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Effect of Forestry Management and Veneer Defects Identified by X-ray Analysis on Mechanical Properties of Laminated Veneer Lumber Beams Made of Beech

Joffrey Viguier, Bertrand Marcon, Stéphane Girardon, and Louis Denaud

Interest in the use of beech as a raw material in engineered wood products for structural purpose has increased in Europe, in particular laminated veneer lumber (LVL). Indeed, this kind of product has exhibited superior mechanical properties with a lower variability compared to solid wood. This study investigated the influence of the forestry management system (*e.g.*, high forest *versus* coppice) and of the veneer defects (*e.g.*, knots and joints) on the mechanical properties of beech laminated veneer lumber (LVL) beams. The research included the measurement of modulus of elasticity and bending strength of 40 LVL beams (50 x 50 x 1200 mm³). Bending strength and modulus of elasticity of beam made from high forest wood compared to coppice wood were respectively higher by 20% and 12%. The impact of natural and manufacturing-process defects on the bending strength was studied using an X-ray imaging system. Defects in the inner layer of LVL beams were detected *via* X-ray. The defects produced by the manufacturing process itself had an effect on the bending strength similar to the natural defects of wood.

Keywords: LVL; X-ray; High forest; Coppice; Mechanical properties; Beech

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INTRODUCTION

In recent years, interest in the use of beech as a raw material in engineered wood products for structural purpose has increased in Europe, particularly in France and Germany, where these renewable resources are available and not fully utilized. Laminated veneer lumber (LVL) is made from rotary peeled veneers that have been dried and then glued together. The grain direction of the layers is mainly oriented in the same direction and parallel to its length. A low proportion of layers can be arranged perpendicular to the grain to improve the dimensional stability. The mechanical continuity of the layers is ensured by a joint between consecutive sheets. There are several types of joints, such as the scarf joint and the crushed-lap joint. This product has exhibited superior mechanical properties in axial bending tests compared to solid wood even when manufactured from lower-grade logs (Aydin *et al*. 2004; Knorz and Van de Kuilen 2012). Indeed, for this kind of product, the defects are randomly distributed throughout the cross-section, which prevents the concentration of stresses at specific locations.

Due to the manufacturing process, the defects are not visible on the faces of the LVL beams. Several studies have shown that the use of an x-ray to detect defects in wood is highly efficient, particularly when detecting knots or any defects that induce significant variations in local density (Schajer 2001; Kim *et al*. 2006; Oh *et al*. 2009; Viguier *et al*.

2017). Moreover, using low-grade materials in the inner plies can reduce the product's costs without decreasing the aesthetic value of the product, provided that only defect-free veneers are used for the visible sides. This approach is well known as a means of extracting the full benefit from second-tier wood.

The mechanical properties of LVL can be affected by several structural factors, such as juvenile wood (Nazerian *et al.* 2011; Girardon *et al.* 2016), jointing method (Özçifçi 2007), lathe checks (Rohumaa *et al.* 2013; Pot *et al.* 2015), load direction (Daoui *et al.* 2011; Kılıç 2011; Bal and Bektaş 2012), veneer thickness (de Melo and Del Menezzi 2014), and log quality (Bayatkashkoli *et al.* 2016).

The influence of silvicultural practice, geographical origin, climate, site quality, tree age, and annual growth ring width on wood quality has been widely studied (Guilley *et al.* 1999, 2004; Bouriaud *et al.* 2004; Moore *et al.* 2009; Karaszewski *et al.* 2013; Dassot *et al.* 2015). However, the influence of the forestry management on the LVL mechanical properties has not been investigated. Two different forestry management systems are mainly used for beech: high forest and coppice. High forests are characterized by stands of single-stemmed trees that originate from seed or from planted seedlings. High forests have relatively high genetic diversity compared with coppice forests due to the fact that they develop from vegetative reproduction. Indeed, in coppice, which is a traditional method of forestry management, young shoots are cut down on short rotations, and in subsequent growth years many new shoots will emerge.

This study investigates two parameters influencing the mechanical properties of LVL: (1) the forestry management, which was explored by means of the comparison of the LVL made out of wood grown in a high forest with LVL composed of coppice wood , and (2) the defects due to processing (especially at the joint), together with the natural defects of wood within the layers of LVL beams, which were explored using an X-ray imaging system, this comparison being based on the modulus of elasticity (MOE) and the bending strength (MOR).

EXPERIMENTAL

Materials

The samples used in the study were 40 beams measuring 50 × 50 × 1200 mm^3. These beams came from panels composed exclusively from wood from high forest or from coppice. In total, 12 logs from two different high forests (National Forest of Planoise, Autun, France and National Forest of Haye, Meurthe-et-Moselle, France) and 15 logs from coppice (National Forest of Châtillon-sur-Seine, Châtillon-sur-Seine, France and National Forest of Corgebin, Chaumont, France) were used. The average log diameters were equal to 57.6 cm and 59.4cm for high forest and coppice logs, respectively. The corresponding coefficients of variation were equal to 7.8% and 9.1%.

The panels were composed of 21 layers, each 2.5 mm thick, and two plies out of the 21 were perpendicularly disposed to prevent cupping after pressing and when in use. The veneers with the grain direction parallel to the main direction were full-size veneer with no scarf joints, whereas the perpendicular veneers were not full-sized. The veneer were dried to 8% using an industrial dryer. A commercial phenol-formaldehyde resin (Bakelite®PF R-03.02.40, Hexion, Lantaron, Spain) with a spread rate of approximately 360 g/m^2 and curing temperature of 130 °C was used as an adhesive. The panels were prepared at the Fernand BRUGERE factory (Châtillon-sur-Seine, France) under the industrial conditions used for beech LVL production. The arrangement is illustrated in Fig. 1. Before testing, the different beams were stabilized and their moisture content were measured using a hygrometer (HT95, GANN, Germany). The mean moisture content was 11.88%.

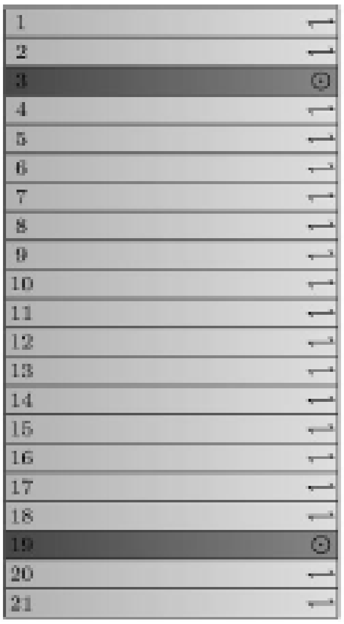


Fig. 1. Arrangement of LVL beams

Methods

Destructive tests

Each beam was tested to the point of failure in the four-points bending test presented in Fig. 2. Bending tests were performed using a distance equal to 18 times the specimen's height between the supports and 6 times between the loading heads, in accordance with the European standards EN 14374 (2005) and EN 408 (2010). The beams were loaded parallel to the glue-line.

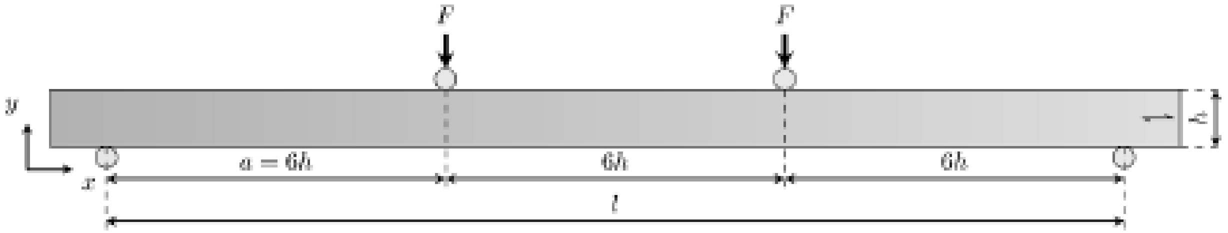


Fig. 2. Mechanical test setup

The global modulus of elasticity was calculated using Eq. 1, where b and h are the thickness and the height of beams (mm), respectively, a is equal to $6h$, l is the span (mm), $F_2 - F_1$ is an increment of load (N) on the linear regression (on the load *vs*. displacement curve) with a correlation coefficient at least of 0.99, and $w_2 - w_1$ is the increment of global displacement (mm) corresponding to the load increment $F_2 - F_1$. The bending strength was calculated according to Eq. 2, where F_{max} is the maximum load during the bending test (N).

$$E_{m,g} = \frac{3al^2 - 4a^3}{4bh^3 \frac{w_2 - w_1}{F_2 - F_1}} \tag{1}$$

$$\sigma_m = \frac{3F_{max}a}{bh^2} \qquad (2)$$

Nondestructive testing – Local density measurements

In addition to the global weighing and measurement of dimensions used to assess the average density, all beams were passed through an X-ray scanner (LuxScan Technologies, Käerjeng, Luxembourg), dedicated to mechanical grading, to measure the local density. Assuming that the gray levels provided by the X-ray images were proportional to the acquired corresponding light intensities, they could easily and accurately be converted into local density maps. Under this condition, Beer-Lambert's law can be applied to determine the density for each pixel of the densities mapping (Kim *et al.* 2006). The final expression of the local density $\rho(x,y)$, averaged through the thickness of the beam, is given by Eq. 3, where t represents the thickness of the beam (mm), a_ρ and b_ρ are linear calibration coefficients, G is the corresponding image pixel's gray level, and x and y are the local spatial coordinates.

$$\rho(x,y)\cdot t(x,y) = a_\rho \cdot \ln(G(x,y)) + b_\rho \qquad (3)$$

The actual values of a_ρ and b_ρ depend on several factors, but they were easily determined by scanning and weighing a batch of boards. These two parameters are in fact the linear regression coefficients between the mean value of the pixel gray level logarithm of the boards, calculated based on the images, and their mean densities multiplied by their respective thickness.

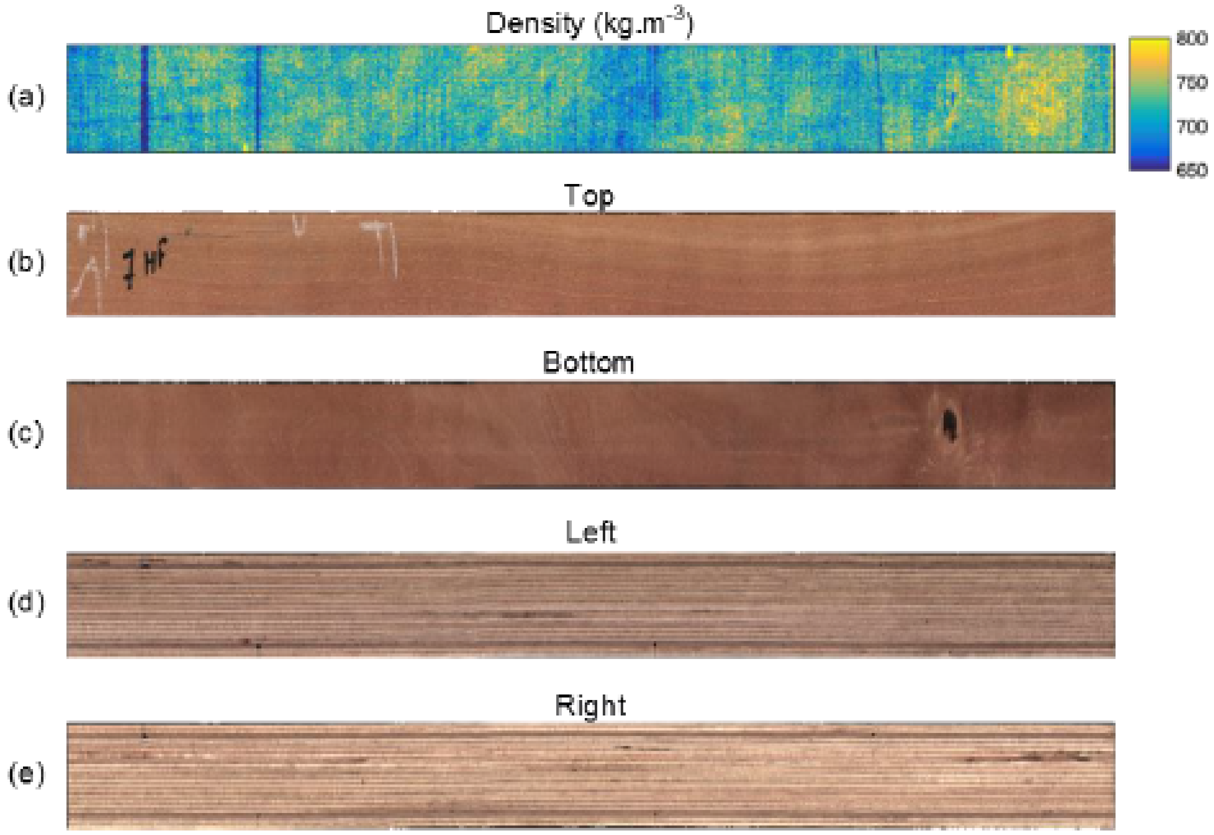


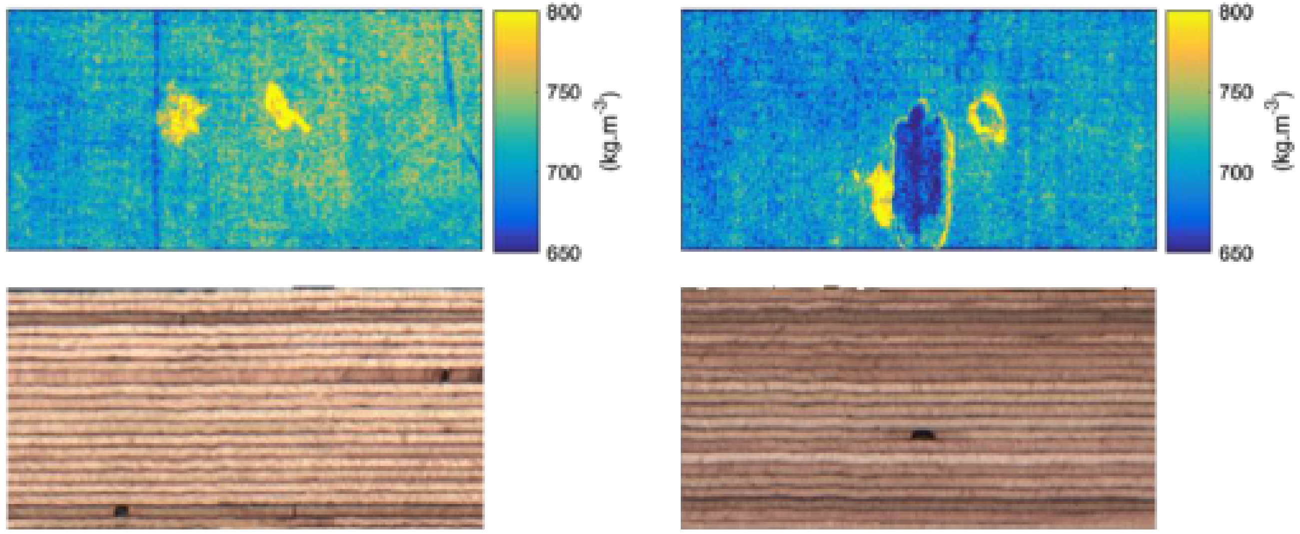
Fig. 3. Data obtained with the scanner

The data obtained from the X-ray scanner are presented in Fig. 3, where the local density maps, averaged along the thickness of the beam, can be seen in the top portion. The resolution is equal to 1 mm along the length of the beam and 0.35 mm along their width; in addition, pictures of the four faces of the beams are shown in the lower portion of Fig. 3. Local variations of density can be observed and indicate the presence of defects in the inner layers of the beam. Indeed, if the density of a layer is nonhomogeneous, due to the presence of a defect or due to the lack of material (which is the case of the straight vertical lines that are shown in Fig. 3), it can induce a density variation of approximately 5%, representing one layer out of the 21 layers, and therefore be recognized. The next section discusses the identification of the different types of defects.

Defect identification

As mentioned before, the presence of a defect in the inner layer of the beams could be detected due to local density variation. The morphological shape and the induced density variation of different types of studied defects are shown in Fig. 4, which identifies them precisely; those defects can be divided into two categories.

(a) Knot (b) Knothole



(c) Crushed-lap joint (d) Gap

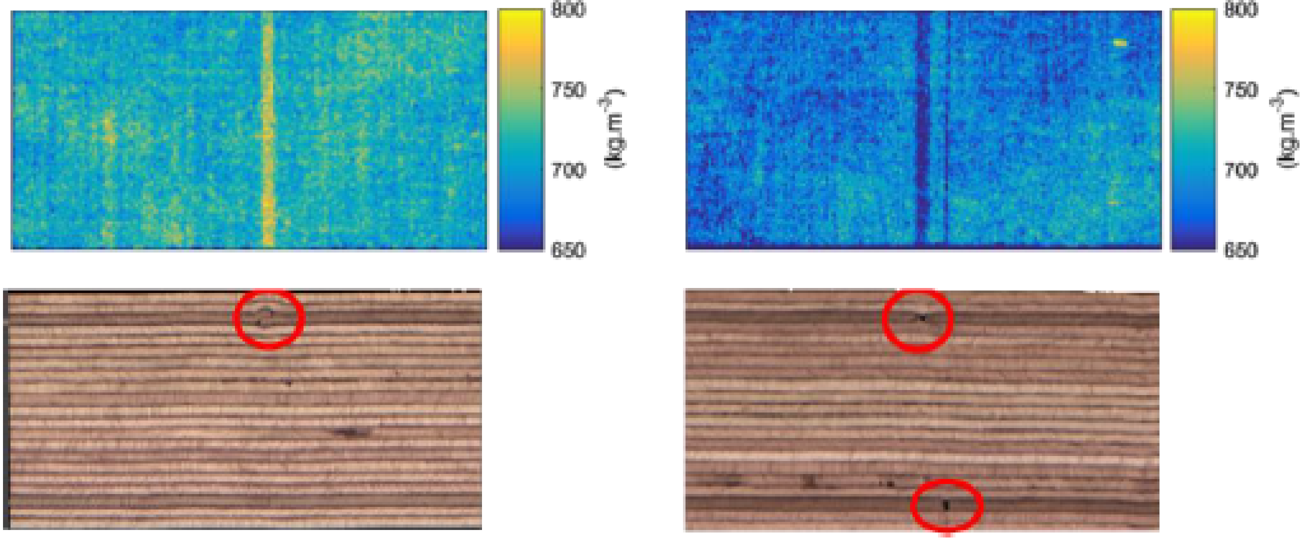


Fig. 4. Defect identification: Morphological shapes and their influence on the local density

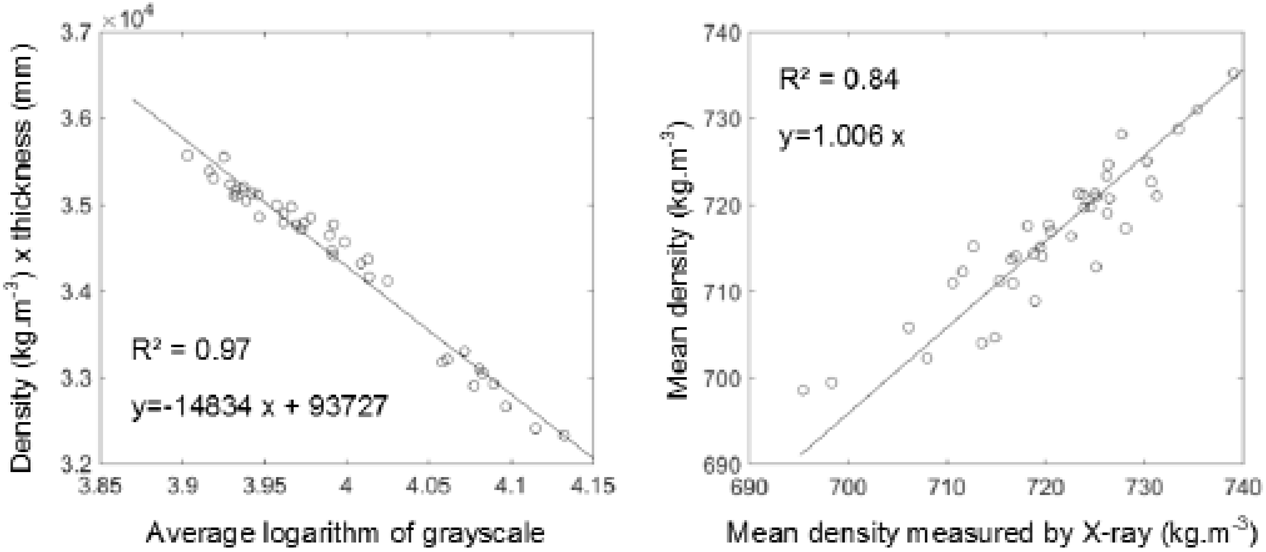
One-way analysis of variance

To compare the influence of the two different forestry management systems and the influence of the different defects, the one-way analysis of variance (ANOVA) technique was used on the properties measured. The purpose of a one-way ANOVA is to determine whether data from different groups have a common mean. It consists of seeking the ratio between the variance between the groups and the variance within the groups. To do this, two estimates of those variances are calculated under the null hypothesis H0 that all group means are equal. The p-value gives the significance level of the test. A p-value smaller than the chosen significance level (0.05 in this study) indicates that at least one of the sample means is significantly different from the others. This analysis has been made using the built-in function anova1 from the software Matlab (MathWorks, R2012a, Natick, USA).

RESULTS AND DISCUSSION

Density Measurements by Means of X-ray

The results of the calibration process are presented in Fig. 5(a). The average density obtained by measuring and weighing the boards was close to the average density measured by X-ray scanning (Fig. 5(b)) for each beam, which highlights the high accuracy of the X-ray method. Indeed, the coefficient of determination had a value up to 0.84 and the root mean square error was equal to 5.6 kg/m^3.



(a) (b)

Fig. 5. (a) Results of the calibration process and (b) comparison between average density measured by X-ray and the average density measured by weighing

Physical and Mechanical Properties

The measured and calculated properties of the different boards, *i.e.*, bending strength, modulus of elasticity, and density, are presented in Table 1. The table shows the rather attractive mechanical properties of the beech LVL beam. The average modulus of elasticity of the 40 beams was higher than 12,000 MPa, and the fifth percentiles of the bending strength and density, respectively, were equal to 70 MPa and 701 kg/m^3. Those values met the requirement of D35 strength grade according to EN 338 (2009). This batch of beams would meet the requirements for an even higher grade (D60) if the modulus of elasticity requirements were not taken into account. It also appeared that the beams made from high forest wood presented better mechanical properties than those made from coppice forest wood and therefore met the requirement for a higher grade too. The low variability of the mechanical properties was also visible: indeed, the coefficient of variation of the bending strength was equal to 11%. In contrast, the coefficient of variation of the bending strength for beech solid wood was approximately 30% (Lanvin 2015). The same result was observed when considering the modulus of elasticity variability, which was only 9.3%, compared to more than 20% for beech solid wood (Lanvin 2015). This low variability confers a high reliability to this type of product for structural purposes. Finally, the densities of the beams made of wood from the two different forestry management systems were similar (717 kg/m^3 compared to 716 kg/m^3 on average); this indicated that the differences in mechanical properties did not arise from density variation. These results revealed that manufacturing LVL, even with low-grade logs, could lead to mechanical properties superior to those of solid wood and with a better recovery rate.

Table 1. Minimum, Average, Maximum, 5% Percentiles Values, Standard Deviation, and Coefficient of Variation for the Different Measured Properties

Forestry	Properties	Min.	Mean	Max.	5% Percentile	Std D.	CV (%)
High forest (n = 20)	σ_m (MPa)	81.8	91.4	102.2	82.9	6.5	7.1
	$E_{m,g}$ (MPa)	11,756	13,193	14,631	11,806	999	7.6
	ρ (kg.m^{-3})	698	717	735	699	9.3	1.3
Coppice forest (n = 20)	σ_m (MPa)	69.8	75.3	80.8	70.2	3.1	4.1
	$E_{m,g}$ (MPa)	10,694	11,727	12,902	10,727	806	6.9
	ρ (kg.m^{-3})	702	716	728	703	7.3	1.1
Overall (n = 40)	σ_m (MPa)	69.8	83.3	102.2	70.7	9.5	11.4
	$E_{m,g}$ (MPa)	10,694	12,460	14,631	10,780	1,164	9.3
	ρ (kg.m^{-3})	698	716	735	701	8.3	1.2

The physical and mechanical properties of the LVL beams produced from wood harvested in high forests and coppice forests are compared in Fig. 6. The p-value of the one-way ANOVA on the density was equal to 0.80; therefore, the difference in terms of density for both practices could not be statistically stated. The average moduli of elasticity were approximately 13,200 MPa and 11,700 MPa for LVL beams made of high forest and coppice forest wood, respectively. The modulus of elasticity for the beams made from coppice wood was on average 11.3% lower than that of beams composed of high forest wood (p = 9.10^{-6}). Finally, the same tendency was observed concerning the bending strength, where the difference was 17% (p = 3.10^{-12}).

Cause of Failure

As mentioned before, x-ray images provide information on the beams' local density. Moreover, those images allowed for the identification of the cause of failure by providing a comparison between the position of the rupture after the destructive mechanical tests with the eventual defect presence at the corresponding position in the x-ray images.

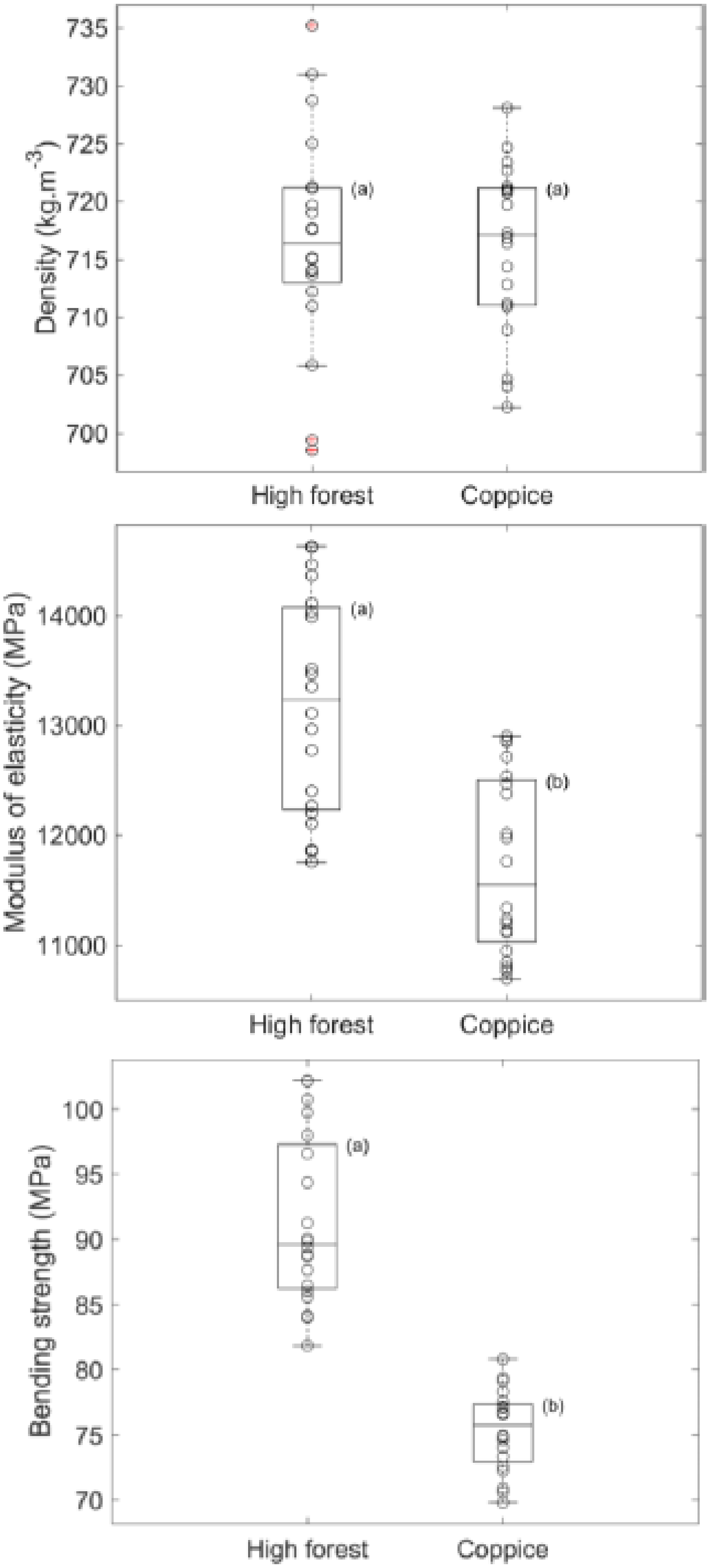


Fig. 6. Influence of the silvicultural practice on the density, the modulus of elasticity, and the bending strength of LVL beams (n = 40)

The distribution of the failure origins observed on the 40 beams is presented in Fig. 7. In 37.5% of the cases, the failure was due to the presence of a knot, including 30% of knots and 7.5% of knotholes. In 40% of the cases, the failure was due to a defect caused by the manufacturing process; among them, 17.5% were due to crushed-lap joints and 22.5% were due to a gap in the joint. It appeared that the defects involved in the failure were nearly evenly divided between defects resulting from the manufacturing process and those resulting from the innate wood defects. In 22.5% of the cases, the failure occurred in an area where no defect was discernible on the density map. Within these 9 beams, where no defect has been observed, 6 were made from high forest wood and 3 from coppice forest; furthermore, the respective average bending strengths of these two groups were 97 MPa and 80 MPa, respectively. Aside from the influence of the defects, LVL beams made from high forest wood exhibited higher intrinsic mechanical properties than the ones made from coppice wood. Those results only highlighted the distribution of causes of failure but did not indicate the impact of these defects on the bending strength.

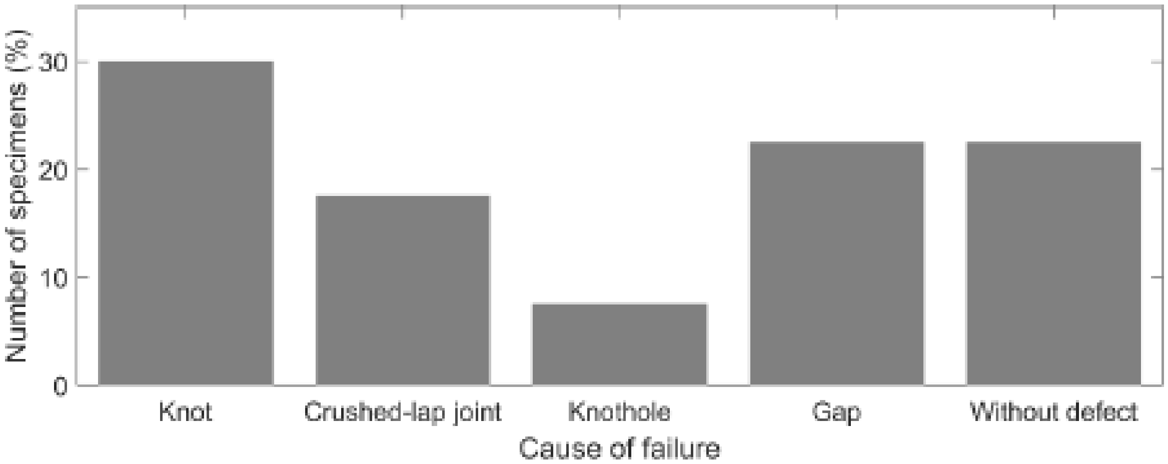


Fig. 7. Distribution of the causes of failure for the 40 beams

Due to the statistical differences in the bending strength observed for the two different forestry management systems, the bending strength was normalized according to the wood origin to be able to compare the influence of each considered defect. This normalization consisted of subtracting the average bending strength over the whole population from the bending strength of each type of wood and then dividing this difference by the population standard deviation. In this way, the effect of the different defects on the bending strength for all samples was compared (Fig. 8).

The analysis of variance (at a significance level of 5%) showed that the average bending strength of the beams with the knots and crushed-lap joints were statistically different from the average bending strength of the beams without any defects. The structural disruption of the layers around the crushed-lap joint (Fig. 4c) may have caused weakness in the cross-section and may have been responsible for the global failures. When the failure was due to the two other types of investigated defects (knotholes and gaps between sheets), there appeared to be no statistical differences between the failure due to their presence and the failure of neat beams. This analysis showed that defects caused by the manufacturing process may have had a similar influence on the bending strength as the innate wood defects.

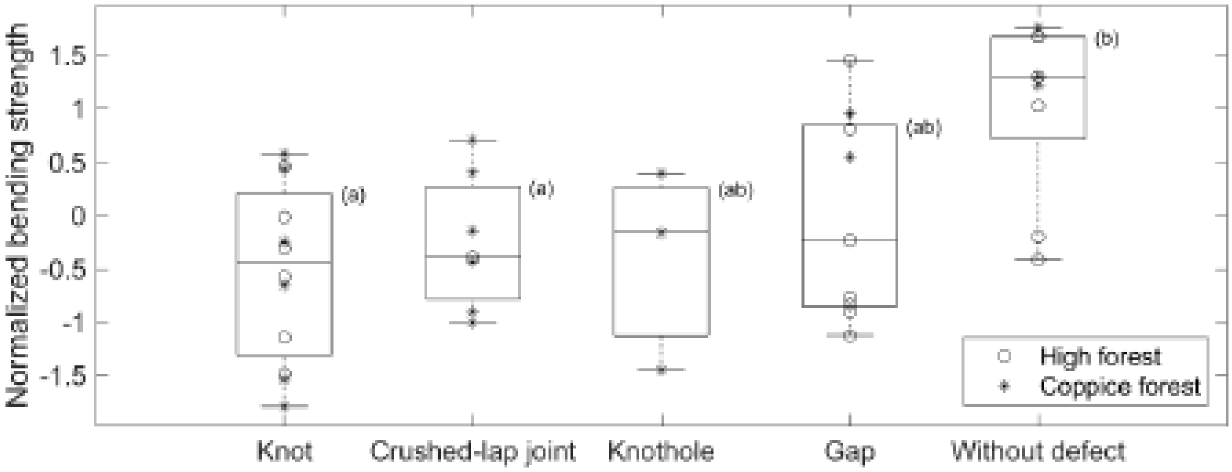


Fig. 8. Bending strength *versus* the identified causes of failure

CONCLUSIONS

1. This study showed that the forestry management system had a strong influence on the mechanical properties of beech laminated veneer lumber. The bending strength of beams made of wood from high forests was 17% higher than the bending strength of beams made of wood from coppice. The moduli of elasticity were 11% higher in the case of the high forest wood.
2. The results also showed that the defects produced by the manufacturing process had a negative effect on the bending strength. This type of defect appeared to have an effect on the bending strength similar to those of the innate defects of wood. In particular, the perturbation of the layers in the vicinity of a crushed-lap joint seemed to have an impact on the bending strength. However, the influence of gaps between sheets on the bending strength was less statistically significant.
3. The efficiency of an X-ray imaging system for detecting and identifying defects on the LVL was demonstrated. Indeed, the local density variation induced by the defects allowed for their detection. Therefore, such a method could be used in the industry to assess the quality of the production and help to control the process parameters.

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REFERENCES CITED

Aydın, I., Çolak, S., Çolakoğlu, G., and Salih, E. (2004). "A comparative study on some physical and mechanical properties of laminated veneer lumber (LVL) produced from Beech (*Fagus orientalis* Lipsky) and Eucalyptus (*Eucalyptus camaldulensis* Dehn.) veneers," *Holz als Roh-und Werkstoff* 62(3), 218-220. DOI: 10.1007/s00107-004-0464-3.

Bal, B. C., and Bektaş, İ. (2012). "The effects of wood species, load direction, and adhesives on bending properties of laminated veneer lumber," *BioResources* 7(3), 3104-3112. DOI: 10.15376/biores.7.3.3104-3112

Bayatkashkoli, A., Sharefpour, M., and Shamsian, M. (2016). "Visual grading of small-diameter poplars for peeling use," *Drewno: Prace Naukowe, Doniesienia, Komunikaty* 59. DOI : 10.12841/wood.1644-3985.145.03.

Bouriaud, O., Bréda, N., Le Moguedec, G., and Nepveu, G. (2004). "Modelling variability of wood density in beech as affected by ring age, radial growth and climate," *Trees* 18(3), 264-276. DOI: 10.1007/s00468-003-0303-x

Daoui, A., Descamps, C., Marchal, R., and Zerizer, A. (2011). "Influence of veneer quality on beech LVL mechanical properties," *Maderas. Ciencia y Tecnologia* 13(1), 69-83. DOI: 10.4067/S0718-221X2011000100007

Dassot, M., Constant, T., Ningre, F., and Fournier, M. (2015). "Impact of stand density on tree morphology and growth stresses in young beech (*Fagus sylvatica* L.) stands," *Trees* 29(2), 583-591, DOI: 10.1007/s00468-014-1137-4.

EN 338 (2009). "Structural timber - Strength classes," European Committee for Standardization, Brussels, Belgium.

EN 408 (2010). "Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties," European Committee for Standardization, Brussels, Belgium.

EN 14374 (2005). "Timber structures - Structural laminated veneer lumber requirements," European Committee for Standardization, Brussels, Belgium.

Girardon, S., Denaud, L., Pot, G., and Rahayu, I. (2016). "Modelling the effects of wood cambial age on the effective modulus of elasticity of poplar laminated veneer lumber," *Annals of Forest Science* 73(3), 615-624. DOI: 10.1007/s13595-016-0569-y

Guilley, E., Hervé, J. -C., Huber, F., and Nepveu, G. (1999). "Modelling variability of within-ring density components in *Quercus petraea* Liebl. with mixed-effect models and simulating the influence of contrasting silvicultures on wood density," *Annals of Forest Science* 56(6), 449-458. DOI: 10.1051/forest:19990601

Guilley, E., Hervé, J. -C., and Nepveu, G. (2004). "The influence of site quality, silviculture and region on wood density mixed model in *Quercus petraea* Liebl.," *Forest Ecology and Management* 189(1-3), 111-121. DOI: 10.1016/j.foreco.2003.07.033

Karaszewski, Z., Bembenek, M., Mederski, P. S., Szczepanska-Alvarez, A., Byczkowski, R., Kozlowska, A., Michnowicz, K., Przytuła, W., and Giefing, D. F. (2013). "Identifying beechround wood quality-distribution of beech timber qualities and influencing defects," *Drewno. Prace Naukowe. Doniesienia. Komunikaty* 56(189). DOI: 10.12841/wood.1644-3985.041.03.

Kim, G. -M., Lee, S. -J., and Lee, J. -J. (2006). "Development of portable X-ray CT system evaluation of wood density using X-ray radiography," *Journal of the Korean Wood Science and Technology* 34(1), 15-22.

Kılıç, M. (2011). "The effects of the force loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL)," *BioResources* 6(3), 2805-2817. DOI: 10.15376/biores.6.3.2805-2817

Knorz, M., and Van de Kuilen, J. (2012). "Development of a high-capacity engineered wood product-LVL made of European Beech (*Fagus sylvatica* L.)," in: *World Conference on Timber Engineering*, New Zealand.

Lanvin, J. -D. (2015). "Correspondance entre classes visuelles et classes de résistance mécanique EN 338 pour le HETRE (*Fagus sylvatica*) de France [Equivalence relations between visual grades and grade from EN338 for french beech (*Fagus sylvatica*)]," in: *Rapport Comission Française* [*French Commission Report*] *BF 002*, FCBA, Paris, France.

de Melo, R. R., and del Menezzi, C. H. S. (2014). "Influence of veneer thickness on the properties of LVL from Paricá (*Schizolobium amazonicum*) plantation trees," *European Journal of Wood and Wood Products* 72(2), 191-198. DOI: 10.1007/s00107-013-0770-8

Moore, J., Achim, A., Lyon, A., Mochan, S., and Gardiner, B. (2009). "Effects of early re-spacing on the physical and mechanical properties of Sitka spruce structural timber," *Forest Ecology and Management* 258(7), 1174-1180. DOI: 10.1016/j.foreco.2009.06.009

Nazerian, M., Ghalehno, M. D., and Kashkooli, A. B. (2011). "Effect of wood species, amount of juvenile wood and heat treatment on mechanical and physical properties of laminated veneer lumber," *Journal of Applied Sciences* 11(6), 980-987. DOI: 10.3923/jas.2011.980.987

Oh, J. -K., Shim, K., Kim, K. -M., and Lee, J. -J. (2009). "Quantification of knots in dimension lumber using a single-pass X-ray radiation," *Journal of Wood Science* 55(4), 264-272. DOI: 10.1007/s10086-009-1031-7

Özçifçi, A. (2007). "Effects of scarf joints on bending strength and modulus of elasticity to laminated veneer lumber (LVL)," *Building and Environment* 42(3), 1510-1514. DOI: 10.1016/j.buildenv.2005.12.024

Pot, G., Denaud, L.-E., and Collet, R. (2015). "Numerical study of the influence of veneer lathe checks on the elastic mechanical properties of laminated veneer lumber (LVL) made of beech," *Holzforschung* 69(3), 337-345. DOI: 10.1515/hf-2014-0011

Rohumaa, A., Hunt, C. G., Hughes, M., Frihart, C. R., and Logren, J. (2013). "The influence of lathe check depth and orientation on the bond quality of phenol-formaldehyde-bonded birch plywood," *Holzforschung* 67(7), 779-786. DOI: 10.1515/hf-2012-0161

Schajer, G. S. (2001). "Lumber strength grading using X-ray scanning," *Forest Products Journal* 51(1), 43.

Viguier, J., Bourreau, D., Bocquet, J. -F., Pot, G., Bléron, L., and Lanvin, J. -D. (2017). "Modelling mechanical properties of spruce and Douglas fir timber by means of X-ray and grain angle measurements for strength grading purpose," *European Journal of Wood and Wood Products* 1-15. DOI: 10.1007/s00107-016-1149-4

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