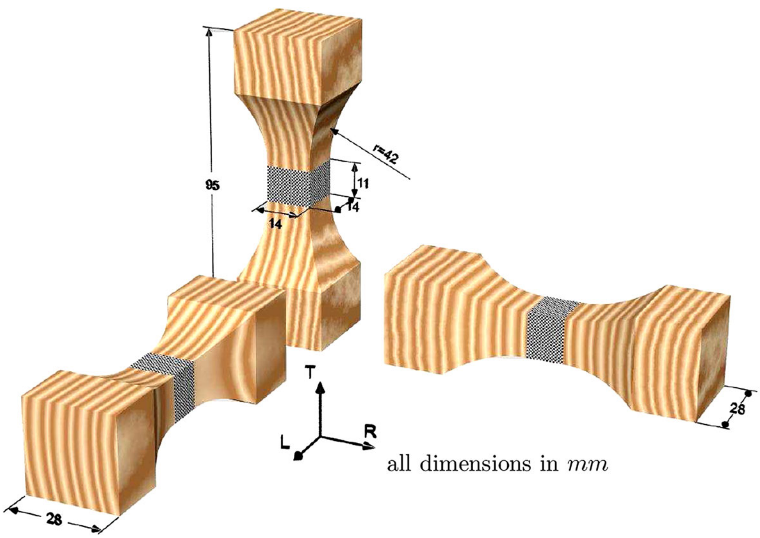

Fig. 1 Dog-bone-shaped specimens for the compression and tension test

limit for the actual measurements. With this limitation, E and v can be measured without damaging the specimens. Therefore, the same samples could be used for both tension and compression tests.

For the measurement of strain, a high contrast random dot texture ("speckle pattern") was applied to an $11 \times 14\ \mathrm{mm}^2$ area on the specimen's waist on at least two adjacent sides (Fig. 1). The speckles were applied with a Harder & Steenbeck evolution airbrush gun in combination with a nozzle cup diameter of 0.8 mm and an airbrush needle with a diameter of 0.4 mm. During the measurement, pictures with a frequency of 2 Hz were taken by using two cameras aiming straight at two adjacent sides of the specimen in the speckle regions. Based on these set of pictures, the surface strains were calculated with a commercial two-dimensional digital image correlation software (VIC 2D, Correlated Solution). This strain measurement is known as the digital image correlation (DIC) technique. This method was explained in Keunecke et al. (2008).

The Young's/elastic moduli (E) are defined as

$$E_i = \frac{\Delta\sigma_{ii}}{\Delta\varepsilon_{ii}} = \frac{\sigma_{ii,2} - \sigma_{ii,1}}{\varepsilon_{ii,2} - \varepsilon_{ii,1}} \quad \text{for all} \quad i \in L, R, T \tag{2}$$

where $\Delta\sigma_{ii}$ and $\Delta\varepsilon_{ii}$, respectively, represent the difference of stresses and strains in i direction. The Young's moduli were measured in the linear elastic range based on linear regression applied to stress and strain diagram. The stress boundaries $\sigma_{ii,1}$ and $\sigma_{ii,2}$ were set at approximately 20 and 40 % of the expected ultimate stress.

The Poisson's ratios (v) are defined as

$$v_{ij} = \frac{\Delta\varepsilon_{ii}}{\Delta\varepsilon_{jj}} = \frac{\varepsilon_{ii,2} - \varepsilon_{ii,1}}{\varepsilon_{jj,2} - \varepsilon_{jj,1}} \quad \text{for all} \quad i,j \in L, R, T \text{ and } i \neq j \tag{3}$$

where ε_{ii} represents the passive strain component in the load direction i and ε_{jj} the active strain component in j direction. The Poisson's ratios were determined from the linear regression between the passive and active strain diagram in the same range as the Young's moduli.

Arcan test

Arcan test (AT) was performed to determine the shear moduli (G) mechanically. This test allows a direct application of shear stresses to the specimen without any additional stresses (compression or torsional), which is often the issue in the conventional shear block test. The specimens were $130 \times 50 \times 8\ \mathrm{mm}^3$ boards with notches (Fig. 2), which were prepared in six different load axes directions (RT, TR, TL, LT, LR, RL). The tests were performed under standard climatic conditions (65 % RH, 20 °C). In total, 10–15 samples were prepared for each loading direction and wood species and acclimatised in the climatic room for at least two months before the tests.

The test with a displacement-controlled rate of 1 mm/min was conducted with the same machine used for the tensile and compression tests. The specimens were loaded up to 60 % of their ultimate stress. To determine the ultimate strength, three

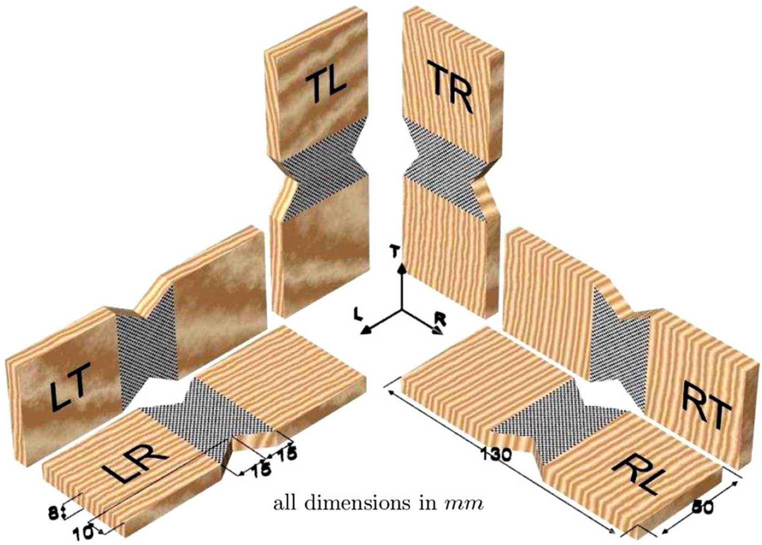

Fig. 2 Arcan test specimens to measure the shear moduli for the six principal orthotropic planes

samples for each loading direction were tested before the actual measurement. The DIC technique was also used for the strain evaluation. During the measurement, pictures with a frequency of 2 Hz were taken on both sides of the specimen containing speckle pattern using two identical cameras. The two sets of pictures were separately analysed to measure the strain on each specimen's surface. The average shear strain was then used for evaluating the shear moduli.

The shear moduli are defined as

$$G_{ij} = \frac{\Delta\sigma_{ij}}{\Delta\varepsilon_{ij}} = \frac{\sigma_{ij,2} - \sigma_{ij,1}}{\varepsilon_{ij,2} - \varepsilon_{ij,1}} \quad \text{for all } i,j \in L,R,T \text{ and } i \neq j \qquad (4)$$

where $\Delta\sigma_{ij}$ and $\Delta\varepsilon_{ij}$ represent the difference of the shear stresses and the shear strain, respectively. The indices i and j represent the direction of the vector normal to the shear surface and the loading direction. The shear moduli were measured in the linear elastic range from the linear regression of the shear stress and twice the shear strain diagram. The shear stress boundaries $\sigma_{ij,1}$ and $\sigma_{ij,2}$ were set to approximately 10 and 50 % of the expected ultimate stress.

Ultrasonic test

The ultrasonic test is a non-destructive testing technique based on the propagation of ultrasonic waves in a material. Two types of wave are used, longitudinal wave and shear/transverse wave. The longitudinal wave shows particle motion along its propagation direction, whereas the shear wave is characterised by particle motion perpendicular to the propagation direction. To determine all independent components of the $[C]$ matrix, at least, three longitudinal, three shear wave velocities

Table 1 Notation for the ultrasound propagation velocities (Ashman et al. 1984)

Wave velocities[a]	Explanation
V_{ii}	Wave velocity of longitudinal wave propagating in the *i* direction and the particle motion (direction of polarisation) in the same direction
V_{ij}	Wave velocity of shear wave propagating in the *i* direction and the particle motion in the perpendicular *j* direction
$V_{ij/ij}$	Wave velocity of quasi-shear wave with propagation along $\mathbf{n} = \left(\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\right)^T$ ($\alpha = 45°$ angle between the *i* and *j* directions) and particle motion on the $i-j$ plane

[a] $i,j \in L,R,T$

propagating along the principal axes and three shear wave velocities measured at a suitable angle to the principal axes (quasi-shear wave) are needed (Bucur 2006). In this study, the selected angle for the quasi-shear wave is $\alpha = 45°$ with respect to principal direction. The notation for the wave velocities is listed in Table 1.

The selected longitudinal and shear waves frequency were 2.27 and 1 MHz, respectively, which lead to the wavelengths (λ) of 0.5–2.5 mm. These frequencies were selected because λ must be as big as possible but smaller than specimen dimension to avoid guided wave effects (Bucur 2006; Zaoui 2002; Kohlhauser and Hellmich 2013). Bigger λ provides a better approximation of the solid continuum to capture the macroscopic wood behaviour. If λ is too small, the interaction of wood year rings cannot be avoided. Moreover, this selected range of frequency (1 MHz or higher) has been successfully attempted in several previous studies for other wood species (Bucur and Archer 1984; Ozyhar et al. 2013; Gonçalves et al. 2011).

In the case of sample dimensions, the requirement of the ultrasonic test is flexible. Any specimen with a thickness of at least three times λ in the propagation direction ($\geq$7.5 mm) can be measured (Bucur 2006; Gonçalves et al. 2011). The maximum specimen thickness is limited by the ultrasound attenuation, which is higher for the cross-grain planes. Hence, specimen dimension can be varied from the millimetre scale to metres (Bucur 2006). The lateral dimensions (width/ length) are not relevant. The high frequency guarantees that the ultrasonic beam is bounded by a cylinder with the size of the transducer diameter. The transducer and receiver must only be placed on two flat and parallel surfaces aligned to each other.

In this study, four different types of cuboid specimens, corresponding to specific material planes (Fig. 3), were used to carry out the ultrasonic test (UT). Each specimen type was manufactured in 3 different edge lengths (16, 13 and 10 mm). They were further acclimatised at RH 50, 65, 85, 95 % and a constant temperature of 20 °C for at least two months before the test as it is done for the mechanical test specimens. Approximately 10–15 specimens were prepared for each type, dimension, wood species and RH level.

The ultrasonic test was performed in each climate room where the samples had been stored. The test was carried out using the Epoch XT flaw detector (complies to EN12668-1 (2010)) with a direct through-transmission technique. A transmitter transducer (Olympus A133S with a diameter of 12 mm for longitudinal waves and

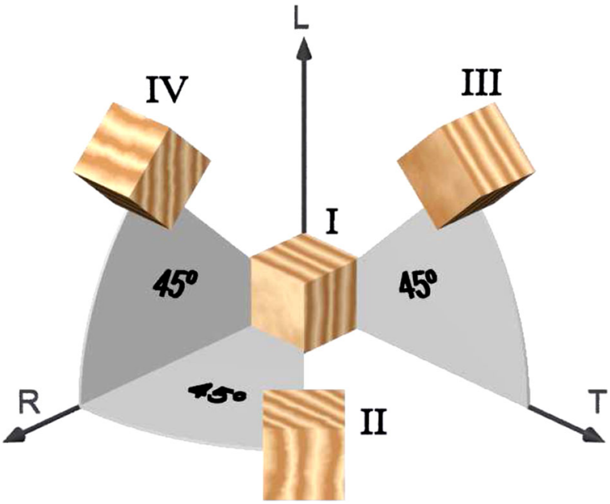

Fig. 3 Specimen types for ultrasound velocity measurements. Each type was produced in three different edge lengths: 16, 13 and 10 mm

Staveley S-0104 with a diameter of 12.7 mm for transversal waves) sends ultrasound waves from one surface of the specimen. A separate receiver detects the first arrival of waves (time of flight) on the opposite surface.

In this experimental test, the flight time of three longitudinal, six shear and three quasi-shear waves propagating on each specimen dimension was recorded for each specimen thickness. The velocities were determined by linear regression between the measured time and the specimen thicknesses. The resulting velocities were then used to estimate the E and ν.

Three different data evaluation techniques were used to evaluate the ultrasound results. The first data evaluation technique, **full stiffness inversion** (UT-FSI), is the method that has been implemented in previous studies (e.g. Bucur and Archer (1984); Kriz and Stinchcomb (1979); Ozyhar et al. (2013)). This technique requires the whole set of the wave velocities to estimate the Young's moduli. Each component of stiffness matrix $[C]$ is calculated using the equations in Table 2. Then, the $[S]$ matrix is calculated by inverting the $[C]$ matrix, from which the whole set of E, G and ν is obtained with Eq. 1.

The second data evaluation technique, **simplified uncorrected** (UT-SU), is a simplified version of ultrasound data analysis, which only requires the wave velocities from specimens type I (Table 2). This method significantly increases the time efficiency of the ultrasonic test. However, the main diagonal terms of the stiffness matrix are assumed equal to E and G (Eq. 5). Or in other words, the off-diagonal terms of the material stiffness matrix are zero, which also means that the ν are zero in every load direction. The calculation of G, which is independent of ν, is not influenced by this assumption. However, it leads to an overestimation of E (Ozyhar et al. 2013).

Table 2 Equation to calculate the stiffness components from the ultrasound wave velocities

Specimen type	Wave velocities	Equation
I	V_{LL}	$c_{11} = \rho V_{\mathrm{LL}}^2$
	V_{RR}	$c_{22} = \rho V_{\mathrm{RR}}^2$
	V_{TT}	$c_{33} = \rho V_{\mathrm{TT}}^2$
	$V_{\mathrm{RT}}/V_{\mathrm{TR}}$	$c_{44} = \left(\rho V_{\mathrm{RT}}^2 + \rho V_{\mathrm{TR}}^2\right)/2$
	V_{TL}/V_{LT}	$c_{55} = \left(\rho V_{\mathrm{TL}}^2 + \rho V_{LT}^2\right)/2$
	$V_{\mathrm{LR}}/V_{\mathrm{RL}}$	$c_{66} = \left(\rho V_{\mathrm{LR}}^2 + \rho V_{\mathrm{RL}}^2\right)/2$
II	$V_{RT/RT}$ [a]	$c_{23} = \sqrt{\left(c_{22} + c_{44} - 2\rho V_{RT/RT}^2\right)\left(c_{33} + c_{44} - 2\rho V_{RT/RT}^2\right)} - c_{44}$
III	$V_{TL/TL}$ [a]	$c_{31} = \sqrt{\left(c_{11} + c_{55} - 2\rho V_{TL/TL}^2\right)\left(c_{33} + c_{55} - 2\rho V_{TL/TL}^2\right)} - c_{55}$
IV	$V_{LR/LR}$ [a]	$c_{12} = \sqrt{\left(c_{11} + c_{66} - 2\rho V_{LR/LR}^2\right)\left(c_{22} + c_{66} - 2\rho V_{LR/LR}^2\right)} - c_{66}$

[a] Quasi-shear wave with angle $\alpha = 45°$

$$E_i \approx c_{ii} = \rho \cdot V_{ii}^2 \qquad \text{for all } i \in 1,2,3$$
$$G_{ij} = G_{ji} = c_{(9-i-j)(9-i-j)} = \left(\rho \cdot V_{ij}^2 + \rho \cdot V_{ji}^2\right)/2 \qquad \text{for all } i,j \in 1,2,3 \text{ and } i \neq j \tag{5}$$

To avoid the overestimation of E, a third data evaluation technique, **simplified corrected** (UT-SC), is proposed. A parametric inversion of the $[S]$ matrix is performed to obtain analytical expressions of the axial stiffness c_{ii} as a function of the E and ν. By operating Eq. 1, exact expressions for the first three diagonal terms of the $[S]$ matrix are obtained. Each stiffness component is equal to E in the corresponding direction multiplied by a certain correction factor (k_i) which is a function of ν (Eq. 6). Assuming that the nominal values of ν are known (e.g. from literature data (LD), from selected mechanical or other ultrasound tests), and their variations among different specimens of the same species introduce a negligible impact on the E calculations, these correction factors can be calculated. By using this method, an accurate E estimation can be performed even though only specimens of type I are available during the ultrasonic measurement.

$$\begin{aligned}
c_{11} &= E_{\mathrm{L}} \cdot k_{\mathrm{L}} \\
&= E_{\mathrm{L}} \cdot \frac{1 - \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TR}}}{1 - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RL}} - \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TR}} - \nu_{\mathrm{TL}} \cdot \nu_{LT} - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TL}} - \nu_{\mathrm{RL}} \cdot \nu_{LT} \cdot \nu_{\mathrm{TR}}} \\
c_{22} &= E_{\mathrm{R}} \cdot k_{\mathrm{R}} \\
&= E_{\mathrm{R}} \cdot \frac{1 - \nu_{\mathrm{TL}} \cdot \nu_{LT}}{1 - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RL}} - \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TR}} - \nu_{\mathrm{TL}} \cdot \nu_{LT} - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TL}} - \nu_{\mathrm{RL}} \cdot \nu_{LT} \cdot \nu_{\mathrm{TR}}} \\
c_{33} &= E_{\mathrm{T}} \cdot k_{\mathrm{T}} \\
&= E_{\mathrm{T}} \cdot \frac{1 - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RL}}}{1 - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RL}} - \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TR}} - \nu_{\mathrm{TL}} \cdot \nu_{LT} - \nu_{\mathrm{LR}} \cdot \nu_{\mathrm{RT}} \cdot \nu_{\mathrm{TL}} - \nu_{\mathrm{RL}} \cdot \nu_{LT} \cdot \nu_{\mathrm{TR}}}
\end{aligned} \tag{6}$$

Results and discussion

The experimental results from mechanical tests and ultrasonic test with four different moisture levels of the woods are presented in Table 3. E and G gradually decrease with increasing wood moisture content (u) for both mechanical (compression (CT) and tension (TT)) and ultrasound (UT) results. Figure 4 shows the influence of moisture on the longitudinal Young's moduli (E_L) for the three different methods. For walnut wood, the E_L obtained from compression, tension and ultrasound test on average decreased by 679, 423 and 184 MPa, respectively, for each per cent increase in u. As opposed to the Young's and shear moduli, no clear trend of the moisture influence for Poisson's ratios can be observed. The Poisson's ratios as obtained from the mechanical tests show a relatively high variability, especially for ν_{TL}. Therefore, the changes of Poisson's ratios cannot be uniquely assigned to the influence of moisture or the inhomogeneity of the wood.

Moreover, the Poisson's ratios (ν) calculated based on the full-stiffness-inversion (UT-FSI) method show inconsistent results. It is expected due to the combination of the wood inhomogeneities, the ill-posed problem arises from the inversion of stiffness matrix. The data of multiple specimens acquired during the ultrasonic measurement were combined to obtain averaged material properties. Since each specimen was introduced with natural inhomogeneity, their properties may slightly vary. Moreover, the inversion of the stiffness matrix is numerically ill-posed. This can be seen by adding uncertainty to synthesise ultrasound data and performing inversion. A typical variance of 0.5–2 % in the ultrasonic velocities may induce errors up to 5 % for E and G and 30% for ν. While the influence of these problems is negligible for E and G, it is clearly pronounced in the resulted ν.

Therefore, ν show unreasonably high values in certain directions (e.g. ν_{RL}, ν_{TL}, ν_{TR}). However, in the other directions (e.g. ν_{LR}, ν_{LT}, ν_{RT}) the ultrasonic and mechanical results show closer agreement. These deviations were also observed in the previous study (Bucur and Archer 1984; Ozyhar et al. 2013). In fact, the ultrasonic results at certain direction (e.g. ν_{TL} for walnut wood at u 7.2 and 9.2 %) are exceeding one. The ν with values exceeding one are considered to be unusual for wood (Ting and Chen 2005). Under static mechanical test, Poisson's ratio with similar values has not been reported for wood.

The results obtained with the three different evaluation techniques are presented in Table 4. However, due to the low availability of supported reference studies for walnut and cherry wood, the correction factor cannot be optimally applied. A full set of material parameters can only be found for walnut (Keylwerth 1951) but only for a specific moisture condition. These data were used together with mechanical test results for comparison. For the validation purposes, correction factors (k) based on the ν of UT-FSI method were also calculated and are presented in Table 4. The cross-validations were made by multiplying E of the UT-FSI with k in the corresponding direction. Since Eq. 6 is formally equivalent to the inversion of the $[C]$ matrix, the results are equal to the component of $[C]$ matrix in the same direction, which is no other than E of the simplified-uncorrected (UT-SU) technique.

Table 3 Elastic properties of walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.)

Experimental data	u (%)	ρ (kg/m^3)	Elasticity moduli (MPa) [CoV (%)]			Shear moduli (MPa) [CoV (%)]		
			E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}
Walnut								
Mechanical tests								
Compression (CT)	7.2	642	12849 (9.19)	1227 (6.08)	1091 (7.35)			
	9.2	693	10721 (9.21)	1149(4.82)	1083 (3.02)			
	12.5	647	10217 (7.76)	968 (4.13)	908 (4.96)			
	15.1	671	6793 (21.2)	907 (10.4)	873 (2.89)			
Tension (TT)	7.2	642	13621 (8.07)	1467 (5.74)	1284 (5.66)			
	9.2	693	11253 (4.85)	1352 (2.72)	1260 (3.45)			
	12.5	647	11094 (8.90)	1170 (4.85)	1124 (3.95)			
	15.1	671	9708 (20.1)	1056 (7.64)	1028 (3.68)			
Arcan (AT)	10.0	561				194 (2.55)	868 (7.10)	1020 (3.45)
Ultrasound full stiffness inversion (UT-FSI)	7.2	635	11598	1518	746	395	1222	1813
	9.2	647	11190	1377	682	264	995	1389
	12.5	628	10906	1151	489	218	863	1173
	15.1	677	10021	1007	408	208	861	1095
Cherry								
Mechanical tests								
Compression (CT)	8.4	559	8947 (10.3)	1634 (7.47)	930 (10.5)			
	10.7	589	8707 (10.7)	1505 (8.39)	720 (13.2)			
	14.2	565	8627 (7.77)	1307 (8.89)	717 (4.77)			
	16.3	562	6808 (12.4)	1079 (5.07)	610 (19.1)			

Table 3 continued

Experimental data	u (%)	ρ (kg/m^3)	Elasticity moduli (MPa) [CoV (%)]			Shear moduli (MPa) [CoV (%)]		
			E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}
Tension (TT)	8.4	559	9826 (8.71)	1830 (5.25)	1069 (9.43)			
	10.7	589	9709 (9.02)	1609 (17.2)	885 (11.7)			
	14.2	565	9396 (9.76)	1502 (7.42)	864 (4.28)			
	16.3	562	8592 (8.76)	1280 (3.94)	825 (12.9)			
Arcan (AT)	10.0	554				218 (3.90)	782 (4.35)	1188 (4.95)
Ultrasound full stiffness inversion (UT-FSI)	8.4	579	9489	1489	884	239	1050	1230
	10.7	560	8238	1384	644	228	895	1112
	14.2	556	7496	1233	509	209	802	956
	16.3	592	7309	1229	475	202	711	950

Experimental data	Poisson's ratio (–) [CoV (%)]					
	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}
Walnut						
Mechanical tests						
Compression (CT)	0.043 (27.5)	0.288 (6.26)	0.035 (15.8)	0.180 (16.3)	0.316 (11.4)	0.519 (4.50)
	0.035 (20.5)	0.290 (8.99)	0.032 (14.5)	0.193 (21.5)	0.297 (1.88)	0.524 (1.84)
	0.033 (6.18)	0.240 (17.2)	0.036 (10.1)	0.131 (46.6)	0.352 (6.61)	0.543 (3.49)
	0.067 (15.3)	0.201 (22.4)	0.059 (8.94)	0.083 (48.8)	0.340 (2.97)	0.559 (3.27)
Tension (TT)	0.075 (19.0)	0.230 (16.1)	0.062 (8.69)	0.125 (33.6)	0.333 (6.34)	0.513 (4.40)
	0.060 (7.67)	0.260 (9.83)	0.065 (7.43)	0.129 (15.4)	0.340 (2.28)	0.541 (2.32)
	0.053 (15.6)	0.250 (14.0)	0.060 (11.0)	0.125 (25.5)	0.394 (6.68)	0.590 (2.51)
	0.066 (12.3)	0.274 (18.3)	0.057 (6.86)	0.115 (45.8)	0.363 (1.72)	0.579 (3.30)

Table 3 continued

Experimental data	Poisson's ratio (–) [CoV (%)]					
	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}
Arcan (AT)						
Ultrasound full stiffness inversion (UT-FSI)	0.061	0.469	0.075	1.173	0.460	0.936
	0.055	0.448	0.079	1.298	0.437	0.883
	0.109	1.035	0.012	0.268	0.416	0.978
	0.094	0.934	0.021	0.525	0.435	1.072
Cherry						
Mechanical tests						
Compression (CT)	0.059 (16.3)	0.289 (10.7)	0.046 (16.6)	0.291 (22.6)	0.344 (2.26)	0.715 (3.18)
	0.055 (5.17)	0.257 (13.6)	0.042 (9.41)	0.242 (14.9)	0.321 (4.34)	0.734 (2.64)
	0.057 (7.16)	0.292 (9.88)	0.048 (16.2)	0.263 (11.6)	0.321 (2.78)	0.768 (4.20)
	0.057 (5.87)	0.179 (15.6)	0.036 (22.8)	0.141 (22.3)	0.348 (4.21)	0.828 (2.17)
Tension (TT)	0.091 (10.0)	0.300 (4.57)	0.067 (4.41)	0.266 (24.1)	0.360 (2.60)	0.736 (2.61)
	0.088 (4.28)	0.303 (16.9)	0.064 (9.98)	0.271 (15.2)	0.350 (3.73)	0.775 (0.99)
	0.083 (7.64)	0.310 (12.6)	0.060 (14.4)	0.259 (15.6)	0.372 (4.30)	0.825 (1.80)
	0.075 (5.88)	0.306 (14.6)	0.055 (19.7)	0.258 (14.1)	0.407 (4.97)	0.877 (2.29)
Arcan (AT)						
Ultrasound full stiffness inversion (UT-FSI)	0.163	1.041	0.027	0.289	0.446	0.752
	0.141	0.838	0.059	0.755	0.372	0.798
	0.117	0.711	0.066	0.966	0.372	0.900
	0.116	0.689	0.052	0.807	0.375	0.971

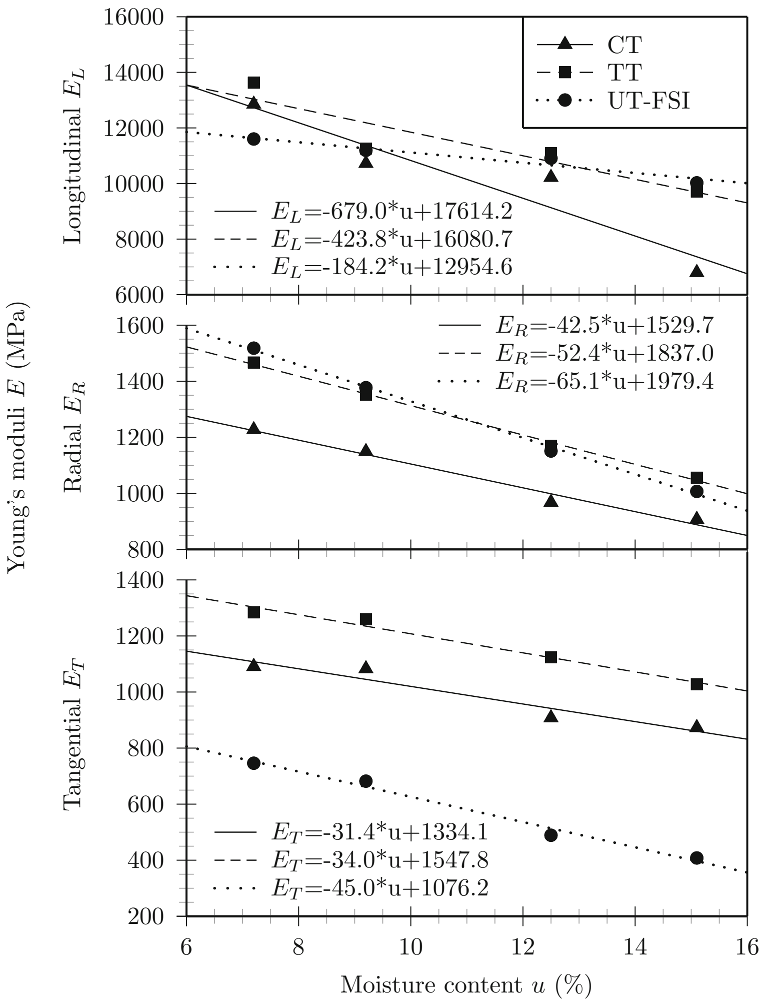

Fig. 4 Moisture-dependent Young's moduli of walnut (*Juglans regia* L.) wood by means of: compression test (CT), tension test (TT) and full stiffness inversion of ultrasonic test (UT-FSI)

The deviation of the E between each method for walnut and cherry wood is presented in Fig. 5 with the average of E resulting from compression (CT) and tension test (TT) as the reference values. Additionally, the ultrasonic results from beech wood obtained from Ozyhar et al. (2013) with mechanical results from Hering et al. (2012); Stamer and Sieglerschmidt (1933) as the reference values are also presented.

As expected, the UT-SU version of ultrasound data often leads to an overestimation of E, for example, for walnut wood at $u = 9.2$–11.0 % and $\rho = 590$–693 kg/m^3 the UT-SU method diverge $\Delta E_L = 47\,\%$, $\Delta E_R = 133\,\%$ and $\Delta E_T = 34\,\%$ from the mechanical tests (Fig. 5). These results have been expected because of the unknown v in the calculation. Although in most of the cases, E obtained by the UT-SU method are overestimated, the E_L and E_T of UT-SU beech

Table 4 Data evaluation results of walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.) at 20 °C/ RH 65 %

Experimental data	u (%)	ρ (kg/m^3)	Elasticity moduli (MPa)			Shear moduli (MPa)			Poisson's ratio (–)						Correction factors (–)		
Walnut			E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}	k_L	k_R	k_T
Mechanical																	
Compression (CT)	9.2	693	10721	1149	1083				0.035	0.290	0.032	0.193	0.297	0.524			
Tension (TT)	9.2	693	11253	1352	1260				0.060	0.260	0.065	0.123	0.340	0.541			
Arcan (AT)	10.0	561				194	868	1020									
Literature data (LD[a])	11.0	590	11416	1214	641	234	714	980	0.052	0.490	0.036	0.636	0.375	0.710			
Ultrasound (UT)																	
UT-FSI (Table 1)	9.2	647	11190	1377	682	264	995	1389	0.055	0.448	0.079	1.298	0.437	0.883	1.447	2.113	2.296
UT-SU (Eq. 6)	9.2	647	16189	2910	1565	264	995	1389	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	1.000
UT-SC (CT) (Eq. 7)	9.2	647–693	15745	2403	1298	264	995	1389	0.035	0.290	0.032	0.193	0.297	0.524	1.028	1.211	1.206
UT-SC (TT) (Eq. 7)	9.2	647–693	15482	2290	1241	264	995	1389	0.060	0.260	0.065	0.123	0.340	0.541	1.046	1.271	1.261
UT-SC (LD[a]) (Eq. 7)	9.2–11.0	590–647	14578	1967	1061	264	995	1389	0.052	0.490	0.036	0.636	0.375	0.710	1.111	1.479	1.475
Cherry	u	ρ	E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}	k_L	k_R	k_T
Mechanical																	
Compression (CT)	10.7	589	8707	1505	720				0.055	0.257	0.042	0.242	0.321	0.734			
Tension (TT)	10.7	589	9709	1609	885				0.088	0.303	0.064	0.271	0.350	0.775			
Arcan (AT)	10.0	554				218	782	1188									
Ultrasound (UT)																	
UT-FSI (Table 1)	10.7	560	8238	1384	644	228	895	1112	0.141	0.838	0.059	0.755	0.372	0.798	1.523	2.068	1.909
UT-SU (Eq. 6)	10.7	560	12542	2862	1230	228	895	1112	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	1.000
UT-SC (CT) (Eq. 7)	10.7	560–589	11943	2104	908	228	895	1112	0.055	0.257	0.042	0.242	0.321	0.734	1.050	1.360	1.355
UT-SC (TT) (Eq. 7)	10.7	560–589	11382	1926	836	228	895	1112	0.088	0.303	0.064	0.271	0.350	0.775	1.102	1.485	1.472

[a] Keylwerth (1951)

wood show good correlation which deviate only by 7 and 13 %, respectively, from the literature data (Hering et al. 2012; Stamer and Sieglerschmidt 1933).

The corrected E based on UT-SC method always show lower values than the UT-SU. In several cases, these values show a better agreement with the mechanical results and literature data (e.g. $\Delta E_{\mathrm{T}} = 6\,\%$ of UT-SC(TT) walnut wood). In another case, however, the values are still overestimated (e.g. $\Delta E_{\mathrm{L}} = 33\,\%$ of UT-SC(LD) walnut wood). In this direction, the UT-FSI provides a better estimation of E ($\Delta E_{\mathrm{L}} = 2\,\%$ of UT-FSI walnut wood). When the UT-SC shows a closer agreement, for example in E_{T} of walnut and cherry wood and E_{L} of beech wood, the E of the UT-FSI is underestimated ($\Delta E_{\mathrm{T}} = -42\,\%$ of UT-FSI walnut wood). In some cases, however, the UT-SC still shows a closer agreement even though the UT-FSI result is not underestimated ($\Delta E_{\mathrm{R}} = 6\,\%$ of UT-FSI beech wood and $\Delta E_{\mathrm{R}} = 7\,\%$ of UT-SC(LD^{c}) beech wood).

The correction factors presented in Table 4 are the compensation values from the overestimated E obtained by UT-SU method. Therefore, the best estimation of E with the simplified-corrected (UT-SC) method can only be obtained when correction factor shows a good agreement with the ratio of UT-SU E and the reference E (average of CT and TT) (SU-ref ratio). As given in Table 5 for both walnut and cherry wood, the closest agreement of k between the SU-ref ratio and the UT-SC is obtained for correction factor in T direction (k_{T}). Hence, E_{T} of UT-SC provide the best estimation (Fig. 5).

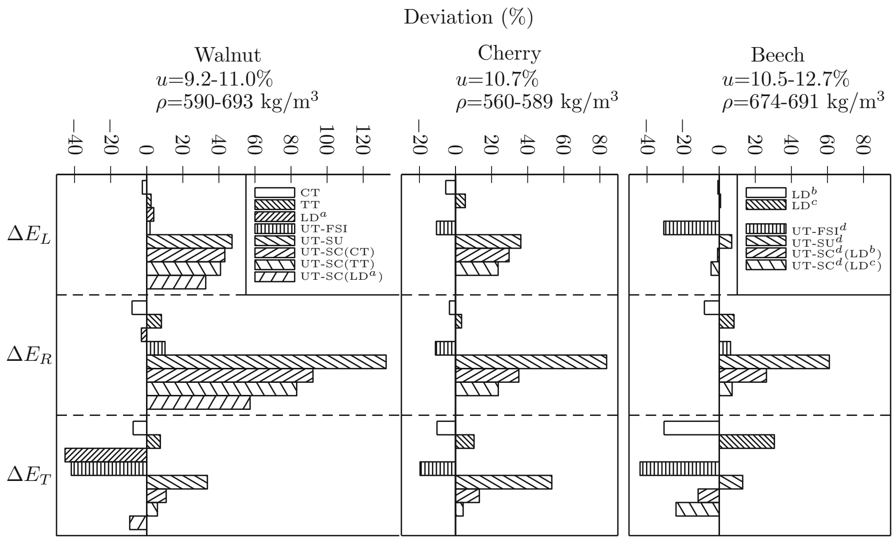

Fig. 5 Deviation of Young's modulus (ΔE_{L}, ΔE_{R}, and ΔE_{T}) of walnut (*Juglans regia* L.) ($u = 9.2$–11.0 %, $\rho = 590$–693 kg/m^3) and cherry (*Prunus avium* L.) ($u = 10.7\,\%$, $\rho = 560$–589 kg/m^3) wood measured with various methods: compression test (CT), tension test (TT), literature data (LD) ([a]Keylwerth (1951)), full stiffness inversion of ultrasonic test (UT-FSI), simplified-uncorrected (UT-SU), simplified corrected by compression test's Poisson's ratios (UT-SC(CT)), Simplified corrected by tension test's Poisson's ratios (UT-SC(TT)) and Simplified corrected by literature data's Poisson's ratios (UT-SC(LD)) and Beech (*Fagus sylvatica* L.) wood ($u = 10.5$–12.7 %, $\rho = 674$–691 kg/m^3) from ultrasonic test (UT) ([d]Ozyhar et al. (2013)) in combination with literature data (LD) ([b]Hering et al. (2012), [c]Stamer and Sieglerschmidt (1933))

Table 5 Correction factors variation of walnut (*Juglans regia* L.) and cherry (*Prunus avium* L.) at 20 °C/ RH 65 %

	Walnut			Cherry		
	k_L	k_R	k_T	k_L	k_R	k_T
Ratio between UT-SU E and the reference E						
SU-ref ratio	1.473	2.327	1.336	1.362	1.837	1.534
Correction factors						
UT-SC (CT)	1.028	1.211	1.206	1.050	1.360	1.355
UT-SC (TT)	1.046	1.271	1.261	1.102	1.485	1.472
UT-SC (LD)	1.111	1.479	1.475			
CoV (%)	4.1	10.7	10.8	3.4	6.2	5.8

Furthermore, when observing the correction factors obtained from mechanical and literature data, a variance of 4.1–10.7 % is considered (Table 5). These variations are considered to be relatively low. Thus, the assumption that the variation of v among different specimens of the same species introduce a negligible impact on the E calculations can be validated.

Table 4 also presents the results of G tested using the Arcan test (AT) and the UT-FSI data for both woods in all six plane directions. The relative difference between both methods using G is relatively low. A high deviation is only observed for G of walnut wood in the LR plane which deviates by 36 % compared to the AT and literature data (LD) (Fig. 6).

The moisture content (u) of the tested walnut and cherry wood is realised to be relatively low (9.2–10.7 % in a normal climate 20 °C, RH 65 %). It is unusual since it has been commonly known that the u of wood stored under normal conditions is approximately 12 %. It is suspected due to the high level of extractive content of the tested wood which disrupts the moisture sorption.

Even though due to the matrix symmetry the relations $\frac{v_{LR}}{E_R} = \frac{v_{RL}}{E_L}$, $\frac{v_{LT}}{E_T} = \frac{v_{TL}}{E_L}$ and $\frac{v_{TR}}{E_R} = \frac{v_{RT}}{E_T}$ are predefined, the mechanical tests as given in Tables 3 and 4 can measure three Young's moduli and six Poisson's ratios independently. Hence, twelve independent elastic parameters including three shear moduli are obtained. This leads to the asymmetry of $[C]$ and $[S]$ matrix. By calculating the $[C]$ or the $[S]$, taking the average value from every corresponding off-diagonal term and continued by a backward calculation to re-obtain the elastic parameters, the mechanical test results can be forced to be symmetric (Table 6). The influence of the matrix asymmetry was relatively high on v (33.12 % for v_{RT}). However, its influence on E and the correction factor (k) was very low (maximum of 1.26 % for E and 1.28 % for k) (Tables 6 and 7). Therefore, it was determined that the mechanical test results were directly used without any further adjustment.

Conclusion and outlook

The change of moisture influences the elastic parameters of walnut and cherry wood. A high moisture level (u) leads to lower Young's (E) and shear moduli (G). Based on the mechanical test results of walnut wood, E_L were on average decreased

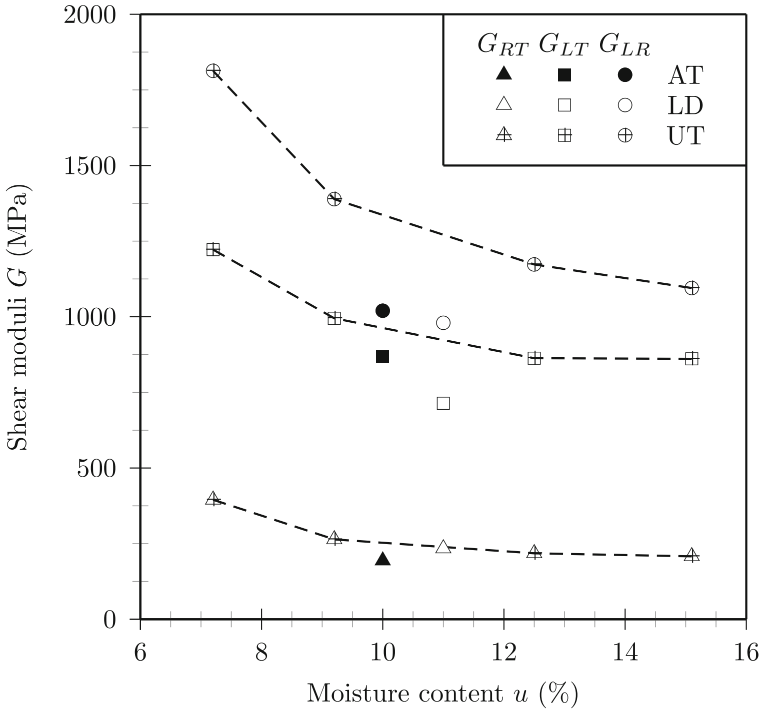

Fig. 6 Moisture-dependent shear moduli of walnut (*Juglans regia* L.) wood obtained with three different methods: Arcan test (AT), literature data (LD), ultrasonic test (UT)

by 679 MPa in compression and 423 MPa in tension for every per cent increase in u. For the Poisson's ratios (ν), however, no clear trend of moisture influence can be observed.

Besides mechanical test, the ultrasound method is also capable of estimating E and G with sufficient accuracy. In fact, in the case of accessing cultural heritage, ultrasound method is preferable to mechanical test. The flexibility of the method in terms of specimen dimensions and the capability of accessing without destroying the specimens make it highly favourable. For large objects or objects with complex geometry, little specimens (±10 mm) can be cut out, which is still much better than large specimens required for mechanical test (±100 mm)

However, the natural wood inhomogeneities and the ill-posed problem of the stiffness matrix inversion during the ultrasound data evaluation often lead to uncertain propagation between the wave velocities and the elastic parameter. While for E and G the influence is negligible, it is clearly pronounced for ν. ν, although mainly influenced by the quasi-shear wave velocities, are also affected by uncertainties in the longitudinal wave velocities. As a result, some ν from the UT-FSI method show strong deviations with respect to the reference mechanical test (e.g. ν_{TL}), whereas for other values, a better agreement is observed (e.g. ν_{RT}).

The UT-FSI method requires the measurement of multiple specimen types (type I, II, III and IV, Fig. 3). The simplified method of E as equivalent to the diagonal

Table 6 Influence of [*C*] symmetry to the elastic parameters of walnut (*Juglans regia* L.)

Experimental data	u (%)	ρ (kg/m^3)	Elasticity moduli (MPa)			Shear moduli (MPa)			Poisson's ratio (–)					
Walnut			E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}
Original results (CT+AT)	9.2–10.0	561–693	10721	1149	1083	194	868	1020	0.035	0.290	0.032	0.193	0.297	0.524
[*C*] symmetry	9.2–10.0	561–693	10714	1135	1070	194	868	1020	0.033	0.327	0.025	0.249	0.395	0.419
CoV (%)			0.06	1.26	1.22	0	0	0	4.23	9.15	22.18	29.23	33.12	19.98

Table 7 Influence of [*C*] symmetry to the correction factor (*k*) of Walnut (*Juglans regia* L.)

Experimental data	u (%)	ρ (kg/m^3)	Correction factors (–)		
Walnut			k_L	k_R	k_T
Original results (CT+AT)	9.2–10.0	561–693	1.028	1.210	1.205
[*C*] symmetry	9.2–10.0	561–693	1.029	1.226	1.220
CoV (%)			0.06	1.28	1.23

terms of the stiffness matrix requires only the ultrasound measurement of specimens type I, which greatly improves the time efficiency of the test by reducing the number of samples to one-fourth. However, it leads to an overestimation, for example for walnut wood with u 9.2–11.0 %, the overestimation $\Delta E_L = 47\,\%$, $\Delta E_R = 133\,\%$ and $\Delta E_R = 34\,\%$ (Fig. 5). The exact correction factors for the simplified method based on nominal v obtained from mechanical tests or literature can alleviate the overcompensation. In most cases, it gave better agreement with the mechanical test results (e.g. ΔE_T of walnut and cherry wood; ΔE_L and ΔE_R of beech wood) (Fig. 5). In other exceptional cases (e.g. ΔE_L, ΔE_R of walnut and cherry wood), the UT-FSI although providing inaccurate Poisson's ratios still gave the best estimation (for walnut wood ΔE_L of UT-FSI $= 2\,\%$ while ΔE_L of UT-SC(LD) $= 32\,\%$). This trend is also observed in the ultrasonic beech results from Ozyhar et al. (2013).

From the presented results, it is clearly shown that the chosen data evaluation method influenced the calculated Young's moduli. In some cases, however, E were still overestimated even after the correction. It is expected due to the propagation of uncertainties from the ultrasound test. Therefore, further work to clarify the reason of the differences between methods will be carried out. For the moment, it seems clear that before applying the ultrasound method to a new wood species, a validation study with respect to mechanical tests should be performed to quantify uncertainties and derive the optimum correction factors.

An extended study is going on to continue this topic. Statistical analysis is performed to investigate the propagation of ultrasound measurement. The objective is to identify the steps, which introduce most uncertainty in the data evaluation, particularly for UT-FSI method. Moreover, several parameters in the ultrasound test (e.g. the influence of geometry, tested point, fibre angle (for specimen type II, III and IV), wavelength and frequency) will be studied further. Furthermore, the ability of the ultrasound method to estimate at least some values of the Poisson's ratio set will be quantitatively discussed. The final goal is to provide an optimised set of equations, which obtains from a reduced ultrasound data set the closest possible agreement with mechanical tests. This established ultrasonic method will be applied in the future to a real wooden historical object to investigate its stiffness properties, which will become the basis of the conservation.

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