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

Claude Feldman Pambou Nziengui,^{a,b,*} Jonas Turesson,^c Rostand Moutou Pitti,^{a,d} and Mats Ekevad^c

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

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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).

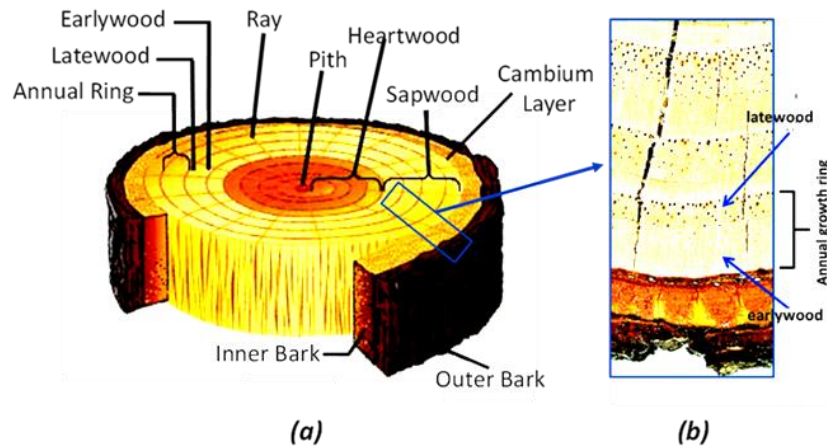


Fig. 1. (a) Cross-section of a tree trunk and (b) annual growth ring of wood

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 of palmetto 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 *et al.* 2020). This kind of region has two types of seasons: a six months' dry season and a six months' rainy season.

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

91 To date, no study has compared tropical species (African tropical region) and
 92 temperate species regarding the link between the growth of annual rings and the
 93 mechanical properties. The reason for this concern is that the tropical species has a
 94 continuous growth of annual rings during the year (Manfoumbi Boussougou 2012;
 95 Ramage *et al.* 2017) and this is not the case for the studied temperate species. Both the
 96 tropical and temperate species are commonly used in structure for heavy and light
 97 frameworks, glulam, paper pulp, fiber panels, in cooperage, packaging, maritime work,
 98 and luxury furniture (Adamopoulos 2009; Treml and Jeske 2012; Sopushynskyy 2017).
 99 In France there were more than 170 Mm³ of white fir and 93 Mm³ of Douglas fir in 2009
 100 (Pambou Nziengui *et al.* 2019). The chosen tropical species are the most widespread
 101 species in the tropical forest of Gabon and also among the most exported and used
 102 species in the field of timber structures (Odounga *et al.* 2018).

103 104 105 EXPERIMENTAL

106 107 Wood specimens

108 The wood specimens were cuboid shaped with the approximately dimensions of
 109 200×10×10 mm³ (Fig. 2). These specimens were cut following the fiber direction (in the
 110 longest direction). A total of 125 clear wood specimens was obtained. The specimens of
 111 temperate species were taken from collapsed beams used in an earlier study of creep tests
 112 (Pambou Nziengui *et al.* 2019; Tran *et al.* 2018). The specimens of tropical species were
 113 cut from butt logs at an approximate position of one meter above the roots of the standing
 114 tree (Odounga *et al.* 2018). To equalize the moisture content (MC) of the specimens, the
 115 specimens were stored in a climate chamber for 48 h. The temperature and the relative
 116 humidity in the climate chamber were set to 20 °C and 64.7%, respectively. Table 1
 117 shows the total number of specimens and the statistical mean of the principal physical
 118 characteristics for each group before the experimental campaign.

119
120 **Table 1.** Number of Specimens and Physical Characteristics for Each Tested
 121 Species Group with Coefficient of Variation (COV) in Parentheses

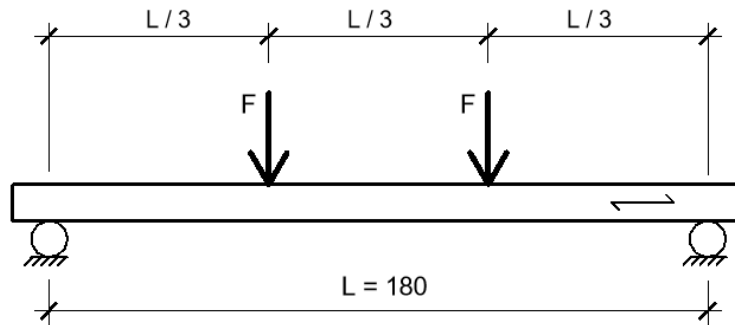
	Species	Name	No.	MC_{mean} [%]	$\rho_{dry, mean}$ [kg/m ³]
Temperate	Douglas fir	DF	30	9.8 (11.1%)	563 (4.5%)
	White fir	WF	48	9.9 (13.6%)	447 (8.1%)
Tropical	Iroko	<i>I</i>	17	9.0 (17.8%)	582 (13.8%)
	Padouk	<i>P</i>	15	8.3 (13.4%)	733 (3.0%)
	Okume	<i>O</i>	15	10.3 (15.7%)	505 (4.1%)

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

123
124 To distinguish the earlywood and latewood, which make up the annual growth
 125 ring, the specimens were scanned in a computed tomography scanner (CT-scanner). The
 126 data from the CT-scanner was visualized and analyzed by the Image J software
 127 (<https://imagej.nih.gov/ij/>).

128 129 Four-points flexural test

130 All specimens were loaded in four-point flexural test until failure by an
 131 electrostatic press (Fig. 2). The four-point bending test set-up was performed according to
 132 the European requirement (EN 1995-1-1 2004) and as presented by (Manfoumbi
 133 Boussougou 2012). The specimens were measured and weighed to determine their
 134 physical parameters (Table 1).
 135



136
 137

138 **Fig. 2.** Four-point flexural test set-up with the fiber direction of the specimen loaded
 139

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

$$142 \quad MOE = \frac{23L^3}{648I_z \left(2 \frac{F_2 - F_1}{W_2 - W_1} - \frac{2L}{5Gbh} \right)} \quad (1)$$

143 where $F_2 - F_1$ is an increase of force on the regression line and $W_2 - W_1$ is the increase of
 144 the corresponding displacement as described in the European standard requirement (EN
 145 1995-1-1 2004). L represents the distance between the two supports (Fig. 2), I_z the
 146 moment of inertia, G is the shear modulus, b and h are the width and height of the
 147 specimen, respectively. Due to lack of data for the tropical species, the influence of G
 148 was neglected. The maximum flexural stress was defined to Eq. 2,

$$149 \quad C_{max} = M_y / I_z \quad (2)$$

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

$$154 \quad M = (LF_{max}) / 3 \quad (3)$$

155 To calculate C_{max} , the length y in Eq. 2 can be set equal to $h/2$ [25]. A comparison
 156 between C_{max} calculated in this study and the maximum flexural failure stress given by
 157 the CIRAD wood collection (Gérard et al. 2011), C_{mcir} , was done.
 158
 159

160 RESULTS AND DISCUSSION

161 Mechanical Characterization of the Specimens in Static Tests

162 The mean values of modulus of elasticity (MOE), maximum loading (F_{max}), and
 163 maximum flexural stress (C_{max}) obtained, for each species studied, are presented in Table
 164 2. The C_{mcir} value is the maximum flexural stress given by the CIRAD wood collection
 165

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

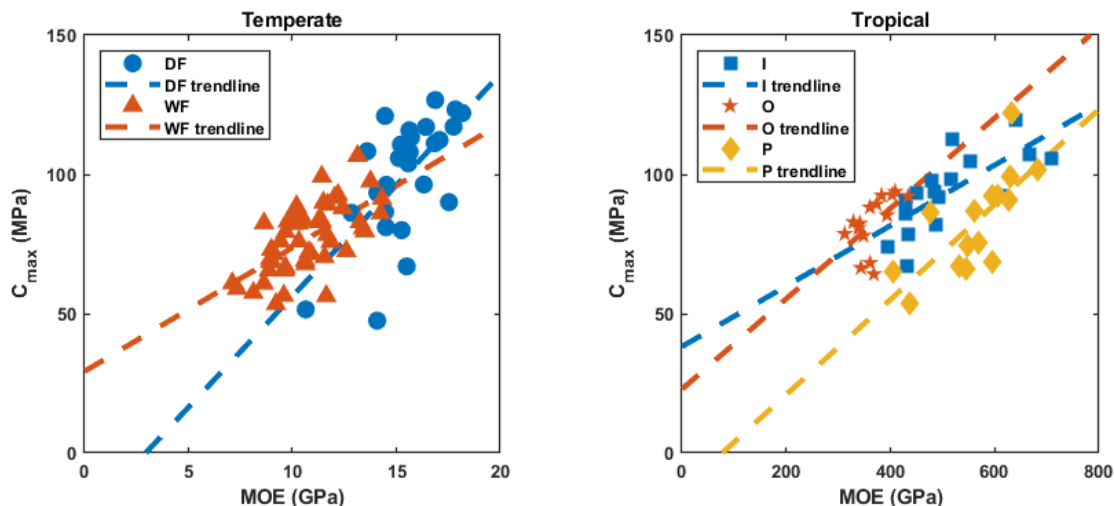
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Table 2. Result from the Four-Point Flexural Test with COV in Parentheses

	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

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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.

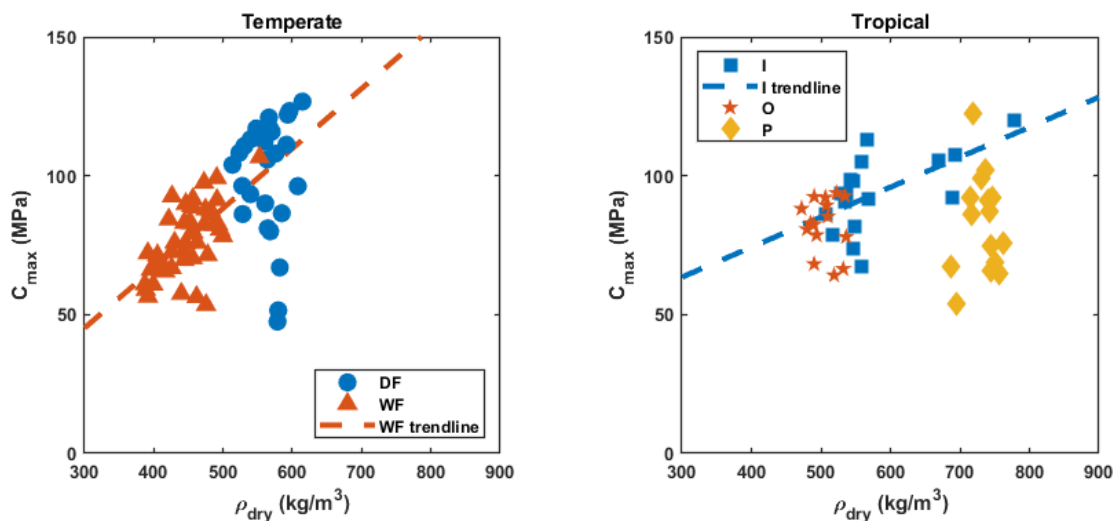


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Fig. 4. Modulus of elasticity (MOE) versus maximum flexural stress (C_{max}) for the groups of temperate and tropical specimens

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

194 kept in the analysis because they could not be classified as statistical outliers. The results
 195 for the temperate specimens were similar for the tropical specimens where the group of
 196 specimens with highest COV could illustrate a trendline with reasonable R^2 -values. The
 197 trendlines in Fig. 4 had an R^2 -value of 0.40 and 0.35 for WF and I, respectively. The
 198 other temperate and tropical specimens resulted in trendlines with low R^2 -values and are
 199 not presented. Iroko (I) was the only tropical group of specimens following a trendline. O
 200 and P did not illustrate a trendline due to the low COV of ρ_{dry} , which were 4.1% and
 201 3.0%, respectively. This variation in ρ_{dry} was too low compared to the COV of ρ_{dry} for I
 202 and WF, which were 13.8% and 8.1%, respectively. This statistical study done on the
 203 intrinsic mechanical characteristics of the specimens from temperate and tropical species,
 204 gives interesting information to build a database of the mechanical properties of the
 205 species studied. This database will be important for the next sections of this work.
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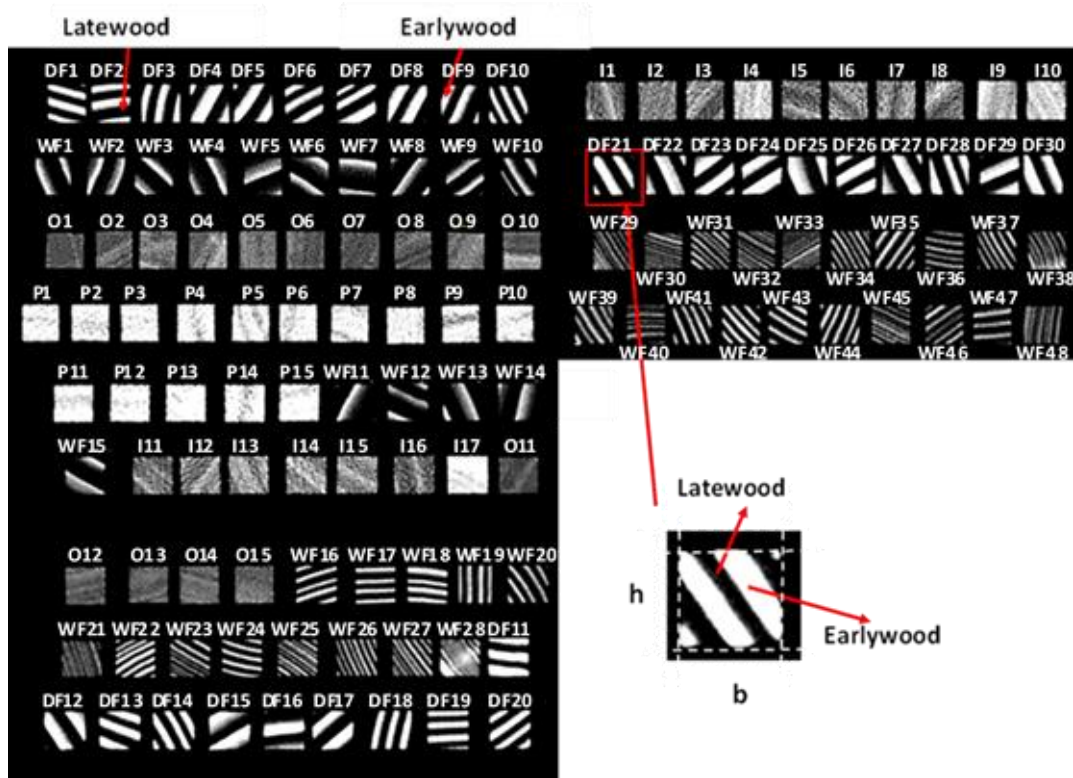


207
 208 **Fig. 5.** Dry density (ρ_{dry}) versus maximum flexural stress (C_{max}) for the groups of temperate and
 209 tropical specimens
 210

211 Cross-section Characterization of the Specimens

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

229 does not make it possible to distinguish the line between earlywood and latewood.
 230



231
 232 **Fig. 6.** Result from the CT-scanner with specimens named and numbered after species
 233

234 Starting from this map (Fig. 5), Image J software was used to examine the width
 235 of the earlywood for the temperate specimens. The results and the summary of the width
 236 mean values of earlywood rings (ϖ_{mean}) and the number mean values of earlywood rings
 237 (NE_{mean}) are presented in Table 3. The tropical specimens had a lower NE_{mean} than the
 238 temperate specimens. Lowest number of NE_{mean} of 1.9 had P. For the tropical specimens,
 239 O had the highest NE_{mean} and COV . The temperate specimens had the highest and lowest
 240 COV of 56.6% (WF) and 22.9% (DF), respectively, for the NE_{mean} . No ϖ_{mean} could not be
 241 measured for the tropical specimens due to difficulty of define where earlywood starts and
 242 latewood ends (see Fig. 5 for specimens of species I, P, and O).
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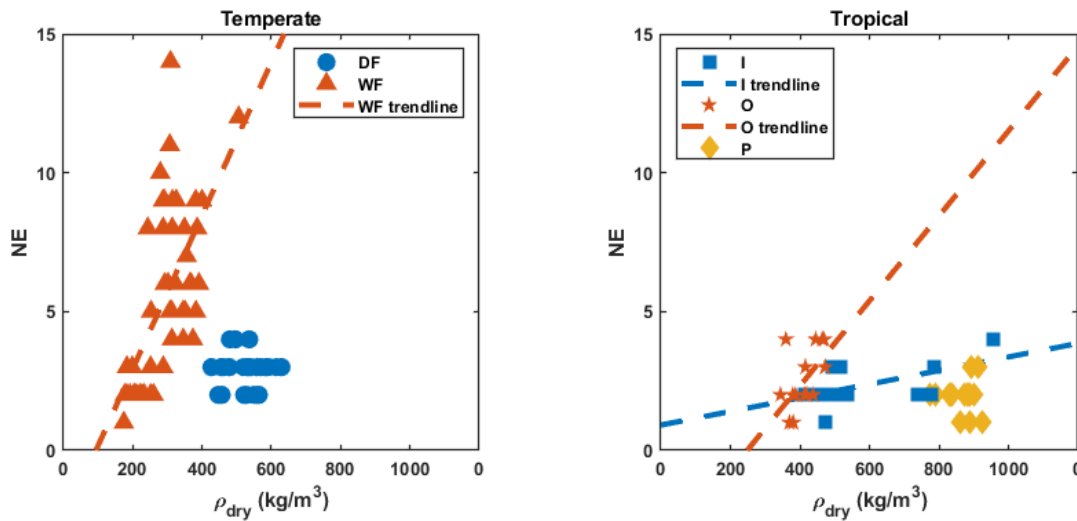
244 **Table 3.** Mean Width (ϖ_{mean}) and Number of Earlywood Rings (NE_{mean}) for the
 245 Groups of Tropical and Temperate Specimens with COV in Parentheses

	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%)

246
 247 **Assessment of the Annual Growth Ring in the Mechanical Properties of the**
 248 **Species Studied**

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

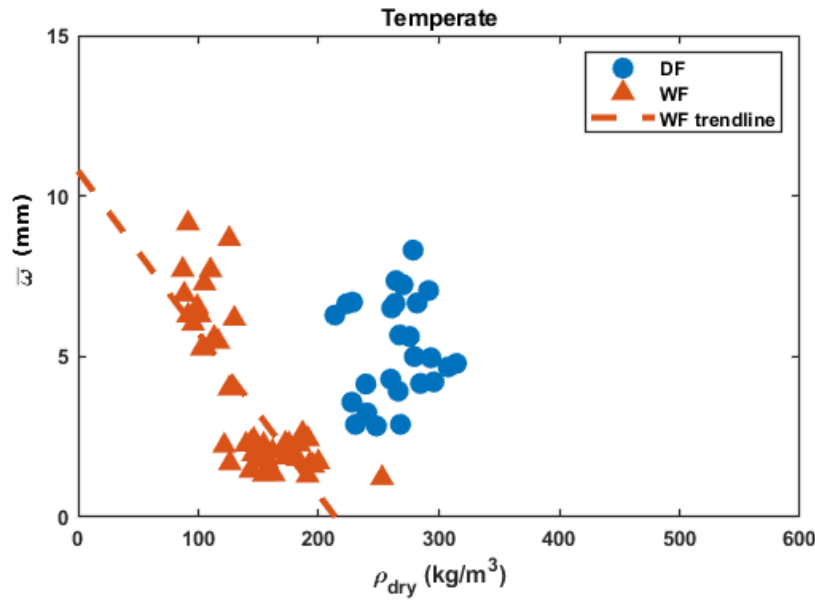
250 comparisons were made between the ρ_{dry} and NE (Fig. 6) and the ρ_{dry} and ϖ (Fig. 7).
 251



252
 253 **Fig. 7.** Dry density (ρ_{dry}) versus the number of earlywood rings (NE) for the groups of temperate
 254 and tropical specimens
 255

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

265 The correlation between the ρ_{dry} versus ϖ for the temperate specimens is
 266 presented in Fig. 7. A negative correlation between ρ_{dry} and ϖ could be seen for the WF
 267 specimens. Due to the low COV of 22.9% and 31.4% for ρ_{dry} and ϖ , respectively, for the
 268 DF specimens it was not possible to see any correlation between ρ_{dry} and ϖ . The trendline
 269 for the group of WF specimens had an R^2 -value of 0.60. A trendline for the group of DF
 270 specimens was not presented due to the low R^2 -value.
 271



272
273 **Fig. 8.** Dry density (ρ_{dry}) versus the width of earlywood rings (ϖ) for the groups of temperate
274 specimens
275

276
277 **CONCLUSIONS**

- 278
- 279 1. An experimental study of the evaluation of the annual growth ring impact on the
280 intrinsic physico-mechanical characteristics of wood has been done. The samples
281 were dimensioned and tested in a four-point flexural test according to the European
282 standard requirement. Two groups of specimens have been studied (temperate and
283 tropical species). To be able to visualize the earlywood and latewood (annual growth
284 ring), the specimens were scanned by a computed tomography scanner before the
285 four-point flexural test.
 - 286 2. The results show that, for temperate species, the distinction between earlywood and
287 latewood make up the annual growth ring and is easily distinguishable. However, for
288 a tropical species the distinction is less clear. The study shows trendlines for the
289 temperate and tropical specimens connecting the modulus of elasticity to the
290 maximum flexural stress. It was also possible to show a trendline between the dry
291 density and the maximum flexural stress for the two groups of temperate and tropical
292 specimens of White fir and Iroko, respectively. Another trendline was shown between
293 the dry density and number of earlywood rings for the group of temperate specimens
294 of White fir and the groups of tropical specimens of Iroko and Okume. A last
295 trendline was shown between the dry density and the mean width of the earlywood
296 rings for the group of temperate specimens of White fir. The mean width of the
297 earlywood rings was not possible to measure for the groups of tropical specimens due
298 to the difficulty of define exactly where earlywood starts and latewood ends.
 - 299 3. The results showed a connection between the annual growth rings of the tree and their
300 intrinsic physico-mechanical characteristics mainly based on the dry density of the
301 wood for both the tropical and temperate specimens. It was possible to show that the
302 dry density was affected by the number and width of the earlywood rings. Moreover,
303 the dry density affected the maximum flexural stress and where the maximum

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

313

314

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316

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