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Mechanical behaviour of sawn timber of silver birch under compression loading

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ABSTRACT
Silver birch is a common European hardwood species possessing stiff and strong material properties. The mechanical properties of birch timber under compression loads are, however, not well defined as the influence of growth characteristics have largely been disregarded in experimental investigations. To address this, the present study investigated the effect of growth characteristics on the mechanical behaviour of birch sawn timber under compression loading, parallel and perpendicular to the grain direction. The results indicate knot size as the dominant parameter for both loading directions, whereas in specimen without knots, density, distance to pith and growth-ring width are dominant for parallel to grain loading and density and growth-ring orientation are dominant under perpendicular to grain loading. On selected specimens, local deformation and failure behaviour is further investigated by means of digital image correlation technique using a novel contrast pattern. Strain fields on specimens loaded parallel to grain reveal localized strain peaks at the cracks within knots and around the topside of knots where abrupt deviations in the grain orientation occur. Specimens loaded perpendicular to the grain display localized strain peaks near the pith and at growth-ring tangential angles around 45°.

1. Introduction
Silver birch is a hardwood with dense, strong and stiff material properties, common to the plywood, furniture and parquet industries. While the favourable mechanical properties make birch well suited for structural applications, it is currently not well established as a load-carrying material in the construction industry (Luostarinen and Verkasalo, 2000). In recent years, there has been an increasing amount of research investigating the potential of hardwoods in construction. For example, studies assessing the mechanical properties and efficacy of grading techniques on European beech demonstrated that high-strength glued-laminated timber (GLT) and cross-laminated timber (CLT) could be efficiently realized (Bläss, 2005; Frese and Riedler, 2010; Ehrhart et al., 2016a, 2016b). Research on the mechanical properties and the influence of growth characteristics on the mechanical properties of other European hardwoods have also recently gained momentum (e.g. Frühwald and Schickhofer, 2005; Säll et al., 2007; Wanninger et al., 2015; Schlotzhauer et al., 2017, 2018). Interest for birch as a structural material has evolved along with these developments. Recent studies on the mechanical properties of birch sawn timber and timber products have indicated birch as a suitable species for structural applications. For example, in a series of studies Solli (2004) and Kilde et al. (2006) concluded that birch can be used for high-strength GLT beams. Jeitler et al. (2016), quantified the mechanical properties of birch timber, GLT and CLT. The study led to two pilot projects, a detached house and an industrial hall which applied both, birch CLT and GLT, in load-carrying applications.

Dunham et al. (1999) had also investigated the flexural properties of structural birch timber and small clear wood samples and identified the influence of growth rate, knots and grain angle on mechanical properties. While other studies have reported mechanical properties for birch, testing has mainly been conducted on small specimen and specimens free from growth irregularities (clear wood), e.g. Jalava (1945); Lavers (1983); Heräjärvi (2004a); Schlotzhauer et al. (2017). Results from these studies, while descriptive of birch clear wood properties, are not indicative of the mechanical properties for structural timber. For an accurate account of strength and stiffness in load-carrying applications, it is imperative that size effects and the inhomogeneous properties of timber are considered.

These studies provide the basis for assessing the structural potential of birch timber and demonstrate the applicability of birch in the construction industry. In general, literature on the influence of growth characteristics and inhomogeneities on the mechanical properties of sawn timber is still lacking for birch, in particular under compression loads. Therefore, for further assessment of the structural potential of birch, the present research investigated the effect of growth characteristics on the strength and stiffness of birch sawn timber under compression loading, parallel and perpendicular to the grain.

2. Materials and method
2.1. Specimens
Silver birch (Betula pendula Roth.) from southern Finland was used in this study. Twenty seven logs were through-and-
through sawn into 60 un-edged planks. Specimens for parallel and perpendicular to grain loading were sawn from the un-edged planks in selected regions, with and without knots (Figure 1). The selection of specimens with knots focused on procuring a wide array of knot characteristics, including knot size, position and orientation. For the qualitative investigation of deformation behaviour around knots (see Section 2.4), specimens with knots located near the centre, as well as specimens with knots located near or partly outside the specimens-edges (all sides) are investigated. Knot clusters are excluded from investigations since they are mainly concentrated near the pith and thus would only be obtained in a small number of specimens. The selection of specimens without knots focused on procuring a wide array of clear wood characteristics, including density $\rho$, distance to pith $d_p$ and growth-ring angle $a_c$ (Figure 1). Specimen dimensions and the sample sizes for each loading direction are summarized in Table 1. The selection captures several growth characteristics in order to investigate their influence on the mechanical properties. They may not be representative of all silver birch.

2.2. Density and visual characteristics

Specimens were kept in a climate chamber at a temperature of 20°C and 65% relative humidity (CEN, 2012). Density ($\rho$) of each specimen was determined at equilibrium moisture content (approx. 12%). Mean values of the density (only knot free samples) are presented in Table 1. It can be observed that the mean density of the specimens selected for perpendicular to grain testing is slightly higher compared to the specimens selected for parallel testing.

Visual inspections were conducted and several growth characteristics, as well as various knot parameters, were documented (Table 2). The (relative) position of the pith and the specimen was determined on the cross-section of the log. The sawn location of the specimen was projected onto the cross-section of the un-edged plank and in combination with cross-section images of all planks, the log was reconstructed (according to annual ring pattern) with the specimen and the pith located (Figure 1). Knot parameters were estimated based on the visible surfaces, assuming an elliptic cone. For knots that were only visible on one side, e.g. encased knots or knots in pith boards, cuts were made after testing to reveal the knot dimensions. Intergrown (sound) and encased (rot) knots are obtained in the samples, however, a suitable visual parameter for this feature was not identified as the majority of knots had some portion of enca- cement which varied along its length and only a small number of knots were fully intergrown or encased.

2.3. Compression tests

Compression test parallel and perpendicular to the grain were conducted to determine mechanical properties. All testing methods and the determination of mechanical properties ($f_{c,0}$, $f_{c,90}$, $E_{c,0}$, $E_{c,90}$) follow the European standard, EN 408 (CEN, 2012). A universal testing machine (UTM), with a maximum applied force of 200 kN, is used along with a rotational loading head at the base. Two linear variable differential transformers (LVDT) were attached on the specimen (centrally positioned) with a gauge length $l_G = 4 \times t = 160 \text{ mm}$, and $l_G = 0.6 \times w = 54 \text{ mm}$, for

| Specimen details | Loading direction: $t \times w \times l$ [mm$^3$] | Parallel to grain | Perpendicular to grain |
|------------------|---------------------------------------------|---------------------|------------------------|
| Specimen details | $40 \times 90 \times 240$ | 26 without knots | 28 with knots |
| Test specifications | $611$ without knots | $160$ | $1.0$ Pre-load [kN] |
| $\rho$ [kg/m$^3$] | 620 | 54 | 0.40 Loading rate [mm/min] |

Note: Specimen thickness $t$, width $w$ and length $l$, sample size $n$, and mean density $\rho$. 

Figure 1. Examples of selection locations within the un-edged boards for parallel and perpendicular to grain test specimens, with and without knots (left). Cross-section view with definitions of growth characteristics, distance to pith $d_p$ and growth-ring angle $a_c$ (right). Specimen length $l$, width $w$ and thickness $t$. 

Table 1. Test specimens and specifications of the compression tests.
parallel and perpendicular specimens, respectively. In the case of knots located in the attachment region, initial gauge length was altered to avoid interference. Table 1 provides a summary of test details. As some of the knots are located (partly) outside the measurement range of the LVDT, the effect of this on stiffness is investigated.

2.4. Digital image correlation

To investigate local deformation behaviour around knots and growth-rings, digital images were captured during tests and digital image correlation (DIC) technology was used to develop strain fields on the surface of selected specimens. A 2D optical system captured images at a frequency of 1/3 Hz during testing. The images were processed and then input into DIC software, GOM correlate, GOM Gmbh, (Braunschweig, Germany). This software uses an automated computer algorithm to determine local displacements and strains according to deformation images. Equivalent (von Mises) strains are determined according to Equation (1), where \( \phi_i \) denotes true strain for each strain component.

\[
\phi_M = \sqrt{\frac{1}{2} \sum_{i=1}^{n} \phi_i^2}
\]  

A novel contrast pattern was applied on the surface of the specimens (Figure 2). This pattern is designed for enhanced accuracy and robustness of the DIC autocorrelation (see Bossuyt, 2013 for details on the theoretical background and optimization of corresponding DIC patterns). As determined from pre-tests, utilization of this pattern demonstrated a significant improvement in displacement resolution, compared to other trial spray-painted stochastic speckle patterns. Together with a high-resolution digital camera (8712 x 5813 pixels) a displacement resolution capable of distinguishing displacement gradients within individual growth-rings could be achieved.

3. Results

The mechanical properties obtained from testing are presented along with their dependency to growth characteristics. The correlation between the mechanical properties and selected growth characteristics are described. The influence of knot parameters are investigated on specimens with knots and the influence of all non-knot related growth characteristics are investigated on specimens without knots. The influence of knots on the mechanical properties is significant.

Not all parameters introduced in Section 2.2 are presented here, as the corresponding parameter might not be statistically representative, e.g. the seldom occurrence of severe spiral grain, i.e. more than 80% of the knot free specimens have a spiral grain angle \( \psi < 7^\circ \).

Consider all knot free specimens, correlation coefficients are determined between density and distance to pith, \( r(p, d_p) = 0.56 \), between density and growth-ring width, \( r(p, RW) = -0.42 \), and between distance to pith and growth-ring width, \( r(d_p, RW) = -0.59 \). These relationships indicate no discrepancy with literature describing the physio-morphological properties of birch wood (e.g. Jalava, 1945; Bhat, 1980; Bhat and Kärkkäinen, 1981; Heräjärvi, 2004b). Moreover, it is mentioned that for a diffuse-porous hardwood such as birch, the dependency between growing-ring width and density is more related to cambial age rather than growth rate (Dinwoodie, 2000).

3.1. Compression parallel to grain

Results from compression parallel to grain test are summarized in Table 3 and Figure 3(a–c). As expected, specimens with knots shows significantly lower mechanical properties (about 20%) and a higher COV. Some specimens have knots located (partly) outside the LVDT range. Considering only

| Parameter                              | Definition                                                                 |
|----------------------------------------|---------------------------------------------------------------------------|
| Distance to pith \( d_p \)             | Distance from centroid of specimen to pith (Figure 1)                     |
| Growth-ring width \( RW \)             | Mean growth-ring width measured (on a representative line) on both cross-sections of the specimen |
| Growth-ring angle \( \alpha_c \)       | Orientation of the growth-ring at centroid of specimen (Figure 1)          |
| Spiral grain \( \psi \)                | Slope of grain, measured using a scribe (in accordance to EN 1310, CEN, 1997) |
| Knot area ratio \( KAR \)              | Ratio of the projected knot area to surface area of the specimen, normal to the load direction (see e.g. Isaksson, 1999) |
| Knot volume \( K_v \)                  | Volume of the representative conical knot section within the specimen      |
| Knot width \( K_w \)                   | Maximum width of all visible knot faces, measured normal to loading direction (in accordance to INSTA 142, 2010) |
| Knot position                         | Distance between the centroid of the projected knot area and the centre of the specimen, measured normal to loading direction |
| Knot orientation                      | Angle between knot axis and loading direction                             |

Table 2. Documented growth characteristics and knot parameters.

| Parameter                              | Definition                                                                 |
|----------------------------------------|---------------------------------------------------------------------------|
| Knot position                         | Distance between the centroid of the projected knot area and the centre of the specimen, measured normal to loading direction |
| Knot orientation                      | Angle between knot axis and loading direction                             |

Figure 2. Example of digital image correlation contrast pattern applied on the surface of a specimen.

Table 3. Mean mechanical properties [MPa] and correlation coefficients between mechanical properties.

|                         | All specimens | Without knots | With knots |
|-------------------------|---------------|---------------|------------|
| \( f_{c,0} \)           | 48.3 (0.15)   | 52.7 (0.10)   | 43.9 (0.14) |
| \( E_{c,0} \)           | 14857 (0.19)  | 16530 (0.12)  | 13620 (0.22) |
| \( r(f_{c,0}, E_{c,0}) \)| 0.87          | 0.91          | 0.81       |
| \( f_{c,90} \)          | 6.8 (0.25)    | 6.5 (0.28)    | 7.1 (0.20)  |
| \( E_{c,90} \)          | 674 (0.31)    | 620 (0.37)    | 729 (0.24)  |
| \( r(f_{c,90}, E_{c,90})\)| 0.83          | 0.85          | 0.80       |

Note: Coefficient of variation (COV) is shown in parentheses.
specimens with knots entirely within the LVDT range, the mean stiffness is slightly lower \( \bar{E}_{c,0} = 13401 \) MPa; with \( r(f_{c,0}, E_{c,0}) = 0.86 \).

One specimen (Figure 3(a): \( f_{c,0} = 48 \) MPa, \( E_{c,0} = 19750 \) MPa) is an observed anomaly. It was cut from a location in the un-edged plank that contained partial (brown-reddish)
discolouration. While, according to literature, this type of discoulisation can be present without any affect on wood mechanical properties (e.g. Hallaksela and Niemistö, 1998; Duchesne et al., 2016), micro-cracking and softened wood are apparent in the discoloured region of this specimen. Therefore, it is likely that the discoloured wood has partially decayed, causing a reduction in strength. This was the only specimen containing this defect and its influence on sample statistics is negligible.

During testing, six specimens did not fail before the maximum force of the UTM. These specimens were planed to slightly smaller dimensions \( (t \times w \times l = 37 \times 82 \times 220 \text{ mm}^3) \) and re-tested until failure. The maximum strength values obtained from re-testing are shown in grey in Figure 3(a,b). According to the results, this method appears reasonable as the re-tested strengths are all above the initial values (determined at the force limit of the UTM) and although the re-tests are performed without LVDTs, the stiffness of the initial and re-tests were compared using the load-head displacement data of the UTM, and only marginal differences were identified. Furthermore, the re-tested data points correspond well with the trends of the remaining test data. All values presented in this paper are based on the LVDT data. It is also important to mention here that excluding these data points or considering them as equality data, would lead to an underestimation of the basic population (e.g. Fink et al., 2018).

3.1.1. Knot free specimens

The correlation between several growth and sawing characteristics and the mechanical properties are summarized in Table 4. Figure 3(b) shows a scatter plot of density vs. strength, in which, a significant correlation is observed for knot free specimens: \( r(p, f_{c0}) = 0.66 \). A similar correlation is determined between density and stiffness, for knot free specimens: \( r(p, E_{c0}) = 0.67 \). The results are in line with other hardwood literature which identify a dependency between density and mechanical properties for clear wood but disregard density as an effective indicator for structural timber (e.g. Heräjärvi, 2004a; Solli, 2004; Blaß, 2005; Frühwald and Schickhofer, 2005; Ehrhart et al., 2016).

Correlations determined between distance to pith and growth-ring width and the mechanical properties indicate clear dependencies: \( r(d_p, f_{c0}) = 0.57 \), \( r(d_p, E_{c0}) = 0.49 \), \( r(RW, f_{c0}) = -0.79 \), and \( r(RW, E_{c0}) = -0.69 \). A strong dependency between ring width and the flexural properties of small clear wood birch specimens is also identified in Dunham et al. (1999). Parameter \( \alpha_c \) shows no clear relationship with strength or stiffness properties \( |r(\alpha_c, f_{c0})| \leq 0.3 \), possibly due to the dominant influence of the aforementioned parameters.

### Table 4. Correlation coefficients between knot free specimens and mechanical properties.

|        | \( p \) | \( d_p \) | \( RW \) | \( \alpha_c \) |
|--------|--------|--------|--------|--------|
| \( f_{c0} \) | 0.66   | 0.57   | -0.79  | -0.26  |
| \( E_{c0} \) | 0.67   | 0.49   | -0.69  | -0.28  |
| \( f_{90} \) | 0.79   | 0.43   | -0.04  | 0.65   |
| \( E_{90} \) | 0.58   | 0.08   | -0.05  | 0.82   |

3.1.2. Knot characteristics

As expected, knot size has a significant influence on mechanical properties. For example, the correlation coefficients between knot volume and compression strength and stiffness are: \( r(K_v, f_{c0}) = -0.48 \) (see also Figure 3(c)); and \( r(K_v, E_{c0}) = -0.48 \). It has to be mentioned that for \( E_{c0} \) only specimens with knots entirely within the LVDT range are considered and the number of samples is rather small, accordingly. Other parameters quantifying knots size (KAR and knot width) show similar dependencies with the mechanical properties. Overall, the relationships identified between knot size and mechanical properties indicate no major difference with those reported for softwoods (e.g. Isaksson, 1999; Vega et al., 2012; Fink, 2014). In contrast to knot size, no significant influence of knot position or knot orientation is identified; however, the number of well-defined cases is rather limited for both parameters.

3.1.3. Deformation behaviour

Under loading parallel to the grain, buckling of fibres (i.e. local shear bands) is observed as the most common failure mode in specimen with and without knots. The same failure mode was reported in Schlotzhauer et al. (2017) for defect-free structural birch timber and other hardwoods and is further described in Dinwoodie (2000). In specimens with knots, fibre buckling occurred predominately in the cross-section region containing the knot, even in the case of minor knots.

Figure 4 illustrates an example of the development of equivalent strains during testing of a specimen with a knot. Strain fields are presented at two load levels: maximum load and after failure. Until maximum load, strain concentrations are mainly visible at the cracks and bark inclusions on the knot and around the top side of the knot. After failure, fibre buckling becomes visible and continues to develop over the full cross-section. Locations of fibre buckling occur where strains are maximized and generally follow a single path across the specimen. Additional examples illustrating the deformation behaviour of birch specimens with knots are shown in Collins and Fink (2018).

The phenomenon of localized strains occurring around the topside of knots may be explained by the presence of local grain deviations. According to Shigo (1997) intergrown knots are formed from a combination of fibres growing into the branch and around the branch while dead knots only have fibre growth that surrounds the knot. Below an intergrown knot, fibres slowly diverge out of plane while the fibres that pass around the branch diverge quickly into the topside of the branch or back to initial growth direction, above the knot. This abrupt change in direction over the top of the knot is observed in the birch timber and in the regions experiencing strain concentrations. This result suggest the importance of fibre directions in the vicinity of knots for determining mechanical properties. Moreover, during the growth of the tree, forces applied from the branch onto the stem can cause the formation of tension wood over the topside of the branch. It is therefore possible that tension wood is present in the region above a knot.
Tension wood in birch is reported to have a considerably lower compression strength, and reduced elastic properties, compared to normal wood (Ollinmaa, 1955). However, the presence of tension wood was not clearly identifiable through visual inspection. In general, studies detailing reliable non-destructive methods for the detection of tension wood in birch is lacking and thus, the presence of tension wood in specimens with knots is undetermined.

3.2. Compression perpendicular to grain

Results from compression perpendicular to grain tests are summarized in Table 3 and Figure 3(d–f). The mean strength and stiffness of all specimens \( f_{c,90} = 6.8 \text{ MPa} \) and \( E_{c,90} = 674 \text{ MPa} \), indicate favourable mechanical properties for birch, compared to softwood species (e.g. Hoffmeyer et al., 2000; Blaß and Görlacher, 2004; Poussa et al., 2007). On average, the mechanical properties for the sample with knots \( (f_{c,90} = 7.1 \text{ MPa}; \ E_{c,90} = 729 \text{ MPa}) \) are slightly higher compared to the sample without knots \( (f_{c,90} = 6.5 \text{ MPa}; E_{c,90} = 620 \text{ MPa}) \). Some specimens have knots located (partly) outside the LVDT range. When considering only specimens with knots entirely within the LVDT range, the stiffness for the sample with knots is \( E_{c,90} = 705 \text{ MPa} \); with \( r(f_{c,90}, E_{c,90}) = 0.79 \).

For specimens with knots, a smaller coefficient of variation (COV) is observed. This can result from the presence of knots (increased density and mechanical properties) but might also be partially related to the sample selection as the number of plain sawn specimens (low stiffness) and rift sawn specimens (high stiffness) is rather different for the two samples.

3.2.1. Knot free specimens

Figure 3(e) shows a scatter plot of density vs. strength. It is clear that higher density is associated with higher strength \( r(\rho, f_{c,90}) = 0.79 \). A similar trend is identified between density and stiffness \( r(\rho, E_{c,90}) = 0.58 \). The growth-ring angle also shows a significant correlation to the stiffness \( r(\alpha_c, E_{c,90}) = 0.82 \) and a smaller correlation to strength \( r(\alpha_c, f_{c,90}) = 0.65 \), as edge sawn (radially loaded) specimens have higher mechanical properties, particularly stiffness, compared to flat sawn (tangentially loaded) specimens.

Due to the significant influence of the growth-ring angle and density, distance to pith and growth-ring width show almost no correlation with mechanical properties \( (|r| < 0.1) \); with the exception of distance to pith and strength, in which, a larger correlation is identified \( r(d_p, f_{c,90}) = 0.43 \).

3.2.2. Knot characteristics

The mechanical properties increased with knots size, as exemplified by the knot volume: \( r(K_v, f_{c,90}) = 0.59 \) (see also Figure 3(f)); \( r(K_v, E_{c,90}) = 0.42 \) (note: only specimens with knots entirely within the LVDT gauge length are considered and the number of samples is rather small, accordingly). Other parameters quantifying knots size \( (KAR \text{ and knot width}) \) show similar dependencies with the mechanical properties. In contrast to knot size, no significant influence of knot position or knot orientation is identified; however, the number of well-defined cases for both position and orientation is rather limited.

3.2.3. Deformation behaviour

Under compression loading perpendicular to the grain, specimen deformation evolves without any visible crack formations or failure. After the elastic limit of the specimen is reached, ductile behaviour is observed as stress increases, at a decreasing rate, for remainder of the test. In order to discuss the deformation behaviour perpendicular to the grain, strain fields are presented for two specimens under load.

Figure 5 shows equivalent strains on the face of a specimen with a knot located near the upper edge. The strain field image is shown at maximum load. Strains peaks are visible within the crack of the knot and on the lower side of the specimen where there is clear wood with a grain direction principally oriented normal to the load direction. It is observed that only minor strains have developed within and around the region of the knot (excluding the knot cracks). This may be partially attributed to density, since wood within knots and the region surrounding the knot, where fibres converge, are (in some species) associated with higher density, compared to the surrounding wood (e.g. Johansson, 2013; Dadzie and Amoah, 2015). This may also be the case for silver birch as the mean density of specimen with knots was around 6%...
higher compared to the specimen without knots. Furthermore, the grain direction of the knot and the surrounding wood is inclined so that a component of the applied load is directed along the stronger axis of the wood.

Figure 6 shows equivalent strains on the cross-section of a knot free specimen, at maximum load. Strain peaks occurring near the pith and at tangential angles between 35° and 55° from the loading direction are observed. Near the pith, juvenile wood is characterized by larger growth-rings and lower density compared to the outer mature wood (Bhat, 1980; Heräjärvi, 2004) and thus, relatively large deformations are expected in this region. Deformations are also dependent on the angle between radial growth direction and the load direction. According to literature, timber under transverse loading exhibits minimum strength and stiffness at angles around 45° to the direction of annual ring growth (Hoffmeyer, 1987; Hoffmeyer et al., 2000; Foley, 2003).

Beside that, strain gradients within individual growth-rings indicate the regions of early and late wood, with early wood showing relatively higher deformations. Within the growth-rings of birch, the majority of wood is early wood with only a small proportion of latewood (Heräjärvi, 2002).

4. Conclusion

Birch timber specimens with a wide range of growth characteristics are experimentally tested under compression loading, parallel and perpendicular to the grain. Based on the results, the statistical dependencies between the mechanical properties and the growth irregularities are investigated and described. As the influence of knots on the mechanical properties is dominating, knot characteristics are investigated on specimens with knots and clear wood growth characteristics are investigated on specimens without knots. Furthermore, qualitative analysis of strain field images, created by 2D digital image correlation technique using a novel contrast pattern that shows improved displacement resolution, are performed. The most important findings of this study are:

- Knot size parameters (knot volume, KAR and knot width) have a significant influence on the mechanical properties for specimens under both parallel and perpendicular to grain loading.
- Strain field images on specimens with knots, loaded parallel to grain, reveal large local deformations at cracks within knots and around the topside of knots where deviations in grain direction and tension wood occur.
- Strain field images on specimens with knots, loaded perpendicular to grain, show that knot regions are associated with lower deformations, i.e., high stiffness, compared to clear wood regions, while localized strain peaks occur in the cracks of knots.
- Knot free specimens under parallel to the grain loading exhibit minimum strength and stiffness at angles from the loading direction.
- Knot free specimens under perpendicular to grain loading show a significant correlation between the mechanical properties and density, distance to pith, and growth-ring width.
- Knot free specimens under perpendicular to grain loading show a significant correlation between the mechanical properties and density as well as growth-ring angle.
- Strain images on the cross-section of knot free specimens, loaded perpendicular to grain, show localized strain peaks near the pith and at tangential angles around 45° from the loading direction.

The results are in line with the results from other investigations on birch and other hardwoods. Some of them have been expected based on the test performed in previous investigations. Nonetheless, a detailed investigation of the influence of growth irregularities on the mechanical behaviour of birch timber was missing. With continued and more specialized investigations on the identified, and other difficult to assess, growth characteristics (e.g., 3D knot and fibre orientation), better predictions of the strength and stiffness of silver birch can be realized, increasing the potential for utilization of the favourable mechanical properties in the construction industry.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Bhat, K. M. (1980) Variation in structure and selected properties of Finnish birch wood. I. Interrelationships of some structural features, basic density and shrinkage [Betula pendula, B. pubescens]. Silva Fennica, 14(4), 384–396.
Bhat, K. M. and Kärkkäinen, M. (1981) Variation in structure and selected properties of Finnish birch wood: iv. Fibre and vessel length in branches, stems and roots [Betula pendula, B. pubescens]. Silva Fennica, 15(1), 10–17.
Blaß, H. J. (2005) Biegefestigkeit von brettschichtholz aus buche. Univ.-Verl. Karlsruhe.
Blaß, H. J. and Görlacher, R. (2004) Compression perpendicular to the grain. In Proceedings of WCTE2004, Lahti, Finland. vol. 2, pp. 435–440.
Bossuyt, S. (2013) Optimized patterns for digital image correlation. In H. Jin, C. Sciammarella, C. Furlong and S. Yoshida (eds.) Imaging Methods for Novel Materials and Challenging Applications, Volume 3 (New York: Springer New York), pp. 239–248.
Duchesne, I., et al. (2016) Wood mechanical properties and discoloured heartwood proportion in sugar maple and yellow birch grown in New Brunswick. BioResources, 11(1), 2007–2019.

Dunham, R. A., Cameron, A. D. and Petty, J. A. (1999) The effect of growth rate on the strength properties of sawn beams of silver birch (Betula pendula Roth). Scandinavian Journal of Forest Research, 14(1), 18–26.

Ehrhart, T., et al. (2016a) Experimental investigation of tensile strength and stiffness indicators regarding European beech timber. In Proceedings of WCTE 2016, Vienna, Austria.

Ehrhart, T., et al. (2016b) Strength grading of European beech lamellas for the production of GLT & CLT. In Proceedings of INTER Meeting Forty-Nine, Graz, Austria.

Fink, G. (2014) Influence of varying material properties on the load-bearing capacity of glued laminated timber. Thesis (PhD). ETH Zurich.

Fink, G., Stadelmann, P. and Frangi, A. (2018) Tensile capacity of finger joint connections -- considering censored data. In Proceedings of WCTE2018, Seoul, Republic of Korea.

Foley, C. (2003) Modeling the effects of knots in structural timber. Thesis (PhD). Lund University.

Fresse, M. and Riedler, T. (2010) Untersuchung von buchenschnittholz (fagus sylvatica L) hinsichtlich der eignung für brettschichtholz (investigation of beech lumber (Fagus sylvatica L) in regard to suitability for glulam). European Journal of Wood and Wood Products, 68(4), 445–453.

Frühwald, K. and Schickhofer, G. (2005) Strength grading of hardwoods. In Proceedings of the 14th International Symposium on Nondestructive Testing of Wood, vol. 2.

Hallaksela, A. M. and Niemistö, P., 1998. Stem discoloration of planted silver birch. Scandinavian Journal of Forest Research, 13 (1-4), 169–176.

Heräjärvi, H. (2004a) Properties of birch (Betula pendula, B. pubescens) for sawmilling and further processing in Finland. The Finnish Forest Research Institute, Research Papers 871.

Heräjärvi, H. (2004b) Static bending properties of Finnish birch wood. Wood Science and Technology, 37(6), 523–530.

Heräjärvi, H. (2004c) Variation of basic density and Brinell hardness within mature Finnish Betula pendula and B. pubescens stems. Wood and Fiber Science, 36(2), 216–227.

Hoffmeyer, P. (1987) The role of grain angle, knots, tension wood, compression wood, and other anomalies on the mechanical properties of wood. Thesis (PhD). Technical University of Denmark.

Hoffmeyer, P., Damkilde, L. and Pedersen, T. N. (2000) Structural timber and glulam in compression perpendicular to grain. Holz Als Roh-und Werkstoff, 58(1-2), 73–80.

INSTA142, (2010), Nordic visual strength grading rules for timber. Suomen Standardisoimislitto SFS.

Isaksson, T. (1999) Modelling the variability of bending strength in structural timber -- length and load configuration effects. Thesis (PhD). Lund University.

Jalava, M. (1945) Suomalaisten männyn, kuusen, koivun ja haavan lujuusominaisuuksista (strength properties of finnish pine, spruce, birch and aspen). Metsätieteellisen Tutkimuslaitoksen, 33.

Jeitler, G., Augustin, M. and Schickhofer, G. (2016) Birch—GLT+ CLT-mechanical properties of glued laminated timber and cross laminated timber produced with the wood species birch. In Proceedings of WCTE 2016, Vienna, Austria.

Johansson, E. (2013) Computed tomography of sawlogs: knot detection and sawing optimization. Thesis (PhD). Luleå tekniska universitet.

Kilde, V., et al. (2006) Bjerks synlige konstruksjoner (Birch in visible constructions). Norsk Treteknisk Institutt, Rapport nr. 67.

Lavers, G. M. (1983) The strength properties of timber, building research establishment report. London: Department of the Environment, Building Research Establishment.

Luostarinen, K. and Verkasalo, E. (2000) Birch as sawn timber and in mechanical further processing in Finland. A literature study. Silva Fennica, 39 (1), 11–47.

Ollinmaa, P. J. (1995) Koivun vetopuun anatomisesta rakenteesta ja ominaisuuksista (On the anatomic structure and properties of the tension wood in birch). Helsinki: Suomen metsätieteellinen seura.

Poussa, M., Tukiainen, P. and Ranta-Manus, A. (2007) Experimental study of compression and shear strength of spruce timber. In Proceedings of CIB-W18-Timber Structures. Univ. of Karlsruhe.

Säll, H., Källsner, B. and Olsson, A. (2007) Bending strength and stiffness of aspen sawn timber. In: COST Action E53 The First Conference: Quality Control for Wood and Wood Products. Warsaw University of Life Sciences.

Schlotzhauer, P., et al. (2017) Effect of size and geometry on strength values and MOE of selected hardwood species. Wood Material Science & Engineering, 12(3), 149–157.

Schlotzhauer, P., et al. (2018) Comparison of three systems for automatic grain angle determination on European hardwood for construction use. European Journal of Wood and Wood Products, 76(3), 911–923.

Shigo, A. L. (1997) A New Tree Biology Facts Photos, and Philosophies on Trees and Their Problems and Proper Care. Eighth Printing (Durham, NE: Shigo and Trees, Associates).

Soll, K. H. (2004) Tensile strength of Nordic birch. In: Proceedings of Meeting Thirty-seven of CIB-W18, paper 37-6. vol. 1.

Vega, A., et al. (2012) Modelling of the mechanical properties of Castanea sativa Mill structural timber by a combination of non-destructive variables and visual grading parameters. European Journal of Wood and Wood Products, 70(6), 839–844.

Wanninger, F., Frangi, A. and Steiger, R. (2015) Bearing stiffness in wood-to-wood compression joints. Engineering Structures, 101, 631–640.