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RESEARCH PAPER

Mechanical properties of secondary quality beech (*Fagus sylvatica* L.) and oak (*Quercus petraea* (Matt.) Liebl.) obtained from thinning, and their relationship to structural parameters

Citra Yanto Ciki Purba[1] · Jana Dlouha[2] · Julien Ruelle[2] · Mériem Fournier[2]

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Abstract

• ***Key message*** **This paper investigates the juvenility limit and structure–property relationship in secondary quality beech (*Fagus sylvatica* L.) and oak (*Quercus petraea* (Matt.) Liebl.). The juvenile wood occupies a very small area near the pith. The stabilization of the different parameters varies over time. Adding the microfibril angle (MFA) and the grain angle to the MOE prediction model significantly improves the quality of the model, despite little variation in both parameters.**

• ***Context*** Using secondary qualities and small logs of hardwoods such as beech and oak for engineered wood products is an increasingly important issue due to the technological challenges of processing smaller logs and denser woods. Secondary quality hardwoods are expected to have less variation in mechanical properties compared to softwoods with high juvenile wood content.

• ***Aims*** The first objective of this study was to investigate the radial variation in wood properties of suppressed growth beech and oak trees obtained from thinning operations. The second objective was to develop a model to predict the mechanical properties of these hardwood species based on their structural parameters.

• ***Methods*** The microfibril angle, ring wood density, and ring width from the pith to the bark were determined using an X-ray densitometer. The modulus of elasticity and modulus of rupture were evaluated on the small clear specimen using a three-point bending test. The wood density, grain angle, and microfibril angle of this small clear specimen were also measured.

• ***Results*** The results show that the juvenile wood in oak has a wider ring and higher microfibril angle, whereas it has wider latewood and higher microfibril angle in beech. For both species, the juvenile wood occupies a very small area, less than 5 cm from the pith. The mechanical properties of oak and beech wood from suppressed growth trees are comparable to properties reported in the literature for dominant trees. The modulus of elasticity of oak was best predicted using wood density, grain angle, and microfibril angle. The modulus of rupture of oak is better predicted with wood density and grain angle, whereas it is best predicted with wood density alone for beech.

• ***Conclusion*** Juvenile wood found in the suppressed growth trees of both hardwoods can be used in place of mature wood. It is important to take structural parameters into account when predicting the mechanical properties of hardwood species.

Keywords Oak · Beech · Thinning · Radial variation · Mechanical properties · Ring properties

1 Introduction

Beech (*Fagus sylvatica* L.) and oak (*Quercus petraea* (Matt.) Liebl.) are the two most important hardwood species in Europe and particularly in France, where the forest resource is dominated by hardwood (IGN 2016). Due to climatic risk mitigation and to the market demand in industrial wood products and fuelwood, there has been a move toward harvesting trees much younger than in the past, as well as an increase in the utilization of small trees that are removed during thinning operations (Fox et al.

Contribution of the co-authors Citra Yanto Ciki Purba: investigation, methodology, conceptualization, data curation, writing–original draft, visualization, funding acquisition.
Jana Dlouha: conceptualization, validation, review and editing.
Julien Ruelle: conceptualization, methodology, validation, resources, review and editing, project administration, funding acquisition.
Mériem Fournier: conceptualization, supervision, review and editing

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Extended author information available on the last page of the article

2004; Paukkunen 2014; Davis et al. 2018). That means that the wood quality of these trees is expected to be lower according to trading standards, i.e., log grades based on diameter, straightness, and visual defects (Koutsianitis and Voulgaridis 2015). Wood properties vary within the ring, from pith to bark and along the tree stem (Burdon et al. 2004; Longuetaud et al. 2017; Vega et al. 2020). The wood quality of small logs is also usually reduced by the variability of mechanical properties associated with juvenile wood, which are linked to changes in several, generally not visible parameters (e.g., wood density or microfibril angle (MFA)), a phenomenon well known in fast-growing softwoods (Maeglin 1987; Burdon et al. 2004; Zobel and Sprague 2012) and less studied in a diversity of species including hardwoods (Woodcock and Shier 2002). Previous research has shown that engineered wood products such as oriented strand board (OSB) and laminated veneer lumber (LVL) have poorer performance results when made from logs with a high content of juvenile wood (Cloutier et al. 2007; Girardon et al. 2016). Juvenile wood is produced near the pith and in the upper parts of the tree by young cambium, and the transition to more mature wood is characterized by a large gradient of wood properties. Whether this variation is the result of ontogeny or tree adaptive response to the environmental conditions is still a matter of debate (Cutter et al. 2007; Downes and Drew 2008; Lachenbruch et al. 2011; Moore and Cown 2017).

Because wood is a complex biological composite, several non-visible quantifiable parameters impact the mechanical properties of clear wood (defined as a specimen of small size without any visual defects). Variations in the mechanical properties of clear wood such as MOE (modulus of elasticity) or MOR (modulus of rupture) are generally associated with variations in wood density linked to latewood percentage, fiber, or tracheid wall thickness, whereas in hardwoods, they are linked to vessel number and size, or the proportion of fiber tissue. Furthermore, independently to wood density, variations in these properties are linked to spiral grain and MFA (Burdon et al. 2004). Mechanistic approaches derived from composite mechanics (Gibson and Ashby 1999) have demonstrated the causal link between MOE or MOR and these parameters (Hofstetter and Gamstedt 2009), beyond statistical empirical observations.

In temperate species, these parameters vary inside the tree ring (from early to latewood) with typical patterns that make the tree ring width an integrative visual parameter, correlated with mechanical properties (Nepveu 1990; Leban and Haines 2007). Oak is a ring-porous species with a pronounced difference between early and latewood, i.e., the larger the ring is, the higher the proportion of latewood and the higher the wood density will be (Nepveu 1990; Zhang et al. 1993, 1994; Guilley et al. 2004). In contrast, beech, as a diffuse-porous species, shows a negative correlation between wood density and ring width but with very little variation (Bouriaud et al. 2004).

The grain angle is a misalignment between the tracheid of fiber direction and the stem axis of the timber. Wood stiffness (MOE) or strength (MOR) depends strongly on the angle between the applied load and the fiber/tracheid orientation (Bodig and Jayne 1982). Therefore, variations in grain angle can significantly impact the mechanical properties (Tsehaye and Walker 1995). Low variations in grain angle are expected in beech and oak (1°–3°) compared to that in some other species (Birot et al. 1980; Guilley et al. 1999).

Among all of the cited parameters, the MFA of crystalline cellulose in the S2 layer of the fiber wall has been less studied as it is less easily measurable (Barnett and Bonham 2004; Donaldson 2008). However, since crystalline cellulose is responsible for cell wall stiffness and strength, its variations can significantly change the value of MOE and MOR (Yang and Evans 2003; Alteyrac et al. 2007; Yin et al. 2011). As for the transition from juvenile to mature wood, many studies have shown that the MFA decreases from pith to bark in both softwood and hardwood species (Cave and Walker 1994; Evans et al. 2000), even if studies are less numerous in hardwoods where MFA is more difficult to measure (Ruelle et al. 2007). The value and variation of MFA in softwoods such as spruce (*Picea abies* (L.) H. Karst.) and pine (*Pinus sylvestris* L.) are commonly higher than those in the hardwood species (Lindström et al. 1998; Lichtenegger et al. 1999; Lestander et al. 2008). Beech and oak have a very low radial variation of MFA and present a high value only in the position close to the pith (Lichtenegger et al. 1999).

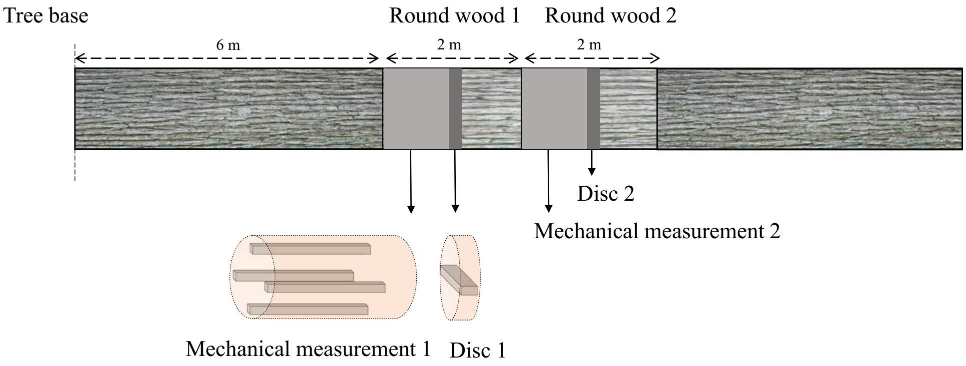
This study aims at characterizing radial variations of mechanical properties of clear wood of secondary quality oak and beech logs recovered from thinned trees. Quite low radial variations are expected compared to conifers or fast growth poplar. If this result is confirmed, it is a positive aspect in favor of the development of timber engineering of these hardwoods that are very common in France but that have been poorly developed for building uses up until now. We will then design and fit a predictive model of these variations on the basis of the wood structural parameters such as wood density, grain angle, and MFA. It is expected that such a model, which is based on physical causality, will fit well even if variations in mechanical properties (MOE and MOR) are low.

2 Material and methods

2.1 Wood material

The wood material used for this study was beech and oak from a mixed forest stand in Lorraine (48.893622 N, 6.741478 E), Grand-Est region, France. The round wood

Fig. 1 Location of round woods and wood samples in the tree



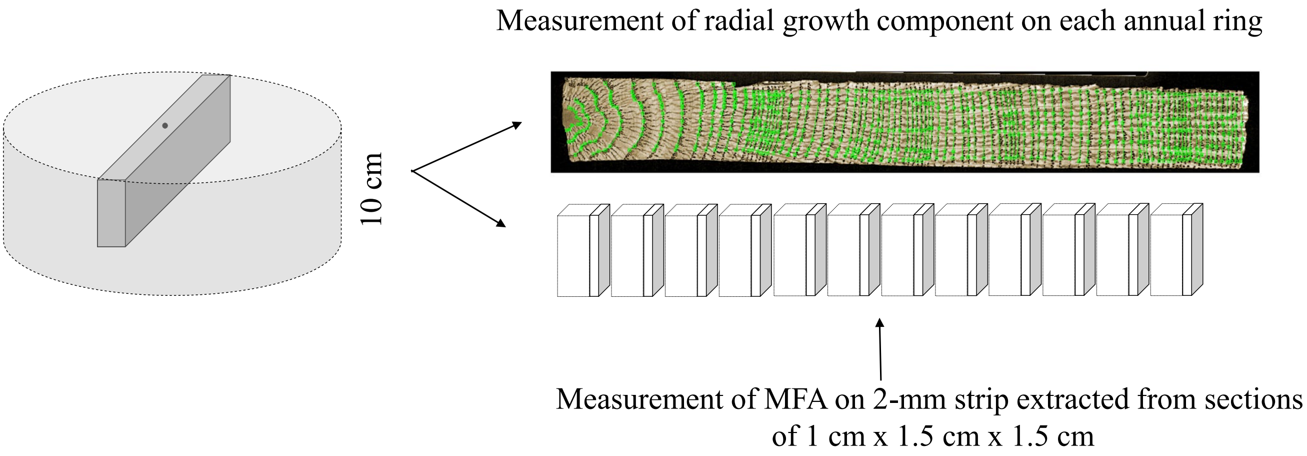


Fig. 2 Specimen preparation for the measurement of the radial variation of wood properties

samples were gathered from trees that were removed during a thinning operation. Five trees were selected for each species and two round woods were extracted from each selected tree. As a result, selected round wood material consisted of 20 logs, 200-cm long, with large end diameters of between 21 and 30 cm. Log grading using a visual method based on EN 1316–1 (2012) was used to classify the round woods into grades C and D based on log diameter and knot presence. C and D grades are differentiated by the presence of unsound knots. Each round wood was extracted from the upper part of the stem (600 and 800 cm above the ground) and typically contained knots, as described in Fig. 1. Oak cambial ages ranged between 61 and 90 years old, while beech cambial ages ranged between 57 and 84 years. Individual cambial ages were determined by the ring number. These round woods represent the wood resources that are not commonly used as raw material for timber construction and engineered wood products (EWP).

2.2 Measurement of the radial growth component using an X-ray densitometer

A disc approximately 10-cm thick was extracted from the central part of each log, as described in Fig. 1. A randomly oriented radial strip (2.5 cm × 5 cm, tangential (T) × longitudinal (L)) was cut in a defect-free zone and conditioned for 1 month at 12% relative humidity at ambient temperature. A radial slice (1 cm × 0.2 cm, $T \times L$) was then cut for X-ray microdensitometry measurements, as described in Fig. 2. Using CERD (i.e., “Cernes sur Eprouvettes Radiographiées en Densité”), an image analysis software (Mothe et al. 1998a), the limit between two adjacent rings was manually assigned, as described in Fig. 2. Each ring was divided into 20 intervals of equal length, with each representing 5% of the ring’s width. The mean wood density was calculated for each interval. The separation of the earlywood from the latewood was automatically set by calculating the tree ring wood density threshold as defined in Mothe et al. (1998b).

The remaining part of the radial strip was then cut into sections of 1 cm in length from pith to bark, as described in Fig. 2. A 2-mm-thick strip was extracted from each section.

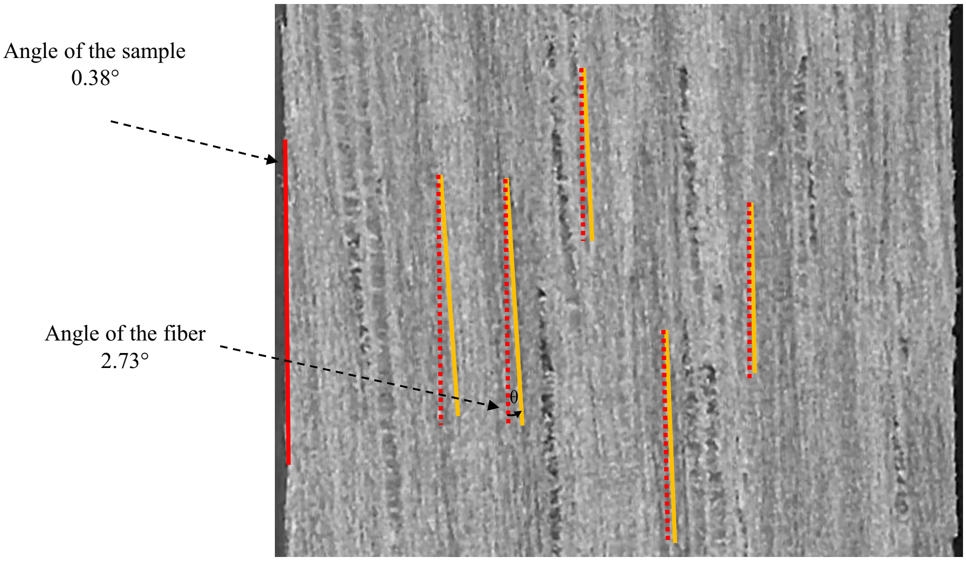


Fig. 3 Measurement of grain angle using ImageJ software. The red line indicates the direction of the sample, while the yellow line indicates the direction of the measured grain. The angle between the two lines was then determined to be the grain angle

The MFA was measured on this 2-mm-thick strip using an X-ray diffractometer (XRD) from Oxford Diffraction. The X-ray generator operating at 50 keV/0.8 mA with a beam diameter of around 300 µm generates CuK_α radiation. To reach the optimum noise, the exposure time was set at 60 s. The *T* parameter was used to calculate the MFA, according to Cave's equation (Yamamoto 1993).

2.3 Measurement of mechanical properties and their related structural properties

For the characterization of mechanical properties, defect-free wood specimens with dimensions of 24 cm × 1 cm × 1 cm were prepared. The wood density was calculated by dividing their mass by their volume in the air-dry state or at 12% moisture content (MC). The wood mechanical properties were measured using a three-point bending method with a universal testing machine where annual rings were orientated horizontally with respect to the load (Instron 5969). The span length used was 150 mm and the loading speed was set at 3 mm min^{-1}. The wood deformation caused by the loading was measured by a video extensometer. The static MOE and MOR were then determined for each wood specimen.

The grain angle was evaluated by scanning specimens used for the destructive test with a high-resolution flatbed scanner at 800 dpi. The images taken were then analyzed using ImageJ software in order to manually measure the grain angle on the surface of the rupture zone. The grain angle was determined as the angle between the direction of the sample and the direction of the grain, as described in Fig. 3.

In addition, the measurement of MFA was also carried out on a 2-mm-thick sample extracted from the rupture zone.

2.4 Data analysis

Descriptive analyses such as mean value and standard error were calculated for each measured property, including the structural and mechanical properties. Analyses of exploratory data showed that both dependent and independent variables were normally distributed based on the D'Agostino-Pearson normality test. Furthermore, the co-linearity of independent variables was also tested. Patterns and outliers were analyzed using the residual plots. All data analyses were performed using the R-software, version 3.6.0.

The mean value and standard error of the measured wood properties from the pith to the bark of all trees were graphically presented. Radial variation of measured properties from pith to bark was fitted to a model described in Fig. 4 and Eq. 1, which is suitable for modeling the transition between juvenile and mature wood (Grzeskowiak 1997; Fajriani et al. 2013). The radial patterns of both suppressed growth beech and oak from the thinning operation decrease from the pith and then tend to stabilize; therefore, the model proposed by Grzeskowiak (1997) was used in this study.

Using this model, it is assumed that 95% of the variation in measured properties due to age is taken into consideration.

$$Y = Ym - (Ym - Yi)^{-T/\tau} \tag{1}$$

$$(Y - Yi) = 0.95(Ym - Yi) \tag{2}$$

As a result, $T = 3\tau$, and the demarcation point calculated in this study is therefore $t = 3\tau + 1$. The model was calculated based on the data covering up to 40 years, and

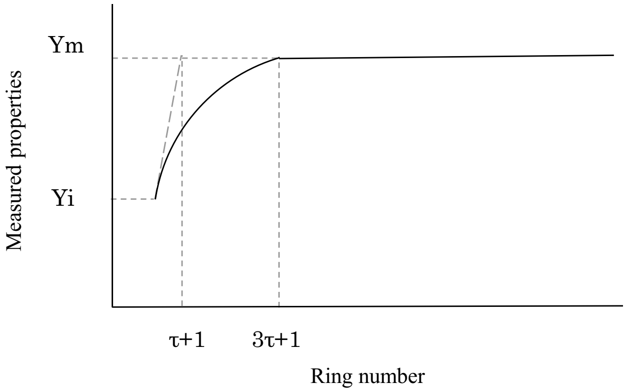


Fig. 4 Modeling the transition between juvenile and mature wood (Grzeskowiak 1997). Ym, the final value of the variation curve before the constant value is achieved; Yi, the value of the first ring; *T*, $t-1$, where *t* is the ring number from the pith; *τ*, the time characteristic of the kinetics of the transition from juvenile to mature wood

assuming that juvenile transition was finished and that the variation in properties we observed was not related to ontogenetic transition but to climate and/or changes in environmental conditions. The modeling efficiency (EF) was used to compare the predicted and measured values, and is expressed in Eq. 3:

$$EF = \frac{\sum_i^n \left(O_i - \overline{\text{O}}\right)^2 - \sum_i^n \left(S_i - O_i\right)^2}{\sum_i^n \left(O_i - \overline{\text{O}}\right)^2} \tag{3}$$

where S = the predicted value and O = the measured value over the course of the simulation (i = time). The best model has an EF close to 1. In addition, the root mean square error (RMSE) of the model was also calculated.

Furthermore, the Pearson coefficient of correlation was analyzed in order to evaluate the relationship among the measured parameters of structural properties and mechanical properties. Various multiple linear regression models were developed for the MOE and MOR, as presented in Eq. 4. The independent variables used were wood density, grain angle, and MFA.

$$y = \beta_1 + \beta_1 x_1 + \cdots + \beta_k x_k + u \tag{4}$$

where u is the standard error:

$$u = \sqrt{\frac{\sum e_i^2}{n-2}} \tag{5}$$

where $e_i = y_i - \hat{y}$.

In order to select the most appropriate regression model, the adjusted coefficient of determination (R^2) and the Akaike Information Criteria (AIC) were also calculated for each model. Analysis of relative importance (RI) was performed in order to calculate the contribution of each parameter of wood properties to the mechanical properties. This analysis was performed using the R package relaimpo (Grömping 2006).

3 Results

3.1 Radial variation of wood properties

Figure 5 shows the radial variation of ring width, ring wood density, and MFA from pith to bark. Mean values for all samples are displayed together with the standard error. It can be seen that the ring wood density, ring width, and MFA were higher near the pith for both species. A nonlinear decrease in the measured wood properties can be seen from the pith to the bark. The average oak earlywood density started at 696 kg m^{-3} and tended to stabilize at 570 kg m^{-3}. Oak ring width near the pith was 1.4 mm and tended to stabilize at 0.5 mm. The average MFA for oak wood near the pith was 12.6° and reached a relatively constant value of 7.6°. The other measured properties of oak wood continued to decrease towards the bark. On the other hand, beech latewood ring width was higher near the pith, with average values of 0.65 mm, and reached a relatively constant value at 0.31 mm. The average MFA for beech near the pith was 11.9° and tended to stabilize at 8.5°. Other measured wood properties tended to decrease nonlinearly from the pith to the bark.

Table 1 presents the demarcation point or limit of juvenile wood calculated using the ring properties and MFA. There are some predictors without results in the table. This happened because some predictors showed the demarcation point beyond age 40, which was the maximum age of data entry used for the model. Therefore, this model is not well suited for these properties. In the case of beech, ring width, as well as ring wood density, did not show any clear transition in the juvenile region. The best predictor of the juvenile transition seemed to be the MFA. For oak, the best predictor of juvenile wood was the earlywood width, followed by earlywood density, MFA, and latewood width.

3.2 Structural and mechanical properties

The mean value and standard error of wood density, grain angle, MOE, and MOR measured on beech and oak are presented in Table 2. Based on the standard error, both species showed relatively low wood density variation on the measured specimen. Despite this low standard error on wood density, the MOE and MOR values were quite varied. The grain angle on the specimen extracted from the secondary

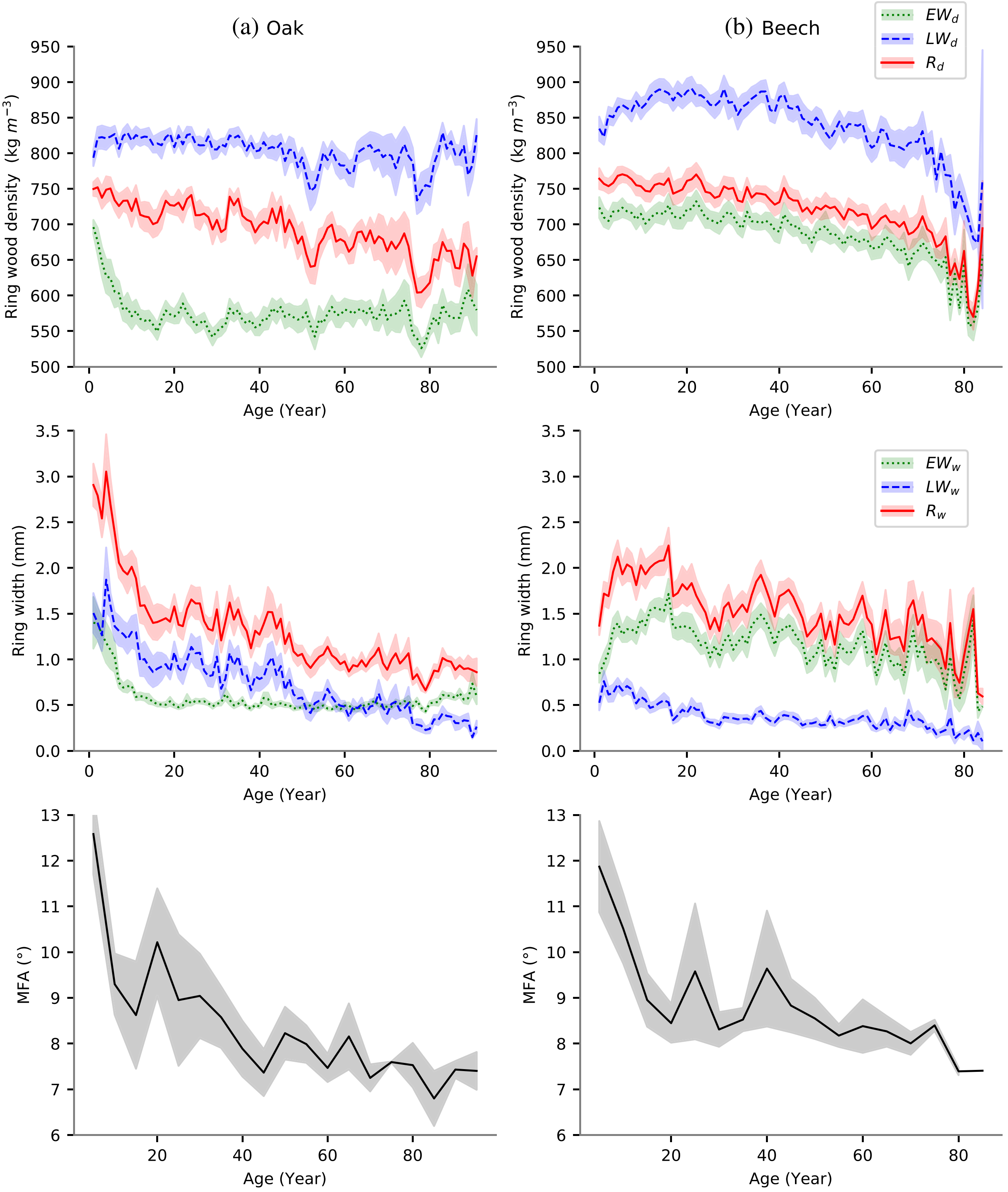


Fig. 5 Radial variation of radial growth component, wood density component, and MFA from the pith to the bark as a function of the cambial age of **a** oak and **b** beech. The solid line and the light color area around each solid line represent the mean value and the standard error measured on each ring from all measured trees. R_w, ring width; EW_w, earlywood width; LW_w, latewood width; R_d, ring wood density; EW_d, earlywood density; LW_d, latewood density

Table 1 Demarcation point of juvenile and mature oak and beech wood based on the model. *t*, demarcation point of juvenile and mature wood; EW_w, earlywood width; LW_w, latewood width; EW_d, earlywood density; LW_d, latewood density; *MFA*, microfibril angle

Species	Predictor	RMSE	EF	Tau	*t*
Oak	LW_w (mm)	0.14	0.55	11.52	35.56
	EW_w (mm)	0.06	0.95	5.35	17.04
	LW_d (kg m^{-3})	-	-	-	-
	EW_d (kg m^{-3})	9.78	0.9	4.05	13.14
	MFA (°)	0.61	0.75	2.26	7.77
Beech	LW_w (mm)	-	-	-	-
	EW_w (mm)	-	-	-	-
	LW_d (kg m^{-3})	9.62	0.28	3.65	11.96
	EW_d (kg m^{-3})	-	-	-	-
	MFA (°)	0.52	0.74	5.33	16.98

Table 2 Mean values of the measured structural and mechanical properties of wood

Wood species	Wood density (g cm^{-3})	Grain angle (°)	MFA (°)	MOR (MPa)	MOE (GPa)
Oak	0.71 (0.01)	2.78 (0.55)	11.32 (0.29)	114.92 (3.65)	14.18 (0.48)
Beech	0.73 (0.01)	2.20 (0.28)	11.06 (0.11)	120.87 (2.54)	14.81 (0.33)

Values in parentheses are standard errors

Table 3 Pearson's correlation among measured characteristics on samples of beech (lower triangle) and oak (upper triangle)

	Wood density	Grain angle	MFA	MOE	MOR
Wood density	1	−0.09	−0.10	0.71***	0.67***
Grain angle	0.03	1	0.38	−0.48*	−0.39
MFA	−0.10	0.31	1	−0.46*	−0.32
MOE	0.75***	−0.18	−0.36*	1	0.93***
MOR	0.77***	−0.12	−0.16	0.9***	1

***Correlation is significant at the 0.001 level; **correlation is significant at the 0.01 level; *correlation is significant at the 0.05 level

quality resources was found to be fairly low and close to 0. The oak used in this study demonstrated a higher variation of wood properties compared to beech. Beech showed slightly higher MOE and MOR than oak.

To understand the influence of wood structural properties on wood mechanical properties, all measured parameters were cross-correlated and presented in Table 3. For both species, the MOE and MOR increased with the wood density. The MOE and MOR decreased following the increase in MFA and grain angle. Nonetheless, the influence of MFA and grain angle was only statistically significant on the MOE. The correlation between MOE and MOR is highly significant for both hardwood species.

Table 4 gives the adjustment results of MOE and MOR regression models, whereas Table 5 shows the selected model whose AIC is the lowest and R^2 the highest for which the independent variables are significant. For oak, the adjusted R^2 of the MOE model showed a better result when using wood density (*RI* = 62%), grain angle (*RI* = 20%), and MFA (*RI* = 18%) as the independent variables. However, the MOR of oak was better predicted using wood density (*RI* = 77%) and grain angle (*RI* = 33%). For beech MOE, the best model was the one that used wood density (*RI* = 84%) and MFA (*RI* = 16%), while the MOR of beech was better predicted with wood density alone without adding grain angle or MFA. The MOE prediction for both species was slightly more accurate than the MOR prediction.

4 Discussion

The area with a high gradient of wood properties is called juvenile wood. This area of juvenile wood is less than 5 cm from the pith. For both species, the ring wood density was slightly higher near the pith. These results are similar to those reported by Bouriaud et al. (2004) and Longuetaud et al. (2017) concerning oak. Previous studies have shown that the wood density of juvenile beech wood could be higher or lower compared to mature wood (Nepveu 1981). Oak, however, demonstrated a decrease in wood density with higher ring numbers by producing narrower rings while maintaining the same earlywood width. Higher wood density on juvenile wood is often associated with understory and late-successional species, which produce dense wood at the beginning of growth in order to increase resistance to biotic damage (Woodcock and Shier 2002; Plourde et al. 2015).

The variation in MFA from pith to bark was found to be relatively low. A higher variation of MFA is generally found in softwood species. A study by McLean et al. (2010) on Sitka spruce (*Picea sitchensis* (Bong.) Carr.) revealed that the stiffness of wood from the internal position is closely related to the MFA. The MFA variation for beech and oak in the internal position is negligible compared to softwood species (Lichtenegger et al. 1999). It is interesting to note that while ring wood density in both species first linearly decreased up to a minimum followed by an increase, MFA does not follow this pattern, indicating that the tree may be able to modify both parameters independently. The mechanical properties of juvenile beech and oak wood may

Table 4 Adjusted R^2, AIC, and errors of the estimate of the linear regression model of MOE and MOR

Species	Dependent variable	Independent variable	Adjusted R^2	AIC	Error
Oak	MOE	Wood density	0.49	102.31	1.73
		Wood density + MFA	0.63	94.86	1.46
		Wood density + Grain angle	0.65	93.66	1.43
		Wood density + MFA + Grain angle	0.71	89.89	1.30
	MOR	Wood density	0.43	205.94	13.76
		Wood density + MFA	0.48	204.67	13.18
		Wood density + Grain angle	0.52	202.48	12.61
		Wood density + MFA + Grain angle	0.52	203.23	12.59
Beech	MOE	Wood density	0.55	112.36	1.27
		Wood density + MFA	0.62	108.67	1.17
		Wood density + Grain angle	0.58	112.07	1.23
		Wood density + MFA + Grain angle	0.62	109.32	1.16
	MOR	Wood density	0.59	245.39	9.39
		Wood density + MFA	0.58	246.89	9.47
		Wood density + Grain angle	0.59	245.67	9.30
		Wood density + MFA + Grain angle	0.58	247.56	9.44

Table 5 Linear regression models with the highest adjusted R^2, lowest AIC, and significant variable for the prediction of MOE and MOR. *D*, wood density; *MFA*, microfibril angle; *GA*, grain angle; *F*, F-statistic; *RSE*, residual standard error

Species	Dependent variables	Independent variables				The goodness of fit statistics			
		Intercept	D (kg m^{-3})	MFA (°)	GA (°)	R^2	AIC	F	RSE
Oak	MOE (GPa)	−0.24	28.63***	−0.47*	−0.27*	0.71	89.89	20.47	1.30
	MOR (MPa)	−30.21	211.57***	-	−2.17*	0.52	202.48	14.12	12.61
Beech	MOE (GPa)	3.66	28.34***	−0.87*	-	0.62	108.67	27.09	1.17
	MOR (MPa)	−51.57	235.16***	-	-	0.59	245.39	46.48	9.39

***Variable is significant at the 0.001 level; **variable is significant at the 0.01 level; *variable is significant at the 0.05 level

act similarly to normal wood since the juvenile wood has high wood density and relatively low MFA. Moreover, the juvenile wood occupied a very small part in the center of the trunk of both species. It may be concluded that juvenile wood found in the suppressed growth trees of both hardwoods can be used in place of mature wood.

The mean wood density of beech found in the present study was slightly higher than the one described by Gryc et al. (2008) on 83-year-old beech on 12% MC (wood density = 0.71 g cm^{-3}). The static MOE was slightly lower than that of beech (MOE = 14.8 GPa) used for manufacturing Glulam, as described by Aicher and Ohnesorge (2011), whereas the MOR was comparable (120.64 MPa) to the one reported by Schlotzhauer et al. (2017) on defect-free beech. On the other hand, oak wood density and MOE were higher than those reported in a previous study on oak (wood density = 0.62, MOE = 9.79 GPa) in Tran et al. (2016). The MOR of oak in this study was 33.2% higher than the one found (86.52 MPa) in the study of Schlotzhauer et al. (2017). Based on the literature, the difference between MOE and MOR in both species should be more visible (Tran et al. 2015, 2016; Schlotzhauer et al. 2017).

Positive correlations between wood density and mechanical properties on oak are contrasted with previously published studies (Polge 1973; Zhang et al. 1994). Generally, in oak, there is no close relationship between wood density and mechanical properties, and some authors have even considered high wood density as a criterion of low-quality oak wood. The positive correlation between wood density and ring width is consistent with numerous studies, indicating that wood density is positively correlated with ring width (Guilley et al. 2004; Genet et al. 2013). The rapid growth of oak, therefore, induces a higher wood density. Oak is a ring-porous species whose increase in ring width is typically associated with higher latewood percentage, denser earlywood and latewood and, consequently, higher mean ring wood density (Zhang et al. 1993). The grain angle negatively influenced the wood mechanical properties, even when the level was very low. The low variation in grain angle found in both species supports previously published studies (Birot et al. 1980; Guilley et al. 1999). Similar to oak, Cibecchini et al. (2016) show that there was no correlation between beech wood density and MOE. In theory, the ring width in diffuse-porous hardwoods such as beech does not affect wood density. However, Bouriaud et al. (2004) reported that there was a low but significant negative correlation between wood density and ring width in beech ($r = -0.14$).

The better prediction of MOE than MOR found in this study is consistent with that of Vega et al. (2012) who modeled the MOE and MOR of chestnut (*Castanea sativa* Mill.) using non-destructive variables and visual grading parameters. For both species, the best MOE model always included the MFA, even when the variation in the MFA value in this study was very weak. The lower influence of MFA on the MOR was already reported by Yang and Evans (2003) when they studied the prediction of MOE and MOR of eucalypt (*Eucalyptus globulus* Labill.) wood using wood density and MFA. The variation in grain angle measured in this study was also very low. However, for oak, the best prediction models always included grain angle. Nevertheless, the variation in the grain angle of oak was slightly higher than that in beech. This could be the reason why the influence of the grain angle was significant for oak but not for beech.

5 Conclusion

This paper investigates the juvenility limit and structure–property relationship in beech and oak wood of secondary quality obtained from thinning. Results showed that the juvenile wood in oak had wider rings and a higher MFA, whereas it had larger latewood and a higher MFA in beech. For both species, the juvenile wood occupied a very small area, less than 5 cm from the pith, and the stabilization of different parameters seems to vary over time. The mechanical properties of oak and beech wood from suppressed growth trees were similar to the properties of dominant trees reported in the literature. As expected, even if the variation of all studied variables was not high, the model fits well. Adding grain angle and MFA to wood density is useful to predict MOE in both species and MOR in oak, confirming that these three parameters are the key ones mechanistically linked to clear wood MOE and MOR.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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Authors and Affiliations

Citra Yanto Ciki Purba[1] · Jana Dlouha[2] · Julien Ruelle[2] · Mériem Fournier[2]

✉ Citra Yanto Ciki Purba
citra.purba@ensam.eu

Jana Dlouha
jana.dlouha@inrae.fr

Julien Ruelle
julien.ruelle@inrae.fr

Mériem Fournier
meriem.fournier@inrae.fr

[1] Arts Et Métiers Institute of Technology, LaBoMaP, Rue Porte de Paris, 71250 Cluny, France

[2] UMR Silva, Université de Lorraine, INRA, 54000 AgroParisTechNancy, France