Elastic symmetry for wood mechanical characterization

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Abstract

Several hypotheses related to the elastical symmetry of wood were developed. Firstly, the material was studied with statical tests, and only one Young's modulus was determined along the fibers. This hypothesis. was abandoned in favor of much more complex symmetry. The orthotropic symmetry was advanced firstly by Felix Savart in XIX th century, in agreement with the structural characteristics of the material. Static techniques were used to measure the mechanical performance of this material used in the first part of XX-th century for the airplanes. Later, the development of technologies and of ultrasonics permitted the measurements of ultrasonic velocities on specimens of several size and shape, that facilitate the access to a set of elastic constants. In this way 9 ultrasonic stiffnesses has been measured and the corresponding 3 Young's moduli, 3 Coulomb moduli and 6 Poisson's ratios, were calculated. The triclinic symmetry is the most complex which allowed the determination of 21 constants.

Key words : wood , elastic symmetry, orthotropic , triclinic

1. Introduction

Wood is a natural fibrous composite. Mechanical characterization of wood behavior is based on the assumption that its properties can be represented by an equivalent homogeneous continuum. It must be clearly understood that the hypothesis of homogeneity of wood material is a very rough one. This hypothesis is a good approximation only in certain wavelength and frequency regimes.

In the early age of Material Science, wood was considered as an isotropic material, later as an orthotropic one , as proposed by Felix Savart in XIXth century [1], and more recently as a solid exhibiting triclinic elastic symmetry. These successive assumptions were imposed by several items, such as : the fine and precise description of the behavior of the material, the errors accepted for the validity of the description and the level of sophistication of the computing devices.

Acoustic energy injected in wood couples several modes on each fiber. The physical properties of the cellular wall and the shape and size of the fibers affect the transmitted acoustic field. When the wavelength becomes of the same order of magnitude as fiber length or diameter, fiber spacing or other physical size characteristics, then the material must be treated such as inhomogeneous.

The heterogeneity and anisotropy of media must be associated to the scale of observation. In the particular case of wood, the acoustical, mechanical and rheological properties are very much what we should expect from a bundle of complex structutred fibers. The physical properties of the cellular wall and the shape and size of fibers affect the transmitted ultrasonic field. The spatial distribution of velocities and frequencies that matched the frequency of wood fibers could explain the viscoelastic behavior of wood as illustrated by its overal parameters.

The anisotropic behavior of wood must be associated to the scale of observation. Acoustic anisotropy of wood is dur to the "ordered" structure at a small scale with respect to the used ultrasonic wave length. It is possible to distinguish two scales of observation such as :

- the textural anisotropy at the scale of "fibers" induced by the preferential orientation of anatomical elements (tracheids, fibers, vessels, etc) during the life of tree
- the microstructural anisotropy related to the cellular wall organization and the structural polycrystalline components.

At macroscopic scale, for experimental purposes, the natural cylindrical geometry of annual rings in trees can be avoided on samples , using trees of relatively big diameters (40 … 60 cm). The specimens must be located far from the pith, in zones of very small ring curvature. This experimental approach is also important in order to avoid physical description of the behavior of wood in curvilinear coordinate system.

2. Mechanical characterization of wood with acoustic methods

The mechanical characterization of wood behavior with acoustic methods can be made at global and local scale. The global characterization is related to the acoustical methods developed in audible and ultrasonic frequency range. The local characterization at the level of anatomical elements (fibers, vessels, etc) can be made with acoustic microscopy.

2.1 Vibratory methods in audible frequency range for global characterization

The vibratory methods in audible frequency range, below 20 kHz, allow the direct, accurate measurements of technical constants of wood in orthotropic symmetry, such as : three Young's moduli, three shear moduli and six Poisson's ratios.

The resonance method is one of the most convenient technique for precise measurement of technical parameters (Young's moduli and shear moduli), that depend upon measuring the resonance frequencies of longitudinal, flexural or torsional resonant modes of a bar shaped sample of circular or rectangular cross-section, or a plate sample. The fact that this technique is resonant ensures that frequency measurements will be highly precise.

Table 1 gives the Young's moduli of one of the most common species, the oak, in three anisotropic directions.

Table 1 : Young's moduli in principal anisotropic directions of oak (*Quercus Spp.*) deduced from longitudinal mode [2]

Anisotropic direction	Density (kg/m3)	Young's moduli (GPa)
R (radial)	654	1.58
T (tangential)	620	0.97
L (longitudinal)	630	12.0

2.2 Ultrasonic methods for global characterization

Applying the principles of Crystal Acoustics and Solid Mechanics to obtain precise estimates of the mechanical properties of solids leads to the development of an ultrasonic technique for measurement of the elastic constants of wood [3]. This technique is based on wave velocity measurements of bulk or surface waves. The relationships between the stiffnesses and velocities are given by the well known Christoffel's equation.

In the hypothesis that wood has an *orthotropic symmetry*, we have to determine nine elastic constants, or nine terms of stiffness matrix [Cij]. Measuring the six diagonal terms of the stiffness matrix from the velocities of bulk waves (dilatation and shear waves) that propagates along the principal symmetry axes is a relatively easy task. Linear equations must be solved in density and squared velocities as to obtain the six diagonal terms of the stiffness matrix. For the three off-diagonal terms of the stiffness matrix the velocities measured out of principal symmetry directions must be considered.

The directional dependency of wood constants renders conventional averaging techniques inapplicable on redundant measurements for off-diagonal terms calculation. To solve this problem an optimization inversion procedure must be used [3].

In the hypothesis that wood has a triclinic symmetry, 21 stiffness terms [4] must be determined, as can be seen from Table 2..

Table 2 : Terms of stiffness matrix [C_{ij}] of oak, in GPa, when the monoclinic symmetry is considered [4]. The axes are denoted such as : 1 = R, 2 = T and 3 = L

$$[C_{ij}] = \begin{array}{cccccc} \mathbf{3.48} & 1.89 & -0.12 & 0.19 & -0.15 & -0.01 \\ & \mathbf{2.06} & 0.61 & 0.34 & -0.08 & 0.03 \\ & & \mathbf{14.7} & -2.27 & 0.77 & -0.03 \\ & & & \mathbf{0.95} & -0.25 & -0.07 \\ & & & & \mathbf{1.46} & -0.09 \\ & & & & & \mathbf{0.33} \end{array}$$

For these experimental data,the measurements were performed on spherical specimens, in immersion technique, as described by [5, 6]. It was found that the direction of highest stiffness term coincide with the direction of the preferred orientation of fibers.

Aside from these, when we turn to the directional properties in RT plane, the R axis seems to predict higher terms than the axis T. This is in agreement with the anatomic structure of wood, that in R direction poses ray cells that facilitate the propagation of ultrasonic energy.

Magnitude of these mechanical parameters can be represented by an ellipsoid, completely specified by three axes. The principal axis of the ellipsoid coincide with the axis of fibers.

In Table 3 is given the deviation from higher symmetries for the real part of stiffness ternsor from the best reference frame.

Table 3 Deviation [%] of the real part of the stiffness tensors of oak wood from higher symmetries [4], compared with an ideal solid.

Elastic symmetry of the solid			
Isotropic	Transverse isotropic	Ortho-tropic	Triclinic
2 constants	5 constants	9 constants	21 constants
72.9%	10.9 %	5.2 %	2.8 %

The best reference frame was determined following the procedure proposed by [5], using Voigt stiffness tensor and dilatation tensor. It was accepted that for the media of orthotropic or higher symmetry the eigenvectors of both tensors are identical and aligned with principal directions, i.e. for monoclinic media the two sets have one vector in common and for triclinic media the two sets have no eigenvectors in common.

Accordingly, provided the complete elasticity tensor in given coordinate axes of arbitrary orientation, it is always possible to determine , from ideal data, the orientation of main symmetry axis .

2.3 Acoustic microscopy for local elastic characterization

Scanning acoustic microscopy (SAM) has emerged as a powerful tool for the microstructural characterization of materials. A qualitative characterization of the elastic properties of solids is obtained directly from SAM images rather a quantitative characterization of such properties can be obtained from an analysis of the V(z) curve, where V(z) is the output voltage of the trasducer as a function of the variation of the distance (z) between the focal plane of the acoustic lens and the sample surface. The periodicity of the minima in V(z) curve is related to the surface acoustic wave velocity of the specimen, propagating between the coupling fluid and the sample surface. Focusing in depth longitudinal and shear waves can be induced. With the values of velocities and of the local density, the local elastic constants of the solid can be calculated.

In the specific case of wood material qualitative characterization was obtained on oak, spruce and pine using a lens focused at 200 MHz [3]. More recently images of the tension wood were obtained at 600MHz frequency, with a resolution of 2µm. [7].

Another aspect of this technique is its subsurface imaging capability. Imaging interface of bonding between two opaque materials and volumetric control can be performed. Using this technique we refer here to the possibility of elastic constants measurements of all anatomic elements (fibers, vessels, microfibrils, etc) and to study the textural anisotropy.

3. Concluding remarks.

A comprehensive understanding of the development of nondestructive techniques for wood and wood –based composites necessitates an interdisciplinary approach

The development of the acoustic methods as an effective means for the examining the physical properties of wood and wood-based composites was based on the understanding of wave propagation phenomena.

Global and local examination of physical properties can be performed. Procedures for global characterization are related to the determination of elastic parameters in ultrasonic and audio frequency ranges.

Techniques for local characterization of wood anatomic elements are related to the development of acoustic microscopy. The unique capability of acoustic microscopy is to give fundamental information about the anatomical features of wood and their elastic properties without damaging natural structural organization.

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