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Rolling shear modulus and strength of beech wood laminations

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Abstract: Previous research indicated that the rolling shear properties of European beech wood (*Fagus sylvatica*) are considerably higher than those of softwood. The aim of the presented investigation was to substantiate previous data on rolling shear modulus and strength of European beech wood and to further evaluate its substitution of softwoods in applications where shear properties are influential, namely as cross layers in cross-laminated timber (CLT). Further, the effect of the annual ring orientation within the boards on shear modulus and strength was of major interest. The beech specimens comprised four different sawing patterns, classified unambiguously with reference to the pith location. The shear properties were determined by 50, two-plate shear tests with specimen cross-section dimensions of 33 mm × 135 mm. A mean rolling shear modulus of 370 N mm^{-2} was obtained, whereby no significant detrimental effect for pith boards with cracks was observed. In agreement with continuum mechanics, the semi-quarter-sawn boards revealed the highest shear moduli whereas the quarter-sawn boards showed roughly 30% lower values. The mean rolling shear strength was 5.6 N mm^{-2} for all specimens, whereby pith specimens resulted in generally lower values. The 5% quantile, disregarding pith specimens, was 4.5 N mm^{-2}. In conclusion, the rolling shear strength and modulus exceed the respective characteristic values for softwoods by roughly factors of 5 and 7, indicating great potential for beech wood cross-layers in CLT.

Keywords: cross-laminated timber (CLT), density, European beech, off-axis properties, rolling shear modulus, rolling shear strength, sawing pattern, two-plate shear test

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Introduction

Rolling shear modulus and strength of the cross layers are decisive mechanical properties in cross-laminated timber (CLT) plates. The composite material CLT is built up in the slab thickness direction by orthogonally crossed layers of boards, hereby closely resembling solid wood-wise the classical plywood build-up of thin, cross-wise layered veneers. Currently, CLT, which is of ever increasing importance globally for medium and high-rise timber buildings, is almost exclusively manufactured from softwood (spruce/fir) boards. All existing European CLT approvals, which are based on the former European Common Understanding Procedure (OIB 2005) or the present European Assessment Document (EOTA 2015) as well as the recently approved European CLT standard EN 16351 (2015) address exclusively softwoods as lamination material. In recent years, the use of hardwoods in wooden construction products has become an ever increasingly important topic in central Europe. Lower grade beech wood (*Fagus sylvatica*, Linnaeus 1753) is utilized almost entirely thermally, but it is obvious that this material should be very apt for CLT buildups. This hypothesis is based on the assumption that the rolling shear properties of beech are probably very satisfactory (Stamer and Sieglerschmidt 1933; Hoefflin and Aicher 2000; Niemz et al. 2015). The intention is to gain a deeper insight into the mechanical properties of beech wood for homogeneous and hybrid CLTs within the framework of an ongoing European WoodWisdom research project on hardwoods. The present paper reports on the rolling shear modulus and strength investigations of single beech board slabs with emphasis on the boards' sawing patterns and herewith associated growth and drying defects.

Theoretical background, materials, and methods

Sawing pattern influence as assessed by the continuum theory: The rolling shear modulus is, apart from one single configuration, not an intrinsic material property, but rather an apparent quantity depending decisively on the annual ring orientation within the board and the stiffness ratios in the radial-tangential growth plan. This can be demonstrated by means of a simplified orthotropic continuum mechanics approach. On the mesoscale, i.e. at edge lengths of a few millimeters, wood can be regarded as a rhombic anisotropic, and thereby termed orthotropic, material with three material coordinate axes orthogonal to each other. Irrespective of the spatial orientation of the three axes, there is always a unique 4th order elasticity tensor C_{ijkl} relating strains and stresses in a precise manner by the relationship:

$$\sigma_{ij}=C_{ijkl}\varepsilon_{ij} \quad (i,j=1,2,3) \tag{1}$$

Several materials have defined, major axes orientations, termed on-axis material coordinates denoted by x, y and z. This is true for natural ideal rhombic orthotropic materials (specifically crystals) and scale dependent approximately orthotropic materials (such as wood) as well as man-made orthotropic composites. In the case of wood, the on-axis directions are related to the tangential t, radial r and longitudinal (fiber parallel) l growth directions; in the following, the association $x=t$, $y=r$, $z=l$ shall hold. Concerning the regarded mechanical problem of (rolling) shear in the radial-tangential growth plane under plane stress conditions, the longitudinal growth direction has no impact and the constitutive equation (1) and thus the 3D problem is in reality a 2D-problem in the $i,j=1,2$ plane.

Let us consider a wooden board or stick cut from the periphery of a large diameter tree. Further, the board shall have a small side aspect ratio of about 1:2 to 1:4 and small absolute dimensions, for instance 20 mm thickness. In this case, the annual ring curvature within the board is engineering-wise negligible. Further, the annual ring angle φ between the off-axis direction 1, chosen deliberately to align with the wide board edge, and the on-axis material direction $x=t$ is almost constant along the board width (Figure 1a). For such idealized board configurations the apparent in-plane (rolling) shear modulus can be easily calculated for any off-axis angle φ by transformation from the known constitutive on-axis properties. Without further derivations, which are given in detail in textbooks on composite theory (e.g. Tsai and Hahn 1980), the apparent rolling shear modulus in the r-t plane can be written as

$$G_r(\varphi)^{-1}=4m^2n^2(S_{xx}+S_{yy}-2S_{xy})+(m^2-n^2)^2S_{ss} \tag{2}$$

where $m=cos\varphi$; $n=sin\varphi$; $S_{xx}=\frac{1}{E_t}$; $S_{yy}=\frac{1}{E_r}$; $S_{ss}=\frac{1}{G_{rt}}$; $S_{xy}=-\frac{\nu_{tr}}{E_r}=-\frac{\nu_{rt}}{E_t}$.

(Note: definitions of Poisson indices here 1st index strain, 2nd index stress.)

With regard to on-axis elasticity properties of beech wood in the rt-plane, literature provides rather little original data (Table 1). For comparison, bench mark data on Norway spruce are also listed. Data in Table 1 reveal that the on-axis (rolling) shear modulus G_{rt} of beech wood is in the range of about 400 to 500 N mm^{-2} and hence roughly ten times larger than the on-axis G_{rt} value of Norway spruce which is about 40 to 60 N mm^{-2}. The modulus of elasticity (MOE) ratio E_r/E_t of beech wood extends from about 1.3 to 2.0 and is hereby in the same range as spruce. In absolute terms, E_r of beech is considerably, roughly 1.6 times, higher, which reflects well the specified density difference of an average factor of 1.5.

The ratio of E_r/G_{rt} of beech ranges roughly from 3 to 5 and in case of spruce 20–40. This stiffness ratio has a fundamental impact on the variation of the apparent (rolling) shear modulus in off-axis material orientations. This is highlighted by the graph in Figure 1b, which depicts the shear modulus ratio $G_r(\varphi)/G_{rt}$ drawn on the ordinate axis as a function of off-axis angle φ. The curves reveal the extremely different situation for both species as depending parametrically on the ratios E_r/G_{rt} and E_r/E_t. Consistently, the extreme values are at $\varphi=0°$,

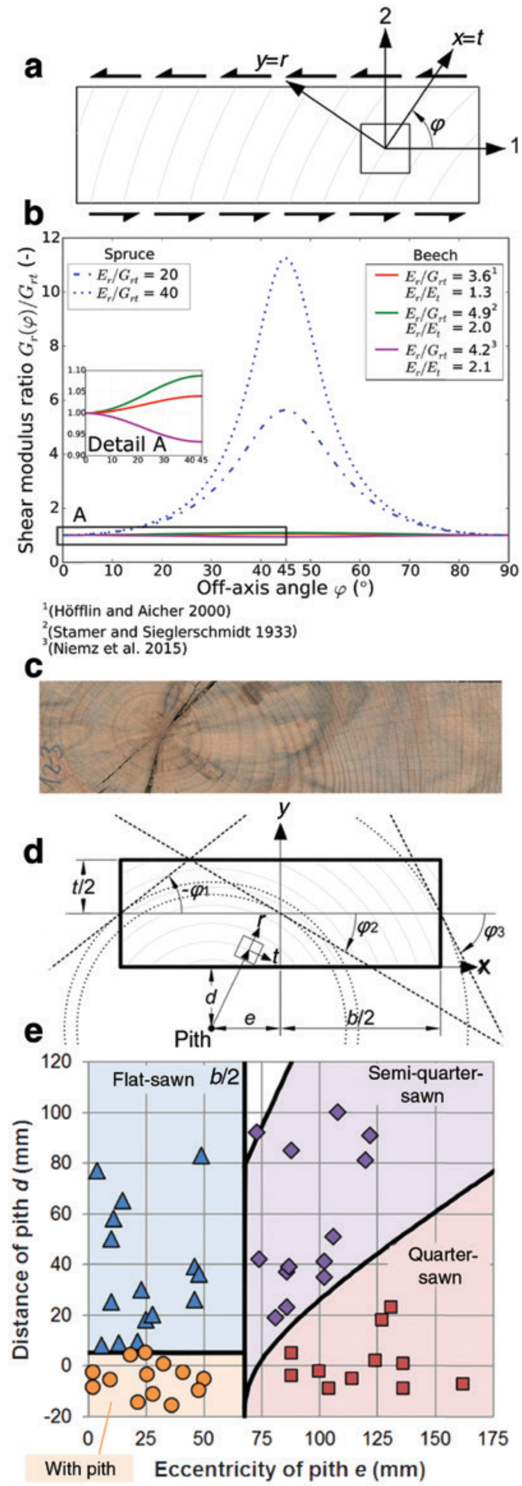

Figure 1: Geometry and sawing pattern definitions as well as analysis of beech wood boards with respect to rolling shear modulus: (a) definition of angle φ between on-axis radial(r)-tangential(t) plane axes and deliberate off-axis coordinates 1,2. (b) Relationship of normalized off-axis shear modulus depending on angle φ for typical ratios E_r/G_{rt} and E_r/E_t of beech and reference spruce wood. (c) View of a typical beech board including pith and the associated cracks. (d) Characteristic dimensions d, e of pith allocation and definition of angles φ_i. (e) Classification of sawing patterns of the rolling shear specimens based on unambiguous annual ring geometry parameters.

Table 1: On-axis stiffness properties in the radial-tangential growth plane of defect free beech wood (*Fagus sylvatica*) and spruce (*Picea abies*) in small clear dimensions.

Species	Density	Modulus of elasticity		Shear modulus	Poisson's ratio		Stiffness ratio		Source
	ρ_{12} (kg m^{-3})	E_r (N mm^{-2})	E_t (N mm^{-2})	G_{rt} (N mm^{-2})	ν_{rt} (-)	ν_{tr} (-)	E_r/E_t (-)	E_r/G_{rt} (-)	
Beech	760	2280	1160	470	0.38	0.71	2	4.9	a
	720	1700	1290	470	0.44	0.58	1.3	3.6	b
	640–690	1580	740	380	0.31	0.61	2.1	4.2	c
Spruce	540	1451	1024	40	0.34	0.48	1.41	36	b
	450	1080	800	45	0.37	0.5	1.35	24	b
	470	–	–	55	–	–	–	–	d

[a]Stamer and Sieglerschmidt (1933).
[b]Hoefflin and Aicher (2000).
[c]Niemz et al. (2015) – E_r and E_t, average of tensile and compression values.
[d]Dumail et al. (2000) – adjusted to 12% moisture content by a factor or 1.04.

45° and 90° whereby $G_r(0,90)/G_{rt}$ =1 throughout. The extreme value of apparent shear modulus G_r at 45° is fully independent of G_{rt} (Eq. 2) and extremely sensitive to the stiffness ratios. For most of the beech wood stiffness configurations given in Table 1, the ratio $G_r(45)/G_{rt}$ is in the range of 1.0–1.1; some on-axis data (Niemz et al. 2015) deliver a ratio of slightly below 1. Thus, on the basis of the rough assessment of the shear stiffness behavior of a beech board as being dependent on annual ring angle φ based on orthotropic continuum assumptions, it can be concluded that $G_r(\varphi)$ of beech wood, in significant contrast to spruce, should not vary in an extreme manner for different board configurations. A deeper theoretical insight would be gained on the basis of a polar anisotropic modeling of the board's stiffness as done for spruce by Aicher and Dill-Langer (2000) and Jakobs (2005), which is however, outside the scope of this paper.

Considerations on two-plate compression-shear tests: Currently, no internationally recognized test procedure for direct determination of the rolling shear strength and apparent shear modulus of a single board exists, representing some of the most important properties for design and calculation of cross-laminated timber (CLT) plates. The European product standard on CLT (EN 16351 2015) does, however, contain detailed provisions on the determination of the integral rolling shear properties of a cross layer consisting of several adjacent boards in three or more layered plates by two somewhat different compression-shear test methods. One test method refers to the two-plate shear test in the European standard EN 789 (2004) which is intended for the determination of in-plane shear properties of panels. Alternatively, a modified version of the stated test method allows for a wider dimensional variability of the specimen, and avoiding the lateral steel plates by transfer of the loads via the lengthwise oriented CLT boards.

Two further possible two-plate compression-shear test principles are provided by i) the European standard EN 408 (2012) on determination of shear strength parallel to the fiber of solid wood and ii) by the ASTM standard D 2718 (2016), serving for the determination of planar shear, i.e. rolling shear of structural panels. Contrary to the European shear tests in EN 789 and EN 408, which prescribe the specimen dimensions very rigorously, ASTM D 2718 followed by Zhou et al. (2014) for determination of rolling shear properties of down-sized black spruce laminations, allows for significantly different specimen sizes by geometrically similar adjustment. In addition, the issue of angle α between the line of the applied shear force V, and the specimen axis or bondline is handled inconsistently in the different mentioned standards. In the case of EN 789, angles in the range of 8–25°, which are dependent upon specimen thickness (6–80 mm), are obtained, whereas the cited alternative EN 16351 procedure, like EN 408, prescribes a fixed load line angle α of 14°. ASTM D 2718 also prescribes a minimum width and height as a function of the thickness, giving a considerably shallower load line angle of about 3 to 5°.

The issue of angle α in the context of direct (two-plate) shear tests, which has a strong impact on the superpositioned normal stresses perpendicular to the rolling shear plane, has been investigated by Feldborg (1991) and Mestek (2011). There are both advantages and disadvantages for the different angles in the range of 3–14°, which is to be further investigated. For lack of any directly applicable standard, the test setup shown in Figure 2a, based on a realization of α≈14°, has been chosen. It should be further mentioned that apart from (quasi) two-plate shear tests, several further test methods for determination of rolling shear properties exist. A bending test with short spans is possible (EN 16351), enabling determination of rolling shear modulus and strength. An additional test approach with shear loaded notched, so-called Iosipescu specimens for on-axis G_{rt} determination, as employed by Dumail et al. (2000) is also possible. However, the latter test is poorly suited for the determination of rolling shear strength.

The beech wood (*Fagus sylvatica*) originated from a forest in Southern Germany, about 50 km north of Stuttgart. The logs from

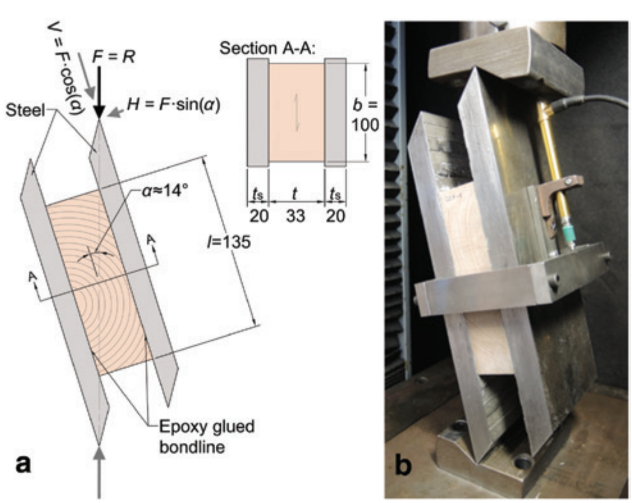

Figure 2: Employed test setup: (a) technical scheme with dimensions (in mm); (b) view of the realized test setup with fixed LVDT slip measurement.

which the boards were cut had bottom and top diameters of 0.7 to 1 m and 0.6 to 0.8 m, respectively. The logs were sawn flatwise as is usual in hardwood processing to slabs/planks of 50 mm thickness. The planks were then air-dried for one year prior to kiln drying to a target moisture content (MC) of 12% within a period of one week. After drying, the planks were sawn to 140 mm wide and 38 mm thick boards, comprising the whole spectrum of possible annual ring configurations. Further, boards were frequently obtained where the annual ring pattern changes within the board, for instance from quarter- to semi-quarter-sawn. A more rigorous definition is given later on. Regarding the growth characteristics, such as, e.g. knots and fissures, the boards cut from the outer stem periphery were almost defect free and had no cracks whereas the boards containing pith or which were located close to the pith contained almost throughout cracks as shown exemplary in Figure 1c. A batch of 200 boards with lengths in the range of 2.5 to 4 m were ordered for various testing purposes, one of which being the here described rolling shear tests. Prior to cutting of the specimens, the boards were planed to a final thickness and width of t=33 mm and l=135 mm, respectively. A total of 50 specimens were then cut with a length (parallel to fiber) of b=100 mm, comprising all of the below discussed annual ring patterns.

In order to assess the effect of the annual ring orientation within a board, termed sawing pattern, this specimen property was measured in a quasi-unambiguous manner and then classified in close alignment with the established annual ring classifications. The unambiguous classification of the sawing pattern was based on a best possible allocation of the pith of the stem from which the board was cut vs. a reference point located at mid-width of the wide cross-sectional board's edge oriented towards the pith. This edge and the related board's face is generally termed "right" board edge or face. The characteristic dimensions for the pith allocation are (Figure 1d): e=eccentricity of the pith vs. mid-width of the board and d=distance of the pith vs. the "right" board edge. In case the pith is located within the thickness t of the board, d is negative and further defined by $|d|\leq t/2$.

The actual determination of e and d was performed by means of both respective end grain face scans of the specimen slabs, which were then processed by a graphical algorithm searching for the best matching pith position with regard to the annual ring contours of the board. The bias related to the specified "exact" origins has not been investigated and is dependent on various factors, such as for instance the stem contour geometry, here throughout assumed to be circular.

As the mathematical description of the annual ring orientation of the board does not enable an immediate grading classification of the board with regard to the established sawing pattern classes, e.g. type quarter-sawn, all specimens were classified with regard to these easily visually perceivable groupings as well. Nevertheless, todays established definitions on sawing patterns based on an average annual ring angle φ for the whole board were found to deliver a too imprecise classification of, most notably, the boards with a pronouncedly changing annual ring angle φ.

To address this issue in a more transparent manner, the determination of the annual ring angle was based on the value $\varphi_{mean}=(\varphi_1+\varphi_2+\varphi_3)/3$ where angles φ_2, φ_1, and φ_3 represent the means of both end grain faces measured along a line at half the board's thickness at mid-width x=0 of the board and at the ends $x=\mp b/2$, respectively (Figure 1d). Based on the φ_i, φ_{mean} and d definitions, the established sawing patterns a, b, c (see below) and a further pattern (d) are specified more precisely as:

$$60°\leq\varphi_{mean}\leq 90° \text{ quarter-sawn (a)}$$

$$30°\leq\varphi_{mean}<60°;\ \varphi_1>0° \text{ semi-quarter-sawn (b)}$$

$$0°\leq\varphi_{mean}<30°;\ \varphi_1\leq 0°;\ d>5 \text{ mm flat-sawn (c)}$$

$$\varphi_1<0°;\ d\leq 5 \text{ mm including pith (d)}$$

Figure 1e reveals for all specimens the relations between the mathematically unambiguous annual ring definition of e and d, and the conventional, here given definitions of sawing patterns (see also Table 2). The geometry parameters e and d enable a cylindrical or polar anisotropic finite element continuum analysis of the board's apparent in-plane stiffness properties, so for instance of shear modulus G_r, not presented in this paper.

Apart from the sawing pattern, the specimens were further classified or measured with regard to density and eventual cross-sectional cracks. Table 2 gives a statistical evaluation of the densities and the geometrical parameters separately for the respective sawing patterns and for the whole sample of specimens. Density ρ_{12} of the specimens ranged from 600 to 740 kg m^{-3}. The mean densities of the four different sawing pattern groups lay closely together, ranging from 651 to 685 kg m^{-3}. Further, the scatter of the densities in each group was comparably small with coefficients of variation of about 5%. Furthermore, the extreme values of the densities of the respective sawing pattern groups did not show very pronounced differences. The specified density values classify the material as typical for beech wood of medium density. According to literature (Kollmann 1982), the density range ρ_{12} of the species is 530…700…890 kg m^{-3}.

In contrast to the density, the geometrical quantities d, e, φ_{mean} and φ_1, describing the sawing pattern, differed definition-wise pronouncedly for the respective annual ring groups. Hereby the sample means of the mean annual ring angles of 15, 47, and 78° obtained for the flat, semi-quarter- and quarter-sawn group conformed very well with the central values 15, 45 and 75° of the conventionally assumed φ_{mean} ranges specified above for the respective sawing patterns.

With regard to macroscopic cracks visible at the end grain faces and on the wide sides, the different sawing pattern groups showed in some instances pronounced/extreme differences. In the case of the quarter- and semi-quarter-sawn specimens, no cracks at all were existent. Three of the 15 flat-sawn board specimens contained cracks. In contrast to the other groups, all 13 specimens containing pith had at times very expressed cracks; Figure 1c shows a typical end-grain crack appearance.

Figure 2a specifies the test scheme and dimensions and Figure 2b shows a view of the realized test setup. The test specimens were glued at room temperature between the steel plates with a special two-component epoxy resin (WEVO EP32 S with hardener WEVO B 22 TS), with a technical approval for glued-in steel rods in timber (DIBt 2014). In order to increase the strength of the bond between steel and beech, the surface of the steel plates was profiled by shallow (1.5 mm), rectangular grooves with a width of 10 mm along the width of the plates. The tests were performed in a screw-driven test machine at a constant rate of cross-head movement of 0.75 mm min^{-1}, whereby failure was achieved within 300±120 s. The relative slip between the two steel plates u, giving the average shear angle of the beech specimen $\tan\gamma=u/t$, was measured by an LVDT, which was fixed on one steel plate by measuring the movement of a steel bracket which was fixed opposite to the other steel plate at mid-length of the specimen. The tests were performed at 20±1°C in a non-climatized test chamber. The load and displacement were recorded continuously. The MC of the beech specimen

Table 2: Compilation of densities and of geometry parameters for sawing pattern classification as well as rolling shear modulus and strength results depending on sawing pattern of the investigated specimens.

	Flat-sawn	Semi-quarter-sawn	Quarter-sawn	Including pith	All	Without pith
Density ρ_{12} (kg m^{-3})						
n (-)	15	13	11	13	52	
Mean	682	655	651	685	669	
SD	36	35	33	30	36	
COV	5%	5%	5%	4%	5%	
Min	621	600	597	645	597	
Max	742	729	694	729	742	
Distance of pith *d* (mm)						
Mean	37	57	1	-5	24	
Min	8	19	-9	-16	-16	
Max	83	100	23	5	100	
Eccentricity of pith *e* (mm)						
Mean	24	95	119	26	62	
Min	4	73	88	2	2	
Max	49	122	162	50	162	
Mean annual ring angle φ_{mean} (°)						
Mean	15	47	78	23	38	
Min	2	30	67	3	2	
Max	30	57	86	35	86	
Annual ring angle φ_1 (°)						
Mean	-41	21	69	-74	-10	
Min	-68	3	44	-88	-88	
Max	-11	34	84	-57	84	
Number of specimens with cracks (-)						
n (-)	3	0	0	13	16	
Rolling shear modulus G_r (N mm^{-2})						
n (-)	14	13	11	10	48	38
Mean	381	419	298	370	370	370
SD	79	44	39	45	70	75
COV	21%	10%	13%	12%	19%	20%
Min	287	327	235	314	235	235
Max	534	473	351	445	534	534
HG	a,b	a	c	b	–	–
Rolling shear strength $f_{v,r}$ (N mm^{-2})						
n (-)	11	10	11	13	45	31
Mean	6.0	6.7	5.3	4.5	5.5	6.0
SD	1.0	0.8	0.5	1.1	1.2	0.9
COV	17%	12%	9%	26%	22%	16%
Min	4.2	5.9	4.5	1.5	1.5	4.5
Max	7.7	8.2	6.2	5.6	8.2	8.2
x_{05}	4.1	5.2	4.4	2.1	3.3	4.5
HG	a	a	b	c	–	–

HG, Homogenous group (groups with the same letter are not statistically different, α=0.05).

during testing was in the range of 9–10.5% (matched specimens, oven-dry method).

The rolling shear modulus G_r as well as the rolling shear strength $f_{v,r}$, were determined according to the relationships given in EN 789 (2004), with a correction for the load-application angle α as specified in EN 408 (2012) as

$$G_r = \frac{(F_2 - F_1) \cdot \cos\alpha \cdot t}{(u_2 - u_1) \cdot l \cdot b} \quad (3)$$

and

$$f_{v,r} = \frac{F_{max} \cdot \cos\alpha}{l \cdot b} \quad (4)$$

where $F_2 > F_1$ are load levels within the elastic material range, and u_2, u_1 are the corresponding slip values; for dimensions t, l and b, see Figure 2a.

The significance of the different sawing patterns on rolling shear modulus and strength values was checked by ANOVA with a further two-sided t-test with unequal variances and confidence level of α=0.05.

Results and discussion

Rolling shear modulus (G_r)

The rolling shear modulus (G_r) was evaluated over the load range of 10 to 40% of the maximum load, within which the load-deformation curves remained strictly linear. The nonlinear load domain started between 55 and 75% of the maximum load. Table 2 contains a statistical evaluation of the G_r results including combined samples (the sample excluding pith boards is here termed "without pith"). Figure 3a depicts the cumulative frequencies of the G_r results with their fitted lognormal cumulative distribution curves. The mean G_r data comprising all specimens of the different sawing patterns was $G_{r,\text{mean}}$=370±70 N mm^{-2}; this value coincides with the average of the means of the respective groups. The extreme values range from 235 to 534 N mm^{-2} and are dependent to some extent on the sawing pattern.

Influence of sawing pattern and density

The pith board group did not show considerably lower values as compared to the other groups, despite the fact that all specimens had cracks. However, the coefficient of variation (12%) was somewhat smaller than that of the combined samples (19%). The mean values of all sawing patterns excluding the quarter-sawn boards were around 390 N mm^{-2}. Hereby, $G_{r,\text{flat,mean}}$ (380 N mm^{-2}) and $G_{r,\text{pith,mean}}$ (370 N mm^{-2}) were on the lower end whereas $G_{r,\text{semi-quarter,mean}}$ (420 N mm^{-2}) was higher. Significantly lower G_r values (see homogeneous groups in Table 2), however, were determined for the quarter-sawn boards throughout the whole distribution range, showing the absolute lowest minimum, mean and maximum values of 220, 300 and 350 N mm^{-2}, respectively. A comparison of $G_{r,\text{quarter}}$ at the mean value level with the G_r of the semi-quarter-sawn specimens, which had the highest mean of all sawing patterns, results in a ratio of 0.71. In comparison to the flat-sawn and pith boards, the difference is still -20%.

The experimental fact that $G_{r,\text{semi-quarter}}$ are the highest values and $G_{r,\text{quarter}}$ represent the lowest is in agreement with the theoretical considerations concerning the relation of G_r and sawing pattern, i.e. with annual ring angle φ. The orthotropic continuum simplification using the on-axis values by Stamer and Sieglerschmidt (1933) and Hoefflin and Aicher (2000) results in the highest off-axis shear modulus at $\varphi=\varphi_{\text{mean}}$=45°, whereas for on-axis values at φ=0° and 90° the minimum of $G_r(0,90)=S_{66}^{-1}=G_{rt}$ is observable. The best quantitative agreement with the test results would be obtained when the on-axis stiffness number ratios are E_r/E_t=1.3 and E_r/G_{rt}=4.6, which are in the sensible range of data (Table 1).

The relationship between G_r and density ρ_{12} for all specimens – irrespective of the individual sawing pattern group – is characterized by a slightly positive (but very weakly) correlated trend (R^2=0.14) towards higher G_r values with increasing density (ρ_{12} in kg m^{-3})

$$G_r(\rho_{12})=0.72\rho_{12}-110.4 \text{ in N mm}^{-2} \quad (5)$$

Rolling shear strength ($f_{v,r}$)

Specimen failure occurred in an abrupt and brittle manner, following the nonlinear peak loading range. The failure appearances differed considerably. In a few cases,

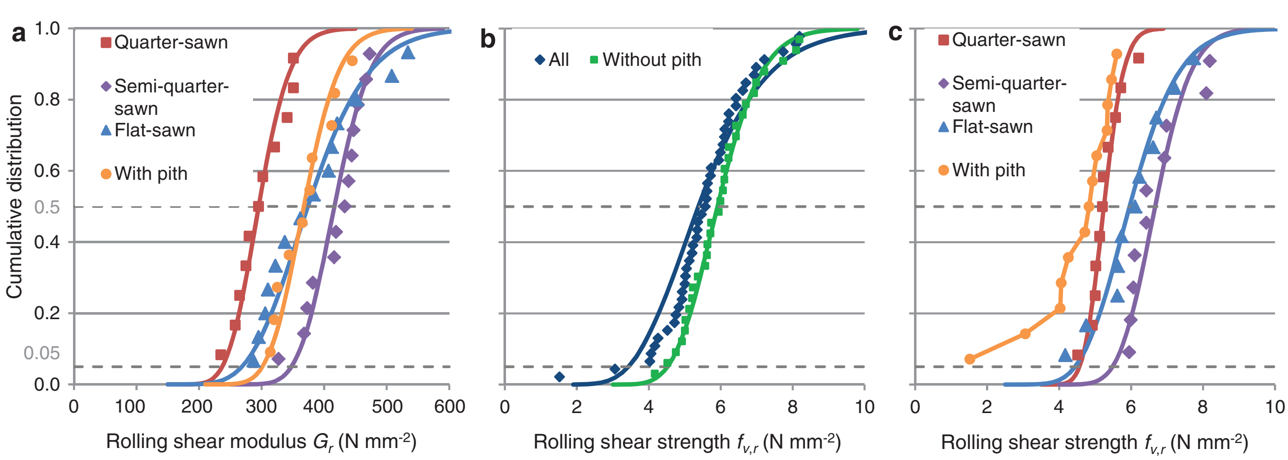

Figure 3: Cumulative frequencies and fitted lognormal distributions of rolling shear results depending on sawing pattern of (a) rolling shear modulus for all sawing patterns, (b) rolling shear strength for all sawing patterns and a subsample without pith specimens and (c) rolling shear strength by sawing pattern, with lognormal distribution for pith specimens excluded (see text).

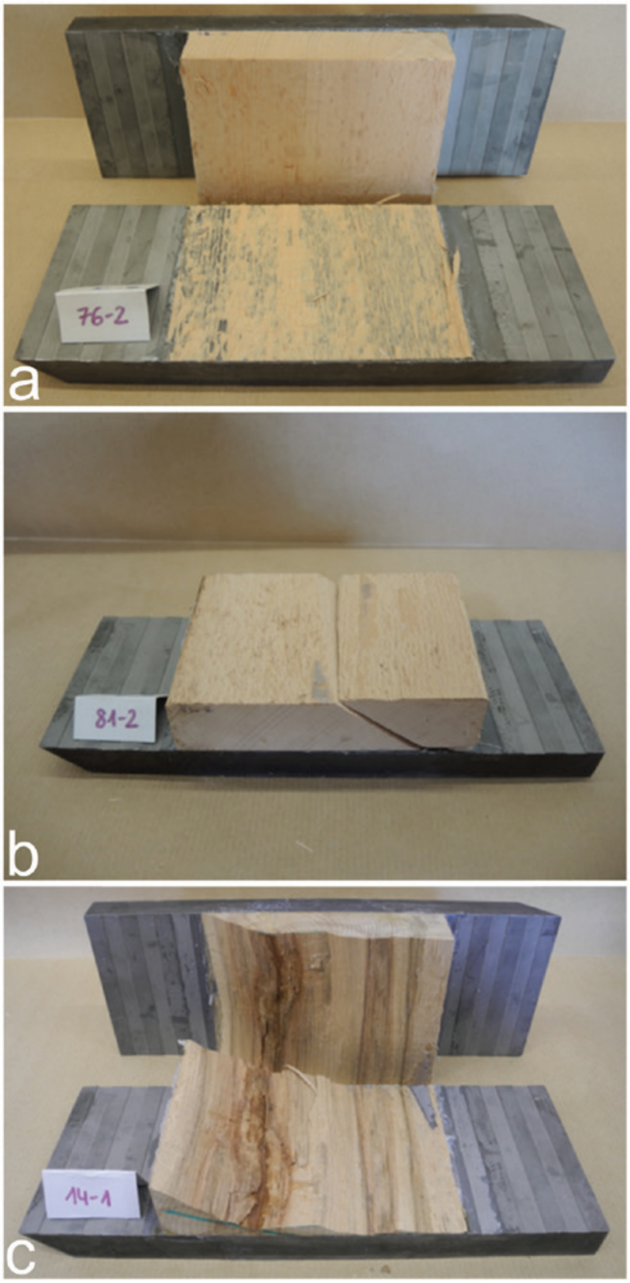

Figure 4: Typical fracture appearances of beech specimens tested in rolling shear, dependent upon sawing pattern: (a) quarter-sawn, (b) semi-quarter-sawn, (c) including pith.

a mixed bondline-interface-wood failure was obtained (Figure 4a and b). In the case of the prevailing wood failures, the appearances ranged from failure planes close and parallel to the steel plate, to typical inclined shear failures diagonally through the specimen. All pith specimens failed by diagonal cracks through the pith, often following the pre-existing cracks (Figures 1c, 4c). The statistical evaluation is compiled in Table 2, where the results are given for the individual sawing pattern groups. The cumulative frequencies together with lognormal fits for two samples are shown in Figure 3b, one comprising all specimens irrespective of sawing pattern and the other one all specimens excluding the boards with pith. The experimentally obtained cumulative frequencies of the shear strength values of the individual sawing patterns are illustrated in Figure 3c including their fitted lognormal distributions. The pith specimens could not be approximated decently by (log)normal functions.

Excluding two obvious outliers in the sample of the pre-cracked pith specimens, the $f_{v,r}$ data ranged from 4.2 to 8.2 N mm^{-2} (mean of all specimens is 5.5 N mm^{-2}). Excluding the two pith specimen outliers, a mean value of 5.7 N mm^{-2} is obtained. An evaluation of all specimens (without pith) delivers $f_{v,r,\text{mean}}$ of 6.0 N mm^{-2}. The characteristic 5% quantile of rolling shear strength, $f_{v,r,05}$, determined according to EN 14358 for all specimens (without pith) is 4.5 N mm^{-2}. A rather similar value of $f_{v,r,05}$=4.7 N mm^{-2} is obtained when a parameter free evaluation is applied by means of the ranking method and linear interpolation of strength values.

Effect of sawing pattern, density and rolling shear modulus

If the pith specimens are included, the rolling shear strength is reduced significantly (Figure 3b and c, Table 2). This effect increases drastically towards the lower cumulative frequencies. Furthermore it is not surprising that the pith specimens provided the two exclusive outliers (1.5 and 3.1 N mm^{-2}), both resulting from highly pre-cracked specimens while all pith specimens contained significant cracking.

Among the other sawing pattern samples are also considerable differences. The semi-quarter-sawn specimens resulted in the highest values. When compared to the averages of the flat- and quarter-sawn specimen groups at the minimum and 5% quantile levels, roughly 35% and 20% higher values are seen. The higher values of semi-quarter-sawn samples are inherently due to the elevated level of rolling shear modulus and the absence of pre-cracked specimens, both related to the specific annual ring orientation.

Density shows no influence on the $f_{v,r}$ data (R^2≈0, Figure 5a, without the two outliers). The correlation of $f_{v,r}$ and G_r independently from the specific sawing patterns (but excluding the two outliers) is denoted by R^2=0.24; the exclusion of all boards with pith gives a moderate correlation between $f_{v,r}$ and G_r (Figure 5b, R^2=0.40).

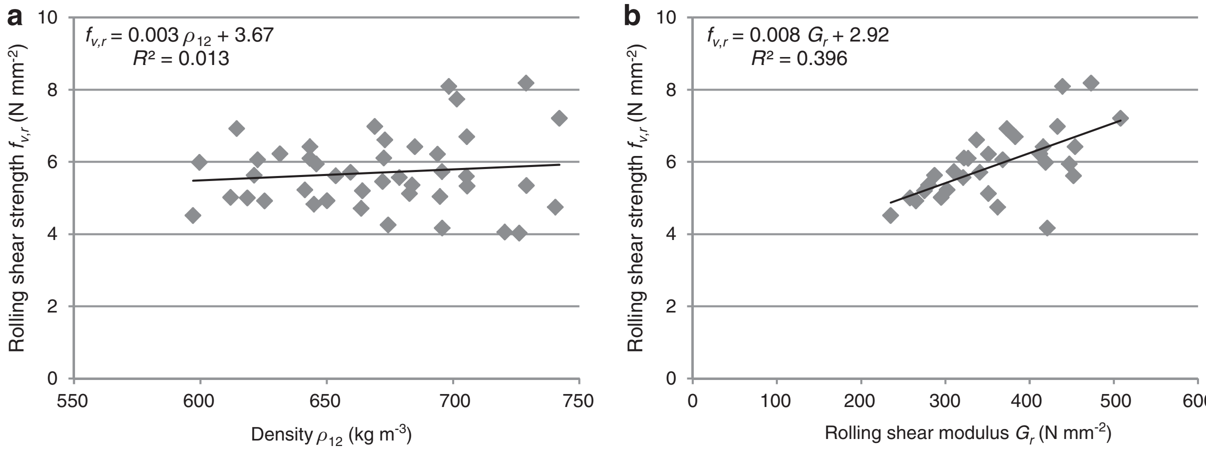

Figure 5: Rolling shear strength correlations (a) with density as well as (b) with rolling shear modulus of the investigated beech wood (boards with pith excluded).

Rolling shear properties of beech vs. spruce

At present, a mean G_r of 50 N mm^{-2} for spruce and fir laminations is in general assumed for design purposes (OIB 2005; EOTA 2015). This value conforms to the experimental data of Fellmoser and Blaß (2004), whereas a computational study (Aicher and Dill-Langer 2000) gave somewhat higher values. Thus, the here obtained experimental value of $G_{r,\text{mean}}$=370 N mm^{-2} exceeds today's softwood design stiffness level by a factor of 7.5. It is obvious that shear modulus and hence cross-sectional shear rigidity will lead to a highly enhanced overall stiffness performance of CLT plates, when the cross-layer(s) perpendicular to the span direction of the plates are made of beech wood boards.

The 5% quantile value $f_{v,r,05}$=4.5 N mm^{-2} (without the pre-cracked pith specimens) exceeds the characteristic $f_{v,r}$ specified for spruce and fir by a factor 5, if the recent technical approvals on CLT in the range of 0.75 N mm^{-2} (unglued narrow edges, e.g. DIBt 2013, ETA-10/0241) to maximally 1.5 N mm^{-2} (glued narrow edges, e.g. OIB 2014, ETA-1470349) are considered. Therefore, beech wood cross-layer(s) should lead to a highly increased limit state behavior in any design situation, where rolling shear strength governs the load capacity, as in the case of stout plates and cantilevers.

Conclusions

The rolling shear properties of European beech wood revealed a significantly higher stiffness and strength performance level as compared to the softwood laminations currently used almost exclusively for CLT plates. A mean rolling shear modulus (G_r) of about 370 N mm^{-2} and a 5% quantile of shear strength ($f_{v,r}$) of 4.5 N mm^{-2} were obtained. These values are better by factors 7 and 5 than the data of spruce and fir. Concerning the annual ring orientation in the boards, i.e. the sawing pattern, the test results are in good agreement with basic theoretical considerations, according to which the semi-quarter-sawn boards deliver a higher stiffness level than the quarter-sawn boards. The latter resulted in the lowest rolling shear moduli. Boards which included pith delivered an equal $G_{r,\text{mean}}$ value as compared to the entity of the other sawing patterns. Similarly to stiffness, $f_{v,r}$ is highest for semi-quarter-sawn boards, whereas specimens including pith resulted in significantly lower strength values. The results substantiate the potential of beech wood as an ideal material for use in cross-layers of advanced hybrid or homogenous CLT in flatwise bending.

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