Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 37 (2022) 25–32

Structural Integrity Procedia

www.elsevier.com/locate/procedia

ICSI 2021 The 4th International Conference on Structural Integrity

Identification of orthotropic elastic properties of wood by digital image correlation and finite element model updating techniques

J. Henriques[a,*], J. Xavier[b], A. Andrade-Campos[a]

[a]*TEMA, Department of Mechanical Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*
[b]*UNIDEMI, Department of Mechanical and Industrial Engineering, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica, Portugal*

Abstract

Computer-aided engineering systems rely on constitutive models and their parameters to describe the material behaviour. The identification process, however, grows in complexity for more elaborated material models, increasing the number of experimental tests needed, therefore time and cost consuming. Recently, with the development of digital image technology, there has been a growing interest in the use of full-field deformation measurements. This advancement has highlighted a new methodology on inverse identification techniques such as the finite element model updating method. This work aims to identify orthotropic linear elastic constitutive parameters of *Pinus pinaster* Ait. wood based on a single uniaxial compressive experimental test. Clear wood specimens oriented in the radial-tangential plane were used and tested under quasi-static loading condition. Full-field displacement and strain maps were obtained using digital image correlation and used to simultaneously identify the whole set of elastic properties through finite element model updating methodology.

Peer-review under responsibility of Pedro Miguel Guimaraes Pires Moreira

Keywords: Wood; Digital image correlation; Inverse identification; Finite element model updating technique; Orthotropic elasticity; Compression tests

* Corresponding author. Tel.: +351 234 370 830;
E-mail address: joaodiogofh@ua.pt

Peer-review under responsibility of Pedro Miguel Guimaraes Pires Moreira
10.1016/j.prostr.2022.02.047

1. Introduction

Wood and wood-based products have been gathering momentum over the past decade due to policies of sustainability and green economy. However, wood is a complex biological material with a heterogeneous and hierarchical structure. A mechanical description has been proposed based on an anisotropic behaviour along with three orthotropic material directions: the longitudinal direction (L) along the tracheids, the radial direction (R) parallel to the rays and the tangential direction (T) to the annual rings.

The characterization of the orthotropic material properties is crucial in computer-aided engineering systems in order to accurately reproduce the material behaviour, fostering innovation with the development of new products and design of structures (Thelandersson and Larsen, 2003). However, the experimental characterization poses several issues due to inherent hierarchical, heterogeneous and anisotropic modelling behaviour of such biological materials. Moreover, stress and strain distributions can be extremely complex due to effects of wood variability (Forest Products Laboratory, 1999). Furthermore, the simulation of processes by finite element analysis is well established. However, the calibration of the material constitutive models is still facing open challenges.

Considering the recent advances in digital image technology, there has been an increasing growth in use of novel optical methodologies in solid and fluid experimental mechanics, which provide full-field measurements. Among these techniques, digital image correlation (DIC) has been exponentially used in the recent past (Avril et al., 2008, Grédiac and Hild, 2012, Andrade-Campos et al., 2020). To take full advantage of these novel optical methodologies, the photomechanic scientific community is using inverse identification techniques, more noticeably the virtual fields method (VFM) (Pierron and Grédiac, 2012) and the finite element method updating (FEMU) method (Martins et al., 2018, Andrade-Campos et al., 2020, Oliveira et al., 2021). Unlike the conventional methods that rely on punctual surface deformation measurements, such as the use of strain gauges, this type of methodology can provide heterogeneous strain fields over the region of the interest of the specimen (Xavier and Pierron, 2018). This novel approach has the potential to reduce the number of experimental tests required to accurately identify material properties, given that the experimental test configuration is rich enough, so that all material properties take a role in the mechanical behaviour. Moreover, it is suitable to tackle current open issues in the identification of mechanical properties for heterogeneous materials, to address the spatial variability of mechanical properties over the region of interest (ROI) of the specimen, in materials such as wood (Pereira et al., 2018) or composites.

This work addresses the identification of linear elastic orthotropic constitutive parameters of *Pinus pinaster* Ait. using a single uniaxial compression test under quasi-static loading conditions, with on-axis rectangular specimens oriented on the radial-tangential (RT) plane. Several images of the experimental tests were recorded by a digital camera, further processed by DIC with suitable settings. As a result, heterogeneous full-field displacement and strain maps with strain gradient fields at the wood growth ring scale were obtained and used to identify the material parameters, such as modulus of elasticity, Poisson's ratio, and shear modulus. The identification was done using the FEMU procedure by the minimization of a cost function that describes the difference between the experimental and numerical results, including the load and strain fields. This work is carried out considering wood as an orthotropic homogeneous material, resulting in four material parameters to be identified from a single configuration test.

2. Methods

2.1. Material and specimen

Pinus pinaster at the diameter at breast height (DBH) of a single tree of approximately 60 years old was tested. Radial boards were initially cut and air-dried to a moisture content of about 12%. Clear wood specimens were then manufactured on the RT plane with nominal dimensions 20(R)×10(T)×4(L) mm^3. The length-to-width ratio of 2 was considered in order to prevent buckling, shear or other non-homogeneous modes of deformation from the compressive test configuration.

2.2. Compression tests and full-field measurements

Compression tests were carried out on an Instron 5848 MicroTester machine with a controlled cross-head displacement rate of 0.5 mm/min. The axial load was measured by a 2 kN load cell. A lubricant was applied between the specimen and the compression platens to reduce friction and avoid excessive barreling. Loading and unloading cycles up to 20 N were performed, before testing and final image focusing, just to accommodate the specimen and enhance the flatness of the contact loading surfaces. Digital image correlation was coupled to the tests to evaluate the specimen deformation across the whole ROI, integrating several annual growth rings. The optical system consisted of Baumer Optronic FWX20 camera with an AF Micro-Nikkor 200mm f/4D ED-IF lens. The field of view covered an area of about 20.5×15.5 mm^2 and the working distance was 742 mm. Speckle pattern was created by airbrush painting, with an average speckle size of 2.714 pixels/0.0365 mm. The lighting system and the exposure time were set to avoid pixel saturation and ensure the best contrast of the speckle pattern. Loading and image recording were synchronized during the test at an acquisition frequency of 1 Hz.

2.3. Digital image correlation: parametric analysis

The 2D-DIC technique was used to provide measurements of the displacements and strains fields over the whole ROI of the specimens, using the MatchID software (MatchID, 2021). The selection of the setting parameters is a key topic when performing measurements through this full-field measurement technique (Cooreman et al., 2008, Pereira et al., 2018). This selection was carried out using the performance analysis module from MatchID software, with a set of different parameter combinations (in a total of 650 analysis), using Affine\Quadratic subset shape functions, bilinear Q4\biquadratic Q8 strain interpolation and a virtual strain gauge (VSG) ranging from 41 to 661 pixels (between 0.54 and 8.73 mm). Fig. 1 summarizes the convergence study performed, comparing the strain component ε_R versus the VSG regarding two selected points: (a) earlywood; (b) latewood.

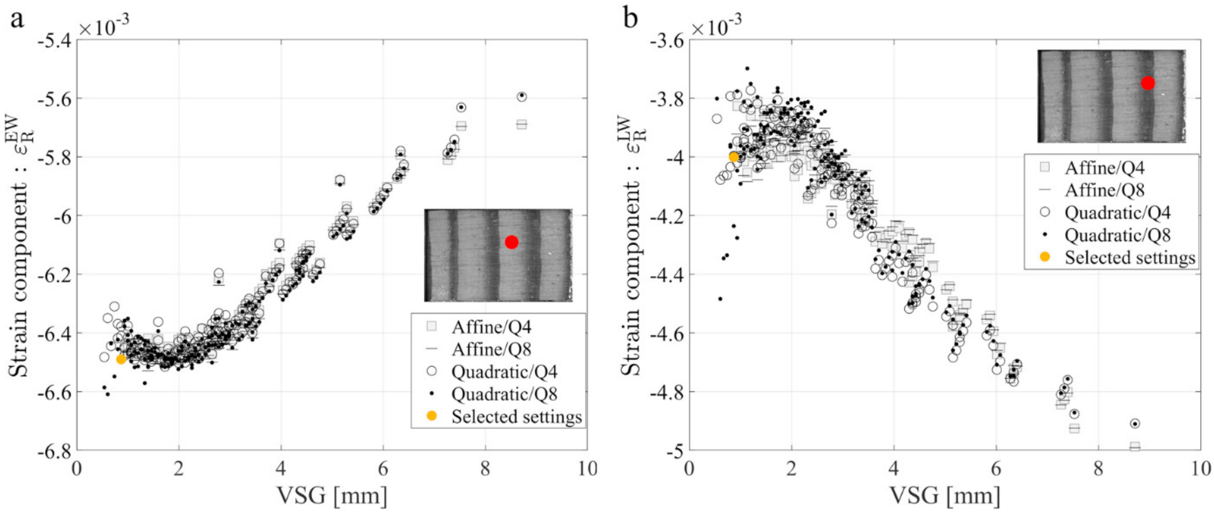

Fig. 1. Signal versus virtual strain gauge for specimen 07: (a) Earlywood; (b) Latewood.

Using a larger VSG leads to a higher level of smoothing of the measurements, minimizing the inherent noise on the experimental data, but also leads to the loss of strain gradients that are expected in heterogeneous materials like wood, generated by the wood growth ring structure (Pereira et al., 2018). Moreover, larger values of VSG seem to lead to a lower strain signal reconstruction (in module) in the earlywood, which is expectable due to the influence of latewood tissue. Similarly, when observing the influence of VSG on strain signal reconstruction in the latewood tissue, larger values of VSG seem to lead to a higher strain signal reconstruction (in module), as a result of the influence of the earlywood tissue. Therefore, a compromise must be found between spatial resolution and accuracy. The selection of the DIC settings was based on this compromise, being chosen a point that gives good spatial resolution, which is particularly important in complex heterogeneous materials, such as wood, and simultaneously good accuracy. As reported in Fig. 1, the selected DIC settings are within a convergence band of DIC settings, where the increase of the

VSG (and loss of spatial resolution) does not have a significant impact on the signal measured. Table 1 summarizes the selected 2D-DIC settings for this study, highlighted in Fig. 1.

Table 1. 2D-DIC settings used for the experimental DIC results, using MatchID DIC Software.

Image resolution, Image conversion factor	1624×1236 px^2, 0.0132 px\mm
Correlation criterion	Zero-normalized sum of square differences (ZNSSD)
Interpolant, subset shape function	Bicubic spline, Quadratic
Subset size, step size	17 px, 5 px
Image pre-filtering	Gaussian, 5 px kernel
Strain window size, strain interpolation	11, bilinear Q4
Strain convention	Green-Lagrange

2.4. Finite element model updating technique

The FEMU is used to identify the four orthotropic linear elastic parameters of wood. The idea behind this method is to iteratively update the unknown material parameter set, by means of an optimization procedure, in order to minimize a cost function that describes the difference between the experimental measurements and finite element analysis (FEA) results. The comparison can be done with different kinds of data: (i) displacements; (ii) strains; (iii) load. This flexibility and ease of implementation makes FEMU one of the most used inverse identification techniques (Martins et al., 2018).

A finite element (FE) model was implemented using ANSYS Mechanical APDL software (ANSYS, 2020), using the DIC-based experimental boundary conditions on the left and right boundary of the specimen, interpolated between DIC and the FEA mesh. Moreover, the elements used are 2D 4-node structural solid elements, mainly quadrilateral, changing to triangular when it is required to fit the irregular geometry of the annual growth rings structure of wood. The element size used is 0.085 mm, which represents a total of approximately 29000 nodes and 28600 elements.

The objective function adopted in this study is described by the difference between the experimental and FEA results, including the load and strain fields:

$$Z(\chi) = (1 - W_{\mathrm{F}})\, IT_{\mathrm{S}}^{\,2} + W_{\mathrm{F}}\, IT_{\mathrm{F}}^{\,2}, \tag{1}$$

where $\boldsymbol{\chi}$ represents the unknown variables (E_{R}, E_{T}, ν_{RT} and G_{RT}) and W_{F} is a weighting coefficient between the strain term (IT_{S}) and force term (IT_{F}). The strain term is described by:

$$IT_{\mathrm{S}} = \frac{1}{3n}\left(\sqrt{\sum_{k=1}^{n} \left| \frac{\varepsilon_{\mathrm{xx}}^{\mathrm{exp}} - \varepsilon_{\mathrm{xx}}^{\mathrm{num}}(\chi)}{\varepsilon_{\mathrm{xx,max}}^{\mathrm{exp}}} \right|^2}^{\,2} + \sqrt{\sum_{k=1}^{n} \left| \frac{\varepsilon_{\mathrm{yy}}^{\mathrm{exp}} - \varepsilon_{\mathrm{yy}}^{\mathrm{num}}(\chi)}{\varepsilon_{\mathrm{yy,max}}^{\mathrm{exp}}} \right|^2}^{\,2} + \sqrt{\sum_{k=1}^{n} \left| \frac{\varepsilon_{\mathrm{xy}}^{\mathrm{exp}} - \varepsilon_{\mathrm{xy}}^{\mathrm{num}}(\chi)}{\varepsilon_{\mathrm{xy,max}}^{\mathrm{exp}}} \right|^2}^{\,2} \right). \tag{2}$$

The variable n represents the number of full-field measurement points, whereas $\varepsilon^{\mathrm{exp}}$ and $\varepsilon^{\mathrm{num}}$ represent the experimental strain field and numerical field, respectively, considering the different components of in-plane strain fields ($\varepsilon_{\mathrm{xx}}$, $\varepsilon_{\mathrm{yy}}$ and $\varepsilon_{\mathrm{xy}}$). The variable $\varepsilon_{\mathrm{xx,max}}^{\mathrm{exp}}$ is the maximum strain value for the respective strain component, following the analogy for the remaining strain components. The force term is described by:

$$IT_{\mathrm{F}} = \frac{F^{\mathrm{exp}} - F^{\mathrm{num}}(\chi)}{F^{\mathrm{exp}}}. \tag{3}$$

Similarly, the variables F^{exp} and F^{num} represent the experimental and numerical load, respectively, for the analyzed stage.

A flowchart describing the material parameters identification chain using FEMU is presented in Fig. 2. An initial set of parameters (χ) is given to the finite element model in order to start the iterative process of FEMU. The numerical results, which are interpolated from the FEA mesh to the DIC mesh in order to match numeral data locations and experimental data points, are required to make an evaluation of the cost function. The iterative process continues using an optimization method to generate the next set of material parameters until a minimum of the objective function is reached, and the parameters set (χ) stagnate. The optimization method used is the Nelder-Mead simplex method, which is a simple direct-search algorithm (Gao and Han, 2012). Here, a simplex is generated beginning with as much vertices as the number of variables plus one, then a sequence of transformations is made with the goal of minimizing the objective function value at its vertices (Oliveira et al., 2021).

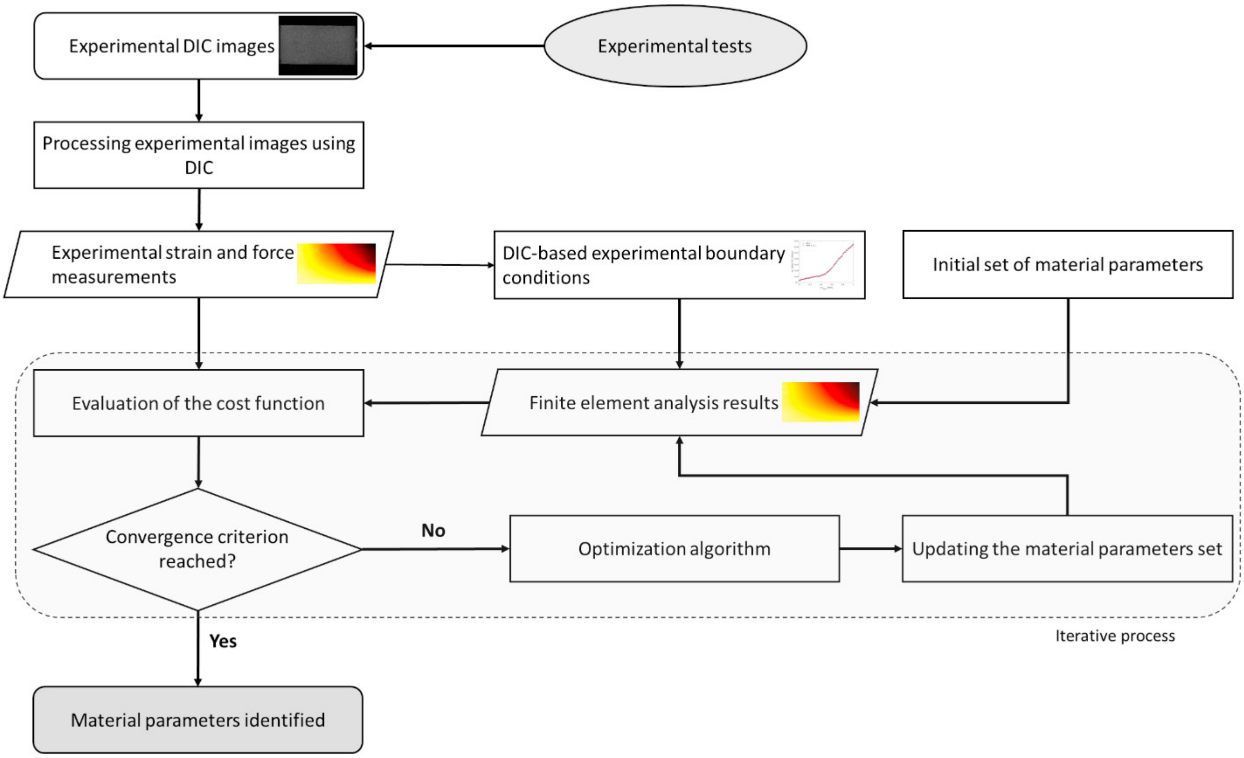

Fig. 2. Flowchart describing the material parameters identification chain using FEMU.

3. Results

3.1. Convergence study for identified parameters

The linear elastic orthotropic constitutive parameters (E_R, E_T, ν_{RT} and G_{RT}) are identified, being the only variables in the optimization process. Moreover, the initial set of material parameters are considered reference values and the W_F used is 10^{-3}, which privileges both the strain and the force terms minimization, as presented in Table 2. The optimization algorithm used is the fminsearch function from the MATLAB software library (MATLAB, 2021). The summary of the final objective function, strain and force terms values, and the comparison between the experimental force measurement and the final numerical force, for the seven specimens, are described in Table 2.

Additionally, the convergence study for all four material parameters identified (E_R, E_T, ν_{RT} and G_{RT}) throughout the identification method, for all specimens, is presented in Fig. 3.

Table 2. Summary of FEMU convergence parameters.

Specimen	$Z(\boldsymbol{\chi})$	IT_S	IT_F	F^{exp} (N)	F^{num} (N)
01	4.894×10^{-4}	2.213×10^{-2}	1.544×10^{-5}	335.0	335.0
02	9.181×10^{-4}	3.031×10^{-2}	1.228×10^{-6}	366.7	366.7
03	2.195×10^{-4}	1.482×10^{-2}	1.983×10^{-5}	120.6	120.6
04	1.543×10^{-4}	1.243×10^{-2}	1.423×10^{-6}	367.7	367.7
05	3.315×10^{-4}	1.822×10^{-2}	3.289×10^{-6}	327.6	327.6
06	1.190×10^{-4}	1.091×10^{-2}	1.356×10^{-5}	148.9	148.9
07	9.555×10^{-4}	3.093×10^{-2}	4.894×10^{-5}	273.4	273.4

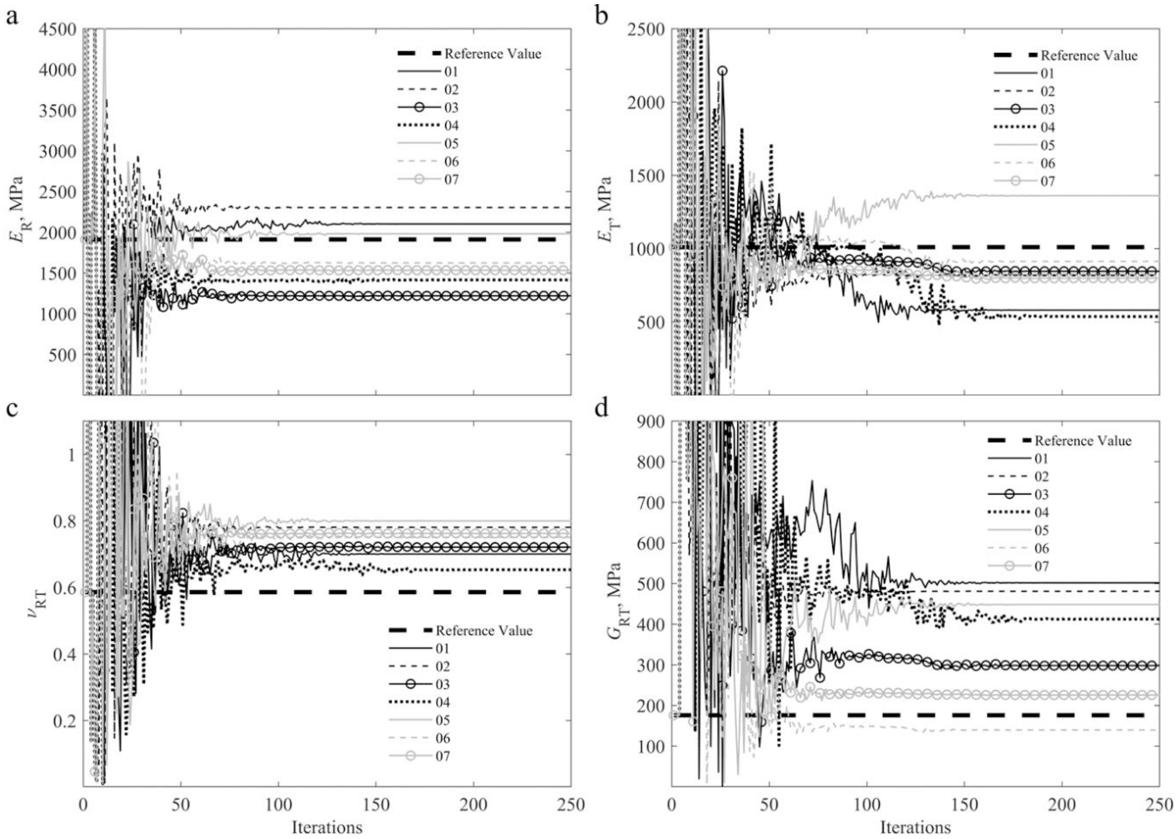

Fig. 3. Convergence study for identified parameters: (a) E_R; (b) E_T; (c) ν_{RT}; (d) G_{RT}.

3.2. Experimental and numerical full-field deformation maps with identified parameters

The difference between experimental full-field strain measurements and numerical strain results are minimized. Fig. 4 shows the experimental DIC strain fields in comparison to the final calibrated numerical strain fields for one of the specimens under analysis. Furthermore, the difference between these two strain fields normalized by the maximum value of strain of its correspondent component is also presented. As expected, in the difference fields it is possible to observe the annual growth rings structure of wood, being a major component of these, due to the numerical homogeneous modelling of wood used in this work.

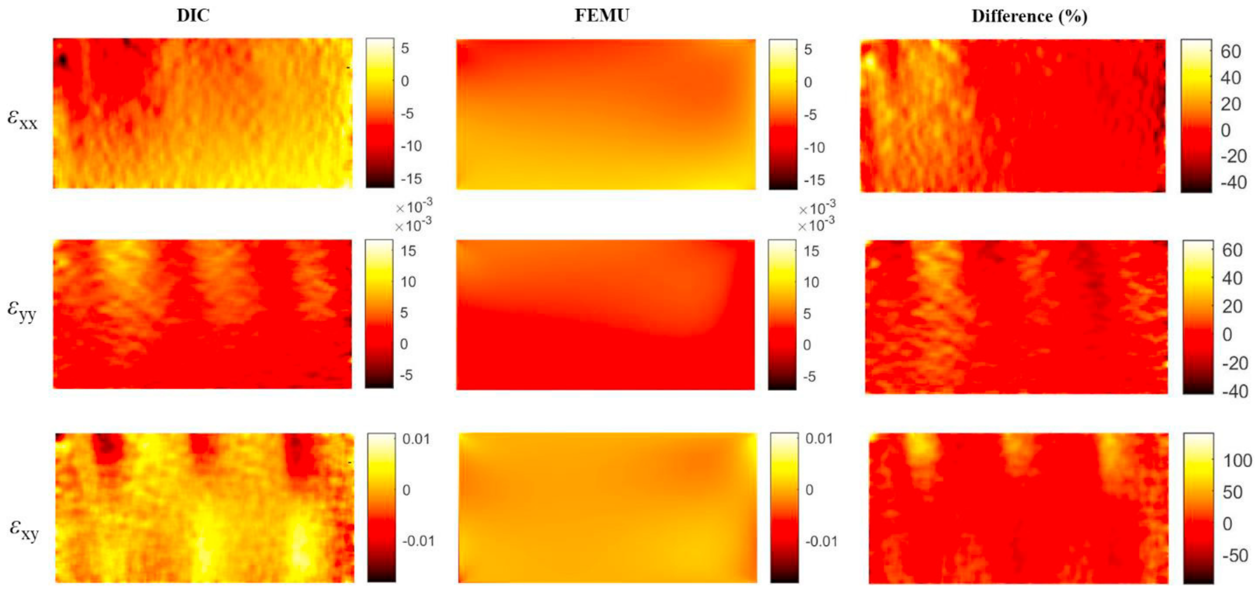

Fig. 4. Experimental and final numerical deformation full-field maps for specimen 06.

3.3. Identified orthotropic linear elastic parameters

The elastic properties of *Pinus pinaster* were determined for the RT plane. Table 3 describes the parameters identified for each specimen, including the mean value, standard deviation and coefficient of variation (COV). The results show some dispersion for each specimen, which is expected due to the inherent natural variability of wood. Moreover, the mean values for the identified parameters agree with reference values for this wood species, particularly the modulus of elasticity on the radial direction and the *Poisson*'s ratio (Forest Products Laboratory, 1999, Pereira et al., 2018). Additionally, the anisotropy ratio $E_R \setminus E_T$ for the mean values is 2.08, which is concordant to the typical values reported in literature for this wood species.

Table 3. Identified orthotropic linear elastic parameters.

	E_R (MPa)	E_T (MPa)	ν_{RT}	G_{RT} (MPa)
Reference parameters	1912	1010	0.586	176
Specimen 01	2102.52	580.34	0.701	501.80
Specimen 02	2304.64	819.56	0.781	481.05
Specimen 03	1220.63	845.02	0.721	298.13
Specimen 04	1415.54	536.49	0.653	412.42
Specimen 05	1981.29	1360.82	0.800	448.38
Specimen 06	1623.79	912.48	0.750	139.58
Specimen 07	1534.10	798.15	0.762	225.78
Mean	1740.36	836.12	0.738	358.16
Standard deviation	395.68	270.23	0.050	138.88
COV (%)	22.74	32.32	6.84	38.78

4. Discussion

The proposed FEMU methodology based on a single uniaxial compression test to simultaneously identify four orthotropic elastic parameters proved to be effective in the identification of two of the four RT linear elastic constitutive parameters of *Pinus pinaster*, being the modulus of elasticity on the radial direction and the *Poisson*'s ratio. The values for the modulus of elasticity on the tangential direction and the shear modulus seem to have a higher variation, with a COV higher than 32% for both parameters. Moreover, the identified mean value for the shear modulus diverges from the reference value reported in literature, which suggests that there is a dependency on the test configuration used and the identifiability of certain material parameters, due to the lack of sufficiently heterogeneous strain fields.

5. Conclusions

The identification of material parameters using full-field measurements and inverse identification techniques have been gathering increased interest by the scientific community due to its capability to revolutionize the way that mechanical experimental tests are performed. The results show the accurate identification of two out of four RT linear elastic parameters of *Pinus pinaster*. Nevertheless, there is the potential to identify all the material parameters with only one test configuration, given that the test configuration submits the material to a combined state of stress and strain, in a way that all material parameters play a role in its mechanical behaviour. In future work, other single test configurations can be inspected in order to enhance the identifiability of wood material properties.

Acknowledgements

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 888153. The authors also gratefully acknowledge the financial support of the FCT under the project PTDC/EME-APL/29713/2017 by UE/FEDER through the programs CENTRO 2020 and COMPETE 2020, and UID/EMS/00481/2013-FCT under CENTRO-01-0145-FEDER- 022083. Authors acknowledge the support by the IC&DT project "THERMECHCHAR – CENTRO-01-0145-FEDER-029713"–BI-16–DEM_TEMA_2020_ THERMECHCHAR – TEMA – Centro de Tecnologia Mecânica e Automação; under the I.P./MCTES FCT and Centro Portugal Regional Operational Program FEDER fund.
Authors acknowledge Fundação para a Ciência e a Tecnologia (FCT - MCTES) for its financial support via the projects UIDB/00667/2020 (UNIDEMI) and UID/ENS/00481/2013-FCT (TEMA).

References

Andrade-Campos, A., Thuillier, S., Martins, J., Carlone, P., Tucci, F., et al., 2020. Integrated Design in Welding and Incremental Forming: Material Model Calibration for Friction Stir Welded Blanks. Procedia Manufacturing 47, 429–434.

ANSYS, 2020. ANSYS mechanical APDL Student Version 2020 R2. ANSYS, Inc.

Avril, S., Bonnet, M., Bretelle, A., Grédiac, M., Hild, F., et al., 2008. Overview of identification methods of mechanical parameters based on full-field measurements. Experimental Mechanics 48(4), 381–402.

Cooreman, S., Lecompte, D., Sol, H., Vantomme, J., Debruyne, D., 2008. Identification of Mechanical Material Behavior Through Inverse Modeling and DIC. Experimental Mechanics 48, 421–433.

Forest Products Laboratory, 1999. Wood Handbook-Wood as an Engineering Material. Gen. Tech. Rep. FPL-GTR-113. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin, U.S.

Gao, F., Han, L., 2012. Implementing the Nelder-Mead simplex algorithm with adaptive parameters. Computational Optimization and Applications 51(8), 259–277.

Grédiac, M., Hild, M., 2012 (Eds.). Full-Field Measurements and Identification in Solid Mechanics. UK: Wiley-ISTE.

Martins, J.,Andrade-Campos, A., Thuillier, S., 2018. Comparison of inverse identification strategies for constitutive mechanical models using full-field measurements. International Journal of Mechanical Sciences 145, 330–345.

MatchID, 2021. Version 2021.1.2. MatchID: Metrology beyond colors, NV, Ghent, Belgium.

MATLAB, 2021. Version 9.10.0 (R2021a). Natick, Massachusetts: The MathWorks Inc.

Oliveira, M., Martins, J., Coelho, B., Thuillier, S., Andrade-Campos, A., 2021. On the Optimisation Efficiency for the Inverse Identification of Constitutive Model Parameters. ESAFORM 2021, 24th International Conference on Material Forming.

Pereira, J., Xavier, J., Ghiassi, B., Louzada, J., 2018. On the identification of earlywood and latewood radial elastic modulus of Pinus pinaster by digital image correlation: A parametric analysis. The Journal of Strain Analysis for Engineering Design 53(8), 566–574.

Pierron, F., Grédiac, M., 2012. The Virtual Fields Method: Extracting Constitutive Mechanical Parameters from Full-field Deformation Springer-Verlag New York.

Thelandersson, S., Larsen, H., 2003. Timber Engineering. John Wiley and Sons.

Xavier, J., Pierron, F., 2018. Measuring orthotropic bending stiffness components of Pinus pinaster by the virtual fields method. The Journal of Strain Analysis for Engineering Design 53(8), 556–565.