Running title: **Wood anatomy and shear strength**

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# Relationship between anatomy and shear strength in wood of *Larix sibirica*

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**Abstract:** In Siberian larch, shear strength (SS) is lower in sapwood (sW) than in mature heartwood (hW) despite of the similarity of their cell structures. SS in sW was not correlated with other properties, not even with density. The aim of the present study was to find parameters affecting the SS in sW. The diameters of earlywood (EW) and latewood (LW) tracheid lumens (RD), as well as their double wall thicknesses (2CWT), were measured from different wood types. 2CWT beside resin canals were measured and rays were counted. The wall:lumen ratio of tracheids was calculated. None of the measured and calculated characteristics correlated significantly with SS in hW, while high 2CWT and wall:lumen ratio of EW increased and large RD decreased SS in sW. Tracheids of sW were larger and their walls were thicker than those of mature hW. The EW of sW sheared through tracheids, but practically never through rays, while in EW of mature hW, both rays and tracheids could be sheared. It is suggested that change in viscoelastic properties, occurring in cell walls during the transformation from sW to hW improve wood shear properties.

**Keywords**: earlywood, heartwood, larch, latewood, lumen diameter, rays, resin canal, sapwood, tracheid, wall thickness

## Introduction

Larches (*Larix* sp.) are widely distributed in the boreal and temperate zone of the Northern Hemisphere, with approximately 10 different species, often forming the Polar or Alpine tree line (Sarvas 1964). No one of these species is native in Finland, but their cultivation is tested in certain areas. Due to its fast growth, good stem form and branch structure, tolerance against frost and snow, and decay resistance, Siberian larch (*Larix sibirica* Ledeb.) is virtually the only larch species cultivated in a marked scale, covering approximately 30,000 ha over the past 50 years in Finland (Rantala and Anttila 2004).

Wood of Siberian larch shears and splinters easily, which may restrict its utilization. Loose splinters are problematic in furniture, floorings, and deckings, and repeated splintering reduces the wood dimension and its strength. Splintering is a consequence of poor shear strength (SS) in relation to density, which is lower in Siberian larch wood than in many other softwoods as engineering wood (Bodig and Jayne 1982; Wagenführ 2007). A good SS parallel to the grain ($SS_{\parallel}$) is highly important in mechanical connections between structural elements, such as dowel joints as well as nail and screw hold and withdrawal capacity (Grekin and Surini 2008). In addition to overall density, Luostarinen and Heräjärvi (2011, 2013) found the following parameters relevant for influencing the SS in Siberian larch heartwood (hW): earlywood (EW) density and width, the proportion of latewood (LW), the number of annual rings at the shear surface, average fibre length, and arabinogalactan concentration, but these parameters were not influential in sW.

SS is significantly lower in sW than in mature hW of Siberian larch (Luostarinen and Heräjärvi 2011, 2013), which is a bit surprising in view of their structural identity. However, the hW contains a lot of arabinogalactan (Côté et al. 1966; Luostarinen Heräjärvi 2013) and also some phenolic compounds as extractives (Venäläinen et al. 2006). The hW extractives also impregnate the cell walls (Imai et al. 2005; Nakaba et al. 2012) and have an essential influence on the natural durability (Venäläinen et al. 2006) and possibly the mechanical wood properties. Oh (2011) carried out bending tests of *Larix kaempferi* (Lamb.) Carr. and observed differences in the modulus of rupture (MOR) between hW and sW. In contrast, in Norway spruce (*Picea abies* (L.) H. Karst.), variations in tracheid wall properties play only a minor role in the variability of SS (Muller et al. 2004b). The microfibril angle (MFA) as one of the factors influencing mechanical properties affects mainly stiffness (Juvonen et al. 1986;

Müller et al. 2004a,b), but also bending strength (Treacy et al. 2000; Deresse et al. 2003; Oh 2011). In shear tests, the $SS_{\parallel}$ is different from bending tests because of the direction of the force. In addition, shear fracture occurs between cells or cell wall layers in thick-walled LW cells, while trans-wall fracture commonly occurs only in thin-walled EW (Gindl and Teischinger 2003). Thus, due to different fracture planes, the MFA has probably less effect on SS compared to bending, tension or compression strengths.

The aim of the present study was to analyse the relationships between selected anatomical characteristics and SS of juvenile wood (jW), maturing hW, mature hW, and sW of *L. sibirica*. The main focus was to find out, which properties possibly affect the SS of sW as no other property, not even density has been observed to affect SS in sW. Furthermore, the reasons for the weakness of sW, compared to mature hW, were discussed taking into account the changes occurring in wood at transition from sW to hW.

## Materials and methods

A total of 16 Siberian larch (*Larix sibirica*) trees, 85 years old, were cut from the plantations of the Natural Resources Institute Finland, Punkaharju, Eastern Finland (61°81’ N, 29°32’ E). Discs for SS and anatomy investigations were sawn from the butt and from the heights of 4.5 and 9 metres. Both anatomy and SS samples were collected from juvenile wood (jW, annual rings 1-5 for anatomy, 1-15 for SS), maturing wood (rings 15-20 for anatomy, 15-30 for SS), outer mature heartwood (hW, at the butt 61–73 years, at the height of 4.5 m, 41–60 years, and at the height of 9.0 m, 21–40 years of cambial age) and sapwood (sW) immediately after the outer heartwood. The annual ring ranges in jW and maturing wood for SS specimens were larger than those for the anatomy specimens, as in some cases, five annual rings did not reach a width of 20 mm, which is needed for the shear surface of the SS specimens. On the other hand, 15 annual rings in juvenile and maturing zones were too large to be cut by the Microm microtome. Therefore, the anatomy specimens were cut from 5 annual rings. In some cases, heart checks around the pith prevented the wood observation beside the pith for SS specimens.

Shear strength (SS, τ) was measured so that the fracture plane was parallel to the rays, i.e. the test was performed in TL-direction (Bodig and Jayne 1982; Reiterer et al. 2002) in which T (tangential) is the direction of the normal vector of the fracture plane and the L (longitudinal,) is the direction of fracture propagation. Unlike in the radial test (RL), in TL direction, both EW and LW, as well as rays, affect the strength (Tan et al. 1995). The final number of acceptable test specimens was 136; specimens, which did not crack correctly along the desired plane were discarded, decreasing the number of sW specimens, in particular. The moisture content (MC) of the specimens was adjusted to ≈12% (based on the dry weigh) by conditioning them at 20 ±2°C and 65 ± 3% RH. The SS was measured by means of a Matertest FMT-MEC 100 kN material testing device, according to the Scandinavian standard (Kucera 1992). The duration of the test from load application to the rupture was experimentally adjusted to take between 90 and 120 s.

The anatomy specimens were softened by boiling in water for 45 min and incubating in a mixture of deionized water, 95% ethanol and glycerol (1:1:3) for one week (Schmitz 2010). Sections with a thickness of 20 µm were cut using a Microm rotary microtome, and stained with safranin–alcian blue (Fagerstedt et al. 1996) and mounted with Depex.

A Leica stereomicroscope and a Leitz Laborlux 12 light microscope, both equipped with a Micropublisher 5.0 camera and ImagePro 7.0 software, served for anatomical observations. The numbers of rays (per mm in T direction) and of resin canals per mm$^2$ were counted from the middle of the specimen via the Leica microscope. Anatomical measurements were done by the Leitz microscope. Double tracheid wall thickness from the radial walls (2CWT), both from EW and LW, was measured from 10 cells from each specimen, from as many annual rings as possible. Also, the 2CWT was measured from 10

EW and LW tracheids, located tangentially next to rays and resin canals. However, as there were no resin canals in all specimens, or their number was low, measurements of tracheids located beside resin canals could not be performed for all specimens, or the number of them may have been lower than 10. Tracheids located both next to a resin canal and a ray were not measured. In addition, the radial diameter of the lumen (RD) of 10 tracheids from both EW and LW was measured. The cells were chosen from the same radial line so that the measured EW cells were located ≈20 cells from the border of the annual ring and the measured LW cells ≈10 cells from the ring border. The results are expressed as the mean of 10 measurements for each characteristics per specimen. The wall:lumen ratio was calculated for both EW and LW, based on the 2CWT of those tracheids, which were not located next to the rays or resin canals and their lumen diameter.

Radial fracture planes of mature hW and sW were observed by a Zeiss Sigma HD VP SEM (5 kV acceleration voltage) at SIBLabs, University of Eastern Finland, Kuopio. The specimens were cut to 5 mm x 5 mm x 5 mm pieces and dried at 102 ±2˚C. Subsequently, they were sputter-coated with gold.

Samples from different heights were combined and analysed statistically in the same group. The connections between SS and anatomical characteristics were calculated by Pearson´s correlation procedure in SPSS 21. Values for correlation between density and SS (Luostarinen and Heräjärvi 2011, 2013) are included in the correlation analyses to show the significance of the correlation between density and SS. Furthermore, as some significant correlations between EW characteristics and SS were observed, these EW characteristics were compared between sW and hW according to the Mann-Whitney´s U-test. Similarly, LW characteristics of sW and mature hW were compared with each other.

## Results and discussion

The SS differences between hW and sW (Fig. 1), as indicated in the Introduction, are most probably due to extractives deposition in hW, as there is no correlation with density in sW (Table 1). The conversion from sW to hW also includes death of parenchyma cells, i.e., mainly ray parenchyma and epithelial cells of resin canals in larch, which is accompanied by lignification and ends up in apoptosis of their cell organelles (Bergström 2003; Song et al. 2011; Zheng et al. 2014). The accumulation of extractives (Kampe and Magel 2013) of larch takes place mainly in EW (Côté et al. 1966), which may be explained by the high number of ring pores that facilitate the transport of metabolism products, while LW tracheids hardly have any pores. The extractives accumulate both in the lumens and in the cell wall (Côté et al. 1966; Imai et al. 2005; Nakaba et al. 2012). The close proximity of extractives to cell wall components and chemical bonds between them lowers the hygroscopicity, fractional void volume and volumetric expansion coefficient in hW (Song et al. 2014). Extractives also modify the viscoelasticity of the cell wall (Matsunaga et al. 2000; Song et al. 2014), possibly by increasing the lignin-softening temperature (Matsunaga et al. 2000). Apparently, cellulose crystallinity is not involved in hW formation, but this matter is still under discussion (El-Osta and Wellwood 1972, Newman 2004).

The anatomy of EW, but not that of LW, is related to SS in sW, while no such relationship was found in any of the hW types (Table 1). The higher the 2CWT and the larger the wall:lumen ratio in EW, the higher is the SS, and the larger the RD, the lower is the SS in sapwood. The 2CWT and RD, and their ratio, are characteristics that commonly affect wood density (de Kort et al. 1991; Mitchell and Denne 1997; Hannrup et al. 2001; Luostarinen et al. 2017), although in Siberian larch, these anatomical characteristics did not correlate significantly with density. The insignificance of these correlations within wood types is possibly due to large density difference between EW and LW (Luostarinen 2011) and high extractive concentration particularly in EW of hW (Côté et al. 1966). Extractive content apparently decreases the density difference between EW and LW.

A decrease in cell size and cell wall thickness was observed between sW and hW both in EW and LW (Table 2). The RD of EW tracheids was 50% and the 2CWT 21% larger in sW than in hW, while in case of LW, the differences were 38% and 44%, respectively. The decrease in the thickness and perimeter of the cell walls may be a consequence of the lower hygroscopicity, fractional void volume, volumetric expansion coefficient, and viscoelastic changes (Matsunaga et al. 2000; Song et al. 2014), which are leading to stiffening and strengthening of the cell walls. Both mature hW and sW specimens contained tissues of different cambial ages because of three sampling heights but all of them were mature, as the cell dimensions stabilize in larch at the age of 15-20 years, the only exception being 2CWT of LW (Luostarinen 2012). . As the wall:lumen ratio correlated with SS only in sW-EW (Table 1), its effect may be connected with the actual cell wall thickness up to a certain limit, as the fracturing mode is dependent on cell wall thickness (Zink et al. 1994). The anatomical threshold values, for example of wall thickness for mechanical behaviour and fracturing mode of wood cells, are not known.

Usually, intrawall shear fracture occurs between $S_1$ and $S_2$ in softwood LW tracheids, while in thinner walled EW tracheids and all ray cells, the fracture mode is commonly transwall (Côté and Hanna 1982; Zink et al. 1994; Gindl and Teischinger 2003). In this study, the shear planes mainly followed these rules, but differences occurred between sW (Fig. 2a) and mature hW (Fig. 2b). In hW-EW, intrawall fracturing of tracheids was observed more frequently than in sW-EW. This intrawall fracturing could occur between any cell wall layers. Concerning transwall fracturing of EW tracheids, small torn shreds from the $S_1$ layer of the loosened half of the same cell were occasionally observed, which may be an intermediate form between intrawall and transwall fracture modes. In EW of mature hW, fracturing occurred occasionally through rays instead of tracheids, while rays fractured practically never in sW-EW. Although lignification may strengthen the rays in the course of hW formation (Zheng et al. 2014), the viscoelastic modifications of the tracheid walls (Song et al. 2014) may be more important. However, these small effects occur simultaneously and thus correlations between ray numbers and SS are difficult to observe. Longui et al. (2017) made similar observations in terms of SS of some Brazilian wood species.

More path transfers (Zink et al. 1994) (Fig. 2.a,b) were observed in sW than in hW of Siberian larch. There were 12 jW, 12 maturing wood, 4 mature hW and 28 sW specimens that fractured through a wrong plane. Path transfer could occur either by rolling the tracheids or by direct breaking off in both hW and sW, although rolling was more common in the latter than in the former (Fig. 2a,b). According to Zink et al. (1994), path transfers occur at discontinuities within wood, of which the crossings of tracheids and rays are most important. In Siberian larch wood, these crossings often caused path changes, but they were equally common within tracheids, particularly in sW. A reason for this may be the numerous ring pores in the radial walls of the EW tracheids, together with the effect of changes in cell walls caused by hW formation. No pores were seen in LW tracheid walls, and the path transfers in LW were mostly, but not always, very abrupt breakages of tracheids, causing rolling in connection with rays. The increased probability of path changes in the shearing of Siberian larch sW is detrimental for its utilization as structural wood.

## Conclusions

The EW tracheid characteristics, both 2CWT, RD and their ratio, are influential for SS in Siberian larch sW, but not in hW. Large 2CWT and wall:lumen ratio increases SS, and large RD decreases it. The dimensions of sW tracheids are larger than those of hW tracheids. The shear fracture of EW is different in sW than in mature hW, excluding rays in sW-EW, which shows more path changes. Modifications caused by hW formation in tracheid walls may both affect the tracheid dimensions and the fracture mode and strengthen the mature hW compared to sW.

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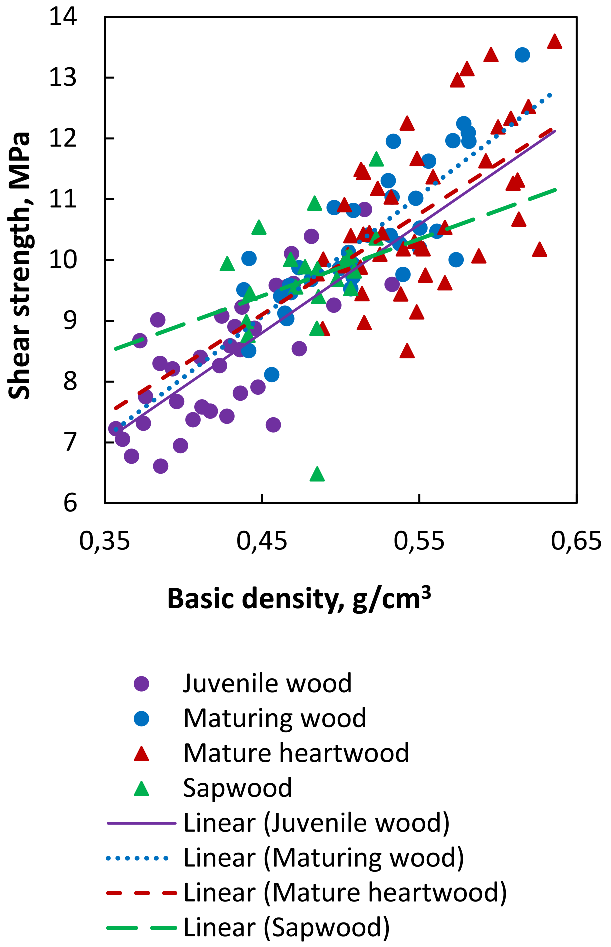
**Table 1**. Pearson´s correlation coefficients (r) and significance levels (* - at 0.05% level, ** - at 0.01% level) and significance (p) between TL shear strength (SS), basic density and anatomical characteristics in *Larix sibirica*. Number in parentheses gives the number of the specimens in the wood type, except for double tracheid wall thickness beside the resin canals the number of specimens is presented below the *p*–values. jW – juvenile wood, hW – heartwood, sW – sapwood, EW – earlywood, LW - latewood

| Wood type/ level of comparison | Property compared with SS | | jW (36) | Maturing wood (36) | Mature hW (44) | sW (20) |
|---|---|---|---|---|---|---|
| Specimen | Basic density | r | 0.732** | 0.816** | 0.558** | 0.261 |
| | | *p* | 0.000 | 0.000 | 0.000 | 0.266 |
| | Density without arabinogalactans | r | 0.681** | 0.749** | 0.309* | 0.123 |
| | | *p* | 0.000 | 0.000 | 0.041 | 0.616 |
| Ring | Number of rays/tangential (mm) | r | 0.073 | 0.052 | -0.058 | -0.259 |
| | | *p* | 0.674 | 0.762 | 0.711 | 0.270 |
| | Number of resin canals ($\text{mm}^{-2}$) | r | 0.271 | 0.53 | 0.045 | -0.034 |
| | | *p* | 0.110 | 0.763 | 0.774 | 0.888 |
| EW | RD of fibre lumens | r | -0.222 | -0.068 | 0.018 | -0.477* |
| | | *p* | 0.194 | 0.693 | 0.908 | 0.033 |
| | Double tracheid wall thickness | r | 0.255 | 0.059 | 0.239 | 0.640** |
| | | *p* | 0.134 | 0.739 | 0.119 | 0.002 |
| | Wall:lumen ratio | r | 0.329 | 0.325 | 0.211 | 0.606** |
| | | *p* | 0.050 | 0.053 | 0.169 | 0.005 |
| | Double tracheid wall thickness | r | 0.049 | -0.026 | -0.128 | 0.415 |
| | beside rays | *p* | 0.777 | 0.879 | 0.407 | 0.069 |
| | Double tracheid wall thickness | r | -0.002 | -0.121 | -0.326 | 0.144 |
| | beside resin canals | *p* | 0.991 | 0.622 | 0.218 | 0.609 |
| | | N | 35 | 19 | 44 | 15 |
| LW | RD diameter of fibre lumens | r | 0.217 | -0.305 | -0.028 | -0.081 |
| | | *p* | 0.205 | 0.070 | 0.858 | 0.734 |
| | Double tracheid wall thickness | r | 0.064 | 0.059 | 0.010 | -0.149 |
| | | *p* | 0.712 | 0.734 | 0.950 | 0.530 |
| | Wall:lumen ratio | r | -0.005 | 0.295 | 0.041 | -0.025 |
| | | *p* | 0.976 | 0.080 | 0.789 | 0.916 |
| | Double tracheid wall | r | -0.051 | -0.107 | -0.056 | -0.227 |
| | thickness beside rays | *p* | 0.768 | 0.535 | 0.719 | 0.336 |
| | Double tracheid wall | r | 0.180 | -0.056 | 0.096 | -0.081 |
| | thickness beside resin canals | *p* | 0.332 | 0.780 | 0.655 | 0.757 |
| | | N | 31 | 27 | 24 | 17 |

**Table 2.** Averages of tracheid characteristics in *Larix sibirica* wood (mean ± StD of the mean), followed by the significance value of Mann-Whitney U -test (M-W U) performed between mature heartwood (hW) and sapwood (sW). ** - significant at 0.01% level. EW - earlywood; LW - latewood

| Wood type | Anatomical characteristics | Mature | | M-W U |
|---|---|---|---|---|
| | | hW | sW | *p* |
| EW | Double wall thickness (μm) | 4.28±0.18 | 5.20±0.11 | 0.000** |
| | Lumen diameter (μm) | 40.27±0.71 | 60.11±0.71 | 0.000** |
| | Wall:lumen ratio | 0.11±0.01 | 0.09±0.00 | 0.000** |
| LW | Double wall thickness (μm) | 12.33±0.32 | 17.07±0.40 | 0.000** |
| | Lumen diameter (μm) | 9.11±0.32 | 13.08±0.46 | 0.002** |
| | Wall:lumen ratio | 1.41±0.05 | 1.42±0.08 | 0.595 |



Linears:
Juvenile wood: $y = 0.78 + 18.82x$
Maturing wood: $y = 0.1 + 19.93x$
Mature heartwood: $y = 1.65 + 16.56x$
Sapwood: $y = 5.2 + 9.36x$

**Figure 1.** Shear strength of *Larix sibirica* wood by wood types and basic density.

**Figure 2.** Scanning electron microscope (SEM) micrograph of *Larix sibirica* a) sapwood and b) mature heartwood after a TL shear test. Thin arrow – path transfer by tracheid rolling, arrowheads – path transfer by breaking off the tracheids in earlywood (EW) and latewood (LW). Thick arrows – fractured rays in LW.