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COMPARATIVE ANALYSIS OF THREE DIFFERENT METHODS USED TO DETERMINE THE ELASTIC MODULUS FOR A CHOICE OF TROPICAL GUIANESE WOOD SPECIES

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Abstract:

This study compares variability in the longitudinal Modulus of Elasticity (MOE) values, measured by three different methods, for eight tropical wood species covering a wide range of densities, a property that has been little described in the literature for some of the species studied. The modulus of elasticity in wood species is one of the main mechanical properties measured to characterize wood materials. However, this property is seldom described for the tropical wood species studied here, and the method used is often variable. The aim is to answer the following questions. In the methods used, what are the main variability factors which influence modulus measurement? Is the modulus different with regard to the solicitation direction (radial or tangential)? Which relationship exists between modulus and density for these species?

The samples were subjected to the four-point bending test, then to the free vibration test and to the forced-vibration test (which allows tests on small samples).The samples were subjected to stress in radial and tangential directions. The modulus values obtained by the different methods were well correlated for most of the species. The relationship between modulus and density was very good at inter-specific level because sampling covered a wide range of densities. But this relationship was not so good for each of the species sampled.

This kind of test was not appropriate for detecting differences in behavior between the two directions of solicitation for these species. The main features of the three methods were summarized, highlighting the advantages of each for the species studied.

***Key words**: density; modulus of elasticity; static and dynamic tests; tropical woods.*

INTRODUCTION

The Modulus of Elasticity (MOE) is one of the main mechanical properties measured to characterize a wood species. With MOE, density, shrinkage and durability, it is possible to easily determine the end-use of a specific wood. MOE is also a key property for implementing and modeling wood building; it is often the only mechanical property available for a species.

Many laboratory methods exist to assess this physical parameter: the method of quasi-static bending, vibration, sound and ultrasonic dynamic methods. Each one has its advantages and disadvantages. Some of these methods, such as bending or vibration tests, are already used on sawmill production lines, or in industrial carpentry or building, but only for a quick strength grading of wood pieces. This was not directly the purpose of our work. Indeed, it is important to be able to compare and assess the relevance of these different laboratory methods because they estimate the same property or magnitude, namely MOE. It should be noted that the methods used differ depending on the requirements. For example, for an accurate description of MOE changes along the radius in the tree, a method based on forced flexural vibrations of free-free beams is used; on the other hand, to

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study wood MOE scattering outside a population, a free vibration test or a bending test is preferred.

The aim of this work was, firstly to compare our values with those existing in the bibliography, secondly to compare the estimated values of three acoustic, vibration and quasi-static methods for species subjected to stress in radial and tangential directions and, lastly, to study modulus data scatter and its relationships with variables such as density and species.

Many studies report on the results obtained with different approaches to local and global static MOE. Boström (1999) studied the differences between various methods used in standards to obtain these parameters. Piter *et al.* (2003), regarding the relationship between global and local MOE, like Aicher *et al.* (2002), proposed a new method for determining local MOE, while Brancheriau *et al.* (2002) produced an analytical formula to transpose the measurements obtained in a 3-point bending test to those obtained by a 4-point bending method. At the same time, several papers covered dynamic methods for determining MOE that were easier to carry out and faster too; the investigation principally dealt with two methods: one based on the time of ultrasound wave propagation between probes, the other based on the measured natural frequency of wooden boards (Marchal and Jacques 1999; Wang *et al.* 2001). The ultrasonic technique is applicable from standing trees to structural timbers. MOE evaluated by this method overestimates MOE compared to static measurement (Divós and Tanaka 2005; Rohanová *et al.* 2010; Hassan *et al.* 2013). The natural frequency technique consists in subjecting a dually-supported piece of timber to an impact (Yang *et al.* 2003; Leite *et al.* 2012). More recently, the focus has been on methods with small samples requiring less material (Bremaud 2006) to simplify grading as measurements are faster, or for characterizing anatomical features of wood (Dinh 2011; Perre *et al.* 2013) with micro devices built for the purpose, but not easy to use. Those studies generally refer to the static bending test as a reference for MOE.

OBJECTIVE

In this work, we compared the static MOE obtained by the European standard EN 408 (2004), with two dynamic methods: bending free-vibration and forced-released vibration, for tropical woods with a wide range of densities.

MATERIALS AND METHODS

Four-point bending test

The four-point bending test was carried out according to standard EN 408 on a universal loading machine (MTS20M). In the 4-point bending test, the loads are applied to a third of the sample. Global MOE is based on a deformation measurement in the center of the beam, and the total deformation measurement is used to calculate MOE_G (Eq. 1). Local MOE is based on a deformation measurement at the center of a central gage length of five times the depth of the section, and the local deformation measurement is used to calculate MOE_L (Eq. 2).

$$MOE_G = \frac{a}{48I}\left(3l^2 - 4a^2\right)\frac{F}{w_g} \text{ [GPa]} \tag{1}$$

$$MOE_L = \frac{al_1^2}{16I}\frac{F}{w_l} \text{ [GPa]} \tag{2}$$

where: I is the moment of inertia of the transverse section: $I = \frac{eh^3}{12}$ [m^4] for the wood geometry used,

e is the thickness, in m,
h is the width, in m,
F is the applied load increment, in N,
w_g and w_l are the deformation increments, in m,
l is the length between the two supports, in m,
a is the distance between the load point and the nearest support, in m
l_1 is the central gage length, in m.

Free vibration test

The BING (Beam Identification by Nondestructive Grading) method initially developed by Bordonné (1989) uses the principle of the spectral analysis of free bending vibration. The sample is placed in elastic supports (rubber bands) in order to generate free vibration. Whenever possible, the supports are placed on the vibration nodes of the fundamental frequency (Brancheriau 2002). Vibration is produced by tapping one end of the specimen using a wood-tipped hammer. The microphone on the other end recovers the acoustic information and transforms it into an electrical signal. The spectral composition of the record is obtained by Fourier Transformation, and the spectrum is analyzed to determine the resonance frequency. Each test is conducted in triplicate and the best determination coefficient is chosen. The calculated specific MOE using the fundamental frequency f_1 is given by Eq. 3 (Bordonné 1989).

$$\frac{MOE_B}{\rho} = 4l^2 f_1^2 \ \text{[GPa/kg/m}^3\text{]} \tag{3}$$

where: l is the specimen length in m,
ρ the wood density, in kg/m^3.

Forced-vibration test of a beam

The non-contact forced-released flexural vibration of a free-free beam apparatus (hereafter called Vibris) was designed by Brémaud (2006), and works with thinner beams. The wood sample is supported by two thin silk threads. As described previously, the supports are placed on the vibration nodes of the fundamental frequency. A scanning frequency is imposed using an electromagnet positioned opposite a very thin steel pad glued to the extremity of the specimen. The amplitude of vibration of the test piece is measured by a non-contact displacement laser sensor. The specific dynamic modulus of elasticity is determined, for the resonance frequency considered, by Eq. 4 according to the Euler-Bernoulli model.

$$\frac{MOE_D}{\rho} = \frac{48\pi^2 l^4}{m_n^4 e^2} f_{Rn}^2 \ \text{[GPa/kg/m}^3\text{]} \tag{4}$$

where: l is the length of the specimen, in m,
e its thickness, in m,
f_{Rn} is the resonance frequency of mode n, in Hz,
m_n is a constant depending on the mode order (for the fundamental, m_1 = 4.730) (Brémaud *et al.* 2012).

Both dynamic methods also enable the measurement of internal damping, an important property of woods that is not covered in this paper.

Material and Sampling

Specimen selection

The eight species were taken from the Paracou experimental site (5°16'N, 52°55'W), a lowland tropical forest near Sinnamary, French Guiana (Gourlet-Fleury *et al.* 2004) except for *Ochroma pyramidale* (Cav. Ex Lam.) Urb. taken from a secondary forest near the Mana River. The wood species were selected in order to cover a wide range of densities (147-1334 kg/m^3) – see Table 1.

Table 1

Material used and mean density of the samples tested

Sample size	360 mm x 20 mm x 20 mm M-samples			➡	360 mm x 10 mm x 3 mm S-samples			
Species		Density ρ_M (kg/m^3)				Density ρ_S (kg/m^3)		
	N	Mean	Min-Max	*CV* (%)	N	Mean	Min - Max	*CV* (%)
***O**chroma* ***py**ramidale* *(Cav ex* Lam)	3	180	160 – 206	10.52	12	203	147 – 265	16.39
***P**arkia* ***ni**tida* Miq.	11	260	227 – 315	9.96	44	265	227 – 389	13.04
***S**imarouba* ***am**ara* Aubl.	11	431	397 – 460	4.65	44	433	384 – 466	5.04
***S**extonia* ***ru**bra* (Mez) *van* der *Werff*	10	573	554 – 601	2.51	40	577	532 – 633	3.80
***D**icorynia* ***gu**ianensis* Amshoff	14	722	694 – 786	3.51	56	720	658 – 823	4.56
***V**ouacapoua* ***am**ericana* Aubl.	11	889	827 – 922	2.78	44	884	823 – 966	3.10
***H**androanthus* ***se**rratifolius* (Vahl) S.	11	962	946 – 977	0.98	44	952	899 – 1 004	2.16
***B**ocoa* ***pr**ouacensis* Aubl.	11	1 310	1 226 – 1 325	1.25	44	1 280	1 183 – 1 334	2.91

Note: *CV* is the coefficient of variation, N is the number of tested samples

Specimen preparation

Density was measured on samples stabilized at a 12% moisture content, and was given as the ratio of specimen mass, as measured with a scale accurate to 0.001g, to a specimen size, as measured with a micrometer in transversal dimensions and with a graduated steel rule in longitudinal dimension.

For the 4-point bending test and for the free vibration test, the specimens were cut to dimensions of 360 x 20 x 20mm^3 (longitudinal x radial x tangential). After these tests, the samples (N = 82) were divided into two slender batches, cut to dimensions of 360 x 10 x 3mm^3 (N = 328): the first along the longitudinal/radial (LR) plane, the second along the longitudinal/tangential (LT) plane (Fig. 1), and then subjected to a forced vibration test.

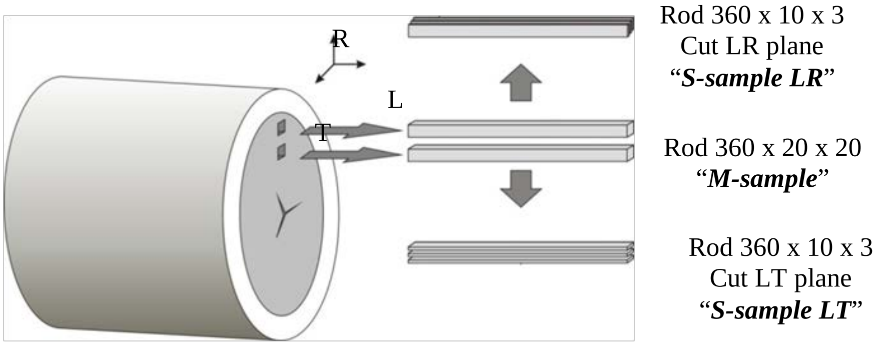

Fig. 1.
Sampling method.

Experimental method

The M-samples were first tested on the 4-point bending instrument, in two directions: in one case, the sample was aligned in the LR plane (length/depth), so the stress direction was tangential; we called the corresponding MOE MOE_{GT} for the global measurement, MOE_{LT} for the local measurement. In the other case, the sample was aligned in the LT plane (length/depth), so the stress direction was radial; we called the corresponding MOE $MOE_{G(L)R}$. The same procedure was used for the free vibration test, giving two MOE values: MOE_{BT} (LR plane) and MOE_{BR} (LT plane).

The S-samples machined along the radial direction (LR) were solicited in a forced vibration test that gave the MOE_{DT} measurement. We called the measurement made on the S-samples machined along the tangential direction (LT) MOE_{DR}. Unlike the previous two methods, it was not possible in this case to take the two measurements on the same sample.

For both dynamic methods, each test was conducted in triplicate. The test result for a sample was the mean value of the measured parameters. Further, these tests gave the specific modulus, while the static bending test gave the modulus.

Experimental conditions

The theoretical accuracy of the density measurement was less than 0.3% for the bigger samples (so called M-samples), i.e. twice as low as the slender samples, so called S-samples (0.6%).

For the static bending tests, the applied load varied from 150 N (*O. py.*) to 600 N (*B. pr.*), at a rate of 66μm/s.

The theoretical accuracy was 4% for the static MOE_G and 4.7% for MOE_L.

The sampling frequency for both dynamic experiments was 100 Hz. The first resonance frequency ranged from 654Hz (*S. ru.*) to 864Hz (*P. ni.*) with the BING device, and from 83Hz (*S. ru.)* to 135Hz (*P. ni.*) with the forced vibration test.

The theoretical accuracy of the specific modulus was 3% for the BING test and 5.9% for the forced vibration test, due to the estimated accuracy of the S-sample thickness measurement.

Statistical method used

The statistical analysis was performed using XLSTAT 2015. Coefficients of correlation between the mechanical properties obtained by the different methods and the densities were first calculated. To discriminate between those correlations, a mean comparison on paired samples was carried out. For regression analysis, the coefficient of determination between observed values and predicted values was calculated. Fig. 4 was produced using the R statistical platform (R Development Core Team, 2011).

RESULTS: EFFECT OF SOLICITATION DIRECTION, DEVICE TYPE AND DENSITY

Correlations between MOE values

Table 2 illustrates the correlation between the different MOE values obtained in the static tests and dynamic tests for all the woods studied, and between the M-density and the S-density. The first part of the table shows correlations between MOE values according to the two directions for each method; the Vibris method did not enable a comparison of the MOE measurements carried out in R and T solicitations, since they were not achieved on the same specimen. The second part shows correlations calculated from mean $MOE_{(R,T)}$ values obtained by the static and BING devices and the mean of the four measured values corresponding to each bulky sample by Vibris. Lastly, the correlations are observed between densities according to the cut direction (LR plane or LT plane). In the case of *O. py.* only one M-sample was cut again for a test in an R solicitation (cut in the LT plane).
Table 3 shows the correlations between density (ρ_M) and mean $MOE_{(R,T)}$ values for the static methods and BING, and between density (ρ_S) and MOE_D, for all the species studied.

Table 2

Correlation between the different MOE values obtained for all the woods studied vs loading direction, test methods and species densities (Pearson's coefficients)

	Loading direction			Different methods				Densities	
Species	$r_{G(R,T)}$	$r_{L(R,T)}$	$r_{B(R,T)}$	$r_{G,L}$	$r_{G,B}$	$r_{G,D}$	$r_{B,D}$	LR plane $r_{(ST,M)}$	LT plane $r_{(SR,M)}$
O. py.	0.997	0.996	0.885	1.000	-0.221	0.942	0.119	0.744	
P. ni.	0.722	0.571	0.799	**0.896**	0.842	0.812	0.663	**0.661**	**0.724**
S. am.	0.824	0.671	**0.946**	0.873	**0.929**	0.866	**0.972**	**0.971**	**0.845**
S. ru.	0.770	0.869	**0.932**	**0.875**	**0.877**	0.763	**0.914**	**0.773**	0.674
D. gu.	**0.824**	0.119	0.773	0.761	0.732	0.541	**0.784**	**0.871**	**0.762**
V. am.	0.569	0.482	**0.971**	**0.968**	**0.891**	**0.909**	**0.919**	**0.912**	0.434
H. se.	0.599	0.161	**0.853**	0.754	0.618	0.456	0.803	0.561	0.331
B. pr.	0.780	0.499	**0.942**	0.733	**0.936**	0.786	0.655	0.104	0.119

Values in bold are different from 0 at an alpha=0.001 significance level
1st column: $r_{(G \text{ or } L \text{ or } B)(R,T)}$: correlation coefficient between radial and tangential load solicitation for global, local and BING methods
2nd column: correlation coefficient between the different methods: $r_{G,L}$ global and local, $r_{G,B}$ global and BING, $r_{G,D}$ global and Vibris, $r_{B,D}$ BING and Vibris
3rd column: correlation coefficient between densities for the two sizes of samples according to machining

Table 3

Correlation between density and MOE for the different methods with G global loading, L local loading, B BING method and D Vibris method (Pearson's coefficients).

$r_{M/S}$	N	meanMOE$_G$	meanMOE$_L$	meanMOE$_B$	N	MOE$_{D,R}$	N	MOE$_{D,T}$
O. py.	*3*	1.000	1.000	-0.226	*4*	0.989	*8*	**0.963**
P. ni.	*11*	**0.941**	0.768	**0.880**	*20*	**0.913**	*24*	0.601
S. am.	*11*	-0.559	-0.525	-0.596	*24*	-0.171	*20*	**-0.471**
S. ru.	*10*	0.787	0.683	0.749	*20*	0.475	*20*	0.516
D. gu.	*14*	0.373	0.097	0.550	*28*	**0.632**	*28*	0.587
V. am.	*11*	0.442	0.432	0.547	*20*	**0.792**	*24*	**0.925**
H. se.	*11*	-0.199	-0.126	-0.226	*20*	0.203	*24*	**0.637**
B. pr.	*11*	0.160	0.250	0.333	*24*	**0.843**	*19*	**0.778**

Values in bold are different from 0 at an alpha=0.001 significance level

Density comparison according to sample size

Minimum, maximum and mean values, and the standard deviation, are shown in Table 1. The density measurements reflected the heterogeneity within the same species, for both M-samples and S-samples. The standard variation in measurements exceeded 10% for the lightest samples (*O. py., P. ni.*), but was less than 5% for the others. The density of the S-samples *O. py.* was generally higher by 5 to 6% than the density of the M-samples, with no particular influence of the cut plane. Conversely, the heaviest wood studied (*B. pr.*) showed scattered S-sample densities that were globally lower than those of the M-samples from which they stemmed (Fig. 2). This difference was confirmed by a t-test whatever the cut plane involved (LR plane, N = 20, t = 4.561, p = 0.000; LT plane, N = 24, t = 2.255, p = 0.034).

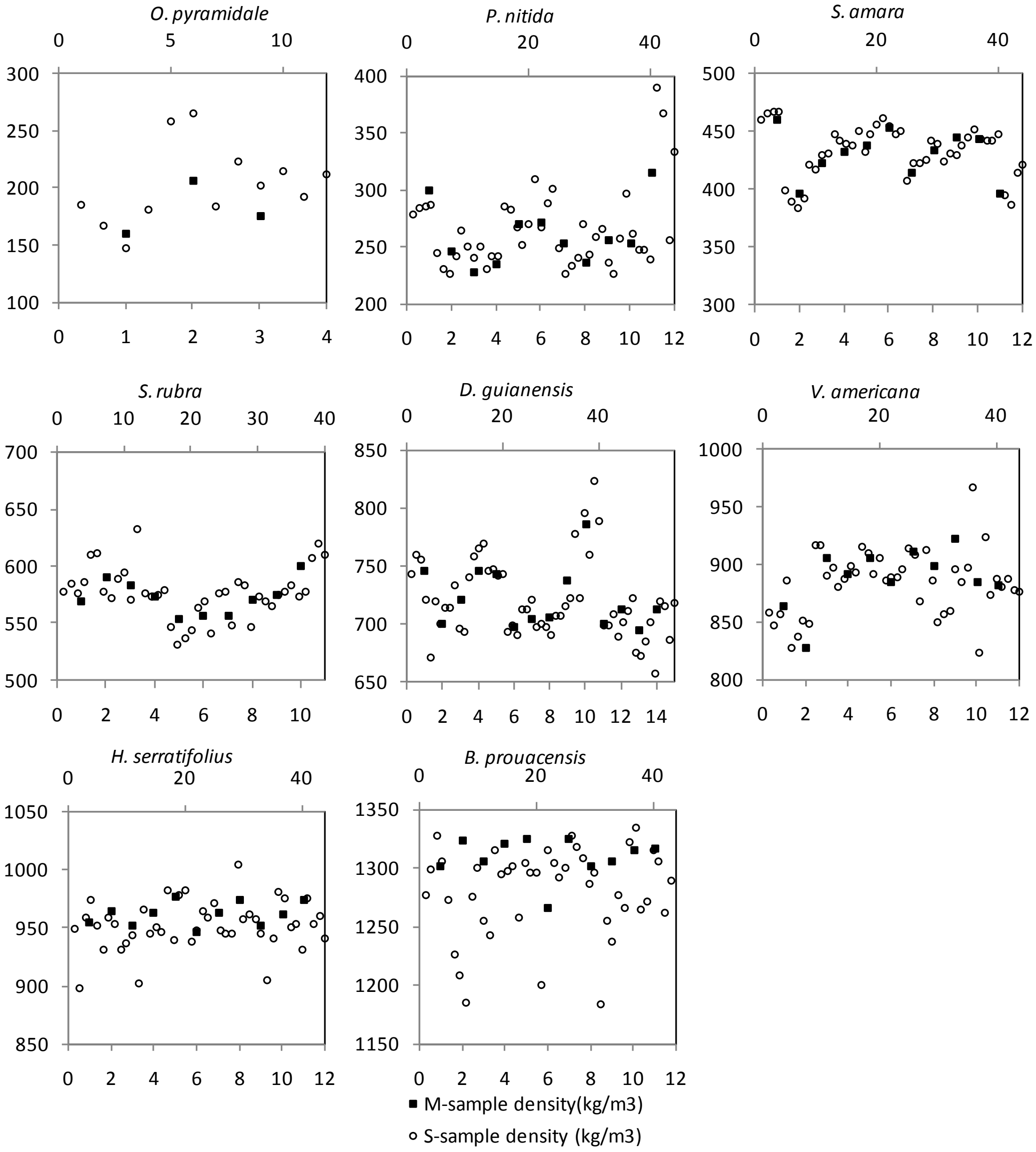

Fig. 2.
Change in density along a radius. Location sample on horizontal axis.

MOE comparison for two directions of solicitation and for different methods

Table 4 shows the MOE values obtained by the different methods for the two directions of solicitation and for the various species studied. Modulus variations are presented as a function of sampling position (Fig. 3). According to the species, the measurement scatterings observed were significantly different with regards to the methods used.

Table 4

Longitudinal MOE (GPa) measured in the radial and the tangential directions by different methods with G global loading, L local loading, B BING method and D Vibris method

		MOE_G	MOE_L	MOE_B	MOE_D
Species	*Loading direction*	***Mean** (min - max)* *Coefficient of Variation (%)*			
O. py.	R	**3.28** (3.00 - 3.62) 7.8	**3.82** (2.94 - 4.91) 21.4	**3.19** (2.49 - 4.26) 24.1	**5.45** (3.45 - 6.74) 24.0
	T	**3.13** (2.77 - 3.62) 11.4	**3.77** (3.44 - 4.23) 8.8	**3.72** (3.20 - 4.40) 13.4	**4.19** (2.82 - 5.32) 18.1
P. ni.	R	**4.94** (3.72 - 5.85) 12.7	**5.17** (3.32 - 6.49) 15.9	**5.95** (4.05 - 8.06) 22.1	**7.07** (4.69 - 12.03) 28.0
	T	**5.00** (4.00 - 6.87) 15.6	**5.35** (4.41 - 7.78) 17.4	**5.71** (3.41 - 9.23) 27.8	**6.15** (4.97 - 9.18) 15.9
S. am.	R	**9.68** (7.81 - 10.62) 11.0	**9.58** (7.67 - 11.07) 12.2	**10.88** (9.04 - 12.03) 10.4	**10.79** (7.78 - 12.35) 10.4
	T	**9.81** (7.79 - 11.86) 10.8	**9.93** (7.77 - 12.35) 13.2	**10.88** (9.07 - 12.13) 10.4	**10.08** (7.90 - 11.81) 12.3
S. ru.	R	**10.11** (8.15 - 13.17) 15.7	**10.85** (9.05 - 12.12) 8.9	**12.11** (10.22 - 15.70) 14.2	**10.66** (7.80 - 13.54) 14.7
	T	**9.57** (7.68 - 11.88) 13.7	**10.53** (7.66 - 14.00) 17.3	**11.94** (10.28 - 15.16) 13.5	**11.79** (8.27 - 20.28) 23
D. gu.	R	**15.11** (13.04 - 16.71) 7.0	**15.69** (13.10 - 17.62) 8.0	**17.26** (16.17 - 18.06) 3.2	**16.00** (9.33 - 19.61) 13.3
	T	**15.01** (13.46 - 16.48) 5.2	**15.74** (14.35 - 17.73) 6.5	**17.55** (16.28 - 19.33) 5.2	**17.17** (14.18 - 22.60) 11.8
V. am.	R	**19.86** (17.08 - 25.04) 10.9	**19.96** (17.57 - 24.09) 8.9	**21.53** (18.82 - 24.74) 8.2	**19.42** (15.17 - 26.39) 13.5
	T	**19.55** (16.52 - 25.22) 12.2	**19.50** (16.41 - 24.63) 12.9	**21.52** (18.66 - 24.40) 8.3	**21.45** (18.11 - 23.02) 6.6
H. se.	R	**21.41** (19.85 - 25.61) 7.0	**21.44** (19.27 - 23.25) 6.6	**22.74** (21.46 - 24.19) 3.5	**21.53** (19.74 - 23.75) 6.0
	T	**21.81** (19.64 - 25.56) 8.7	**21.93** (19.42 - 26.87) 11.5	**22.71** (21.35 - 24.15) 3.7	**21.13** (17.87 - 24.02) 6.4
B. pr.	R	**29.84** (27.95 - 33.21) 5.4	**28.65** (25.68 - 31.01) 6.8	**32.56** (30.31 - 36.32) 5.7	**29.72** (23.25 - 33.88) 9.7
	T	**29.90** (27.03 - 33.23) 5.7	**28.80** (26.28 - 32.36) 6.5	**32.49** (29.94 - 36.65) 6.3	**30.57** (24.11 - 35.81) 11.1

Modulus-density relation

Fig. 4 shows MOE_D variations versus density. When considering our species as a single population, the correlation of the data set with the density was excellent ($r > 0.9$). However, if each species was taken separately, this finding was not necessarily verified any more (Table 3).

DISCUSSION

Comparing our results with those in the literature

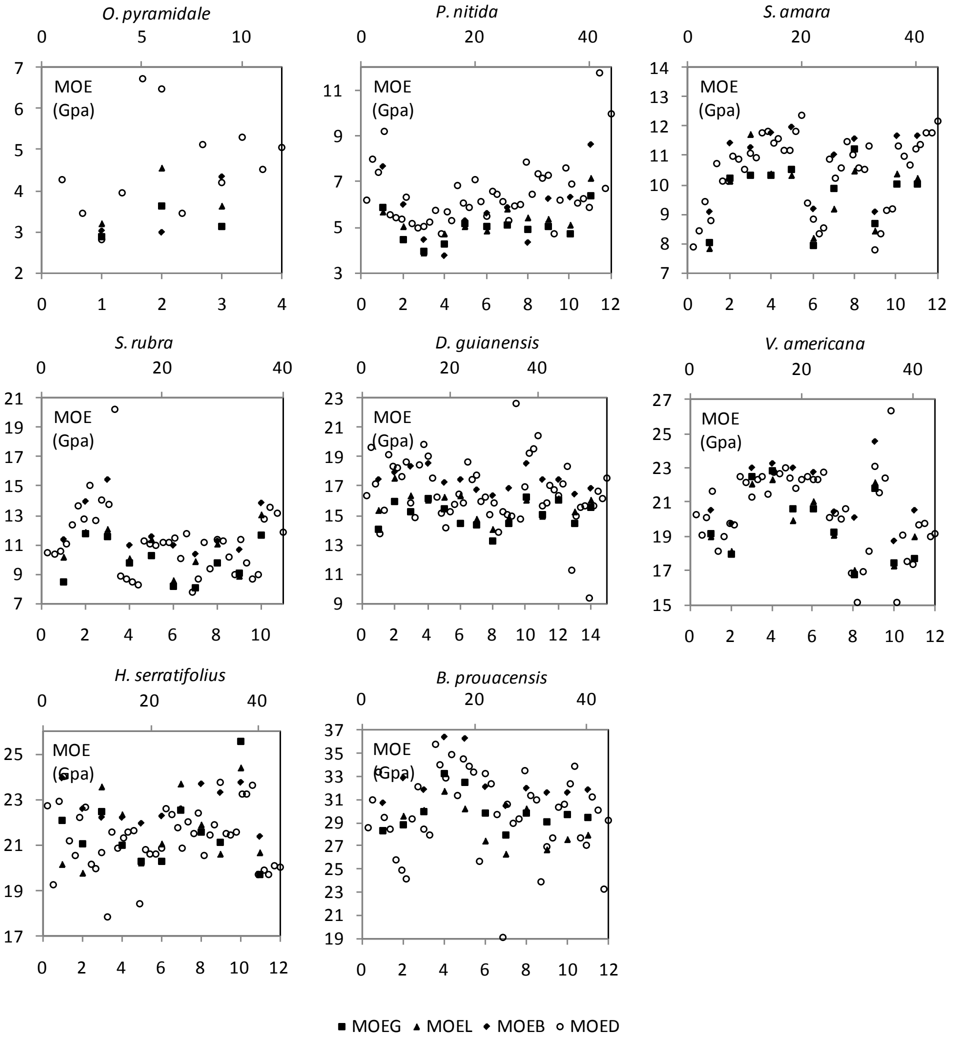

Fig. 3.
Change in MOE versus sampling location.

The static and BING methods are well described for hardwoods and softwoods of temperate areas, but the literature regarding these methods applied to the species studied in this paper is rather limited. Although some databases are partially completed, the implementation method and/or sample sizes are not indicated (Guitard and El Amri 1987, Kretschmann 2010, Tropix CIRAD). The results relative to the studied species showed lower MOE values when the density was lower (all methods combined), than the data referenced in the Tropix database. According to Brémaud (2006), MOE values measured by Vibris are 10% lower on average than those of CIRAD databases, which may be partly explained by the fact that the sample is smaller, thus more sensitive to local variations in grain angle (for species with an interlocked grain), or due to local variations in the microfibril angle (MFA). Relationships between wood stiffness and MFA generally show decreasing longitudinal MOE with increasing MFA (Yamamoto *et al.* 2001, Barnett and Bonham 2004, Ruelle *et al.* 2007).The most detailed data which we listed concerned *D. gu.*, *S. am.*, *S. ru.*, *H. se.* and *B. pr.*

D. gu. sample measuring 50mm x 150mm², solicited in static tests under EN 408, showed a MOE of 21.48GPa for a density of 725kg/m^3 (Ravenhorst *et al.* 2004); at equivalent density, the mean MOE_G of our samples was smaller (15.06GPa). The MOE (Vibris method) of an air-dried wood of 50 x 12 x 2mm^3 was 15.12GPa for a 600kg/m^3 density (Dlouhá *et al.* 2011); if we extrapolated the MOE trends in Fig. 4, our measurement would be weaker. Baillères *et al.* (1998), on samples sized

55 x 138 x 3000mm^3 and for a density of 700 to 950kg/m^3, showed a MOE of 19.75GPa in static solicitation (EN 408) and 20.94 in BING solicitation, which are values substantially higher than ours (mean MOE$_B$ = 17.41GPa) with the same methods. Grain or local MFA variations make the moduli of smaller samples more sensitive.

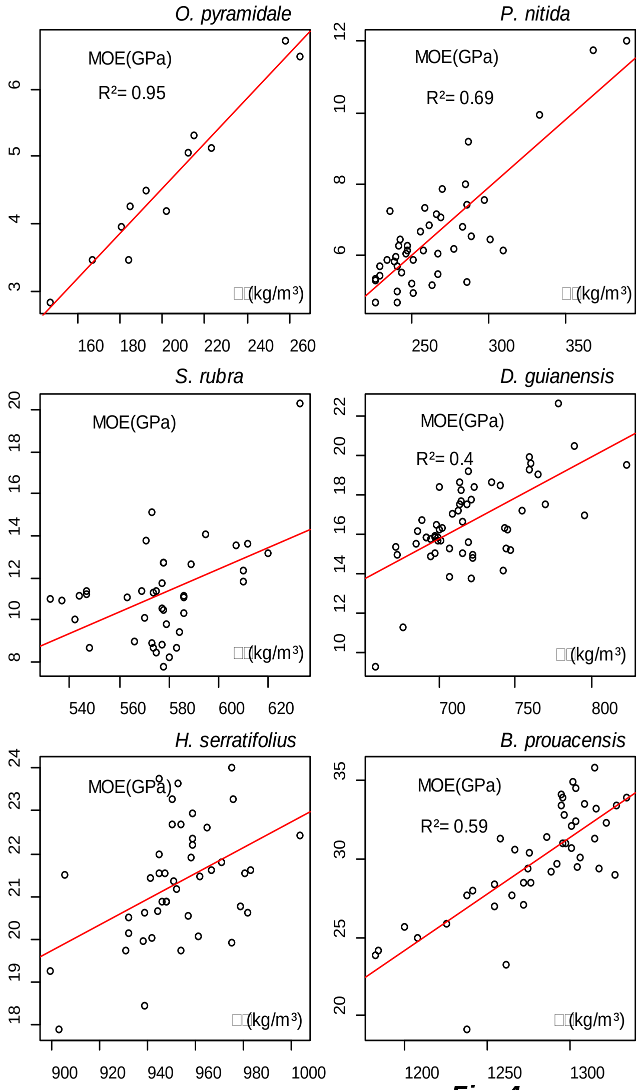

Fig. 4.
Change in MOE$_{D(R,T)}$ versus density for the eight species studied.

Determination coefficients R² are indicated when the p-value of the linear fitting model is lower than 1‰.

S. am. presented a MOE measured by the Vibris test on 2 x 8 x 200mm^3 samples of 9.38GPa for a density of 391kg/m^3 (Zhang *et al.* 2011); the *MOE$_D$* values obtained on the studied woods were around this value. When measured by BING on samples 12 x 12 x 200mm^3 in size and a density ranging from 310 to 360kg/m^3, the MOE varied from 10.54 to 11.45GPa for tension wood, and from 7.01 to 8.94GPa for opposite wood (Ruelle *et al.* 2010). These values were in accordance with our *MOE$_B$* measurements for which we also observed two populations, but we cannot conclude on the existence of tension wood because it is not visually recognizable.

The MOE of *S. ru.*, on 150 x 2 x 12mm^3 samples, for a density ranging from 470 to 550kg/m^3, measured by DMA, ranged from 6.76 to 12.30GPa (Mc Lean *et al.* 2012), which were values very close to the measured *MOE$_D$* (11.22GPa, on average). For boards measuring 45 x 20 x 1900mm^3 and for a mean density of 682kg/m^3, Teles *et al.* (2011) indicated a mean MOE of 15.31GPa for a static test according to ASTM D4761 (2003), and 16.74GPa for a dynamic test (measurement of the beam’s natural frequency after the board was hammered). These values are well above our *MOE$_G$* (9.84GPa) or MOE_B (12.03GPa), but the density and volume of our samples were lower.

For *H. se.* with a mean density of 1000kg/m^3 (25 x 25 x 410mm^3 in size), Del Menezzi *et al.* (2010) measured a static MOE according to ASTM D143-94 (2000) of 18.79GPa, and 20.41GPa for a dynamic method. Although our $MOE_{G,B}$ values were significantly higher (21.61GPa and 22.72GPa, respectively), the gap in the measurements between both methods was of the same order of magnitude. Vibris measurements (Bremaud *et al.* 2012), on 150 x 12 x 2mm^3 samples for a density of 850kg/m^3, led to a MOE of 19.72, which is less than the mean of our values (MOE_D = 21.32GPa with ρ_S = 952kg/m^3).

B. pr., also studied by this author with the same apparatus on samples of the same dimensions, showed a MOE of 32.76GPa for a density of 1260kg/m^3, a value higher than our mean MOE_D (30.09GPa for ρ_S = 1281kg/m^3).

To conclude, it was found that MOE, for the same species, was substantially different when the samples originated from two distinct trees (McLean *et al.* 2011). Nevertheless, the values of our measurements were well encompassed by the literature data.

Effect of loading direction

The BING apparatus did not distinguish modulus values according to loading direction, regardless of the species (Table 4). The weakest correlations found were linked to a greater scattering of measurements in the case of *P. ni.* with, in particular, two samples that gave a MOE_{BT} value 40% lower than the MOE_{BR} value. Conversely, for *D. gu.*, it was most of the MOE_{BT} values that were very slightly higher than MOE_{BR}.

Generally, MOE_{GR} was better correlated to MOE_{GT} than MOE_{LR} to MOE_{LT} (cf. Table 2, first three columns) with, in particular, a much degraded correlation between local measurements for *D. gu.* and *H. se.*. Indeed, for *D. gu.*, one third of local measurements showed MOE_{LR} values that were quite different from MOE_{LT}, the differences being ±15%, with no clear trend. Scattering was even greater for *H. se.*, where no direction seemed privileged, but with half of the samples showing $MOE_{L(R,T)}$ values that differed by 12%, and even reaching 27%. The $MOE_{G(R,T)}$ values for *H. se.* were also poorly correlated, but there was less scattering. For *V. am.*, the correlations between local and global measurements in radial and tangential directions were low, while the correlation between local and global measurements, for a given direction, was good ($r_{(G,L)T}$ = 0.896 and $r_{(G,L)R}$ = 0.973). Lastly, in most cases, we found greater scattering in tangential solicitation than in radial solicitation for local measurements (Table 4).

According to Grotta *et al.* (2005), who worked on 10 x 10 x 300mm^3 samples of Douglas fir (ASTM 2003 standard), MOE did not differ along the growth rings and MOE variations were weaker if the load was applied along the LR plane instead of the LT plane with very slight bending. While the measurement scatter of M-sample MOE_T for *D. gu.* (global or local), or *S. ru.* (BING), and of S-samples for *O. py.*, *P. ni.*, *D. gu.* and *V. am.* was indeed less than that of MOE_R, this was not the case for *P. ni.*, *V. am.*, or *H. se.* (global or local). The 8 species tested did not display especially marked anatomic heterogeneity (no large woody radius, no marked growth-ring observed), but the decrease in scale may reveal local heterogeneity. For example, a *B. pr.* showing a defect in the LR plane gave a MOE_{DT} of 19.10GPa.

For the Vibris tests, we found MOE_{DR} values that were slightly higher than the MOE_{DT} values for *O. py.*, *P. ni.*, and *S. am.*, while *S. ru.*, *D. gu.* and *V. am.* showed the reverse behavior. The static measurements did not reflect such a situation, and the MOE variational trends obtained by the different methods were rather the same (Fig. 3). The fact that the tangential and radial measurements were not carried out on the same sample made it difficult to draw any conclusion.

All the observations failed to demonstrate a difference in behavior, if it existed, between load directions, indicating that this kind of test was not appropriate for detecting differences for those species. In contrast, it seemed preferable to apply loading along the R or T direction, depending on the species, to reduce measurement variance.

Comparison of the methods used

Hereafter, MOE_G is chosen as the reference value (Table 2, fourth to sixth columns).

MOE_L vs. MOE_G

The correlations between global and local measured values were good.

The MOE_L and MOE_G values for *V. am.*, *S. am.* and *H. se.* were equivalent. MOE_L overestimated MOE_G: from 5 to 6% for *P. Ni.*, 8% for *S. ru.*, up to 16% for *O. py.*, and from 4 to 5% for *D. gu.*, whereas *B. pr.* presented a MOE_L value around 4% lower than MOE_G. In these last two cases, the difference was of the same order of magnitude as the theoretical accuracy.

These observations did not tally with those of either Boström (1999), Holmqvist and Boström (2000), or Nocetti's conclusions (Nocetti *et al.* 2013) for the softwoods studied. Furthermore, the last authors observed slightly higher MOE_L values (8.6%), but with $MOE_L>MOE_G$ for high moduli (over 8.3 GPa). However, softwoods are locally more heterogeneous since they alternate a layer of dense wood (final wood) and a layer of light wood (initial wood) in each ring and local measurements are more sensitive to wood defects. Moreover, due to their ontogeny, they have many knots, especially in large-dimension beams. The tested woods were homogeneous tropical hardwoods and our small samples were free of any apparent knots, which may explain this behavior. As the values were not obtained on the same material, conclusions have to be drawn with care, but we can say that the global and local MOE values of our samples were in good agreement.

MOE_B vs. MOE_G

Moduli obtained by the BING apparatus were well correlated with those obtained in the static tests, except for *O. py.*. But for it, the number of samples was not enough for a significant statistical analysis.

MOE measurements by the BING apparatus were systematically higher than $\mathrm{MOE_G}$, but in different amounts (Fig. 3): 5% for *H. se.*, 9% for *V. am.* and *B. pr.*, 11% for *S. am.*, up to 15% (*P. ni.*, *D. gu.*) and even 20% (*S. ru.*). In addition, the $\mathrm{MOE_B}$ values for *O. py.*, *P. ni.* and *H. se.* could be locally lower than the $\mathrm{MOE_G}$ values. This behavior may have arisen from disturbances of higher order modes of the frequency spectrum (Baillères *et al.* 1998).

The MOE_B values were more scattered for *O. py.*, *S. ru.* and *P. ni.*, but the standard deviation of the BING measurements was less than for the static tests for *H. se.*. Haines *et al.* (1996) also found that scatter was greater for MOE values smaller than 9GPa.

Most of the comparative studies found in the literature deal with softwoods. Measurements by BING are systematically higher than in static tests, by 6% for a static MOE of 11.36GPa (Leite *et al.* 2012), by 11% with static MOE values ranging from 9.09 to 12.9GPa (Yin *et al.* 2010), by 12% for a static MOE ranging from 3 to 8GPa (Hossein *et al.* 2011), and by 13% with a static MOE of 11.73GPa (Liang and Fu 2007). The measured MOE_B on tropical woods studied in this paper accurately reflected what is observed in other species with the same modulus.

MOE_D vs. MOE

The results obtained by the Vibris apparatus were compared with those of the other two methods. Measurement scatter was quite variable with the species involved, as well as with the solicited direction (Table 4).

Mean MOE_D vs. MOE_G

Unlike the previous methods, there was no pair of points for each measurement, since one measurement with the 4-point test or BING apparatus matched four separate measurements with the Vibris apparatus. Thus, the mean of the four measurements obtained by Vibris was compared with the corresponding value of the measurement obtained in the static tests (Table 2, sixth column). Here also, the measurements in the dynamic method were higher than those in the static one: 4% for *V. am.* (the same order of magnitude as the theoretical accuracy), 7% for *S. am.*, 10 to 12% for *D. gu.* and *S. ru.*, and up to 27% (*P. ni.*) and 36% (*O. py.*). However, there were two exceptions: *B. pr.* and *H. se.* showed identical mean MOE values for both methods, but measurements on *B. pr.* displayed a greater standard deviation in the dynamic tests than in the static tests, while a lower standard variation was observed for MOE_D than for MOE_G in the case of *H. se.*. Note that MOE measurements with Vibris may be locally lower than MOE_G. With the usual geometry (l/h = 120) of the specimens in the study, the contribution of shear should have been negligible in the first bending mode, whatever the wood type, so the contribution of shear properties did not under-evaluate MOE_D.

Few studies have been undertaken on slender specimens. Haines *et al.* (1996) reported results obtained by resonance flexure tests on small specimens of spruce less than 1mm thick, 5mm wide and 30mm long. He indicated that, although the results were only qualitative, the observed difference between the mean of the static modulus and dynamic modulus measurements was less than 3% for a static MOE of 13.6GPa, but the method used and the species considered were different. According to this author, the viscoelasticity of wood material or lignin is the most likely source of the difference noted. Lack of homogeneity may also have played a role.

Mean MOE_D vs. MOE_B

MOE_D was globally weaker than MOE_B, by 4 to 5% for *S. am.*, *V. am.*, and *D. gu.*, and by 6% for *H. se.,* which were differences of the same magnitude as the theoretical accuracy, by 8% for *S. ru.,* and for *B. pr.* MOE_D was higher than MOE_B by 3% for *O. py.* and by 11% for *P. ni.*.The two dynamic methods were rather well correlated (cf. table 2, seventh column) for *S. am.*, *S. ru.*, *D. gu.* and *V. am.*, but less in the other species studied. *O. Py.* showed a globally higher density after machining M-samples along the LT plane (cf. Table 1 and Fig. 2), which was equivalent to overvaluing MOE_D (it should be remembered here that dynamic MOE is derived from specific MOE), whereas *B. pr.* had a globally lower density after machining, which was equivalent to undervaluing MOE_D. These differences may be linked to machining (crushing of the cell walls for *O. py*., streaks for *B. pr.*).
Ilic (2003), compared different dynamic methods for differently sized specimens (20 x 20 x 300mm^3 and 20 x 2 x 150mm^3) from hardwood and softwood species, and highlighted that the results between dynamic measurements were well correlated, within the same species. Anatomical characteristics, such as the angle of cellulose microfibrils (S2 layer) and wide rays (rays of parenchyma cells), could be expected to have an effect by diverting the fiber direction away from the longitudinal direction and possibly lowering wood stiffness.

The originality of the Vibris test was to enable wood characterization on a smaller scale, which revealed the diversity of the behavior in the M-samples. Furthermore, dynamic methods make it possible to evaluate wood viscoelasticity by measuring the damping coefficient (tanδ). Further investigations should make it possible to characterize these properties more finely, and specify them for each of the species studied.

MOE vs. density

Density is known to be a good MOE predictor, with the linear model (Guitard and El Amri 1987). In their analysis, Ravenhorst *et al.* (2004) showed that it is difficult to make reliable prediction models for all hardwood species individually, unlike softwood species such as pine and spruce. On the other hand, when hardwood species are not considered as an individual population, but are merged together to form one large “timber” population, then the correlation between non-destructive measured properties and bending strength appears to be good. We made the same ascertainment for the prediction of MOE using density. The linear regression applied to the tests carried out showed that, on the one hand, there was no notable difference depending on the solicited axis for the M-samples and, on the other hand, that the elastic properties of wood can, overall, be quite well correlated to density, with a coefficient of correlation over 0.97. When applied to each of the species separately, the correlation was rarely significant.

When observing the MOE versus density relationship for each of the eight species separately (Fig. 4), we found a positive relationship between these two variables for most species. However, the correlation was only really significant for five species and was even inverted for *S. am.,* for which it was clearly two populations in our data, one with MOE lower than 9 or 10GPa (static or dynamic measurements), the other with a higher modulus, and in both cases a weak dependence of the modulus relative to the density. Conversely, the MOE variations of *H. se.* were substantial while density varied little.

This increase in the variability of properties within the tree was not exceptional. It has been described by many authors such as McLean *et al.* (2012) for MOE or Williamson and Wiemann (2010), Schüller *et al.* (2013) for density. In much tropical forest, trees are subjected to various conditions and social positions during growth (more or less protected, more or less exposed to the elements). Changes in environmental conditions during development lead to different functional needs at wood level, sometimes causing significant variations in the properties within the tree.

At inter-specific level, MOE measurements were strongly correlated with those for density, irrespective of the apparatus used. For global MOE, for example, density explained 96.1% of variability by a linear regression, on all the tested species. When testing the species effect by an analysis of covariance (ANCOVA), it was found that adding the species to density as an explanatory factor only added 0.8% of explanation for the model (adjusted $R^2 = 0.969$). The fact that we sampled a very large range of densities (160 to 1325kg/m^3) minimized the species effect with regard to the density effects.

CONCLUSION

The three methods used were quite equivalent in terms of the reliability of the results, each having experimental features enabling a focus on either measurement speed, or on shaping ease, or on measurement accuracy.

This study also highlighted the importance of sampling.

Intra-individual and inter-individual variability was substantial for some species, and it is advisable to take care when sampling, so that it is representative enough of the “average behavior” of the species. Conversely, a Vibris apparatus enables very precise measurements in order to study the variability of properties within the tree.

Dynamic methods make it possible to evaluate wood viscoelasticity by measuring the damping coefficient (tanδ). As the viscoelasticity of wood material could be the most likely source of the difference noted between static and dynamic methods, further investigations will be carried out to test interpretations.

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