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SHORT NOTE

ELASTIC CONSTANTS OF SIX WOOD SPECIES MEASURED WITH THE RESONANT BEAM TECHNIQUE

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ABSTRACT

The elastic properties of six wood species were determined using the resonant beam technique. By stimulation of transverse vibrations and analyzing the responding oscillations of carefully prepared rectangular beams of wood, simultaneous determination of one Young's modulus and two shear-moduli on one specimen is possible. Using three different cutting orientations along the principal material directions all three Young's moduli and three shear moduli can be determined. This paper presents the application of this technique to six wood species: two softwoods, two hardwoods and two tropical woods.

KEYWORDS: Resonant beam technique, wood, elastic constants.

INTRODUCTION

In the literature on wood mechanics, wood is generally treated as an orthotropic material (Bodig and Jayne 1993, United States Department of Agriculture 2010 (5/1–5/2 pp), Wagenführ and Scholz 2008, Kollmann and Côté 1968). Usually three orthogonal directions are used to describe the material: the longitudinal direction L – macroscopically parallel to the stem and microscopically parallel to the fibre direction, the radial direction R – pointing from the pith to bark and the tangential direction T – tangentially to the circumference of the stem and anatomically parallel to the year-rings. The full elastically description of such an orthotropic material requires 9 independent parameters: 3 Young's moduli, 3 shear moduli and 3 Poisson's ratios. Knowledge of these parameters is necessary to model the deformations and stresses in wood under mechanical loads in the elastic range for e. g. wooden constructions, but these data is often available only partially or not at all for rarer wood species. This paper aims to add the mechanical data of six wood species to the available datasets.

As testing method, the resonant beam technique (RBT) was chosen. With the resonant beam technique (Bucur 2006, Hearmon 1958, Hearmon 1946, Hearmon 1957, Hearmon and Barkas 1941, Kollmann and Krech 1960, Lins et al. 1999), it is possible to determine six of the nine parameters of an orthotropic material with three carefully prepared prismatic specimens oriented in principal material axes L, R and T. The resonance beam technique is therefore a very efficient method to measure elastic constants, especially for the determination of the shear moduli. Reliable data on elastic constants is prerequisite for numerical modelling of wood.

MATERIALS AND METHODS

Resonant beam technique

The resonant beam technique works by analysing the free transverse vibration spectra of prismatic beams (specimen). One modulus of elasticity along the beam and two shear moduli perpendicular to each other can be obtained from a single specimen by turning the specimen by 90° along its longitudinal axis. The specimen is suspended on two loops of fibre bundles connected to piezoelectric transducers and to allow free transversal vibrations. On one end, the specimen is excited by a piezoelectric transducer with a sinusoidal signal of defined frequency; on the other end, the oscillations of the specimen are registered with a piezoelectric receiver. Sweeping the excitation frequency slowly from low to high (0.1 kHz – 60 kHz) and measuring the vibrations at the receiver side, a spectrum will be obtained. This experimental spectrum shows several resonance peaks, which are further compared to the theoretical resonances obtained by solving numerically Timoshenko's beam theory for an initial guess of parameters (Timoshenko 1922, 1921, Hearmon 1958). Timoshenko's beam theory is a further development of the classical Euler-Bernoulli-beam-theory taking account for rotatory inertia and shear deformations (Hearmon 1958). The model parameters are then varied to minimize the sum of squares between the modelled and the measured resonance frequencies. The experimental technique applied for this work is described in more detail by Lins et al. (1999) and Puchegger et al. (2003a, 2003b, 2005, and 2006).

Wood

For this study, six wood species covering a wide range of densities and properties were chosen. The softwoods were Western red cedar (*Thuja plicata*) and European larch (*Larix decidua* Mill.), the two hardwoods from temperate climates were oak (*Quercus robur*) and beech (*Fagus sylvatica*) and the two tropical hardwoods were wenge (*Milettia laurentii*) and courbaril (*Hymenaea courbaril*).

All raw materials were stored in standard climate at 20°C and 65% relative humidity to allow the moisture content to be in equilibrium with the atmosphere before specimen preparation. Specimens were then prepared from planks of stem wood and raw densities were measured. Care was taken to prepare specimens with their material axis parallel to the cutting planes of the prismatic specimens (Fig. 1). The size of the specimens was not uniform, as it depended on orientation and uniformity of growth. A typical size e. g. of longitudinal specimens was 100 x 10 x 12 mm. A minimum of six samples were prepared and scanned for each species.

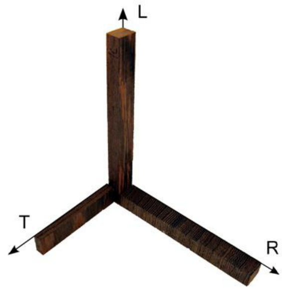

Fig. 1: Prismatic specimens of wenge cut in principal material directions.

RESULTS AND DISCUSSION

The results of the mechanical constants from the fitting procedure are summarized in Tab. 1 and the results from literature data are summarized in Tab. 2.

Tab. 1: Experimental results for raw-density and elastic constants of investigated wood species.

	ρ (kg·m^{-3})	E^L (GPa)	E^R (GPa)	E^T (GPa)	G^{LR} (GPa)	G^{LT} (GPa)	G^{RT} (GPa)
Western red cedar	370 (19)	9.36 (0.17)	1.18 (0.14)	0.67 (0.17)	0.91 (0.25)	0.38 (0.31)	0.18 (0.10)
European larch	583 (14)	13.89 (1.60)	1.37 (0.37)	1.02 (0.07)	0.64 (0.27)	0.64 (0.18)	0.51 (0.94)
Beech	764 (32)	21.24 (0.60)	1.92 (0.04)	1.06 (0.07)	1.20 (0.35)	1.74 (1.03)	0.49 (0.09)
Oak	636 (26)	13.09 (0.27)	1.97 (0.06)	0.96 (0.01)	1.20 (0.29)	1.01 (0.34)	0.32 (0.01)
Wenge	836 (58)	19.93 (1.60)	2.80 (0.03)	1.62 (0.30)	1.53 (0.15)	1.61 (0.41)	0.52 (0.09)
Courbaril	955 (11)	16.29 (0.32)	3.47 (0.06)	2.77 (0.70)	2.16 (0.52)	1.52 (0.85)	0.72 (0.28)

*(Standard deviations in parenthesis).

Moduli of elasticity perpendicular to grain and shear moduli could not be found for all investigated species in literature, especially shear moduli were missing (compare Tab. 2). This confirms the necessity of this work. To compare at least averaged data for softwoods and hardwoods with literature, averages of the elastic constants were calculated and normalized by the longitudinal Young's modulus. The literature values were calculated from table 5-1 of (United States Department of Agriculture 2010). Ratios of averaged parameters from experimental data for softwood and hardwood agree reasonably well with the ratio from literature (Tab. 3), neglecting the influence of density for this rough approximation. Remarkable in Tab. 3 is the increasing ratio of the radial modulus of elasticity to the longitudinal modulus of elasticity, which reflects the increasing amount of ray tissue from softwood to tropical wood. Whereas the moduli of elasticity can be determined in an accurate way from transverse vibrations the shear moduli are more difficult to determine due to the anisotropic structure of the material. The methodical error increases if the shear modulus is of the same order as the Young's modulus (Puchegger et al. 2005). This is valid especially for G^{RT}, where the specimen length orientation is either allocated to the radial or the transverse direction of wood. Additional sources of errors are density gradients within the samples due to the annual structure and grain deviations like interlocked grain observed e. g. for Wengé and Courbaril. These inhomogeneities in density strongly influence the shear coupling in free vibration. Therefore, the spectra measured were distorted and damped, which made identification of some of the resonance peaks more difficult and increased the measurement error. See also Lins et al. (1999) for a deeper discussion on measurement errors.

Tab. 2: Raw-density and elastic constants of investigated wood species from literature.

	ρ ($kg·m^{-3}$)	E^L (GPa)	E^R (GPa)	E^T (GPa)	G^{LR} (GPa)	G^{LT} (GPa)	G^{RT} (GPa)
Western red cedar	370* 310***	8.0* 7.7***	-	-	-	-	-
European larch	590*	12.0*	-	-	-	-	-
Beech	890*	14.0*	2.28*	1.16*	1.64*	1.08*	-
Oak	690*	13.0*	1.5*	0.82*	0.88*	0.62*	-
Wenge	860**	17.5**	-	-	-	-	-
Courbaril	950** 800***	15.7** 14.9***	-	-	-	-	-

*(Niemz 1993, 217-220 pp.), **(Wagenführ 2000, (399-400 pp., 121-122 pp.)), ***(United States Department of Agriculture 2010 (2/22 pp., table 5–5a)).

Tab. 3: Average ratios of elastic constants referenced to the longitudinal modulus of elasticity. Ratios calculated from United States Department of Agriculture (2010) table 5-1 and compared to average experimental data from Tab. 1.

	E^T/E^L, (%)	E^R/E^L, (%)	G^{LR}/E^L, (%)	G^{LT}/E^L, (%)	G^{RT}/E^L, (%)
softwood	5.7	9.6	8.2	7.7	0.9
exp. softwood	7.3	11.0	6.7	4.4	3.0
hardwood	5.7	11.4	8.9	6.7	1.8
exp. hardwood	5.9	11.3	7.0	8.0	2.4
Exp. tropical wood	12.1	17.3	10.2	8.6	3.4

CONCLUSIONS

The resonant beam technique is a reliable and fast method to determine Young's moduli and shear moduli of orthotropic materials like wood with a relatively low effort regarding the shape and the number of specimens. The experimental results for the moduli of elasticity correspond reasonably well with literature data, while no complete set of reference values could be found for the investigated species. The resonance beam technique applied to other wood species could be a powerful tool to help filling these gaps.

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