Non-destructive measurement of orthotropic elastic properties of wood samples by their modal impulse response

Al FAY Alaa[1,2], ARNOULD Olivier[1], CORN Stéphane[2], LANGBOUR Patrick[3], JULLIEN Delphine[1]

[1] Wood team, LMGC, Univ Montpellier, CNRS, Montpellier, France

[2] DMS team, LMGC, Univ Montpellier, IMT Mines Alès, CNRS, Alès, France

[3] UR BioWooEB, CIRAD, Montpellier, France

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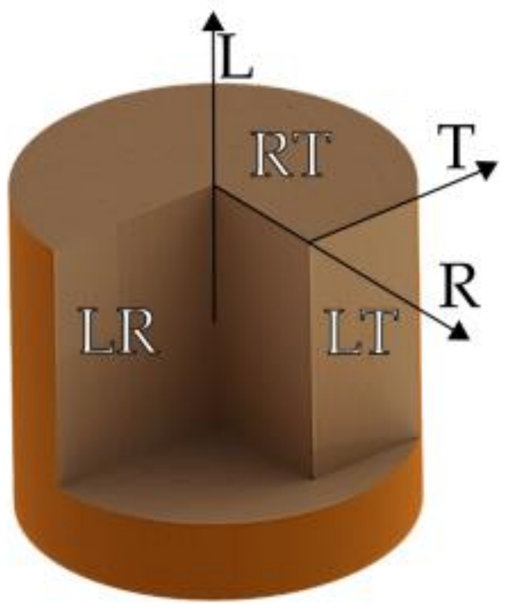
Context and objectives

Samples from CIRAD's "xylotheque [1]"

- Wood represents a major class of versatile materials in mechanics, comparable to metals on various criteria such as annual world production tonnage.
- The density of wood is 5 to 10 times lower than that of metals.



Orthotropic cylindrical coordinate system [2]

- Contrary to the longitudinal elastic modulus (E_L), the knowledge of the transverse (E_R and E_T) and shear (G_{RT}, G_{LT} and G_{LR}) elastic properties of this orthotropic, heterogeneous, hygroscopic and variable material is still limited due to a lack of rapid and efficient characterization tools and methods.

Objectives of this study

- Fast measurement of most elastic constants of a single wood sample.
- Enhancing the CIRAD wood database [1] with orthotropic elastic constants on a wide range of wood species.
- Analyze the correlations between macroscopic elastic behaviour and ultrastructural parameters, including density and microfibril angle (MFA).

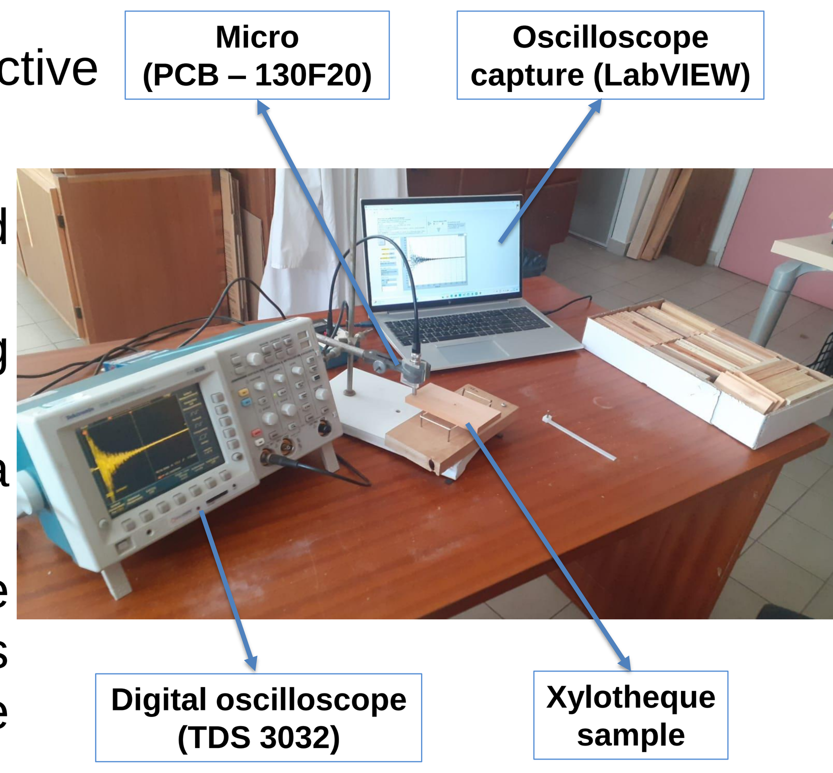
Materials and methods

Samples from *CIRAD's xylotheque*

⇨ All dimensions (not-modifiable) ~ **13 cm x 6 cm x 1 cm**

The method used was a fast and non-destructive test by impulse modal analysis:

- Samples (free from knots) were suspended on soft rubber bands.
- Vibrations were induced in the sample using either a small hammer or a steel ball.
- Responses of samples were recorded by a high-sensitivity microphone (PCB - 130F20).
- Signals acquired using digital oscilloscope (TDS 3032) and modal parameters (eigenfrequency and damping ratio) were identified using MODAN (LSCF method).



Impulse modal analysis system

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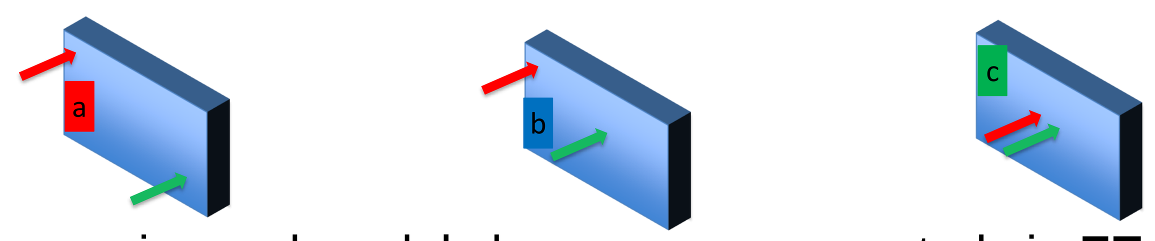
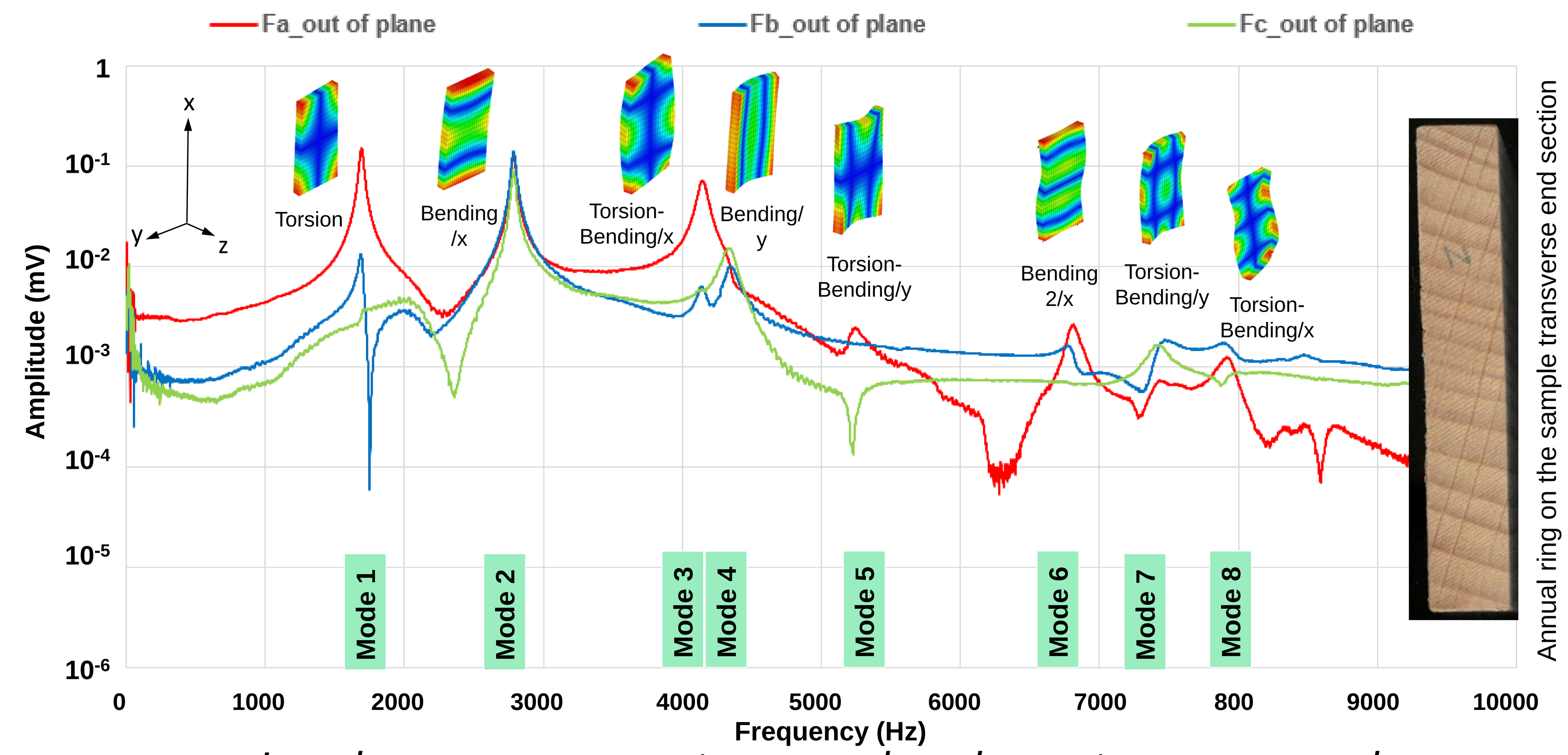
Identification procedure

- Experimental mode identification using different positions of impact and micro / vibration nodes:

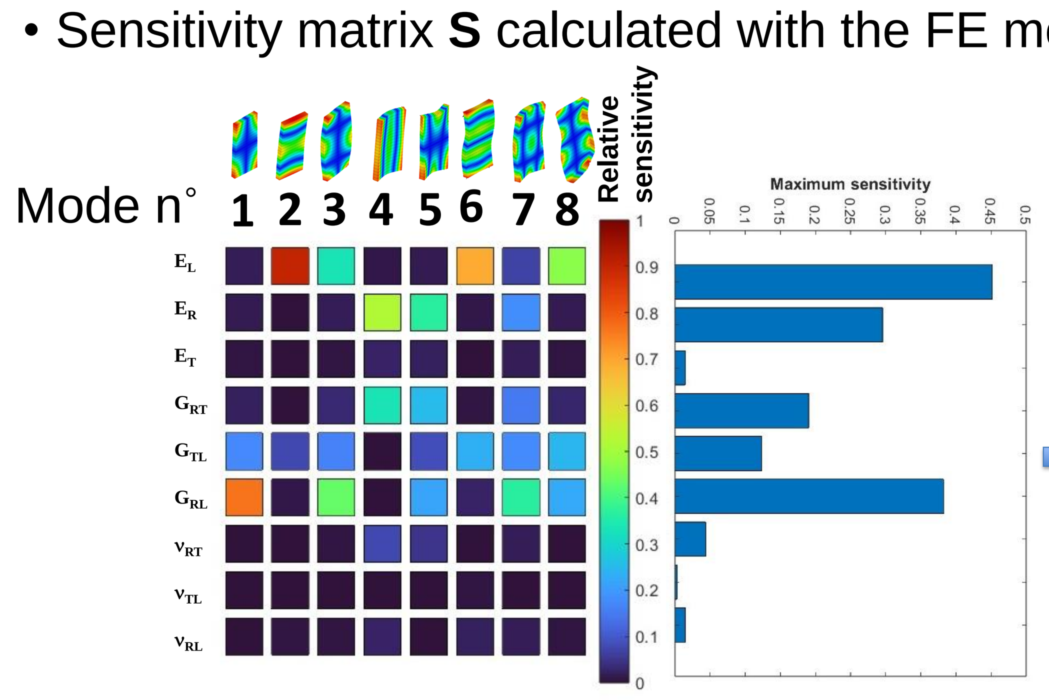


➢ Eigenfrequencies and modal shapes were computed via **FE (Cast3m)**, initialized with standard stiffness-density relationships [3], taking into account annual ring orientation and curvature on the two transverse end sections, and grain angle.



Impulse response spectra, case: beech quarter-sawn sample

- Sensitivity matrix **S** calculated with the FE model:



- Minimum number of modes to be considered for identification:

➢ Min/max eigenvalues **λ** of the pseudo-Hessian matrix $\mathbf{H}=\mathbf{S}^T\mathbf{S}$

➢ Identifiability index $I = log_{10}\frac{\lambda_{max}}{\lambda_{min}}$

➢ Result: the set of eigenmodes {**1, 2, 4, 6, 7**} allows for robust identification (I < 2) [4] of **5 elastic constants** for the xylotheque wood sample.

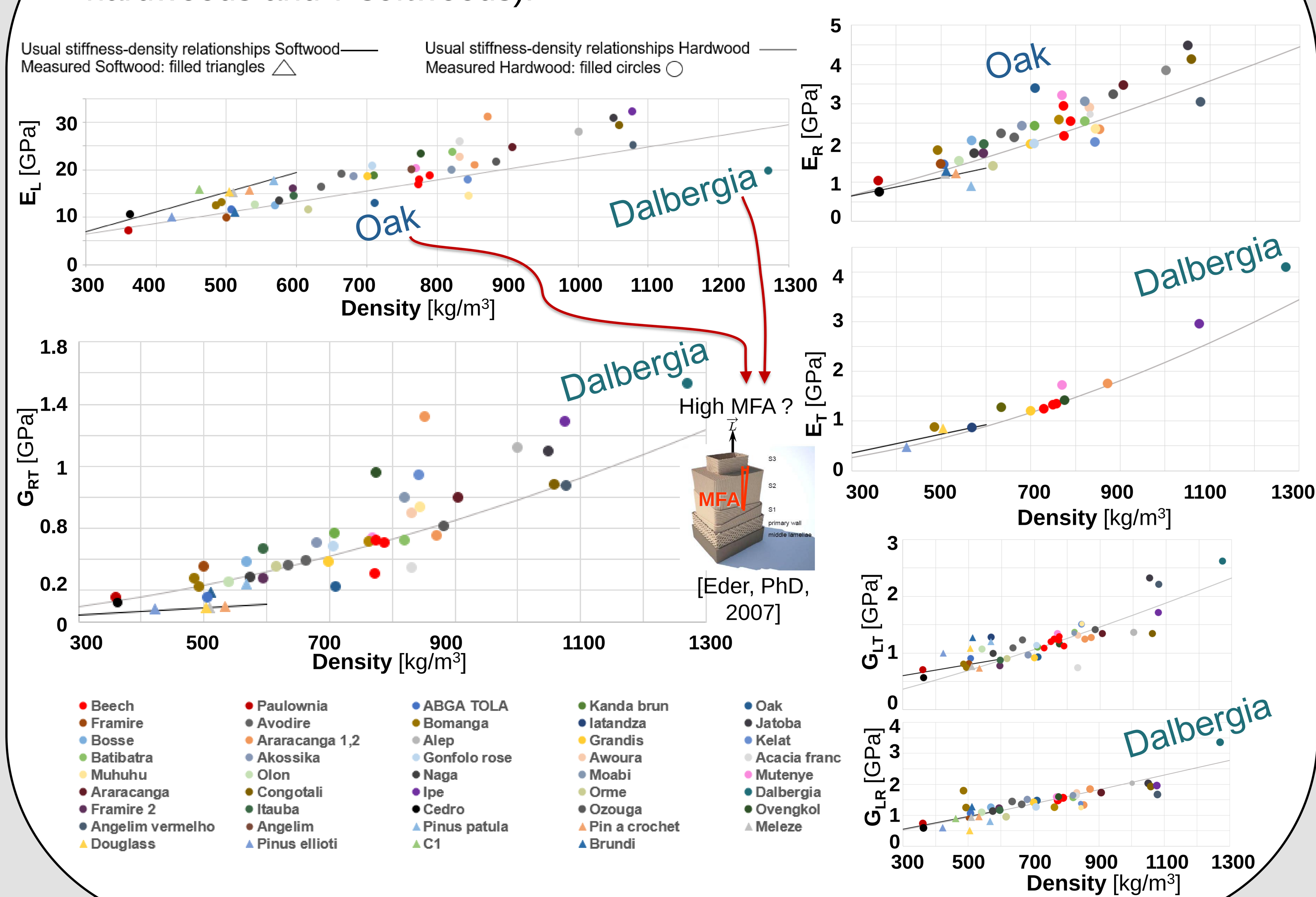
- Inverse identification using Matlab+Cast3m (**FEMU**):

➢ Minimization of frequency error:

$$\Delta_i = \sum_{j=1}^{n}\left(\frac{f_m^j - f_n^k(C_i)}{f_m^j}\right)^2$$

Identified elastic constants

E_L, E_R, E_T, G_{RT}, G_{LT} and G_{LR} *vs* density for **52 samples of 41 species** (45 hardwoods and 7 softwoods):



Conclusions/Perspectives

- **Robust identification** of five elastic constants of parallelepiped wood samples.
- Elastic constants **globally close** to usual stiffness-density relationships [3] for density < 900 kg/m³ but significant deviations > 900 kg/m³ [5].
- Usual model includes only density, **not MFA or extractives**.
- Calculation of elastic constants for additional wood samples over a large density range.
- Compare our results with US time-of-flight and quasi-static testing (in progress).
- Determine the uncertainty of identified parameters (in progress).
- XRD measurement of MFA directly on "xylotheque" samples (in progress).
- Study the relationship between wood's macroscopic elastic constants and anatomical properties (density and MFA).

References

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[5] Longo R. et al. (2017) Elastic characterization of wood by Resonant Ultrasound Spectroscopy (RUS): a comprehensive study. Wood Science and Technology, 52:383–402. DOI: 10.1007/s00226-017-0980-z