Experimental Assessment of the Annual Growth Ring's Impact onthe Mechanical Behavior of Temperate and Tropical Species

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This study presents an innovative experimental protocol linking a nondestructive (on computed tomography scanner) and destructive approach (bending test on electrostatic press). This study aims to evaluate the annual growth ring's impact on the mechanical behavior of wood. The tests were carried out on temperate specimens (*Pseudotsuga menziesii* and *Abies alba* Mill) from the Massif Central Region of France and tropical specimens (*Aucoumea klaineana* Pierre, *Milicia excelsa*, and *Pterocarpus soyauxii*) from Gabon. The connection between the mechanical parameters, taken from these tests and their structural characteristics are also highlighted. Based on these results, a database was formed of the annual growth ring's impact on the mechanical characteristics of these species. The results show that there is a link between the annual growth ring, and the mechanical and physical characteristics of the species. The number and width of the earlywood ring and its mechanical properties are also investigated for each type of species. This comparison and the link highlighted was possible due to the study of the impact of dry density's specimens, considered in this work as an adjustment parameter on the study of the mechanical behavior of these species.

Keywords: Tropical species; Temperate species; Congo basin forest; Massif central forest; Bending test

*Contact information: a: Université Clermont Auvergne, CNRS, Institut Pascal, BP 10448, 63000 Clermont-Ferrand, France; b: USTM, Ecole Polytechnique de Masuku (EPM), LareVa Bois, BP 901 Franceville Gabon; c: Luleå University of Technology, Division of Wood Science and Engineering, Department of Engineering Sciences and Mathematics, Forskargatan 1, 931 87, Skellefteå, Sweden; d: CENAREST, IRT, BP 14070, Libreville, Gabon; *Corresponding author: pclaudefeldman@gmail.com*

INTRODUCTION

Predicting the behavior of wood under mechanical or environmental stress is essential to improve the design and durability of timber structures (Gérard et *al*. 2011). This refers to the understanding of the various physical and mechanical characteristics of wood. This understanding is affected by the multitude of climates encountered throughout the world, which attribute to each species endemic characteristics proper to the environment in which the species is found (Manfoumbi Boussougou 2012). One explanation of these intrinsic characteristics could be given by the anatomical structure for each species (Fig. 1).

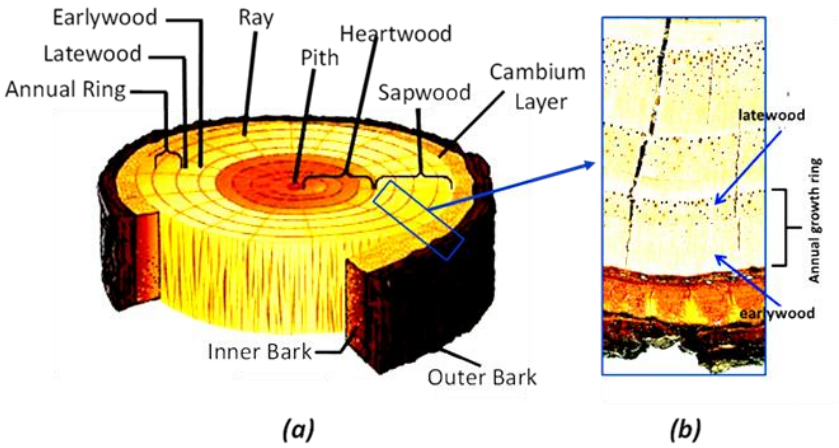

Fig. 1. (a) Cross-section of a tree trunk and (b) annual growth ring of wood

The microscale structure in wood globally affects its mechanical behavior. This can be investigated due to advancements in theoretical, numerical, and experimental approaches. Gershon *et al*. (2010) have shown that it is necessary to know the microscale structure ofpalmetto wood to be able to optimize its fracture toughness. Another work on palmetto wood (Saavedra Flores 2016) explains that there are influences of several micro-structural features (such as cellulose content and its crystallinity, the microfibril angle, and the cell-wall thickness of micro-fibers) on the Young modulus and density. The growth of annual rings affects the mechanical behavior of wood (Miksic 2013). Wood is a heterogeneous, anisotropic, and hygroscopic natural composite material, with high strength and stiffness relative to its weight (Mishnaevsky and Qing 2008; Bahar 2019). By starting from these hypotheses, Stanzl-Tschegg (2006) noted that the structure of wood is highly optimized for the needs of living trees. This does not mean that wood is optimized for usage in constructions where this article is focusing. The study by Morales-Conde and Machado (2017) assesses the cross-section for variation of timber bending of modulus of elasticity and brings more information linked to our work. The authors show, despite the stress waves approach used, a great correlation between the cross-sectional variation and the modulus of elasticity of the wood studied, which roughly fits with the aims of this study. Based on previous studies (Jaskowska-Lemańska and Wałach 2016; Ramage et *al.* 2017; Zeller et *al*. 2017; Abdelmohsen et *al*. 2018), it is logical to say that the mechanical behavior of wood is based on its micro-structural features, for example content of cellulose, fibril angles, and the annual growth rings.

This work aims at performing an experimental comparative study on five species with different physico-mechanical characteristics. The study is made possible due to a specific experimental approach built by connecting annual growth rings with global mechanical behavior by determining their intrinsic mechanical characteristics. Five species were studied: two European temperate species from the Massif Central in France, Douglas fir (*Pseudotsuga menziesii*) and White fir (*Abies alba* Mill); and three tropical species from Gabon, Okume (*Aucoumea klaineana* Pierre), Iroko (*Milicia excelsa*) and Padouk (*Pterocarpus soyauxii*). The difference between the chosen species is the climate of their habitat. In Gabon, for example, the climate shows a mean annual rainfall of 1900 mm, a mean relative humidity of 85%, and mean annual temperature of 27 °C (Medzegue *et al*. 2007; Pambou Nziengui *et al*. 2017; Engonga Edzang *e*t *al*. 2020). This kind of region has two types of seasons: a six months' dry season and a six months' rainy season.

During the dry season, almost no rainfall occurs in comparison to the rainy season when most of the rainfall occurs. Thus, the quantity of water absorbed by the tree during the rainy season becomes very important for the growth of the tree.

To date, no study has compared tropical species (African tropical region) and temperate species regarding the link between the growth of annual rings and the mechanical properties. The reason for this concern is that the tropical species has a continuous growth of annual rings during the year (Manfoumbi Boussougou 2012; Ramage et *al*. 2017) and this is not the case for the studied temperate species. Both the tropical and temperate species are commonly used in structure for heavy and light frameworks, glulam, paper pulp, fiber panels, in cooperage, packaging, maritime work, and luxury furniture (Adamopoulos 2009; Treml and Jeske 2012; Sopushynskyy 2017). In France there were more than 170 Mm^3 of white fir and 93 Mm^3 of Douglas fir in 2009 (Pambou Nziengui et *al*. 2019). The chosen tropical species are the most widespread species in the tropical forest of Gabon and also among the most exported and used species in the field of timber structures (Odounga *et al*. 2018).

EXPERIMENTAL

Wood specimens

The wood specimens were cuboid shaped with the approximately dimensions of 200×10×10 mm^3 (Fig. 2). These specimens were cut following the fiber direction (in the longest direction). A total of 125 clear wood specimens was obtained. The specimens of temperate species were taken from collapsed beams used in an earlier study of creep tests (Pambou Nziengui *et al*. 2019; Tran et *al*. 2018). The specimens of tropical species were cut from butt logs at an approximate position of one meter above the roots of the standing tree (Odounga *et al*. 2018). To equalize the moisture content (MC) of the specimens, the specimens were stored in a climate chamber for 48 h. The temperature and the relative humidity in the climate chamber were set to 20 °C and 64.7%, respectively. Table 1 shows the total number of specimens and the statistical mean of the principal physical characteristics for each group before the experimental campaign.

Table 1. Number of Specimens and Physical Characteristics for Each Tested Species Group with Coefficient of Variation (*COV*) in Parentheses

	Species	Name	No.	MC_{mean} [%]	$\rho_{dry,\,mean}$ [kg/m^3]
Temperate	Douglas fir	DF	30	9.8 (11.1%)	563 (4.5%)
	White fir	WF	48	9.9 (13.6%)	447 (8.1%)
Tropical	Iroko	*I*	17	9.0 (17.8%)	582 (13.8%)
	Padouk	*P*	15	8.3 (13.4%)	733 (3.0%)
	Okume	*O*	15	10.3 (15.7%)	505 (4.1%)

No.: number of specimens; MC_{mean}: mean moisture content; $\rho_{dry,\,mean}$: mean dry density

To distinguish the earlywood and latewood, which make up the annual growth ring, the specimens were scanned in a computed tomography scanner (CT-scanner). The data from the CT-scanner was visualized and analyzed by the Image J software (https://imagej.nih.gov/ij/).

Four-points flexural test

All specimens were loaded in four-point flexural test until failure by an electrostatic press (Fig. 2). The four-point bending test set-up was performed according to the European requirement (EN 1995-1-1 2004) and as presented by (Manfoumbi Boussougou 2012). The specimens were measured and weighed to determine their physical parameters (Table 1).

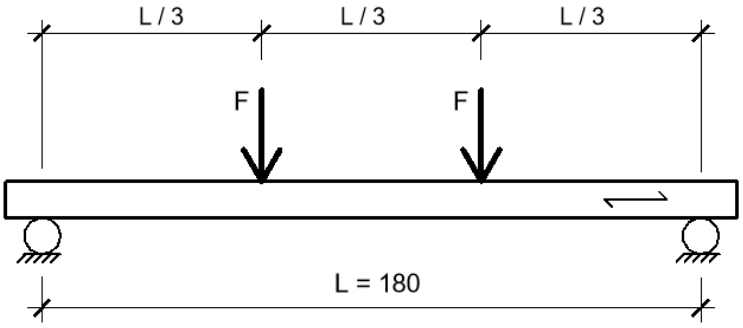

Fig. 2. Four-point flexural test set-up with the fiber direction of the specimen loaded

The modulus of elasticity (MOE) was calculated for each specimen according to Eq. 1,

$$MOE = \frac{23L^3}{648I_z\left(2\frac{F_2-F_1}{W_2-W_1}-\frac{2L}{5Gbh}\right)} \quad (1)$$

where F2-F1 is an increase of force on the regression line and W2-W1 is the increase of the corresponding displacement as described in the European standard requirement (EN 1995-1-1 2004). L represents the distance between the two supports (Fig. 2), I_z the moment of inertia, G is the shear modulus, b and h are the width and height of the specimen, respectively. Due to lack of data for the tropical species, the influence of G was neglected. The maximum flexural stress was defined to Eq. 2,

$$C_{max}=M_y/I_z \quad (2)$$

where M is the flexural moment at the maximum force, F_{max}, during the four-point flexural test, y is the distance from the neutral axis to the area of highest flexural moment and I_z the moment of inertia. For this four-point flexural test set-up, M was calculated as presented by Eq. 3,

$$M=(LF_{max})/3 \quad (3)$$

To calculate C_{max}, the length y in Eq. 2 can be set equal to h/2 [25]. A comparison between C_{max} calculated in this study and the maximum flexural failure stress given by the CIRAD wood collection (Gérard et al. 2011), C_{mcir}, was done.

RESULTS AND DISCUSSION

Mechanical Characterization of the Specimens in Static Tests

The mean values of modulus of elasticity (*MOE*), maximum loading (F_{max}), and maximum flexural stress (C_{max}) obtained, for each species studied, are presented in Table 2. The C_{mcir} value is the maximum flexural stress given by the CIRAD wood collection

(Gérard *et al*. 2011). The highest MOE_{mean} of 15.6 GPa was obtained for DF species. The lowest MOE_{mean} of 9.2 GPa was calculated for O. The lowest and highest F_{max}, mean was measured for WF and DF, respectively and the specimens with largest variation among the tropical and temperate species was P and DF, respectively. By taking into account the results of (Gérard *et al*. 2011) and its dry density (Table 1), P was expected to have the highest C_{max} mean among all tested species, but according to Table 2, it had a lower C_{max} mean but with the highest *COV*. In general, all tested species (except WF and P) had a higher C_{max}, mean than C_{mcir}. These results highlight the intra-extra trees variability, which exists for specimens taken from the same trees.

Table 2. Result from the Four-Point Flexural Test with *COV* in Parentheses

	Name	MOE_{mean} (GPa)	$F_{max,\ mean}$ (N)	$C_{max,\ mean}$ (MPa)	C_{mcir} (MPa)
Temperate	DF	15.6 (10.5%)	522 (20.7%)	102 (20.4%)	91
	WF	10.7 (16.4%)	383 (15.3%)	77 (16.0%)	80
Tropical	*I*	12.8 (18.1%)	492 (13.7%)	94 (14.8%)	87
	P	14.1 (13.5%)	407 (21.6%)	83 (21.5%)	116
	O	9.2 (9.1%)	422 (12.7%)	82 (11.9%)	62

Figure 3 shows the evolutions of the C_{max} *versus MOE* for all tested specimens. There was an increasing C_{max} for a higher *MOE*. This behavior is observable for the both temperate and tropical specimens. The difference in *COV*, which exists for the groups of specimens presented in Table 2 is also visible in Fig. 3 by the highlighting of the dispersion, which seems large for DF (for the temperate specimens) and P (for tropical specimens). The groups of specimens with lower *COV* (O and WF) showed a non-scattering pattern in Fig. 3 compared to groups of specimens with higher *COV*. The R^2-values for the trendlines were calculated as 0.41, 0.41, 0.53, 0.30, and 0.53 for DF, WF, I, O, and P, respectively.

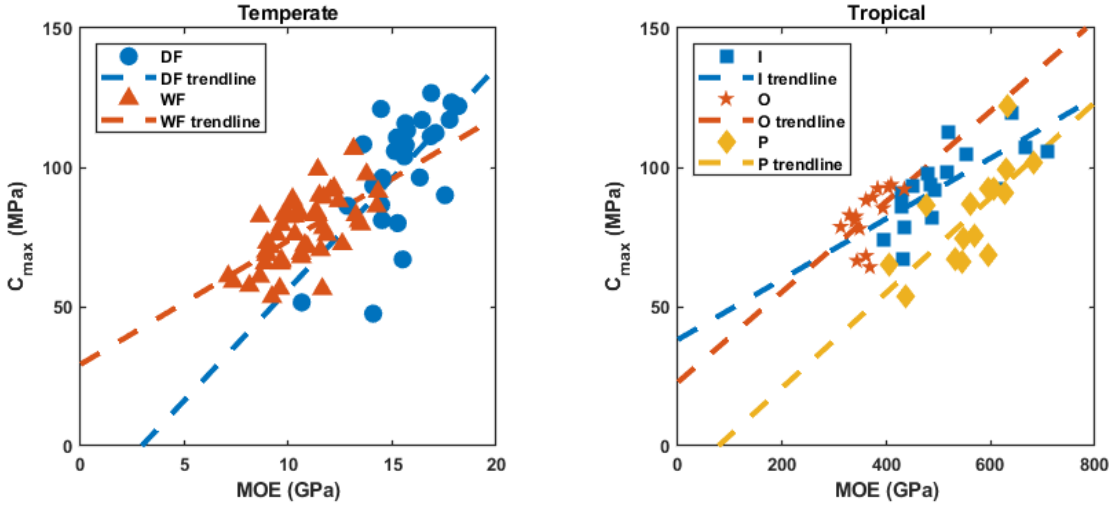

Fig. 4. Modulus of elasticity (MOE) versus maximum flexural stress (C_{max}) for the groups of temperate and tropical specimens

Figure 4 shows a comparison between the ρ_{dry} and C_{max}. Due to the low *COV* for the ρ_{dry} of the DF, the DF specimens are non-scattered. The lower values of C_{max} for some DF specimens occur due to material variations. The DF specimens with lower C_{max} were

kept in the analysis because they could not be classified as statistical outliers. The results for the temperate specimens were similar for the tropical specimens where the group of specimens with highest *COV* could illustrate a trendline with reasonable R^2-values. The trendlines in Fig. 4 had an R^2-value of 0.40 and 0.35 for WF and I, respectively. The other temperate and tropical specimens resulted in trendlines with low R^2-values and are not presented. Iroko (I) was the only tropical group of specimens following a trendline. O and P did not illustrate a trendline due to the low *COV* of ρ_{dry}, which were 4.1% and 3.0%, respectively. This variation in ρ_{dry} was too low compared to the *COV* of ρ_{dry} for I and WF, which were 13.8% and 8.1%, respectively. This statistical study done on the intrinsic mechanical characteristics of the specimens from temperate and tropical species, gives interesting information to build a database of the mechanical properties of the species studied. This database will be important for the next sections of this work.

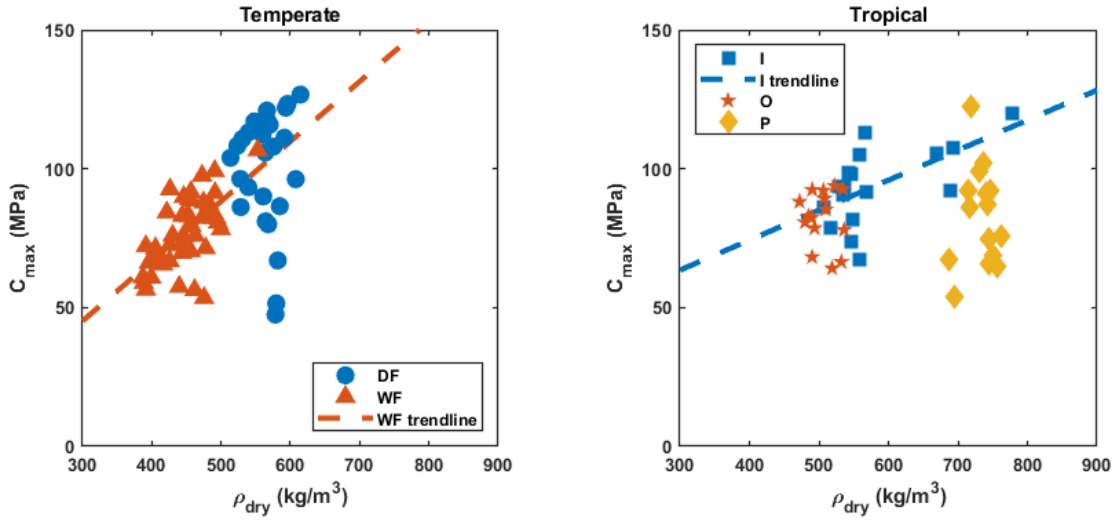

Fig. 5. Dry density (ρ_{dry}) versus maximum flexural stress (C_{max}) for the groups of temperate and tropical specimens

Cross-section Characterization of the Specimens

The CT scans of specimens cross-sections are presented in Fig. 5. The earlywood and latewood, which make up the annual growth ring of tree, are illustrated with white and black color, respectively. The distinction between earlywood and latewood is easily observable for the temperate specimens (Fig. 5, DF and WF species), but on the cross sections of the tropical specimens, the distinction of annual growth ring is almost impossible to see (Fig. 5; O, I and P species). These observations are in accordance with the literature (EN 1995-1-1 2004; Sopushynskyy *et al*. 2017), which shows that the distinction between earlywood and latewood is therefore not obvious in tropical species. The main explanation of the non-perception of this difference, for the tropical specimens, could be given by the harsh climate met in the region of their growth and the fact that the tropical species has a continuous growth of the annual rings during the year (Manfoumbi Boussougou 2012; Ramage *et al*. 2017). Specifically, for the P specimens the distinction between the lines of latewood and earlywood seems very difficult to observe, which is the same case for O and I. In the specimens O2, O12, I3, I5 (Fig. 6), there is little distinction observable between the latewood and earlywood of these tropical species. The density difference through the specimen could explain the difference. By taking into account this result, globally for the tropical species, the scanning of their cross-section

does not make it possible to distinguish the line between earlywood and latewood.

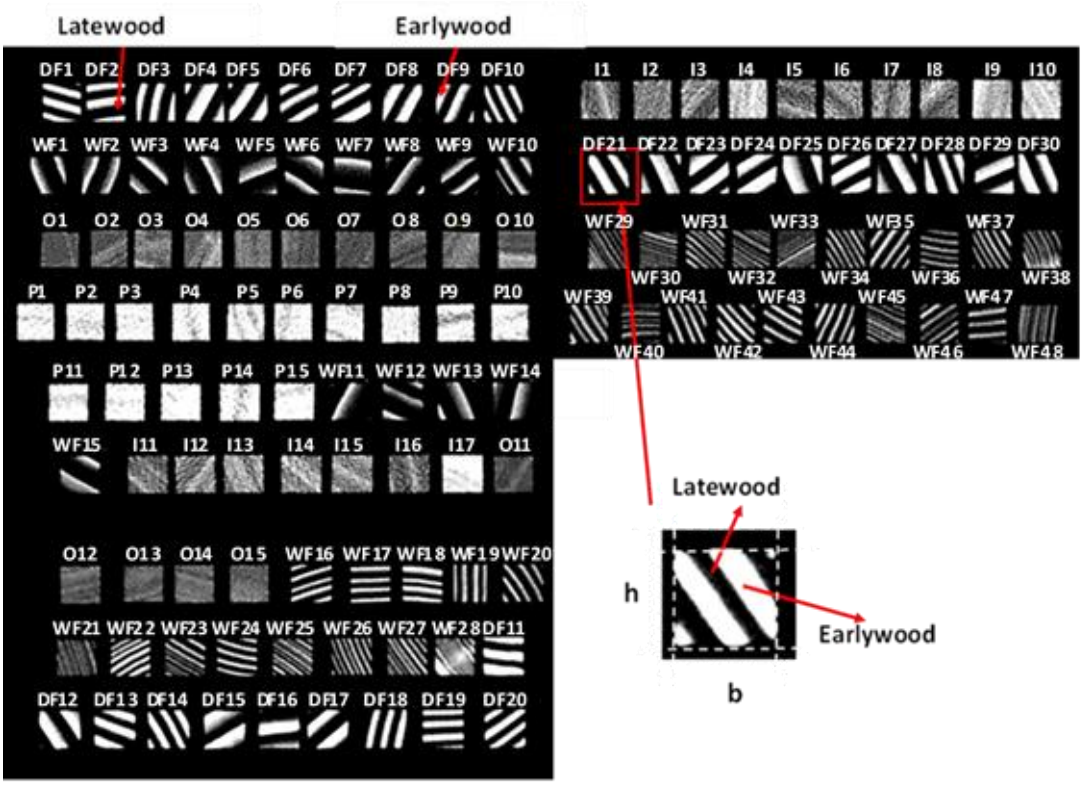

Fig. 6. Result from the CT-scanner with specimens named and numbered after species

Starting from this map (Fig. 5), Image J software was used to examine the width of the earlywood for the temperate specimens. The results and the summary of the width mean values of earlywood rings (ϖ_{mean}) and the number mean values of earlywood rings (NE_{mean}) are presented in Table 3. The tropical specimens had a lower NE_{mean} than the temperate specimens. Lowest number of NE_{mean} of 1.9 had P. For the tropical specimens, O had the highest NE_{mean} and *COV*. The temperate specimens had the highest and lowest *COV* of 56.6% (WF) and 22.9% (DF), respectively, for the NE_{mean}. No ϖ_{mean} could not be measured for the tropical specimens due to difficulty of define where earlywood starts and latewood ends (see Fig. 5 for specimens of species I, P, and O).

Table 3. Mean Width (ϖ_{mean}) and Number of Earlywood Rings (NE_{mean}) for the Groups of Tropical and Temperate Specimens with *COV* in Parentheses

	Name	ϖ_{mean} [mm]	NE_{mean}
Temperate	*DF*	5.07 (31.4%)	2.8 (22.9%)
	WF	3.37 (69.6%)	5.5 (56.6%)
Tropical	*I*	-	2.3 (29.9%)
	P	-	1.9 (30.7%)
	O	-	2.5 (45.6%)

Assessment of the Annual Growth Ring in the Mechanical Properties of the Species Studied

To understand the effects of the annual growth ring on the mechanical behavior,

comparisons were made between the ρ_{dry} and NE (Fig. 6) and the ρ_{dry} and ϖ (Fig. 7).

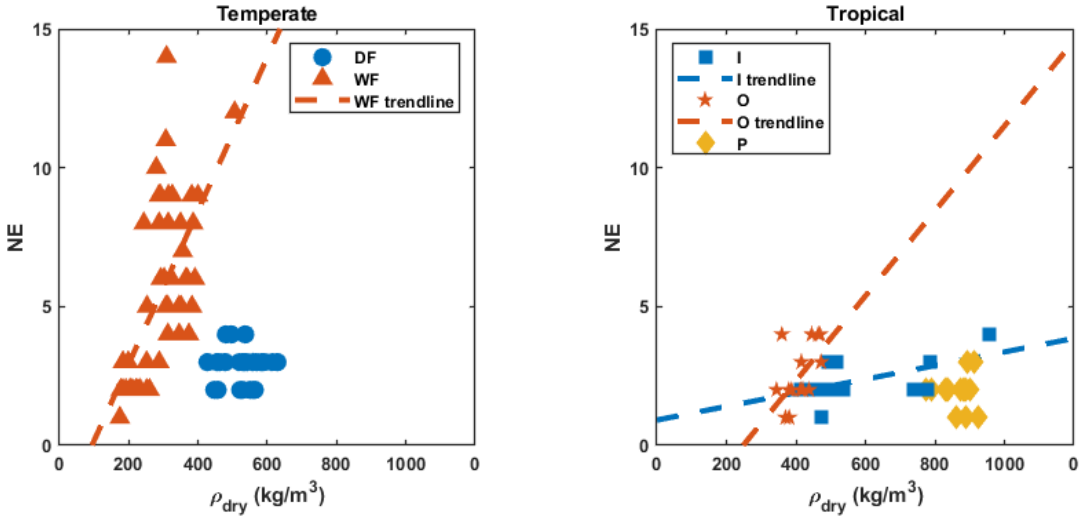

Fig. 7. Dry density (ρ_{dry}) versus the number of earlywood rings (*NE*) for the groups of temperate and tropical specimens

The temperate specimens show that there was a correlation between the ρ_{dry} and *NE*. This conclusion was drawn only from the WF specimens and not the DF specimens due to the DF specimens low *COV* of 22.9%. For the tropical specimens, a correlation between ρ_{dry} and *NE* is difficult to see due to the low spread of the specimens. The illustrated trendlines for the tropical specimens had lower R^2-values of 0.30 and 0.32 for I and O, respectively, compared to the R^2-value of 0.40 for WF. The tropical trendlines was showing a positive correlation between ρ_{dry} and *NE* but due to the lower R^2 values, the trend is not as clear as for the temperate specimens. For the group of DF specimens and the group of P specimens trendlines were not presented due to the low R2-values.

The correlation between the ρ_{dry} *versus* ϖ for the temperate specimens is presented in Fig. 7. A negative correlation between ρ_{dry} and ϖ could be seen for the WF specimens. Due to the low *COV* of 22.9% and 31.4% for ρ_{dry} and ϖ, respectively, for the DF specimens it was not possible to see any correlation between ρ_{dry} and ϖ. The trendline for the group of WF specimens had an R^2-value of 0.60. A trendline for the group of DF specimens was not presented due to the low R^2-value.

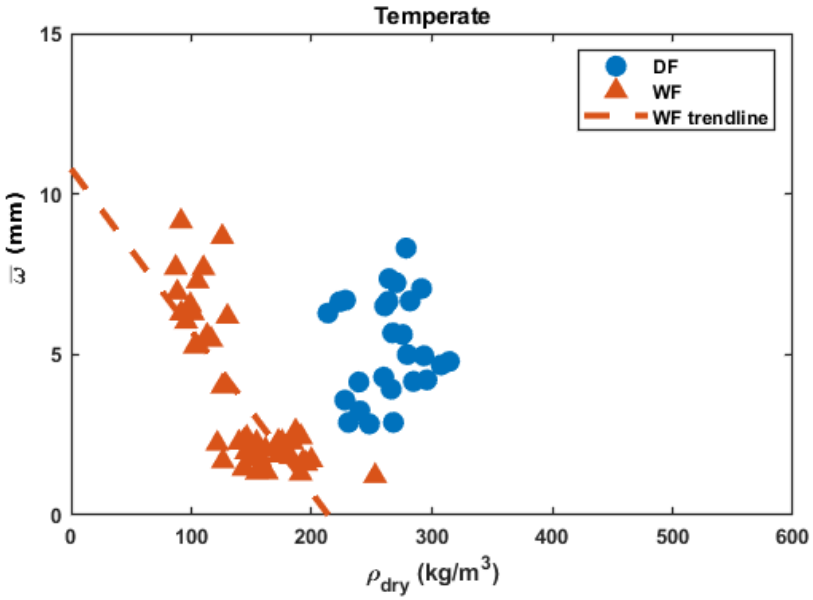

Fig. 8. Dry density (ρ_{dry}) versus the width of earlywood rings (ϖ) for the groups of temperate specimens

CONCLUSIONS

1. An experimental study of the evaluation of the annual growth ring impact on the intrinsic physico-mechanical characteristics of wood has been done. The samples were dimensioned and tested in a four-point flexural test according to the European standard requirement. Two groups of specimens have been studied (temperate and tropical species). To be able to visualize the earlywood and latewood (annual growth ring), the specimens were scanned by a computed tomography scanner before the four-point flexural test.

2. The results show that, for temperate species, the distinction between earlywood and latewood make up the annual growth ring and is easily distinguishable. However, for a tropical species the distinction is less clear. The study shows trendlines for the temperate and tropical specimens connecting the modulus of elasticity to the maximum flexural stress. It was also possible to show a trendline between the dry density and the maximum flexural stress for the two groups of temperate and tropical specimens of White fir and Iroko, respectively. Another trendline was shown between the dry density and number of earlywood rings for the group of temperate specimens of White fir and the groups of tropical specimens of Iroko and Okume. A last trendline was shown between the dry density and the mean width of the earlywood rings for the group of temperate specimens of White fir. The mean width of the earlywood rings was not possible to measure for the groups of tropical specimens due to the difficulty of define exactly where earlywood starts and latewood ends.

3. The results showed a connection between the annual growth rings of the tree and their intrinsic physico-mechanical characteristics mainly based on the dry density of the wood for both the tropical and temperate specimens. It was possible to show that the dry density was affected by the number and width of the earlywood rings. Moreover, the dry density affected the maximum flexural stress and where the maximum

flexural stress is strongly connected to the modulus of elasticity. This results in an increased number of earlywood rings which then results in an increased modulus of elasticity and increased maximum flexural stress. These results illustrate the need to have a fairly large number of specimens to avoid the large variation noted within the mechanical properties determined in this work. These results are interesting but are limited by the fact that it is a new experimental approach used for this type of study. It could be necessary for the next experimental study to create a method to distinguish clearly the annual growth rings of tropical species by increasing, for example, the size of the samples to be studied.

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