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Numerical study of the influence of veneer lathe checks on the elastic mechanical properties of laminated veneer lumber (LVL) made of beech

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Abstract: Laminated veneer lumber (LVL) is a well-known high-performance engineered wood product suitable for structural applications. However, the peeling process can induce lathe checks of the veneer with various depth and spatial frequencies. In this study, a finite element model (FEM) is proposed to describe and to analyze the influence of veneer lathe checks on the elastic properties of LVL. Firstly, the typical lathe check depths and frequencies were determined by means of different compression rates of the pressure bar when peeling. These experimental results served as input to the model to compare the influence of check depth and frequency on the elastic behavior of an LVL beam in four-point bending. The checks were modeled as free spaces in the cross-section that can be partially filled with glue. The results show that the longitudinal modulus of elasticity is marginally affected by checking, while the shear rigidity of the LVL beam is significantly reduced in edgewise bending if checks are not glued. Gluing checks, even under consideration of a low Young's modulus of glue, highly reduces the effect of checking on the elastic mechanical properties of LVL.

Keywords: Laminated veneer lumber; lathe checks; veneer, mechanical properties.

Introduction

Laminated veneer lumber (LVL) is made of several wood veneers bound together mostly in grain direction. LVL is used in many structural applications because of its good mechanical properties. The modulus of rupture in bending (MOR) of LVL is higher than solid wood with less variations because of the even distribution of natural defects such as knots, slope of grain or splits (Ebihara 1982; Laufenberg 1983; Leicester 1969; Youngquist et al. 1984; Marchal et al. 2009; Sinn et al. 2009). Hoover et al. (1987) showed that the number of layers in hardwood LVL increases bending strength both edgewise and flatwise. The quoted authors did not find any significant effect on the modulus of elasticity (MOE) nor on the shearing strength. Conversely, Ebihara (1981) found that shear modulus and shear strength parallel to grain of both edgewise and flatwise LVL decrease while veneer thickness increases. But in terms of MOE or MOR in three-point bending tests there are not always clear differences. Some of the contradictory results in terms of shear strength may be explained by different glue bond quality and the type of lathe checks.

Lathe checks are created by the cutting geometry during peeling process (Leney 1960; Lutz 1974; Thibaut 1988). Thibaut and Beauchene (2004) proposed a simplistic cutting force model able to describe chip formation and lathe check generation (Fig. 1). Depending on several parameters as veneer thickness, wood density and wood temperature, the energy required to produce the veneer during cutting can be lower by splitting than by shearing. Indeed, the cutting geometry generates a traction stress field which favors check opening (see Fig. 1).

For homogenous woods and for given cutting conditions, the thicker the veneers, the larger are the check depth and the interval between checks (Pałubicki et al. 2010; Denaud et al. 2007). Lathe check frequency, depth and orientation influence plywood panels shear strength (DeVallance et al. 2007; Rohumaa et al. 2013). However, the influence of checks on LVL mechanical properties is not yet clarified in the literature, especially for thick veneers. In the latter case with less plies, the production time and glue consumption are shorter, but the mechanical properties are lowered (Daoui et al. 2011; Rahayu et al 2013).

In focus of the present paper is beech as a diffuse-porous wood with relatively indistinct growth rings, which is considered as a relative homogenous material well suited for LVL production (Cown and Parker 1978; Venet 1987; Collardet and Besset 1997). It is an up-coming material for LVL production (Pollmeier 2013). Experimental results on late checking of beech veneer are important input parameters of lathe check simulation and calculation. The present paper proposes a numerical model in which lathe check parameters are known, which enables to be free from the variability of checking due to wood heterogeneity. This approach gives a better understanding of the influence of check parameters on the mechanical properties.
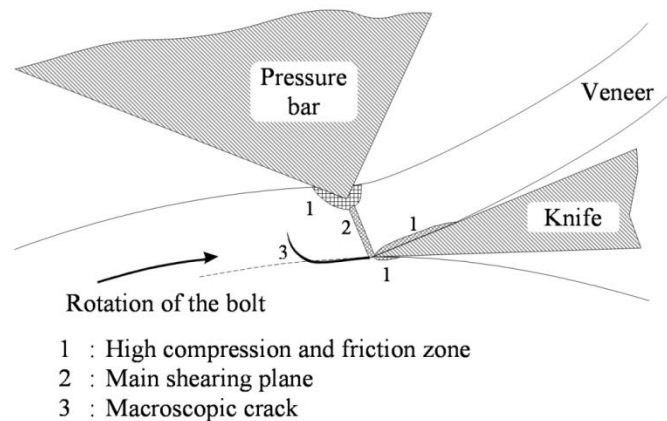
Figure 1: Main mechanical phenomenon during the peeling process (inspired by Thibaut and Beauchene (2004)).

1 : High compression and friction zone
2 : Main shearing plane
3 : Macroscopic crack

Material and methods

Veneers were peeled by means of the lathe of LaBoMaP in A&M ParisTech Cluny, equipped with a pressure bar. This system compresses wood just ahead the cutting edge (see Fig. 1), so that lathe check formation is limited (Atkins 2009; Marchal et al. 2009). The compression rate of the pressure bar is defined as the radial penetration of the pressure bar into the wood divided by the nominal thickness of the veneer. Four sets of veneer were peeled with compression rates of 0% (no pressure bar), 5%, 10% and 15%. Compression rate of 0% and 5% were obtained by peeling the upper log in the tree between diameters of 40 cm and 28 cm, and between diameters of 28 cm and 7.5 cm, respectively. Compression rate of 10% and 15% were obtained by peeling the lower log in the tree between diameters of 44 cm and 33 cm, and between diameters of 30 cm and 7.5 cm, respectively. Different pressure bar compression rates enables to obtain different checks depths and intervals with the same veneer thickness. Hence, the influence of lathe checks on LVL mechanical properties can be studied independently of veneer thickness. Apart from the vertical gap of the pressure bar, which is deduced from the compression rate, the peeling settings were kept constant for each set. Parameters: Two contiguous logs of the same beech tree were peeled (length 60 cm, diameter 48 cm) with a cutting speed of 1 m.s^{-1}. Veneer thickness was 3 mm and the horizontal gap of the pressure bar was 1 mm (1/3 of veneer thickness). Knife angle: 20°; pitch angle: 0°; vertical gaps: 0, 0.15, 0.3 or 0.45 mm according to the compression rate.

Several veneer bands (free from defects) were sawn to be scanned with the SMOF apparatus (Pałubicki et al. 2010). The measuring technique of the SMOF consists in bending the veneer over a pulley to observe checks. A line-scan camera records pictures of the opened checks with a resolution of 0.01 mm, while veneer rotates around the pulley. Fig. 2a and 2b give examples obtained with compression rate of 0% and 10%, respectively. An algorithm described in Pałubicki et al. (2010) can automatically detect the position of the tip of the checks as shown in Fig. 2a and 2b. This position is recorded and thus provides information about the depth of each check and the interval between two successive checks. The mean and the variance of the depth and the interval of lathe checks were computed for each compression rate. Then, check frequency was computed as the number of checks

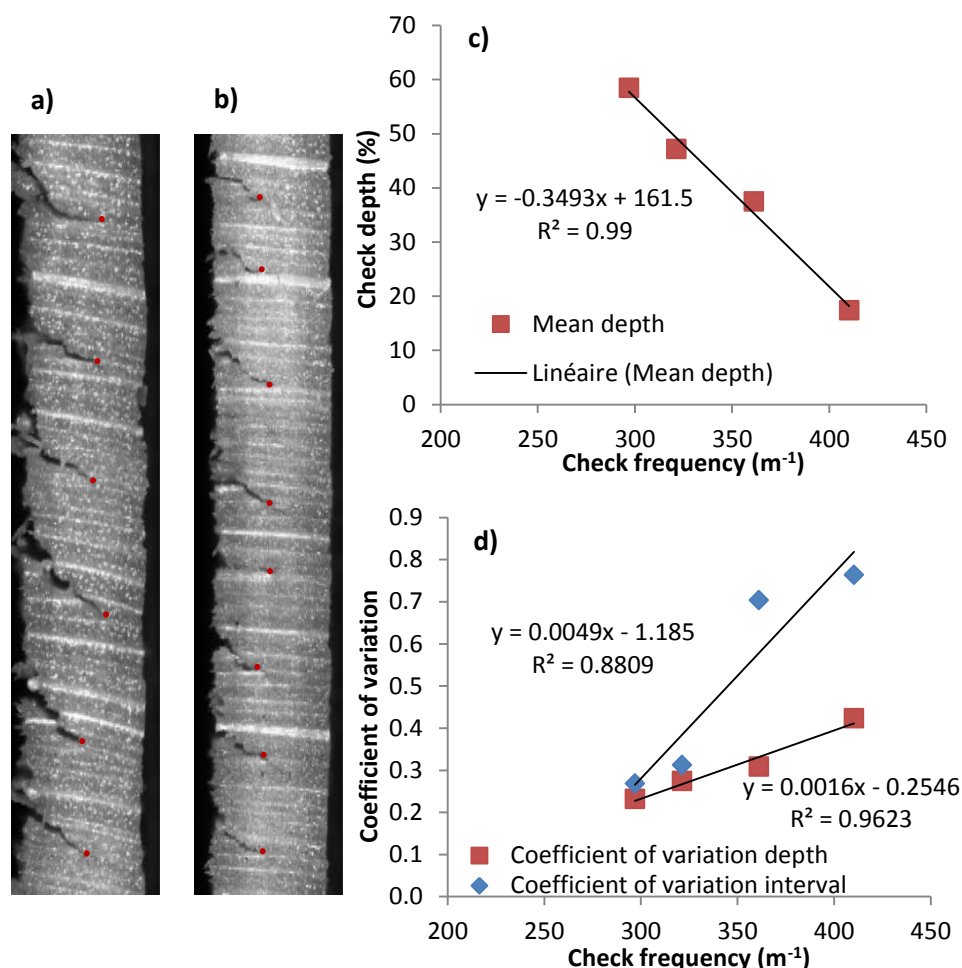divided by the length of veneer measured. At least 822 checks were measured for each compression rate.

Figure 2: SMOF images of checked veneers obtained with compression rates of the pressure bar of 0% (a) and 10% (b). The red dots show the position of the tip of each check. (c) Mean check depth according to check frequency of veneers obtained using different compression rates of the pressure bar.

Results and discussion

Table 1 presents mean and coefficient of variation (CoV) of depth and interval that were measured for each compression rate. For compression rate between 0 and 15%, check frequency increases from 297 to 410 m^{-1}. While check frequency increases, the mean check depth decreases linearly, with a coefficient of determination (R^2) of 0.99 (Fig. 2c). The equation of this linear relationship is:

$$d\% = -0.3493\,f + 161.5 \qquad (1)$$

Where $d\%$ is the mean check depth (% of thickness, which is a constant of 3 mm here), and f is the check frequency.

     Similar results were obtained when considering veneer thickness variation and check frequency (Pałubicki et al. 2010; Denaud et al 2007; Thibaut 1988). However, to the best of the authors' knowledge, this is the first time that such a linear relationship between mean check depth and check frequency is noted as a result of different compression rates of the pressure bar. Only four different compression

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rates were tested, so this result should be verified by further measurements, but it provides a promising approach for modeling.

The CoV_{depth} and $CoV_{interval}$ are greater than 0.23 and increase with check frequency (Fig. 2d). As a result, the variability in terms of depth and interval increases with check frequency. The statistical moments of higher order are not presented here, but can be seen in Dupleix et al. (2013), for example.

Table 1: Statistical characteristics of veneer checking for different compression rates of the pressure bar.

| Parameter | Pressure bar compr. rate | | | |
	0 (%)	5 (%)	10 (%)	15 (%)
Veneer thickness (mm)	3	3	3	3
Length of veneer measure (mm)	822	1518	1620	950
Number of checks	245	489	586	391
Check frequency (m^{-1})	297	321	361	410
Mean check depth (mm)	1.75	1.42	1.12	0.52
Mean check depth (%)	58.4	47.2	37.5	17.4
Standard deviation depth (mm)	0.41	0.39	0.35	0.22
Standard deviation depth (%)	13.6	12.9	11.5	7.4
Coefficient of variation depth	0.23	0.27	0.31	0.42
Mean interval (mm)	3.37	3.11	2.77	2.44
Standard deviation interval (mm)	0.90	0.97	1.95	1.86
Coefficient of variation interval	0.27	0.31	0.70	0.76

Mechanical properties of a checked LVL beam by numerical modeling

The EN 14374 (2005) standard states that the measure of the MOE of LVL shall be carried out in accordance with EN 408 (2012) method. It is four-point bending test with a beam height in the direction of the force of at least 100 mm when tested edgewise and 38 mm when tested flatwise. Such dimensions are not useful when modeling the homogenous beech wood, where no size-effect is expectable in the numerical modeling of the elastic behavior of clear wood without dispersed defects. The large dimensions induce unnecessary larger computation times. The French standard NF B51-016 (1987) proposes the following smaller dimensions for a four-point bending test: height 20 mm, width 20 mm, and the span 320 mm. Thus these dimensions were adopted for the numerical model.

Finite element model (FEM)

In the numerical model, wood is considered as a homogenous, elastic, and orthotropic material. As pointed out above, beech is particularly homogenous. The mechanical properties of beech used in the model were published by Guitard (1987); see Table 2. Glue is considered as en elastic isotropic material with Poisson ratio set to 0.3 and Young modulus initially set to 1000 MPa (Table 2). This modulus may be underestimated, but it will be demonstrated that this assumption is appropriate.

Table 2: Mechanical properties of beech wood (at 12% moisture content according to Guitard 1987) and glue that are used in the finite element model. R radial, L longitudinal, T tangential. Mod. modulus.

Wood mechanical properties:	
Young mod. in R direction E_R (MPa)	2040
Young mod. in T direction E_T (MPa)	867
Young mod. in L direction E_L (MPa)	14100
Shear mod. in R-T plane G_{RT} (MPa)	500
Shear mod. in T-L plane G_{RL} (MPa)	1850
Shear mod. in R-L plane G_{TL} (MPa)	980
R-T poisson ratio ν_{RT}	0.726
L-R poisson ratio ν_{LR}	0.365
L-T poisson ratio ν_{LT}	0.464
T-R poisson ratio ν_{TR}	0.309
R-L poisson ratio ν_{RL}	0.053
T-L poisson ratio ν_{TL}	0.029
Glue mechanical properties:	
Young modulus (MPa)	1000
Poisson ratio	0.3

The FEM of the checked LVL beam is built in *ANSYS® Mechanical, Release 14.0* program with 3-D quadratic solid elements. An elementary pattern of checked veneer is defined thanks to a given interval between checks and veneer thickness (Fig. 3a). The width of the checks is taken equal to 7% of the interval in its larger part. This width is divided by 3 at the half depth of the check, and then the width of the check decreases until check's tip. The possible gluing of the checks is modeled by means of an element that fills check lips as shown in Fig. 3b. This glue element has the mechanical properties of glue as defined in Table 2. For beams with glued or non-glued checks, the pattern of Fig. 3a or 3b is repeated in the height and the width of the beam (Fig. 3c). Notice that the interlayered glue bond is not modeled, which means that the glue bond is considered to behave as wood material. The section of Fig. 3c is extruded in the longitudinal direction (Fig. 3d) to build the beam, which dimensions are set according to NF B 51-016 (1987). The distance between a loading position and the nearest support in the bending test is 80 mm. As shown in Fig. 3d, only half of the beam is modeled because of the symmetry of loading and geometry.

As shown in Fig. 3c, the check depth and the interval between checks are constant for a given LVL beam. It is assumed that these parameters are linearly dependent by application of Eq. 1. This modeling enables to highlight the effect of lathe check depth and frequency regardless of their natural variability shown previously. However, because of the imposed cross-section of 20 mm x 20 mm for the beam and because of the basic pattern defined in the model, the number of veneers and the number of intervals must be integers. Thus, veneer thickness cannot be 3 mm as in experimental works, but is defined as 2.86 mm in order to have a whole number of veneers in the cross-section (7 veneers). It is assumed that this difference of 4.6% in veneer thickness does not influence the relationship between lathe check frequency and mean check depth. According to this relationship, the possible check frequencies range between 200 and 450 m^{-1} (4 to 9 intervals in the width of the LVL beam), since the range of possible check frequencies is limited by the depth (between 0% and 100% of veneer thickness). The models of the six possible checked veneers are presented in Fig. 3e.
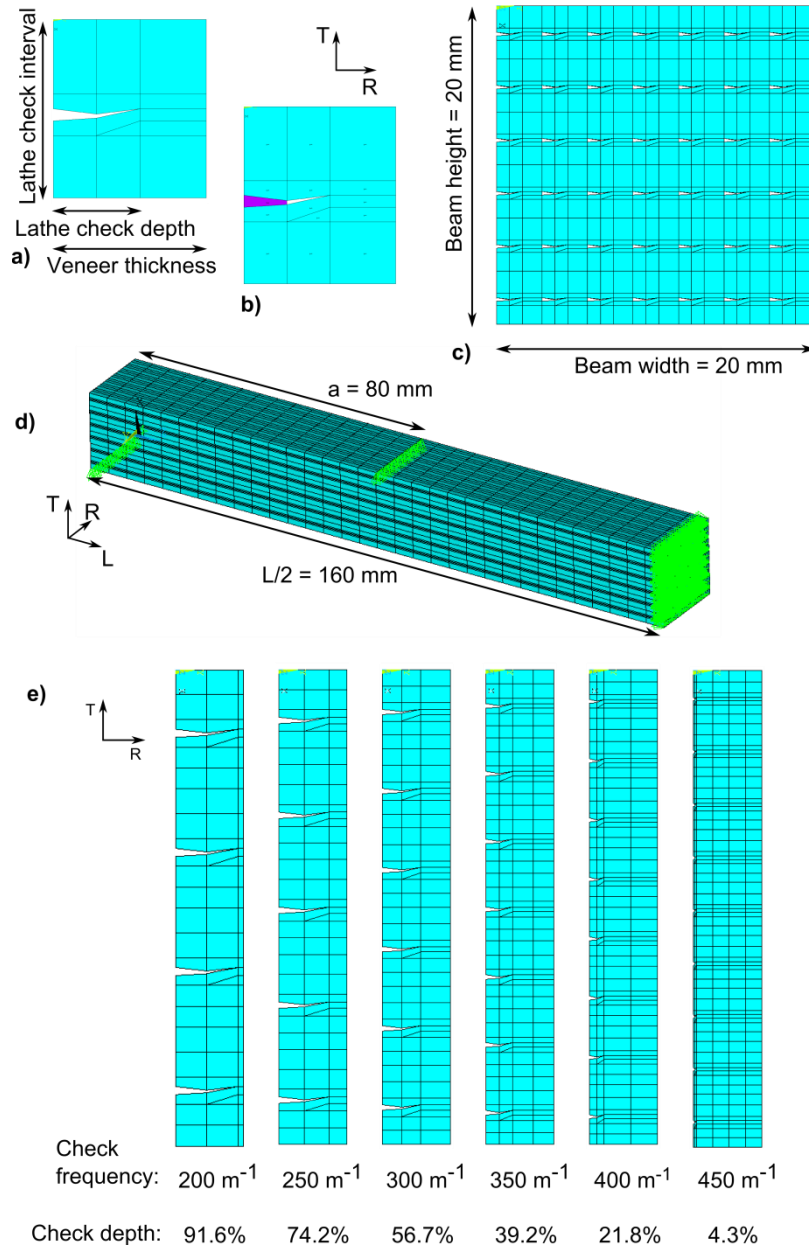
Figure 3: Finite element model of checked LVL beam tested in edgewise condition. (a) Basic pattern; (b) basic pattern with glued check (glue is in purple color); (c) beam cross section (check frequency 300 m^{-1}); (d) half of the beam (green triangular symbols represent boundary conditions); (e) finite element model of the six different checked veneers used in the LVL beam model with different check frequency and check depth that respect the linear relationship of equation 1.

Calculations of elastic mechanical properties

In the proposed linear elastic FEM, a constant load is imposed at the loading position defined by NF B51-016 (1987). Then, the MOE is calculated depending on beam displacements. EN 408 (2012) defines two different MOE that depend on the measurement method (Fig. 4).

Local modulus

The local modulus is calculated based on to the measurement of the deflection in a zone of length l_1 located between the loading positions (Fig. 4a), where the beam is subjected to pure bending. The local modulus of the LVL beam in bending, $E_{LVL,l}$, is defined as:

$$E_{LVL,l} = \frac{al_1^2 F}{16 I w_l} \qquad (2)$$

Where a is the distance between a loading position and the nearest support in the bending test, l_1 is the length of the beam on which the local deflection is measured, F is the total load, I is the second moment of area, and w_l is the local deflection taken at the neutral axis as shown in Fig. 4a.

Eq. 2 is applied in EN 408 (2012) and NF B51-016 (1987). Because it is calculated in a pure bending zone, the local modulus is the actual MOE of the LVL beam in the longitudinal direction (Nocetti et al. 2013).
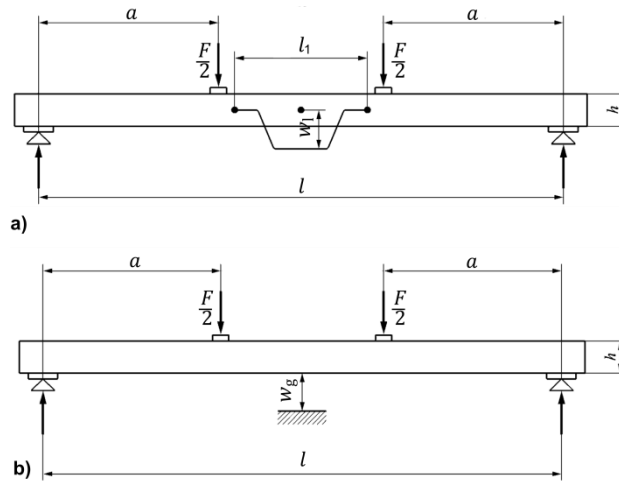

Figure 4: Four-point bending test with local (a) and global (b) measurement of the deflection.

Global modulus

The EN 408 (2012) standard provides a second method of MOE calculation, called "the global method". This consists of measuring the total deflection at the mid-span of the beam, thus, a deflection that is due both to bending and shear effects. The global modulus in bending $E_{LVL,g}$ is calculated as:

$$E_{LVL,g} = \frac{3al^2 - 4a^3}{2bh^3 \left(2\frac{w_g}{F} - \frac{a}{kGbh} \right)} \qquad (3)$$

Where a is the distance between a loading position and the nearest support in the bending test, l is the support span, b is the width of the beam, h is the height of the beam, F is the total load, w_g is the total deflection at the mid-span of the beam

(taken at the bottom of the beam *cf.* Fig. 4b), k is the shear coefficient ($\mathrm{k} = {}^5/_6$ in EN 408 (2012), and G is the shear modulus.

Eq. 3 results from the application of the Timoshenko beam theory for an isotropic material (Timoshenko 1921). For an orthotropic material, the equation linking the vertical displacement to the longitudinal MOE is much more complex (Tang 1972, Sullivan and Van Oene 1986). Consequently, the global modulus as defined in EN 408 (2012) does not correspond exactly to the longitudinal MOE of the material, but is an approached value (Nocetti et al. 2013). In the frame of the present work, the global modulus is used to characterize the influence of lathe check on the total deflection at the mid-span. In Eq. 3, the shear modulus used is that of wood material, that is G_{TL} in edgewise bending and G_{RL} in flatwise bending (see Table 2 for numerical values of shear modulus).

Shear modulus

Eq. 3 serves for calculating the shear modulus of the LVL beam resulting from the application of the Timoshenko beam theory for an isotropic material, noted G_{LVL}:

$$G_{LVL} = \frac{a}{kbh\left(2\dfrac{w_g}{F} - \dfrac{3al^2 - 4a^3}{2bh^3\,E_{LVL}}\right)} \qquad (4)$$

where E_{LVL} is the longitudinal modulus of the beam. This modulus can be considered to be equal to the local modulus, because the local modulus is the actual MOE of the LVL beam. The other parameters are the same as in Eq. 3.

Model results

Global and local modulus

The local modulus and global modulus were calculated for LVL beams with glued or non-glued checks, both in edgewise or flatwise bending. The results are presented in Fig. 5a and 5b, respectively.

While the check frequency increases, both type of moduli increase. Therefore, the greater the check depth, the lower the modulus, even if checks are less frequent. This shows that according to the observed relationship between these parameters (Eq. 1), the effect of check depth increment overcomes the effect of check frequency decrement.

Local modulus

The variations of parameters as check frequency, loading direction or gluing of the checks change the local modulus at most by 2.5%. Thus, the bending modulus of LVL is not highly influenced by lathe checks because these affect the inertia of the beam only marginally. These results are in accordance with experimental studies which did not find clear difference in the MOE of beams made of different veneer thicknesses (*i.e.* different check depth and frequency) (Ebihara 1981; Hoover et al. 1987).

For each check frequency, there is a relative difference lower than 0.5% between the local modulus of beam with glued checks and with non-glued checks, or between flatwise and edgewise loading. Therefore, check gluing has a minor influence on the longitudinal MOE of LVL beams.
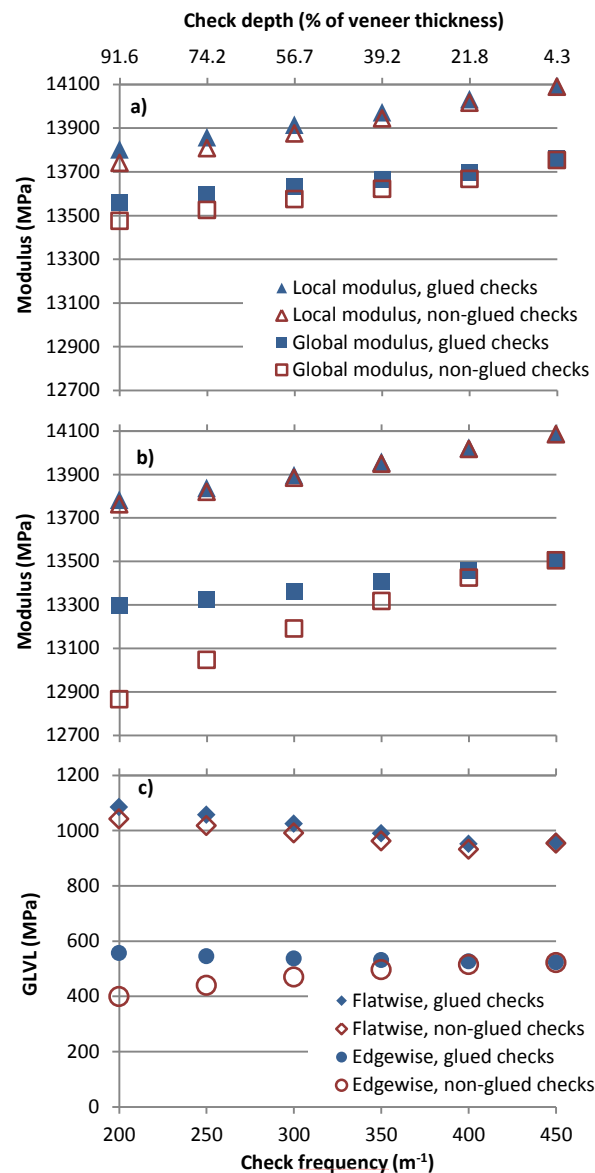

Figure 5: Mechanical properties of an LVL beam obtained by finite element modelling according to checks depth, frequency and gluing: local and global modulus obtained in flatwise (a) and edgewise (b) condition, shear modulus (c) computed by application of conventional Timoshenko beam theory (equation 4). Open symbols: checks are not glued; closed symbols: checks are partially glued.

Global modulus

The global modulus is lower if the beam is bent edgewise (Fig. 5b) instead of flatwise (Fig. 5a). For beams with glued checks, the average relative difference between the global modulus of this two loading directions is 4.1%. As a result, the

global modulus is more influenced by the bending direction than the local modulus. This is because the shear displacements taken into account in the computation of the global modulus (Eq. 3) are different: the shear modulus in the R-L plane, which is loaded in flatwise bending is higher than the shear modulus in the T-L plane, which is loaded in edgewise bending (Table 2).

For beam with glued checks, the global modulus varies by about 1.5% between check frequency of 200 m^{-1} and 450 m^{-1}, both in edgewise or flatwise bending. For beam with non-glued checks, the global modulus varies by about 2.1% in flatwise bending (Fig. 5a) and by 5.0% in edgewise bending (Fig. 5b) for check frequency between 200 m^{-1} and 450 m^{-1}. As a result, the global modulus is more influenced by the checks gluing than the local modulus if tested in edgewise bending. This behavior is due to the shear displacements that are more important in edgewise bending because checks are horizontal, thus they are more subjected to shear. This lead to a lower global modulus in edgewise bending for beam with deep checks, as shown in Fig. 5b. Following the above explanation, a more curved shape of lathe check may lead to a more significant decrease of global modulus in flatwise bending.

LVL shear modulus

The evolution with check frequency of the shear modulus of LVL beams resulting from the application of the Timoshenko beam theory for an isotropic material (Eq. 4) is presented in Fig. 5c. The shear modulus calculated in flatwise bending (diamond shapes in Fig. 5c) is higher than in edgewise bending (circles in Fig. 5c), which can be justified by the difference in the material shear modulus according to loading direction (higher shear modulus in the R-L plane than in the T-L plane, Table 2).

However, the results presented in Fig. 5c show that the shear modulus of the LVL is lower than the shear modulus of the material by a factor close to 2. This is observed even for the LVL beam with the higher check frequency, thus the shallower checks and the higher homogeneity of the cross-section, which is surprising. A second unexpected result is that the shear modulus increases while check frequency decreases in flatwise bending and for beam with glued checks in edgewise bending. An increase of the shear modulus with check frequency was expected, due to the shallow checks, which leads to a more homogeneous cross section. This is only observed for an LVL beam with non-glued checks in edgewise bending. These behaviors can be explained by the fact that the shear moduli are calculated here by inversed formulas of EN 408 (2012) that relies on the Timoshenko beam theory for an isotropic and homogenous material. By doing so, the shear modulus does not correspond to the shear modulus of the material. Yoshihara et al. (1998) showed that the conventional Timoshenko bending theory may lead to erroneous shear moduli by experimental and FEM. The shear modulus is often underestimated if the span to depth ratio becomes higher (Fig. 3 in Yoshihara et al. (1998)), when the stress concentration disturbs stress distribution. We can add that orthotropy may also be the reason because the equations applied are different to those applied in the isotropic case (Tang 1972; Sullivan and Van Oene 1986). A correction of the shear coefficient may improve the shear modulus consistency but the depth to span ratio and the mechanical properties of wood may influence the results (Yoshihara et al. 1998). In the present study, the heterogeneity due to the checks can be another cause of discrepancy between the shear modulus

of the material and the shear modulus of the LVL beam determined based on the conventional beam theory. Therefore, a correction was not applied here, and it is not standard ($k = {}^5\!/_6$ in EN 408, 2012). Accordingly, absolute values and variations with check frequencies of the shear modulus as calculated in Eq. 4 cannot be interpreted. However, G_{LVL} is an interesting parameter to follow since it characterizes the shear rigidity of a checked LVL beam in the frame of conventional beam theory. For a given bending direction and check frequency (*i.e.* a given direction of orthotropy and level of heterogeneity), this shear modulus can be used to compare the relative influence of check gluing on the shear rigidity of LVL beams.

For each direction of bending and each check frequency, LVL beams with glued checks have higher shear rigidity than beams with non-glued checks (Fig. 5c). This result was expected as glue increases the rigidity of the global structure. The difference in shear rigidity depends on the check frequency. As check frequency decreases, and thus check depth increases, the difference between LVL beams with glued checks and LVL beam with non-glued checks becomes higher. The relative difference in shear rigidity as calculated in Eq. 4 between beam with glued and beam with non-glued checks in edgewise bending is 39% for a check frequency of 200 m^{-1}, and only 0.1% for a check frequency of 450 m^{-1}. In flatwise bending, this relative difference is 4.2% for a check frequency of 200 m^{-1}, and 0.6% for a check frequency of 450 m^{-1}. As a result, the influence of check gluing is lower in flatwise bending than in edgewise bending. As already mentioned for the interpretation of global modulus results, the proposed explanation for this behavior is that in edgewise bending checks are horizontal so shear deformation are higher than in flatwise bending, for which checks are vertical. Furthermore, deep checks induce higher concentrations of shear than small checks. This effect is amplified by the fact that in this model checks are inline in radial direction (Fig. 3c), which is the most disadvantageous case for shear. One can note that for a different check geometry, for example more curved checks, the results may be different as curved checks may be more subjected to shear while tested in flatwise bending, which must result in a higher influence on the shear rigidity.

To study the influence of the Young's modulus of the glue, a higher value of glue modulus (8000 MPa) has been tested. The relative increase of LVL shear rigidity in edgewise bending between beam with glued checks with a glue modulus of 8000 MPa and 1000 MPa, respectively, is between 6.6% (check frequency of 200 m^{-1}) and 2.7% (check frequency of 350 m^{-1}). By considering the effect of check gluing which increases shear rigidity between 39% (check frequency of 200 m^{-1}) and 7.0% (check frequency of 350 m^{-1}), the value of modulus of the glue has only a second order effect for check frequencies lower or equal to 350 m^{-1}. For higher frequencies, the effect of both check gluing and glue modulus are negligible (below 2%).

Conclusion

The proposed FEM of an LVL beam with checked veneers is based on the assumption of a periodic distribution of similar checks with a constant depth. It has been shown experimentally that there is a linear relationship between check depth and frequency when changing the compression rate of the pressure bar in the peeling process of beech wood. This linear relationship is used to model different veneer qualities for the same veneer thickness.

The numerical simulations of a four-point bending test show that the local modulus, *i.e.* the longitudinal MOE of LVL beams is not highly influenced by the different check frequencies (less than 2.5% of relative difference). The global modulus calculated according to EN 408 (2012) standard is more influenced by checking in edgewise bending than in flatwise bending, which is explained by the higher influence of checks on the shear deformation if they are horizontal in the bending test. However, the gluing of the checks considerably reduces their influence on the global modulus, even with a MOE of glue fourteen times lower than the longitudinal MOE of wood. This is also illustrated by the calculation of the shear modulus according to the Timoshenko beam theory for an isotropic and homogeneous material, which enables to show that the relative difference in shear rigidity can reach 39% between beam with glued checks and beam with non-glued checks in edgewise bending. This ratio is a maximum that is reached because of a specific repartition and shape of checks in the model. Further numerical simulations will be performed to study the influence of the check pattern, check distribution, or veneer thickness on LVL mechanical properties.

The results of this numerical study suggest that the gluing of lathe checks is a parameter that must be followed to interpret the possible variations in global modulus or shear rigidity of LVL beams. Further experiments are recommended to test the shear behavior of LVL as a function of the amount of glue applied.

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