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Rolling Shear Properties of some European Timber Species with Focus on Cross Laminated Timber (CLT): Test Configuration and Parameter Study

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1 Introduction

Cross laminated timber (CLT) has gained popularity and relevance in the construction industry during the past decade. Its versatile applicability, economic competitiveness as well as an increasing social consciousness for sustainable constructions have been main reasons for this positive development. Its laminar composition enables CLT to withstand in- and out-of-plane loads. Due to its structure featuring orthogonally oriented adjacent layers, in CLT loaded out-of-plane, shear and more specific rolling shear has to be considered in ultimate (ULS) as well as serviceability limit state (SLS) design. This is because rolling shear constitutes a potential failure mechanism and contributes a noticeable amount to the overall deflection. Comprehensive knowledge on rolling shear modulus \( (G_R) \) and strength \( (f_{R}) \) is therefore of utmost importance for
an adequate design of CLT structures. Previous investigations on rolling shear properties and their influential parameters have primarily been performed numerically and using Norway spruce (Picea abies).

The main goal of our contribution, based on investigations detailed in Ehrhart (2014), was to identify the most important parameters for rolling shear characteristics and to quantify their influence. Furthermore, information about the rolling shear performance of several timber species was analysed to investigate their potential for use in CLT-products. In view of upcoming new timber species increasingly pushed into the market, investigations on rolling shear comprised also some hardwood and other softwood species with a potential to be used for (cross) laminated timber products.

1.1 Available test configurations

Robust and replicable test configurations are essential to assess mechanical properties of timber. For most timber properties, such configurations are already implemented in international standards. Regarding rolling shear, standardised configurations and methods are not available yet. Studies reflect a variety of diverse testing methods to determine rolling shear modulus and / or strength by using quite different approaches (Figure 1.1).

![Figure 1.1 Some test configurations for determining rolling shear properties proposed by Hassel et al. (2009), Xavier et al. (2009) and Dumail et al. (2000) (left to right)](image-url)

Beside these configurations, which focus on testing clear wood and board segments, there are additional configurations in discussion emphasizing the determination of rolling shear properties of the product CLT. Mestek (2011) adapted the sandwich configuration to allow also testing of CLT-elements. The draft version of prEN 16351 (2011) provides bending configurations with reduced spans from which rolling shear stiffness and strength can be derived. Gehri (2011) suggested a bending test of a five-layer CLT-plate with only the outermost layers oriented parallel to the supporting direction. This to enlarge the potential area for shear field measurements in the area exposed to rolling shear (Figure 1.2).

Figure 1.2 Left: setup suggested by Gehri (2011); Right: standard CLT structure

1.2 Potential influencing parameters on rolling shear properties

Beside others, the timber species itself is one major “parameter” for mechanical properties. Regarding strength and stiffness at all grain angles, most European hardwood timber species show higher characteristics than softwoods, Kollmann (1936). Bendtsen (1976) reported also significant differences between the rolling shear characteristics found by analysing nine structural softwoods.

Numerous studies have proven significant correlation between density and most mechanical properties of timber, at least for clear wood. Görlacher (2002) carried out bending vibration tests using board segments of Norway spruce and found positive (but low) correlation between density and rolling shear modulus.

Past investigations outline sawing pattern as one major parameter for the rolling shear modulus $G_R$. This was concluded in Aicher & Dill-Langer (2001), Jakobs (2005) and Feichter (2013) by numerical studies and in Görlacher (2002) based on eigenfrequency measurements.

Theoretical analysis on the load bearing behaviour of CLT in shear by Kreuzinger & Scholz (2001) showed that rolling shear strength depends on the ratio of undisturbed board’s width – which can be either the actual width or the distance between stress reliefs – and its thickness. To consider this geometric effect, a reduction of strength by means of the factor $k_{\text{Red}}$ is proposed. Experimental tests by Mestek (2011) confirmed the dependency and the results agreed well with values predicted using $k_{\text{Red}}$. 
2 Material and methods

2.1 Material

2.1.1 Timber species

Because of its major importance to the construction industry and data availability from previous experimental and numerical studies on rolling shear, Norway spruce (*Picea abies* (L.) Karst.) was chosen as the reference timber species. This comprises also all parameter variations, which are described hereafter. For comparison a second coniferous wood, pine (*Pinus sylvestris* L.), was investigated.

Regarding the microstructure of wood, a general distinction between coniferous- and deciduous wood is given (*Figure 2.1*). Due to the concentrated clustering of vessels in the earlywood of ringporous hardwood species with subsequent potential to influence at least the failure mechanism, species featuring these characteristics have to be distinguished from diffuse porous species. Birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.) and poplar (*Populus spp.*) were investigated as representatives of the group of diffuse-porous deciduous timber species. Ash (*Fraxinus excelsior* L.) was the only ringporous timber species in this study.

*Figure 2.1 Tangential cuts (above) and microscopic cross cut (below) of spruce, pine, poplar, beech, birch and ash (from left to right) (from Grosser & Teez 1985)*

2.1.2 Adjustment factors for physical properties in regard to moisture content

According to EN 408, all specimens were conditioned at 20 °C and 65 % relative humidity. Density, rolling shear modulus and strength were related to the reference moisture content of $u_{\text{ref}} = 12 \%$ by considering 0.5 % (*EN 384*), 2 % (*Neuhaus 1981*) and 3 % (*Brandner et al. 2012; Ringhofer et al. 2014*), respectively, per percent moisture difference. Density of all specimens was determined to investigate the influence on rolling shear properties for different timber species, sawing patterns and boards’ geometries.

2.1.3 Geometry of the boards

The cross sectional geometry of CLT-products has not been standardised yet. Dimensions of boards and plates vary depending on the manufacturer, although – at least in Europe – board or layer thicknesses of 20, 30 and 40 mm are more and more common. Furthermore, specific production-techniques requiring stress reliefs influence the final setup. To cover common geometries, boards with a constant thickness ($t_l$) of
30 mm and a varying width $w_l$ of 120 (reference), 60 and 180 mm were investigated (Figure 2.2). Thus, the tested ratios $w_l / t_1$ were two, four and six. To separate the parameter “board geometry” from other parameters, like density, annual ring width, sawing pattern, reaction wood and other timber characteristics, specimens for both $w_l / t_1$ ratios were cut subsequently from the boards. Consequently, in both series comparable densities were achieved (Table 2).

### 2.1.4 Sawing pattern

Depending on the former location in the log, the radial distance between specimen’s cross section centre and the pith ($r$), different grain patterns are generated. We investigated radial distances $r$ of 30 ($\pm$ 10) (rift and half-rift grain), 60 and 100 mm (flat grain) by a realized but negligible eccentricity $e$ of $\pm$ 5 mm (Figure 2.2).

![Figure 2.2 Investigated sawing patterns and board geometries](image)

### 2.1.5 Test plan

The test plan is outlined in Table 1. For getting significant statistics on a reference basis, the so-called “reference sample” comprised 40 specimens of Norway spruce, with a radial distance $r$ of 60 mm and a width $w_l$ of 120 mm. All other samples comprised 20 specimens each and a setting where only one parameter was changed while the others remained according to the reference sample. In each sample, only one segment per board was used to assure representative results and to maintain full variability.

<table>
<thead>
<tr>
<th>group</th>
<th>no.</th>
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<th>$r$ [mm]</th>
<th>$w_l / t_1$</th>
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<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
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<td>60</td>
</tr>
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<td>2.1</td>
<td>20</td>
<td>birch</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>20</td>
<td>ash</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>2.3</td>
<td>20</td>
<td>poplar</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>2.4</td>
<td>20</td>
<td>beech</td>
<td>60</td>
<td>4</td>
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<td>20</td>
<td>spruce</td>
<td>60</td>
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</table>
2.2 Methods

2.2.1 Test configuration

Purity of shear stress, variability of specimen dimensions and necessary effort were taken into account as most important decision parameters in choosing the method used in this work (Figure 2.3). It is based on the shear configuration given in EN 408 (2010) and considers the modifications suggested by Mestek (2011). Beech wood loading plates were used for softwood timber species and poplar. All other hardwood timber species were tested using steel plates. Additionally conducted numerical finite element (FE) analysis confirmed the suitability of the configuration and a uniform distribution of shear stresses in the main field of interest. Stresses perpendicular to the shear plane were relatively low, but exceeded transverse tensile- respectively compression strength locally in areas very close to the edges (Figure 2.3, middle and right).

Rolling shear strength was calculated according to EN 408 (2010) using Eq. (1). By means of displacement transducers, the relative displacement of the loading plates (x) was measured and $G_R$ could be calculated using Eq. (2).

$\alpha \ F$

$\mathcal{T}$ ... area of high tensile stress perp. to the grain

$\mathcal{C}$ ... area of high compressive stress perp. to the grain

The angle between shear plane and force direction ($\alpha$) was 14° for all tests and the length of the board segment (l) was 100 mm.

$$f_R = \frac{F_{\text{max}} \cos \alpha}{l \cdot W_i}$$  \hspace{1cm} (1)

$$G_R = \frac{\Delta t_R}{\Delta y_R} = \frac{\Delta F \cdot \cos \alpha \cdot t_i}{l \cdot W_i \cdot \Delta x}$$ \hspace{1cm} (2)

According to EN 408 (2010), $G_R$ was calculated between 0.1 $F_{\text{max}}$ and 0.4 $F_{\text{max}}$. Using vertical advancing rates of 0.4 up to 0.8 mm/min, $F_{\text{max}}$ was almost always reached within 300 ± 120 s.
3 Results and discussion

Main results of this study are summarised in Table 2. It contains values for rolling shear modulus and strength as well as determined density and moisture content for all samples.

Table 2 Rolling shear properties by groups: main statistics

<table>
<thead>
<tr>
<th>group</th>
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<th>COV [%]</th>
<th>range</th>
<th>$\bar{x}$</th>
<th>COV [%]</th>
<th>$\bar{\sigma}$</th>
<th>range</th>
<th>$\bar{x}$</th>
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<td>10</td>
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<td>401:527</td>
<td>459</td>
<td>11.4</td>
<td></td>
</tr>
</tbody>
</table>

3.1 Correlation between density and $G_R$ resp. $f_R$

Considering all investigated timber species in the regression and correlation analysis on the relationship density vs. rolling shear properties (Figure 3.1), high correlation exists.

![Figure 3.1](image)

$G_{R,12} = 0.76 \rho_{12} - 241 \\
R = 0.92$

$R_{F,12} = 0.01 \rho_{12} - 2.38 \\
R = 0.92$

Doing the same analysis for each timber species separately, for softwoods no significant correlation between density and the rolling shear properties is observed. A possible explanation for this might be found in the anatomy of coniferous wood species:
for example in Norway spruce, both, early- and latewood have quite constant densities of about 300 kg/m³ and 900 to 1,000 kg/m³, respectively. Since the thickness of latewood is relatively constant over the entire life of such a tree, the thickness of the earlywood zones varies with the yearly growth conditions and thus decisively influences the average density of a certain piece of wood. Following the circumstance, that rolling shear failure takes commonly place in the interface zone between early- and latewood of two subsequent years, the earlywood density may indicate the magnitude of shear properties.

By analysing the relationship between rolling shear properties and the density specific for each hardwood species high correlations are found (Figure 3.1). Compared to softwoods, in case of ring porous species the interface between the early- and latewood of two subsequent years may again act as the primary failure domain, however, because of a nearly constant thickness of earlywood over the years of tree’s life, the average wood density becomes decisively affected by the thickness of the latewood. Considering diffuse porous species, a more or less homogeneous density profile over the entire thickness of annual rings can be assumed.

3.2 Correlation between $G_R$ and $f_R$

The regression analysis on rolling shear strength vs. modulus, done by comprising all investigated timber species, confirms the generally observed positive correlation between these two mechanical properties (Figure 3.2). By analysing the same relationship separately for each timber species, high correlation is found for ash, birch and beech, while low and debateable values are observed for spruce, pine and poplar.

![Figure 3.2 Rolling shear modulus vs. strength](image)

3.3 Influence of the sawing pattern on rolling shear properties

This and the next section discuss outcomes from a parameter study, which only comprises Norway spruce.

Boards with large distance to the pith generally tend to own lower ring widths and increasing amount of mature wood which both consequence higher densities. Therefore, given a positive correlation between rolling shear properties and density, higher strengths would be expected when increasing the radial distance to the pith $r$. However, a corresponding positive correlation between $r$ and the rolling shear strength $f_R$ was not observed (Figure 3.3). The mean values of 1.88, 1.88 and 1.84 N/mm² given
for $r = 30$, 60 and 100 mm, respectively, are on equal basis. One possible explanation could be found in different sawing patterns causing different rolling shear modulus. Assuming that shear failure occurs under a certain distortion, lower $G_R$ would cause lower strengths for outer boards. Thus, these two effects just seem to compensate each other.

![Graphs showing relationship between $G_R$ and $r$](image)

**Figure 3.3** Relationship between the radial distance to the pith, indirectly causing changes in the sawing pattern and the rolling shear modulus (left) and strength (right); for Norway spruce

However and conform to previous studies by Aicher & Dill-Langer (2001), Jakobs (2005), Görlacher (2002) and Feichter (2013), a distinct relationship between the radial distance to the pith, indirectly causing changes in the sawing pattern from rift or half-rift gain to flat grain, and $G_R$ is given. Although previous studies report a non-linear relationship between $G_R$ and $r$, within the investigated range of sawing patterns, an almost linear reduction of $G_R$ for increasing $r$ is observed (Figure 3.3, left).

### 3.4 Influence of board geometry on rolling shear properties

The geometry of a board shows to have a strong influence on both, rolling shear strength and modulus.

Compared to the reference width of $w_l = 120$ mm, the average strength and modulus decrease by 40 % and 30 %, respectively, when $w_l$ is reduced to 60 mm. However, they raise by approximately 20 % and 50 %, respectively, when $w_l$ becomes 180 mm (Figure 3.4).

Distribution of shear stresses is not constant along the segment’s cross section. In areas close to the edges, tensile stresses perpendicular to grain arise increasingly. The actual shear stress in these areas is lower than calculated using Eq. (1). However, in inner zones, actual stresses exceed those calculated. The lower the ratio $w_l / t_i$, the higher the stress peaks and the larger the gap between the actual and calculated stress (Figure 3.5). This causes lower determined rolling shear strengths for lower $w_l / t_i$ ratios.
In our study only boards with negligible eccentricity to the pith, \( e \), were used. Consequently, changes in width of the boards also lead to changes in the grain orientation at the board’s edges, i.e. wider boards show an increasing amount of half-rift and flat grain oriented annual rings in their peripheral zones. As already discussed before (3.3), this leads to higher values of rolling shear modulus, which demonstrates the difficulty in separating the influences caused by the ratio \( w/t \) from that dedicated to the sawing pattern.

![Figure 3.4 Rolling shear properties of Norway spruce: variation of the radial distance to the pith (indirectly sawing pattern) and \( w/t \)](image)

Figure 3.5 Qualitative distribution of shear stresses in boards with a \( w/t \)-ratio of two and four

3.5 Rolling shear properties of different timber species

The rolling shear properties of all tested timber species are overall very promising (Figure 3.6).

Strength and modulus determined for Norway spruce confirm and partly exceed values reported in previous studies. Bendtsen (1976) for example reported \( f_{R,\text{mean}} \) of 1.79, 1.88 and 1.79 N/mm\(^2\) for red, black and white spruce, respectively. Mean rolling shear modulus found was 68, 73 and 58 N/mm\(^2\), however, no information about sawing pattern is provided. Nevertheless, in our comparative study for Norway spruce
the lowest properties are observed. Properties of pine and poplar surpass those of spruce significantly. Pine particularly shows high rolling shear modulus and poplar a remarkable strength. Birch performs very well too with strength and modulus about double as high than for spruce. Beech and ash show outstanding rolling shear properties and reach values about three times higher than found for spruce (Figure 3.6).

Figure 3.6 Rolling shear properties of different timber species: (left) modulus, (right) strength

4 Conclusion

4.1 Test configuration

Experiences made regarding the test configuration are very promising. Rolling shear failure along one or few annual rings was observed for most species (Figure 4.1), board-geometries and sawing patterns. Finite element (FE) analysis of the test configuration already showed local areas of stresses perpendicular to the grain. Small primary cracks were indeed observed during several tests in areas close to the edges (Figure 4.2, left). As they occurred exclusively after removing the displacement transducers, influence on measured rolling shear modulus can be excluded. Independent fracture pattern after failure indicates that the influence of small primary cracks is also negligible in calculating strengths.

In-depth investigations on the interaction between rolling shear and stresses perpendicular to the grain done by Mestek (2011) showed that compression tends to affect rolling shear strength positively. Following his model and due to the low angle between force direction and shear plane ($\alpha$), negligible influence on the rolling shear behaviour can be assumed.
Investigation of the bonding surface after failure indicated that the bonded connection between the loading plates and specimen was sufficiently strong (Figure 4.2). However, the surfaces of a few birch and beech specimens were covered with wood fibres by less than 50%.

Figure 4.1 Typical failures of specimens: spruce, pine, poplar, birch, beech and ash (from top left to bottom right)

Efforts and costs for preparation and conducting the tests were relatively low and geometrical variations of specimen easy to perform. Loading plates out of beech appear adequate for softwood species and poplar. We therefore propose to record the configuration described for the determination of rolling shear strength and modulus in EN 408 (2010).

Figure 4.2 Primary crack ① and from that independent failure (left); bonding surface after failure of a spruce (middle) and birch (right) specimen

In a follow-up of this study, three-point bending tests using Norway spruce boards of the same population as base material were carried out, Wilding et al. (2014). Shearfield measurements on 5-layer beams featuring a standard CLT structure, i.e. subsequent orthogonal layering, and the structure suggested by Gehri (2011) – with only the outermost layers oriented parallel to the supporting direction (Figure 1.2) – led to $G_{R,app,mean}$ of 188 (apparent value because of the orthogonal middle layer) and $G_{R,mean} = 110$ N/mm$^2$, respectively. Thus, results of bending tests using the structure suggested by Gehri agree very well with those obtained from single segment testing.
4.2 Rolling shear properties

Results of in total more than 200 tests confirm previous findings, extend knowledge on rolling shear behaviour and allow identifying sawing pattern and board geometry as the main parameters influencing the rolling shear properties $G_R$ and $f_R$, respectively.

For Norway spruce, overall $G_{R,\text{mean}} = 100 \text{ N/mm}^2$ and $f_{R,k} = 1.4 \text{ N/mm}^2$ are found. Current values for $G_{R,\text{mean}}$ and $f_{R,k}$ given in European technical approvals of different CLT producers (e.g. ETA-06/0009, ETA-06/0138 and ETA-10/0241), lie at about 50 N/mm$^2$ and 0.85 : 1.5 N/mm$^2$, respectively. As a minimal $w_l / t_l$-ratio of four is defined for boards in transverse layers in the same ETAs, it appears that the potential of timber is partly underestimated in the design process and for product characterisation. A circumstance which also frequently arises in comparisons of global (over the entire span) and local (only within area of constant moment) bending modulus, gained from four-point bending tests on CLT plates. Depending on the actual sawing patterns of the material used for CLT production, especially the values regulated currently for rolling shear modulus seem to be on a very conservative basis. This also by considering that boards within transverse layers commonly show varying sawing patterns.

Table 3 Proposed rolling shear characteristics for $w_l / t_l \geq 4$

<table>
<thead>
<tr>
<th></th>
<th>$f_{R,k}$ [N/mm$^2$]</th>
<th>$G_{R,\text{mean}}$ [N/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>spruce</td>
<td>1.4</td>
<td>100</td>
</tr>
<tr>
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<td>180</td>
</tr>
<tr>
<td>ash, beech</td>
<td>4.0</td>
<td>350</td>
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</table>

However, decreasing ratios of $w_l / t_l$ distinctly decrease $G_R$ and $f_R$. Comparable effects are assumed in boards with stress reliefs and comparable relief-distance vs. thickness ratios. As further differentiation in sawing patterns in CLT-production processes appears practicable questionable, representative values for all locations in the log – by taking into account preferable used board geometries and their relationship to radial positions due to the sawing process – are needed. A proposal for boards with a ratio $w_l / t_l \geq 4$ is presented in Table 3. Eq. (3) and (4) are proposed to determine properties of spruce boards with a lower ratio.

$$f_{R,k} = \min \left\{0.2 + 0.3 \cdot \frac{w_l}{t_l}, \frac{1.4}{1.4}\right\}$$  \hspace{1cm} (3)  

$$G_{R,\text{mean}} = \min \left\{30 + 17.5 \cdot \frac{w_l}{t_l}, \frac{100}{100}\right\}$$  \hspace{1cm} (4)

In comparison to Norway spruce and the range of investigated timber species, the outstanding rolling shear properties of beech and ash are outlined which impose these species to be used in CLT. Pine, poplar and birch have also a great potential as base material for CLT.
Available information on rolling shear properties in international standards has yet been very limited. Results of this study therefore seem in particularly relevant for EN 338 (2009), where only values for shear strength and modulus parallel to the grain are listed. Findings of this study could also contribute to EN 14080 (2013) and prEN 16351 and have potential to supplement important points to these standards.

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6 References


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