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Characterization and valorization of secondary quality hardwood as structural material

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Invité

**Characterization and valorization of secondary
quality hardwood as structural material**

**Caractérisation et valorisation des feuillus de
qualité secondaire comme matériau structurel**



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The preparation of samples and the characterization of structural, physical and mechanical properties were carried out at UMR Silva, formerly known as LERFOB (Laboratoire d'Etude des Ressources FOrêt-Bois), INRA Grand-Est, France. Half of the logs were transported to the LaBoMaP (Laboratoire Bourguignon des Matériaux et Procédés), ENSAM, Cluny, France where they were rotary peeled. The characterization of the veneer, the fabrication of the LVL and all mechanical tests were also performed in this laboratory.

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List of abbreviation, acronym, and symbols

γ	: Specific gravity
D	: Density
DP	: Demarcation point
$E_{m,g}$: Global modulus of elasticity
EW	: Earlywood
Ew	: Edgewise
EW_d	: Earlywood density
EW_w	: Earlywood width
$F_2 - F_1$: The increment of load on the regression line with a correlation coefficient of 0.99 or better (N)
f_m	: Modulus of rupture (MOR)
FSP	: Fiber saturation point
Fw	: Flatwise test
GA	: Grain angle
G-layer	: Gelatinous layer
Glulam	: Glue laminated timber
HSD	: Honestly Significant Difference
I	: The second moment of inertia (mm^4)
l	: Length of the test piece between the testing machine grips (mm)
l_1	: Gauge length for the determination of the local MOE
LEI	: Difference between the density of LW and EW
LRT	: Longitudinal, radial, tangential
Ls	: Longitudinal shrinkage
LVL	: Laminated veneer lumber
LW	: Latewood

LW _d	: Latewood density
LW _w	: Latewood width
MC	: Moisture content
MFA	: Micro Fibril Angle
MOE	: Modulus of Elasticity
MOED	: Dynamic modulus of elasticity
MOES	: MOE Static
MOR	: Modulus of Rupture MOR
ns	: Model is not significant
PVAc	: Polyvinyl Acetate
Rd	: Ring density
Rs	: Radial shrinkage
R _w	: Ring width
SMOE	: Specific MOE
SMOF	: <i>Système de Mesure d'Ouverture des Fissures</i>
SMOR	: Specific MOR
T	: t-1, where t is the ring number from the pith
Ts	: Tangential shrinkage
V ₂ -V ₁	: The increment of displacement of the loading tools corresponding to F ₂ -F ₁ (mm)
V _s	: Volumetric shrinkage
w ₂ - w ₁	: The increment of local deflection corresponding to F ₂ -F ₁ (mm).
XRD	: X-Ray Diffractometer
Y _i	: The value of the first ring
Y _m	: The final value of the variation curve before the constant value is achieved

List of publication and presentation

Publications

Purba C., Pot G., Viguiet J., Ruelle J., Denaud L. (2019) The Influence of Veneer Thickness and Knot Proportion on the Mechanical Properties of Laminated Veneer Lumber (LVL) Made of Secondary Quality Hardwood. *European Journal of Wood and Wood Product* (Under Review)

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Husein, I., Sadiyo, S., Purba, et al. (2014). Electrical properties of Indonesian hardwood case study: *Acacia Mangium*, *Swietenia Macrophylla* and *Maesopsis Eminii*. *Wood Research*, 59(4), 695-704.

Presentation

Radial variation of wood properties on hardwood recovered from thinning, Poster presentation at Journées Scientifiques Du GDR 3544 Sciences Du Bois 2018, Cluny, France.

The mechanical properties of laminated veneer lumber (LVL) made of secondary quality oak and beech: the effect of veneer thickness. Poster presentation at wood conference on timber engineering (WCTE) 2018 Seoul, Republic of Korea.

Mechanical Properties of Laminated Veneer Lumber (LVL) Made from Secondary Quality Oak and Beech, Poster presentation at Journées Scientifiques du GDR 3544 Sciences du Bois 2017, Nantes, France.

Characterization and Modelization of Mechanical Properties on Free Defect Hardwood, Poster presentation at Séminaire Annuel Ecole Doctorale RP2E 2017, Nancy, France

Qualification, Characterization and Valorization of Secondary Quality Beech from Thinning, Poster presentation at Journées Scientifiques Du GDR 3544 Sciences Du Bois 2015, Clermont Ferrand, France.

Chapter 1

Chapter 1

General introduction

1.1. Overall context of the study

Hardwood dominates not only the standing stock but also the surface area of the French forests. As opposed to available forest resources, wood harvested and timber produced are dominated by softwood resource due to the lack of tested practices and information about the quality of hardwood. On the other hand, the new forest management system with intensive silviculture tends to produce secondary quality hardwood that is not suitable to be used directly as a construction material since they contain high proportions of defects. In addition, due to climatic risk mitigation and to the market demand in industrial wood products and fuelwood, there has been a shift toward harvesting trees much younger than in the past, and an increase in the utilization of small trees that are removed during thinning operations. Improving the added-value of these abundant hardwood with secondary quality is essential.

The presence of various wood defects such as knots, grain deviation, juvenile wood, and reaction wood restrict the utilization of secondary quality hardwood as a material for construction. To achieve a better valorization of small and suppressed growth hardwood trees, it is important to have a better understanding regarding the variation of wood properties. The valorization of this resource as a structural material also requires optimization of its mechanical properties through the reconstitution into an engineered wood product such as laminated veneer lumber (LVL). LVL is a wood-engineered product made of veneers that are glued together with the grain orientated mainly parallel to the panel length. LVL is commonly used for structural and nonstructural applications such as flooring, furniture, and construction. Compared to solid wood, the production process of LVL allow homogenization of resource defects, thus an improvement for mechanical properties and dimension stability. Moreover, LVL is available in a large dimension and can provide higher stiffness and strength than solid wood.

1.2. Hardwood vs softwood: Paradox of French forest resources and timber production

Based on the plant reproduction and the wood structure, trees are divided into hardwoods and softwoods. Hardwoods are mostly deciduous trees that shed their leaves during the autumn and winter. The hardwoods are angiosperms, which means that their seeds are enclosed in the ovary of the flower. From an anatomical point of view, hardwoods are porous because they contain vessel elements. Hardwoods have a more complex structure than softwood as they have a greater number of cell types.

On the other hand, softwoods mostly have needle like leaves which are evergreen. Botanically, softwoods are gymnosperm meaning that the seeds are not enclosed in the ovary

of the flower. An important similarity in the anatomy of hardwood and softwood trees is that when they reached maturity, the cells died even in the sapwood. The only cell remaining alive that can be found on both softwoods and hardwoods are known as parenchyma.

France has the largest hardwood forest in the European Union, where the forest resource is mainly composed of softwoods (FAO 2015). Figure 1.1 illustrates that 67% of the French forest area is covered by hardwood species, which is the equivalent of 9.9 million hectares. Latest forest inventory data shows that the hardwood standing stock is almost two times higher than the softwood, with the hardwood volume at about 1.725 million m³ whereas softwood at around 971 million m³ (IGN 2016).

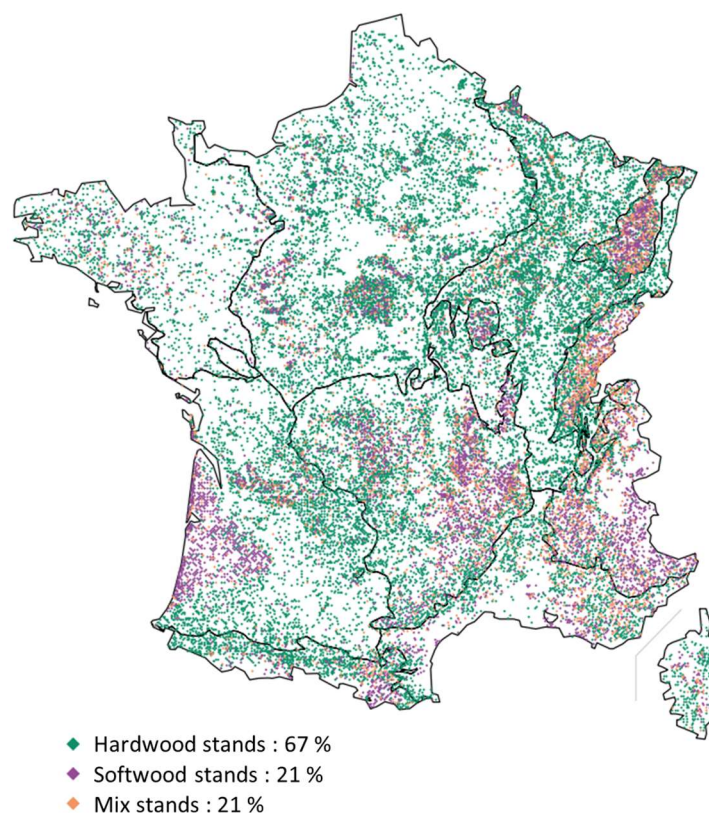


Figure 1.1. Distribution of forest stand composition in France (IGN 2016)

Two hardwood species, namely oak and beech, already represent 42 % of total France standing stock which includes both hardwood and softwood species. Oak dominates by 31 % and beech by 11% of total volume (IGN 2016). While the volume of standing hardwoods has continued to increase over the last 25 years, there is a decline in the harvest of hardwoods and they are becoming less and less used in the field of wood construction. Figure 1.2 describes the paradox between the availability of wood in the forest and the timber harvested in France.

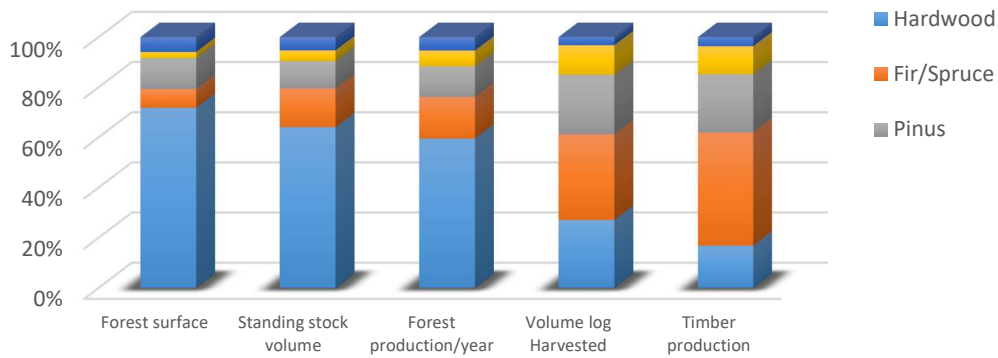


Figure 1.2. Forest resources and production of softwood and hardwood timber in France (Ministère de l'Agriculture et de l'Alimentation 2017)

If this resource in the upstream is not found in the downstream, it is not because of lack of availability, processing technology, or the quality of French hardwoods but because of low demand for hardwoods. All specialists and professionals agree that the current market does not solicit and encourage the use of hardwoods sufficiently. As an indication, in the field of construction 95% of the sawn timber used is softwood species, compared with only 5% of oak. As such, in the field of construction, glued structural elements feed a market of over €1100 M. At the same time, demand for French hardwoods from China continues to increase but remains in the form of roundwood (Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt 2016). The construction sector remains far from the dominant market in Europe in the use of solid wood, and it is undergoing major changes under the constraints of sustainable development. For this reason, the French government has initiated several research projects to develop the product and the innovative solution to valorize local hardwood resources in the construction sector.

1.3. Wood quality

Mitchell (1961) explained the quality of wood as a result of the physical and chemical characteristics of a tree or its parts which enabled it to meet the properties required for different end products. Wood quality is very much related to perception and is therefore difficult to measure. For example, at various levels of the production of wood-based products, there are different perceptions of good quality wood. For forest managers, wood quality is related to stem diameter, stem form, growth rate, and tree resistance to diseases. For sawn timber production, the quality of wood can be associated with defects, size, and straightness. In the pulp and paper industry, the chemical composition is an important factor that influences pulp yield and quality. Accordingly, in the end, consumers have a perception of the quality of wood that depends on the end use because each final product has a unique set of requirements.

Wood produced by hardwood trees such as oak and beech can be used in various types of applications. But compared to softwoods, hardwoods have a lower proportion of stems than softwoods. For example, the proportion of stems for spruce is about 90% while beech is only about 50% (Pöhler et al. 2006). In addition, due to the presence of red heart on beech, there are a large number of beech fall into class C (Huss and Manning 2003; Petráš et al. 2016). The color of the wood is also important for end users, thereby affecting the prices.

High-quality roundwood is mainly used as a raw material for veneer, whereas some of the secondary quality of wood can be used for sawn wood and the remainder used for firewood, particleboard, fiberboard, and pulp and paper. High quality oak is easy to work with but the relatively hard to find (Croisel and Collet 2016). Hardwood resources are undoubtedly dominated by secondary quality wood (Luppold and Bumgardner 2003).

Clearly, it is the final use that determines the characteristics of the timber required and therefore the quality of the material. In the production of wood for structural applications, available dimensions, dimensional stability, and mechanical performance are important for ensuring good performance and safety. These properties are controlled by the wood structures at the cellular level. There are numerous internal and external factors influencing the quality of wood.

1.4. Factors affecting the wood quality

Macdonald and Hubert (2002) classified the factors affecting wood quality into three categories: differences in genetics, location factors, and silvicultural practices. Selection of genotypes for seed and breeding populations based upon diameter, height, and stem traits directly affect the quality of wood produced. Such genetic characteristics are moderate to highly heritable. Tree adaptation to the environmental condition like well drained soils, good fertility, and a low exposure results in increase of the volume growth and reduces the risk of damages due to wind exposure (Johnson and Gartner 2006; Cherry et al. 2008).

Indeed, silvicultural practices such as initial spacing, thinning and pruning also influence the wood quality. Larger initial distances between trees reduce the competition with adjacent trees and therefore increase the access to light and nutrients. Consequently, previous studies show that the initial distance correlates positively with the stem diameter, ratio of the live crown and crown diameter (Fabris 2000; Briggs et al. 2007; Hein et al. 2008). Thinning, another silvicultural practice aimed to reduce tree competition by removing some low quality trees, before the crown enclosed has the same effect as the initial distance. Thinning after the crown enclosed, however, allows the production of knot free wood at the lower part of the stem (Macdonald and Hubert 2002). Pruning, removal of three branches, reduces the knot on the stem surface. In addition, some studies also suggest that pruning accelerates the transition from young to mature wood (Briggs and Smith 1986; Macdonald and Hubert 2002).

1.5. The wood characteristic affecting the mechanical and physical properties

Wood density

Wood density is widely regarded as one of the most important wood quality characteristics, having a major effect on both yield and quality of fibrous and solid wood products (Panshin and Zeeuw 1980; Zobel and Buijtenen 1989). Wood density influences wood physical and mechanical properties. Generally, wood with higher density is associated with higher mechanical properties. But high wood density also leads to higher shrinkage and swelling. In many cases, high density, particularly in hardwoods, is also known to be a problem in wood gluing. The cell wall density is more or less constant, the variation of wood density is mainly regulated by the amount of open spaces in its structure, i.e., lumen size of tracheids

or fibers, voids on the cell wall and the occurrence of vessels in hardwoods. There are only a few studies on the effect of wood density on the mechanical and physical properties of oak and beech. However, the results of these studies are inconsistent from one study to another (Polge 1973; Cibecchini et al. 2016).

Generally, in oak, there is no close relationship between density and mechanical properties (Nepveu 1990; Neusser et al. 1975; Zhang and Zhong 1992). For sessile oak, low density is generally considered as an indicator of high quality wood (Polge 1973). Accordingly, higher wood density causes problems as it tends to shrink and swell more than the lower one thus results in more significant drying defects (Nepveu 1981; Zhang et al. 1994a).

Growth ring

The growth ring is a collection of cells produced in the same period and composed of two parts which are called earlywood and latewood. Earlywood is formed at the beginning of the growing season while latewood is formed during the latter growing season. In the temperate forests, earlywood formed over spring season whereas latewood over summer. There are two main types of growth rings structure in hardwood species, which are ring porous and diffuse porous. For ring porous woods, the transition between earlywood and latewood is abrupt where the vessels number and diameter is lower in latewood. In contrast, the transition of vessel number and diameter from early to latewood is gradual in diffuse porous woods. It is, therefore, more challenging to separate earlywood from latewood in the case of diffuse porous wood.

Previous studies on oak show that wood density is positively correlated with growth components such as ring width. This means that rapid growth is favorable for obtaining high density wood (Nepveu 1990; Zhang et al. 1993, 1994b; Guilley et al. 2004). An increase of growth ring width in ring porous species such as oak is generally associated with higher latewood percentage, denser earlywood and latewood, and consequently higher mean ring density (Zhang et al. 1993). On the other hand, for diffuse porous hardwoods such as beech and maple, Hakkila (1989) reported that the variation of the ring width hardly affects the variation of wood density. Nevertheless, a recent study by Bouriaud et al. (2004) shows that the correlation between wood density and ring width was quite low ($r = -0.139$) but statistically significant. Therefore, the variations of wood density can be difficult to understand, since it is not a single property but a combination of several ring components such as earlywood and latewood densities, and the proportion of latewood.

Microfibril Angle (MFA)

The cell wall of wood is mainly constructed by three regions, which are middle lamella, the primary wall, and the secondary wall as described in Figure 1.3. Each region is mainly composed of crystalline cellulose (microfibrils), amorphous hemicellulose and lignin. The adhesion of the individual cells is ensured by the middle lamella which is primarily made up of pectin and lignin. The primary wall consists of randomly oriented cellulose microfibrils. All individual microfibril is inclined around 0° - 90° relative to the long axis of the cell. The secondary wall, on the other hand, is more regular and parallel. The secondary layers are divided into three different layers called S_1 , S_2 , and S_3 . The S_2 layer is the most crucial layer as it is the thickest layer accounts for 75 to 85% of the wall thickness which makes the most

significant contribution to the overall properties of the cell wall. The S_2 is characterized by high lignin content and low microfibril angle (5° to 30°).

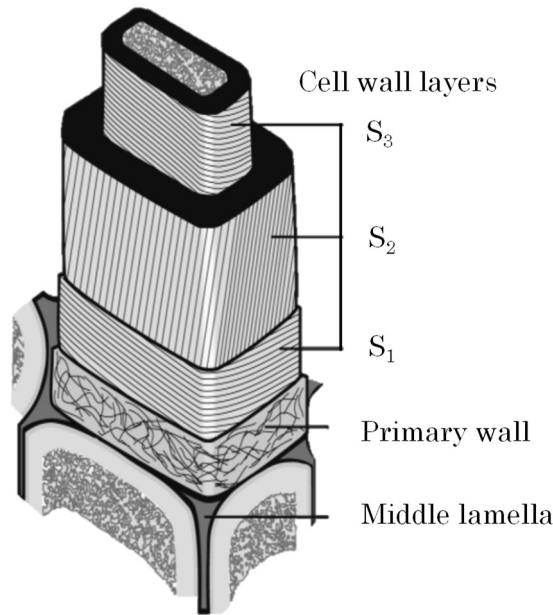


Figure 1.3. The structure of wood cell wall (Rowell 2012)

In addition to wood density, MFA, i.e. the microfibril angle of the S_2 layer of the secondary wall, is also considered as a key variable explaining the numerous variations in physical and mechanical properties of wood (Cave 1968; Yamamoto and Kojima 2002; Rowell 2012). Lichtenegger et al. (1999) reported that the MFA variation observed from pith to the bark was generally higher in the softwood species like spruce and pine than in the hardwood species like oak and beech. For softwood species like black spruce, the MFA alone explains 72% of the MOE variation, while the combination with wood density increases it to 90% (Alteyrac et al. 2007). As a consequence of a smaller MFA variation on beech and oak, MFA would only marginally affect the mechanical and physical properties of the two hardwood species.

1.6. Wood defects and abnormalities: Relationship with wood characteristic, mechanical properties and physical properties

Grain angle

Due to the highly anisotropic nature of wood, a small misalignment between the fiber direction and the longitudinal axis of a wood piece can lead to significant changes in the mechanical properties of wood. This misalignment, referred to as grain angle, can result either from the way the wood is cut from the log or from the natural spiral along the life of the tree. The natural spiral grain is caused by the internal stresses in the tree including the geotropic response and the environmental conditions like winds (Harris 1969). High grain angle on timber induces lower mechanical properties (Pope et al. 2005; Brännström et al. 2008; Viguier et al. 2015, 2017a). In addition, high grain angle also causes warping and twisting of the wood during the wood drying process (Harris 1969). Previous studies have reported low variation of grain angle on oak and beech (Birot et al. 1980, Guilley et al. 1999).

Knot

Wood knots are remnants of branches. It appears as round and brown pieces of wood in flatsawn timber and can be cut along the length in quarter sawn timber (known as spike notes). Knots can be classified into loose knot or tight knot. Loose knot are formed when a dead branch is embedded in the forming growth ring. Tight knot, on the other hand, is formed by a living branch.

Knots are the single most important defect related to the mechanical properties. The strength reducing effect of knot is influenced by the form, size, number, position of knot, and the load subjected. Grain angle is also the main reason why knots are considered as the most strength reducing defects (Viguier et al. 2015, 2017a). The fiber disturbance around a knot rather than the knot itself often causes the failure. Loose knots generally disturb the grain angle less than tight knots (Forest Product Laboratory 2010).

Juvenile wood

Juvenile wood is the wood located in the area close to the pith created at the beginning of the radial growth that can be characterized by a large gradient of wood properties and relatively lower mechanical properties compared to mature wood (Moore et al. 2009; Zobel and Sprague 2012). Juvenile wood is not only characterized by inferior wood properties compared to mature wood, but it is also often associated with a higher degree of knottiness (Panshin and Zeeuw 1980). The presence of juvenile wood causing problems such as warping, excessive shrinking or swelling, and fuzzy grain when sawing, veneering, and drying the wood. Intensive forestry tends to increase the proportion of juvenile wood relative to the mature wood that results in reduced lumber strength, and a decrease of pulp yields.

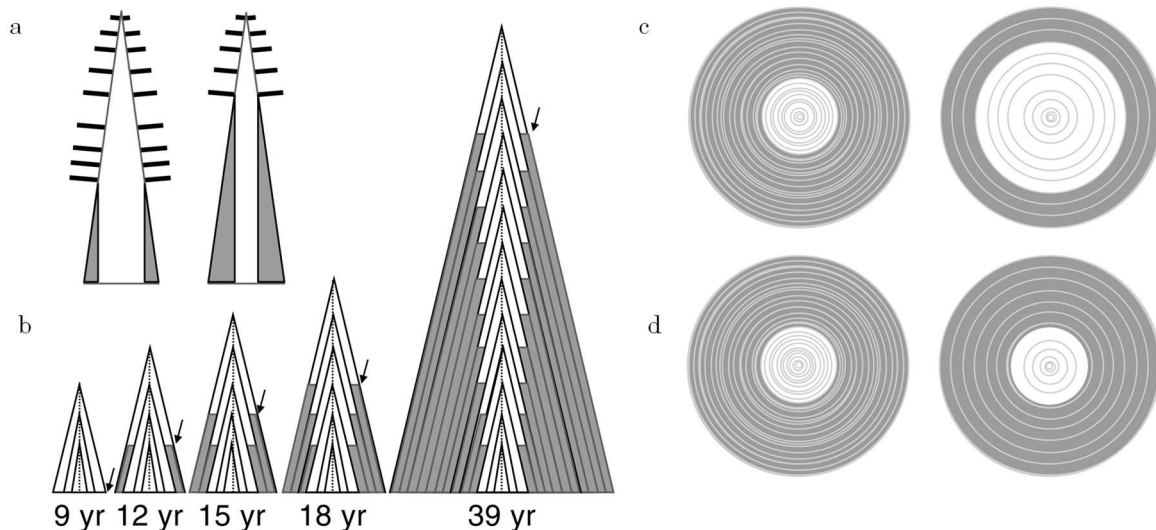


Figure 1.4. Determination of the transition point between juvenile (white) and mature wood (gray) based on (a) The position of the live crown; (b) Cambial age. Transition after 9 years where each sheath of the tree representing 3 years growth. At any stage of tree growth, juvenile wood is produced at cambial age of 9 years and mature wood is produced after (arrow); (c) Cambial age. Shown schematically for transition age of 9 years for a slow-grown and a fast-grown tree; (d) Stem diameter (Meinzer et al. 2011).

There is no universal position where wood properties reach a constant value. The changes of wood properties are gradual from the pith to the mature wood where it reaches a relatively constant value. This constant value and its pattern themselves highly varied between wood properties, trees, and growing sites (Cown et al. 1991; Fabris 2000). As a consequence, the separation point between juvenile and mature wood also vary between species, the method used, and the characteristic under consideration (Zobel and Sprague 2012). Several mechanistic hypotheses on the location of juvenile wood are existing and are based on the position of the live crown, cambial age or by diameter as described in Figure 1.4 (Meinzer et al. 2011).

The number of rings and distance from pith have been used to separate the juvenile from mature wood. The identification was based on visual assessments on the pattern of latewood percentage, densitometry, fiber or tracheid length, and microfibril angle from the pith to the periphery of the trunk (Cown 1973; Shiokura 1982; Abdel-Gadir and Krahmer 1993; Fabris 2000; Larson et al. 2001; Mansfield et al. 2009). There have been some reports on the variation of wood properties and the juvenile wood of beech and oak (Helińska-Raczkowska and Fabisiak 1991; Helińska-Raczkowska 1994; Guilley et al. 2004; Bouriaud et al. 2004).

Reaction wood

Trees control the spatial position of their axes (stem or branches) by generation of asymmetrical stress (Fournier et al. 1994; Clair et al. 2013). Asymmetry of maturation stresses induces a bending moment which maintains (growing branches) or corrects (accidentally tilted stem) the spatial position of axes (Alméras et al. 2006). To achieve an important bending moment, trees are pushed to produce an unusual level of maturation stresses. Tissues with the unusual level of maturation stresses is called reaction wood.

While hardwood trees generate highly tensile stressed tissues called tension wood on the upper side of leaning axes, conifers produce so called compression wood on the lower side of leaning axes (Fang et al. 2008; Abasolo et al. 2009). In many species of hardwoods such as beech, poplar, oak and chestnut, tension wood contains fibers with a special morphology and chemical composition due to the development of gelatinous layer (Fang et al. 2008; Clair et al. 2010). This layer usually used as a tool to identify the presence of tension wood in hardwoods.

Occurrence of reaction wood is most often associated with branches or tilted trees. However, it is also frequently reported in straight stems in a number of species including Beech (Gartner 1997; Washusen et al. 2003). The presence of reaction wood generally reduces the quality of wood products. At the tree level, the presence of tension wood increases the log end cracks in hardwood as the gradient of stress in the stem periphery increase in the case of hardwood. Moreover, tension wood also associated with higher longitudinal shrinkage and lumber twisting. For some hardwood species, the wood density of tension wood is higher than normal wood which is associated with the thickening of cell wall by the gelatinous layer (Jourez et al. 2001; Christensen-Dalsgaard et al. 2007; Ruelle et al. 2007). Despite this, the MFA of tension wood is generally lower than that of normal wood (Clair et al. 2006).

The literature studies show contrasting results on the effect of thinning on the growth stress level on tree periphery (Evans and Jackson 1972; Polge 1981; Ferrand 1982; Mitchell 2000).

Nevertheless, our recent study on the growth stresses in old beech poles shows that there was no effect of thinning on the value and intensity of the growth stress (Purba et al. 2015). On the other hand, our study also demonstrated the positive correlations between the proportion of gelatinous layer and the growth stress index. Furthermore, a negative correlation was found between the growth stress index and the vessel proportion which was due to the decrease of vessel frequency.

1.7. Secondary quality hardwood and its potential for structural application

High-quality hardwoods for furniture and veneers generally come from natural forests or traditional silviculture in semi-natural forests. Such forests cannot produce high quality wood without also producing a significant proportion of low quality wood. At the same time, new forest management systems based on intensive silviculture tend to produce wood with lower quality. In addition, in order to mitigate climate risks and to fulfill the market demand for industrial wood products and fuelwood, there has been a shift towards harvesting much younger trees than in the past and using smaller trees that are removed during thinning operations. In addition to the small log dimension, this low quality wood contains various wood defects including the high presence of knots, grain deviation, juvenile wood, and growth stress which are restricting its utilization as structural materials.

Even with the latest sawing technologies, the production of sawn timber from low quality wood has shown persistent problems related to log recovery rate, wood drying, stability, durability, appearance quality, and profitability (Leggate et al. 2000; Washusen et al. 2009; Blackburn et al. 2011; McGavin et al. 2014). Therefore, the valorization of this resource as structural material requires better knowledge of the wood properties and improvements of the mechanical properties through the reconstitution into engineered wood products in the form of glue laminated timber (Glulam), laminated veneer lumber (LVL), or cross laminated timber (CLT). These three kinds of engineered wood product are the main products used for the construction of the modern high rise timber building.

Multi-storey timber construction offers an attractive solution to meet the rapidly growing human population and the growing number of people living in the cities. The modern constructions are dominated by steel and reinforced concrete, but these materials are non-renewable resources and consume high amounts of energy while also generating a lot of carbon emissions. In recent years, multi-storey wood building has gained global attention. The government of some countries such as Japan even enact a law in order to promote large wooden building (Inoue et al. 2018). Other countries like Canada and France also actively promote the development of tall timber building (Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt 2016; Mohammad et al. 2018).

Apart from the high recovery rate wood processing like fiberboard and particle board, the processing of low quality hardwood into veneer shows a high recovery rate especially compared to the conversion into sawn timber (McGavin et al. 2006, 2014; Hopewell et al. 2007). Sawn products are used to make CLT and Glulam, while veneers are used to make LVL. This means that lower quality hardwoods will be better converted to LVL where the biomass will be optimized. Compared to solid wood, LVL has several advantages: it has greater dimensional stability, can be manufactured in large dimensions, contains fewer wood

defects as it is dispersed during the manufacturing process, and therefore provides higher mechanical properties.

LVL is made of veneer glued together by adhesives. However, unlike plywood where the layers are perpendicular, LVL veneer layers are mainly parallel to the grain direction. LVL is suitable for both structural and non-structural applications. Structural applications of LVL include headers and beams, roof rafters, and long-span trusses whereas non-structural applications include door, window frames, and furniture components.

The mechanical properties of LVL are affected by the quality of its components, which are veneers and adhesives (Daoui et al. 2011; Pot et al. 2015; Vigui r et al. 2017b, 2018). During the veneering process, the wood tends to split along the grain. This splitting, referred as lathe check in Figure 1.5, occurs due to the tension force of the lathe knife which pulls the veneer away from the peeler block and flattens the veneer from its natural curvature (DeVallance et al. 2007). In addition to the presence of knots on the surface of the veneer made of secondary quality wood, the formation of lathe checks on the loose side of the veneer surface caused by the peeling operations also defines the veneer quality (Thibaut 1988).

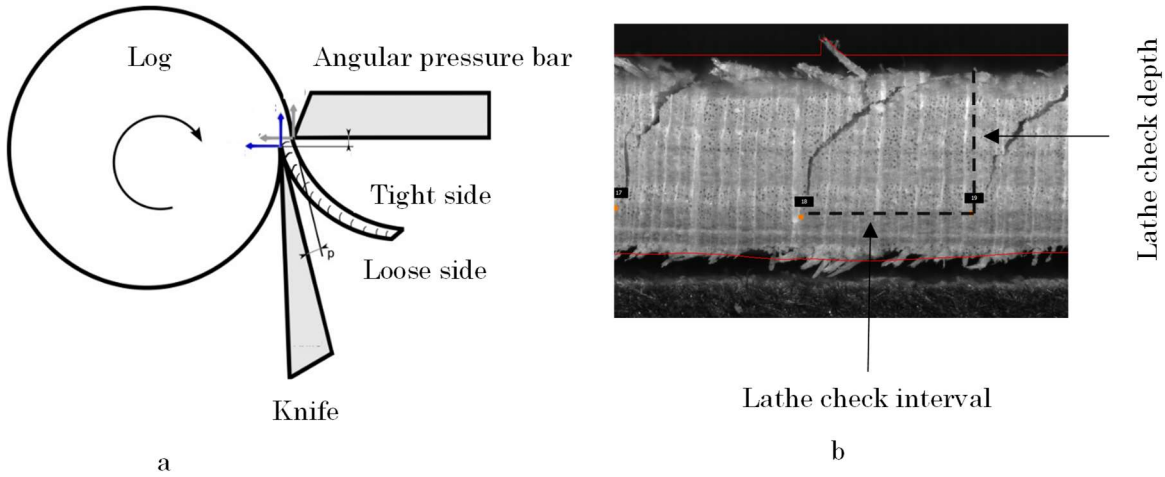


Figure 1.5. a) Diagram of rotary peeling b) Measurement of lathe check depth and interval using SMOF device

Thicker peeling thickness generally leads to deeper lathe checks and larger lathe checks interval (Denaud et al. 2007; Pa ubicki et al. 2010). This is one of the reasons why the thickness of the veneer shows some influences on the mechanical properties. It is also generally accepted that a lower veneer thickness distributes defects better and consumes more adhesives, which leads to higher mechanical properties (Ebihara 1981). Nevertheless, the results of previous studies have shown conflicting results (Schaffer et al. 1972; Hoover et al. 1987; Kilic et al. 2006; Daoui et al. 2011; Rahayu et al. 2015).

The use of thicker veneer for the manufacture of LVL will help to reduce the glue consumption, shorten the production time and ultimately increase the profitability. In more recent studies on LVL made from hardwood species, it has been reported that increasing veneer thickness causes only slight weakening on the MOE and MOR of the LVL (Daoui et al. 2011; Pot et al. 2015; Rahayu et al. 2015). Pot et al. (2015) further state that increasing veneer thickness influences mechanical properties by lowering the shear modulus of LVL. The report of the authors cited, however, is only based on numerical studies and has not yet been clarified on a large number of experimental measurements.

1.8. Objectives of the PhD

The French forests are dominated by hardwood in terms of available resource. In addition, low-quality or secondary quality wood is the major part of these resources. Young thinning, top wood and early harvested wood are secondary quality resources that have great potential for high-value applications (Eckelman 1993; Marchall 1995; McKeever 1997; Knudson et al. 2007). Such resources have not been sufficiently exploited and have been widely used only for firewood and composite wood including fiberboard and particleboard. Finding an alternative way to use these abundant resources is therefore essential.

Secondary quality hardwoods are not suitable to be used directly as a construction material as they contain various defects. The use of this resource as a structural material requires a better understanding of its wood properties and an optimization of its mechanical properties. Based on the problems mentioned above, this PhD thesis was aimed to:

1. Better understand the wood properties of secondary quality oak and beech which are the two most important hardwood species in France and understand how to use this material based on the measured parameters related to wood quality.
2. Understand the relationship among measured parameters related to wood quality and their influence on the wood physical and mechanical properties in order to find an optimal utilization for structural application.
3. Optimize the properties of a chosen final product, i.e., LVL based on the wood properties previously measured, veneer thicknesses, and knottiness.

This PhD thesis consists of 6 chapters. The first chapter presents the context and state of the art concerning the French forest, wood production, wood quality, wood properties, veneer quality, and LVL. Chapters 2, 3 and 4 provide the results in the form of a set of draft articles. The second chapter discusses the radial variation of wood properties from the pith to the bark. The third chapter establishes the relationship between the structural properties of wood and its physical and mechanical properties. Chapter four explains the influence of veneer thickness and the proportion of knots on the veneer surface in relation to the mechanical properties of LVL. In chapter five, all the results explained in the previous articles are discussed and the conclusion and perspectives are presented.

Chapter 2

Chapter 2

Radial variation of wood properties of hardwood recovered from thinning

2.1. Introduction

Beech and oak are the two most abundant hardwood species in Europe and particularly in France (IGN 2016). The even aged beech stand is normally harvested around 100 - 140 years while oak around 150-250 years (Pardé 1978; Von Wühlisch 2008; Schall et al. 2018). New forest management systems based on intensive silviculture, however, commonly favored shorter rotation through the use of faster growing breed that typically produce lower wood quality (Zell et al. 2004; McLean et al. 2016). In addition, there has been an increase of the utilization of wood from young trees removed during the forest management practice.

During the development of the tree stands, the number of trees per hectare is often reduced, thus allowing trees with a higher potential to grow faster thanks to the increase of space and a better access to nutrients, water and sunlight. This operation, called as thinning, involves felling many young and small diameter trees that may contain high proportion of juvenile and tension wood. Consequently, due to its smaller diameter, higher knottiness, and higher proportion of juvenile and tension wood, the wood removed from thinning generally categorized as low quality wood. These characteristics are limiting the utilization of this material. Therefore, finding an alternative use of these abundant resources is essential as they have been insufficiently explored and commonly sold for firewood and pulp industry. To achieve a better valorization of the wood issued from small and suppressed broadleaved trees, it is important that the wood properties and its variations are better characterized.

Juvenile wood, the wood located in the region close to the pith created at the beginning of the radial growth, can be characterized by a large gradient of wood properties and relatively lower mechanical properties compared to mature wood or outerwood (Moore et al. 2009; Zobel and Sprague 2012). It has been less described in hardwoods and in semi-natural forests of long cycles (120-220 years) as oak or beech. There is no universal position within a stem at which wood properties reach a quasi-steady state value; the progression from juvenile and mature wood is usually gradual, and the steady-state values as well as the pattern themselves can vary between wood properties, as well as between individual trees and sites (Cown et al. 1991; Fabris 2000). The separation point between juvenile and mature wood is depended on the species, the method used, and the characteristic under consideration (Zobel and Sprague 2012). There are several mechanistic hypotheses on the location of the juvenile wood which are based on the position of the live crown, cambial age or by diameter (Meinzer et al. 2011).

Number of rings and distance from pith has been used to separate the juvenile from mature wood where the identification was based on visual assessments of latewood percentage, densitometry, fiber or tracheid length, and micro fibril angle (Abdel-Gadir and Krahmer 2007; Cown 1973; Fabris 2000; Larson et al. 2001; Mansfield et al. 2009; Shiokura 1982). Consequently, the separation point between juvenile and mature vary according to the wood properties under consideration.

In the present study, beech and oak represents two type of ring distribution in hardwoods i.e. ring-porous and diffuse-porous. In the ring-porous hardwoods the changes of basic density are influenced by ring width, while basic density of diffuse-porous hardwoods is almost independent of ring width. From the standpoint of wood density, juvenile wood is poorly delimited if ring-porous hardwoods have vigorous growth, but it is clear in diffuse-porous hardwoods in all cases (Fukazawa 1984). This study aimed to understand the radial variation of wood properties in beech and oak remove during thinning operation. The properties of cell wall material (specifically MFA) and the amount of cell wall (density) both affect the mechanical properties of wood (MOE longitudinal). The microfibril angle (MFA), earlywood and latewood density, and ring width were measured from the pith to the bark. As the final utilization of this wood is for the structural purpose, it was interesting to understand the effect of different wood radial position on the wood mechanical properties. We divided the sample into two categories based on the radial position inside the trunk. The first category called internal originated from the position nearest to the pith while the second category from the nearest position to the bark. The wood density, MOE, and shrinkage of both radial positions were compared.

2.2. Materials and methods

Wood material

The wood material used for the present study were beech (*Fagus sylvatica*), and oak (*Quercus petraea*) issued from a mixed forest stand in Lorraine (48.893622 N, 6.741478 E), Grand-Est region, France. Trees were removed during a thinning operation and corresponded therefore to suppressed trees. Five trees per species were cut. Oak ages ranged between 61 and 90 years old while beech ages ranged between 57 and 84 years. In total, the round wood material comprised of 20 logs of 150 cm long with diameters between 21 and 30 cm. The extraction of samples from the tree is described in Figure 2.1. Two logs of 2 m in length were cut from the upper part of the trunk and generally contained knots. Log grading using a visual method based on EN 1316 classified the round woods into the grade C and D based on logs diameter and the presence of knot.

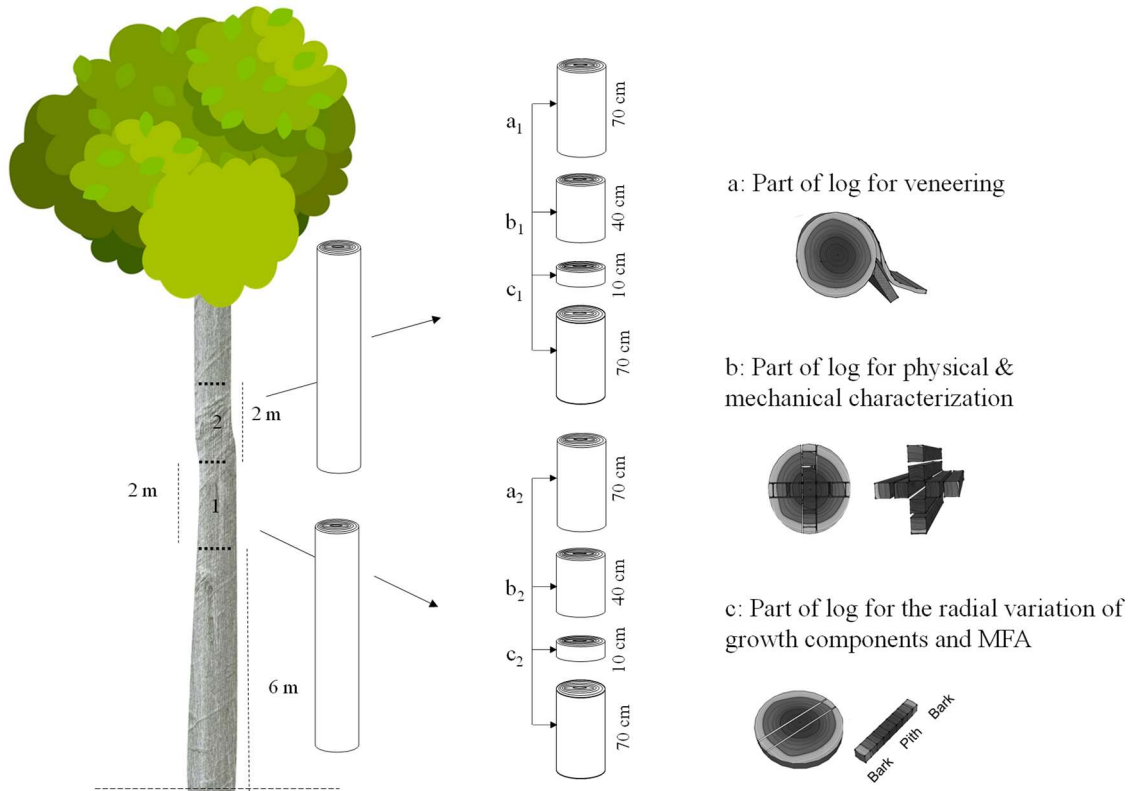


Figure 2.1. Samples extraction from the tree and its corresponding measurements

Measurement of radial growth component using X-ray

3 cm-thick disc was extracted from the central part of each log (part c) as described in Figure 2.1. A radial strip (2.5 cm x 5 cm, T x L) was cut in a defect-free zone and conditioned during one month at 12% relative humidity at ambient temperature. A radial slice (1 x 0.2 cm², T x L) was then cut for X-ray micro-densitometry measurements as described in Figure 2.2. Using the CERD software, the limit between two adjacent rings were manually assigned as described in Figure 2.2. Each ring was divided into 20 intervals of equal length, with each representing 5% of the ring's width. The mean density was calculated for each interval. More details of the microdensitometer analysis are explained in Mothe et al. (1998b, a).

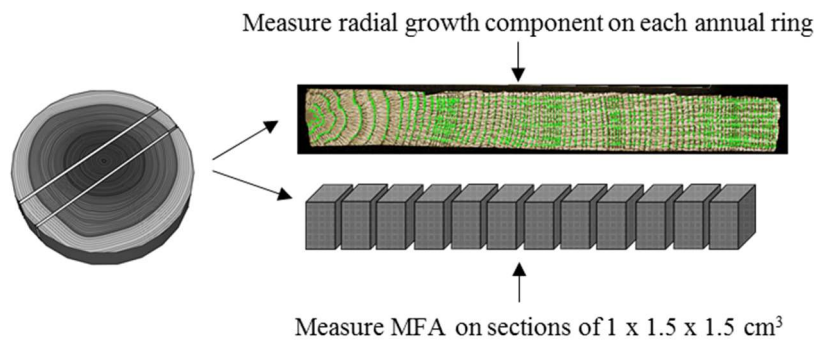


Figure 2.2. Specimen preparation for the measurement of radial variation of wood properties

Measurement of MFA

The remaining part of the radial strip was then cut in 1-cm thick samples from pith to bark as described in Figure 2.2. The MFA was measured on each ring by using an X-ray diffractometer (XRD) from Oxford Diffraction. The X-ray generator operating at 50 keV/0.8 mA with beam diameter around 300 μm generates CuK_α radiation. To reach the optimum noise, 60 seconds of exposure time was employed. The T parameter was used to calculate The MFA according to Cave's equation (Yamamoto et al. 1993).

Non-destructive evaluation of wood stiffness

Each log was cut into 8 wood specimens with a dimension of $380 \times 20 \times 20 \text{ mm}^3$ from part b of the log as described in Figure 2.1. These wood specimens were extracted from 8 different positions where 4 specimens were in internal position and the remaining in external position. Specimen for the internal position was extracted from the nearest area to the pith while the specimen for the external position was extracted from the nearest area to the bark. The wood samples were dried into 12% of moisture content. The dynamic MOE was measured using a nondestructive test (Bing) which based on vibration method (Brancheriau and Bailleres 2002; Ruelle et al. 2007). Measurement of vibration is performed by positioning the samples on highly elastic supports. Vibrations are produced by an impact at one end and recorded by a microphone at the other end. The setup for Bing measurement is described in Figure 2.3. The wood density was calculated by dividing their mass by their volume in the air-dry state.

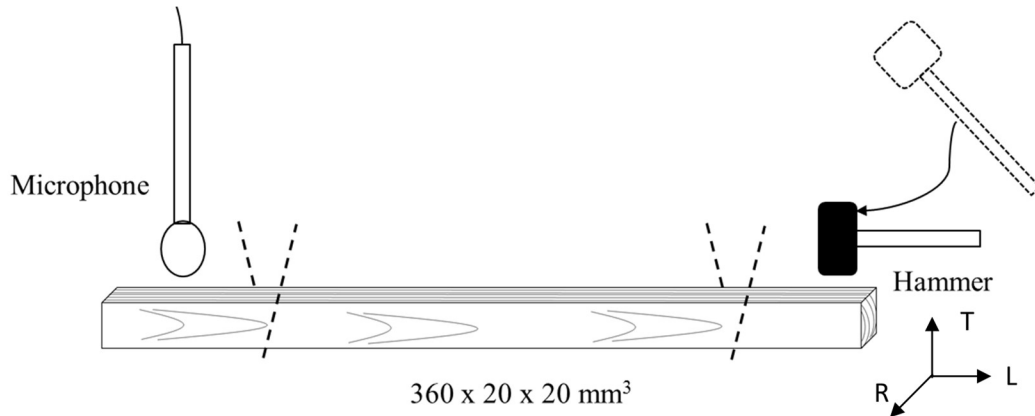


Figure 2.3. Measurement of dynamic MOE using Bing method

Shrinkages

Longitudinal shrinkage was evaluated on the specimen of $50 \times 20 \times 20 \text{ mm}^3$ (LRT) while the radial and tangential shrinkage were measured on the specimen of $10 \times 20 \times 20 \text{ mm}^3$ (LRT). The specimens from shrinkage were extracted from the Bing specimen from part b of the log as described in Figure 2.1. The volumetric shrinkage was calculated by using the data of the three-dimensional shrinkage (LRT) measured on two different samples as illustrated on Figure 2.4. The fiber saturation point (FSP) was evaluated using the intersection point of surface shrinkage calculated using radial and tangential shrinkage only.

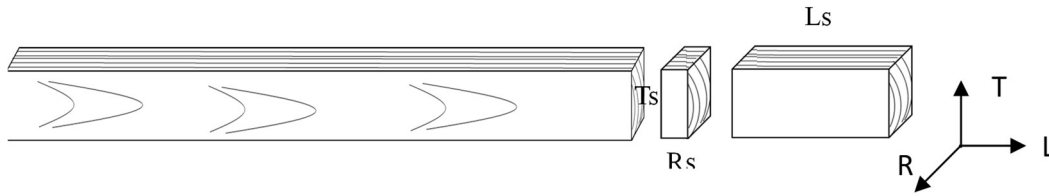


Figure 2.4. Extraction of specimens for measurement of longitudinal shrinkage (L_s), radial shrinkage (R_s), and tangential shrinkage (T_s)

Measurement of physical properties

For the measurement of shrinkage, 70 wood specimens with dimension of $380 \times 20 \times 20 \text{ mm}^3$ were prepared. The shrinkage samples were then cut from these wood specimens. Longitudinal shrinkage was evaluated on the specimen of $50 \times 20 \times 20 \text{ mm}^3$ (LRT) while the radial and tangential shrinkage were measured on the specimen of $10 \times 20 \times 20 \text{ mm}^3$ (LRT). The volumetric shrinkage was calculated by using the data of the three-dimensional shrinkage (LRT). The fiber saturation point (FSP) was evaluated using the intersection point of surface shrinkage calculated using radial and tangential shrinkage only. The number of rings was also recorded. The wood specific gravity was calculated as the oven-dry weight of the specimen divided by the volume of the specimen in the saturated condition.

Data analysis

Descriptive analysis such as mean value, standard error and standard deviation were calculated for each measured wood properties. Radial variation of measured properties from the pith to the bark was presented graphically. Radial variation of measured properties from pith to bark was fitted by a logistic model described in Figure 2.5 and Equation 2.1 which is suitable to model a transition between juvenile and mature wood (Grzeskowiak 1997):

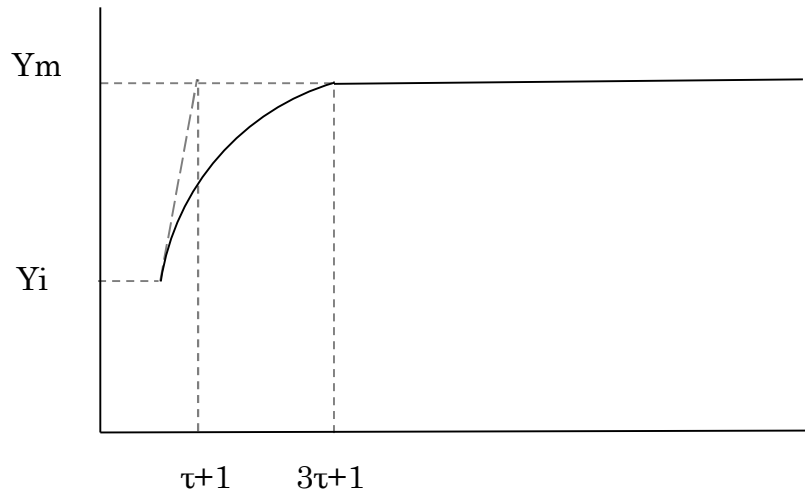


Figure 2.5. Modelling the transition between juvenile and mature wood (Grzeskowiak 1997)

Y_m = the final value of the variation curve before the constant value is achieved; Y_i = 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. Using this model, it is assumed that 95% of the variation in measured properties due to age is accomplished.

$$Y = Ym - (Ym - Yi)^{-T/\tau} \quad (2.1)$$

$$(Y - Yi) = 0.95 (Ym - Yi) \quad (2.2)$$

As a result $T = 3\tau$ and thus $t = 3\tau + 1$.

To evaluate the influence of wood radial position on the wood structural, physical, and mechanical properties, multi-factor analysis of variance (ANOVA) and Tukey's HSD (Honestly Significant Difference) multiple comparison tests were carried out. ANOVA and Tukey's HSD were performed at a level of significance of 0.05 using R-software. Furthermore, the coefficient of correlation was analyzed in order to evaluate the relationship between measured parameters.

2.3. Results & Discussion

Figure 2.6 shows radial variation of all measured parameters. Mean values for all samples are displayed together with the standard error. Figures for individual measurements are provided in the appendix A of the PhD manuscript. Juvenile wood of both species, oak as well beech has higher density and higher MFA. Some differences may be however observed between species. In oak, the difference in density is due to high density of earlywood, while in beech, the denser juvenile wood is mainly due to higher latewood proportion. Ring width varies significantly more in oak than in beech.

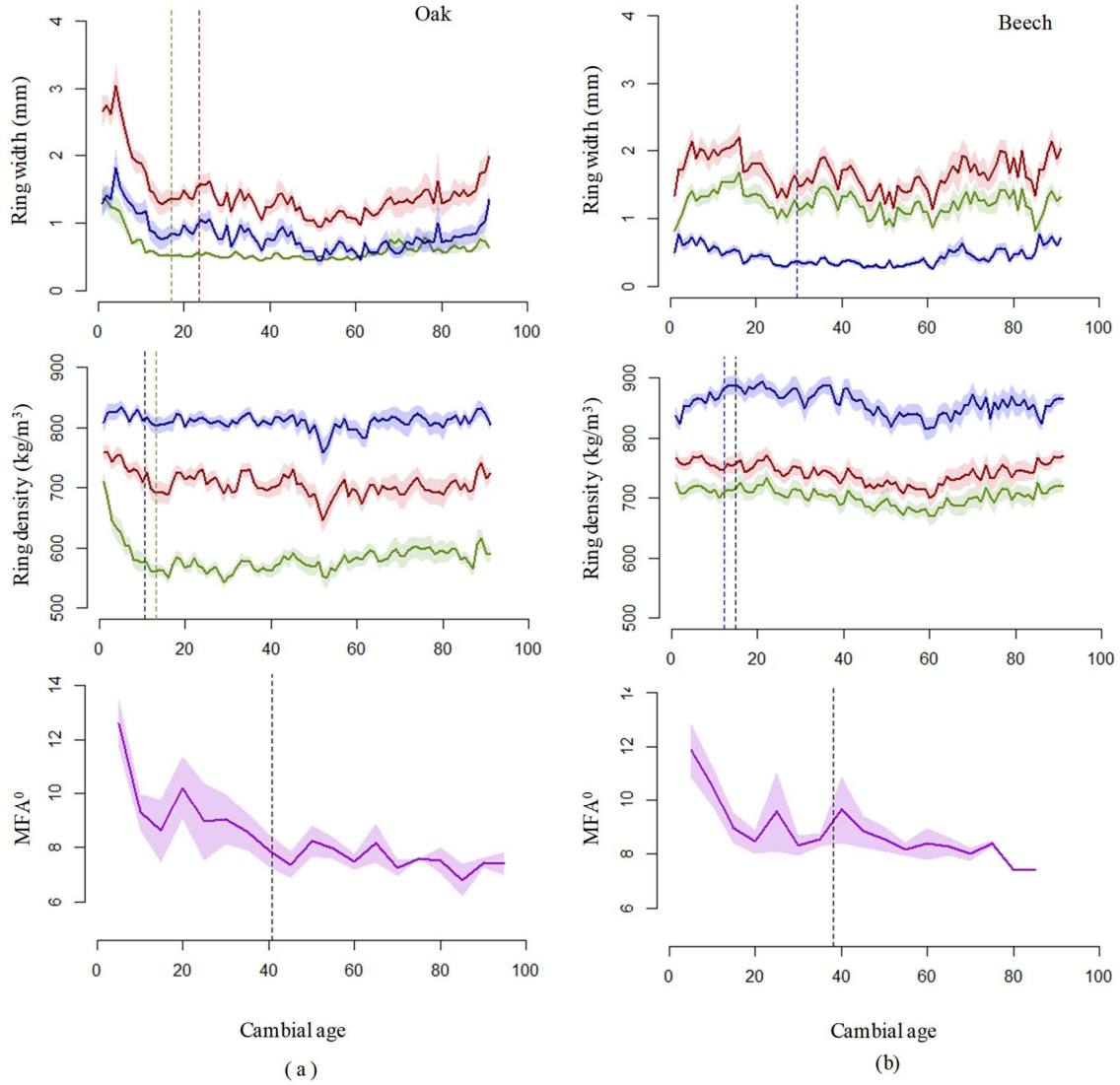


Figure 2.6. Radial variation of radial growth component, wood density component and MFA from the pith to the bark as a function of the cambial age of a) Oak and b) Beech. The solid line and the light color area around each solid line represent the mean value and the standard error measured on each ring from all measured tree.

To find the limit of juvenile wood, we fitted the logistic model to each parameter measured and assessed if the model and all its parameters were significant. First, we used all data available and in the second run, we used only the data up to 40 years supposing that juvenile transition was finished and that variation in properties we observed were not related to ontogenetic transition but to climate and/or changes in environmental conditions. Figure 2.7 shows the fitting of logistic model with the variation of the difference between the density of LW and EW.

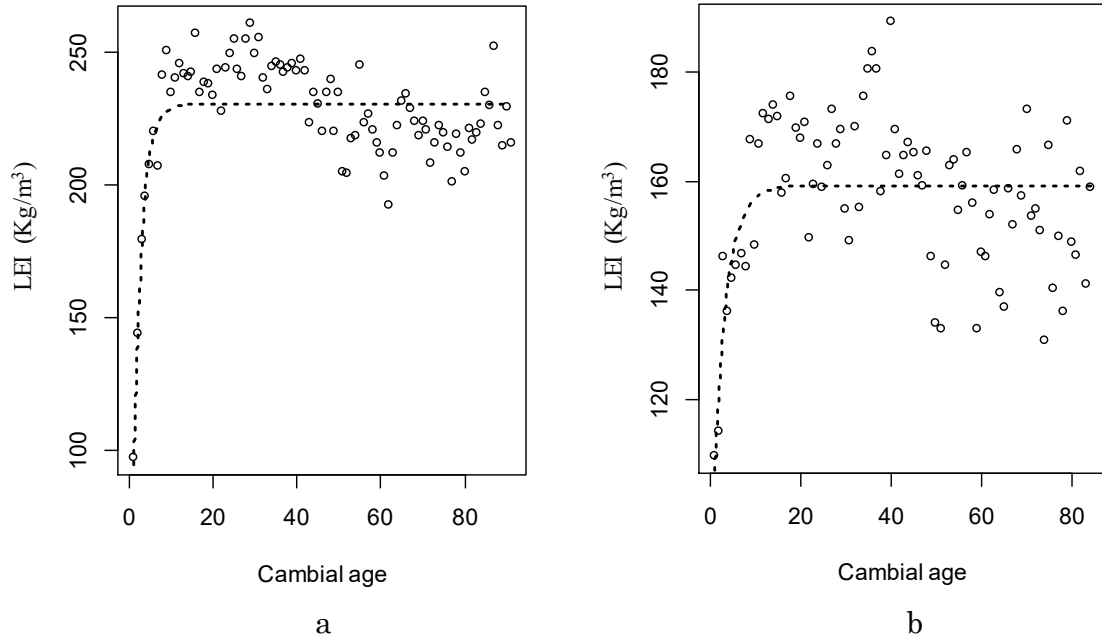


Figure 2.7. Fitting logistic model with the variation of LEI (difference between the density of LW and EW) of a) Oak, and b) Beech

Table 2.1 presents the demarcation point or limit of juvenile wood as predicted for each parameter. Considering oak, the best predictor of the juvenile wood limit seems to be the EW width followed by the LEI (difference between the density of LW and density of EW) when data are limited to first 40 years. Definitely, better fits are achieved when data are limited to first 40 years. It's interesting to note that all parameters do not stabilize at the same time, for example the LW width in oak wood take two much longer to stabilize than EW width.

Table 2.1. Demarcation point of juvenile and mature oak and beech wood based on model

Species	Oak				Beech			
Data	All ring		Data \leq 40 rings		All ring		Data \leq 40 rings	
Predictor	DP	R ²	DP	R ²	DP	R ²	DP	R ²
R _d	26.06*	0.38	ns	-	ns	-	ns	-
R _w	24.45***	0.71	23.58***	0.89	ns	-	ns	-
EW _w	14.46***	0.74	17.07***	0.95	25.50*	0.25	62.78*	0.74
LW _w	43.67***	0.57	17.07***	0.61	ns	-	ns	-
EW _d	10.18***	0.59	13.21***	0.91	61.22*	0.23	ns	-
LW _d	ns	-	ns	-	ns	-	12.25**	0.54
LEI	10.23***	0.43	10.48***	0.92	8.86*	0.2	14.78***	0.67
MFA	40.80**	0.76	ns	-	38.10*	0.69	ns	-

DP, Demarcation point of juvenile and mature wood; R_d, Ring density; R_w, Ring width; EW_w, Earlywood width; LW_w, Latewood width; EW_d, Earlywood density; LW_d, Latewood density; LEI, LW_d - EW_d; Stars show that model is significant at level 0.001***, 0.01**, and 0.05* whereas ns means that the model is not significant.

In case of beech, ring width as well as ring density do not show any clear transition in the juvenile region. The best predictor of the juvenile transition seems to be the LEI. Again, EW width is stabilizes much later than LEI. Considering the MFA, the stabilization comes later than EW width in oak or LEI in beech however the resolution of the MFA measurements was lower (we measured sections of 1 cm) and transition of other parameters (EW width for oak and LEI for beech) comes often between first and second or second and third MFA sample so that we need to measure more samples in the first three cm which was not possible in time because the diffractometer was out of service. It is also interesting to note that while ring density in both species first linearly decreases 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.

Several studies have quantified the radial variation of wood properties of beech and oak (Helińska-Raczkowska 1994; Lebourgeois 1999; Bouriaud et al. 2004; Skomarkova et al. 2006; Tulik 2014; Longuetaud et al. 2017). Higher earlywood density on oak juvenile wood indicated the lower porosity on juvenile wood compared with the mature one which is consistent with the literature reporting a higher amount of vessel in mature wood rings of oak (Helińska-Raczkowska 1994; Leal et al. 2006). The ring properties are more or less stable after this point. Furthermore, the demarcation point found in the present work closely corresponds with the one indicated by Guilley et al. (2004) on dominant trees of oak which shows that the ring width decrease from pith to ring 20-25 and increase larger after this point. In addition, other report by Leal et al. (2006) on 40 years old oak also indicated that the vessel diameter is stabilizing after 15-20 years. Nevertheless, both studies mentioned above were not aimed to determine the separation point between juvenile and mature wood. None of them also had mentioned that their values refer to juvenile or mature wood. For the sake of comparison, the separation point was interpreted based on the descriptive analysis on the graphical data whereas the present study used a model to predict this separation point.

A study on the dominant trees of beech by Bouriaud et al. (2004) shows that the ring density tends to decrease from pith to the bark. Those authors added that the ring width is decreasing from the pith to the cambial age of fewer than 20 years and rise larger up to 4.5 mm after this point which is three times larger than ring width found in this study. The turning point indicated on that work fits well to the demarcation point found for beech in our paper. However, after the demarcation point, the ring width is somewhat stabilized unlike what has been observed in dominant trees which probably related to limited resources of suppressed beech trees. Dissimilar trends of radial variation of oak and beech ring width after the demarcation point found between the present work and the literature may be due to the contrast in tree status.

The variation of MFA on oak found in our study was lower compared to the previous study by Lichtenegger et al. (1999) which reported that on oak, the MFA is decreasing from pith to the periphery where the MFA on oak decrease from 20° to 0° after 40 mm of distance from the pith and then stays constant. Moreover, Lichtenegger et al. (1999) also has reported that the MFA on the near pith is 0° and stays constant to the bark which is contradicted with our results. Nevertheless, the variation of MFA on both hardwood was much lower compared

with softwood. The MFA of *Picea abies* varies from 30°-0° and the MFA of *Pinus sylvestris* can even go up to 50° (Lichtenegger et al. 1999).

Variation of structural and physical properties related to wood radial position inside the trunk

Further analysis on the difference of wood from internal (close to the pith) and external (close to the bark) position are presented in Table 2.2. We compared both position in order to observe the evolution of wood structural and physical properties between the two positions. The wood specific gravity in internal position was slightly higher than external position. The difference was statistically significant at 0.05 level for beech but not statistically significant for oak. Correspondingly, the fiber saturation point was higher in wood from the internal position where the difference was also statistically significant. Furthermore, the volumetric shrinkage along with radial and tangential shrinkage was higher in the internal position. Longitudinal shrinkage showed no significant difference between the two positions.

Table 2.2. Comparison between internal and external wood in terms of average values of structural and physical properties

Species	Position	γ	FSP (%)	Ls (%)	Rs (%)	Ts (%)	Vs (%)
Oak	Internal	0.57 ^a	32.9 ^b	0.4 ^a	6.8 ^b	10.8 ^a	16.8 ^b
		(0)	(2.9)	(0.1)	(0.6)	(1.2)	(1.1)
	External	0.56 ^a	30.7 ^a	0.5 ^a	5.7 ^a	10.2 ^a	15.3 ^a
		(0)	(2.0)	(0.1)	(0.4)	(1.0)	(1.2)
Beech	Internal	0.58 ^b	35.2 ^b	0.4 ^a	6.6 ^b	12.8 ^b	18.5 ^b
		(0)	(2.7)	(0.1)	(0.6)	(0.7)	(0.9)
	External	0.56 ^a	33.5 ^a	0.5 ^a	5.7 ^a	12.2 ^a	17.2 ^a
		(0)	(2.2)	(0.3)	(0.4)	(0.8)	(1.0)

□, specific gravity; FSP, fiber saturation point; Ls, Rs, Ts, Vs, longitudinal, radial, tangential, and volumetric shrinkage from green to the oven-dry condition. Different letters above the numbers signify statistically different populations, based on posthoc Tukey's HSD tests ($p < 0.05$). Values in parenthesis are standard deviations.

The higher values observed for radial and volumetric shrinkage and FSP in the internal position could be related to its higher specific gravity. Previous study on oak shows that wood density has positive correlation with Ts and Vs, negative correlation with Ls, and no correlation with Rs (Deret-Varcin 1983). More recent study on beech also shows positive correlation between wood density and Vs (Gryc et al. 2008a). FSP is important as it shows the point where the mechanical properties increase and the wood volume decrease with the decrease of moisture content below this point (Babiak and Kúdela 1995). Further analysis is needed to explain the variation of the shrinkage and FSP as it is not only influenced by wood density but also affected by the wood structure itself and the extractives content inside the wood (Babiak and Kúdela 1995; Hernández 2007).

Variation of mechanical properties related to wood radial position inside the trunk

Figure 2.8 shows the difference in wood density and MOE between the internal and external position in Beech and oak. Concerning wood density, this result is similar to the previous result from X-ray analysis which demonstrated higher ring density in internal position than external position. However, higher wood density did not result in higher MOE, especially for oak. The difference of MOE value between internal and external position was not statistically significant at 0.05 level for oak whereas for beech the external position shows higher MOE than the internal one.

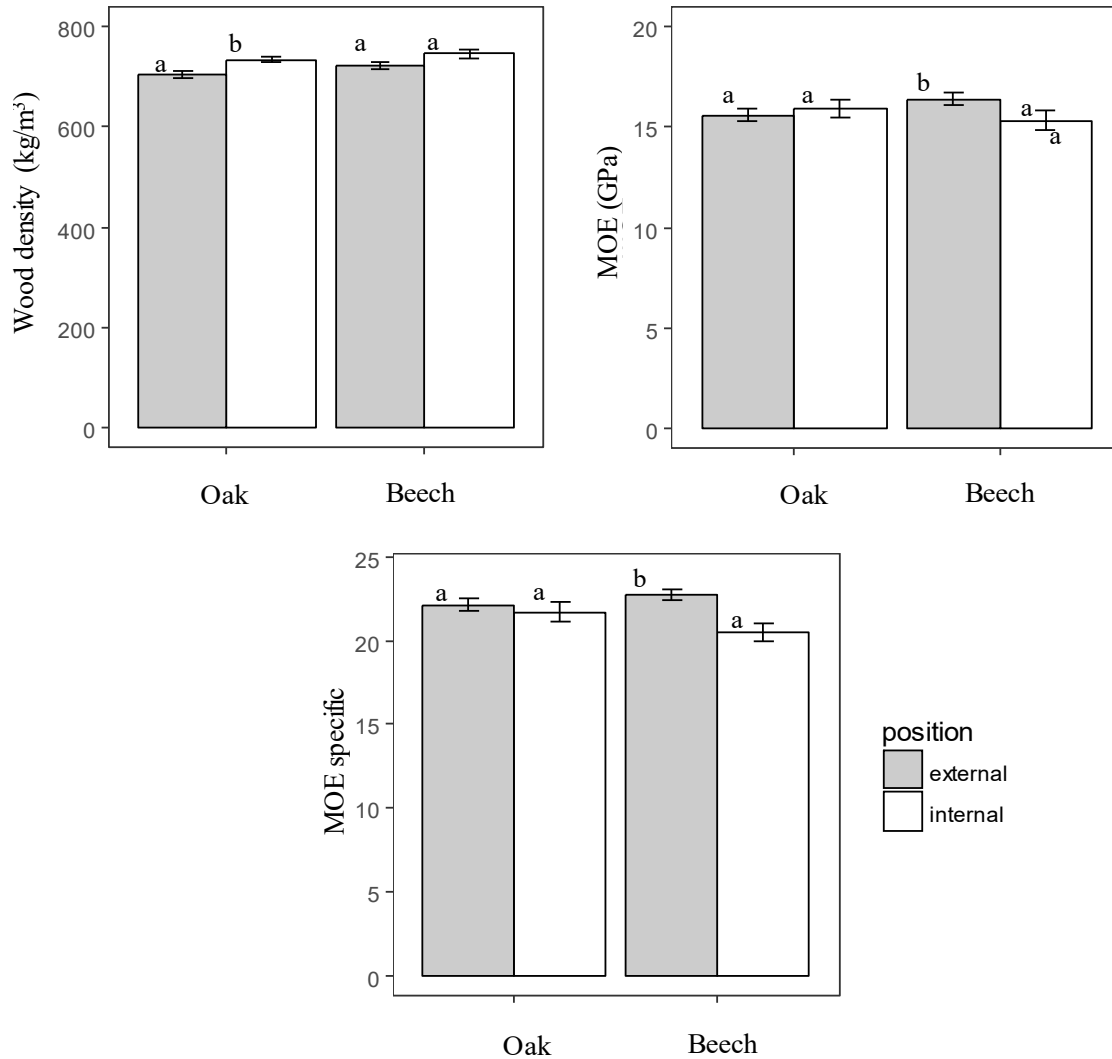


Figure 2.8. Comparison between internal and external wood in terms of average values of mechanical properties. Different letters above the numbers signify statistically different populations, based on posthoc Tukey's HSD tests ($p < 0.05$).

The wood density is higher in the area closer to the pith than away from pith. But the wood mechanical properties are not controlled by the wood density alone. Other than wood density, another important wood structural property affecting the wood mechanical properties is the MFA. Generally, the wood stiffness and strength decrease with the increase of the MFA (Evans and Ilic 2001; McLean et al. 2010). The tradeoff between wood density and microfibril angle may be the reason behind this trend. High microfibril angle may cancel the effect of

high density in the internal position. For beech, the MOE is relatively higher on external position. Further research should be done in order to explain the influence of wood structural properties on the variation of the mechanical properties.

The results show slightly higher wood density and swelling on juvenile wood but relatively comparable stiffness with mature wood which complies with the previous results report by Gryc et al. (2008b) on beech. That paper reported that the difference of density and other properties between juvenile and mature wood are not huge. The density on juvenile wood was slightly higher than mature wood which can be explained by a higher number of rays than mature wood. Rays generally has higher density than wood itself. The number of vessel was higher in juvenile wood but the vessel was around 40% smaller than mature wood (Dumitrascu 2010). In that study, five first ring from the pith and five last rings (five rings closest to the bark) were defined as juvenile and mature wood respectively.

Effect of wood radial position on the relation between wood density and dynamic MOE

The previous result demonstrated higher density on internal position than external position yet similar stiffness on both positions. Therefore, wood maturity should affect the correlation between wood density and stiffness. Both parameters were plotted and presented in Table 2.3. Beech dynamic MOE was better correlated with wood density than oak. For both species, the wood density was better correlated with MOE dynamic for the external position.

Table 2.3. Correlation between wood density and stiffness on the wood recovered from internal and external position of oak and beech

Species	Position	r
Oak	Internal	0.25
	External	0.49**
Beech	Internal	0.43*
	External	0.69***

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

This difference may be explained by the higher variation of MFA in the internal position. Radial variation analysis indicated that on the external position, the MFA variation is much lower than internal. Furthermore, it was also showed that the MFA value in internal position is highly varied between individual trees. More precise MFA pattern by means of measuring MFA on each ring can help to prove this phenomenon. However, further measurement could not be done because the diffractometer was out of service.

Previous study by McLean et al. (2010) on spruce radial wood properties support this explanation. Their study showed that there was no correlation between wood density and stiffness on the internal part of spruce. In contrast, there was a positive correlation between both parameters on the external position ($r^2=0.77$). The authors added that the stiffness on the internal position more closely related with the MFA. Nevertheless, the MFA variation for

beech and oak in internal position is nothing compared to softwood species (Lichtenegger et al. 1999).

2.4. Conclusions

Juvenile wood for oak has bigger ring and higher MFA while for beech has larger latewood and higher MFA. The area of juvenile wood on both species were below 5 cm from the pith which is due to the fact that these were suppressed trees that growth under hard condition thus developed small annual ring. As for the perspective of further processing of these trees such as veneering, there will be no or low part juvenile wood peeled as it is concentrated on the small region near the pith. Juvenile wood has slightly higher wood density and swelling but relatively comparable stiffness with mature wood. For both species, the wood density was better correlated with MOE dynamic for the external position which can be explained by the higher variation of MFA in the internal position.

Chapter 3

Chapter 3

Characterization of mechanical and physical properties of secondary quality hardwood issued from thinning in relation with structural parameters

3.1. Introduction

Hardwoods are abundant and adapted to climate and soils in central Europe, yet structural uses of timber are mainly limited to softwoods due to the lack of tested practices and information about the wood quality (Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt 2016). Consequently, the valorization of hardwood for structural application has been an interesting issue. The high wood density, high shrinkage, high variation of wood properties, and combined with high price generally restrained the use of hardwood for timber production. Nevertheless, the price of secondary quality hardwood such as oak of grade C can be only a half of grade B which makes it attractive to use for the timber (Jourez et al. 2010).

In addition, 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, and also increase in the utilization of small trees that are removed during thinning operations (Fox et al. 2004; Paukkunen 2014; Davis et al. 2018). However, the wood properties of this secondary quality hardwood remained to be assessed as currently the use of beech sawn timber for structural application such as Glulam is limited to middle and high qualities. To achieve a better valorization of small and suppressed broadleaved trees, a better understanding of its wood properties is important.

Wood is a complex biological composite with physical and mechanical properties highly dependent on its structure. The structure and organization of its different cell type and macromolecules such as lignin and cellulose can evolve from one tree to another or within the tree, in response to the environmental constraint. This adaptive respond induces modification of the typology of cell differentiation that results in high variation of the wood structure and its organization. The variations inside the wall of the fibers that make up the wood such as the orientation of the cellulose organized in the form of microfibrils or so-called as microfibril angle (MFA), is a key variable explaining the numerous variations in wood physical and mechanical properties (Cave 1968; Yamamoto and Kojima 2002). MFA has been studied extensively in softwood (Jakob et al. 1994; Meylan 1967; Sahlberg et al. 1997; Wardrop 1952). Lichtenegger et al. (1999) demonstrated that the MFA is decreasing from pith to the bark where the MFA value and its variation was generally higher in the softwood species such as spruce and pine than in the hardwood species such as oak and beech. Beech has very low MFA variation and only shows a large distribution of MFA in the position close to the pith while oak MFA is higher below 2 cm of distance from the pith (Lichtenegger et al. 1999).

The organization of the different cell types, in particular, the proportion of fibers, affects the major physical wood property, i.e., the wood density. Higher wood density generally associated with higher wood mechanical properties (Ilic 2001, 2003). Therefore, knowledge of the wood density, which parameters are affecting the density, and how density may or not affects the mechanical strength will provide the information necessary to achieve the full utilization potential of wood. Moreover, the mechanical properties of the timber also need to be assessed before the material can be used in structural applications, either as structural members or in glued products such as glue laminated timber (Glulam) or cross laminated timber (CLT). The wood mechanical properties such as stiffness can be assessed rapidly using nondestructive methods. Furthermore, a small misalignment between the fiber direction and the longitudinal axis of a timber, referred to as grain angle, can lead to significant changes in the mechanical properties of wood. Literature studies show that the variation of grain angle in beech and oak is fairly low ($1^{\circ} - 3^{\circ}$) unlike in some softwood species (Birot et al. 1980, Guilley et al. 1999). Nevertheless, higher grain angle can indeed be found especially on the area surrounding the knots.

Tree status, climate, and silviculture affect the growth of tree biomass. The wood growth rate is generally measured by the annual ring width or simply called as ring width. Previous studies on ring-porous species such as oak show that wood density is positively correlated with the ring width which means that rapid growth is favorable to get high-density wood (Nepveu 1990; Zhang et al. 1993, 1994b; Guilley et al. 2004). In contrast, diffuse porous species like beech shows a very low negative correlation between wood density and ring width (Bouriaud et al. 2004). There are few studies on the effect of wood density on the mechanical properties on oak and beech (Polge 1973; Cibecchini et al. 2016). Nevertheless, high density in oak and beech is generally considered as an indicator of low-quality wood as it causes higher shrinkage thus results in higher drying defects (Nepveu 1981; Deret-Varcin 1983; Zhang et al. 1994a; Gryc et al. 2008a).

There are few studies on the physical and mechanical properties of secondary quality oak and beech recovered from thinning. The first objective of this study was to characterize the structural, physical, mechanical properties of beech and oak. The second objective was modeling the mechanical and physical properties in hardwood based on the structural properties, i.e., wood density, grain angle and ring width.

3.2. Material and Method

Tree selection and specimen preparation

The wood material used for this study were beech (*Fagus sylvatica*) and oak (*Quercus petraea*) sourced from a local forest in Lorraine, Grand-Est region, France. The round wood samples were gathered from the tree removed during thinning of a mixed forest stand. Five trees were selected for each species and two round wood was extracted from each selected tree. As a result, selected round wood material comprised of 20 logs of 150 cm long with diameters between 21 and 30 cm. Log grading using a visual method based on EN 1316 classified the round woods into the grade C and D based on logs diameter and the presence of knot. Oak ages ranged between 61 and 90 years old while beech ages ranged between 57 and 84 years. Each round wood was extracted from the upper part of the stem and generally contained

knots. The sampling methods has been described in Figure 2.1. These round woods represent the wood resources that are not commonly as raw material for timber construction.

Measurement of mechanical properties using static and dynamic methods on small specimen.

For the characterization of mechanical properties, 66 specimens with a dimension of 240 x 10 x 10 mm³ were prepared. The dynamic MOE was measured using a nondestructive test (Bing) which based on vibration method (Brancheriau and Bailleres 2002; Ruelle et al. 2007). The wood density was calculated by dividing their mass by their volume in the air-dry state. The wood mechanical properties were then re-measured using three-point bending method using the universal testing machine (Instron 5969). The span length used was 150 mm and the loading speed at 3 mm/minute. The wood deformation caused by the loading was measured by a video extensometer. The static MOE and MOR were evaluated from each wood specimen. The number of ring of both edges of the specimen was also recorded as an indication of the ring width. The ring width was calculated by dividing the specimen dimension in radial direction with the number of rings.

Measurement of grain angle

The grain angle was evaluated by scanning specimens used for the destructive test, both small specimens and small rods. The grain angle measurement was performed on the surface of the rupture zone. The images taken were then analyzed using software called Image-J in order to measure the grain angle manually. The grain angle was measured by comparing the measured angle of the sample and angle of grain. The measurement is described in Figure 3.1

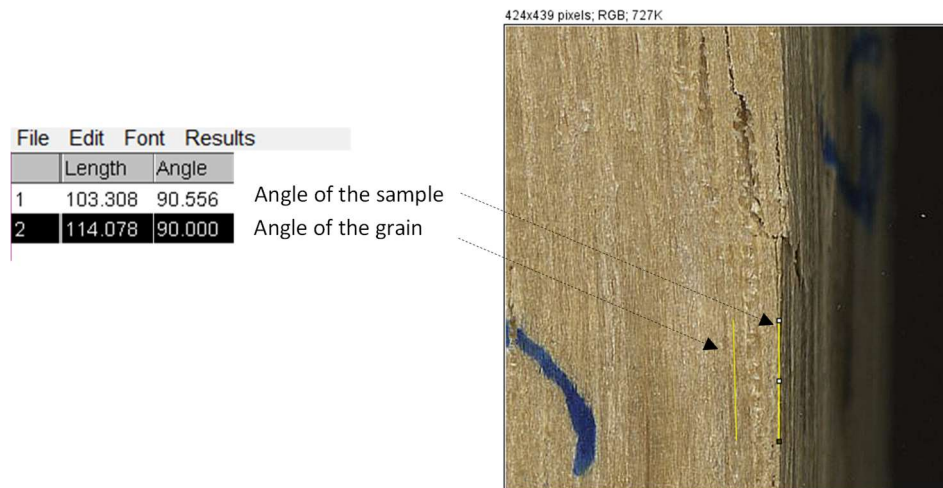


Figure 3.1. Measurement of grain angle using Image-J

Data analysis

Descriptive analysis such as mean value and standard deviation were calculated for each measured property including the structural, physical, and mechanical properties. The specific MOE was calculated as the measured MOE divided by the density of the specimen. The coefficient of variation was used to compare the variation of density and the mechanical

properties. Furthermore, the coefficient of correlation were analyzed in order to evaluate the relationship among the measured parameters of structural properties, mechanical properties, physical properties, and the growth component. All the analysis were performed by using the R-software.

3.3. Results and discussion

Structural and mechanical properties

The mean value and standard deviation of wood density, grain angle, MOE, and MOR measured on beech and oak are presented in Table 3.1. Based on the standard deviation, both species show relatively low density variation on measured specimen. Despite this low standard deviation on wood density, the MOE static, MOE dynamic, specific MOE, and MOR show a quite different value. On the other hand, the grain angle of the specimen extracted from the secondary quality resources was fairly low and close to zero. Oak used in this study demonstrated a higher variation of wood properties compared to beech. Beech shows slightly higher MOE and MOR than oak.

Table 3.1. Mean values of measured wood structural and mechanical properties

Wood species	Wood density (g/cm ³)	MOE Static(GPa)	MOE Dynamic (GPa)	MOR (MPa)	Grain angle	Specific MOE
Oak	0.72 (0.06)	14.14 (2.29)	15.63 (2.55)	115.28 (17.6)	2.73 (2.61)	19.69 (2.5)
Beech	0.73 (0.05)	14.69 (1.84)	16.67 (2.01)	120.32 (14.54)	2.21 (1.64)	20.06 (1.82)

T, tangential; R, radial. Values in parenthesis are standard deviations

Beech mean density found in the present study was slightly higher than the one described by Gryc et al. (2008) on 83 years old beech on 12% MC (density= 0.71 g/cm³). The static MOE was slightly lower than the beech (MOE= 14.8 GPa) used for manufacturing the Glulam as described by Aicher and Ohnesorge (2010) while the MOR was comparable (120.64 MPa) to the literature reported by Schlotzhauer et al. (2017) on free defect beech. On the other hand, oak density and MOE was higher than the literature on oak (density= 0.62, MOE= 9.79 GPa) on Tran et al. (2016). The MOR was 33.2 % higher than oak (86.52 MPa) presented by Schlotzhauer et al. (2017). Based on literature the difference between MOE and MOR on both species should be more visible (Tran et al. 2015, 2016; Schlotzhauer et al. 2017).

Table 3.2 shows the specific density, shrinkage on the three directions and the fiber saturation point on both species. Indeed, for both species, the highest shrinkage was found on tangential direction followed by radial, and axial direction. This kind of shrinkage pattern is quite common in wood (Zobel and Buijtenen 2012). For oak, Ts was 1.7 times Rs while the Rs was 14.1 times Ls. On the other hand, beech Ts was two times Rs while Rs was 14.3 times Ls. The specific density on both species are comparable, but the FSP and volumetric shrinkage were slightly higher on beech than oak. FSP on both species were only marginally higher than 30% MC which is widely considered as the typical limit of FSP.

Table 3.2. Mean values of the physical properties

Wood species	γ	FSP (%)	Ls (%)	Rs (%)	Ts (%)	Vs (%)
Oak	0.57	31.72	0.44	6.23	10.47	16.05
	(0.03)	(2.71)	(0.11)	(0.76)	(1.1)	(1.35)
Beech	0.57	34.34	0.43	6.14	12.49	17.86
	(0.03)	(2.64)	(0.21)	(0.65)	(0.8)	(1.13)

γ , specific gravity; FSP, fiber saturation point; Ls, Rs, Ts, Vs, longitudinal, radial, tangential, and volumetric shrinkage from green to the oven-dry condition. Values in parenthesis are standard deviations

For beech, the Ls, Rs, Ts, and Vs were slightly lower compared to Gryc et al. (2008a) who indicated that the beech shrinkage in his study is 0.56 %, 7.61 %, 15.5 %, and 25.02 % respectively. Oak shrinkage properties were slightly higher than oak reported by Deret-Varcin (1983) where the Ls= 0.12 %, Rs=2.90 %, Ts= 11.6, and Vs = 15 %. Previous studies showed that wood physical properties are affected by the growing site and condition (Deret-Varcin 1983; Gryc et al. 2008a).

Characteristics affecting the mechanical properties

The correlation among wood density, grain angle, ring width, and mechanical properties of the wood specimen of the two species are presented in Table 3.3. The mechanical properties measured using nondestructive and destructive methods such as MOE dynamic, MOE static, and MOR of both wood species were positively correlated with the wood density. The correlations were statistically significant at 0.001 level. For both species, the wood density shows the highest correlation with MOR followed by MOE static and MOE dynamic. The correlation between density and mechanical properties was better on beech than oak. Furthermore, for both species, there was no correlation between wood density and grain angle.

Wood density shows positive correlations with the ring width for both species. These correlations were statistically significant at the 0.001 level. Indeed, wood density and ring width were better correlated for oak than beech, this can be related to the various wood structure as oak is a ring porous species while beech show a diffuse porous ring structure. For beech, ring width shows no correlation with mechanical properties. Unlike beech, the increase of ring width on oak wood is significantly correlated with mechanical properties. This effect of ring width to density in oak may be responsible for the lower correlation of wood density and mechanical properties on oak than beech. The different type of vessel distribution may affect this correlation between density and mechanical properties.

The grain angle shows negative correlations with mechanical properties. For oak, the correlation of grain angle with MOE was statistically significant at 0.01 level better than the correlation with MOR which was only statistically significant at 0.05 level. On the other hand, for beech, the correlation of grain angle with all measured mechanical properties was not significant. The grain angle on oak was better correlated with both MOE and MOR measured from static method than the MOE measured nondestructively.

Table 3.3. Correlation among measured characteristic on selected samples of beech (lower triangle) and oak (upper triangle).

Parameters	D	R _w	GA	MOED	MOES	SMOE	MOR	SMOR
D	1	0.71***	-0.03	0.59***	0.66***	0.28*	0.67***	0.25*
R _w	0.42***	1	0.22	0.29*	0.29*	-0.03	0.47***	0.16
GA	0.03	0.19	1	-0.45***	-0.45***	-0.58***	0.35**	0.46***
MOED	0.72***	0.17	-0.17	1	0.96***	0.90***	0.94***	0.87***
MOES	0.74***	0.13	-0.18	0.98***	1	0.90***	0.92***	0.79***
SMOE	0.35**	-0.10	-0.28*	0.88***	0.89***	1	0.80***	0.88***
MOR	0.77***	0.19	-0.11	0.87***	0.90***	0.73***	1	0.89
SMOR	0.39**	-0.04	-0.21	0.73***	0.76***	0.79***	0.88***	1

D, wood density; R_w, ring width; GA, Grain angle; MOED, MOE Dynamic; MOES, MOE Static; SMOE, Specific MOE static; SMOR, specific MOR;
 ***Correlation is significant at 0.001 level; **Correlation is significant at 0.01 level; *Correlation is significant at 0.05 level

Table 3.3 also shows that the MOE dynamic has high correlations with MOE static and MOR ($\alpha=0.001$). Moreover, for both species, the MOE dynamic was better correlated with MOE static than MOR. The MOE dynamic and MOE static are plotted in figure 3.2. For the prediction of MOR, the MOE dynamic showed better correlation on oak than beech.

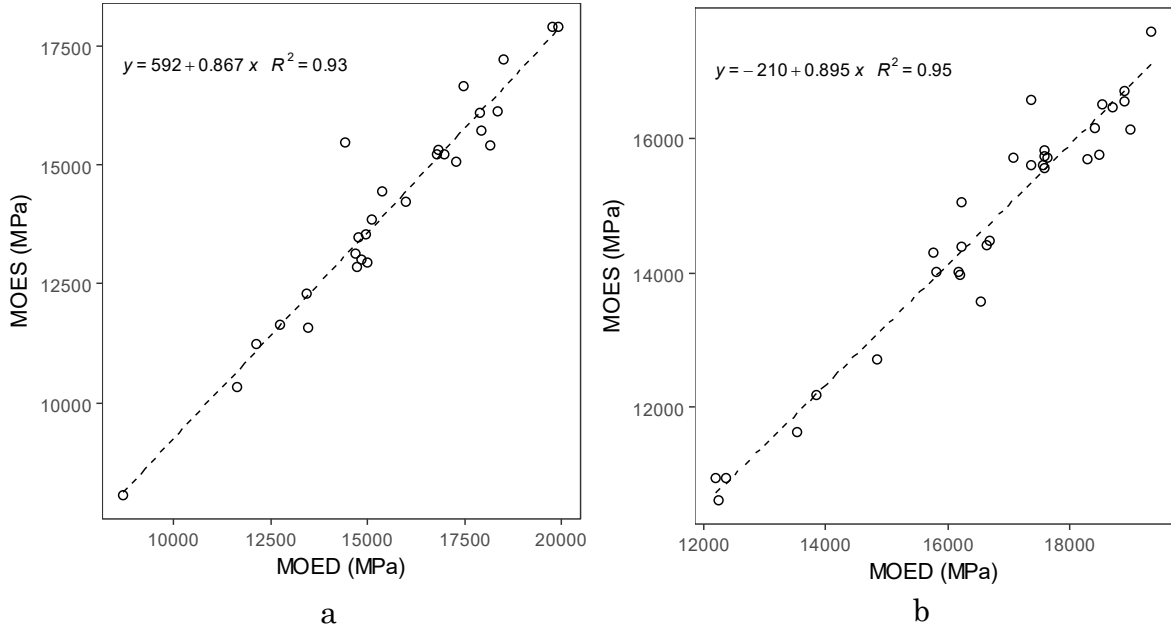


Figure 3.2. Correlation between MOE static (MOES) and MOE dynamic (MOED) on Oak, and b) Beech

Positive correlations between wood density and mechanical properties on oak are contrasting with previous studies (Polge 1973; Zhang et al. 1994a). Generally, in oak, there is no close relationship between wood density and mechanical properties and some even considered high density in oak as a criterion of low-quality wood. The positive correlation between wood density and ring width was in accordance with literature reported that the wood density is positively correlated with ring width (Guilley et al. 2004; Genet et al. 2013). This means that rapid growth on oak induced higher wood density. Oak is a ring-porous species whose radial growth increase within a tree is generally associated with higher latewood percentage and denser earlywood and latewood, and so higher mean ring density (Zhang et al. 1993). The grain angle influenced the wood mechanical properties negatively even when the level was considered low. The low variation of grain angle found on both species is supported by previous 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 on 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 on beech ($r = -0.14$). That study was in contrast with our result on the negative correlation between ring number and wood density which indicated a positive correlation between ring width and wood density.

Characteristics affecting the physical properties

The correlations among measured structural and physical properties including specific gravity, ring width, shrinkage, and FSP on both species were analyzed and presented in Table 3.4. Consistent with the previous results on the correlation between wood density and ring width, the specific gravity also shows a positive correlation with the ring width, that may induce good correlation level between ring width and the others measured physical properties. These correlations were statistically significant at 0.001 level on oak and 0.01 level on beech. Increase in wood density rise up the Ts, Rs, and Vs while decrease the Ls. For oak, the correlations between specific gravity and physical properties were statistically significant at 0.001 level for Ts and Vs, at 0.01 level for Rs, and at 0.05 level for Ls. For beech the correlations were statistically significant at 0.001 level for Rs, Ls, and Vs, and at 0.01 level for Ts.

Table 3.4. The correlation between structural and physical properties of oak (upper triangle) and beech (lower triangle).

	y	R _w	Ts	Rs	Ls	Vs	FSP
y	1	0.55***	0.64***	0.50**	-0.31*	0.75***	0.24*
R _w	0.43**	1	0.29*	0.68***	-0.22	0.57***	0.47*
Ts	0.45**	0.37**	1	0.21	-0.16	0.87***	0.40*
Rs	0.56***	0.02	0.44**	1	-0.27	0.67***	0.63**
Ls	-0.52***	-0.18	-0.18	-0.33*	1	-0.26	-0.16
Vs	0.58***	0.25*	0.89***	0.80***	-0.29*	1	0.63***
FSP	-0.21*	0.8	0.39*	0.26	0.25	0.39*	1

□, Specific gravity; RW, Ring width; Ls, Rs, Ts, Vs, longitudinal, radial, tangential, and volumetric shrinkage from green to the oven-dry condition; FSP, fiber saturation point. ***Correlation is significant at 0.001 level; **Correlation is significant at 0.01 level; *Correlation is significant at 0.05 level

For oak, ring width shows a good correlation with physical properties, except for Ls. For this shrinkage the correlation was not significant at 0.05 level. For beech ring width shows correlation with Ts ($\alpha=0.01$) and Vs ($\alpha=0.05$), but no correlation was found with Rs and Ls.

The correlation between FSP and specific gravity was positive on oak ($\alpha=0.05$) but negative on beech ($\alpha=0.05$). For oak, the FSP has statistically significant positive correlations with ring width at 0.05 level while no correlation was found on beech. For both species, FSP has statistically significant positive correlation with Vs where the correlation was much better on oak ($\alpha=0.001$) than beech ($\alpha=0.01$). Furthermore, other than Vs, the FSP of both oak and beech shows a good correlation with Rs.

The positive correlation found between beech wood density and Vs in this study ($R^2 = 0.484$) supports previous work by Gryc et al. (2008a). Deret-Varcin (1983) also confirms our result on oak by showing that oak wood density and ring width are positively correlated with the shrinkage. The wood density was positively correlated with the shrinkage in all direction

while ring width positively correlated with Vs and Ts but negatively correlated with Ls. In the case of the broad-rayed wood species, such as oak and beech, shrinkage results may support the hypothesis that rays are one of the factors responsible for transverse shrinkage anisotropy because the ray volume is up to 17% – 22% of the wood tissue in oak and beech (Skaar 1988).

3.4. Conclusions

There was a positive correlation between specific gravity and ring width on both species but the correlation was slightly higher in oak. For oak, ring width also shows positive correlations with Ts, Rs, Vs, and FSP while on beech it shows positive correlations with Ts, Vs, FSP. The ring density on oak was highly correlated with the LW width and density. Unlike oak, beech ring density was not correlated with ring width but affected by both LW and EW density.

Chapter 4

Chapter 4

The Influence of Veneer Thickness and Knot Proportion on the Mechanical Properties of Laminated Veneer Lumber (LVL) Made from Secondary Quality Hardwood

4.1. Introduction

Hardwood dominates both the surface area and standing stock of French forests (IGN 2016). In contrast, the wood harvested and the timber produced are dominated by softwood (Ministère de l'Agriculture et de l'Alimentation-Agreste 2017). Forests cannot produce high-quality wood without also producing a large quantity of low-grade wood. Moreover, the new forest management systems based on intensive silviculture generally produce low-quality wood. Young thinnings, top wood and early harvested wood are secondary resources that have great potential for high-value applications (Eckelman 1993; Marchall 1995; McKeever 1997; Knudson et al. 2007).

The presence of various wood defects such as knots, grain deviation, juvenile wood and reaction wood restricts the utilization of secondary quality hardwood for structural materials. The presence of knots and knotholes in timber induces zones with weaker strength where defects will most likely start. Knots also create a larger area around the knot that has high grain angle deviation (Viguier et al. 2015, 2017a). In addition, young trees are usually characterized by a high proportion of juvenile wood (Bendtsen 1978; Kretschmann et al. 1993). Juvenile wood is a zone close to the pith created at the beginning of the radial growth that can be characterized by lower mechanical properties compared to mature wood (Moore et al. 2009; Zobel and Sprague 2012). Finding an alternative use for these abundant resources is essential. These resources have been insufficiently explored and commonly used only for firewood and wood composite (fiber and particle board). The valorization of this resource as structural material requires better characterization of its mechanical properties and better knowledge of the effect of the defects on mechanical properties.

Laminated Veneer Lumber (LVL) is an engineered wood product made from rotary peeled veneer glued together with the grain generally oriented parallel to the panel length. LVL is usually used for structural and nonstructural applications such as flooring, furniture and construction (Ozarska 1999; Lam 2001). Compared to solid wood, LVL has dispersed defects due to the production process, a better dimensional stability, is available in large dimensions, and provides higher Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) (Ebihara 1981; Youngquist et al. 1984).

Previous studies reported that veneer quality influences the mechanical properties of LVL (Daoui et al. 2011; Pot et al. 2015; Viguier et al. 2017b, 2018). Generally, LVL mechanical strength increases with the number of veneers inside the LVL (Schaffer et al. 1972; Hoover et al. 1987; Kilic et al. 2006). Thinner veneer distributes the defects (knots, knotholes, split and slope of grain) better than thicker veneer and improves the LVL strength (Ebihara 1981).

On the other hand, increasing the number of veneers inside the LVL demands much more glue and more numerous steps for its production. Moreover, other studies also reported that the increase in veneer thickness decreases the shear strength and shear modulus of LVL, especially in the edgewise direction (Ebihara 1981; Pot et al. 2015). Rotary peeling creates lathe checks on the loose side of the veneer surface (Thibaut 1988). Veneer lathe check properties are commonly characterized by the lathe check depth and lathe check interval. Under the same cutting conditions, higher peeling thickness produces veneer with deeper lathe checks and a greater distance between two consecutive checks (Denaud et al. 2007; Pałubicki et al. 2010). According to Pot et al. (2015), the decrease in shear modulus with the increase in veneer thickness in the edgewise direction is caused by the presence of lathe checks, which are almost perpendicular to the veneer surface and, consequently, more penalizing in the edgewise than in the flatwise direction. Nevertheless, the quoted authors report was based on numerical studies and has not yet been clarified on a large number of experimental measures.

Increasing veneer thickness helps to decrease glue consumption and production time. More recent studies in LVL made of hardwood species reported that increasing veneer thickness resulted in minor weakening of the MOE and MOR of LVL (Daoui et al. 2011; Pot et al. 2015; Rahayu et al. 2015). The first objective of this study was to better understand the relationship between veneer properties and mechanical properties of LVL made of secondary quality hardwood. Most of the previous studies in hardwood LVL were performed using LVL made of knot-free veneer. Viguier et al. (2018) reported the influence of grain angle and its deviation around the knot on the MOE and the MOR of LVL but none have quantified the relationship with the proportion of knots. Lathe check properties and knot proportion were used to characterize the quality of veneer, taking account of the radial variation of the veneer inside the tree trunk that provides different wood properties, i.e., internal and external position. The second objective of this paper was to study the effect of veneer thickness on LVL mechanical properties and propose an adapted veneer thickness that provides optimum mechanical properties. It was expected that a compromise would have to be made between lathe check properties generated during wood peeling and wood knot proportion.

4.2. Materials and methods

Wood material

Beech (*Fagus sylvatica* L.) and oak (*Quercus petraea* Liebl.) were used for this study. These are the two major hardwood species in Europe and particularly in France (IGN 2016). Twelve logs were gathered during the thinning of tree stands in a local forest in Lorraine, France. The log diameters varied between 21 and 30 cm, with a length of 150 cm. Oak tree age ranged between 61 and 90 years, whereas beech age varied between 57 and 84 years. Each log was extracted from the upper part of the tree (above 5 m from the ground) and generally contained knots.

Veneer preparation

To minimize veneer lathe checks, all logs were soaked in hot water (60°C) for 24 hours. They were then cut into veneers using a rotary veneer lathe. Three classical veneer thicknesses for

LVL and plywood products (2.1 mm, 3 mm, 4.2 mm) were used. The angular pressure bar of the rotary peeling machine was maintained at 5% for all thicknesses (the gap between the knife and pressure bar was 5% lower than the expected veneer thickness). These settings, which take log quality (relatively high density, knots, and limited log diameter) into account, were used to produce moderate checked veneers. Each log was peeled to produce one particular veneer thickness. The veneers were numbered and clipped in 0.6 x 0.5 m² sheets and dried using a vacuum drying device to reduce veneer moisture content (MC) to 18% and then air-dried to about 10% MC at the same time to limit drying time and drying cracks.

Measurement of veneer lathe checks and weighted knot proportions

The quality of fresh veneers was assessed by measuring lathe check depths and lathe check intervals (distance between two adjacent lathe checks). The measurement was performed on 10-cm-wide bands of fresh-cut veneer with a length of 20–60 cm. These veneer bands were taken from the edge of the veneers right after the peeling process ended. Lathe check depths and intervals were immediately measured using a *Système de Mesure d'Ouverture des Fissures* (SMOF) device to characterize the green veneer (Pałubicki et al. 2010). These two parameters were measured on a large proportion of veneers (around 40% of veneer from each veneer thickness). Approximately 11,500 lathe checks were used for this study.

A photograph of each dry veneer was taken before being laminated. The images of the veneer surface were analyzed using Image-J software to measure the weighted knot proportion. The percentage of knot surface to the total veneer surface was calculated and defined as knot proportion. The position of each knot on the veneer surface was also recorded. The veneer weighted knot proportion was calculated by multiplying the knot proportion by a factor of correction based on the knot position along the veneer length (parallel to the fiber direction). This factor of correction was determined according to the variation of the bending moment along a beam subjected to a 4-point bending test. Factor correction 1 was used for the section with the maximum bending moment, which lies in the middle area of the tested beam. Factor corrections 0.5 and 0 were used for the second section and the section closer to the support, respectively, as presented in Figure 4.1.

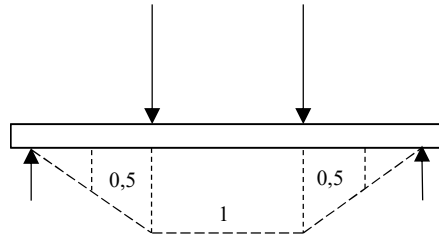


Figure 4.1. Scheme of the factor of correction applied to knot proportion according to the knot position along the veneer.

LVL production

Veneers from each log were divided into two categories by their radial positions inside the trunk, i.e., internal and external veneer. The internal veneers originated from the zone closer to the center of the trunk, whereas the external veneers were closer to the bark. The limit between the two zones was the midpoint between the first and the last peeled veneer. This

separation gives two groups with different mechanical properties, even if this could not be considered as a limit between mature and juvenile wood.

Table 4.1. Peeling setup, number of panels, and number of test specimens prepared for the mechanical test of LVL made of secondary quality hardwood.

Wood species	Veneer position	Veneer thickness	Number of veneer layers	Panel	Test specimen
Oak	Internal	2.1	10	4	32
		3.0	7	4	32
		4.2	5	4	32
	External	2.1	10	4	32
		3.0	7	4	32
		4.2	5	4	32
	Internal	2.1	10	4	32
		3.0	7	4	32
		4.2	5	4	32
Beech	External	2.1	10	4	32
		3.0	7	4	32
		4.2	5	4	32
	Internal	2.1	10	4	32
		3.0	7	4	32
		4.2	5	4	32

The veneers were glued together with the grain oriented parallel to the panel length using PVAc (Polyvinyl Acetate) as an adhesive. The glue spread of each glue line was 180 g/m². Glued veneers were pressed under a pressure of 0.8 MPa for about 60 minutes at ambient temperature. For each combination of treatment (wood species, veneer position inside the tree trunk and veneer thickness), four LVL panels were prepared (Table 4.1). Altogether, 48 LVL panels were used for this study. The final dimensions of the LVL panel were 500 x 250 x 21 mm³. After gluing and pressing, the LVL panels were stacked and stabilized for two weeks before mechanical tests.

Measurement of LVL mechanical properties

Nine test specimens were prepared with a dimension of 500 x 21 x 21 mm³ from each LVL panel. The MC of the LVL specimens was determined before the mechanical tests. The mean MC values obtained were 10.81% for oak LVL and 10.77% for beech LVL with a standard deviation of 0.18 % and 0.2 % respectively. Destructive tests and nondestructive tests based on the vibration method were used for measuring the LVL mechanical properties. Two loading directions were studied, i.e., flatwise and edgewise. For the flatwise bending test, the load direction was perpendicular to the glue lines, whereas for the edgewise test, the load direction was parallel to the glue lines. The dynamic MOE and shear modulus were measured in both loading directions using a nondestructive test called Bing (Brancheriau and Bailleres 2002; Brancheriau et al. 2007).

For the destructive tests, one half of the samples was used for the flatwise bending test and the other half for the edgewise bending test. These 4-point bending tests made it possible to

measure the MOE and the modulus of rupture (MOR). A local MOE and a so-called global MOE were calculated from the same test. The specific modulus was also calculated by dividing the measured modulus with the LVL density. The test arrangement is described in Figure 4.2.

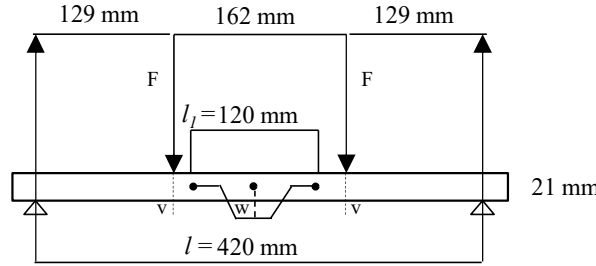


Figure 4.2. Test arrangement for the 4-point bending test to measure local MOE.

The local MOE is the MOE computed between the two central loading heads, in a zone of pure bending. It was calculated using this formula:

$$E_{m,l} = \frac{al_1^2(F_2 - F_1)}{16I(w_2 - w_1)} \quad (4.1)$$

where a = distance between a loading position and the nearest support in a bending test (129 mm here), l_1 = gauge length for the determination of the local MOE (120 mm in this case), I = the second moment of inertia (mm^4), $F_2 - F_1$ = the increment of load on the regression line with a correlation coefficient of 0.99 or better (N), and $w_2 - w_1$ = the increment of local deflection corresponding to $F_2 - F_1$ (mm).

The global MOE was computed from the deflection of the whole beam and not just the pure bending zone. Deflection was calculated based on the movement of the loading tools. Equation 4.2 shows how the global MOE is computed. Shear effects, punching under the loading heads, and deformations of the loading machine are not taken into account using this calculation method. However, this so-called global MOE provides valuable information that takes the whole specimen deformation into account, which is of interest for such heterogeneous material, whereas the local MOE may be too local.

$$E_{m,g} = -\frac{a^2(F_2 - F_1)}{6I(V_2 - V_1)}(3l - 4a) \quad (4.2)$$

where l = length of the test piece between the testing machine grips (mm), $V_2 - V_1$ = the increment of displacement of the loading tools corresponding to $F_2 - F_1$ (mm), and the other parameters are the same as those in Equation 4.1.

Data analysis

To evaluate the influence of different wood species, veneer thickness, veneer position and loading direction on the LVL mechanical properties, multi-factor analysis of variance (ANOVA) and Tukey's HSD (Honestly Significant Difference) multiple comparison tests were carried out. ANOVA and Tukey's HSD was performed at a level of significance of 0.05 using R-software. The coefficient of correlation and the coefficient of determination were used to

evaluate the relationship between measured parameters. Paired t-tests were used to analyze the influence of veneer position on LVL mechanical properties.

4.3. Results and discussion

Veneer quality

Lathe check depth and lathe check interval

Mean lathe check depth and lathe check interval for each veneer thickness and wood species are presented in Table 4.2. Both the lathe check depth and the lathe check interval were affected by the veneer thickness. Statistical analysis showed that the difference in lathe check depth and lathe check interval among veneer thickness was statistically significant ($p < 0.05$). From the thinnest to the thickest veneer, there was an increase in lathe check depth of 40% and 57% for oak and beech, respectively. Correspondingly, the lathe check interval on the thickest veneer rose sharply by 95% and 118% for oak and beech, respectively. Oak had deeper lathe checks and higher lathe check intervals than beech for veneer with a 2.1-mm thickness. This difference was statistically significant at the 0.05 level. The lathe check depth and the lathe check interval were relatively the same for both species for veneer with a 3-mm and 4.2-mm thickness. The results obtained for oak are interesting. Indeed, this species is less homogenous than beech (larger rays and a big difference between earlywood and latewood density), but shows similar behavior. The lathe check properties of oak veneers have never been reported before. Unlike oak, beech lathe check properties have been studied more extensively (Denaud et al. 2007; Pałubicki et al. 2010; Daoui et al. 2011; Rohumaa et al. 2018).

Table 4.2. Effect of peeling thickness on the mean lathe check depth and lathe check interval on oak and beech veneer surfaces.

Species	Oak			Beech		
Veneer thickness (mm)	2.1	3	4.2	2.1	3	4.2
Mean lathe check depth (%)	54.9 ^a (2.7)	67.7 ^c (6.3)	76.9 ^d (3.8)	46.3 ^b (5.3)	63.8 ^c (4.2)	72.9 ^d (3)
Mean lathe check interval (mm)	1.9 ^a (0.2)	2.6 ^c (0.2)	3.7 ^d (0.3)	1.7 ^b (0.2)	2.5 ^c (0.1)	3.7 ^d (0.3)

Different letters above the numbers signify statistically different populations, based on Tukey's post hoc HSD tests ($p < 0.05$). Values in parentheses are standard deviations

Knot proportion

Knot proportion on veneer surface of secondary quality oak and beech

Figure 4.3 compares the veneer knot proportion (unweighted) on different positions in the log and different veneer thicknesses. The aim was to determine the influence of veneer radial position inside the trunk on knot proportion. Knot proportion is important since it demonstrates the quality of veneer used in this study and highlights the possible variations of mechanical properties of the different veneers according to their position in the log or

thickness. The highest knot proportion on oak veneer was found on 4.2-mm-thick veneer in the internal position, whereas the minimum was for the veneers of the same thickness, but in the external position. The knot proportion for oak veneer with a 2.1-mm and 3-mm thickness was fairly similar. On the other hand, the highest knot proportion on beech veneer was found for the thinnest veneers and the lowest for the thickest veneers. Of course, veneer thickness has no influence on the knot proportion, but this result is interesting to take into account when discussing the mechanical properties measured below. In particular, beech veneers with a 4.2-mm thickness present a much lower knot proportion than other veneers (below 0.5%). Figure 4.3 also demonstrates that the veneer knot proportion was generally higher on the surface of veneer peeled from the internal part of the tree than the external part except for beech veneers with a 4.2-mm thickness. Trimmed knots on the edge of the veneer in the internal position may have caused one peeled 4.2-mm-thick log to reveal a higher knot proportion in the external position.

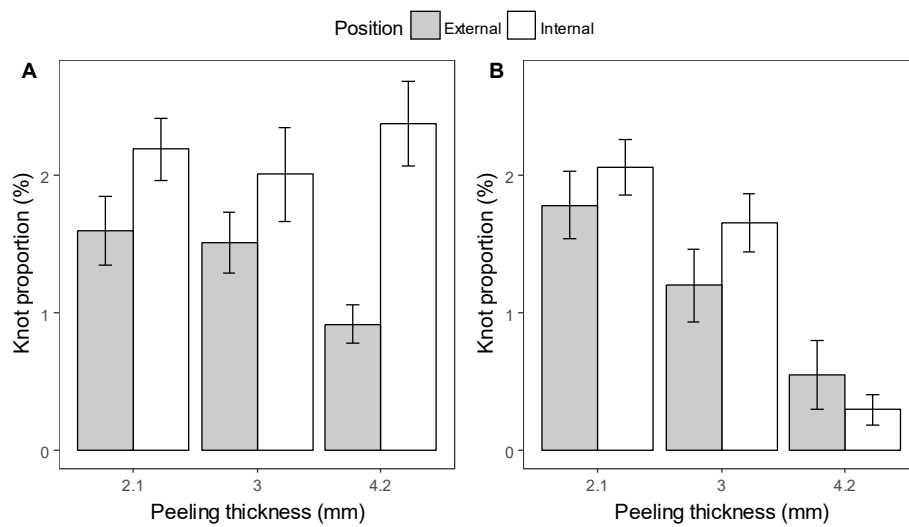


Figure 4.3. Knot proportion of (A) oak veneer and (B) beech veneer according to different peeling thicknesses and veneer position inside the trunk.

Figure 4.4 compares the mean knot size and frequency between the internal and external position on the two wood species. It describes the increase in knot frequency and the decrease in knot diameter from the bark to the center of the trunk. During peeling, the outer part of the log was cut first and then followed by the inner part. Knot diameter is bigger at the position closer to the bark and becomes smaller towards the inside. Since log diameter is bigger on the outer side and knot diameter is also bigger, peeled veneer from the external position only contained a small number of big knots. Bigger log diameter leads to a greater distance between knots related to wood peeling. When the peeling diameter becomes smaller, the knots also become smaller. As a result, since the distance between knots is closer, peeled veneer in the internal position contains a higher number of knots. As a consequence of the higher number of knots, internal veneers contain a higher knot proportion than the external veneers. The increase in knot proportion from the periphery to the center of the log has also been reported on a white spruce veneer (Knudson et al. 2007). Furthermore, McGavin et al. (2014) reported that the higher proportion of knots in addition to less mature wood properties (e.g., lower wood density) produced lower MOE compared with veneer sheets recovered from

the periphery of eucalyptus, which generally yields higher MOE. In addition, lower MOE on LVL made of juvenile wood has also been reported in poplar (Rahayu et al. 2015).

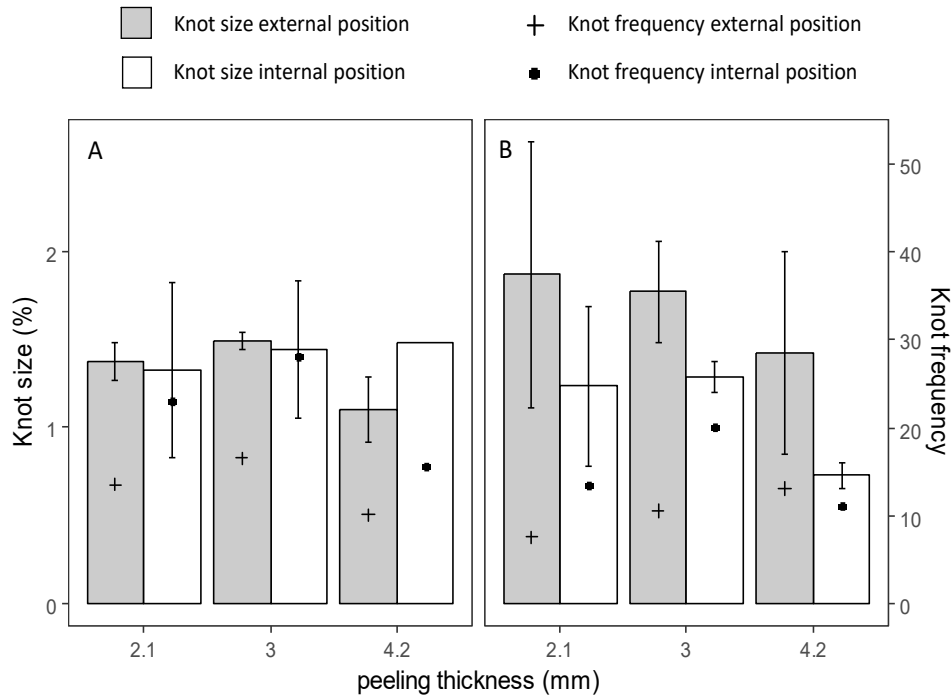


Figure 4.4. Mean knot size and frequency of (A) oak veneer and (B) beech veneer according to different peeling thicknesses and veneer position inside the trunk.

The influence of veneer radial position on LVL mechanical properties

In Table 4.3, the density and mechanical properties of internal and external positions measured using destructive testing are compared. For oak, the LVL made of internal veneer has a relatively higher density than the LVL made of external veneer. The difference was statistically significant at the 0.05 level. A previous study reported that oak ring density and ring width decrease with the increase of the distance to the pith (Nepveu 1990). This decrease of oak ring density by cambial age explains the difference of the LVL density between both veneer positions. Nevertheless, for beech LVL, the difference of LVL density between both positions was insignificant at the 0.05 level.

Table 4.3. Comparing density, MOE and MOR of LVL made of internal veneer and external veneer.

Species	Test direction	Parameters	Internal	External
			Mean	Mean
Oak	Flatwise	LVL density (Kg/m ³)	751.44 ^b (37.7)	742.2 ^a (33.2)
		E _{m,g} (GPa)	9.4 ^a (2)	9.7 ^a (1.4)
		f _m (Mpa)	57.7 ^a (14.6)	58.8 ^a (12)
	Edgewise	E _{m,g} (GPa)	9.8 ^a (1.6)	10.3 ^a (1.1)
		f _m (Mpa)	58.8 ^a (13.4)	63.3 ^a (9.4)
Beech	Flatwise	LVL density	740.3 ^a (38.4)	731.4 ^a (68.1)
		E _{m,g} (GPa)	9.8 ^a (1.4)	10.5 ^b (1.3)
		f _m (Mpa)	65.9 ^a (10.9)	72.1 ^b (11)
	Edgewise	E _{m,g} (GPa)	9.4 ^a (1.1)	10.1 ^b (1.6)
		f _m (Mpa)	63 ^a (9.1)	71.8 ^b (17.7)

f_m, Modulus of rupture (MOR); E_{m,g}, Global modulus of elasticity (Global MOE). Different letters above the numbers signify statistically different populations, based on Tukey's post hoc HSD tests (p < 0.05). Values in parentheses are standard deviations.

On the contrary, MOE and MOR were significantly higher on beech LVL made of external veneers. For oak, the differences are not significant at the 0.05 level. These results showed that, generally, LVL made of veneers closer to the pith (internal) produce lower mechanical properties compared to the external veneers. This difference was due to the variation explained above of knot proportion on these two positions where the external veneer contains a lower knot proportion compared to the internal veneer, thus providing better mechanical properties. The higher knot proportion on the surface of internal veneer may be related to natural pruning. Knudson et al. (2007) reported that the number of knots in spruce veneers increases from sapwood to heartwood. This author explained that more natural pruning occurred on older trees. Lower mechanical properties on the internal veneer of beech may also be caused by the presence of a small part of juvenile wood. Mature wood on the external position may provide greater strength on oak LVL.

The influence of veneer thickness on mechanical properties of LVL made of secondary quality hardwood

Table 4.4 presents the mechanical properties of oak and beech LVL measured using destructive tests. In addition, it also provides the specific modulus of elasticity (SMOE) for both local and global measurements. The objective of using specific modulus was to precisely compare the effect of veneer thickness on the mechanical properties of LVL without any distortion due to the different wood densities. There was no significant influence of testing direction on the mechanical properties for either species. Previous studies show contrasting results on the effect of the loading direction to LVL mechanical properties. Nevertheless, the results in this study are similar to previous reports on beech, poplar and pine (Burdurlu et al. 2007; Daoui et al. 2011; Souza et al. 2011; Rahayu et al. 2015).

As expected, global MOE and SMOE are generally lower than local ones, which can be explained by the punching under the loading heads, the disregard of shear effects, and deformations of the loading machine. Generally, the relationships between LVL made of different veneer thicknesses are maintained, regardless of whether global or local MOE are considered, showing the relative homogeneity of mechanical behavior along the length of an LVL beam.

Table 4.4. Comparing local MOE, global MOE and the specific MOE measured using destructive methods on beech and oak LVL made of different veneer thicknesses.

Veneer thickness (mm)	Local MOE (GPa)		Global MOE (GPa)		MOR (MPa)		Local SMOE (MNm/kg)		Global SMOE (MNm/kg)	
	Fw	Ew	Fw	Ew	Fw	Ew	Fw	Ew	Fw	Ew
Oak LVL										
2.1	10.5 ^a	10.5 ^a	9.2 ^a	9.8 ^{ab}	59.3 ^{ac}	61.9 ^{bc}	14.0 ^a	14.1 ^a	12.3 ^a	13.2 ^{ac}
	(1.8)	(1.6)	(1.5)	(1.1)	(12.2)	(9.3)	(2.6)	(2.3)	(2.2)	(1.6)
3	13.3 ^{bc}	13.6 ^c	10.6 ^{bc}	11.1 ^c	63.4 ^c	68.2 ^c	17.8 ^{bc}	18.1 ^c	14.1 ^{bc}	14.7 ^c
	(1.8)	(1.8)	(1.8)	(1.1)	(14.1)	(10.2)	(2.6)	(2.8)	(2.5)	(1.7)
4.2	10.6 ^a	11.1 ^{ab}	8.9 ^a	9.3 ^a	51.1 ^a	53.3 ^{ab}	13.9 ^a	15.4 ^{ab}	11.6 ^a	12.9 ^{ac}
	(2.5)	(2.5)	(1.4)	(1.3)	(11.1)	(11.3)	(4.7)	(4.1)	(3.3)	(1.9)
Beech LVL										
2.1	10.6 ^a	10.1 ^a	9.3 ^a	8.8 ^a	68.4 ^{ab}	62.9 ^a	14.3 ^a	13.7 ^a	12.7 ^{abc}	12.1 ^a
	(1.4)	(1.5)	(0.8)	(0.9)	(9.2)	(8.4)	(1.8)	(1.8)	(1.2)	(1.2)
3	13.2 ^{bc}	12.8 ^b	11.0 ^c	10.6 ^{bc}	72.0 ^{ab}	72.2 ^{ab}	17.7 ^b	16.4 ^{ab}	14.8 ^d	13.6 ^{bd}
	(2.3)	(1.9)	(1.6)	(1.6)	(12.1)	(20.2)	(3.4)	(3.7)	(2.3)	(3.1)
4.2	13.8 ^{cd}	13.9 ^d	9.7 ^{ab}	9.6 ^a	64.2 ^{ab}	65.0 ^{ab}	18.8 ^b	18.4 ^b	13.8 ^{bd}	13.7 ^{ad}
	(2.6)	(1.7)	(0.7)	(0.6)	(11.8)	(5.7)	(5.8)	(6.5)	(1.3)	(0.8)

Fw, flatwise; Ew, edgewise. Values followed by a different letter within a column are statistically different at P = 5% (ANOVA and Tukey's HSD test). Values in parentheses are standard deviations.

For oak, the highest local and global SMOE were found for LVL made from 3-mm-thick veneers. The oak LVL made from 2.1-mm- and 4.2-mm-thick veneer showed relatively similar values of local and global SMOE. The highest SMOE values for beech were found for LVL made from 3-mm- or 4.2-mm-thick veneers, which are not significantly different ($p < 0.05$). It should be recalled, however, that 4.2-mm-thick beech veneers presented a lower knot proportion. The highest mean MOR value for both species was found on LVL made of 3-mm-thick veneer, whereas the lowest was on the LVL made of the thickest veneer. However, the differences are not significant for beech at the 0.05 level.

The standard deviation of local and global SMOE rises with the increase in veneer thickness. The increase of the standard deviation of both local and global SMOE may be related to the effect of the distribution of defects. Since the defects are better distributed in the LVL made of thinner veneer, the variation of SMOE tends to be lower compared to the LVL made of thicker veneer. For LVL with thicker veneer, the defects are more concentrated and therefore generate more variations of SMOE. These results are consistent with previous reports in poplar (Rahayu et al. 2015).

Based on the three mechanical parameters compared and its standard deviation, 3-mm-thick veneer generally produced the optimum LVL mechanical properties. This veneer thickness complies with the common veneer thickness used to produce LVL, i.e., 3-3.5 mm (Pollmeier 2013). According to the literature, the thinnest veneer should provide the best mechanical properties since more veneer layers inside the LVL should give a better distribution of defects and, consequently, better mechanical properties. This contradiction may be explained by the different wood quality used in this research. In general, the previous study used knot-free or much less defective veneer to produce LVL. It appears that in the present study, the lowest veneer thickness had the highest knot proportion (Figure 4.3), and could thus have influenced the results. It is, however, difficult to separate the effect of knots from the effect of veneer thickness and lathe checks in this case.

Table 4.5. Mechanical properties of LVL made of some hardwood species

Reference	Species	Method	Veneer thickness	MOE (Gpa)
Burdurlu et al. 2007	Beech	3 point	3 mm	8,35
Rahayu et al. 2015	Poplar	4 point	3 mm	8,20
Shukla & Kamden 2008	Aspen	3 point	3 mm	8,20
Shukla & Kamden 2008	Maple	3 point	3 mm	9,90
Aydin et al. 2004	Eucalyptus	3 point	2.1 mm	8,99

As expected, the MOE and MOR of beech LVL made of secondary quality beech in this study are much lower than those in a previous study using knot-free LVL (Aydin et al. 2004; Burdurlu et al. 2007; Daoui et al. 2011; Knorz and van de Kuilen 2012). Table 4.5 describes the LVL mechanical properties of some hardwood species. Burdurlu et al. (2007), who studied the effect of ply organizations and loading direction on beech LVL MOE and MOR, reported that beech mean MOE in the flatwise and edgewise directions were 12,679.6 MPa and 13,235.10 MPa, respectively, whereas the mean MOR were 152.36 MPa and 148.30 MPa, respectively. Compared to knot-free beech LVL, the mean MOE measured in the present

study is more than 25% lower, whereas the mean MOR is more than 50% lower. Furthermore, compared to the mechanical properties of beech LVL reported by Daoui et al. (2011), the mean MOE value is also more than 25% lower, but the MOR value is only about 30% lower. Nevertheless, the MOE of LVL made of the secondary quality oak and beech in the present study are comparable or even higher than the MOE of LVL made of other hardwood species such as eucalyptus, maple, aspen and poplar (Aydin et al. 2004; Shukla and Kamdem 2008; Rahayu et al. 2015). Although the mechanical properties of LVL made from secondary quality beech and oak are acceptable, further studies are needed to assess its suitability for the manufacture of commercially acceptable LVL with regard to the recovery rates and production costs.

Dynamic shear modulus

Table 4.6 provides the dynamic MOE and shear modulus measured using the vibration method. The highest dynamic SMOE for both species was found on the LVL made of 3-mm-thick veneer. These results are consistent with the trend on global SMOE previously observed. However, the dynamic MOE was always higher than that found in previous studies (Daoui et al. 2011; Souza et al. 2011; Rahayu et al. 2015). Nevertheless, these results are important since they measure the MOE along the specimen, unlike the local MOE, while also confirming the computation used for the global MOE.

Table 4.6. Comparing the mechanical properties measured using a nondestructive test according to different veneer thicknesses and loading direction.

Veneer thickness (mm)	Dynamic SMOE (MNm/kg)		Shear SMOE (MNm/kg)	
	Fw	Ew	Fw	Ew
Oak LVL				
2.1	17.3 ^b (1.8)	16.6 ^a (1.9)	0.9 ^a (0.3)	1.1 ^b (0.2)
3	18.8 ^c (1.2)	18.8 ^b (1.4)	0.9 ^a (0.2)	0.8 ^a (0.2)
4.2	15.9 ^a (2)	16.5 ^a (1.9)	1.2 ^b (0.4)	0.8 ^a (0.2)
Beech LVL				
2.1	15.5 ^a (1.3)	14.9 ^a (1.3)	1.1 ^a (0.2)	0.9 ^b (0.2)
3	17.7 ^b (2.4)	17.9 ^b (3.8)	1.3 ^b (0.3)	0.9 ^b (0.1)
4.2	17.0 ^b (1.2)	17.2 ^b (0.7)	1.1 ^a (0.3)	0.7 ^a (0.1)

Fw, flatwise; Ew, edgewise. Values followed by a different letter within a column are statistically different at $P = 5\%$ (ANOVA and Tukey's HSD test). Values in parentheses are standard deviations.

For the edgewise test, the LVL made of the thinnest veneer generated the highest shear modulus for both species at the 0.05 level. The thicker the veneer is, the lower the shear modulus will be. The decrease in the shear modulus for the edgewise direction with thicker veneer in this study confirmed the previous report by Pot et al. (2015) who studied the effect of veneer lathe checks on beech MOE using a numerical approach. In addition, Melo and Menezzi (2014) also reported the decrease in shear strength by the increase in veneer thickness in LVL made of Parica (*Schizolobium amazonicum*). However, the correlation between lathe check and shear modulus could be biased by the direction of the lathe checks. Pot et al. (2015) explained that the lathe check is more penalizing in the edgewise direction because it is almost perpendicular to the veneer surface.

The relationship between veneer quality and LVL mechanical properties

Influence of lathe check properties on LVL specific shear modulus and MOR

To understand the effect of lathe check on LVL mechanical properties, the correlations among the measured parameters were analyzed and presented in Table 4.7. In agreement with the literature, these results demonstrate the positive correlation between lathe check depth and lathe check interval (Palubicki et al. 2010). Deeper lathe check increases the distance between two lathe checks and lowers the check frequency. The correlation between lathe check depth and lathe check interval in oak ($r = 0.99$) was better than beech ($r = 0.77$).

Specific shear modulus and MOR showed negative correlations with lathe check depth and check interval except for flatwise tested oak. An increase in lathe check depth and lathe check interval tended to lower the specific shear modulus in the edgewise direction, as mentioned before. The correlation between both parameters was better in the edgewise than in the flatwise test. Contrary to specific shear modulus, MOR has a better correlation with lathe check properties in the flatwise direction. Increased lathe check depth and check interval decreased the LVL strength.

Table 4.7. Correlation between lathe check properties and LVL mechanical properties in edgewise (upper triangle) and flatwise (lower triangle)

Species	Parameter	Check depth	Check interval	Shear specific	MOR
Oak	Check depth	1	0.99***	-0.57*	-0.43
	Check interval	0.99***	1	-0.60**	-0.46
	Shear specific	0.43	0.45	1	-0.14
	MOR	-0.57*	-0.60*	-0.28	1
Beech	Check depth	1	0.77**	-0.82**	-0.13
	Check interval	0.77**	1	-0.51	-0.08
	Shear specific	-0.49	-0.36	1	-0.01
	MOR	-0.54*	-0.31	0.43	1

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

The negative correlation between lathe check depth and shear modulus supported previous reports by Ebihara (1981). In addition, this author also reported that shear strength parallel to the grain direction on both edgewise and flatwise LVL decreases when the veneer thickness increases. A more recent study by Pot et al. (2015) proposes a numerical model able to explain this trend. No correlation was found between lathe check properties and MOE. These results were also in accordance with previous reports on the effect of lathe check and veneer thickness on the MOE (Ebihara 1981; Hoover et al. 1987; Pot et al. 2015).

Influence of weighted knot proportion on global SMOE

The correlation between weighted knot proportion and global SMOE are presented in Table 4.8. Two types of weighted knot proportions were used for the analysis. The first used the weighted knot proportion of all of the veneer layers that constituted the LVL. The second weighted knot proportion was calculated using the data from the two outer veneers only.

Both weighted knot proportions revealed negative correlations with SMOE. These negative correlations could be seen on both hardwood species and the two test directions. The increase in weighted knot proportion on the veneer surface decreases the global SMOE on oak and beech LVL. The correlations in the edgewise direction are better using weighted proportions from all of the veneer. Flatwise tested oak was better correlated with the weighted knot proportion of the outer veneer. Beech revealed better correlation than oak for both weighted knot proportions.

Table 4.8. The correlation between weighted knot proportion of all of the veneers and the outer veneer with SMOE in the flatwise and edgewise direction.

Species	Test direction	All veneers		Outer veneers	
		Linear equation	r ²	Linear equation	r ²
Oak	Flatwise	y = -1.0631x + 17.11	0.33	y = -1.6549x + 17.152	0.43
	Edgewise	y = -1.371x + 18.505	0.57	y = -1.5072x + 17.822	0.44
Beech	Flatwise	y = -2.9489x + 19.601	0.73	y = -2.9095x + 18.906	0.70
	Edgewise	y = -2.5942x + 18.624	0.71	y = -2.1979x + 17.717	0.50

For the edgewise direction, the LVL MOE is determined by the sum of the MOE of each veneer. The contribution of each layer to the LVL MOE is equal. This explains the better correlation using the weighted knot proportion of all the veneers in the edgewise direction compared to the use of outer veneers.

For the flatwise direction, the location of each veneer determines their contribution to the LVL MOE. This different contribution of each layer is due to the different stresses faced by the outer layers in comparison to the central layers (Girardon et al. 2016). This can explain why correlations with flatwise SMOE were better (or similar) for beech using the data from outer veneers.

Effect of the weighted knot proportion on SMOR

The correlations between the two types of weighted knot proportions and SMOR are presented in Table 4.9. Low negative correlations were found between both parameters on both species and the two loading directions. The correlations of weighted knot proportion

with LVL MOR were lower compared to the LVL SMOE. For both species, the correlation between the weighted knot proportion of all of the veneers was better in the edgewise than the flatwise direction. For both test directions, the correlations were better using the weighted knot proportions of all of the veneer except for flatwise beech that was slightly better correlated with the weighted knot proportion of the outer veneer.

Table 4.9. The correlation between weighted knot proportion of all of the veneer and the outer veneer with SMOR in the flatwise and edgewise direction.

Species	Test direction	All veneer		Outer veneer	
		Linear equation	r ²	Linear equation	r ²
Oak	Flatwise	$y = -0.0043x + 0.0962$	0.10	$y = -0.0026x + 0.0923$	0.02
	Edgewise	$y = -0.01x + 0.1099$	0.36	$y = -0.008x + 0.1016$	0.15
Beech	Flatwise	$y = -0.015x + 0.1233$	0.35	$y = -0.0157x + 0.1204$	0.37
	Edgewise	$y = -0.0146x + 0.1198$	0.42	$y = -0.0107x + 0.1133$	0.22

4.4. Conclusions

High knot proportions were found on the surface of veneer prepared from secondary quality hardwood. Veneer lathe check depth and interval increase with the increase in veneer thickness. For both species, the 3 mm thick veneer has provided the optimum mechanical properties for LVL. The testing direction had no significant influence on the mechanical properties of either species. The average MOE values obtained were 13.2 GPa for beech LVL and 13.3 GPa for oak LVL, whereas the MOR were respectively 72.0 MPa and 63.4 MPa in the flatwise direction. Such mechanical properties are comparable to those of LVL manufactured from other species of hardwood. The increase in weighted knot proportion provided lower MOE and MOR on LVL. The weighted knot proportion can better predict the LVL MOE. Deeper lathe checks and higher lathe check intervals generated lower shear modulus in the edgewise direction for both species. No correlation was found between lathe check properties and LVL MOE. The radial position of veneer inside the tree trunk influences the physical and mechanical properties of LVL. Internal veneer produced higher LVL density but provided lower mechanical properties than external veneer. These lower mechanical properties were due to a higher knot proportion on the internal veneer surface than the veneer from external position.

Chapter 5

Table 5.1 Summary of the significant results

Chapter	Results
1	<ul style="list-style-type: none"> a. Juvenile areas were 20-25 years of below 5 cm of distance from the pith. b. The difference on physical and mechanical properties between juvenile and mature wood were statistically significant but not huge.
2	<ul style="list-style-type: none"> a. Both physical and mechanical properties of oak and beech were highly influenced by wood density b. Oak structural, physical and mechanical properties were also affected by the growth speed. c. The ring density on oak was highly correlated with the LW width and density.
3	<ul style="list-style-type: none"> a. Internal veneer produced higher LVL density but provided lower mechanical properties than external veneer. b. Veneer knot proportion highly influenced LVL mechanical properties c. Lower mechanical properties were due to higher knot proportion on the veneer surface form internal position than external position. d. Higher veneer thickness produced LVL with lower shear modulus induced by deeper lathe checks.

Chapter 5

General discussion

Wood quality depends on many factors including tree genetics, growing site conditions, and silvicultural practices. As a consequence, such factors will determine the stem diameter, growth rate, wood density, MFA, grain angle, knottiness, juvenile wood, and reaction wood. These parameters have strong influences on the mechanical and physical properties of wood. The measurement of these parameters and its effect on the physical and mechanical properties of secondary quality hardwood assisted us to determine the potential use of secondary quality hardwood on the basis of the measured qualities. The influences of the external factor such as the growth condition on the wood quality related to juvenility have been discussed in chapter 2. Correlations among structural properties (measured wood quality parameters) and their impact on physical and mechanical properties were also discussed in Chapter 3. In chapter 4, we demonstrated the use of secondary quality hardwoods as a building material through the manufacturing of LVL. We have also optimized the quality of the LVL by varying the veneer thicknesses, radial positions, and knot proportions.

5.1. The properties of secondary quality hardwood

Young and small diameter hardwoods harvested during thinning operations exhibit smaller ring widths compared to those found in the literature on dominant trees. Such suppressed trees show some variation within the annual ring component in the first years of the tree's life and then remain relatively constant, whereas the dominant trees show the very same variation in the first years, but even higher variation after the tree has been released from the competition by the thinning operation. This part of wood formed in the first years of growth of the tree is called juvenile wood.

Radial variation of wood properties and the influence of juvenile woods

The properties of beech and oak wood are dissimilar from the pith to the bark. In the early rings, a very rapid change of the measured properties was observed, followed by a gradual change of the following rings into mature wood. Some fluctuation has occurred in the properties of the wood measured on the part of mature wood that may be related to the presence of reaction wood, called tension wood in hardwood species. The presence of the G-layer on the tension wood makes the wall thicker, reduces the porosity and increases the wood density (Jourez et al. 2001; Christensen-Dalsgaard et al. 2007; Purba et al. 2015). The gradual changes in early rings and the fluctuation of wood properties caused by the presence of tension wood make it more difficult to identify the separation point of juvenile and mature wood.

The juvenile wood of oak is characterized by a wider early and latewood, a greater earlywood density and a higher MFA than mature wood. Such higher density of earlywood can be

related to lower porosity which is consistent with the literature reporting a lower vessel lumen diameter in juvenile than mature rings of oak (Helińska-Raczkowska 1994). Juvenile wood can be found in a very small area in the center of the trunk. The point of separation between mature and juvenile wood of oak is around 17-24 rings from the pith based on the variation of ring components. On the other hand, beech juvenile wood has higher latewood proportion, a smaller difference between LW density and EW density and a higher MFA than mature wood. The mature wood of beech begins after 15 rings from the pith based on variation of the difference between LW density and EW density.

The physical and mechanical properties of internal and external wood have been compared. Juvenile wood was labeled as internal wood while mature wood was labeled as external wood. From the results, it can be seen that the wood density, FSP, Vs, Rs and Ts in both species are higher in the internal position than in the external position. Conversely, the longitudinal shrinkage was relatively unchanged from one position to another. The higher FSP and shrinkage in the internal position may, however, be related to the higher specific gravity. In previous studies on oak and beech, the increase of Vs with higher wood density has been reported (Deret-Varcin 1983; Gryc et al. 2008b).

Higher wood density did not generate a higher MOE in the internal position may be due to the fact that the MFA on the first rings is greater than in the external position. High MFA variation may negate the effect of high density on the mechanical properties in the internal position. Oak has relatively similar MOE in both positions while beech MOE is significantly higher on the external position than on the internal position. This higher MOE on external for beech may be attributed to the lower MFA variation between the two-positions on beech compared to the MFA variation on oak. A previous study on beech by Gryc et al. (2008) which show slightly higher wood density and swelling on juvenile woods, but a relatively similar MOE between the two positions supports these results. In addition to lower porosity, the slightly higher density of wood in the internal position may be related to a higher number of rays in juvenile wood than in mature wood. Rays are generally denser than the wood itself.

Since the difference between internal and external wood in terms of mechanical and physical properties on both hardwoods was relatively small and the juvenile wood only occupied a very small part in the center of the trunk, it can be concluded that juvenile wood found in the suppressed trees of both hardwoods can be used in place of mature wood. Nevertheless, this part of the research has not yet taken into account the presence of knots on both types of wood.

The demarcation point in this study was determined based on the variation of the properties of the ring components and MFA from the pith to the bark. Such a demarcation point was found based on the average value of all measured trees. The properties of the ring component were measured on the individual rings, but the MFA was measured on the sections that were 1 cm wide. These parameters were appropriate for this study since the principal objective of this study was to see whether or not the juvenile wood will be cut into veneer during rotary peeling. However, in biological or ecological studies, the variation in MFA should be better characterized by measuring it for each ring. For a clearer separation point at the tree level, other parameters such as the vessel diameter and the number of vessels can also be employed.

5.2. The effect of wood density and ring width on physical and mechanical properties

Influence of wood density

The physical and mechanical properties of the two hardwood species were correlated with the density of the wood. For both hardwood species, the mechanical properties were found to be positively correlated with wood density. The wood density showed the highest correlation with the MOR, followed by the static MOE and the dynamic MOE. All these positive correlations between wood density and mechanical properties were contrasted with previous studies in which there was generally no significant relationship between wood density and the mechanical properties of the oak (Polge 1973; Zhang et al. 1994a). In some cases, a high wood density for oak is even perceived as a lower quality criterion for wood. The reasons for this contrast with the literature may be that the range of wood density in our study is lower than in previous studies.

In addition, the wood density also influences the physical properties of both hardwood species. From the results, it was shown that the increase in wood density increases the Ts, Rs, and Vs and decreases the Ls. Positive correlation found in this study between beech wood density and Vs ($R^2 = 0.484$) supports previous work by Gryc et al. (2008a). For wood species with large rays like oak and beech, such correlation may support the hypothesis that rays are one of the factors responsible for transverse shrinkage anisotropy because the ray volume is up to 17 – 22% of the wood tissue in oak and beech (Skaar 1988). Furthermore, there was no correlation between wood density and grain angle. The grain angle, however, shows negative correlations with the mechanical properties of both hardwood species, even when the variation of grain angle was considered low.

Influence of ring width

The ring width shows positive correlations with wood density on both hardwood species. Indeed, the wood density and ring width were better correlated on ring porous species like oak than on diffuse porous species like beech. This positive correlation between wood density and ring width is in accordance with the literature, indicating that rapid growth on the oak produces a higher wood density (Genet et al. 2013; Guilley et al. 2004). On diffuse porous hardwoods such as beech, on the other hand, the ring width is not supposed to affect the density. By contrast, a study by Bouriaud et al. (2004) on beech reported a small but significant negative correlation between wood density and beech ring width ($r = -0.14$) which has led to greater confusion in the result. However, the ring width did not influence the mechanical properties of beech wood. As opposed to beech, the increase in the ring width on oak wood significantly increases the mechanical properties.

The ring density on oak was highly correlated with the latewood width and density. Contrary to oak, beech ring density was not correlated with ring width but was influenced by the density of both latewood and earlywood. Certainly, the different types of vessel distribution also influence the correlation between wood density and mechanical properties.

For oak, the ring width has positive correlations with Ts, Rs, Vs and FSP, whereas for beech, it has negative correlations with Ts, Vs and FSP. The positive correlation between beech wood density and Vs supports the previous reports of Gryc et al. (2008a). Deret-Varcin (1983)

also corroborates our results on oak by indicating that the oak wood density and ring width were positively correlated with shrinkage.

Both the density and ring width had a great influence on the physical and mechanical properties of oak in particular. According to some literature, the density of the rays is higher than that of the wood itself. Therefore, the rays are expected to influence the ring wood density. Consequently, when it comes to modelling mechanical and physical properties by multiple correlation, adding rays to the model may improve its reliability.

5.3. Influenced of veneer thickness and wood properties on the quality of LVL

The valorization of secondary quality hardwood as a construction material requires an optimization of its mechanical properties by reconstituting it into engineered wood and an optimization of the recovery rate by transforming it into veneer. As a result, lower quality hardwoods will be best converted to LVL where both biomass and mechanical properties will be optimized. Similar to the LVL made of knotless veneer, the LVL made of knotty veneer has also generated different mechanical properties with the different veneer thicknesses on the inside. Oak LVL made of 3 mm thick veneer produced the optimum local SMOE, global SMOE, and SMOR while beech LVL optimum local SMOE was at 3 mm veneer, global SMOE at 4.2 mm veneer and SMOR was at 3 mm veneer. Considering all the measured mechanical properties, including stiffness, strength and shear properties, as well as its standard deviation, it can be concluded that 3 mm thick veneer provides the optimal mechanical strength on LVL made of secondary quality hardwood. This thickness corresponds to the one commonly used in the LVL industry.

As anticipated, the stiffness and strength of beech LVL made from secondary quality beech were well below that of the previous study using knotless LVL. Nevertheless, the stiffness of LVL made from secondary quality oak and beech is equal to or even higher than that of LVL made from other hardwood species including eucalyptus, maple, aspen, and poplar (Aydin et al. 2004; Shukla and Kamdem 2008; Rahayu et al. 2015).

The parameters of veneer quality measured in this study, including the knot proportion, the lathe check properties and the radial position of veneer relative to the center of the trunk, affect the mechanical properties of the LVL. Indeed, high knot proportions were found on the surface of veneer prepared from secondary quality hardwood. The increase in weighted knot proportion, calculated using a correction factor based on the position of the knot along the length of the veneer, results in lower MOE and MOR on LVL.

The lathe check depth and interval on the veneer surface increase with the increase of veneer thickness. Deeper lathe check and larger lathe check interval generate lower shear modulus in edgewise direction for both species. In addition, there was no correlation found between the two lathe check properties and LVL MOE. These findings are consistent with previous reports on the effect of lath check properties on LVL MOE (Ebihara 1981; Hoover et al. 1987; Pot et al. 2015).

The radial position of veneer inside the tree trunk influence the physical and mechanical properties of LVL. Internal veneer produced higher LVL density but induced lower mechanical properties than external veneer. These lower mechanical properties were due to

higher knot proportion on the internal veneer than on the external veneer. During peeling, the outer part of the log was cut first then followed by the inner part. Knots diameter is bigger at the position closer to the periphery and gets smaller to the inside. Since log diameter is bigger on the outer side while the knots diameter is also bigger, peeled veneer from the external position only contained a little number of big knots. Bigger log diameter provides higher distance between knots related to wood peeling. As the peeling diameter decreases, the knots diameter and the distance between knots also decrease. Consequently, peeled veneer in the internal position contains a higher number of knots and therefore a higher knot proportion than the external veneers.

In addition to the peeling mechanism, the higher knot proportion on the surface of internal veneer may be also related to the natural pruning. In a study by Knudson *et al.* (2007), it has been reported that the number of knots in spruce veneers increases from sapwood to heartwood. The quoted author explained that more natural pruning happened on older trees. Besides a higher proportion of knots, lower mechanical properties on internal veneer of beech may also be attributed to the presence of small part of juvenile wood. The more mature wood on the external position can provide higher strength on the LVL.

5.4. Perspective

Valorization of secondary quality hardwood as Glulam.

By conducting a study on glued laminated wood made from secondary quality hardwood, we will be able to compare the recovery rate of woody biomass between the veneer and sawn wood. The quality of glued laminated wood depends on the quality of the wood, adhesives and finger joints. Some work has been done in the first year of the PhD thesis related to the bonding quality. The focus was on the relation of wood surface roughness and the wood structural parameters with wood the bonding quality of Glulam. The hypothesis of the study was that a slight degradation of the wood surface would improve the quality of the bonding, especially in beech, which generally has an excessively smooth surface that is hard to glue. The results of the glue shear strength were obtained from the measurement based on EN 14080, modified methods of EN 14080 and EN 302. For all tests, 100% failure in wood was observed on both smooth and degraded surface. Such a result cannot be used since it indicates the shear strength of the wood instead of the glue shear strength. As a result, it is impossible to evaluate the effect of surface roughness on the bonding strength of the wood.

Modeling the effect of knot proportion on the log surface to the quality of LVL

From this study, it was shown that the knot proportion weighted by the knot position could explain the LVL mechanical properties. In addition, it also revealed that the knot diameter becomes smaller and the knot frequency increases as the peeling process approach the center of the log. Based on this finding, it can be concluded that knot characteristics such as the knot diameter and its position on the log surface can be used to predict the LVL mechanical properties. This could be achieved by conducting a study that includes X-ray tomography of the logs, measuring the weighted proportion of knots on the veneer surface and testing the mechanical properties of LVL.

Economic feasibility of the manufacture of LVL from secondary quality beech and oak

The current study reports the technical feasibility of LVL made of secondary quality beech and oak. While the mechanical properties of LVL manufactured from secondary quality beech and oak are satisfactory, further studies are required to assess its suitability for the manufacture of commercially acceptable LVL in terms of the production costs.

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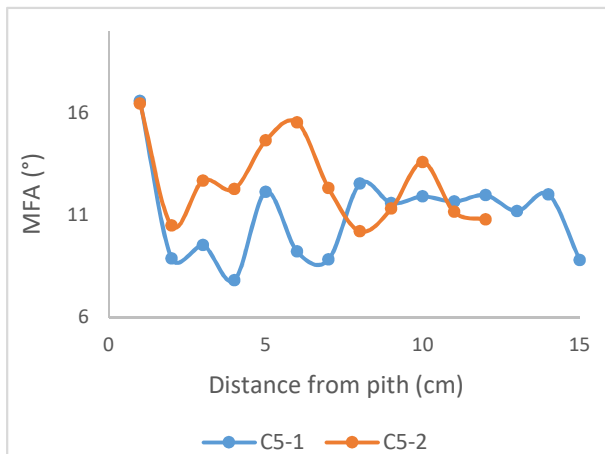
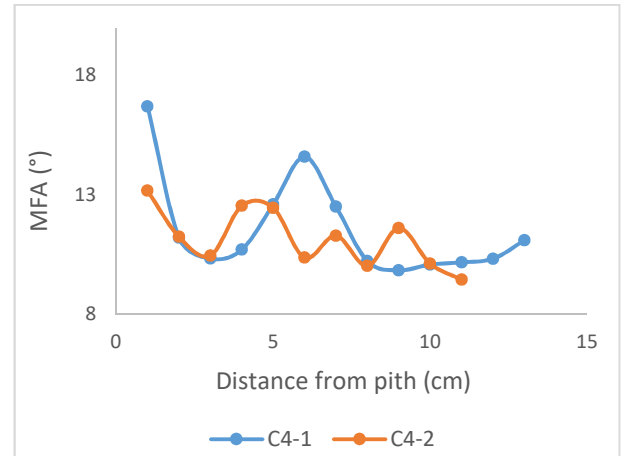
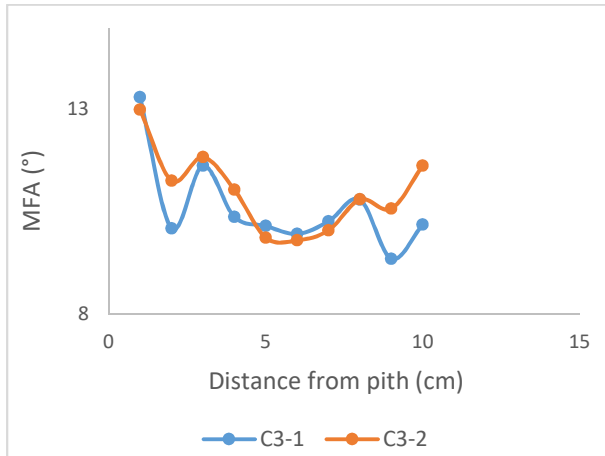
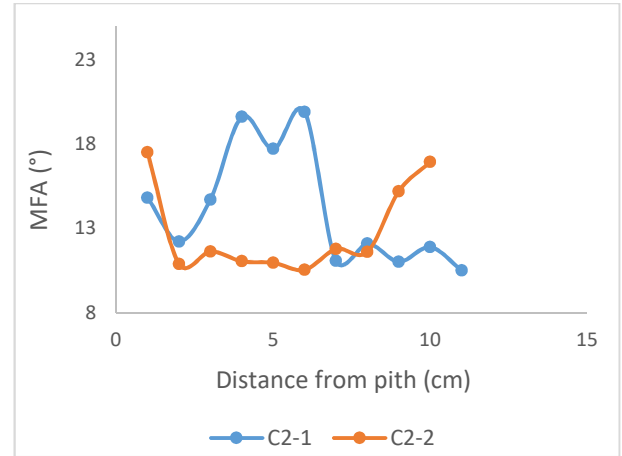
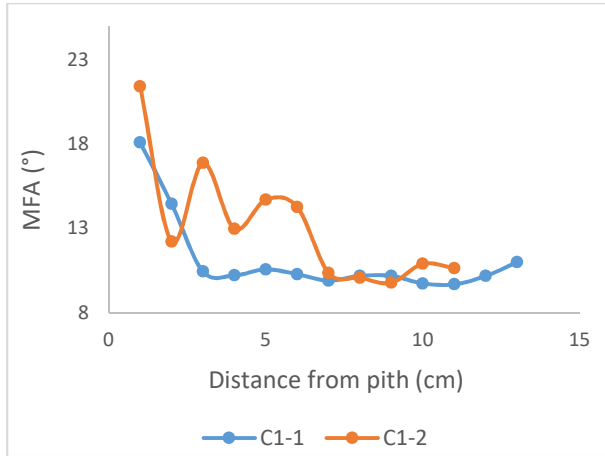
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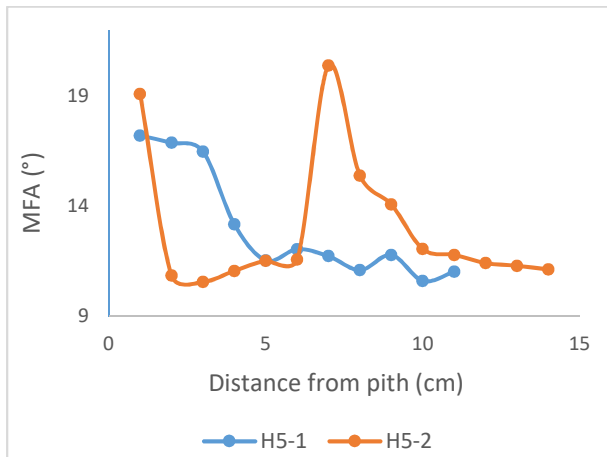
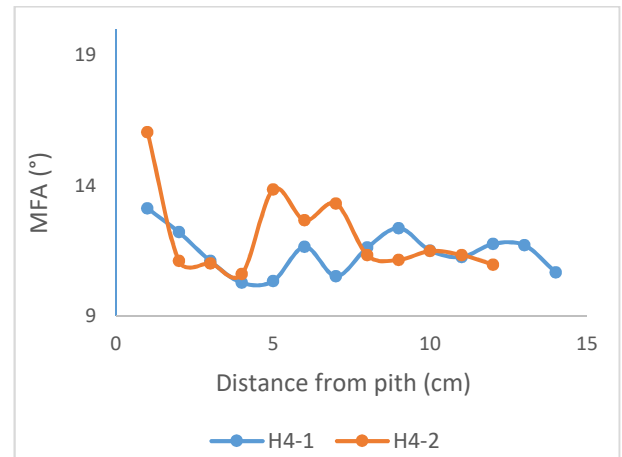
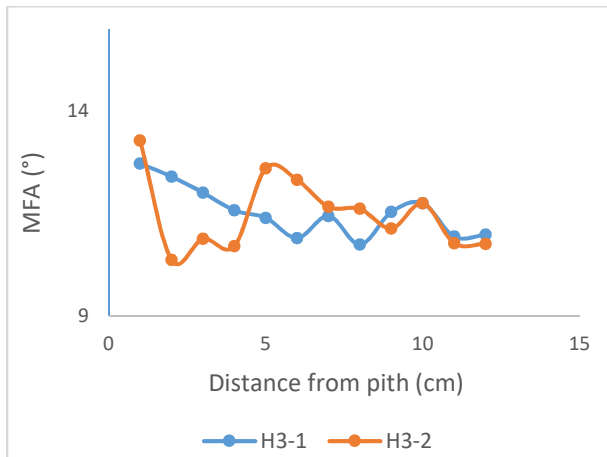
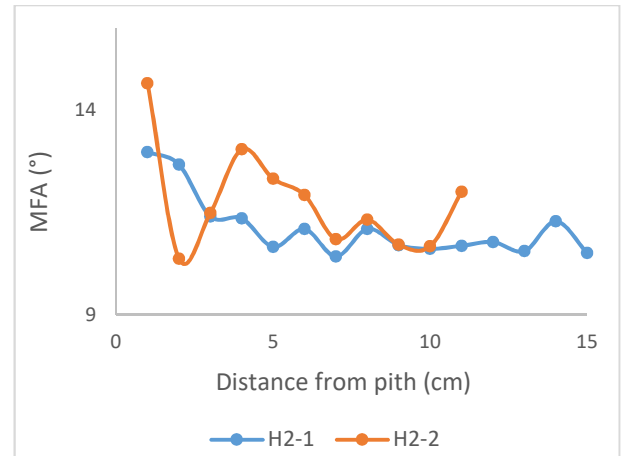
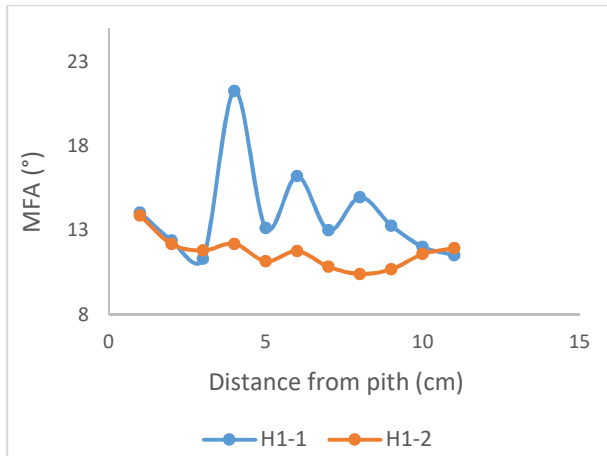
Appendix

Appendix A-Radial variation of wood properties from pith to the bark: patterns on individual tree

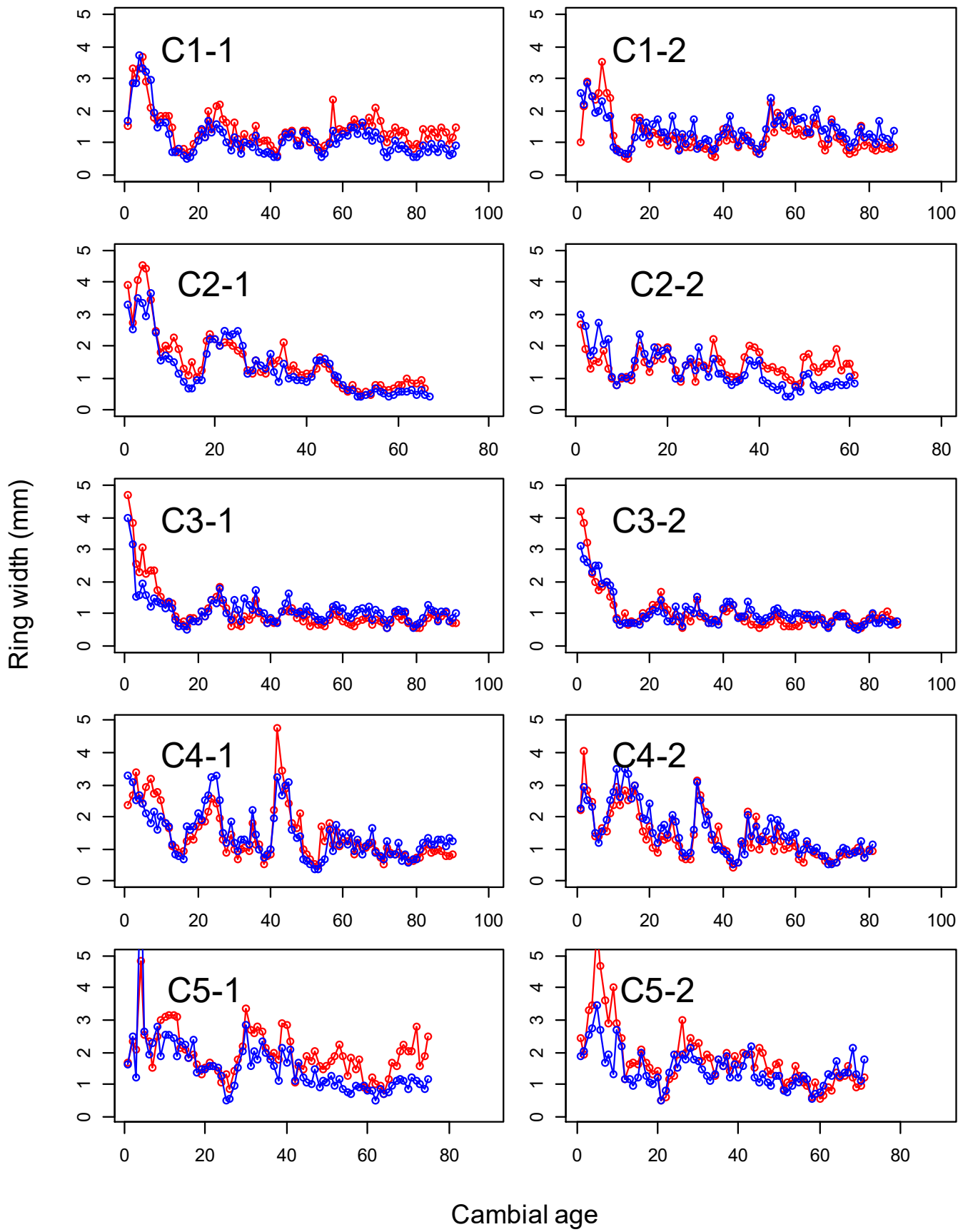
MFA variation of Oak



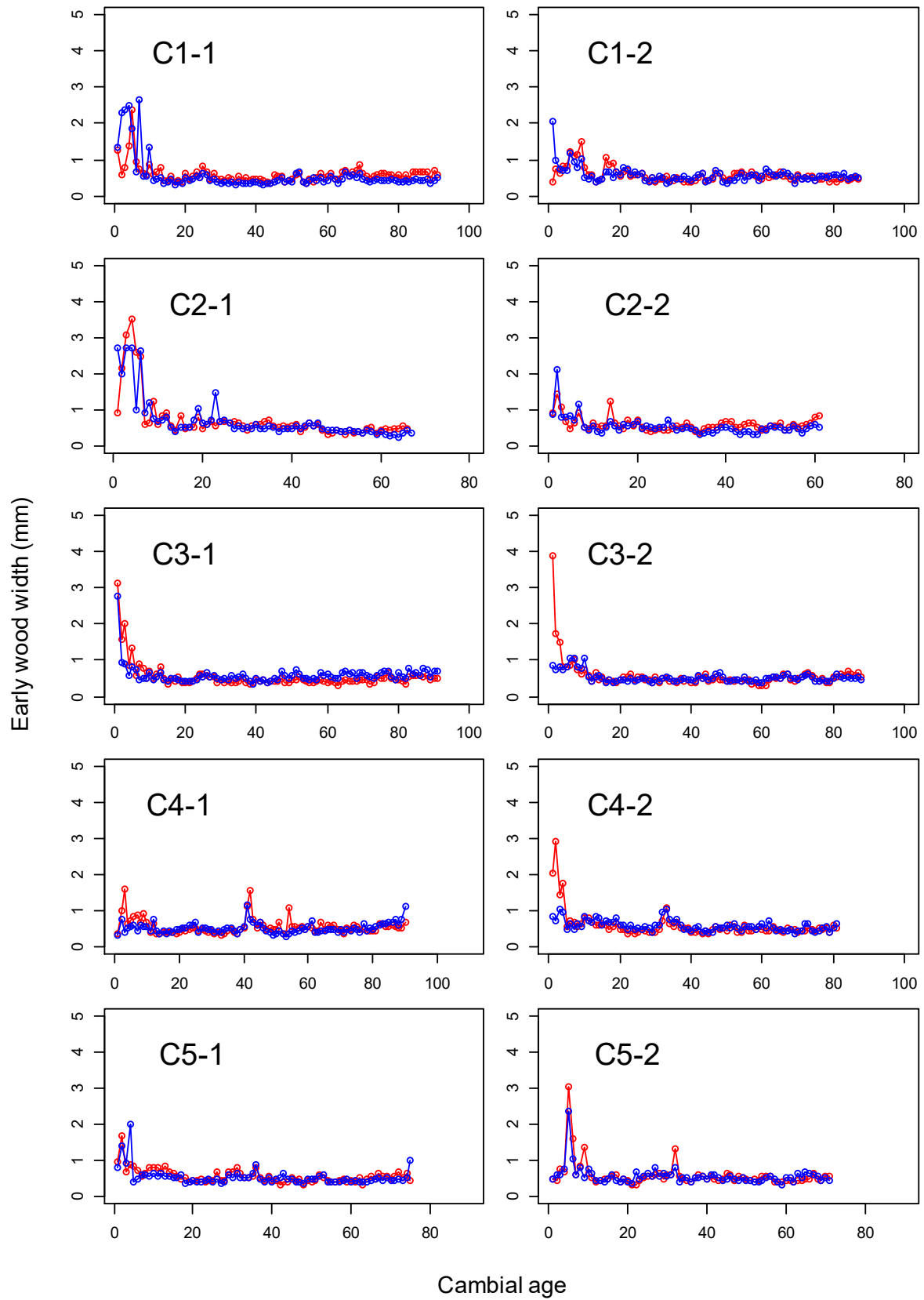
MFA variation of Beech



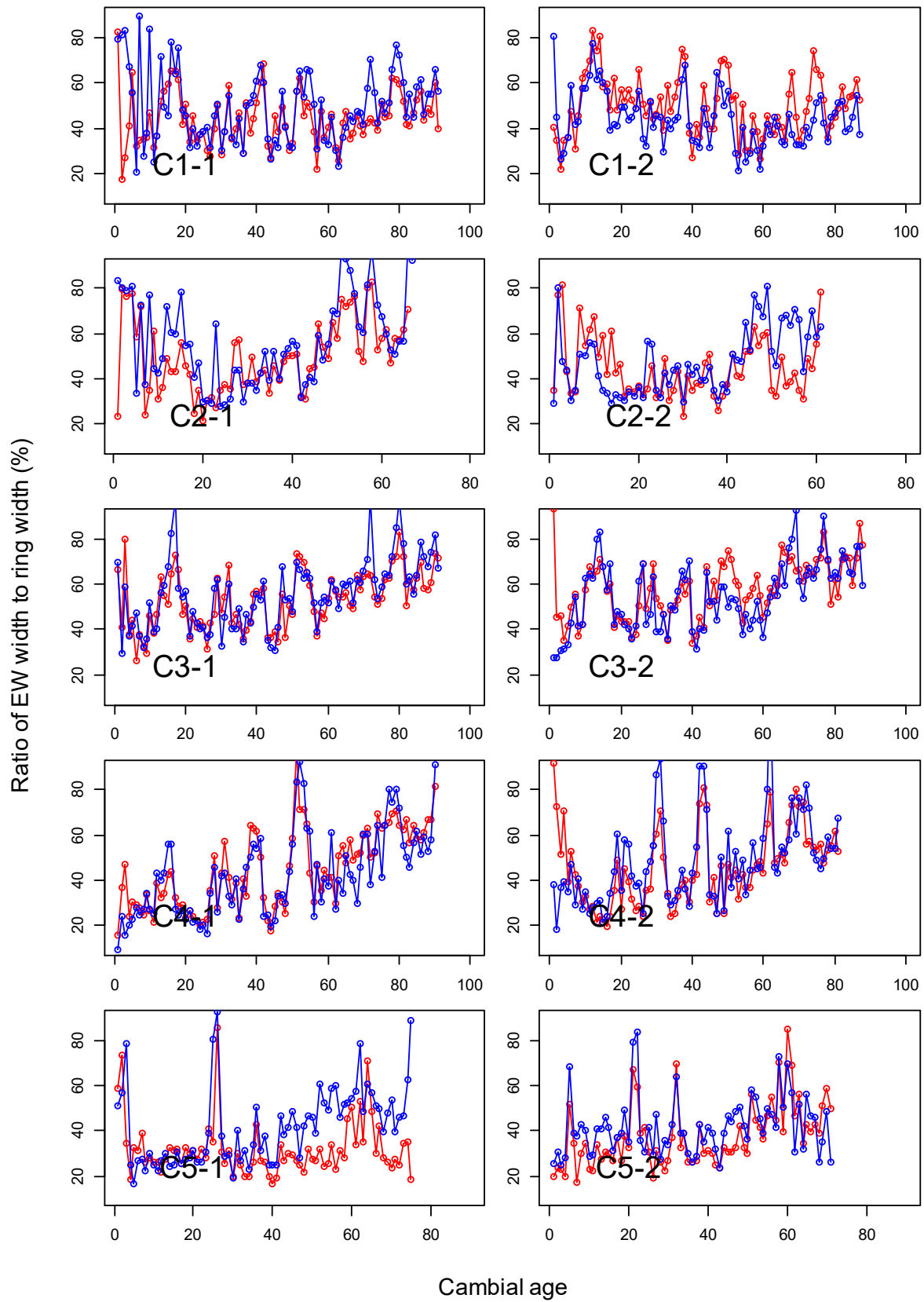
Variation of Ring width in Oak



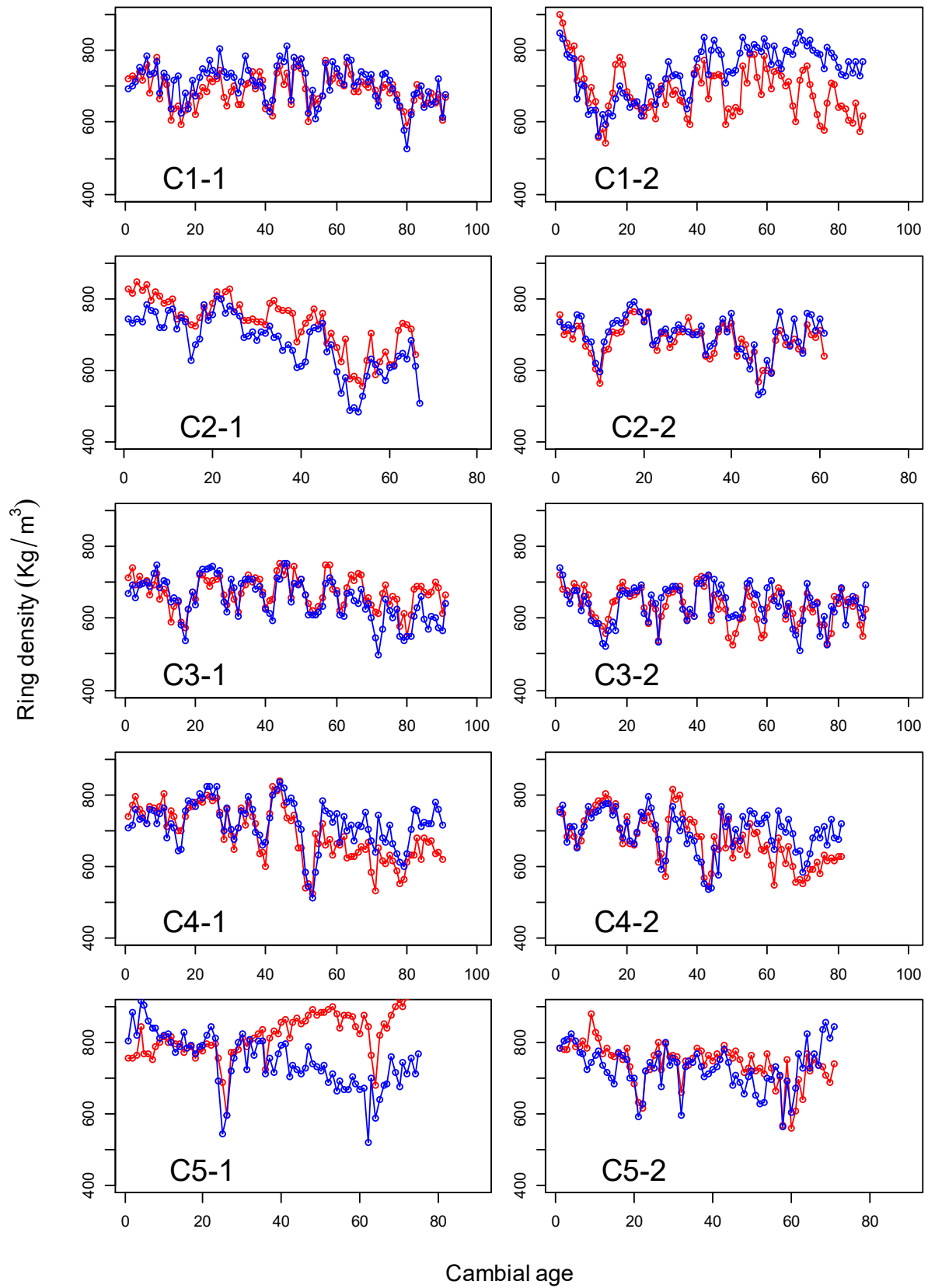
Variation of earlywood width in Oak



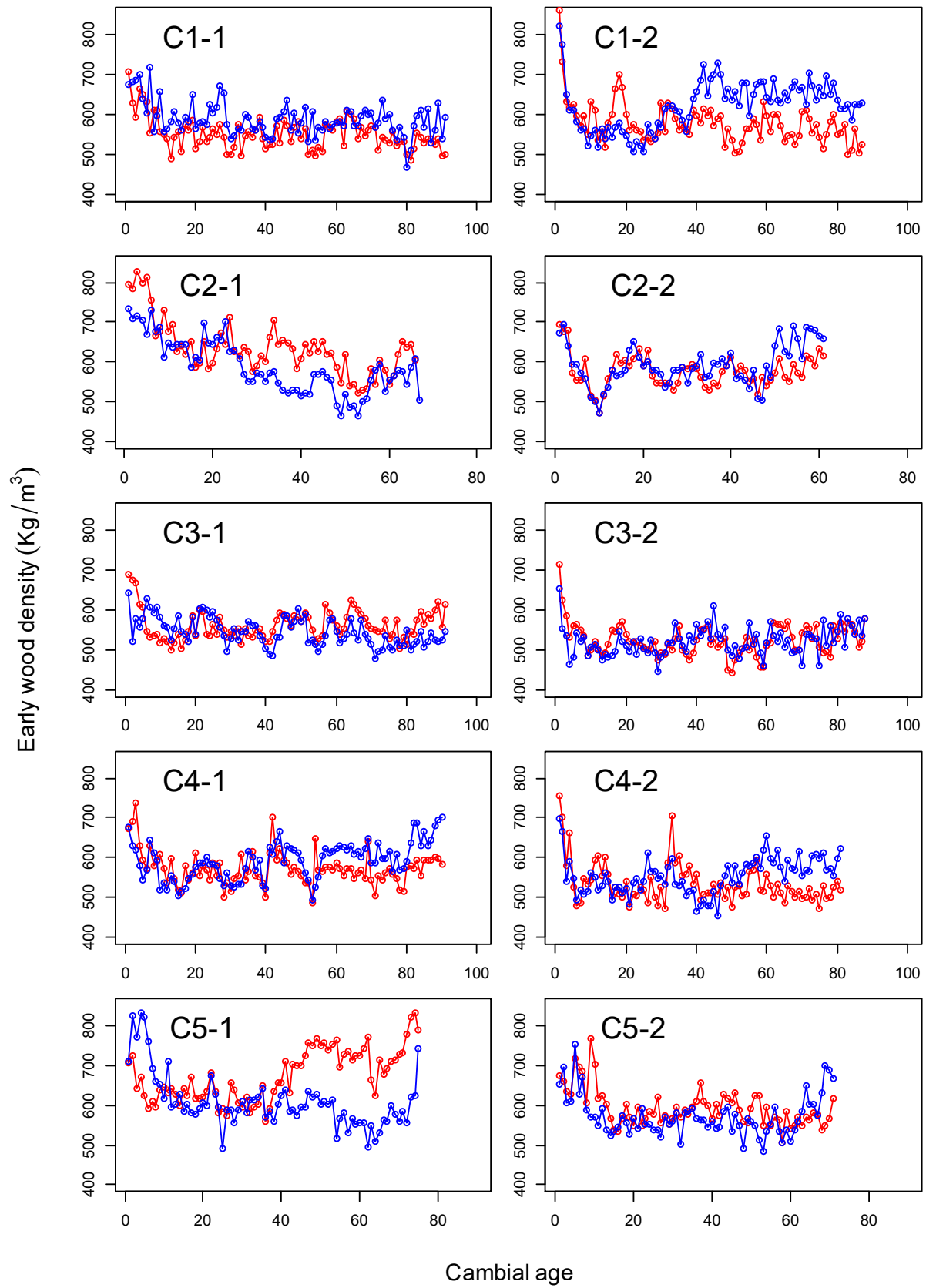
Variation of earlywood proportion on oak



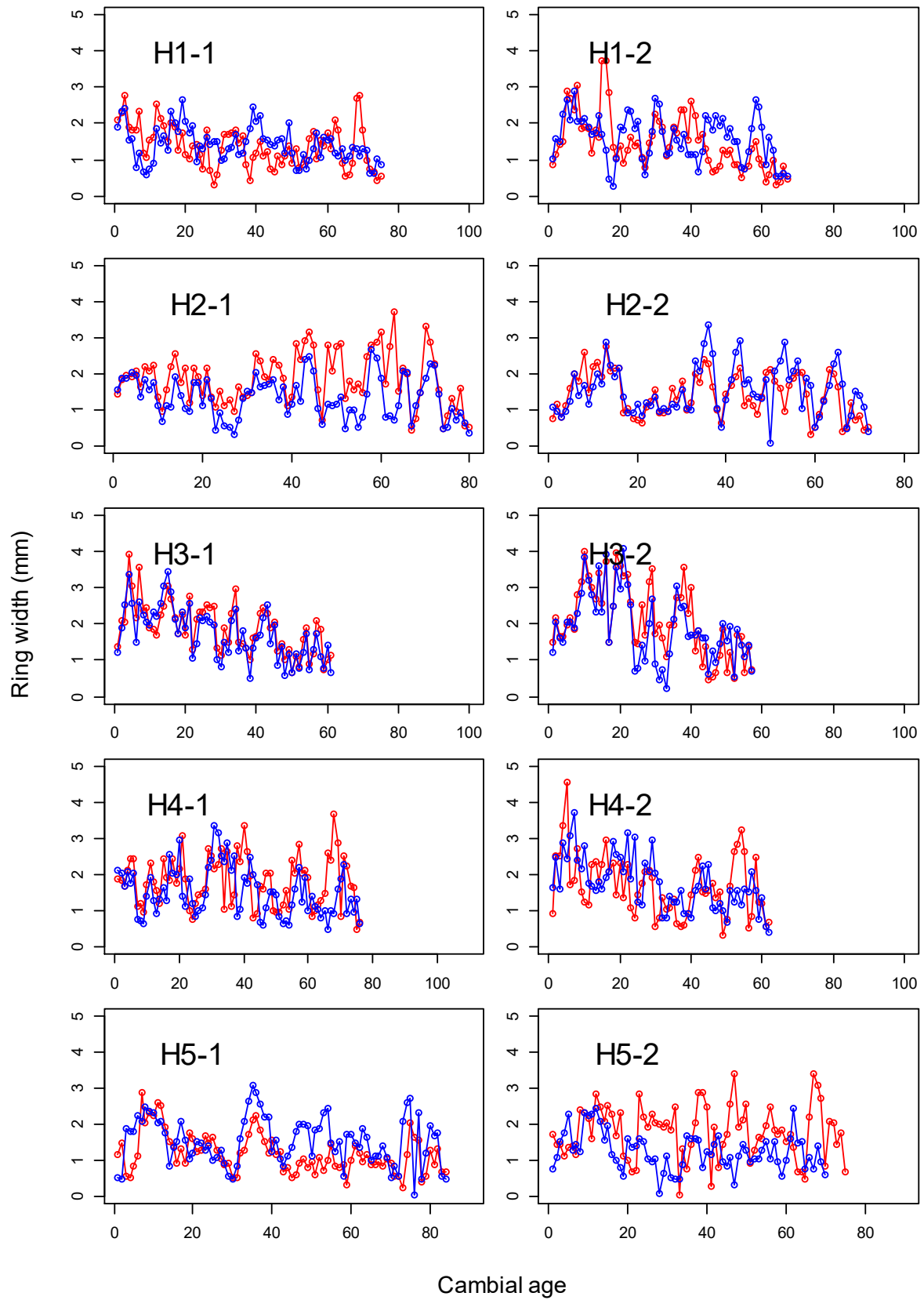
Variation of Ring density in Oak



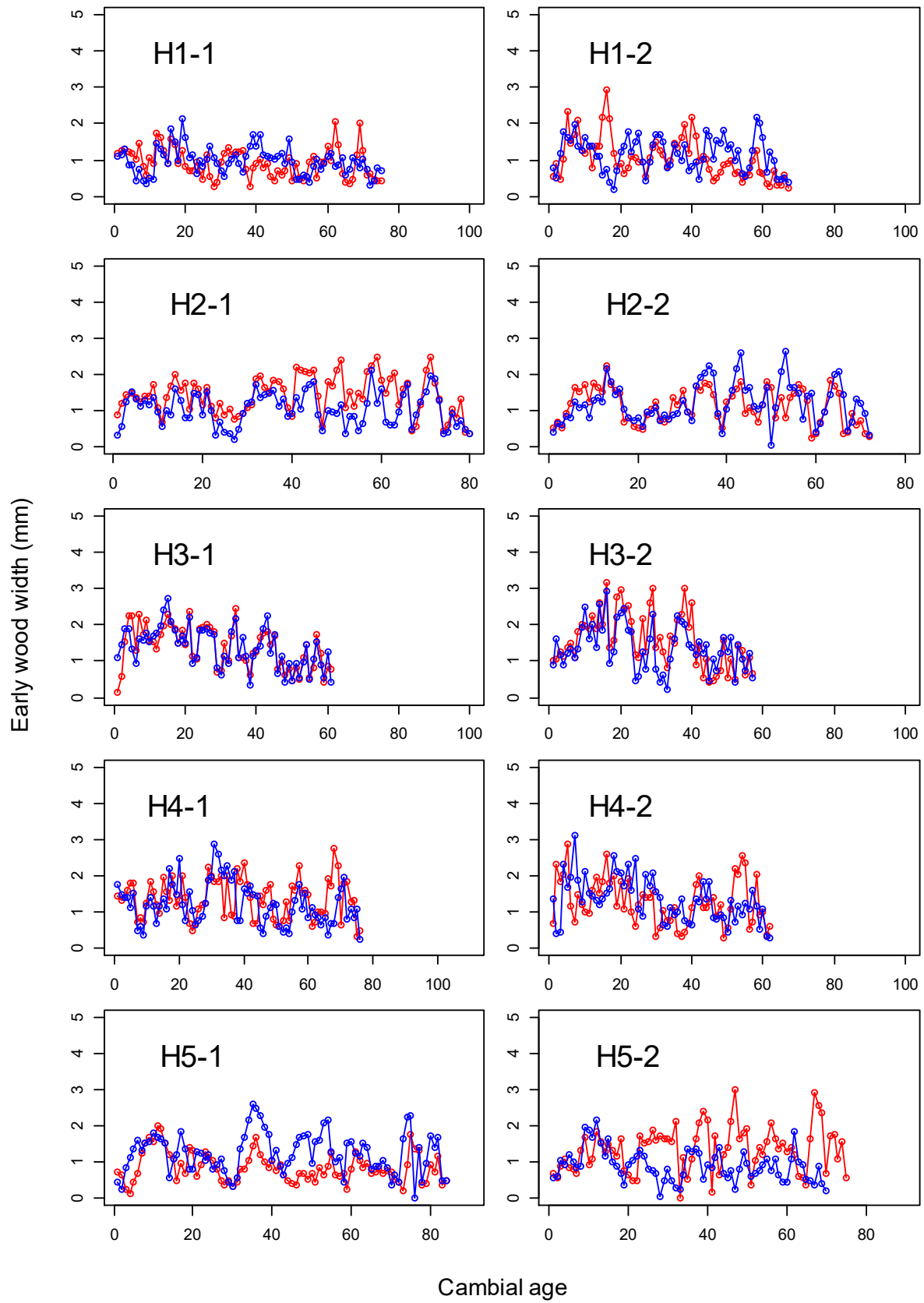
Variation of Earlywood density in Oak



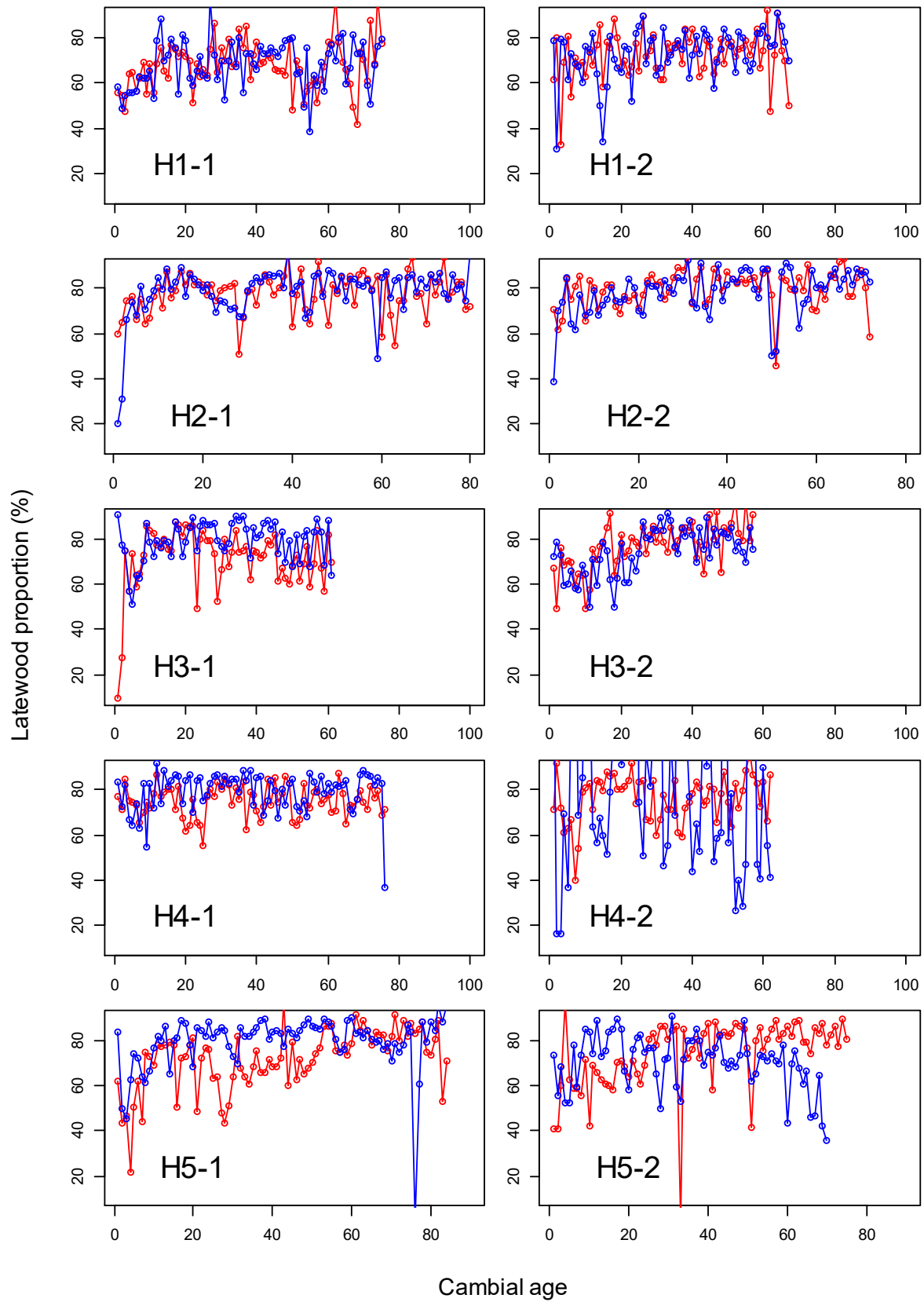
Variation of Ring width in Beech



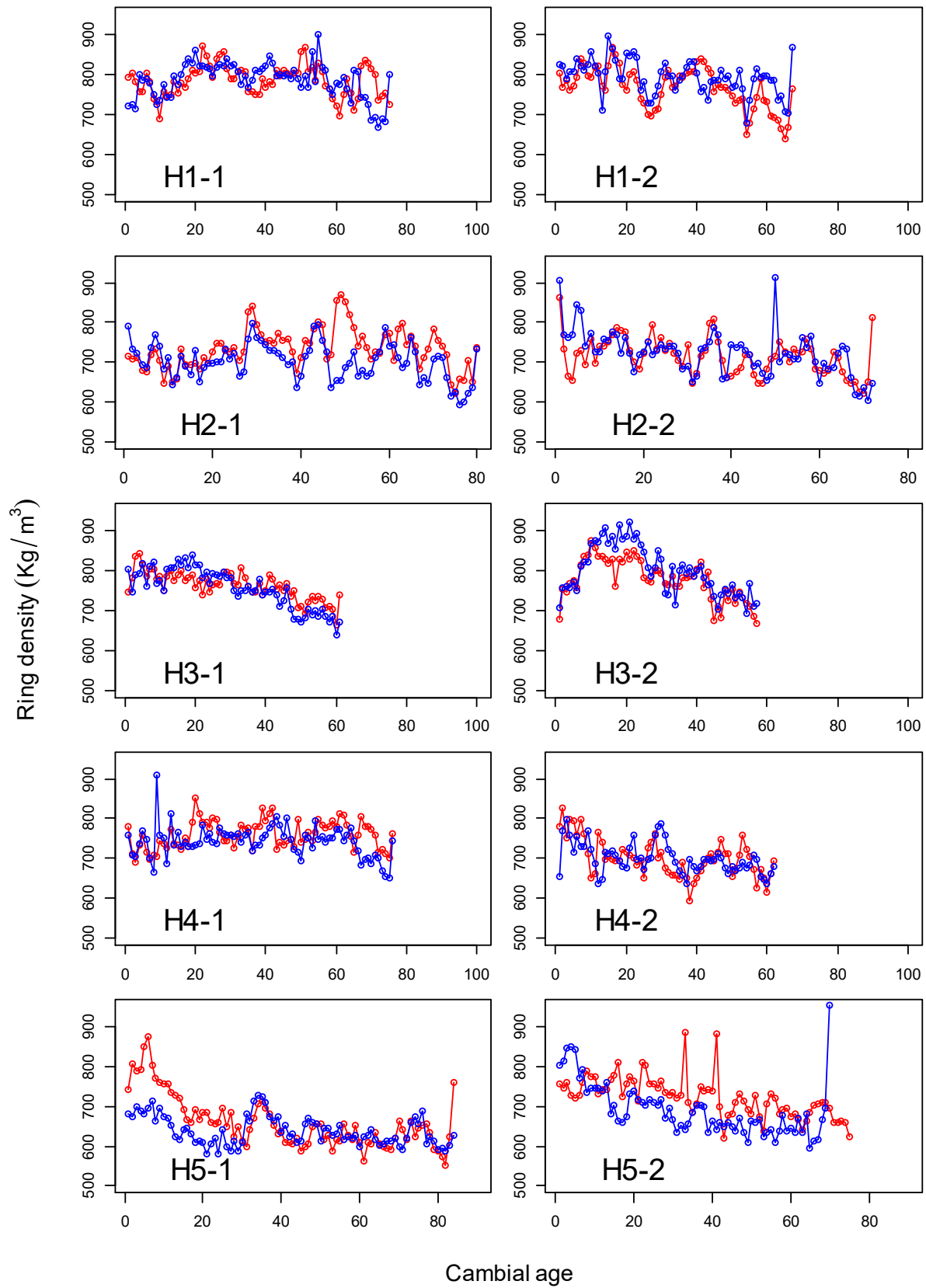
Variation of earlywood width in beech



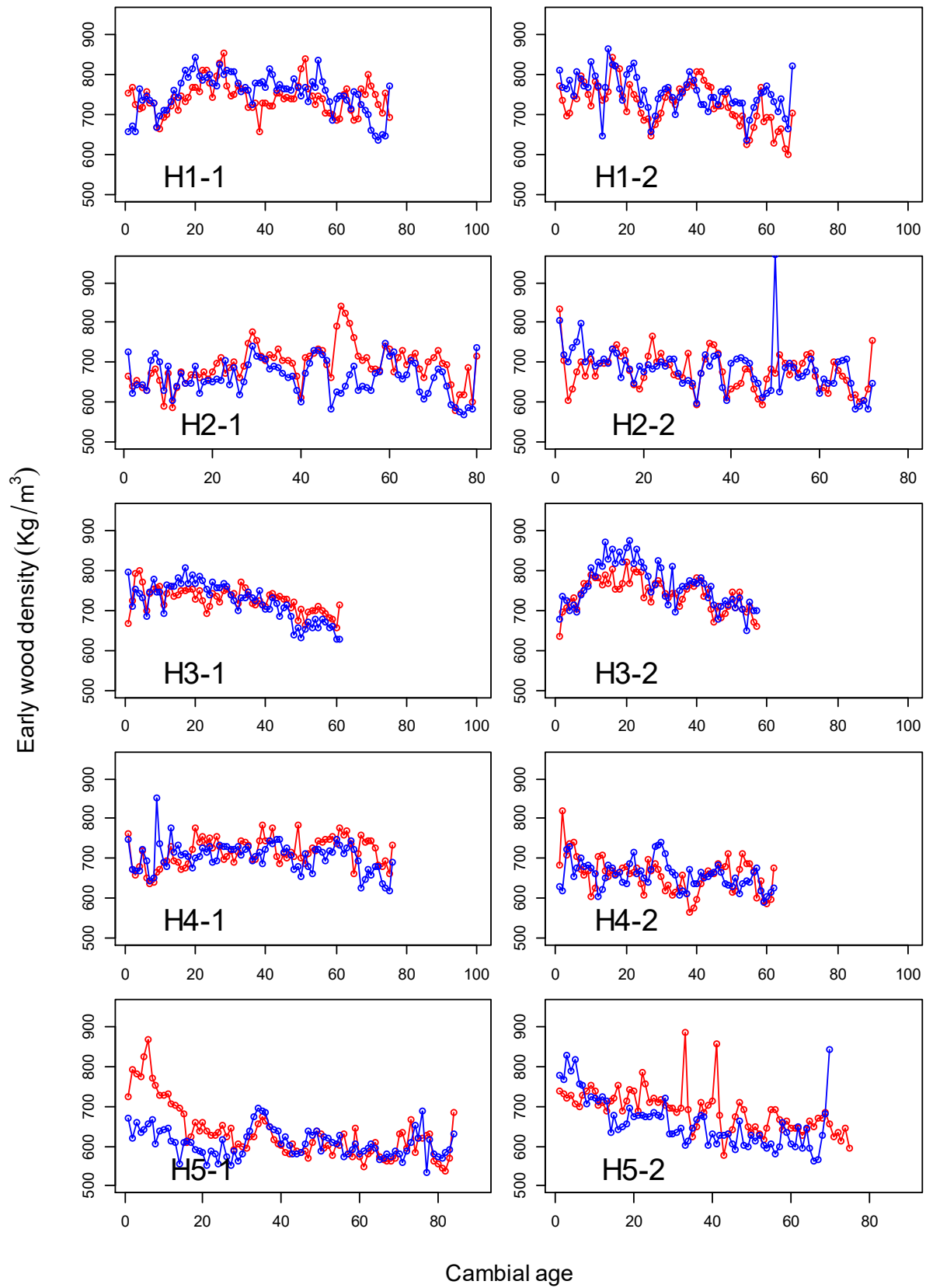
Radial variation of earlywood proportion in beech



Variation of Ring density in Beech



Variation of Earlywood density in Beech



Appendix B-Improvement bonding quality through slight degradation on wood surface

Introduction

Machined wood surfaces may appear to be smooth and flat, but microscopic examination shows peaks, valleys, and crevices littered with loose fibers, debris, and cavities (vessels and fibers). Wood surface roughness is substantial parameter influencing final quality of the wood products (Aguilera and Martin 2001; Brown 2002; Vitosytė et al. 2015). Surface roughness characterizes the fine irregularities on a machined surface by measuring the height, width, and shape of the peaks and valleys produced by woodworking operations or by anatomical structural properties (Magoss 2008). In relation with gluing, poor surface roughness tends to form low bond durability since it provides lower reaction area between wood and adhesives. In contrast, over rough surface forms weak bond durability caused by over penetration. In addition, Collett (1972) reported that a roughened surface affects the bond strength by promoting a more spontaneous spreading, which in turn leads to improved wetting. Wenzel (1936) also demonstrated that the contact angle between glue and wood varies directly with wood surface roughness.

Belfas et al. (1993) reported better shear strength on glued blocks sanded with the sand paper 80 grit. Light roughening on wood surface through sanding allows better glue penetration and increase glue spreading. Obviously anatomical structural elements also play important role in this matter. Wood surface roughness is highly varied with wood species, density, wood anatomical structure, moisture content, and machining conditions (Kilic et al. 2006; Malkoçoğlu 2007; Aslan et al. 2008; Magoss 2008). Previous reports showed various wood structure parameters affecting surface roughness such as grain figure, density, earlywood/latewood, cell structure, and juvenile wood (Kilic et al. 2006). Wood density exerts a strong influence on the surface roughness (Aguilera and Martin 2001; Kminiak and Gaff 2015). A study by Gurau (2014) in oak, beech, and spruce showed that surface roughness in latewood was higher than in earlywood. Species with a finer texture (smooth and glassy) such as beech has a smoother surface roughness compared to species with a coarse texture (Thoma et al. 2015). In addition, Barčík et al. (2009) reported that surface roughness of the juvenile wood is lower than in the mature wood. Reaction wood in hardwood so-called tension wood potentially affects the surface roughness since it tends to form wooly surface after sawing (Brown 2002). There is no literature found yet that study the effect of tension wood on surface roughness.

Several studies showed the effect of surface roughness on bonding strength. A study by Shida and Hiziroglu (2010) on surface roughness in Japanese cedar showed that higher bonding strength can be achieved by having a rougher surface. The Same result also found by Hiziroglu et al. (2014) when studying the bonding strength of pine, nyatoh, and oak related to surface roughness. In this part, we will prepare two kinds of surface, defined as good surface and degraded surface to evaluate the different in its bonding quality. The aimed of

this part is to understand the effect of surface roughness on bonding quality and explained the anatomical properties affecting surface roughness and bonding quality in beech and oak.

Material

The wood material used were secondary quality oak and beech with defects i.e. splits, cracks, insect holes, fungi attack, and loose knot, obtained from local sawmill called Mapibois in St-dié des Vosges, Lorraine. There were 120 lumbers with a dimension of 100 cm x 10 cm x 4.5 cm consisted of 30 flat sawn beech, 30 quarter sawn oak, 30 quarter sawn beech, and 30 quarter sawn oak.

Method

Characterization secondary quality hardwood from the local sawmill.

We measured wood density, modulus of elasticity (MOE), and modulus of rupture (MOR) using nondestructive (Bing) and destructive test using wood with a dimension of 380 x 20 x 20 mm³.

Glulam fabrication

We made two kinds of surfaces with different roughness i.e. good surface vs degraded surface. The good surface was obtained from planing while the degraded surface was continued treated with manual sanding perpendicular to grain angle using sand paper of 80 grits. Each lumber surface roughness was measured using P-test. Then, this lumber was glued using MUF to produce Glulam with six laminate with a dimension of 100 cm x 10 cm x 18 cm.

Characterization of wood wettability related to different wood surface roughness

To see the effect of surface roughness on wettability, we measured the contact angle of water and wood right after water dropped to the wood surface. The measurement was done at 3 positions for each surface using microscope equipped with a goniometer eyepiece. The contact angle is measured by rotating the goniometer eyepiece so that the hairline passed through the point of contact between droplet and veneer and was tangent to the droplet at that point. All measurements were made 5 seconds after the drop.

Measuring bonding strength based on EN 14080

To see the effect of treatment on the strength of the glue joint, the shear test sample with dimension of 50 x 50 x 180 mm³ was extracted. Glue shear strength was measured on all 5 glued surface of each shear sample.

Result

Characterization secondary quality hardwood from local sawmill

The measurement was done using 16 wood specimen of oak and 12 beech with a dimension of 360 x 20 x 20 mm³. The wood material preparation was done by disregarding annual ring angle. Most of beech wood specimen contains insect's holes and oak wood specimen have irregular grain angle.

Wood density

Variation of beech and oak density are presented in Figure 1. Here we can see higher variation in wood density in oak than beech. Oak density range is 545- 842 kg/cm³ while beech density range is 696-791 kg/cm³. This value is in accordance with literature that reported density in beech is 670-740 kg/m³ and oak is 690 -790 kg/cm³ (CIRAD 2012). In term of average density, beech has higher average density 748,6 kg/cm³ than oak 651,8 kg/cm³.

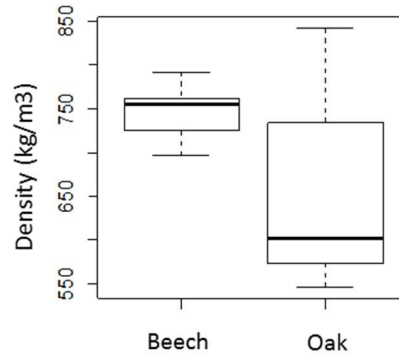


Figure 1. Density variation in oak and beech

Modulus of elasticity (MOE) of beech and oak Using Bing and destructive test

MOE was measured using non-destructive (Bing) followed by destructive test using the universal testing machine with three-point loading. The result of MOE measurements using Bing is presented in Figure 2. It shows that MOE variation in Oak 6469- 18197 MPa is higher than beech 12250-15510 MPa. Average MOE of beech 13872 MPa is slightly higher than oak 10355 MPa. This result also tells us that Bing is a reliable method for MOE measurement in the small clear wood specimen.

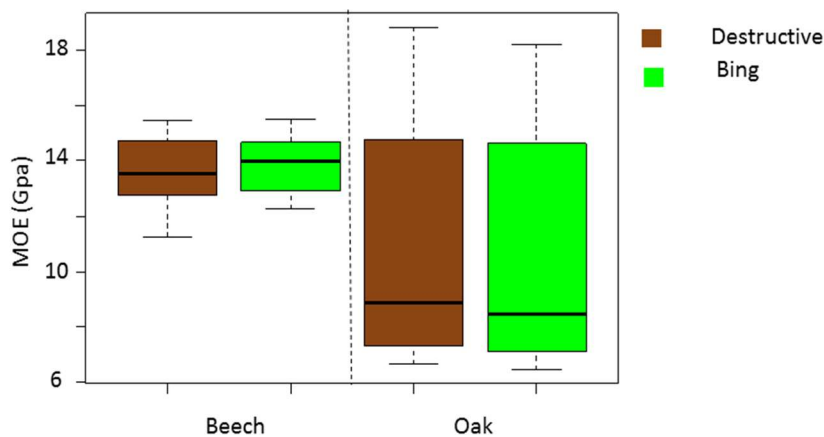


Figure 2. MOE variation from destructive and nondestructive test

Modulus of Rupture (MOR) of beech and oak Using destructive test

While MOE describes wood rigidity, MOR describes wood strength. Results on MOR measurement of beech and oak are presented in Figure 3. Variation in MOR is higher in oak (36-149 MPa) than in beech 100-136 (MPa). Beech also has higher Average MOR than oak.

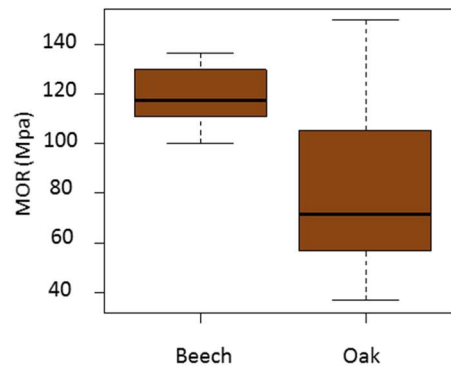


Figure 3. MOR variation in oak and beech from destructive test

Relationship between density and mechanical properties of secondary quality hardwood

To see the relationship between wood mechanical properties and its density, MOE and MOR were put in a plot with wood density. In Figure 4a, It demonstrates high positive correlation between MOE and wood density in oak ($r^2=0.94$) and much lower correlation in beech ($r^2=0.13$). It tells us that increase in wood density will increase wood MOE.

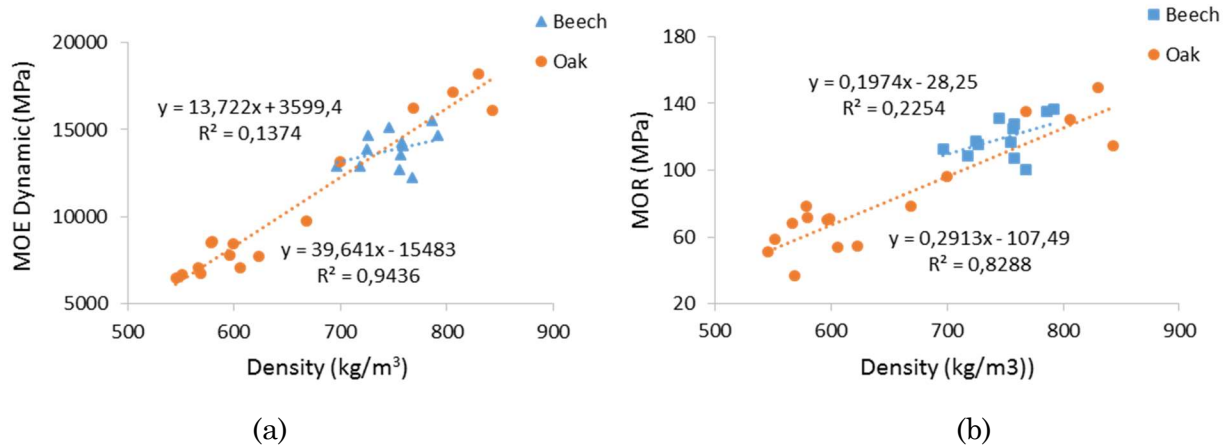


Figure 4. a) Relationship between density and MOE dynamic, b) Relationship between density and MOR

In Figure 4b, we plot MOR and density. We can see also a high positive correlation between both variables in oak ($r^2=0.83$) and lower correlation in beech ($r^2=0.22$). So increase in density will increase wood strength. Lower correlation between density with MOE or MOR in beech may be due to its irregular grain orientation and lower density variation compares to oak.

Characterization of planed and sanded surface properties

Surface Roughness on planed and sanded surface of oak and beech measured with P-test

For the measurement of wood surface roughness, we use P-test to measure average surface roughness (RA) on each wood surface. P-test is an easy and fast way to measure surface roughness. We presented the results in Figure 5. Apparently, there are overlapping in box plots spread among the box plots, which demand further analysis using statistical tools.

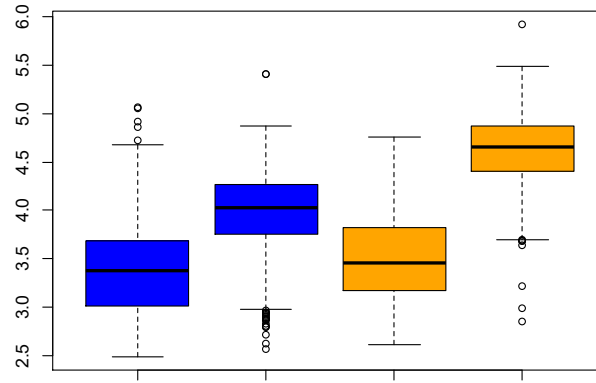


Figure 5. Surface roughness in planed and sanded surface of oak and beech measured with P-test

We used Mann-Whitney-Wilcoxon Test to see the different among this treatment and presented it in Table 1. The null hypothesis is that the distributions of x and y differ by a location shift of μ and the alternative is that they differ by some other location shift (and the one-sided alternative "greater" is that x is shifted to the right of y). If the p-value is less than the chosen alpha level (0.05), then the null hypothesis is rejected. It shows that all the treatment are no identical populations and that the different is statistically significant. Back to Figure 5, we can conclude that the different in average roughness is statistically significant among all the treatment. P-test measurement demonstrates higher surface roughness in sanded surface than in planed surface. There are also different roughness in Planed oak and planed beech where oak has higher roughness than beech. Following the same trend Sanded oak has higher surface roughness than sanded beech.

Table 1. Mann-Whitney-Wilcoxon test of surface roughness in planed and sanded surface of oak and beech

	Planed Beech	Sanded Beech	Planed Oak	Sanded Oak
Planed Beech		2.2e-16	2.794e-08	
Sanded Beech	2.2e-16			2.2e-16
Planed Oak	2.794e-08			2.2e-16
Sanded Oak		2.2e-16	2.2e-16	

Surface Wettability

Surface wettability was measured on 3 wood surfaces from each treatment. Measurement of contact angle was done 5s after water droplet was dropped on the wood surface. The smaller the contact angle, the better the wettability is. We presented the results in Figure 6 which also showing overlapping among box plot. To see whether the different statistically different or not we continue with Mann-Whitney-Wilcoxon test in Table 2.

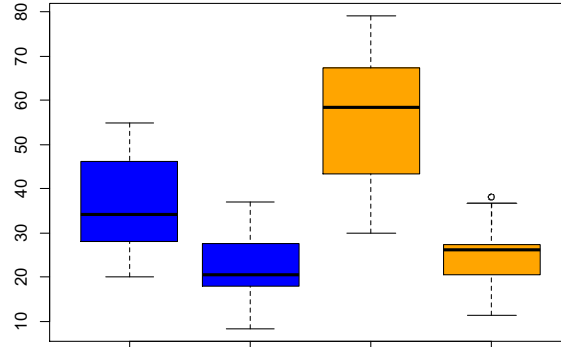


Figure 6. Contact angle of water on surface of sanded and unsanded beech and oak

The test shows that the all the p-values are smaller than 0.05 except for sanded beech and sanded oak. So, in conclusion, sanded surface has better wettability than planed surface. Sanded beech and oak have relatively same wettability. Planed oak has better wettability than planed beech.

Table 2. Mann-Whitney-Wilcoxon Test on contact angle of water on surface of sanded and unsanded beech and oak

	Planed Beech	Sanded Beech	Planed Oak	Sanded Oak
Planed Beech		0.005424	0.001515	
Sanded Beech	0.005424			0.4496
Planed Oak	0.001515			9.05e-08
Sanded Oak		0.4496	9.05e-08	

Bonding strength of planed and sanded surface test according To EN 14080 and modified Test

A shear test based on EN 14080 always produced failure in wood. Results cannot be used since it told us wood shear strength instead of bonding shear strength. At the time we thought that there was a problem with apparatus that holding the wood sample. Some modification in wood specimen and test were put in place. Here is some list of the modification.

Modification on the wood sample by using trait C on both sides of glued surface. We continue using compression force as in EN 14080 and as the results failure still happened in wood and not in glued surface.

Modification by using the wood sample with trait C on both glued sides and using traction force instead of compression. Most of the failure happened in wood but 1 sanded beech, 1 planed beech, 1 planed oak failed in glue line

Modification by narrowing the glue surface on both sides and using traction force instead of compression results in failure in the wood on all wood samples.

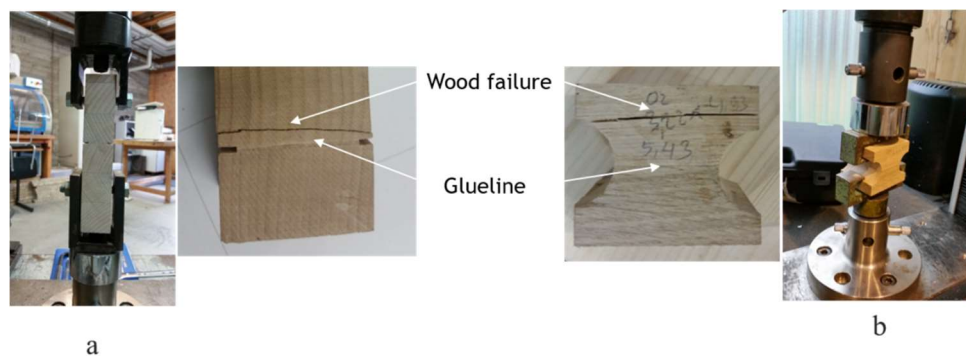


Figure 7. a) Modification by making trait C and using traction test, b) Modification by narrowing the glue surface and using traction test

Test on Bonding Strength According To EN 302

We decided to continue the shear test using another standard called EN 302. This test requires small sample with a dimension of 150 x 20 x 10 mm³. This test was done with 25 wood specimen where no planed beech was tested. This test also produced failure in wood in all samples and not the glue line so the wood failure percentage (WFP) can't be calculated. As a conclusion, glue strength of MUF in our test is higher than wood shear strength itself. Moreover, results show wood shear strength and not the glue shear strength. So, wood shear strength for oak range is 0.34-0.93 N/mm² and beech is 1.24-2.04 N/mm². Beech shear strength is higher than oak.

Conclusion

The glue shear strength was measured using EN 14080, several modified methods, and EN 302. All test demonstrated 100% failure in wood. This result cannot be used since it shows wood shear strength and not the glue shear strength. In results, we cannot evaluate the effect of surface roughness on wood bonding strength. This results demonstrated that there was no gluing problem related to the quality of the wood surface.

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Appendix C- Growth stresses in old beech poles after thinning: distribution and relation with wood anatomy

Growth stresses in old beech poles after thinning: distribution and relation with wood anatomy

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Abstract In the present study, we investigated the reaction of small diameter but old beech poles to canopy opening with particular interest in occurrence of growth stresses which allows the tree to maintain or correct its spatial position. We studied the relationships between growth stresses and (i) thinning treatment and (ii) anatomical structure. Forty-two beech poles were used for the study, half of which were thinned in 2007. We measured the growth stresses indicators (GSI) at eight positions around the trunk periphery and wood anatomical characteristics including proportion of G-fibers and vessel characteristics. Surprisingly, thinning treatment did not affect the average growth stress level and intensity of reaction in old beech poles. This rather unexpected result may be related to the high age of these trees and/or the high reaction wood occurrence prior to thinning resulting from the growth in suppressed condition. Considering the relationship between the proportions of G-fiber and the level of growth stresses, a significant positive correlation was found in agreement with previous studies on other species. Further, a negative correlation was found between vessel surface area and GSI level. Vessel frequency was also decreasing with the increasing GSI level and proportion of G-fibers.

Keywords Beech · G-fiber · Growth stress · Thinning

Introduction

In contrast with the majority of man-made structures, tree stems exhibit a complex field of internal stresses resulting from the growth process (Kubler 1987). These so-called growth stresses result from an overlap of two components: accumulation of support stresses and maturation stresses. Gradual increase in crown weight induce compression stress (Spatz and Brüchert 2000) while the maturation of the newly formed wood layer lead to the tensile pre-stresses called maturation stress (Fournier et al. 1990). Maturation stresses appear after cell lignification. During the maturation of the newly formed wood, the cells, which grow every year on the stem periphery, contract longitudinally while the lignified wood cells already formed impede this contraction.

Pre-stresses are useful for living trees, since they improve the mechanical resistance of the stem against temporary bending loads. Wood has a high-tensile strength parallel to fiber direction but is relatively weak in compression. When wood is subjected to local axial compression, axial buckling can be avoided by tensile pre-stresses (Bonser and Ennos 1998). Tensile pre-stresses at the tree periphery therefore compensate the relatively low compressive strength of green wood. Pre-stresses are also important for the tree postural control. Its asymmetrical distribution around the tree circumference provides a motor system allowing the postural control of the tree and the stems and branches reorientation.

Trees control the spatial position of their axes (stem or branches) by generation of asymmetrical stress (Fournier et al. 1994; Clair et al. 2013). Asymmetry of maturation stresses induces a bending moment which maintains (growing branches) or corrects (accidentally tilted stem) the spatial position of axes (Alméras et al. 2006). To

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achieve an important bending moment, trees are pushed to produce an unusual level of maturation stresses. Tissues with the unusual level of maturation stresses is called reaction wood. Occurrence of reaction wood is most often associated with branches or tilted trees; however, it is also frequently reported in straight stems in a number of species including Beech (Gartner 1997; Washusen et al. 2003; Jullien et al. 2013).

Motor processes of posture control differs between deciduous trees and conifers. While deciduous trees generate highly tensile stressed tissues called tension wood on the upper side of leaning axes, conifers produce so called compression wood on the lower side of leaning axes (Yoshida et al. 2002; Clair et al. 2003; Fang et al. 2008; Abasolo et al. 2009). Apart from the high levels of maturation stresses, tension wood presents some distinctive physical and anatomical features when compared to 'normal wood' (IAWA 1964). Tension wood has high longitudinal shrinkage, wider rings, low lignin, wider cellulose crystallite and high crystallinity (Ruelle et al. 2007; Mellerowicz and Gorshkova 2012; Washusen and Evans 2001).

In many species of hardwoods such as beech, poplar, oak and chestnut, tension wood contains fibers with a special morphology and chemical composition due to the development of gelatinous layer (Clair et al. 2006, 2010; Fang et al. 2008). This layer usually used as a tool to identify the presence of tension wood in hardwoods. However, this layer is not always observed in the tension wood of some species (Clair et al. 2006). Gelatinous layer has a jelly-like appearance with low MFA (Washusen and Evans 2001; Ruelle et al. 2007), high mesoporosity (Chang et al. 2009), high crystalline cellulose, and low lignin content (Mellerowicz and Gorshkova 2012).

Previous reports have shown that in chestnut and poplar there is a significant relationship between the proportion of the gelatinous layer and growth stresses. The higher the proportion of the gelatinous layer in tension wood, the higher the growth stress in trees. It indicates that the amount of G-layer largely controls the stress level in trees (Fang et al. 2008; Clair et al. 2003; Dassot et al. 2012). Besides the G-layer, a decrease in the frequency of vessels in tension wood was reported by Ruelle et al. (2006) in 21 tropical tree species and by Jourez et al. (2001) for poplar.

It is well known that silvicultural treatments such as thinning affect the tree morphology. Thinning tends indeed to reduce height growth and stimulates diameter growth which is in general explained by the increased post-thinning wind loads (Evans and Jackson 1972; Mitchell 2000) as thinning will open the canopy, increase the canopy roughness, decrease the sheltering effects from surrounding trees and increase the tree exposure to wind (Zhu et al. 2003). This will lead to higher stress to the stem and may

stimulate the tension wood production. However, thinning was reported to improve the tree stability by long-term effects on growth and development of trees (Polge 1981; Ferrand 1982). Some research shows that higher spacing of trees seems to be a good solution to lower the level of growth stress in beech stands and heavy thinning are to be made to reduce growth stresses in beech stands (Polge 1981; Jullien et al. 2013) while some others did not found any effect of thinning treatment or tree spacing (Dassot et al. 2012; Valencia et al. 2011).

In this paper, we focus on the effects of canopy opening on (i) the growth stresses level and intensity of reaction on the tree stem circumference and (ii) on the relationship between growth stress level and anatomical features such as G-fibers proportion and vessels characteristics.

Materials and methods

Site location and tree selection

Trees for the present study were harvested in Grand Poiremont, Haute Saône, France from stands with natural regeneration forest consisting of beech, oak, spruce, maple, and birch. Stands are located at altitude of 470 meters above sea level with 1218 mm rainfall (ONF 2014). Forty-two beech poles aged from 60 to 100 years were used for the study, with diameters ranging from 9.5 to 20.9 cm and heights from 11 to 25 m. Half of them was released from the competition 6 years before harvesting while the other half continued to growth in high competition. Releasing from the competition was done by removal of all competitor trees in a radius of 12 m from the released pole. One of released poles has buckled so that only twenty treated poles are considered in the following analysis.

Growth stress measurement and modeling the distribution of GSI

Stresses growth indicators were measured using the single hole method (Fournier et al. 1994). This method consists in measuring the displacement of two pins (initial distance is 4.5 cm) caused by the stress release after a 2 cm hole has been drilled between the pins. Outer layer up to the cambial layer is removed before the measurement. Two pins are fixed in a stem along the fiber direction using a template. A frame equipped with a micrometer is then mounted on the pins and the micrometer is set to zero. A 10 mm deep hole is drilled between the pins to release the stress leading to displacement of the two pins recorded by the micrometer. This displacement expressed in μm is called growth stress indicator (GSI) and is directly proportional to longitudinal growth stress at the trunk periphery, the conversion factor

depending on each species mechanical properties (Sassus 1998). As such, values of GSI are good indicators of the relative growth stresses level for intraspecific comparison (Clair et al. 2003).

The GSI measurements were done at the 1.3 m height at eight positions equally distributed around the stem circumference (Fig. 1). The objective was to characterize the distribution of the GSI and determine the location of tension wood. The first measurement was done at the upper side of the tree at position of maximal tilt angle estimated with an inclinometer prior to the GSI measurements. The azimuth of the first GSI point was also measured. Measurements were conducted in February–March 2014 before the beginning of the growth season.

As the first position is expected to correspond to tension wood, the distribution of GSI around the stem circumference was described by a cosine function:

$$y = A + B \cos(\theta + \pi)$$

where A is the average value of GSI, B is the difference between the maximal and minimal value of GSI divided by two or the magnitude of GSI asymmetry (intensity of reaction), and θ is the angular difference between the position of the GSI peak as estimated from the tilt measurement and the position of the estimated maximal value. Estimation of the θ value is important for further measurements of the tension wood properties. An example of the distribution of the GSI around the trunk circumference and its modelled values are shown in Fig. 1.

Anatomical measurements

Selection of samples

After the measurement of GSI, trees were felled and a 5 cm thick disc was collected at the breast height. Specimens for the anatomical measurements were selected based on the

histogram of all the GSI values recorded. The aim was to cover the complete range of GSI observed in beech poles. GSI values were classified in 14 classes. When possible, 3 thinned and 3 control trees were chosen from each class, and all specimens were used in GSI classes with frequency lower than six. In total, 64 specimens were used for anatomical observations.

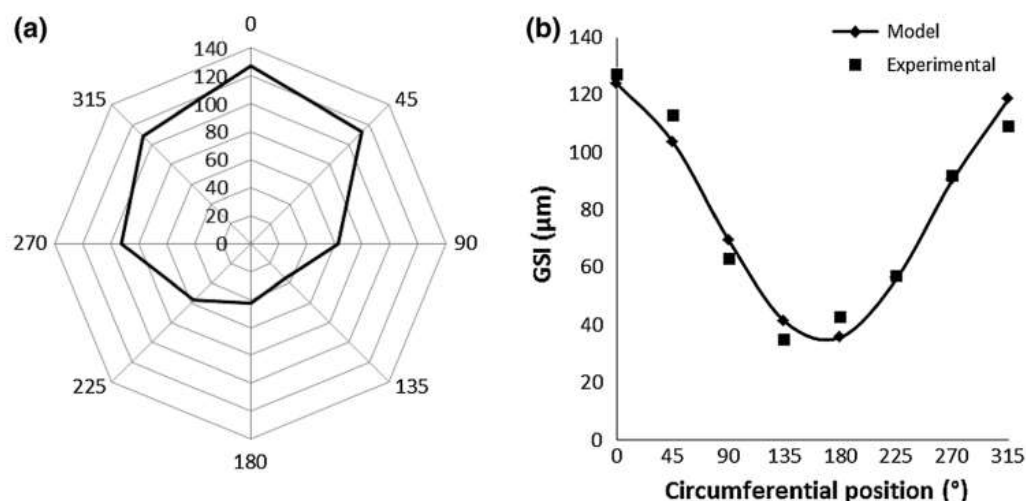
Proportion of G-fibers

To characterize the anatomical structure as close as possible to the GSI measurements, small blocks of (0.5 cm × 1.5 cm; R × T) were extracted from the disk. Cross sections approximately 20 μm thick were cut with a microtome and double-stained with safranin and blueastrato highlight the presence of the G-layer in blue as illustrated in Fig. 2b. To determine the proportion of fibers with G-layer i.e., G-fibers, one single image was taken of each sample covering the whole sample surface. Image capture was performed using a digital camera (Sony XCD-U100CR). Image-J software was then used to quantify the area occupied by G-fibers in the section. The algorithm was developed by Badia et al. (2005) and is based on the subtraction of the red component of the image from the blue one. This operation enhances the distinction between G-fibers and other tissues. A common threshold was then used to separate them. The percentage of G-fibers value was deduced without ambiguity from histograms where pixels were identified as belonging to G-fibers and other tissues.

Vessel anatomical characteristics

The samples used were the same sample for proportion of G-fiber but images were taken at a magnification 5× to enable finer analysis of the vessel morphology. Seven photos were taken at 7 different positions distributed

Fig. 1 **a** Distribution of GSI around the stem circumference, position from 0° to 315° indicate the position of GSI measurements, **b** example of the correspondence between the cosine model and experimental values



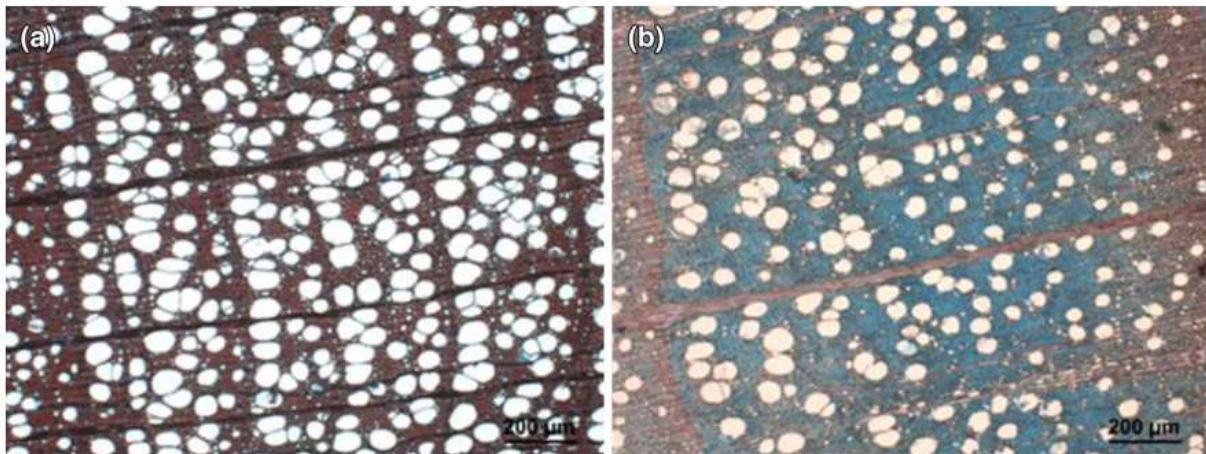


Fig. 2 **a** Transverse sections of wood without G-fibers, **b** transverse sections of wood with G-fibers

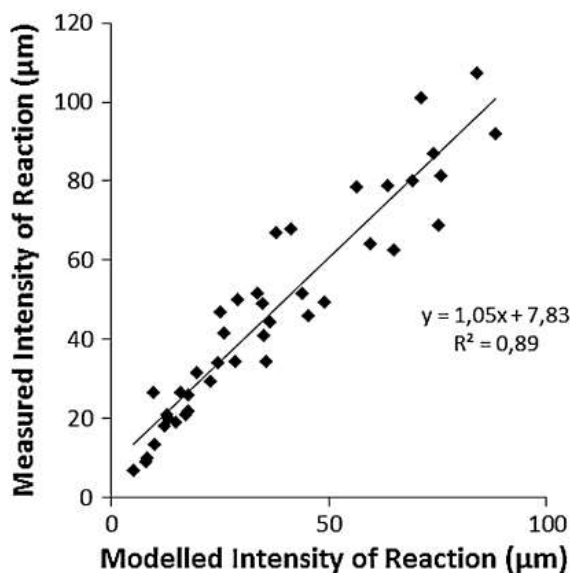


Fig. 3 Agreement between measured and modelled intensity of reaction

evenly on each sample. Proportion of vessel was calculated as total vessel area/total surface of image. Vessels radius and vessel frequency were also calculated to estimate the hydraulic performances of wood tissues.

Results and discussion

Suitability of the cosine model to describe the GSI distribution around the stem circumference

Concerning the agreement between the modeled and experimental values of average GSI (A) and the intensity of reaction (B), the A parameter (modelled) is exactly the average GSI (A measured). The agreement is very good for B values (Fig. 3), showing that globally, a cosine model

using three parameters i.e., the average GSI, the difference between maximum and minimum GSI, the azimuth (angle) of the tension wood peak—fits well the experimental data (average $R^2 = 0.64$).

Effect of thinning to GSI distribution

To know whether there is a difference in GSI distribution between thinned and control trees, we compared the average GSI and intensity of reaction in both treatments. Figure 4 shows that there is no statistical difference in GSI average and intensity of reaction wood between thinned and control trees.

Our results show that there is no effect of thinning on the GSI average value and their intensity of reaction. Previous studies concerning this subject show contrasting tendencies. On one hand Polge (1981) found that heavy thinning reduced growth stresses in 35-year-old beech trees that had been thinned 3 times since seedlings. Another report by Jullien et al. (2013) confirms these results. It shows that higher spacing between trees induced higher growth rates related to lower growth stresses. On the other hand, Dassot et al. (2012) studied the tension wood occurrence in spacing trial and highlighted a strong effect of diameter range of trees on the production of tension wood but no additional effect of the tree spacing. Further, Medhurst et al. (2011) showed increase in average value of GSI in 22 years old *E. nitens* trees 16 years after thinning as well as increase of the average GSI value on the wind side of trees similarly to Valencia et al. (2011). Also report by Washusen et al. (2005) suggests increase in tension wood occurrence 4 years after thinning of *E. globulus* trees, 12 years old during tree collection, based on the observation of increased cellulose crystallite width.

The lack of changes in the GSI distribution in our poles may be related to their high age. We can expect that 60–100 years old poles may react differently to the canopy

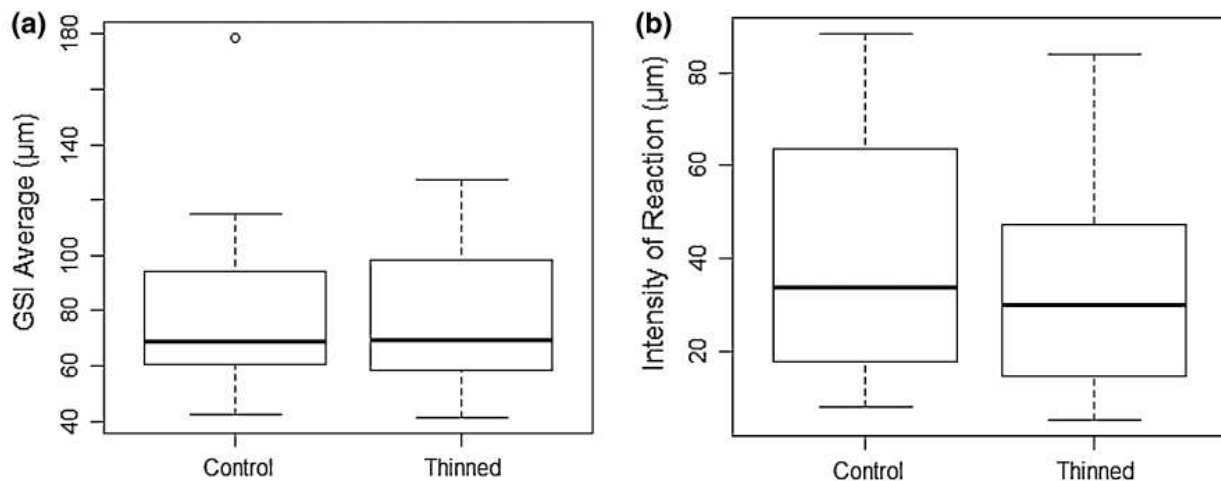


Fig. 4 **a** Average GSI between control and thinned trees, **b** intensity of reaction between control and thinned trees

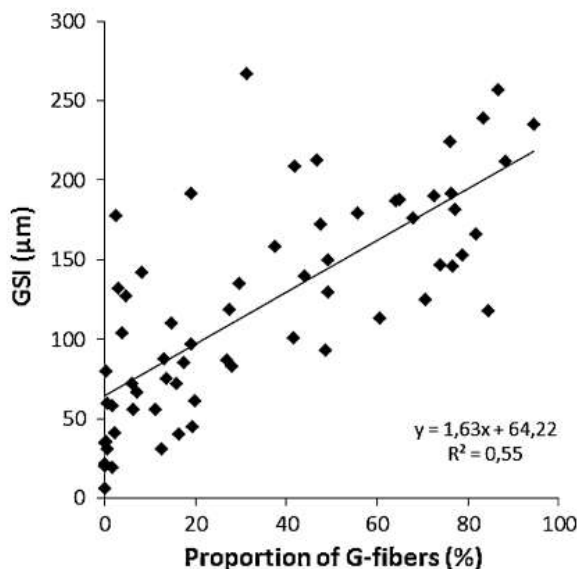


Fig. 5 Relationship between proportion of G-fibers and GSI

opening when compared with young trees. Another possible explanation is related to the social status of our trees. As suppressed trees, the poles may need to often reorient their stems in order to benefit from each light pocket compared to well establish dominant trees leading to quite high tension wood occurrence before thinning. Therefore, in our situation, thinning is not a high stimulus of reorientation leading to higher intensity of reaction nor a release of biomechanical constraints associated to GSI decreasing.

Relationship between GSI and anatomical features

Proportion of G-fibers and GSI

The proportion of G-fibers is plotted against GSI in Fig. 5. It shows a positive relationship between the two variables. Larger the G-fibers proportion, higher the GSI value is.

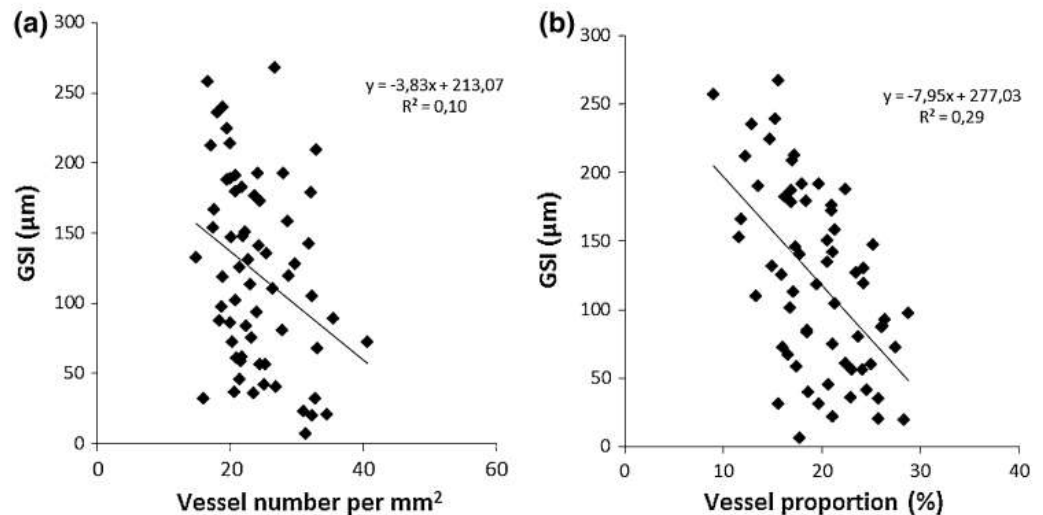
Such a result was expected, as maturation tensile stresses are known to reach extreme levels in pure cellulosic G-fibers (Clair et al. 2003). Similar correlations were reported for example by Fang et al. (2008). However, the R^2 value reported by Fang et al. (2008) is 0.716 which is slightly higher than the value reported in this study (0.533). This difference can be explained by the differences between the methods of GSI measurements: Fang et al. (2008) used the strain gauge method which is a more localized measure. Results show also that a high variability of GSI, (from 0 to 180), is observed when no tension wood (almost no G-fibers, proportion below 5 %) is observed. Such variations demonstrate that as previous authors emphasized (Clair et al. 2003), other features that typical G-layers, probably at the cell wall level, can lead to high intensity of reaction and tree reaction, even without typical tension wood.

Effect of GSI on vessel proportion and vessel frequency

Figure 6a shows the relationship between GSI and vessel proportion. The result indicates a negative correlation between vessel proportion and GSI. Larger the GSI values, lower the vessel proportion is. Relationship between GSI and vessels frequency is shown in Fig. 6b. It shows a slight negative relation between both variables.

Our result shows that vessel proportion decreases when GSI increase. Vessel frequency is also decreasing with the increase of GSI and the proportion of G-fibers. No relation was found between size of vessels and GSI or proportion of G-fibers. It suggests that lower vessel proportion is due to a lower vessel frequency and not to a change in size of the vessel elements. These results are consistent with research by Jourez et al. (2001) who found the vessel elements decreasing in frequency in tension wood of poplar. A decreasing in the frequency of vessel in tension wood was

Fig. 6 **a** Relationship between vessel frequency and GSI, **b** relationship between vessel proportion and GSI



found also by Ruelle et al. (2006) in 21 tropical trees. Christensen-Dalsgaard et al. (2007) study the changes in vessel anatomy in response to mechanical loading in six species of tropical tree. She found that the smallest vessels and the smallest vessel frequency were found in the parts of the trees with the greatest stresses or strains. These changes appear to be an adaptation towards reinforcing mechanically loaded areas.

Conclusion

Thinning treatment did not affect the GSI average values and intensity of reaction in old beech poles. This rather unexpected result may be related to the high age of these trees and long growth period in suppressed condition. Considering the relationship between the proportions of G-fibers and the level of GSI, a significant positive correlation was found in agreement with previous studies on other species. Further, a negative correlation was found between vessel proportion and GSI level, mainly due to decrease in vessel frequency.


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Appendix D - Contract for the purchase of firewood (roundwood)

Agence de Metz UT de Albestroff Sarralbe Triage de Bénestroff	 Office National des Forêts DT Lorraine	Forêt Domaniale de Bénestroff Exercice 2017
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CONTRAT DE VENTE DE BOIS DE CHAUFFAGE A LA MESURE CLAUSES PARTICULIERES

Entre l'Office National des Forêts, représenté par Mme MENDOW Nancy , Agent Patrimonial
Adresse : Maison Forestière de Wuisse - 57170 - WUISSE
Tél. : 0616426554 Mail : nancy.mendow@onf.fr
en sa qualité de **vendeur** qu'il détient en application de l'art. L 214-6 du code forestier, ci-après dénommé l'ONF
d'une part,

Et INRA Nancy
Adresse : Route d'Amance - 54280 CHAMPENOUX
Tél. : Mail :
ci-après dénommé « le **cessionnaire** »,
d'autre part,

Article 1 : Cadre de la vente -

Le présent contrat constitue le formulaire de vente prévu à l'art. 3 des clauses générales des ventes de bois aux particuliers ci-joint. Il contient les clauses particulières qui viennent en complément à ces clauses générales et au règlement National d'Exploitation Forestière. Il **vaut, après signature des deux parties, permis d'exploiter** tel que prévu par le Code forestier.

Article 2 : Objet de la vente -

La présente vente porte sur une coupe de bois et/ou de produits de cette coupe, préalablement désignés par l'ONF. S'agissant d'une **vente à la mesure**, le prix total de la vente sera fixé après le dénombrement des bois.

Lot n° :	Désignation des produits :	Billons de hêtre et de chêne
Parcelles :	13	
Volume présumé : (à titre indicatif)	10	mètres cubes apparents de référence (Stères)
Prix unitaire TTC :	gratuit	€ / mètre cube apparent de référence (Stères)

Article 3 : Destination du produit vendu -

La présente vente de bois est consentie en vue de **satisfaire exclusivement au chauffage du domicile personnel** du bénéficiaire. Celui-ci s'engage par la signature du contrat à ne donner que cet usage au bois vendu. Il déclare ne pas bénéficier par ailleurs de bois dans le cadre de cessions ou affouages pour la même saison d'exploitation. Tout autre usage ou **toute revente est interdit** et pourra être considéré comme un détournement au préjudice du vendeur de bien pour un autre usage que celui en vue duquel il a été vendu (code pénal), ou comme l'exercice d'actes de commerce clandestins (code du travail).

Article 4 : Conditions de l'exploitation et de l'enlèvement -

L'exploitation et l'enlèvement seront effectués suivant les présentes clauses particulières et les directives qui pourront être données par l'agent patrimonial. Ils seront faits dans les limites du lot indiquées par celui-ci et dûment reconnues par le cessionnaire. Le cessionnaire est tenu d'exploiter tout son lot. L'exploitation de tiges non désignées fera l'objet de poursuites pénales conformément au code forestier.

SECURITE

Il est **fortement conseillé** au cessionnaire de porter les **équipements de protection individuels** précisés aux clauses générales de vente.

Point de rencontre avec les secours :	EGLISE DE BENESTROFF
N° d'appel par portable : 112 ou 18	

PERIODES D'EXPLOITATION ET D'ENLEVEMENT DES BOIS

L'exploitation et le débardage sont interdits :

- les jours de chasse collective inscrits au calendrier,
 - en cas de conditions météorologiques défavorables, notamment les jours de grand vent.
- Par dérogation aux clauses générales de ventes de bois aux particuliers :

Travail le dimanche :	Interdit
Travail les jours fériés :	Interdit
Périodes interdites, observations : A compléter par l'agent patrimonial	<input checked="" type="checkbox"/> Sol sensible au tassement : si coché, classe PROSOL : 3-très sensible non praticable une pie de l'année Le cessionnaire doit utiliser du matériel adapté à ces conditions et limiter l'impact de son activité sur les sols.

DELAIS

Abattage, façonnage, enstérage : A compléter par l'agent patrimonial	30 Mars 2017
Débardage et enlèvement des bois : A compléter par l'agent patrimonial	31 Août 2017 sous conditions de portance du sol

MODE DE DESIGNATION DES BOIS A EXPLOITER

Mode de désignation des bois : A compléter par l'agent patrimonial	Hêtres et chênes désignés par l'Agent
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L'exploitation des bois non désignés fera l'objet de poursuites pénales conformément au code forestier.

TRAITEMENT DES REMANENTS

Les rémanents recèlent la majorité de la richesse minérale de l'arbre et doivent être laissés en forêt pour préserver la fertilité des sols. Ils seront dispersés sur coupe au fur et à mesure de l'exploitation, hors des taches de semis et en dehors des trouées. Il est interdit de les brûler. Les **branches de moins de 7 cm de diamètre sont des rémanents et ne devront en aucun cas être enlevées.**

PRESENCE DE CLOISONNEMENTS D'EXPLOITATION, COURS D'EAU ET D'EQUIPEMENTS PARTICULIERS, AUTRES CONSIGNES PARTICULIERES

Présence de cloisonnements d'exploitation - Si oui, équidistance : 36 m Obligation de maintenir les tracteurs et fendeuse si autorisé exclusivement sur les cloisonnements d'exploitation existant. Le non respect de ces clauses est passible de sanction de 5ème classe (1500 €).	Non
Présence d'un cours d'eau ou autre zone humide : (leur franchissement ou l'abattage de tiges vers ceux-ci est interdit en application du code de l'environnement) Si oui précisions :	Non

Présence d'un équipement particulier : (bornes, lignes électriques, canalisations, patrimoine culturel, vestiges archéo...)	Nature de l'équipement :
Utilisation d'une fendeuse :	Autorisé sur sol portant
Autres consignes particulières : A compléter par l'Agent patrimonial	

Article 5 : Dénombrement -

La date pour le dénombrement sera fixée par l'ONF ou le représentant du propriétaire. Les résultats en seront opposables au cessionnaire en cas d'absence de celui-ci.

Article 6 : Enlèvement -

Les produits ne pourront être enlevés **qu'après remise du permis d'enlever par l'ONF** qui sera effectuée au vu de la preuve du paiement. Tout enlèvement effectué avant la délivrance du permis donnera lieu aux sanctions prévues par le code forestier.

Pour l'Office National des Forêts,

L'agent patrimonial (date et signature) 11/03/2017

Le cessionnaire (date et signature)

PERMIS D'ENLEVER	
Vu le certificat de paiement remis, le cessionnaire est autorisé à enlever le volume ci-dessous de son lot :	
	m3 apparents de référence (Stères)
L'agent patrimonial (date et signature)	

CLAUSES GÉNÉRALES DES VENTES DE BOIS AUX PARTICULIERS (Document 9200-11-CCG-BOI-005 vC 05/14)

Chapitre 1 : CADRE JURIDIQUE

Article 1 - Champ d'application

Les présentes clauses générales sont applicables à tout contrat de vente de bois provenant de forêts relevant du régime forestier et conclu à la diligence de l'ONF avec un particulier, dénommé "cessionnaire" dans la suite des présentes clauses.

Article 2 - Cadre légal et réglementaire

Les ventes de bois aux particuliers sont régies par l'article R. 213-69 du code forestier, relatif aux cessions de produits accessoires, et par ses articles L. 213-12 à 15, L. 261-4 et S. R. 213-39 et R. 261-3 à 7, s'agissant de l'exploitation et de l'enlèvement des bois.

Article 3 - Opposabilité et organisation des pièces contractuelles

Les présentes clauses générales, les clauses particulières et le formulaire de vente forment le contrat de vente. Celui-ci s'impose au cessionnaire ainsi qu'à toute personne travaillant pour son compte. Le règlement national d'exploitation forestière (RNEF) est également opposable à tout cessionnaire, dès lors qu'il présente en forêt pour exploiter ou enlever des bois. Le RNEF est consultable et téléchargeable sur le site internet de l'ONF à l'adresse <http://www.onf.fr>, ainsi qu'après de l'agent de l'ONF. Le cessionnaire déclare en avoir pris connaissance et l'accepter. Il appartient au cessionnaire de s'assurer du respect intégral des dispositions du RNEF, par toute personne intervenant en forêt pour son compte ou de son fait.

Chapitre 2 : FORMATION DU CONTRAT ET PARTIES CONTRACTANTES

Article 4 - Formation du contrat

La vente de bois aux particuliers se fait par le biais d'un contrat de vente écrit, passé de gré à gré et signé des deux parties.

Article 5 - Les parties contractantes

Le contrat de vente est passé et conclu entre l'ONF et le cessionnaire.

L'ONF ne vend des bois aux particuliers que pour leurs besoins domestiques locaux. Il se fixe les conditions de cession, notamment le prix et les conditions d'exploitation et d'enlèvement. Si les bois proviennent de forêts des collectivités ou d'autres personnes morales, l'ONF doit avoir recueilli préalablement l'accord du propriétaire sur le principe de la vente et sur le prix avant d'y procéder. Le cessionnaire est une personne physique résidant à proximité de la forêt d'où provient le bois. Les produits achetés sont destinés à son usage strictement personnel. La vente est donc formellement insaisissable.

Chapitre 3 : PRODUITS VENDUS, TRANSFERT DE PROPRIÉTÉ ET DES RISQUES

Article 6 - Qualifications des produits vendus

Les produits, originaires de forêts relevant du régime forestier, sont des bois vendus sur pied ou façonnés, à la mesure ou en bloc.

La quantité par cessionnaire est limitée à ses besoins domestiques sans pouvoir excéder 30 m³ par foyer et par an en volume apparent de référence, ce dernier correspondant au volume de bois contenu dans un cube de 1 m x 1 m x 1 m et pour des bois de coupes en billes de 1 mètre, bles empilés.

Les bois vendus sur pied sont exclusivement des perches, petits bois et houppiers. Les bois vendus sur pied à la mesure sont destinés par le cessionnaire en longueur fixe définie puis sont réceptionnés et cubés par l'ONF ou le propriétaire. Les bois vendus façonnés sont cubés par l'ONF ou le propriétaire.

Le cessionnaire déclare connaître le lot qu'il achète, pour l'avoir visité et estimé.

Article 7 - Transfert de propriété et des risques

Le transfert de propriété intervient :

- Pour les ventes à la mesure, à l'issue du démontrement ;
- Pour les ventes en bloc, dès la signature du contrat.

Le cessionnaire déclare disposer en permanence d'une assurance couvrant sa responsabilité civile personnelle, l'attestation correspondante devant pouvoir être fournie à toute demande de l'ONF.

L'ONF et le propriétaire forestier ne peuvent être tenus pour responsables des accidents qui surviendraient au cours de l'exploitation et de l'enlèvement des bois. Le cessionnaire déclare être seul responsable, pour lui-même et pour toute personne intervenant en forêt pour son compte ou de son fait des dommages provoqués par le chute des bois dont il doit effectuer l'exploitation ou l'enlèvement, de paiement des restitutions, dommages et intérêts, pour tout préjudice provoqué en forêt.

Le cessionnaire est responsable des infractions commises à l'occasion de l'exploitation et de l'enlèvement des bois dans les conditions prévues par le code forestier.

Chapitre 4 : EXPLOITATION ET ENLÈVEMENT DES BOIS

Article 8 - Conditions générales d'exploitation et de l'enlèvement des bois

Le permis d'exploiter et le permis d'enlever sont délivrés par l'agent de l'ONF. Le cessionnaire ne peut commencer l'exploitation des bois avant d'en avoir obtenu par écrit le permis d'exploiter. La remise de ce permis marque le point de départ de sa responsabilité. Il devient gardien des bois au sens de l'article 1384 du Code civil.

Le cessionnaire ne peut enlever les bois qu'après obtention du permis d'enlever, pour les bois vendus à la mesure.

Les modalités de mise à disposition des bois sont les suivantes :

	Vente de bois sur pied	Vente de bois façonné
En bloc	Permis d'exploiter : sur présentation du certificat de paiement *	Permis d'enlever : sur présentation du certificat de paiement *
A la mesure	Permis d'exploiter : à la signature du contrat Permis d'enlever : sur présentation du certificat de paiement, après démontrement	Permis d'enlever : sur présentation du certificat de paiement, après démontrement

* Le certificat de paiement n'est délivré par le comptable de la vente qu'après encaissement réel du montant de la vente, sauf pour des lots exceptionnels de moins de 1.000 € TTC vendus à des clients habituels et à jour de leurs paiements antérieurs.

Le cessionnaire, ou toute personne intervenant en forêt pour son compte ou de son fait, doit constamment être porteur du contrat de vente correspondant, avec mention du (des) permis délivré(s) et des présentes clauses générales. Il lui est interdit à tout moment, y compris pour l'enlèvement des produits. Toute intervention est interdite le dimanche et jours fériés, ainsi que par temps de nuit sauf autorisation prévue par le contrat de vente. D'autres périodes d'interdiction peuvent être prévues par l'ONF aux clauses particulières du contrat de vente.

Article 9 - Sécurité et responsabilité du cessionnaire

Toute intervention en forêt, pour exploiter les bois avec organisation d'un chantier d'exploitation, ou simplement pour enlever les bois, est de l'entière responsabilité du cessionnaire. Le cessionnaire déclare avoir connaissance des consignes de sécurité.

Article 10 - Organisation de l'exploitation

L'abattage et le façonnage de tiges non désignées pour être exploitées (tiges réservées, arbres bio...) sont interdits ; l'abattage et le façonnage des bois désignés peuvent se faire avec des outils à moteur (tronçonneuse...), uniquement s'ils utilisent des biolubrifiants.

Les souches doivent être coupées ras de terre, leur hauteur au sol devant être inférieure à 8 cm. Les bois seront essorés hors des taches de semis, en bordure des chemins, et en aucun cas contre les arbres.

Pour toute vente à la mesure, le démontrement des bois a lieu à la date fixée par l'agent de l'ONF ou par le propriétaire ou son représentant.

Article 11 - Organisation de l'enlèvement des bois

Le débarras se fera uniquement par les chemins et cloisonnements existants et si les conditions climatiques le permettent (soit généralement hors temps de pluie, soit détrempé et temps de dégel).

Article 12 - Délais

Sauf mention contraire aux clauses particulières, les délais d'exploitation et d'enlèvement sont les suivants :

	Vente de bois sur pied	Vente de bois façonné
En bloc	4 mois pour exploiter et enlever les bois, à partir de la délivrance du permis d'exploiter	1 mois pour enlever les bois, à compter de la délivrance du permis d'enlever
A la mesure	4 mois pour exploiter les bois, à compter de la délivrance du permis d'exploiter, puis 1 mois pour les enlever à partir du permis d'enlever	1 mois pour enlever les bois, à compter de la délivrance du permis d'enlever

Parmi ces délais, le contrat de vente est rédigé de plein droit. Les bois restant sur coupe sont alors considérés abandonnés par le cessionnaire et l'ONF ou la collectivité propriétaire peut en disposer librement. Le paiement du prix de vente par le cessionnaire reste cependant acquis à l'ONF ou à la collectivité propriétaire.

L'agent de l'ONF peut également fixer des délais plus détaillés, par phase (abattage, débarras...), aux clauses particulières du contrat.

Article 13 - Remise en état des lieux

Les lieux doivent être remis en état par le cessionnaire dès la fin de l'enlèvement des bois, ou à défaut à l'arrêt de son intervention en forêt, selon les directives de l'agent de l'ONF. Aucun déchet d'origine artificielle (papiers, bidons, bouteilles...) ne doit subsister sur le parterre du lot, ni se trouver à l'extérieur des limites de parcelles.

Sauf mention contraire aux clauses particulières, les résidus seront éparpillés au sol, hors des taches de semis et des trouées.

Il est interdit de les brûler.

Chapitre 5 : CONDITIONS FINANCIÈRES

Article 14 - Prix de cession

Le prix de vente s'entend TVA incluse.

Pour les ventes à la mesure, le prix n'est fixé définitivement qu'après le démontrement des bois. Le prix figurant au sein du contrat de vente n'est qu'un prix indicatif. Il est défini en m³ apparent (sa référence) ou en m³ plein, un m³ apparent de bois correspondant à 1 m³ d'enlèvement de bois coupé en longueur de 1 m. Quand les bois sont découpés en longueur inférieure à 1 m, 1 m³ d'enlèvement représente plus que 1 m³ apparent, les coefficients de conversion sont les suivants :

Longueur de bûche	1 m	50 cm	40 cm	33 cm	25 cm
Nombre de m ³ apparent par m ³ d'enlèvement	1	1,25	1,36	1,43	1,67

Pour les ventes en bloc, le prix est fixé définitivement dès la signature du contrat. Comme les bois sont vendus sans garantie de quantité, on n'est qu'à titre purement indicatif et non contractuel que le volume approximatif estimé en tonnes.

Article 15 - Modalités de paiement

Le paiement des bois est effectué au comptant, auprès de l'agent de l'ONF en forme domaniale, et auprès du comptable local ou de son mandataire (à l'exclusion de tout agent ONP) dans les forêts des collectivités et autres forêts relevant du régime forestier.

Pour toute vente de produits domaniaux, un paiement par chèque émis à l'ordre de l'ONF est exigé sauf cas exceptionnel.

Chapitre 6 : SANCTIONS, PÉNALITÉS, RÈGLEMENT DES LITIGES

Article 16 - Sanctions et pénalités

Le non respect des présentes clauses générales, des clauses particulières propres à la vente, ainsi que du règlement national d'exploitation forestière, pour lequel aucune pénalité n'est prévue par le code forestier, est sanctionné d'une pénalité de 50 euros TTC redevable envers l'ONF.

De plus, le cessionnaire est tenu à la réparation du préjudice éventuel résultant de ce non respect, notamment en cas de dommage à la forêt. Enfin, le cessionnaire est redevable envers le propriétaire de la forêt du montant évalué par l'agent de l'ONF des travaux de remise en état des lieux relatifs à la réalisation, si ceux-ci n'ont pas été effectués à la date limite de l'exploitation et du débarras ou à la réalisation du contrat.

Le cessionnaire qui aurait causé des dommages non réparés à l'environnement, ou qui aurait gravement enfreint aux règles de sécurité, ou qui aurait fait commerce du bois acheté, outre la possibilité de poursuites judiciaires, ne sera pas admis à procéder à de nouveaux achats.

Article 17 - Règlement des litiges

Pour tous les litiges susceptibles de s'élever à l'occasion de l'exécution du contrat de vente, les tribunaux judiciaires français sont seuls compétents. Le tribunal territorialement compétent est celui du lieu de formation du contrat de vente.

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Résumé élargi de la thèse

Résumé élargi de la thèse

Introduction général

Les feuillus dominant à la fois la superficie forestière et le volume de bois sur pied des forêts françaises. Deux essences de feuillus, le chêne et le hêtre, représentent à elles-seules 42 % du total volume de bois sur pied en France, qui comprend à la fois des essences feuillues et résineux. (IGN, 2016). En revanche, la récolte de bois d'œuvre et la production de sciages sont dominées par le bois résineux en raison du manque de pratiques éprouvées et d'informations à grande échelle sur la qualité du bois feuillus (Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt, 2016; Ministère de l'Agriculture et de l'Alimentation, 2017). D'autre part, le nouveau système d'aménagement forestier avec la sylviculture intensive tend à produire des feuillus de qualité secondaire qui ne peuvent être utilisés directement comme matériau de construction car ils contiennent une forte proportion de défauts (Croisel and Collet, 2016; Luppold and Bumgardner, 2003).

Comparé au bois résineux, les feuillus présentent une proportion de tiges plus faible. Par exemple, la proportion de tiges pour l'épicéa est d'environ 90 % alors que celle des hêtres n'est que d'environ 50 % (Pöhler et al. 2006). De plus la présence de cœur rouge sur le hêtre entraîne une dévalorisation très importante de son bois (Huss and Manning 2003; Petrás et al. 2016).

Le chêne de haute qualité est facile à travailler mais relativement difficile à trouver (Croisel and Collet, 2016). Le bois rond de première qualité est généralement utilisé comme matière première pour le tranchage et déroulage tandis qu'une partie du bois de la qualité secondaire peut être utilisée pour le sciage et le reste pour le bois d'industrie et bois énergie. Il est indéniable que les ressources en bois feuillus sont dominées par le bois de qualité secondaire (Luppold and Bumgardner 2003). De plus, en raison de l'atténuation des risques climatiques et de la demande du marché pour les bois d'industrie et le bois énergie, nous constatons une tendance à récolter des arbres beaucoup plus jeunes que le passé et une augmentation de l'utilisation de petits arbres qui sont prélevés en éclaircie.

Pour la production de bois destiné à des applications structurelles, les dimensions disponibles, la stabilité dimensionnelle et les performances mécaniques sont des paramètres très importants pour assurer de bonnes performances et de la sécurité. Ces paramètres sont liés aux structures au niveau cellulaire qui sont influencées par des facteurs internes tels que la génétique et des facteurs externes tels que les caractéristiques du terrain et les méthodes sylvicoles (Macdonald and Hubert, 2002). Pendant le développement des peuplements, le nombre d'arbres par hectare est réduit afin de fournir plus d'espace, de nutriments, d'eau et de lumière aux arbres qui ont un fort potentiel. Cette opération, appelée éclaircie, entraîne l'abattage d'un grand nombre d'arbres jeunes et de petits diamètres qui contiennent une forte proportion de bois juvénile et de bois de tension.

La présence de nombreux défauts du bois tels que les nœuds, la déviation du fil du bois, le bois juvénile et le bois de réaction restreint l'utilisation des feuillus de qualité secondaire en tant que matériau structurel. Une meilleure compréhension des variations de propriétés du

bois est importante afin de mieux valoriser les feuillus de petit diamètre qui sont soumis à une forte compétition (arbre dominé). Les variations liées à la maturité du bois de certains paramètres, comme la densité, affectent les propriétés mécaniques du bois. Cependant, ces propriétés mécaniques du bois ne sont pas contrôlées uniquement par la densité du bois. Une autre caractéristique structurale importante du bois qui influe sur les propriétés mécaniques du bois est l'angle de micro-fibrilles (MFA). En général, la rigidité et la résistance du bois diminuent avec l'augmentation de l'AMF (Evans and Ilic 2001; McLean et al. 2010).

La valorisation de cette ressource en tant que matériau structurel nécessite une amélioration de ses propriétés mécaniques par la reconstitution en produits d'ingénierie bois tel que le LVL (Laminated Veneer Lumber ou Lamibois). Le LVL est fabriqué à partir de placages déroulés et collés avec le fil orienté principalement en parallèle avec la longueur du panneau. Le LVL est généralement utilisé pour des applications structurelles et non structurelles telles que les revêtements de sol, les meubles et la construction. Comparé au bois massif, le LVL présente plusieurs avantages : les défauts du bois dont il est issu sont atténués et dispersés au travers du processus de production, ce qui permet d'obtenir une meilleure stabilité dimensionnelle. De plus, le LVL est disponible en grandes dimensions et offre une rigidité et une résistance supérieures à celles du bois massif.

Le bois issu de jeunes arbres coupés lors des éclaircies, les surbilles, et le bois récolté précocement sont des ressources secondaires qui ont un grand potentiel pour des applications à haute valeur ajoutée (Eckelman 1993; Knudson et al. 2007; Marchall 1995; McKeever 1997). Ces ressources n'ont pas été suffisamment explorées et n'ont été couramment utilisées que pour le bois énergie et le bois d'industrie, dont les panneaux de fibres et les panneaux de particules. De ce fait, il est essentiel de trouver une autre façon d'utiliser ces ressources abondantes. En se basant sur les problèmes mentionnés ci-dessus, ce travail de thèse visait à :

1. Mieux comprendre les propriétés du chêne et du hêtre de qualité secondaire et comprendre comment utiliser ce matériau en fonction de paramètres mesurés relatifs à la qualité du bois.
2. Comprendre la relation entre différents paramètres de qualité du bois mesurés et leur influence sur les propriétés physiques et mécaniques du bois afin de trouver une utilisation optimale pour des applications structurelles.
3. Optimiser les propriétés d'un produit final choisi, soit le LVL, en fonction des propriétés du bois préalablement mesurées, de l'épaisseur du placage et de la nodosité du bois.

Cette thèse est composée de 6 chapitres. Le chapitre 1 explique le contexte et l'état de l'art en ce qui concerne les propriétés du bois, la qualité du placage et les propriétés du LVL. Les chapitres 2, 3 et 4 présentent les résultats obtenus sous la forme de projets d'article. Le chapitre 2 porte sur la variation radiale des propriétés du bois de la moelle à l'écorce. Le chapitre 3 associe les propriétés structurelles du bois avec les propriétés physiques et mécaniques. Le chapitre 4 présente l'influence de l'épaisseur du placage et de la proportion de nœuds sur les propriétés mécaniques du LVL. Le chapitre 5 aborde une discussion générale de tous les résultats exposés dans les articles et fournit la conclusion et les perspectives.

Variation radiale des propriétés du bois de feuillus issus d'éclaircie

Introduction

Au cours du développement des peuplements forestiers, le nombre d'arbres par hectare est bien souvent réduit, ce qui permet aux arbres ayant un meilleur potentiel de grossir plus rapidement grâce à une augmentation de l'espace et un meilleur accès aux nutriments, à l'eau et à la lumière du soleil. Cette opération, appelée éclaircie, est effectuée en abattant de nombreux arbres jeunes et de petit diamètre qui sont susceptibles de contenir une forte proportion de bois juvénile et bois de tension. Le bois juvénile est le bois situé dans la région à proximité de la moelle, créé au début de la croissance radiale. Il est souvent caractérisé par un gradient de propriétés du bois et des propriétés mécaniques relativement inférieures à celles du bois mature (Moore et al. 2009; Zobel and Sprague 2012). Le bois juvénile des feuillus et des forêts semi-naturelles de longue durée (120-220 ans) a été moins bien décrit que celui des résineux. Fukazawa (1984) a défini le bois juvénile de feuillus comme la région allant de 5-8 cm de la moelle à l'écorce, quel que soit leur taux de croissance. Néanmoins, le point de séparation entre le bois juvénile et le bois adulte dépend de l'espèce, la méthode utilisée et la caractéristique examinée (Zobel and Sprague 2012). Il existe plusieurs hypothèses sur la localisation du bois juvénile qui sont généralement basées sur la position du houppier vivant, l'âge cambial ou le diamètre du tronc (Meinzer et al. 2011). Pour mieux valoriser les bois feuillus de petit diamètre qui vivent sous forte concurrence (arbre dominé), une meilleure connaissance de la variation des propriétés du bois est importante.

Cette étude visait à comprendre la variation radiale de la structure et des propriétés du bois chez les jeunes hêtres et chênes issus de l'éclaircie. Comme l'utilisation finale de ce bois est destinée à la construction, l'effet des différentes positions radiales du bois sur les propriétés mécaniques et physiques du bois a été étudié. L'angle des microfibrille (AMF), la densité du bois initial et final et la largeur de cernes ont également été mesurés de la moelle à l'écorce puisqu'il s'agit de variables potentielles à utiliser comme indicateurs des propriétés mécaniques et physiques. Nous avons divisé l'échantillon en deux catégories en fonction de la position radiale à l'intérieur du tronc. La première catégorie dite interne provient de la position la plus proche de la moelle et la deuxième catégorie de la position la plus proche de l'écorce. La densité du bois, le module d'élasticité longitudinal et les retraits des deux positions radiales ont été comparés.

Matériel et méthodes

5 hêtres et 5 chênes ont été récoltés lors des éclaircies dans une forêt locale en Lorraine, en France. Le matériel utilisé dans cette étude se compose de 20 billons de 150 cm de longueur avec des diamètres compris entre 21 et 30 cm. L'âge du chêne variait entre 61 et 90 ans et celui du hêtre entre 57 et 84 ans. Tous les billons ont été prélevés en partie haute du tronc et contiennent généralement des nœuds.

Une rondelle de 3 cm d'épaisseur a été prélevée de la partie centrale de chaque billon. Une barrette de 2 mm d'épaisseur a été préparée de l'écorce à l'écorce à travers la moelle, puis scannée aux rayons X afin de mesurer les composantes de croissance radiale (largeur du bois initial, largeur du bois final et largeur du cerne) et la densité qui lui correspond (Mothe et al.

1998). La partie restante a ensuite été coupée en sections de 1 cm de long, de la moelle à l'écorce, et numérotée consécutivement. L'AMF a été mesurée sur chaque section à l'aide d'un diffractomètre à rayons X (XRD). Nous avons ensuite divisé l'échantillon en deux catégories en fonction de la position radiale à l'intérieur du tronc. La première catégorie dite interne provient de la zone la plus proche de la moelle et la deuxième catégorie de la zone la plus proche de l'écorce.

Chaque billon a été découpé en 8 éprouvettes d'une dimension de 380 mm x 20 mm x 20 mm (LRT). Quatre échantillons sont issus de position interne et le reste en position externe. Les échantillons de bois ont été séchés à 12 % de taux d'humidité. Le MOE dynamique a été mesuré à l'aide d'un dispositif d'essai non destructif (Bing ®) basé sur une méthode vibratoire (Brancheriau et al. 2007). Après avoir évalué le retrait longitudinal (Ls), radial (Rs) et tangentiel (Ts), le retrait volumétrique (Vs) a été calculé en utilisant les données des Rs et Ts. Le point de saturation de la fibre (PSF) a été évalué en utilisant le point d'intersection du taux d'humidité du bois et du retrait calculé également en utilisant Rs et Ts.

Resultats et discussion

Le bois juvénile du chêne présente des cernes plus grands, une densité plus importantes et un AMF plus élevé. Une densité plus élevée de bois initial sur le bois juvénile de chêne indique une porosité plus faible, ce qui est conforme à la littérature indiquant une quantité supérieure de vaisseaux dans les cernes du bois adulte du chêne (Helińska-Raczkowska 1994; Leal et al. 2006). Le point de démarcation trouvé dans le présent travail est proche de celui qui est indiqué dans Guilley et al. (2004) sur les chênes dominants et dans Leal et al. (2006) sur les chênes de 40 ans. Néanmoins, les deux études mentionnées ci-dessus ne visaient pas à déterminer le point de séparation entre le bois juvénile et le bois adulte. Aucun d'entre eux n'a également mentionné que leurs valeurs se réfèrent au bois juvénile ou mature.

Le bois juvénile de hêtre a une largeur de bois final plus importante et un AMF plus élevé. Le point de démarcation du bois mature chez le hêtre semble se situer autour de 15 ans sur la base de la variation radiale. Bouriaud et al. (2004) ont montré que la largeur de cerne diminue depuis la moelle jusqu'à un âge cambial inférieur à 20 ans puis augmente jusqu'à 4,5 mm après ce point, ce qui est trois fois plus grand que la largeur de cerne trouvée dans cette étude. Le point de démarcation de cette étude correspond bien au point de démarcation trouvé pour le hêtre dans notre étude.

La région de bois juvénile sur les deux espèces est comprise dans les 5 cm distant de la moelle, ce qui est peut-être lié au statut des arbres étudiés. En ce qui concerne la perspective de transformation ultérieure de ces arbres en placage par exemple, il n'y aura aucun bois juvénile enlevé ou sinon peu de bois juvénile car il est concentré dans une région très proche de la moelle.

La comparaison entre les différentes positions considérée montre que la densité du bois, le point de saturation des fibres (PSF), Vs, Rs et Ts dans les deux espèces est plus élevée en interne qu'en externe. Le PSF et le Vs sont plus élevés dans la position interne, probablement du fait d'une densité plus élevée. L'augmentation du Vs avec la densité du bois a été signalée dans des études antérieures sur le chêne et le hêtre (Deret-Varcin 1983; Gryc et al. 2008b).

Le MOE du hêtre est nettement plus élevé en position extérieure. En revanche, le MOE du chêne n'est pas affecté par la position radiale. Comme la densité du bois en position interne est plus élevée la différence entre les deux espèces peut s'expliquer par une variation d'AMF plus importante en interne. Le compromis entre la densité du bois et l'AMF peut-être la raison de cette tendance.

Les résultats montrant une densité et une retrait du bois légèrement plus élevés sur les bois de la position interne mais un MOE relativement comparable avec les bois de la position externe sont conformes au rapport précédent de Gryc et al. (2008) sur le hêtre. La densité du bois juvénile était légèrement supérieure à celle du bois adulte, ce qui peut s'expliquer par un nombre de rayons plus élevé que celui du bois adulte. Les rayons ont généralement une densité plus élevée que les autres tissus.

La position radiale du bois affecte la corrélation entre la densité et la rigidité du bois. Pour les deux espèces, la densité du bois est mieux corrélée avec le MOE dynamique sur la position externe. Cette différence peut s'expliquer par la variation plus importante de l'AMF dans la position interne.

L'influence de la structure du bois sur les propriétés mécaniques et physiques des bois feuillus de qualité secondaire issus de l'éclaircie

Introduction

Le bois est un composite biologique complexe dont les propriétés physiques et mécaniques dépendent fortement de sa structure. La réponse adaptative à la contrainte environnementale apporte une modification de la typologie de la différenciation cellulaire qui se traduit par une forte variation de la structure du bois et de son organisation. L'organisation des différents types de cellules, en particulier la proportion de fibres, affecte la principale propriété physique du bois, c'est-à-dire la densité du bois. La densité de bois plus élevée est généralement associée à des propriétés mécaniques du bois plus élevées (Ilic, 2003, 2001). Cependant, une densité élevée dans le chêne et le hêtre est généralement considérée comme un indicateur de bois de mauvaise qualité, car elle provoque un retrait plus élevé, ce qui entraîne des défauts de séchage plus importants (Deret-Varcin 1983; Gryc et al. 2008a; Nepveu 1981; Zhang et al. 1994a). Il existe peu d'études sur l'effet de la densité du bois sur les propriétés mécaniques du chêne et du hêtre (Cibecchini et al. 2016; Polge 1973). Basé sur des études littéraires, il y a aucune étude dédiée spécifiquement sur la caractérisation des propriétés physiques et mécaniques du chêne et du hêtre de qualité secondaire récupéré au cours d'éclaircies.

Des études précédentes sur le chêne ont montré que la densité du bois est positivement corrélée avec la largeur de cerne, ce qui signifie qu'une croissance rapide est favorable pour obtenir du bois à haute densité (Guilley et al. 2004; Nepveu 1990; Zhang et al. 1994b, 1993). Le hêtre montre également une corrélation positive entre la densité du bois et la largeur des cernes, mais beaucoup plus faible que le chêne (Bouriaud et al. 2004). Le premier objectif de cette étude était de caractériser les propriétés structurelles, physiques et mécaniques du hêtre et du chêne de qualité secondaire issu d'éclaircie. Le deuxième objectif était de mieux comprendre les relations entre certains paramètres tels que la densité, l'angle du fil et la largeur de cerne avec les propriétés mécaniques et physiques de cette ressource.

Matériel et méthodes

Les propriétés mécaniques du bois ont été mesurées sur des éprouvettes d'une dimension de 240 x 10 x 10 mm³ par une méthode non destructive (Bing) suivie d'une méthode de flexion en trois points (Instron 5969). L'angle de fil a été évalué en scannant les éprouvettes utilisé pour l'essai destructif. La mesure de l'angle du grain a été effectuée à la surface de la zone de rupture. Les images prises ont ensuite été analysées à l'aide d'un logiciel nommé Image-J afin de mesurer manuellement l'angle du fil. Le nombre de cerne des deux bords de ces échantillons a été enregistré comme une indication de la largeur de cerne.

Le retrait longitudinal a été évalué sur l'échantillon de 50 x 20 x 20 mm³ (LRT) tandis que le retrait radial et tangentiel a été mesuré sur l'échantillon de 10 x 20 x 20 mm³. Le retrait volumétrique a été calculé en utilisant les données du retrait tridimensionnel. Le point de saturation de la fibre (FSP) a été évalué en utilisant le point d'intersection du retrait de

surface calculé en utilisant uniquement le retrait radial et tangentiel. Le nombre de cernes a également été enregistré.

Resultats et discussion

Nos résultats montrent que les propriétés mécaniques mesurées à l'aide de méthodes non destructives et destructives telles que la dynamique MOE, la statique MOE et la MOR des deux essences de bois étaient positivement corrélées avec la densité du bois. L'angle de fil influençait négativement les propriétés mécaniques du bois, même lorsque le niveau était considéré très faible. Les corrélations positives entre la densité du bois et les propriétés mécaniques du chêne contrastent avec les études précédentes (Polge 1973; Zhang et al. 1994a). Généralement, en chêne, il n'y a pas de relation proche entre la densité du bois et les propriétés mécaniques et certains considèrent même la densité élevée en chêne comme un critère de non-qualité du bois. Comme pour le chêne, Cibecchini et al. (2016) montrent qu'il n'y a pas de corrélation entre la densité du bois de hêtre et le MOE.

En effet, la densité du bois et la largeur des cernes étaient mieux corrélées sur des essences à zone poreuse comme le chêne que sur des essences poreuses diffuses comme le hêtre. Cet effet de la largeur de cerne par rapport à la densité du chêne peut être responsable pour la corrélation plus faible entre la densité du bois et les propriétés mécaniques du chêne que pour celles du hêtre. La corrélation positive entre la densité du bois et la largeur de cerne est conforme à la littérature (Genet et al. 2013; Guilley et al. 2004). Cela signifie que la croissance rapide sur le chêne induit une densité de bois plus élevée. Par contre, Bouriaud et al. (2004) ont signalé une corrélation négative faible mais significative entre la densité du bois et la largeur des cernes sur hêtre ($r = -0.14$). Cette étude était en contraste avec notre résultat montrant la corrélation négative entre le nombre de cernes et la densité du bois qui indiquait une corrélation positive entre la largeur des cernes et la densité du bois.

La densité de cernes sur le chêne était fortement corrélée avec la largeur et la densité LW. Contrairement au chêne, la densité des cernes de hêtre n'était pas corrélée à la largeur des cernes, mais affectée à la fois par la densité LW et EW.

L'augmentation de la densité du bois remonte également les Ts, les Rs et les Vs, tandis que les Ls diminuent. Comme la corrélation entre la densité spécifique et la largeur de cerne sur le chêne était positive, la corrélation entre la largeur de cerne et les propriétés physiques était dans le même sens que celle observée sur la densité du bois. Cependant, la corrélation avec Ls n'était pas significative au niveau 0,1. En revanche, la largeur de cerne sur hêtre montre une corrélation avec Ts ($\alpha=0.05$) et Vs ($\alpha=0.1$), mais aucune corrélation n'a été trouvée avec Rs et Ls.

Influence de l'épaisseur du placage et de la proportion de nœuds sur les propriétés mécaniques du LVL fabriqué à partir de feuillus de qualité secondaire

Introduction

Le bois issu des éclaircies de jeunes arbres, les surbilles, et le bois récolté précocement sont des ressources secondaires qui ont un grand potentiel pour des applications à haute valeur ajoutée (Eckelman 1993; Knudson et al. 2007; Marchall 1995; McKeever 1997). La présence de nombreux défauts tels que les nœuds, la déviation de l'angle de fil, le bois juvénile et le bois de réaction restreint l'utilisation de feuillu de qualité secondaire pour les matériaux de construction. La présence de nœuds crée des zones de moindre résistance et crée également une zone autour du nœud qui présente une grande déviation de l'angle fil (Viguier et al. 2017a, 2015). Les jeunes arbres sont généralement caractérisés par une forte proportion de bois juvénile (Bendtsen 1978; Kretschmann et al. 1993). Le bois juvénile est une zone proche de la moelle créée au début de la croissance radiale qui peut être caractérisée par des propriétés mécaniques inférieures à celles du bois mature (Moore et al. 2009; Zobel and Sprague 2012). La valorisation de cette ressource comme matériau structurel nécessite une meilleure connaissance de ses propriétés mécaniques et une meilleure caractérisation de l'effet des défauts sur les propriétés mécaniques.

Le LVL (Laminated Veneer Lumber ou Lamibois) est un produit d'ingénierie du bois fabriqué à partir de placages déroulés et collés avec le fil orienté principalement en parallèle avec la longueur du panneau. Les études précédentes ont montré que la qualité du placage influence les propriétés mécaniques du LVL (Daoui et al. 2011; Pot et al. 2015; Viguier et al. 2018 2017b). Viguier et al. (2018) ont signalé l'influence de l'angle du fil et de sa déviation autour du nœud sur le MOE et MOR du LVL, mais aucun n'a quantifié la relation avec la proportion des nœuds.

Généralement, l'utilisation de placages moins épais permet une meilleure distribution des défauts par rapport à l'utilisation de placages plus épais et donc, permet une amélioration de la résistance du LVL (Ebihara 1981). Par conséquent, les placages moins épais augmentent le nombre de placages à l'intérieur du LVL et exigent donc beaucoup plus de colle et plus d'étapes pour sa production. L'augmentation de l'épaisseur du placage aide à réduire la consommation de colle et le temps de production. Des études récentes sur le LVL réalisées sur des essences feuillues ont révélé que l'augmentation de l'épaisseur du placage avait provoqué un affaiblissement mineur du MOE et MOR de LVL (Daoui et al. 2011; Pot et al. 2015; Rahayu et al. 2015). Il est apparu dans certaines études que l'augmentation de l'épaisseur du placage diminuait la résistance au cisaillement et le module de cisaillement du LVL, en particulier dans le sens d'essai sur champ (Ebihara 1981; Pot et al. 2015). Mais le rapport de Pot et al. (2015) s'appuie sur des études numériques et n'a pas encore été confirmé sur un grand nombre de mesures expérimentales. Le déroulage crée des fissures sur le côté libre de la surface du placage (Thibaut 1988). Dans les mêmes conditions de déroulage, une épaisseur de déroulage plus élevée produit du placage avec des fissures plus profondes et une plus grande distance entre deux fissures consécutives (Denaud et al. 2007; Pałubicki et al. 2010).

Le premier objectif de cette étude était de mieux comprendre les relations entre les propriétés du placage et les propriétés mécaniques du bois feuillu de qualité secondaire. La plupart des études précédentes sur le LVL des bois feuillus ont été réalisées avec du LVL réalisé à partir de placages de bonne qualité.

Les propriétés de fissuration et la proportion de nœuds ont été utilisées pour caractériser la qualité du placage, en tenant compte de la variation radiale du placage à l'intérieur du tronc de l'arbre qui fournit différentes propriétés du bois (position interne et externe). Le deuxième objectif de cet article était d'étudier l'effet de l'épaisseur du placage sur les propriétés mécaniques du LVL et de proposer une épaisseur de placage adaptée qui offre des propriétés mécaniques les plus performantes. Un compromis devait être trouvé entre les propriétés de fissuration générées pendant le déroulage du bois et la proportion de nœuds sur la surface du placage.

Matériel et méthodes

Des billons tirés de hêtres et chênes récoltés au cours de travaux d'éclaircie dans une forêt locale en Lorraine, France, ont été utilisés pour cette étude. Pour limiter la fissuration sur les placages, tous les billons ont été plongés dans l'eau chaude à une température de 60°C pendant 24 heures. Ensuite, les billons ont été déroulés en trois différentes épaisseurs (2,1 mm, 3 mm, 4,2 mm). Par la suite, les placages ont été séchés à l'aide d'une machine de séchage sous vide afin de réduire le taux d'humidité du placage à 18 %, avant de sécher à l'air à environ 10 %.

La qualité des placages frais a été évaluée en mesurant la profondeur et les intervalles de fissure avec un Système de Mesure d'Ouverture des Fissures (SMOF). La mesure a été effectuée sur des bandes de placage fraîchement coupées d'une largeur de 10 cm et d'une longueur de 20 cm, prélevées sur le bord des placages immédiatement après la fin du processus de déroulage.

Chaque placage sec a été photographié avant d'être laminé. Les images de la surface du placage ont été analysées à l'aide du logiciel Image-J. Le pourcentage de la surface du nœud par rapport à la surface totale du placage a été calculé et défini comme la proportion de nœuds. La position de chaque nœud sur la surface du placage a également été enregistrée. La proportion pondérée de nœud du placage a été calculée en multipliant la proportion de nœud par un facteur de correction basé sur la position du nœud le long de la longueur du placage.

Les placages ont été collés avec le fil orienté en parallèle à la longueur du panneau en utilisant du PVAc (Polyvinyl Acetate) avec un grammage de 180 g/m². Les placages collés ont ensuite été pressés sous une pression de 0,8 MPa pendant environ 60 minutes dans une presseuse à froid.

Pour la mesure des propriétés mécaniques, 8 éprouvettes d'une dimension de 500x21x21 mm³ ont été extraits de chaque panneau LVL. Le module d'élasticité dynamique (MOE) et le module de cisaillement ont été mesurés à plat ou sur champ en utilisant un essai non destructif appelée Bing. Suite au test non destructif, nous avons effectué un essai de flexion 4 points pour mesurer le MOE et le module de rupture (MOR).

Résultats et discussion

Nos résultats montrent que la profondeur et l'intervalle de fissure sont plus élevés lorsque l'épaisseur du placage augmente. Les résultats obtenus pour le chêne sont intéressants et n'ont jamais été rapportées auparavant. En effet, cette essence est moins homogène que le hêtre mais présente un comportement similaire.

La surface de placage préparé à partir de bois de feuillus de qualité secondaire présentait des proportions élevées de nœuds. Le placage de la partie intérieure présente une proportion de nœuds plus élevée que le placage de la partie extérieure du tronc. Le déroulage de la partie extérieure des grumes qui a un diamètre plus important produit une distance plus élevée entre les nœuds. Lorsque le diamètre de déroulage devient plus petit (vers le cœur), les nœuds deviennent également plus petits et la distance entre les nœuds diminue. En conclusion, La fréquence du nœud augmente alors que le diamètre du nœud diminue de l'écorce vers le centre du tronc.

Chaque épaisseur de placage à l'intérieur du LVL génère des propriétés mécaniques différentes. Le LVL fabriqué à partir de placages de 3 mm d'épaisseur permet d'obtenir les propriétés mécaniques optimales pour les deux essences de feuillus. Le module d'élasticité de LVL fabriquées en chêne et hêtre de qualité secondaire dans la présente étude est comparable ou même supérieur au MOE de LVL réalisés avec les autres essences de bois feuillues comme l'eucalyptus, l'érable, le tremble et le peuplier (Aydın et al. 2004; Shukla and Kamdem 2008; Rahayu et al. 2015).

Une augmentation de la profondeur et de l'intervalle de fissure tend à abaisser le module de cisaillement spécifique sur champ et à diminuer la résistance du LVL dans les deux directions d'essai. Aucune corrélation n'a été trouvée entre les propriétés de fissure et le MOE. Ces résultats sont également en accord avec les rapports précédents sur l'effet de la fissuration et de l'épaisseur du placage sur le MOE de LVL (Ebihara 1981; Hoover et al. 1987; Pot et al. 2015).

La proportion de nœuds pondérés permet de mieux prédire le MOE du LVL. L'augmentation de la proportion de nœuds pondérés sur la surface de placage diminue le SMOE global sur le chêne et le hêtre LVL. De faibles corrélations négatives ont été trouvées entre les proportions pondérées de nœuds et le SMOR pour les deux espèces et les deux directions de chargement.

La position radiale du placage à l'intérieur du tronc de l'arbre influence les propriétés physiques et mécaniques du LVL. L'utilisation de placages intérieurs produit une densité de LVL plus élevée, mais fournit des propriétés mécaniques plus faibles que les placages extérieurs. Ces propriétés mécaniques plus faibles sont dues à une proportion plus élevée de nœuds sur la surface de placage interne que sur le placage issu de position externe.

Discussion générale

Une meilleure connaissance de la variation des propriétés du bois est importante afin d'atteindre une meilleure valorisation des arbres de qualité secondaire qui sont caractérisés par de faibles dimensions de billons, une forte proportion de nœuds, une forte déviation de l'angle de fil, une forte proportion de bois juvénile, et de fortes contraintes de croissance. Cette variation des propriétés du bois dans la direction radial est contrôlée par la maturité du bois.

Nos résultats ont montré que le bois juvénile pour le chêne étudié présente des cernes de croissance plus larges et un AMF plus élevé, tandis que le bois juvénile du hêtre étudié a une proportion de bois final plus importante et un AMF plus élevé. Le bois juvénile se caractérise par une densité et un retrait un peu plus élevés, mais il présente une rigidité relativement comparable à celle du bois adulte. Le bois juvénile des deux espèces se trouvait à une distance inférieure à 5 cm de la moelle, ce qui est peut-être dû au statut des arbres, dominés au moment de la production de ce bois. En ce qui concerne la perspective de transformation éventuelle de ces bois en placages par déroulage, la partie de bois juvénile déroulée sera très faible car elle est concentrée dans une région très proche de la moelle.

Les variations de propriétés structurales du bois affectent généralement ses propriétés physiques et mécaniques. Nos résultats ont montré que le module d'élasticité et module de rupture des deux espèces de feuillue étaient fortement influencés par la densité du bois. Il y a une corrélation positive entre la densité et la largeur des cernes chez deux espèces, mais elle est plus marquée chez le chêne. Chez le chêne, la largeur de cerne montre également des corrélations positives avec T_s , R_s , V_s et le PSF tandis que sur le hêtre, elle montre des corrélations positives avec T_s , V_s et le PSF. La densité des cernes sur le chêne est fortement corrélée à la largeur et à la densité du bois final. Contrairement au chêne, la densité des cernes de hêtre n'est pas corrélée à la largeur de cernes, mais affectée à la fois par la densité du bois initial et du bois final.

Les chapitres 2 et 3 ont démontré que les propriétés mécaniques des feuillus de qualité secondaire étudiés sont élevées. Outre les possibilités d'utilisation de ce matériau comme bois scié, il peut également être transformé en matériaux structuraux optimisés tels que le CLT, le Glulam et le LVL. La transformation de bois feuillus de qualité secondaire en placages offre un taux de valorisation plus élevé que la transformation en bois scié (Hopewell et al. 2007; McGavin et al. 2014, 2006). La transformation de feuillus de qualité secondaire en LVL permettra d'optimiser la valorisation de la biomasse ligneuse et ses performances mécaniques. En effet, de fortes proportions de nœuds ont été trouvées sur la surface du placage déroulé à partir de feuillus de qualité secondaire.

La profondeur et l'intervalle de la fissuration sur la surface du placage augmentent avec l'épaisseur du placage. Le LVL possède des propriétés mécaniques différentes selon l'épaisseur du placage, ceux sont les placages de 3 mm d'épaisseur qui génèrent les propriétés mécaniques optimales pour le LVL des deux essences de feuillus. Les propriétés mécaniques sont comparables à celles du LVL fabriqué à partir d'autres essences de bois feuillus. Une hausse de la proportion de nœuds pondérés entraîne une baisse du module d'élasticité et de rupture de LVL. Une augmentation de la profondeur et des intervalles de fissures génère un module de cisaillement plus faible sur champ pour les deux espèces. Aucune corrélation n'a

été trouvée entre les propriétés de fissuration et les propriétés mécaniques du LVL. La position radiale du placage à l'intérieur du tronc de l'arbre influence les propriétés physiques et mécaniques du LVL. Le placage de la partie intérieure du tronc a produit une densité de LVL plus élevée, mais a fourni des propriétés mécaniques plus faibles que le placage de la partie extérieure du tronc. Ces propriétés mécaniques plus faibles sont dues à une proportion de nœuds plus élevée sur la surface de placage de la partie interne que sur le placage de la partie externe du tronc.

Perspectives

1. Valorisation des feuillus de qualité secondaire sous forme de lamellé-collé.

La première année de thèse a fait l'objet de quelques travaux sur la qualité du collage. Nous nous sommes concentrés sur la relation entre la rugosité de la surface du bois, les paramètres structurels du bois, et la qualité de collage du lamellé-collé. L'hypothèse était qu'une légère dégradation de la surface du bois améliorerait la qualité du collage, surtout chez le hêtre qui a généralement une surface trop lisse donc difficile à coller. Les essais de cisaillement ont été effectués conformément aux normes EN 14080, EN 302 et à d'autres méthodes. Tous les tests ont démontré 100% de rupture au niveau du bois sur les assemblages. Il est impossible d'utiliser ce résultat car il nous permet de mesurer uniquement la résistance au cisaillement du bois et non celle de la colle. En conséquence, nous n'avons pas pu évaluer l'effet de la rugosité de surface sur la résistance des collages sur le bois.

2. Modélisation de l'effet de la proportion de nœuds à la surface de billon sur la qualité du LVL

Cette étude a démontré que la proportion de nœuds pondérée par la position du nœud peut expliquer les propriétés mécaniques du LVL. De plus, le diamètre et la fréquence des nœuds étaient plus petits et plus élevés lorsque nous déroulons le billon plus proche vers le centre. Basé sur ce résultat, les caractéristiques du nœud telles que le diamètre et la position sur la surface de billons peuvent être utilisées pour expliquer les propriétés mécaniques du LVL.

Title : Characterization and valorization of secondary quality hardwood as structural material

Keywords : Oak, Beech, Juvenile wood, Mechanical properties, Shrinkage, LVL, Secondary wood quality

Abstract :

Hardwood dominates the standing stock and the surface area of the French forests. As opposed to available forest resources, harvested wood and timber produced are dominated by softwood due to the lack of tested practices and information about the quality of hardwood. In addition, due to climatic risk mitigation and to the market demand in industrial wood products and fuelwood, there has been a shift toward harvesting trees much younger than in the past, and an increase in the utilization of small trees that are removed during thinning operations. The presence of various wood defects such as knots, grain deviation, juvenile wood, and reaction wood restrict the utilization of secondary quality hardwood as a material for construction. To achieve a better valorization of small and suppressed growth hardwood trees, it is important to have a better understanding regarding the variation of wood properties. The valorization of this resource as a structural material requires an optimization of its mechanical properties through the reconstitution into engineered wood product such as laminated veneer lumber (LVL).

Beech and oak were used for this study. The round wood material comprised of 20 bolts classified into class C and D Log based on EN 1316. The microfibril angle, radial growth component, and wood density component were measured from pith to bark. The mechanical properties were measured using the static and dynamic method. Directional shrinkage, volumetric shrinkage, and fiber saturation point were measured. The correlations were analyzed among the measured parameters of structural properties, mechanical properties, physical properties, and the growth component. The bolts were peeled into three different thicknesses (2.1, 3, and 4.2 mm). The quality of fresh veneers was assessed by measuring veneer knot proportion, lathe check depth and lathe check interval. Forty-eight LVL panels glued together using polyvinyl acetate were prepared. The Static Modulus of Elasticity (MOE), Dynamic MOE, Modulus of Rupture (MOR) and shear modulus were measured using destructive and non-destructive method.

Juvenile wood for oak has bigger ring and higher MFA while for beech has larger latewood and higher MFA. As for the perspective of further processing of these trees such as veneering, there will be no or low part juvenile wood peeled as it is concentrated on the small region near the pith. Juvenile wood has slightly higher wood density and swelling but relatively comparable stiffness with mature wood. The MOE and MOR of both wood species were highly influenced by the wood density. There was a positive correlation between specific gravity and ring width on both species but slightly higher in oak. On oak, ring width also showed positive correlations with T_s , R_s , V_s , and FSP while on beech it showed positive correlations with T_s , V_s , FSP.

Veneer lathe check depth and interval increase with the increase in veneer thickness. For both species, the 3 mm thick veneer has provided the optimum mechanical properties for LVL. The testing direction had no significant influence on the mechanical properties of either species. The increase in weighted knot proportion provided lower MOE and MOR on LVL. The weighted knot proportion can better predict the LVL MOE. Deeper lathe checks and higher lathe check intervals generated lower shear modulus in the edgewise direction for both species. The radial position of veneer inside the tree trunk influences the physical and mechanical properties of LVL. Internal veneer produced higher LVL density but provided lower mechanical properties than external veneer. These lower mechanical properties were due to a higher knot proportion on the internal veneer surface than the veneer from external position.

Titre : Caractérisation et valorisation des feuillus de qualité secondaire comme matériau structurel

Mots clés : Chêne, Hêtre, Bois juvénile, Propriétés mécaniques, Retrait, LVL, Bois de qualité secondaire

Résumé :

Les feuillus dominent à la fois la superficie forestière et le volume de bois sur pied des forêts françaises. En revanche, la récolte de bois d'œuvre et la production de sciages sont dominées par le bois résineux en raison du manque de pratiques éprouvées et d'information sur la qualité du bois feuillus. De plus, en raison de l'atténuation des risques climatiques et de la demande du marché pour les bois d'industrie et le bois énergie, nous constatons une tendance à récolter des arbres beaucoup plus jeunes que le passé et une augmentation de l'utilisation de petits arbres qui sont prélevés en éclaircie. La présence de nombreux défauts du bois tels que les nœuds, la déviation du fil du bois, le bois juvénile et le bois de réaction restreint l'utilisation des feuillus de qualité secondaire en tant que matériau structurel. Une meilleure compréhension sur la variation des propriétés du bois est importante afin de mieux valoriser les feuillus de petit diamètre qui vivent sous une forte compétition. La valorisation de cette ressource en tant que matériau structurel nécessite une amélioration de ses propriétés mécaniques par la reconstitution en produits d'ingénierie bois tel que le LVL.

Le hêtre et chêne ont été utilisés pour cette étude. Le bois rond est composé de 20 billons classifiés en classe C et D selon la norme EN 1316. L'angle de microfibrille (AMF), les composantes de croissance radiale et la composante de densité du bois ont été mesurées de la moelle à périphérie du tronc. Le retrait directionnel, le retrait volumétrique (Vs) et le point de saturation des fibres (FSP) ont été mesurés. Les corrélations ont été analysées entre les différents paramètres mesurés. Les billons ont été déroulés en trois épaisseurs différentes (2,1, 3 et 4,2 mm). La qualité des placages frais a été évaluée en mesurant la proportion de nœuds, la profondeur de fissure et son intervalle. Quarante-huit panneaux LVL collés à polyvinyl acétate ont été préparés. Le module d'élasticité statique (MOE), le module d'élasticité dynamique, le module de rupture (MOR) et le module de cisaillement ont été mesurés en utilisant des méthodes destructives et non destructives.

Le bois juvénile pour chêne a le cerne plus large et l'AMF plus élevée, tandis que le bois de hêtre a le bois final plus large et l'AMF plus élevé. Concernant la transformation de ces arbres comme le placage, il n'y aura pas ou peu de bois juvénile déroulé car il est concentré sur la petite région près de la moelle. Le bois juvénile présente une densité et un retrait légèrement plus élevés, mais une rigidité relativement comparable à celle du bois adulte. La densité du bois a fortement influencé le MOE et le MOR des deux essences de bois. Une corrélation positive entre la densité spécifique et la largeur des bagues a été observée chez les deux espèces, mais elle est légèrement supérieure chez le chêne. Sur chêne, la largeur de cerne a également montré des corrélations positives avec Ts, Rs, Vs et FSP, tandis que sur hêtre elle a montré des corrélations positives avec Ts, Vs, FSP.

Pour les deux essences, le placage de 3 mm d'épaisseur a fourni les propriétés mécaniques optimales pour le LVL. L'augmentation de la proportion de nœuds pondérés a entraîné une baisse du MOE et du MOR du LVL. La proportion pondérée du nœud permet de mieux prédire le MOE du LVL. Une augmentation de la profondeur et de l'intervalle de fissure tend à abaisser le module de cisaillement spécifique dans le sens sur chant et diminué la résistance du LVL dans les deux directions d'essai. La position radiale du placage à l'intérieur du tronc de l'arbre influence les propriétés physiques et mécaniques du LVL. Le placage intérieur a produit une densité de LVL plus élevée, mais a fourni des propriétés mécaniques plus faibles que le placage extérieur. Ces propriétés mécaniques plus faibles étaient dues à une proportion plus élevée de nœuds sur la surface de placage interne que sur le placage de la position externe.