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Determination of the elastic constants of thermally modified beech by ultrasound and static tests coupled with 3D digital image correlation

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ABSTRACT

Fagus sylvatica L. (European beech) is one of the most widespread hardwood species growing in Europe, which is currently undergoing of in-depth research for the development of engineering products to use its excellent mechanical properties. As its natural durability is low, heat treatment is investigated as a means to enhance its biological durability, as well as its dimensional stability. Reliable models with a full material description including the elastic constants are necessary for material and structural modelling and design. The aim of this work was to comprehensively characterise European beech subjected to three different intensities of heat treatments. It is described as an orthotropic material by determining all of the independent elastic constants: three Young's moduli, three shear moduli and six Poisson's ratios. Both static (by compression) and dynamic (by ultrasound) experimental methods were considered for comparison purposes. The compression tests were coupled with 3D digital image correlation (DIC) technique to perform optical full-field analyses of strains. Characterization of untreated beech was also carried out and compared with literature values. The usual assumption of symmetry of the compliance matrix was verified. The results confirmed that heat treatment influenced the elastic behaviour of the material. However, the impact of the treatment differed among the elastic components, with non-uniform trends with the intensity of the heat treatments.

1. Introduction

Fagus sylvatica L. (European beech) is one of the most important and widespread hardwood species growing in Europe. There is a very high and steadily increasing share of this wood in European forests due mainly to forest policies and the progressing climate change [1]. Currently, beech is primarily used in the furniture industry. However, there is active research on the development of engineering products from beech for the construction industry taking into account the high mechanical properties of this species [1]. Even so, beech shows high shrinkage and low natural durability, so use in outdoor environments without protective treatments are not envisioned.

In this sense, heat treatment is considered one of the most effective preservative methods used to enhance mainly biological durability and dimensional stability of wood [e.g. [2–4]] and an established alternative to other treatments that may be harmful to the environment. A significant disadvantage is, however, a reduction in fracture toughness and strength [e.g. [5–7]], which can limit the range of structural applications, with the most common uses of thermally-treated wood as cladding, decking, garden furniture, and interior joinery. A better understanding of the effect of thermal treatment on mechanical behaviour could open new markets for timber construction. For example, research has been carried out into the use of thermally modified European beech in load bearing members for industrial buildings or noise protection barrier systems for roads [7,8]. Given the large resource of European beech, thermal treatment could allow it to be used for the development of new value-added products for outdoor applications, as an alternative to tropical hardwoods or impregnated softwoods.

If heat-treated European beech is to be used as a structural material, it will be necessary to carry out accurate structural analysis and modelling of its behaviour. Alongside strength parameters, the elastic constants which characterize its deformation under load are vital to such

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models, and so their determination is of considerable interest.

Wood is anisotropic, and is usually considered for engineering purposes as an orthotropic material, defined by its properties in three directions: longitudinal (L), radial (R), and tangential (T) [9,10]. Consequently, twelve elastic engineering parameters are required for a complete elasto-mechanical characterization in any computational model: three Young's moduli (E_L, E_R, E_T), three shear moduli (G_{LR}, G_{LT}, G_{RT}), and six Poisson's ratios (ν_{LR}, ν_{RL}, ν_{LT}, ν_{TL}, ν_{RT}, and ν_{TR}). These parameters can be reduced to nine when symmetry conditions in the stiffness matrix are applied. A theorical background of orthotropic elasticity in wood can be found in Bodig and Jayne [11].

The elastic characterization in wood involves therefore a great experimental effort, especially due to the need of several specimens oriented along the different orthotropic directions when commonly experimental testing methods are applied. Nonetheless, experimental work on the elastic behaviour of different species has been performed by numerous researchers.

Classical experimental methods for wood characterization are mechanical tests following compression or tension configurations. In them, displacement or strains used to be recorded by mechanical or electrical measurement systems (e.g. strain gauges, inductive strain devices, extensometers) [e.g. [12,13]]. However, recent development of full-field optical measurement techniques such as digital image correlation (DIC), grid/moiré method, speckle and moiré interferometry or shearography, have enabled novel mechanical tests for material characterization. Particularly 2D and 3D optical measurements systems based in DIC are being increasingly used in recent studies for the the determination of the elastic constants in wood [e.g. [14,15]]. This is a non-contact technique which shows clear advantages in comparison with conventional techniques: it is entirely non-intrusive, so does not influence the specimen during testing; and it measures accurate deformations over the whole visible surface of the specimen in three dimensions. The latter is crucial for heterogeneous materials and leads to more robust results considering the strong variability inherent to wood. In addition, these techniques have allowed the development of testing procedures to reduce the number of necessary specimens [16].

Another remarkable experimental method which has drawn increasing attention in elastic characterization of wood is ultrasonic testing. It is a very efficient non-destructive technique which allows fast measurements in small-size specimens, advantages highlighted by [17–19]. The development of fast measurement techniques is important to increase the number of available data for wood. In many studies, ultrasonic testing was limited to the determination of the elastic moduli. However, it is also possible to obtain all the elastic constants using specimens with the grain angles oriented to the different planes of ortotropy [e.g. [18,20,21]].

There is comprehensive research on the mechanical characterization of elastic properties in untreated European beech by different experimental techniques [e.g. [13,18,21–32]]. On the contrary, only few studies have dealt so far with the investigation of the influence of heat treatments on the elastic constants for this species. Widmann et al. [7] reported experimental data on different mechanical properties in order to benchmark the thermally treated beech at around 180–190 °C to the European EN 338 strength class system for structural timber. Regarding the elasticity constants, E_0 and E_{90} were derived from tension parallel to grain and compression perpendicular to grain tests respectively. Sebera et al. [33] provided the E_L values of thermally treated beech subjected to 180 °C and 200 °C obtained from compression tests. Fajdiga et al. [34] and Straže et al. [35] determined also from compression tests the E_L and E_T moduli of heat treated beech at 210 °C. Wetzig et al. [36] reported the three Young's moduli and two Poisson ratios (ν_{LR} and ν_{LT}) of heat-treated beech subjected to two different treatment atmostpheres from static and ultrasound tests, and the three shear moduli by ultrasound alone. Loidl et al. [37] carried out initial work on similar material to that used in the present study to derive the three Young and shear moduli (but not the Poisson's ratios) by means of the resonant beam technique method. However, to the authors' best knowledge, there are no research which provide a complete data set of the twelve elastic constants of thermally treated European beech: some of the Poisson's ratios have not been derived by any method; for other constants, namely the shear moduli, there are no reported values obtained from common static tests, taking into account that test method may affect the results.

The main objective of the present study is to provide a complete data set of elastic engineering constants (the three Young's moduli, the three shear moduli and the six Poisson's ratios) for untreated and thermally treated European beech (*Fagus sylvatica* L.) modified at three different heating temperatures. Dynamic and static measurement techniques were compared to this aim: ultrasound and compression tests. In the latter, optical full-field analysis of strains was performed by means of a 3D non-contact optical device based on the digital image correlation (DIC) method. In the process, the usual assumption of symmetry of the compliance matrix was verified. The determined elastic constants provide fundamental input parameters for reliable models with a full material description necessary for material and structural modelling and design.

2. Theoretical background

2.1. The compliance matrix [S]: Mechanical characterization

Derived from Voigt's [38] crystal elasticity theory, wood is regarded as a rhombic crystalline material with linear elastic mechanical properties which differ according to three orthotropic axes (L, R, T) orthogonal to each other. This elastic model of the material can be expressed by the generalized Hooke's law which considers a linear relationship between stresses and strains in the form (Eq. (1)):

$$[\varepsilon_{kl}] = [S_{ijkl}][\sigma_{ij}] \tag{1}$$

where $[\varepsilon]$ corresponds to the strain vector defined by elongations, ε, and shear strains, γ; $[\sigma]$ denotes the stress vector formed by the normal stresses, σ, and shear stresses, τ; and $[S_{ijkl}]$ is the compliance matrix composed of twelve compliance components, s_{ij}, which are function of the so-called elastic engineering parameters, also referred as elastic constants, expressed in Eq. (2). These parameters can be determined by mechanical tests as will be described in section 3.3.

$$\begin{pmatrix} \varepsilon_L \\ \varepsilon_R \\ \varepsilon_T \\ \gamma_{RT} \\ \gamma_{TL} \\ \gamma_{LR} \end{pmatrix} = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{RL}}{E_R} & -\frac{\nu_{TL}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{LR}}{E_L} & \frac{1}{E_R} & -\frac{\nu_{TR}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{LT}}{E_L} & -\frac{\nu_{RT}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{TL}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} \begin{pmatrix} \sigma_L \\ \sigma_R \\ \sigma_T \\ \tau_{RT} \\ \tau_{TL} \\ \tau_{LR} \end{pmatrix} \tag{2}$$

In the previous expression, the twelve compliance components can be reduced to nine since symmetry condition may be satisfied according to the elasticity theory, where elastic deformation is non-dissipative [11]. In this regard, the off-diagonal terms are related as follows (Eq. (3)):

$$-\frac{\nu_{RL}}{E_R} = -\frac{\nu_{LR}}{E_L}; -\frac{\nu_{TL}}{E_T} = -\frac{\nu_{LT}}{E_L}; -\frac{\nu_{TR}}{E_T} = -\frac{\nu_{RT}}{E_R} \tag{3}$$

Accordingly, three Young's moduli, three shear moduli and just three Poisson's ratios instead of six are the independent elastic constans needed to build the compliance matrix of the material. Deeper fundamentals on the elastic constants in wood can be seen in [11,39].

2.2. The stiffness matrix [C]: Ultrasound characterization

The stiffness matrix and the compliance matrix have an inverse relation by the form $[C_{ijkl}]^{-1} = [S_{ijkl}]$. Accordingly, the material elastic model can be expressed by the generalized Hooke's law as (Eq. (4)):

$$[\sigma_{ij}] = [C_{ijkl}][\varepsilon_{kl}] \tag{4}$$

Assuming symmetry of the non-diagonal terms, the stiffness matrix is composed by nine independent terms (Eq. (5)) which can be determined by ultrasound tests.

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{5}$$

The relationship between elasticity and wave propagation theories has the origin in the Christoffel equation (Eq. (6)):

$$(C_{iklm}n_k n_1 - \rho V^2 \delta_{im})u_m = 0 \tag{6}$$

This equation represents a set of three homogeneous first degree equations at u_1, u_2 and u_3. n denotes the components of the wave vector; δ_{im} is the unit tensor or the Kronecker delta which becomes 1 when $i = m$, and 0 if $i \neq m$. The term $C_{iklm}n_k n_1$ can be simplified by λ_{im}, known as Christoffel tensor.

By solving the corresponding equations and taking into account the displacement vectors of the particles or polarization (see [40] for more details), it is possible to determine the diagonal terms of the stiffness matrix [C] according to [17]:

$$C_{LL} = C_{11} = \rho V_{LL}^2$$

$$C_{RR} = C_{22} = \rho V_{RR}^2$$

$$C_{TT} = C_{33} = \rho V_{TT}^2$$

$$C_{RT} = C_{44} = \rho (V_{RT}^2 + V_{TR}^2)/2$$

$$C_{LT} = C_{55} = \rho (V_{LT}^2 + V_{TL}^2)/2$$

$$C_{LR} = C_{66} = \rho (V_{LR}^2 + V_{RL}^2)/2 \tag{7}$$

being ρ the material density (kg/m^3) and V the wave velocity (m/s), with the first subscript denoting the direction of propagation and the second one the direction of polarization.

The off-diagonal terms of the stiffness matrix are obtained as follows:

$$(C_{12} + C_{66})n_1 n_2 = \left[(C_{11}n_1^2 + C_{66}n_2^2 - \rho V_\alpha^2)(C_{66}n_1^2 + C_{22}n_2^2 - \rho V_\alpha^2) \right]^{1/2}$$

$$(C_{23} + C_{44})n_2 n_3 = \left[(C_{22}n_2^2 + C_{44}n_3^2 - \rho V_\alpha^2)(C_{44}n_2^2 + C_{33}n_3^2 - \rho V_\alpha^2) \right]^{1/2}$$

$$(C_{13} + C_{55})n_1 n_3 = \left[(C_{11}n_1^2 + C_{55}n_3^2 - \rho V_\alpha^2)(C_{55}n_1^2 + C_{33}n_3^2 - \rho V_\alpha^2) \right]^{1/2} \tag{8}$$

where α is the wave propagation angle outside the symmetry axes (45°); $n_1 = \cos\alpha$, $n_2 = \sin\alpha$, $n_3 = 0$ when α is taken in relation to axis 1 (plane 12); $n_1 = \cos\alpha$, $n_3 = \sin\alpha$ and $n_2 = 0$ when α is taken in relation to axis 1 (plane 13); and $n_2 = \cos\alpha$, $n_3 = \sin\alpha$ and $n_1 = 0$ when α is taken in relation to axis 2 (plane 23).

When all the terms of the stiffness matrix [C] are determined, the calculation of the compliance matrix [S] can be performed by the inverse matrix $[C]^{-1}$ and therefore obtain the whole set of elastic constants. This procedure is known as full-stiffness-inversion method. It requires specimens oriented at different angles with respect to the man directions L, R and T (see details in section 3.2). There are other simplified evaluation techniques that only require specimens oriented along the main directions thus increasing the time efficiency of the tests, such as the simplified-uncorrected technique in Bachtiar [41]. According to it, the off-diagonal terms of [C] are considered zero (and therefore also the Poisson's ratios), but it overestimates the values of Young's moduli [21]. In Bachtiar [41] the alternative simplified-corrected technique is also proposed to correct the Young's moduli by means of a k-factor expressed as a function of the Poisson's ratios, which could be taken from the literature. In the present study, the full-stiffness-inversion method was applied.

3. Materials and methods

3.1. Material

European beech (*Fagus sylvatica* L.) was provided by Mitteramskogler GmbH, Austria. The pre-dried (to approximately 8–12% MC) boards were modified at heating temperatures of 180° (Mezzo, hereafter referred as T1), 200° (Forte, referred as T2) and 230° (Forte exterior, referred as T3) in a dry three-stage heat-treatment process: phase 1) a fast increase of oven temperature is performed followed by a gradual increase using heat and steam until almost zero moisture content in wood is reached. Steam acts as protection gas, keeps process slightly pressurized and replaces oxygen inside chamber; phase 2) actual thermal modification is carried out with an increase of temperature to wanted level which is kept constant during some hours; phase 3) cooling and re-conditioning stage to bring moisture content of wood back to the desired level. More details on the process data are commercially sensitive and thus cannot be published. Both treated and untreated (control) specimens were obtained from the same "twin" board (one half thermally treated and the other half untreated) in order to reduce variability.

Small-clear specimens were prepared for each treatment batch (Fig. 1) oriented in the different anatomical directions as will be specified in next subsections. Prior to testing, the specimens were conditioned at 20 °C and 65% relative humidity until equilibrium moisture content was reached. Mean moisture contents of 11.6%, 6.2%, 4.3 and 4.1% were measured by T0, T1, T2 and T3 batches, respectively, of the specimens destined to ultrasound tests, and analogously 11.4%, 6.3%, 4.3 and 4.2% for the groups of compression tests. Densities were also measured from the conditioned specimens. The mean densities for the different batches of ultrasound tests were: 633 kg/m^3 (T0), 679 kg/m^3 (T1), 599 kg/m^3 (T2) and 648 kg/m^3 (T3). The mean densities of the specimens used in the compression tests were: 677 kg/m^3 (T0), 694 kg/m^3 (T1), 624 kg/m^3 (T2) and 640 kg/m^3 (T3). The difference in mean density is thought to be consistent with random sampling rather than an effect of the treatment.

3.2. Ultrasound tests

A series of five prismatic specimens following the orientations represented in Fig. 2 were required for ultrasound testing [20]. Specimens 1 and 2 of 20 × 30 × 70 mm^3 were oriented along the main axes to derive the diagonal terms of the stiffness matrix (only one of the two specimens

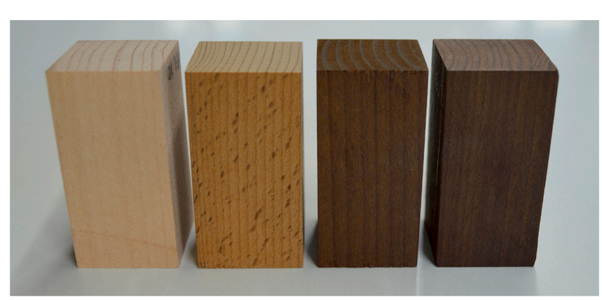

Fig. 1. Control and thermally treated beech samples. From left to right: untreated, Mezzo, Forte and Forte exterior.

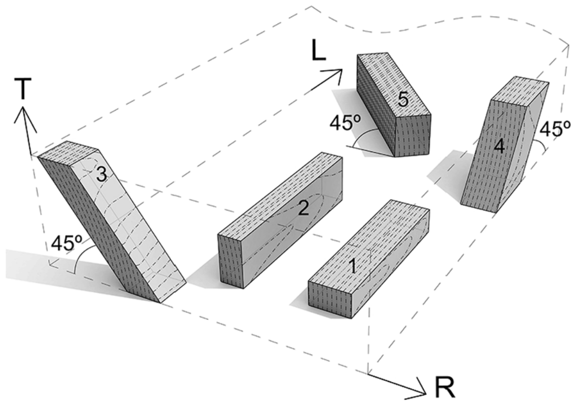

Fig. 2. Specimen orientations for ultrasound tests.

would be strictly necessary). Specimens 3, 4 and 5, with 30 × 30 mm^2 cross-section and length adapted to the board thickness (45 mm), were oriented 45° to the planes RT, LT and LR, so the remaining components of the stiffness matrix could be obtained. The 45° angle was chosen taking into account studies carried out by Bucur and Archer (1984) [18], which concluded that this angle produced the smallest relative error when finding the C_{13} term of the stiffness matrix (see section 2.2). Eight specimens per orientation in every batch of treatments (and untreated wood) were tested.

An Olympus Epoch 600 portable device (Fig. 3) equipped with longitudinal and transverse Panametrics-NDT Olympus plane transducers of 1 MHz nominal frequency and 15 mm external diameter was used.

The flight time of the waves propagating on each specimen was recorded. The wave velocity, V, for each specimen was derived from the measured time and the specimen length. The elastic constants were consequently obtained considering the wave velocity and the material density, ρ, according to the description specified in section 2.2.

When longitudinal transducers are positioned on the specimen faces parallel to the main axes L, R and T, a longitudinal wave is released which propagate and polarize directionally along such axes and consequently V_{LL}, V_{RR} and V_{TT} velocities can be obtained. Similarly, by placing the transverse transducers on the corresponding faces, the wave propagation takes place along the major axes and polarize along the perpendicular one. In this way V_{LR}, V_{RL}, V_{LT}, V_{LT}, V_{RT} and V_{TR} velocities are derived. From specimens oriented at 45°, V_{α} can be obtained for each plane by means of transverse transducers [18]).

Wavelengths (λ) of 5 mm in the longitudinal direction, 2.5 mm in the radial direction, and 1.8 mm in the tangential direction were selected, resulting in a minimum ratio of path length per wavelength (L/λ) of 18 (L values somewhat greater than λ are recommended to approximate to the hypothesis of infinite wave propagation mode [17,42]).

Both transducers had an outer diameter of 18 mm, which fitted to the specimen's dimensions. To improve coupling as much as possible and keep constant pressure throughout measuring, pure starch glucose was used as couplant gel between both transducers and the specimens.

3.3. Compression tests coupled with digital image correlation technique

Small clear prismatic specimens were also subjected to mechanical compression tests in order to get all the elastic constants of the untreated and heat-treated beech.

A 3D stereovison system based on the digital image correlation principle (DIC), ARAMIS® 3D [43], was used for strain measurements. Its coupling to universal testing machine is easy since it is a white-light technique and does not need any specific equipment such anti-vibration tables or laser, required by other interferometric measurement devices.

The system comprises two CCD cameras of 5 Megapixels resolution with 35-mm lens, positioned facing the specimen to be tested (Fig. 4). A stereovision angle of 25° between both cameras was set. A reference field of view of 65 mm × 55 mm was selected. The base distance between cameras was adjusted to 110 mm, making it match the centre of the especimen and the centre of the images. It corresponded to a working distance of 340 mm. The depth of field was adjusted to 46 mm to image each pair of orthogonal adjacent faces of the prismatic specimen. Two light sources were adjusted in order to guarantee an even illumination of the specimen and to avoid local over-exposure.

The DIC system was calibrated before testing using a calibration panel with a dimension similar to that of the region of interest. In the procedure, some images are taken successively by translating and rotating the calibration panel with respect to the optical device. In this way, a measurement volume is defined in which the specimen must fit.

The method requires a textured pattern (speckle pattern) created onto the specimen surface to be analysed. A thin coating of matt white aerosol spray paint was applied, followed by a spot distribution of airbrush black paint, which gave a suitable contrast.

Once the device and specimens were prepared, images of the surface of interest were recorded during testing. These images are mapped by correlation of facets formed by a group of pixels, within which an independent measurement of the displacement is calculated. The strain field is finally obtained by analyzing the geometrical deformation produced in the images. Therefore, it is important for the accuracy of the measurements, to decide an appropriate facet size. In the present work, a facet size of 15 × 15 pixel^2 was considered to offer a good compromise with the region of interest size and the pattern quality of the specimen. In order to enhance spatial resolution, a facet step size of 13 × 13 pixel^2 was chosen for an overlap of 2 pixels. The in-plane displacements were then numerically differentiated on a base computation size of 5 subsets.

The compression tests were carried out using a universal testing machine. The specimens were placed in such a way that the deformation field at two adjacent faces could be visible by the optical equipment and measured simultaneously. The specimens were loaded under displacement control between 0.2 and 0.4 mm/min. Synchronized stereo images of the patterned surface with the different loading stages were recorded

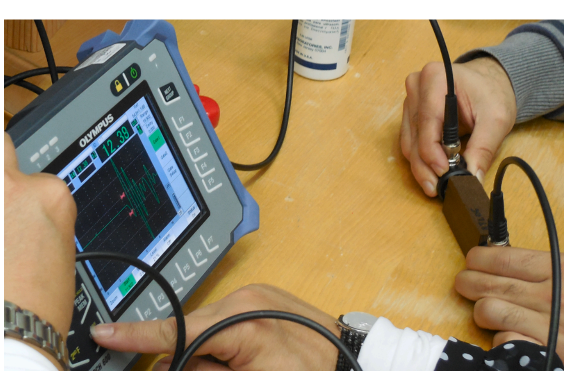

Fig. 3. Ultrasound testing device.

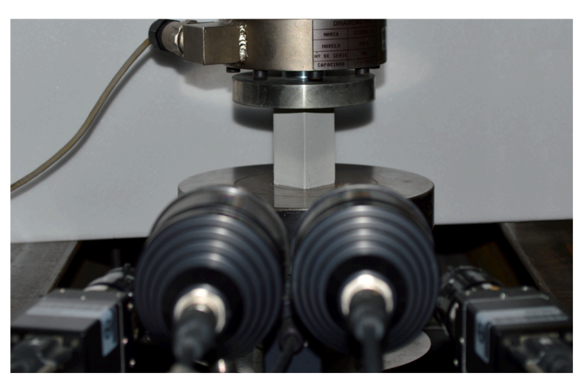

Fig. 4. Compression set-up coupled with ARAMIS® 3D.

every second. Most of the test were kept in the elastic range in order to derive all of the possible elastic constants from the same specimen. Some tests were continuted to failure.

The Young's moduli were processed afterwards as the ratio of the stress (σ_i) to the respective strain (ε_i) in the load direction (Eq. (10)). It corresponds to the slope of the elastic region in the stress–strain curve, and was evaluated as the result which provides the maximum coefficient of determination, R^2.

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i}, i \in R, L, T \tag{10}$$

The Poisson's ratios were determined by the relationship between two strain components optically recorded: the active strain component (ε_i) in the load direction, and the passive strain component (ε_j) normal to the load direction (Eq. (11)) in each of the two visible faces of the specimen by the optical device.

$$\nu_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}, \; i,j \in R, L, T \; and \; i \neq j \tag{11}$$

Accordingly, three different compression set-ups were followed:

- Compression tests parallel to the grain as specified in ISO 13061-17:2017 [44] on specimens of 30 × 30 mm^2 cross-section and 60 mm length, from which E_L, ν_{LR} and ν_{LT} were derived.
- Two compression tests perpendicular to the grain by applying the load along the radial and tangential directions respectively following ISO 13061–5:2020 [45]. Prismatic specimens of 30 × 60 mm^2 of compression surface and 30 mm height were used in these cases. E_R, ν_{RL} and ν_{RT} (from radial test) and E_T, ν_{TL} and ν_{TR} (from tangential test) were calculated.

Eight specimens in every batch of treatments (and untreated beech) were tested to derive the Young's moduli and Poisson's ratios.

In order to determine the three shear moduli, three 45° off-axis compression tests relative to every of the three orthotropic directions were executed. To this aim, batches consisting of eight to thirteen prismatic specimens with the grain oriented 45° to the load direction were tested. Specimens of 30 × 30 × 60 mm^3 were used for LR and RT planes and 30 × 30 × 38 mm^3 for the LT plane due to the limitation thinckness of the board. Vertical strain in the load direction, ε_V, and horizontal strain in the transverse direction, ε_H, were recorded from the front face of the specimen visible by the optical device in every of the three configurations. The shear moduli G_{LR}, G_{LT} and G_{RT} were determined according to Eq. (12).

$$G_{LR} = \frac{\tau_{LR}}{\gamma_{LR}} = \frac{\sigma_V}{2(\varepsilon_H - \varepsilon_V)}; \quad G_{LT} = \frac{\tau_{LT}}{\gamma_{LT}} = \frac{\sigma_V}{2(\varepsilon_H - \varepsilon_V)}; \quad G_{RT} = \frac{\tau_{RT}}{\gamma_{RT}} = \frac{\sigma_V}{2(\varepsilon_H - \varepsilon_V)} \tag{12}$$

4. Results and discussion

4.1. Ultrasound parameters

Table 1 shows the ultrasonic wave velocities along different propagation and polarization directions from heat treated beech by the three treatments T1, T2 and T3 in comparison to the untreated beech wood (T0). The coefficient of variation (CoV) from all the specimens with each treatment is included in brackets.

As can be seen, the V_{ii} differ in each of the orthotropic directions. For the untreated material, the measured mean value of V_{LL} was double the mean V_{RR}, which is in agreement with the results obtained from beech by Ozyhar et al. [21]. This relation was similar in the case of heat-treated beech, with slightly higher mean V_{LL} value for the most severe heat treatments. The mean V_{TT} was approximately one third of the V_{LL} (1/4 was reported in Ozyhar et al. [21]).

Table 1
Mean values and coefficient of variations (percentage in brackets) for the wave propagation velocities in heat treated (T1, T2, T3) and untreated (T0) beech from ultrasound tests.

V [m/s]	T0	T1	T2	T3
$V_{11} \equiv V_{LL}$	4932 (2.0)	4986 (2.5)	5271 (3.9)	5339 (2.8)
$V_{22} \equiv V_{RR}$	2390 (1.8)	2448 (4.1)	2351 (6.5)	2334 (2.6)
$V_{33} \equiv V_{TT}$	1647 (2.0)	1840 (9.2)	1650 (5.7)	1671 (2.7)
$V_{44} \equiv V_{RT} \equiv V_{TR}$	905 (5.5)	913 (5.6)	884 (2.1)	905 (3.3)
$V_{55} \equiv V_{LT} \equiv V_{TL}$	1252 (5.0)	1391 (5.1)	1473 (3.7)	1336 (7.6)
$V_{66} \equiv V_{LR} \equiv V_{RL}$	1463 (11.0)	1627 (4.4)	1586 (4.4)	1630 (1.5)
$V_{12} \equiv V_{QLR}$	1836 (3.1)	1854 (3.1)	1821 (4.6)	1832 (1.8)
$V_{13} \equiv V_{QLT}$	1344 (2.2)	1490 (3.5)	1409 (4.7)	1374 (3.3)
$V_{23} \equiv V_{QTR}$	1036 (3.7)	989 (3.7)	940 (5.9)	1056 (6.0)

It is known that ultrasound velocity can be affected by factors such as moisture content, temperature or density, the latter being found one of the most dominant structural factors by some researchers. Increasing velocities trends with increasing densities were found in Bader et al. [23] from studies on different untreated hardwood species. Yilmaz and Aydin [46] did not report significant relation between V_{LL} and densities in heat treated oriental beech exposed to different temperatures in the process of determining the Young's modulus in longitudinal direction. In the present work, V_{LL} values were higher for heat-treated beech than for the untreated material. However, there is also no clear trend between wave velocities and heat treatment intensities, as there was neither trend between densities and treatment intensities. Even so, velocities from the different batches remained within a similar range.

Considering the average density of each group of treatment and the velocities specified in Table 1, the coefficients of the stiffness matrix were determined (Table 2).

4.2. Strain measurements

The 3D DIC system (ARAMIS® 3D) coupled with the compression tests for stereovision measurements provided 3D coordinates for each pair of images recorded during testing and then converted to relative displacements and strains. As mentioned above, the 3D system made it possible to measure two adjacent faces of the specimens simultaneously. This made it possible to check the uniformity of measurements on both sides and thus avoid possible defects in the testing or specimens manufacture. The measured working area was divided into a large number of facets (around 700 facets at the smallest faces and over 1500 at the largest) which provided corresponding strains. These strains at the working area data were finally averaged.

Figure 5 shows the results of strains on the two visible faces of a representative specimen subjected to a compression test with the load applied along the longitudinal direction. The time evolution of the strain during testing reveals an expected scenario, with increasing contraction

Table 2
Mean values and coefficient of variations (percentage in brackets) for the stiffness coefficients in heat treated (T1, T2, T3) and untreated (T0) beech from ultrasound tests.

C [MPa]	T0	T1	T2	T3
C_{11}	15,396 (3.6)	16,885 (6.3)	16,678 (8.9)	18,476 (4.1)
C_{22}	3617 (4.1)	4075 (10.1)	3329 (13.9)	3534 (6.5)
C_{33}	1672 (3.3)	2510 (17.5)	1627 (13.6)	1690 (6.3)
C_{44}	520 (11.2)	568 (11.4)	469 (6.2)	532 (8.1)
C_{55}	994 (10.2)	1315 (10.4)	1301 (5.2)	1164 (15.8)
C_{66}	1369 (22.3)	1801 (9.5)	1512 (10.4)	1721 (2.6)
C_{12}	1612 (19.1)	2253 (30.0)	1907 (27.5)	2029 (21.2)
C_{13}	1315 (12.9)	2098 (34.7)	1586 (21.9)	1439 (17.4)
C_{23}	1000 (13.7)	1819 (19.6)	1196 (10.8)	882 (21.8)

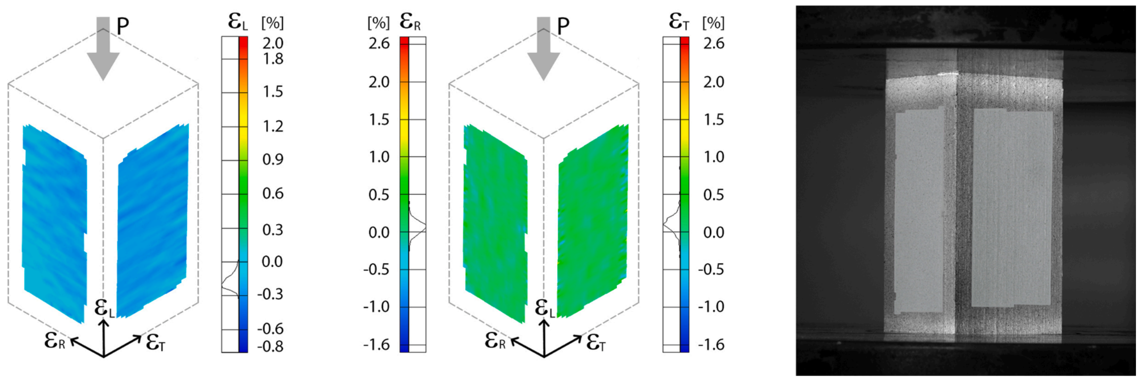

Fig. 5. Distribution of longitudinal (left), radial and tangential (middle) strains measured by DIC for a load of 22.9 kN in longitudinal direction. Measurement area marked on the specimen (right).

of the specimen in the axial direction (negative strain) and elongations in the transverse directions.

Similarly, Figs. 6 and 7 illustrate the three strain distributions on representative specimens subjected to compression perpendicular to the grain along the radial and tangential directions, respectively.

The horizontal and vertical strain distributions on a representative specimen subjected to oblique compression along the LR shear plane is exemplarity shown in Fig. 8.

As can be oberseved from Figs. 5-8, the strains were uniformally distributed on the specimens' faces. Possible boundary effects were avoided by restricting the strain measurements to the central area of the faces avoiding the edges. Even the small strains were reliably computed due to the subpixel accuracy of the DIC algorithm.

As indicated in the colourmaps and histograms in Figs. 5-8, there was a significant variation in strain across the surface of each specimen. Fig. 8 demonstrates that this variation is substantially due to real underlying variations in the strain in the material, rather than simply measurement noise, since it follows the orientation of the ring structure of the wood. In order to deal with measurement noise and material variation, it is valid to take the mean value of the strain on the face of the specimen.

A representative example of the curve-fitting process to determine the elastic constants determination is shown in Fig. 9.

In this example, an untreated beech specimen was loaded radially and mean strains on the RT surface were determined. As seen in Fig. 9 left, the E_R was derived from the slope of the elastic region in the stress–strain curve which provided the maximum R^2 (above 0.99). In Fig. 9 right, horizontal and vertical strains are plotted for the same data set. The values follow an acceptable narrow path. The slope of the linear regression corresponded to the Poisson's ratio ν_{RT} (0.73).

4.3. *Elastic constants*

Table 3 shows the mean values and the corresponding coefficient of variation of the different elastic constants that characterize untreated beech wood (T0) in comparison to modified beech at the three heat treatments (T1, T2 and T3) by ultrasound technique and compression tests.

The results grouped by Young's moduli, shear moduli and Poisson's ratios are discussed below.

4.4. *Young's moduli*

Figure 10 illustrates together the mean values and ranges of variation of Young's moduli obtained from the different heat treatments and the two testing methods for a better direct comparison.

In general, as can be deduced from the results, the stiffness of beech is not negatively affected by heat treatments. Sometimes the differences in elastic constants are not high, and in some cases the stiffness is increased in the heat-treated material compared to the untreated one. There is also no clear correlation among treatment intensities and values of elastic constants, although they all remain in the same range.

According to the Young's moduli results, the influence of heat treatments is more pronounced in the longitudinal direction than in radial or tangential. Overall, E_L values were higher for heat-treated beech than for untreated regardless of the measurement method, which support the general findings published for European heat-treated beech in [e.g. [7,33,34]].

In particular, there is an increase in the mean E_L values of approximately 12%, 23% and 20% between the untreated beech and T1, T2 and T3 treatments respectively, if we consider the static tests. These increases are somewhat lower than those reported by Sebera et al. [33] for beech treated in steam atmosphere at similar temperatures to T1 and T2 (increases of 15% and 38% respectively) from compression tests. Fajdiga et al. [34] reported an increase of 29% in E_L for heat-treated beech at 210 °C from compression tests. Meanwhile, the values reported by Wetzig et al. [36] for heat-treated beech in nitrogen atmosphere, also obtained from compression tests at normal environmental conditions,

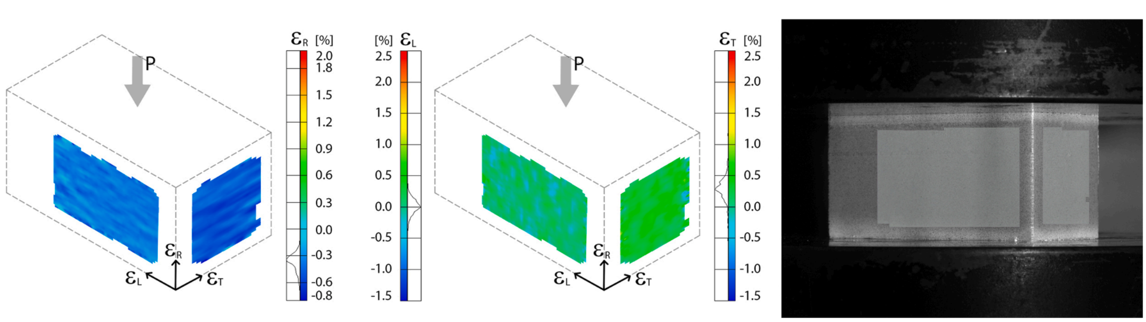

Fig. 6. Distribution of longitudinal (left), radial and tangential (middle) strains measured by DIC for a load of 14.5 kN in radial direction. Measurement area marked on the specimen (right).

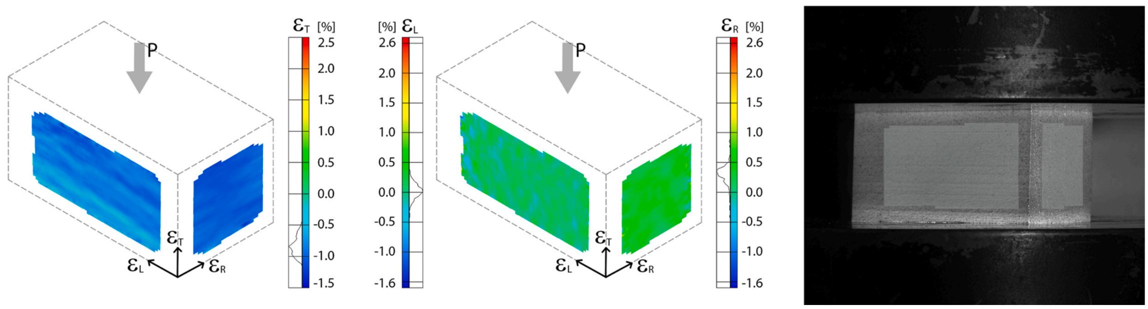

Fig. 7. Distribution of longitudinal (left), radial and tangential (middle) strains measured by DIC for a load of 12.8 kN in tangential direction. Measurement area marked on the specimen (right).

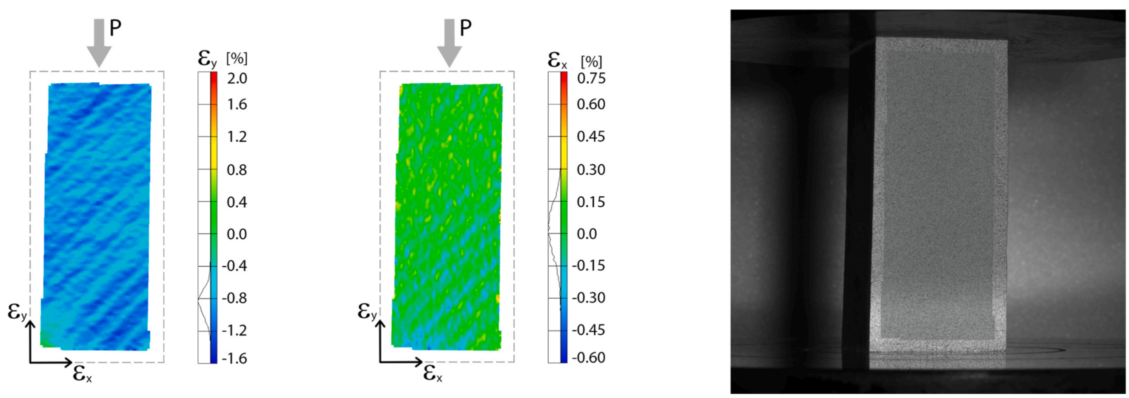

Fig. 8. Vertical (left) and horizontal (middle) strain distributions measured by DIC for a 45° LR loading configuration at 17.1 kN. Measurement area marked on the specimen (right).

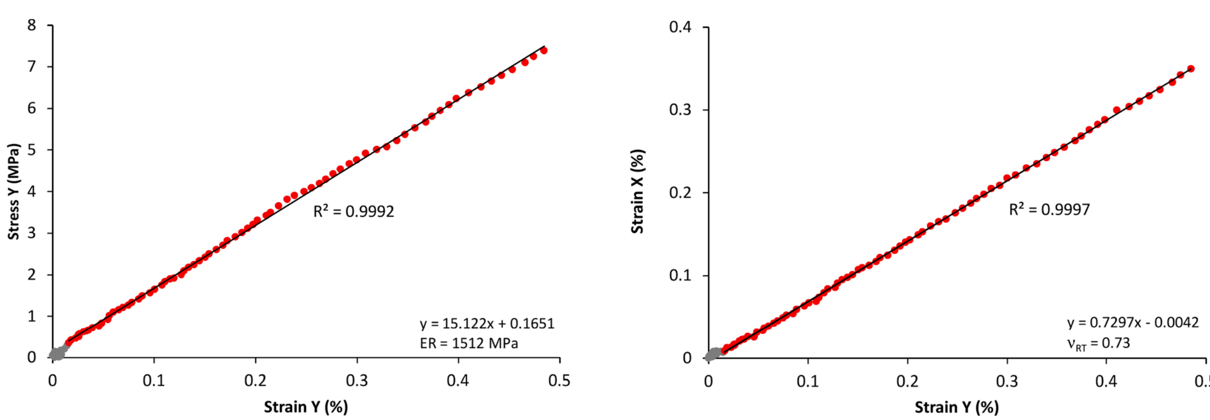

Fig. 9. Representative curves for T0 specimen loaded at radial direction: stress versus radial strain (left); horizontal (x) versus vertical (y) strains (right).

were rather similar to those of the reference material, and even reported lower values in the case of heat treated wood in steam atmosphere. This trend is similar to that obtained by Loidl et al. [37] using beech subjected to three treatments equal to those of the present work, where an increase in only 2% occurred with T1 (Mezzo) treatment. However, E_L of T2 (Forte) and T3 (Forte exterior) decreased by approximately 9.6% and 3.2%, respectively, with respect to the reference material. It should be noted that these latter results were obtained using the resonant beam technique and not from compression tests, so it can be deduced that the test method has a considerable influence on the results, even within different static tests themselves. This fact has already been proved by several authors. For example, greater E_L values from tensile than compression tests in heat-treated and untreated beech were reported in Wetzig et al. [36]. This tension–compression inequality of the elastic properties was also revealed in Ozyhar et al. [26] for untreated beech.

The non-linear increase in Young's moduli with treatment intensities is not only observed in the longitudinal direction, but also in the radial and tangential ones from static compression tests. This non-linear trend has already been shown in Yilmaz and Aydin [46], where elastic moduli in longitudinal direction seemed to increase for softer treatments and decrease for more severe ones. This may be related to the fact that lower moisture content of the specimens subjected to more intense treatments can positively affect the stiffness properties (a negative relationship between wood stiffness and moisture content is generally observed [e.g. [21,22,26]), but this effect may be surpassed by significant degradation of the chemical compounds [46], particularly the hemicellulose components of the polysaccharide complex [3]. This idea is supported by findings in heat treated wood presented by [e.g. [37,46,47]], where softer heat treatments showed and increase of this parameter while severe treatments tended to reduce it. As mentioned by Borůvka et al. [47],

Table 3
Mean values (x) in MPa and coefficient of variation (CoV) in % for the elastic constants of heat treated and untreated beech by compression and ultrasound tests.

		T0 Ultras.	T0 Compr	T1 Ultras.	T1 Compr	T2 Ultras.	T2 Compr	T3 Ultras.	T3 Compr
E_L [MPa]	x	14,078	13,811	14,821	15,443	14,798	16,930	16,619	16,559
	CoV	3.5	9.6	11.6	3.0	12.9	9.5	6.4	7.1
E_R [MPa]	x	2953	1590	2707	2031	2397	1866	2942	1811
	CoV	2.0	34.0	14.7	29.0	18.8	16.7	7.8	30.7
E_T [MPa]	x	1339	832	1586	1101	1132	834	1404	891
	CoV	6.6	13.9	12.5	32.2	14.9	13.2	7.7	19.2
G_{LR} [MPa]	x	1369	1108	1801	1433	1512	1479	1721	1344
	CoV	20.8	18.3	10.7	10.4	11.7	11.0	2.4	2.9
G_{LT} [MPa]	x	994	706	1315	723	1301	801	1164	929
	CoV	9.6	19.7	11.8	39.9	6.9	38.2	14.8	12.6
G_{RT} [MPa]	x	520	349	568	328	469	234	532	305
	CoV	10.5	15.3	12.8	17.9	7.7	17.2	7.6	17.2
ν_{LR}	x	0.27	0.44	0.25	0.43	0.29	0.39	0.40	0.45
	CoV	41.9	3.5	60.3	9.1	49.2	6.5	35.1	15.1
ν_{RL}	x	0.05	0.06	0.05	0.07	0.05	0.06	0.07	0.05
	CoV	41.5	48.1	72.9	39.7	62.9	52.5	46.1	33.0
ν_{LT}	x	0.63	0.51	0.62	0.51	0.76	0.49	0.65	0.46
	CoV	21.3	5.9	42.9	23.4	26.7	13.4	25.9	10.5
ν_{TL}	x	0.06	0.04	0.07	0.05	0.06	0.03	0.05	0.03
	CoV	18.0	55.5	49.3	62.2	25.8	27.4	27.2	28.0
ν_{RT}	x	0.55	0.62	0.68	0.55	0.69	0.66	0.45	0.64
	CoV	16.5	12.2	4.3	3.8	8.1	14.0	27.7	12.4
ν_{TR}	x	0.24	0.32	0.40	0.35	0.33	0.29	0.21	0.30
	CoV	12.2	13.0	20.4	15.3	18.4	14.7	28.4	18.4

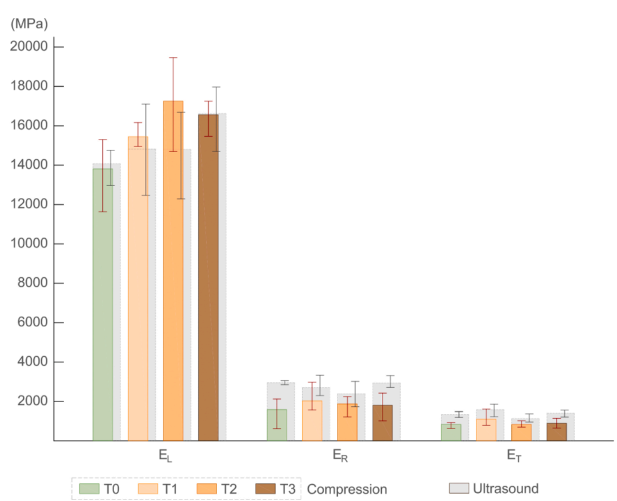

Fig. 10. Mean value and variation range for the Young's moduli of heat-treated and untreated beech obtained by ultrasound and compresion tests.

although changes in the polymerization degree may appear at low temperatures (above approx. 150 °C), it is proven by different studies that the decomposition of hardwood xylan of the hemicellulose begins at a temperature close to 200 °C in a normal atmosphere. Changes at temperatures below 200 °C have also been observed in lignin, despite it being a more thermally stable component [3].

If we look at the results from the dynamic tests, the increases in E_L appear to be less pronounced in comparison to static test results, approximately 5% for T1 and T2, and 18% for T3 in relation to T0, again without a clear trend regarding the intensity of the treatments.

Similarly, in the case of Young's moduli in transverse directions (E_R and E_T) slightly higher values can be associated with the heat-treated sets compared to the reference material from the static results. In particular, the increase in the mean E_R values was of approximately 28%, 17% and 14% for T1, T2 and T3 treatments, respectively, relative to untreated beech. The greatest improvement in E_T was also produced for T1 with 32%, whereas the improvement for T2 and T3 was smaller. Studies of Fajdiga et al. [34] in heat treated beech at 210 °C reported an increase in E_T by 16%, a little bit greater than that of the present work but still not too significant. Loidl et al. [37] reported and increase in stiffness with respect to reference material for Mezzo treatment, but a decrease in the cases of Forte and Forte exterior based on a resonant beam technique. Although the positive or negative effect with respect to untreated wood does not completely coincide with the present study, there is a similarity in terms of the decrease in the mean value of E_R and E_T with the severity of the treatment.

Unlike static results, the increasing stiffness is not expressed by E_R and E_T obtained from the dynamic tests, where heat treated beech offered greater or less values than untreated material depending on the treatment. In Wetzig et al. [36], the tangential modulus of elasticity in heat treated beech from ultrasound tests was clearly lower than in untreated material, but in the radial direction it depended on the type of heat treatment. Therefore, a clear overall statment on the influence of the heat treatment cannot be established in this case. A reason may be that micro-cracks and other inner faults might occur due to temperature exposure, so the prediction of the Young's moduli could be affected by these discontinuities [46]. Even so, the E_R and E_T values for the different treatments in the present work remain more or less in the same range.

These previous results clearly show that stiffness changes depend, in addition to the level of thermal treatment, also on the direction of mechanical loading and the cellular wood structure. The changes on a cellular level along the grain are presumably less affected during the thermal treatment so the compression stiffness is not negatively reduced in comparison with untreated material.

It is a known that Young's moduli for wood obtained by ultrasonic tests tend to give higher values than comparable ones obtained by static tests [e.g. [19,22]]. In heat-treated beech, Wetzig et al. [36] deduced E_L values up to 44% higher by ultrasound than compression methods. As shown, this general tendency is in accordance with the E_R and E_T results from this study (up to 62% higher values in heat treated beech by ultrasounds), but not entirely in E_L, although the high variability of these results must be taken into account.

The elastic anisotropy of wood expressed by the E_L:E_R:E_T ratio was stated by Bodig and Jayne [11] as approximately 20:1.6:1. The Young's moduli ratios obtained from the present study deviate slightly from this relationship (see Table 3). In this sense, it should be noted that the general relationship presented by Bodig and Jayne [11] comes from studies with different species.

The E_L:E_T ratios were different for each procedure: the ratios derived from ultrasound were around 1.6 times lower than those from static tests for all the heat treatments and reference groups. However, the E_R:E_T ratios remained widely unchanged regardless of heat treatment or testing procedure, with Young's moduli obtained in the radial direction ranging between 1.7 and 2.3 times greater than those corresponding to the tangential direction. This important difference beteween radial and tangential moduli in heat treated wood was also reported by Wetzig et al. [36]. This could be due to ray cells acting as reinforcements of the tissue in the radial direction.

Wood is a heterogeneous natural material, which implies great variability in mechanical properties [11]. It is exhibited by the Young's moduli coefficient of variation, especially in the radial direction. In longitudinal direction, the coeffient of variation exhibited lower values (below 10%).

In light of the scarce literature research on the determination of the elastic constants in heat-treated European beech and also considering the variability in the type of heat treatment, Table 4 presents a compilation of literature results of elastic moduli in untreated beech obtained in similar climatic conditions to the present study for comparison. It must be taken into account that moisture content, density, experimental method or specimen shapes are influencing factors that complicate direct comparisons.

Overall, the Young's moduli values obtained in the present research are of the same order of magnitude that those compiled from literature. Even the high values derived from ultrasound tests showed reasonable similarity with those in literature. In addition, as mentioned before, it is known from investigations that values determined by ultrasound methods are usually higher than those determined by static tests. From the literature compilation for unmodified beech, it becomes noticeable mainly in the radial moduli of elasticity. Also noticiceable is the remarkably wide range of variation of the longitudinal Young's modulus, varying from 9160 to 19100 MPa.

4.5. Shear moduli

Regarding the three shear moduli obtained from the compression and ultrasound tests performed in this work (Table 3), the effect of the three heat treatments in comparison to the untreated beech is illustrated in Fig. 11.

Overall, the mean shear moduli of heat-treated beech tended to be higher than those of the untreated material in LR and LT planes regardless of the measurement method, although the differences were not extremely large. That was not so clearly true in the TR plane, where

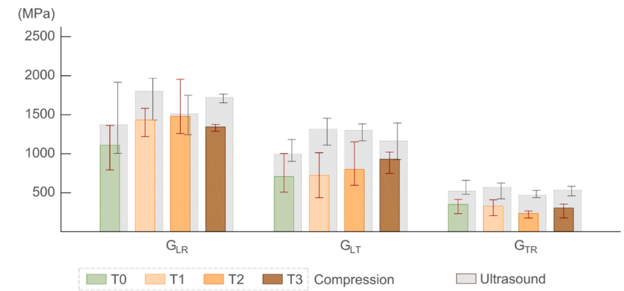

Fig. 11. Mean value and variation range for the shear moduli of heat-treated and untreated beech obtained by ultrasound and compression tests.

the shear modulus results were quite similar or even lower for heat treated beech than for the corresponding unmodified material. Higher shear values for heat treated beech than for unmodified beech under the same moisture conditions as here were also found by Wetzig et al. [36] from ultrasound tests when the treatment was performed in steam atmosphere. For the treatment performed under nitrogen atmosphere, higher shear modulus than that of the untreated material was exhibited in LR direction, but on the contrary G_{LT} and G_{TR} were found to be lower. In the case of Loidl et al. [37] using resonant beam technique, neither was a similar trend found for the three shear moduli, with slightly lower G_{LR} and G_{LT} for the three heat treatments than for untreated beech but equal or slightly higher G_{TR}.

Greater values were attained once more from ultrasound than static tests in the present work. Sometimes such differences are high. This could be due to natural variability of the wood as different specimens were used for ultrasound and mechanical tests. In any case, the results for untreated beech from both type of tests are in the same range than those reported in literature (Table 5). In the best knowledge of the authors, no shear moduli of heat treated beech from compression tests are reported in literature (just from ultrasounds mentioned before [36]), which prevents comparison within this material.

A ratio of approximately 3.2(LR):2(LT):1(TR) between the material planes of untreated beech is derived from compression tests in the present study. In the case of heat treated beech from the same tests, the ratios resulted slightly higher, that is, 4.4–6.3(LR):2.2–3.4(LT):1(TR).

The results from ultrasound tests also revealed little higher ratios for the modified material, and the three treatments show quite analogous ratios among them (2.6(LR):1.9(LT):1(TR) in untreated beech and 3.2 (LR):2.2–2.8(LT):1(TR) for the treated material). As can be seen from Table 5, similar ratios for shear moduli in untreated European beech

Table 4
Young's moduli of untreated beech from static and ultrasound tests and comparison with literature values.

	Test method	ρ (kg/m^3)	ω (%)	E_L (MPa)	E_R (MPa)	E_T (MPa)
STATIC TESTS						
This study	**Comp + DIC**	**677**	**11.4**	**13,811**	**1590**	**832**
[22]	Comp + DIC	691	12.5	13,900	1900	606
[25]	Comp + DIC	674	11.9	9690	1290	810
[26]	Comp + DIC	674	11.3	11,060	1650	750
[27]	Comp + DIC	678	–	15,020	1882	1132
[13]	Comp + gaug	629	10.8	12617–17980	1027–1537	642–1041
[26,28]	Tens + DIC	661	11.3	10,560	1510	730
[25]	Tens + DIC	674	11.9	10,460	1480	530
[29]	Flex & Tors	750	12	11,900	1700	1030
[30]	Torsion,static	–	12	–	1100	580
[48]	Compilation	740	10.5	14,000	2280	1160
ULTRASOUND TESTS						
This study	**Ultr 1 MHz**	**633**	**11.6**	**14,078**	**2953**	**1339**
[18]	Ultr 1 MHz	674	–	9160	1851	1037
[21]	Ultr 2.27 and 1 MHz	–	12.7	9560	2200	490
[23]	Ultr 100 kHz	700	10	14,650	–	–
[24]	ResoUltras	717	7–9	19,100	2700	1200

Table 5
Shear moduli of untreated beech from static and ultrasound tests and comparison with literature values.

	Test method	ρ (kg/m^3)	ω (%)	G_{LR} (MPa)	G_{LT} (MPa)	G_{TR} (MPa)
STATIC TESTS						
This study	**Comp + DIC**	**677**	**11.4**	**1108**	**706**	**349**
[13]	Comp + gaug	629	10.8	527–945	398–499	169–373
[29]	Flex & Tors	750	12	975	762	366
[30]	Torsion,static	–	12	1110	770	220
[31]	Torsion	631–708	12	977	757	–
[32]	Shear frame	697	8.6	953	688	234
[48]	Compilation	740	10.5	1640	1080	470
ULTRASOUND TESTS						
This study	**Ultr 1 MHz**	**633**	**11.6**	**1369**	**994**	**520**
[18]	Ultr 1 MHz	674	–	1396	978	356
[22]	Ultr 1 MHz	711	11.9	1280	855	486
[21]	Ultr 2.27 and 1 MHz	–	12.7	1240	930	380
[23]	Ultr 100 kHz	700	10	1430	1130	500
[24]	ResoUltras	717	7–9	1590	1100	530

were reported in literature, where approximately 3(LR):2(LT):1(TR) seems valid from various studies using ultrasound tests.

4.6. Poisson's ratios

Regarding Poisson's ratios, they are the less studied elastic constants due to the delicate instruments required to determine them. According to Bodig and Jayne [11], Poisson's ratios do not seem to be influenced by density or other anatomical material features in any clear way. On the contrary, there are other literature in which differences within and between species and also influence by factors, such as moisture content or specific gravity, are stated. However, there is a lack of information about the effects of heat tretament on Poisson's ratios for wood.

The six Poisson's ratios of beech wood as affected by the three heat treatments in comparison with the untreated material obtained from the present work are represented in Fig. 12.

The Poisson's ratios seem to be rather insensitive to heat treatments as no essential distinction between treated and untreated beech was observed. Also no great differences between treated and untreated beech were reported by Wetzig et al. [36] on the two Poisson's ratio that they studied. To the authors' knowledge, there are no other works that derive Poisson's ratios in heat-treated beech, but insensitivity to heat treatment intensities is also found in other species. For example, Yilmaz et al. [49] demostrated no significant effect of heat treatment on Poisson's ratio from oak wood despite small fluctuations in the values.

Passive lateral strain components along the tangential direction of the specimens led to the highest values of the Poisson's ratios (ν_{LT} and ν_{RT}), followed by Poisson's ratios from lateral strains along the radial direction (ν_{LR} and ν_{TR}). The smallest Poisson's ratios were those obtained from specimens where lateral passive strains were produced along the longitudinal direction (ν_{RL} and ν_{TL}).

The mean values of the Poisson's ratios obtained from static tests ranged from 0.03 (in TL plane) to 0.66 (in RT plane). The variation range in the case of ultrasound results was slightly greater, from 0.05 (in RL and TL planes) to 0.76 (in LT plane).

Namely, the mean ν_{LR} in the range of 0.39–0.45 for heat treated beech obtained from the present study is comparable to the result in Wetzig et al. [36] also for heat treated beech from compression tests (0.33). However, the mean $\nu_{LT,}$ ranging between 0.46 and 0.51, was significantly higher than the 0.08 reported by Wetzig et al. [36].

The Poisson's ratios are usually characterized by a high variability, wich is observed by the high CoV in some of the results from the present research, especially when the longitudinal direction corresponds to the passive lateral strain component (ν_{RL} and ν_{TL}), exceeding CoV's of 50% in some sets. This is a well-known problem in wood testing [11], since strains in longitudinal direction are too small for satisfactory and accurate measurments. Therefore, it is a common practise to derive these constants from relationships using the determined Young's moduli. Also in specimens tangentially oriented, it is difficult to guarantee growth rings to be completely parallel to the loading direction over the whole specimen.

The high natural variability in the Poisson's ratios for untreated European beech wood was also evidenced in other estudies [e.g. [22,26,28]], where similar high CoV's values for Poisson's ratios were reported.

Due to the high scatter, it is also not possible to make clear statements about the influence of heat treatment on the Poisson' ratios of beech wood. Higher number of specimens should be tested for better statistical significance.

Table 6 summarizes the obtained Poisson's ratios of untreated beech by static and ultrasound testing in comparison with corresponding results from literature.

In general, and considering the natural variation mentioned before, all determined Poisson's ratio measured at standard climatic conditions by static tests and DIC measurements correspond well with the respective literature values for beech listed in the table. However, this similarity is not exhibited by the sets of ultrasound results, with great differences especially within ν_{LR} and ν_{LT} ratios, which makes this

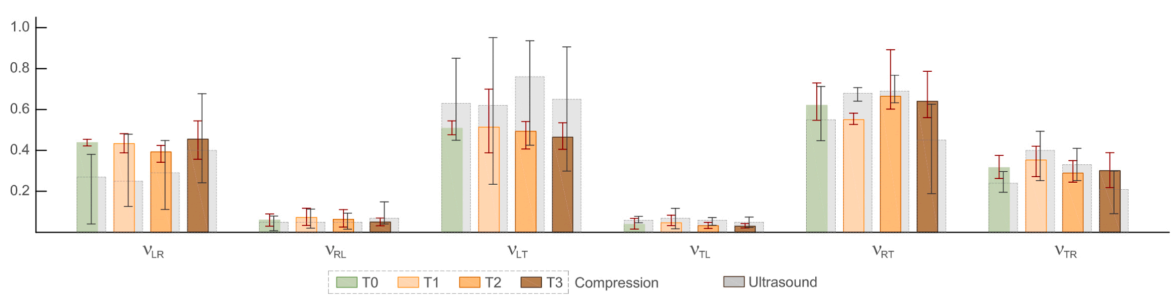

Fig. 12. Mean value and variation range for Poisson's ratios of heat-treated and untreated beech obtained by ultrasound and compression tests.

Table 6
Poisson's ratios of untreated beech from static and ultrasound tests and comparison with literature values.

	Test method	ρ (kg/m^3)	ω (%)	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL}	ν_{RT}	ν_{TR}
STATIC TESTS									
This study	**Comp + DIC**	**677**	**11.4**	**0.44**	**0.06**	**0.51**	**0.04**	**0.62**	**0.32**
[22]	Comp + DIC	691	12.5	0.27	0.07	0.24	0.09	0.64	0.27
[25]	Comp + DIC	674	11.9	0.13	0.06	0.22	0.08	0.65	0.33
[26]	Comp + DIC	674	11.3	0.55	0.15	0.51	0.09	0.75	0.32
[13]	Comp + gau	629	10.8	0.41–0.71	–	0.34–0.72	–	0.44–0.64	–
[26,28]	Tens + DIC	~661	11.3	0.43	0.04	0.58	0.04	0.61	0.31
[25]	Tens + DIC	674	11.9	0.24	0.07	0.18	0.04	0.61	0.27
[30]	Torsion	–	12	–	–	–	–	0.77	0.29
ULTRASOUND TESTS									
This study	**Ultra 1 MHz**	**633**	**11.6**	**0.27**	**0.05**	**0.63**	**0.06**	**0.55**	**0.24**
[18]	Ultra 1 MHz	674	–	1.24	0.25	0.90	0.10	0.26	0.15
[21]	Ultra 1 MHz	–	12.7	0.08	0.02	2.26	0.11	1.02	0.23

methodology less reliable. Highly accurate optical measurement techniques (as DIC) show more confidence to establish Poisson's ratios. Even so, it is worth noting the similarity between the static and dynamic Poisson's ratios from the research presented here.

Unlike the Young and shear moduli, the Poisson's ratios obtained from ultrasound tests do not exhibit a general tendency of higher values than those from ultrasound method.

Ozyhar et al. [26] revealed that the loading method had greater influence on the Poisson's ratios than the moisture content. They reported overall higher Poisson's ratios in compression than the corresponding values in tension. The differences were more pronounced for the ratios from specimens with the radial as the loading direction (ν_{RL} and ν_{RT}) and, to a lesser extend, for the specimens loaded in tangential direction (ν_{TR} and ν_{TL}). Even so, the lack of data on the tension–compression relationship of wood's Poisson's ratios prevents a deeper verification of the results, and a general statement can not be made by looking at all the data listed at the table. In fact, the mean ν_{TL} from the present work corresponds better with the results derived from tension tests by Ozyhar et al. [26].

4.7. Compliance parameters

Finally, the compliance matrix [S_{ijkl}] of Eqs. (1) and (2) was derived using the data from Table 3. The measurement of the six Poisson's ratios enables a discussion of the material symmetry expressed by the corresponding non-diagonal compliance components.

Table 7 provides an overview of the determined compliance parameters for unmodified and thermally modified beech by the three treatments obtained both by static and ultrasound tests.

As can be seen by the results, there is no clear correlation between mean compliance values and treatment intensities. What is noticed is that thermo-treated beech values from compression tests are lower than those of untreated material except for the case of s_{44}, for wich the variations among batches are more significant. However, the compliance values derived from ultrasound method do not show an analogous behaviour, with some cases where the mean compliance parameter of the heat treated wood was greater than the untreated material.

For simplicity, in order to reduce the unknown coefficients for the material description, symmetry in the orthotropy compliance matrix of wood is usually assumed, so the non-diagonal parameters (s_{ij} and s_{ji}) are often taken as equal. It is relatively satisfied for various wood species. Even though, several studies have pointed out discrepancies between the corresponding values of such non-diagonal parameters [e.g. [11,19,22,25]], being sometimes almost decoupled.

Comparing the non-diagonal compliance parameters from the present work (Table 6), very low deviations are observed between the components in RT planes for T0, T2 and T3 batches obtained from compression tests, being in the range of 2–5%. However, beech treated by T1 amounted 17% of difference. In the case of the values related to the LT plane, deviations in approximately 20 to 37% are noticed. Finally, different magnitudes of deviations were found for the LR plane, being almost negligible for T3, and approximately 18%, 24% and 40% for T0, T1 and T2, respectively.

Even so, these deviation percentages are below those reported in other studies using European beech. Deviations up to 35% were derived for RT plane and even exceeded more than 100% for LR and LT planes (being almost decoupled) from static tests in [19,22,25].

Meanwhile, it is noticeable the very low deviations in the non-diagonal compliance elements obtained from ultrasound tests (Table 6) where a maximum of 13% was shown for untreated beech in LR plane. For most of the other pairs of non-diagonal elements, the difference was even less than 6%.

Therefore, the results indicate overall that the orthotropic symmetry for the three planes is largely satisfied for each of the heat treatment batches and test method, specially for the results from ultrasound tests.

Table 7
Compliance paramenters of heat treated and untreated beech determined by compression and ultrasound tests.

	T0 Ultras.	T0 Compr	T1 Ultras.	T1 Compr	T2 Ultras.	T2 Compr	T3 Ultras.	T3 Compr
$s_{11} = 1/E_L$	7.10	7.24	6.75	6.48	6.76	5.91	6.02	6.04
$s_{22} = 1/E_R$	33.86	62.89	36.94	49.24	41.72	53.59	33.99	55.22
$s_{33} = 1/E_T$	74.68	120.19	63.05	90.83	88.34	119.90	71.23	112.23
$s_{44} = 1/G_{RT}$	192.31	286.53	176.06	304.88	213.22	427.35	187.97	327.87
$s_{55} = 1/G_{LT}$	100.60	141.64	76.05	138.31	76.86	124.84	85.91	107.64
$s_{66} = 1/G_{LR}$	73.05	90.25	55.52	69.78	66.14	67.61	58.11	74.40
$s_{21} = -\nu_{LR}/E_L$	1.92	3.19	1.69	2.78	1.96	2.30	2.41	2.72
$s_{12} = -\nu_{RL}/E_R$	1.69	3.77	1.85	3.45	2.09	3.22	2.38	2.76
$s_{31} = -\nu_{LT}/E_L$	4.48	3.69	4.18	3.30	5.14	2.89	3.91	2.78
$s_{13} = -\nu_{TL}/E_T$	4.48	4.81	4.41	4.54	5.30	3.60	3.56	3.37
$s_{32} = -\nu_{RT}/E_R$	18.63	38.99	25.12	27.08	28.79	35.37	15.30	35.34
$s_{23} = -\nu_{TR}/E_T$	17.92	38.46	25.22	31.79	29.15	34.77	14.96	33.67

5. Conclusions

The elastic properties of European beech and thermally modified beech at three different treatment intensities were quantified using both compression tests, coupled with a 3D digital image correlation technique, and ultrasound method. The results confirm a general influence of the heat treatments. However, the impact of the heat treatment differs between the elastic components. Results indicate that the elastic moduli are affected by the heat treatment to a greater extend than the Poisson's ratios. However, no clear correlations among treatment intensities and elastic constants were observed.

Overall, the Young's moduli and shear moduli (except G_{TR}) exhibited and increase in mean value for heat-treated material (for the three heat treatment cases) with respect to the untreated one when static compression tests were considered. In the case of ultrasound results, all three treatments showed greater values of elastic constants except, once again, G_{TR} and additionally the two Young's moduli in the transverse direction.

No essential distinction between treated and untreated beech was observed for the Poisson's ratios, which did not follow uniform trends with heat treatments and were the paremeters of highest variability.

Good comparability of the current results with literature references can be ascertained. In particular, all determined Poisson's ratio (whose determination is usually more difficult) from compression tests corresponded well with the respective literature values for untreated beech. Therefore, the accuracy of strain measurement by DIC is satisfactory for his purpose, confirming it as a potential tool for wood characterization. However, this similarity was not exhibited by the sets of ultrasound results, which makes this methodology less reliable to establish Poisson's ratios. The mean values obtained by ultrasonic waves were in most of the elastic properties and batches clearly higher than those from static tests.

The compliance parameters of heat-treated beech values from compression tests were lower than those of untreated material except for that related to G_{TR}. Relatively low deviations were obtained between the respective non-diagonal compliance parameters, so the orthotropic symmetry for the three planes was largely satisfied for each of the heat treatment batches and test methods.

The twelve elastic constants provide a basis for modelling of thermally treated beech structures, thus giving added-value to this product in the construction industry.

CRediT authorship contribution statement

José Luis Gómez-Royuela: Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Almudena Majano-Majano:** Conceptualization, Formal analysis, Investigation, Resources, Supervision, Writing - original draft, Writing - review & editing. **Antonio José Lara-Bocanegra:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Thomas P.S. Reynolds:** Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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