Original article

Maximilian Pramreiter*, Sabine C. Bodner, Jozef Keckes, Alexander Stadlmann, Florian Feist, Georg Baumann, Emad Maawad and Ulrich Müller

Predicting strength of Finnish birch veneers based on three different failure criteria

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Abstract: The use of wood in high-performance composites based on laminated veneer products, plywood or wood hybrid elements thereof requires accurate prediction of strength of each individual ply. Previous research has shown that one dominating factor influencing the strength of birch veneers is the fibre orientation. The present study investigates the validity of the failure criteria after Tsai-Hill, Hoffmann and Kollmann for thin birch veneers under tensile loading. The fibre orientation in- and out-of-plane was measured by means of wide-angle X-ray scattering. Tensile strength and threshold values were determined in laboratory experiments. Pearson correlation between the predicted strength and actual strength ranged from 0.836 up to 0.883. Best correlation ($r = 0.883$) was achieved for Kollmann using a combined angle between in- and out-of-

plane fibre orientation. It was shown that the failure criteria commonly used for manmade fibre reinforced composites are also applicable for thin birch veneers.

Keywords: failure criteria; fibre orientation; non-destructive testing; strength prediction; wide angle X-ray scattering.

1 Introduction

On a macroscopic scale manmade fibre reinforced composites are a combination of fibres such as glass or carbon embedded in an amorphous matrix e.g. epoxy (Nielsen and Landel 1994). The orientation of the fibres within the composite can be arranged freely to optimize strength and fit the demand of the finished product (Flemming and Roth 2003). Wood is a natural material structured at multiple hierarchical levels (Fratzl and Weinkamer 2007). On the cell-wall level it can be understood as a natural fibre reinforced composite made up of fibrous cellulose embedded in amorphous lignin and hemicellulose (Fratzl 2007). On the tree ring level fibre orientation is the predominating factor influencing strength and stiffness (Kollmann and Cote 1968). The fibre orientation itself is influenced by a multitude of growth and environmental factors (Richter 2015). Therefore, wood can be seen as a biological fibre reinforced composite with somewhat arbitrary fibre orientation. It is usually considered in applications with static loads that require high elastic stability e.g. beams or columns for building constructions (Bodig and Goodman 1973; Panshin and Zeeuw 1964). Due to its variability within the same species as well as within a single tree (Marra 1979) predictability of different properties of individual wood elements (i.e. lumber, beams, veneers, etc.) for load-bearing structures is an important issue (Bucur 2003; Ross 2015).

Besides established fields of application for wood and wood products e.g. glue-laminated-timber, laminated-veneer-lumber, plywood, furniture, pulp and paper, current research efforts also investigate the capabilities of

*Corresponding author: Maximilian Pramreiter, Department of Material Science and Process Engineering, Institute of Wood Technology and Renewable Materials, University of Natural Resources and Life Sciences Vienna, Austria (BOKU), Konrad Lorenz Strasse 24, 3430, Tulln a.d. Donau, Austria,
E-mail: maximilian.pramreiter@boku.ac.at. <https://orcid.org/0000-0003-0283-5936>

Sabine C. Bodner and Jozef Keckes, Department of Materials Science, University Leoben, Jahnstrasse 12, 8700, Leoben, Austria,
E-mail: sabine.bodner@unileoben.ac.at (S.C. Bodner),
Jozef.Keckes@unileoben.ac.at (J. Keckes)

Alexander Stadlmann and Ulrich Müller, Department of Material Science and Process Engineering, Institute of Wood Technology and Renewable Materials, University of Natural Resources and Life Sciences Vienna, Austria (BOKU), Konrad Lorenz Strasse 24, 3430, Tulln a.d. Donau, Austria, E-mail: alexander.stadlmann@boku.ac.at (A. Stadlmann), ulrich.mueller@boku.ac.at (U. Müller)

Florian Feist and Georg Baumann, Vehicle Safety Institute (VSI), Graz University of Technology, Inffeldgasse 23/I, 8010, Graz, Austria,
E-mail: florian.feist@tugraz.at (F. Feist), georg.baumann@tugraz.at (G. Baumann)

Emad Maawad, Institute of Materials Physics, Helmholtz-Zentrum Geesthacht, Max-Planck-Str.1, D-21502 Geesthacht, Germany,
E-mail: emad.maawad@hzg.de. <https://orcid.org/0000-0003-4500-2301>

wood for high performance based composites such as automotive parts (Baumann et al. 2019; Berthold 2016; Müller et al. 2019b). To reduce costs and time the product development cycle within the automotive industry is strongly supported by computer aided engineering (CAE) e.g. finite element modelling (FEM) (Gu 2017). Predicting the behaviour of wood using FEM is a key challenge when introducing wood in such high-performance applications. A constitutive model describes the material response under mechanical (or multi-physical) loading. A material card is an implementation of a constitutive model in a FE code, where characteristic values describing e.g. elasticity, plasticity, damage and failure are entered (Klein 2012). Needed material values include the modulus of elasticity, the shear modulus, the Poisson's ratio, the density and the strength. Additionally, the viscoelastic behaviour (Navi and Stanzl-Tschegg 2009) and strain rate dependency (Polocoşer et al. 2017) also need to be considered when utilizing wood for structural applications. To support reliable simulation results the representing material values need to be precise and reliable (Müller et al. 2019a).

Based on these requirements it is clear that an accurate, reliable, reproducible and non-destructive method to predict relevant material parameters of wood, including strength, is needed. Current research in the area of strength prediction is dealing with either standing trees or logs (Mahler and Hauße 2000; Turpening 2011), sawn lumber (Diebold et al. 2000; Rohanova et al. 2011; Sandoz et al. 2000; Stapel and Van De Kuilen 2014) and engineered wood products (EWPs) (Gilbert et al. 2017a, 2017b; Hunt et al. 1989; Mansfield et al. 2016; Meder et al. 2002). Most of these methods include the measurement of strength influencing factors such as density, dynamic modulus of elasticity or fibre orientation. One dominating factor influencing strength of wood is the fibre deviation within the material (Keckes et al. 2003; Pramreiter et al. 2020a). Within the wood industry the most common failure criteria to describe strength in relation to fibre orientation was first described by Hankinson (1921). The model is based on empirical results for compression under different fibre orientations. Kollmann (1934) later adopted the model in order to increase the applicability. Based on empirical results the model can be used for strength as well as elastic properties and can be established for different wood species. To build the curve threshold values for tension or compression are needed. The slope in turn is based on an empirical value which needs to be adopted for each dataset. In contrast to wood the failure criteria used for man-made fibre reinforced composites are solely based on the fundamental strength concepts for tension, compression and shear under uniaxial or biaxial loading (Jones 1999).

The threshold values for tension or compression are still needed. Additionally, the threshold in-plane shear strength of the material is needed. This constitutes the biggest difference to Kollmann (1951) and is true for failure criteria after Tsai-Hill (1950), Tsai and Wu (1971) and Hoffmann (1967).

The present study aims to investigate the accuracy of different failure criteria for fibre reinforced composites for the bio-composite wood. Eberhardsteiner (2002) discussed the application of failure criteria according to Tsai-Hill (1950), Tsai and Wu (1971) and Hoffmann (1967) for spruce wood. The failure criterion Tsai and Wu (1971) and its accuracy when applied to wood have been investigated in detail (Eberhardsteiner 2002; Mascia and Nicolas 2012) and was therefore not included in this work. The Tsai and Wu (1971) criterion exhibits satisfactory capabilities to predict strength based on its increased number of terms in the curve fitting equation. However, the determination of the interaction coefficient (F_{12}) requires an expensive biaxial test without distinctly increasing the accuracy (Jones 1999). Therefore, the focus of the present work was laid on criteria after Tsai-Hill (1950) as well as Hoffmann (1967). Furthermore, the accuracy of the empirical failure criteria Kollmann (1951) should be evaluated for thin hardwood veneers. Thin birch veneers with different fibre orientation were used for the tests. The fibre in-plane and out-of-plane orientations were determined by means of wide-angle X-ray scattering (WAXS). The tensile strength was determined according to the standard DIN 789 (2005) using an universal testing machine.

It was hypothesized that a sound prediction of strength can be achieved using different failure criteria according to Kollmann (1951), Tsai-Hill (1950) or Hoffmann (1967). Additionally, it was hypothesized that Tsai-Hill (1950) and Hoffmann (1967) show higher correlation with strength than Kollmann (1951), because they are not empirical models but are solely based on fundamental strength concepts. Furthermore, it was assumed that the combination of in- and out-of-plane fibre orientation yields a higher correlation than maximum in in-plane fibre orientation alone.

2 Materials and methods

2.1 Fibre orientation samples

Partly samples and data from an earlier study (Pramreiter et al. 2020a) were used to investigate the fibre orientation. Twenty unsorted Finnish birch (*Betula pendula*) veneers (sourced from Koskisen, Järvelä, Finland) with a thickness of $0.6 \text{ mm} \pm 0.05 \text{ mm}$ were prepared.

Figure 1: Sample geometries.

(A) shows the sample for WAXS and tensile strength measurements including the measuring spots used to determine the fibre orientation (also used in Pramreiter et al. 2020a); (B) shows the sample geometry used to determine the threshold values for the failure models (top: tensile strength parallel to the fibre direction, middle: tensile strength perpendicular to the fibre direction and bottom: in-plane shear strength).

The unsorted sample batch included a random number of different quality veneers (A, B and C) according to the suppliers veneer grades (Koskisen 2020). Therefore, the veneers contained a small number of defects such as knots and bark inclusions. The size of the specimens was dictated by the WAXS experiments. It was decided to measure the fibre orientation at seven points along the centre line of the specimens. Geometry and measuring spots are shown in Figure 1A. Raw data obtained from these samples can also be found in the supplementary material (Supplementary Table S1).

2.2 Threshold samples

In order to establish the failure criteria threshold values for shear strength, longitudinal and perpendicular tensile strength were determined. A total of 25 samples for each test setup, with a thickness of approximately 0.6 ± 0.05 mm, a width of 30 ± 0.1 mm and a length of 100 ± 1 mm, were laser cut (Epilog Zing 24, cameo Laser Franz Hagemann GmbH, Germany) out of A-grade (Koskisen 2020) Finnish birch (*B. pendula*) veneers (sourced from Koskisen, Järvelä, Finland). The A-grade veneers were visually pre-sorted to ensure that the resulting fibre orientation of the threshold samples deviated as little as possible from the desired direction. Despite the pre-sorting of the veneers a slight deviation from 0 or 90° was expected to still be present. The sample geometry for each test setup is depicted in Figure 1B. After preparation, the samples were stored under standard climate conditions ($20 \pm 2^\circ\text{C}$ and $65 \pm 5\%$ relative humidity) (ISO 554 1976) until no change in mass could be observed in a 6 h increment.

The Hoffmann failure criterion also needed threshold values for parallel and perpendicular compression. The investigated veneers were only about half a millimetre thick. Because of that compression tests were not feasible. In order to apply the failure criterion literature values from Ross (2010) were used. He reported parallel as well as perpendicular compression strengths for birch. The results presented by Ross (2010) for parallel compressive strength are in agreement with findings from Wagenführ (2006) and Sell (1989). Therefore, the values

Table 1: Testing conditions for the evaluated properties according to DIN 789 (2005).

	σ_φ	Xt	Yt	S
Span-length (mm)	210	30	30	10
Pre-force (N)	100	10	5	5
Testing speed (mm/min)	2.0	1.0	0.5	0.5

provide a confident replacement for the compression tests. Raw data obtained for parallel and perpendicular tensile strength as well as in-plane shear strength can also be found in the supplementary material (Supplementary Tables S2–S4).

2.3 Strength

The tensile strength (σ_φ , Xt , Yt) as well as in-plane shear strength (S) were determined using a universal testing machine (Z100, Zwick/Roell, Ulm, Germany) (DIN EN 789 2005). The load cell had a capacity of 100 kN and achieved a resolution of 0.06 N. The testing conditions for the different properties are summarized in Table 1. The tests were stopped after a 30% force reduction was reached. The resulting tensile strength was only valid when failure occurred between the clamping area, within the constant cross-section of 10 ± 0.1 mm or 40 ± 1 mm width. Observed shear values on the other hand were only valid when failure occurred between the angled cuts along the fibre direction of the 10 ± 0.1 mm intact cross-section. Additionally, veneers pre-damaged during the test setup were also considered invalid. The initial batch of fibre orientation samples contained 20 specimens while a total of 25 threshold samples for each load case were tested. The number of valid samples for each category can be found in Table 2. The invalid samples were not considered in the statistical analysis. The strength of the fibre orientation samples was also part of an earlier study (Pramreiter et al. 2020a).

Table 2: Material properties.

	Fibre orientation samples				Threshold samples				
	σ_φ (MPa)	ρ (kg/m ³)	α_2 (°)	β (°)	Xt (MPa)	Yt (MPa)	S (MPa)	Xc (MPa)	Yc (MPa)
No.	18	18	18	18	24	19	23	Ross	
Mean	95	605	5.25	3.31	153*	3.7*	8.5*	56.3*	6.7*
Min.	37	469	2.35	1.46	113	2.8	5.8	–	–
Max.	160	684	8.86	7.09	191	4.5	11.3	–	–
CoV	37%	13%	37%	55%	14%	13%	21%	–	–

The section “Fibre orientation samples” includes all values determined from the WAXS samples (see Figure 1A), which are also reported elsewhere (Pramreiter et al. 2020a). The section “Threshold samples” includes all values determined from the threshold samples (see Figure 1B).

*Base values used for the failure criteria.

2.4 Fibre orientation

In order to determine an orientation of crystalline cellulose nanofibrils and wood cells (see Figure 2) with respect to the sample axis 1, a wide-angle X-ray scattering (WAXS) characterization was performed. Therefore, axially cut wood slices with a thickness of 0.6 ± 0.05 mm were analysed in transmission diffraction geometry at the P07B beamline of Petra III synchrotron source in Hamburg. The scattering experiments were performed using a monochromatic beam with an energy of 87.1 keV and a beam cross-section of $\sim 500 \times 500$ μm . The tests were performed under ambient climate conditions (~ 20 °C and $\sim 50\%$ relative humidity). The diffraction data were recorded by a Perkin Elmer two-dimensional (2D) flat panel detector of 2048×2048 pixels with a pixel pitch of ~ 200 μm . The detector was positioned ~ 1.3 m downstream from the sample. The distance as well as the detector geometry were calibrated using a LaB6 standard. The two-dimensional diffraction patterns with cellulose 200 reflections were integrated using the software Fit2D in order to obtain radial distributions of diffraction intensities along the Debye-Scherrer rings. The obtained diffraction data is commonly used to determine the microfibril angle (mfa) within the wood cell wall (Donaldson 2008). Additionally, a global in- and out-of-plane deviation of the bulk wood fibre can be obtained by rotating the veneer along its principle axis during the experiment. The distributions were used to evaluate global in- and out-of-plane orientations defined by angles α_1 and α_2 , respectively, within the axially cut wood sections (see Figure 2). The evaluation was performed using the procedure described by Reiterer et al. (1998). The calculated fibre orientation achieved a precision of approximately $\pm 1^\circ$.

Figure 2: Possible fibre orientation within the wood section. α_1 describes the angle between the longitudinal direction and the tangential direction. α_2 describes the angle between the longitudinal direction and the radial direction. β describes the spatial angle of the fibre in relation to the longitudinal axis. (Adopted from (Pramreiter et al. 2020a)).

Previous research (Pramreiter et al. 2020a) investigated the influence of the microfibril angle as well as in- and out-of-plane fibre orientations on the tensile strength of birch veneers. It was shown that best correlation between strength and fibre orientation was achieved with either maximum α_2 or the combination of in- and out-of-plane fibre orientation. The combined angle β was calculated according to Eq. (1) (Papula 2009),

$$\beta = \arccos \left(\cos \frac{\alpha_1 \times \pi}{180} \times \cos \frac{\alpha_2 \times \pi}{180} \right) \times \frac{180}{\pi} \quad (1)$$

where β is the combined angle (°), α_1 is the deviation out-of-plane (°) and α_2 is the deviation in-plane (°).

2.5 Failure criteria

The first criterion (Kollmann) considered uses the tensile strength parallel and perpendicular to axis 1 (see Figure 2) to predict the off-axis strength according to Eq. (2),

$$\sigma_\varphi = \frac{Xt \times Yt}{Xt \times \sin^n \varphi + Yt \times \cos^n \varphi} \quad (2)$$

where σ_φ is the off-axis strength (MPa), Xt is the tensile strength along axis 1 (see Figure 2) (MPa), Yt is the tensile strength along axis 2 (see Figure 2), n is an empirical value between 1.5 and 2 (–) and φ is the fibre orientation (°). Kollmann (1934) introduced an empirical value n to Hankinson’s (1921) equation in order to make the criterion applicable for tension ($n = 1.5$ – 2.0) as well as compression ($n = 2.5$ – 3.0). Based on this influence different n can be considered when applying Kollmann to predict strength.

The second criterion (Tsai-Hill) was established by Hill (1950) and is an adoption of Tsai (1965, 1966). The Tsai-Hill failure criterion uses strength, either in tension or compression as well as shear strength to predict off-axis strength according to Eq. (3),

$$1 = \frac{(\sigma_\varphi \times \cos^2 \varphi)^2}{Xt^2} - \frac{(\sigma_\varphi \times \cos^2 \varphi) \cdot (\sigma_\varphi \times \sin^2 \varphi)}{Xt^2} + \frac{(\sigma_\varphi \times \sin^2 \varphi)^2}{Yt^2} - \frac{(\sigma_\varphi \times \sin \varphi \times \cos \varphi)^2}{S^2} \quad (3)$$

where σ_φ is the off-axis strength (MPa), Xt is the tensile strength along axis 1 (see Figure 2) (MPa), Yt is the tensile strength along axis 2 (see Figure 2), S is the in-plane shear strength (MPa) and φ is the fibre orientation (°).

The third criterion (Hoffmann) was developed by Hoffmann (1967) and is based on Hills (1950) basic equation for failure of an

orthotropic fibre reinforced composite. Compared to the Tsai-Hill criterion Hoffmann made adaptations to account for different strengths in compression and tension. The Hoffmann failure criterion uses strength in compression and tension as well as shear strength to predict off-axis strength according to Eq. (4),

$$1 = \frac{(\sigma_\varphi \times \cos \varphi)^2 - \sigma_\varphi \times \cos \varphi^2 \times \sigma_\varphi \times \sin \varphi^2}{Xc \times Xt} + \frac{(\sigma_\varphi \times \sin \varphi)^2}{Yc \times Yt} + \frac{Xc - Xt}{Xc \times Xt} \times (\sigma_\varphi \cos \varphi^2) + \frac{Yc - Yt}{Yc \times Yt} \times (\sigma_\varphi \sin \varphi^2) + \frac{(\sigma_\varphi \times \sin \varphi \times \cos \varphi)^2}{S^2} \quad (4)$$

where σ_φ is the off-axis strength (MPa), Xt is the tensile strength along axis 1 (see Figure 2) (MPa), Yt is the tensile strength along axis 2 (see Figure 2), Xc is the compression strength along axis 1 (MPa), Yc is the compression strength along axis 2 (MPa), S is the in-plane shear strength and φ is the fibre orientation ($^\circ$).

Data were handled using Excel 2016 (Microsoft, Redmond Washington, USA). Mathematical operations were done with Mathcad 15 (ptc Mathcad version 15.0, PTC, Boston, USA). Curve fitting of the Kollmann criterion was done using the non-linear regression tool in SPSS 24 (IBM SPSS Statistics version 24.0, IBM, New York, USA).

3 Results and discussion

3.1 Sample properties

The determined properties of the different veneers are summarized in Table 2. The results of the “fibre orientation samples” were already discussed in an earlier publication (Pramreiter et al. 2020a) and are summarized again in Table 2. More detailed information on the data can be found elsewhere (Pramreiter et al. 2020a). With a CoV of 37% tensile strength values showed a relatively high scattering. Lower mean value in comparison to literature values (Sell 1989) and high variability can be explained with the unsorted sample batch. Values reported in literature are almost defect free, whereas own samples contained some defects resulting in fibre deviations. The results for fibre orientation α_2 and β have also been discussed previously (Pramreiter et al. 2020a). Variability was explained there by a multiple of possible defects (e.g. knots, trunk curvature and tapering) kept in the unsorted batch.

In comparison, the “threshold samples” which were used to create the failure criteria included only sorted veneers with little to no visible defects and therefore marginal fibre deviation. Therefore, the obtained results show less variability than the samples for fibre orientation as seen in Table 2. The tensile strength parallel to the grain was between 113 and 192 MPa with an average of 153 MPa and a CoV of 14%. These results are slightly higher than literature values (Sell 1989; Wagenführ 2006) stating an average of about 140 MPa for birch wood. The tensile strength

perpendicular to the grain resulted values between 2.8 and 4.5 MPa, with an average of 3.7 MPa and a CoV of 13%. This in turn was around half of typical literature values (Kollmann 1951; Wagenführ 2006) stating an average of about 7.0 MPa. Tensile strength perpendicular to the grain was about 2.5% of the strength parallel to the grain. This ratio falls slightly below typical values in literature (Kollmann 1951; Niemz 1993) stating a ratio of about 3–4%. Tests for threshold shear strength resulted values between 5.8 and 11.3 MPa with an average of 8.5 MPa and an CoV of 21%. This was again around half of typical literature values (Wagenführ 2006) stating an in-plane shear strength of about 14.5 MPa.

Considering the production process of veneers, lathe checks induced during slicing/peeling of the veneers (Buchelt et al. 2018) are an important strength influencing factor. Due to the high bending forces in front of the blade and the low tensile strength perpendicular to the grain of wood, cracks are induced parallel to the wood fibres (Antikainen et al. 2015). The resulting cracks can decrease the initial veneer thickness up to 90% (Dupleix et al. 2013) leading to a vital loss in cross section and furthermore decreasing the overall strength of the veneer compared to solid wood (Pfriem and Buchelt 2011). Bekhta et al. (2009) reported a decrease of parallel tensile strength of about 24% and about 87% for perpendicular tensile strength. No literature was found in regards to in-plane shear strength of thin veneers. However, the influence of the lathe checks on the in-plane shear strength will also present, since the reduced cross-section also reduces the surface area available to transfer shear forces. Consequently, the resulting shear strength will be reduced compared to solid wood with an intact cross section.

Additionally, the thickness of the veneers being 0.6 ± 0.05 mm a reversed size effect compared to solid wood samples with increased dimensions could be the reason for the higher parallel tensile strength. Different literature (Barrett 1974; Buchelt and Pfriem 2011; Büyüksarı et al. 2017; Mukam Fotsing and Foudjet 1995; Pedersen et al. 2003; Zauner and Niemz 2014) investigated the relationship between tension, compression as well as bending strength and sample size for soft- and hardwoods. Considering thicker samples with dimensions ranging from multiple millimetres to centimetres, literature (Barrett 1974; Mukam Fotsing and Foudjet 1995; Pedersen et al. 2003; Zauner and Niemz 2014) indicates a size effect, i.e. strength decreases with increasing size. However, according to Buchelt and Pfriem (2011) this effect is partly reversed when thickness is decreased below 1 mm. They tested tensile strength parallel and perpendicular to the grain of thin hardwood veneer (0.5 mm thick) as well as solid wood

samples (4 mm thick). They found no significant decrease for parallel tensile strength, while the tensile strength perpendicular to the grain of thin veneers was around half that of solid wood. In spite of the possible influence of sample size, the difference in perpendicular strength will predominantly be a result of the production technique causing the formation of lathe checks in the veneers. Büyüksarı et al. (2017) reported similar findings for tensile strength parallel to the grain for 0.8 mm thick softwood samples. Compared to the findings in literature the reported threshold values seem to be a solid base for further investigations. The basic dataset of the reported results can be found as supplementary material to this article.

3.2 Failure criteria

The established failure curves Kollmann (1951), Tsai-Hill (1950) and Hoffmann (1967) are depicted in Figure 3. Based on the original formulation given by Kollmann (1951), Tsai (1966) and Hoffmann (1967) the threshold levels at 0 and 90° are only influenced by the threshold tensile strength or threshold compression strength, respectively. Therefore, all three failure criteria spanned from 153 ± 12 MPa parallel to the grain (0°) down to 3.7 ± 0.28 MPa perpendicular to the grain (90°), the two average threshold values in tension and the respective confidence level (99%). The shape of the curve is established by using either the threshold shear values (8.5 ± 0.94 MPa) for Tsai-Hill and Hoffmann or the empirical value n for Kollmann.

3.3 Predicting strength

In the following, the feasibility and practicability of the investigated failure criteria for predicting the tensile

Table 3: Pearson correlation of the two relevant fibre orientations maximum α_2 and β and the different failure criteria (Hoffmann 1967; Kollmann 1951; Tsai-Hill 1950) with the tensile strength of 18 veneer samples.

	Lower limit		Mean		Upper limit	
	β (°)	α_2 (°)	β (°)	α_2 (°)	β (°)	α_2 (°)
Kollmann	0.871	0.860	0.878	0.837	0.883	0.836
n^*	1.499	1.813	1.421	1.723	1.355	1.647
Tsai-Hill	0.870	0.859	0.868	0.860	0.866	0.860
Hoffmann	0.854	0.861	0.849	0.861	0.845	0.861

*Optimum n for Kollmann criterion based on non-linear regression. The threshold values for the failure criteria are based on the average strength (mean) plus (upper limit) and minus (lower limit) the corresponding confidence interval (99%).

strength of thin birch veneers will be investigated and discussed.

The failure criteria were used to predict the off-axis strength of the 18 fibre orientation samples based on the corresponding in-plane and out-of-plane fibre orientation, respectively. The correlation between the predicted strength and the actual strength obtained with tensile tests is summarized in Table 3. In general, the correlations for the three failure criteria were highly significant, with correlation coefficients (r) ranging from 0.836 up to 0.883, which were partly higher than values reported in the literature (Brännström et al. 2008; Olsson et al. 2013). Olsson et al. (2013) obtained correlations of 0.825 up to 0.843 for bending tests of spruce wood. They used an empirical model based on different factors including grain angle. Brännström et al. (2008) investigated strength prediction by means of tracheid laser scattering technique and reported a correlation of about 0.548 for spruce wood with different geometries. Highest correlation ($r = 0.883$) was achieved with Kollmann and the angle β . This contradicts the initial hypothesis that Tsai-Hill and Hoffmann would

Figure 3: Failure surfaces according to Kollmann (1951), Tsai-Hill (1950) and Hoffmann (1967) based on the established threshold values and the corresponding confidence level (99%). For Kollmann $n = 1.5$, based on the ranges defined by Kollmann (1951).

reach higher correlations. However, a few factors need to be considered in regards to the prediction quality and accuracy of the established criteria. The empirical criterion Kollmann provides more flexibility in data fitting due to the empirical factor n , which is further amplified by the small number of fibre orientation samples. In addition, the measured in- and out-of-plane fibre orientations only span from $1.46 \pm 1^\circ$ up to $8.86 \pm 1^\circ$ only covering the initial part of the full failure curve. While the resulting correlations provide a solid base for further improvements, they do not support a generalised ranking of the different criteria against each other.

The correlation between the failure criteria and the actual strength of the veneers is further depicted in Figure 4 using maximum α_2 and Figure 5 using β . While Tsai-Hill and Hoffmann yielded the same curves, Kollmann provided different shapes based on the empirical n in the equation. The influence of different n is best seen when Figures 4 and 5 are compared. In the present study n was established via non-linear regression based on the threshold and fibre orientation samples. This resulted in $n = 1.813$ for α_2 and $n = 1.355$ for β . These results partly contradicted values suggested by Kollmann (1951) mentioned in the previous section.

The steep decrease in strength of about 50% after 5° for all three failure criteria shown in Figure 5 partly deviated from literature suggesting a decrease in tensile strength of about 50% after 15° (Kollmann 1951). These differences can be explained by the previously mentioned lathe checks causing an amplified decrease in strength. An increased ratio between strength in longitudinal direction and perpendicular direction leads to an increased slope of the curve. This is further supported by findings from Ross (2010). Beside the lathe checks also the sensitive tensile strength compared to bending or compression of wood could be a possible explanation. According to Dinwoodie (2001), tensile strength diminishes faster when fibre orientation increases compared to bending or compression strength. Based on these findings it was presumed that a combination of the lathe checks and the sensitivity led to this steep decrease.

Furthermore, the combined angle β seemed to be more suitable to predict strength as Kollmann as well as Tsai-Hill yielded a higher correlation compared to maximum α_2 (see Table 3). As mentioned previously the orientation of the fibre within the wood greatly influences the strength of the material (Pramreiter et al. 2020a, 2020b; Stanzl-Tschegg 2009). Compared to α_2 which represented the fibre

Figure 4: Failure curves according to Kollmann (1951), Tsai-Hill (1950) and Hoffmann (1967) and strength of 18 fibre deviation samples with maximum α_2 . For Kollmann $n = 1.813$, based on non-linear regression in SPSS. The failure indicators of σ_φ represent the accuracy of the measured angles ($\pm 1^\circ$) and the 99% confidence interval for the determined strength.

Figure 5: Failure curves according to Kollmann (1951), Tsai-Hill (1950) and Hoffmann (1967) and strength of 18 fibre deviation samples with β . For Kollmann $n = 1.355$, based on non-linear regression in SPSS. The failure indicators of σ_φ represent the accuracy of the measured angles ($\pm 1^\circ$) and the 99% confidence interval for the determined strength.

orientation in-plane β contained information about the fibre orientation in- as well as out-of-plane. Therefore, an increased correlation for β was expected as it represents the fibre orientation in two dimensions. This was in line with other literature (Viguier et al. 2015) discussing the influence of the possible planes of fibre orientation and their influence on the strength of the material.

All three of the presented failure criteria enabled accurate prediction of the tensile strength of thin birch veneers to a certain extent. Previously mentioned downsides (low range of fibre orientations and small sample number) require different improvements to further increase the correlation and therefore improve the general accuracy and reliability of the criteria. The fibre orientation was determined based on seven pre-defined measuring points within the veneer samples. Increasing the measured volume or guiding the measured area towards areas of high interest could further enhance the accuracy of the measured fibre orientation. In addition, it is especially necessary to also investigate higher fibre orientations in order to validate the full failure curve. The established threshold values are the result of around 20 measurements. Increasing the sample size could be the bases to further tweak the failure curve. Furthermore, re-introducing previously discarded properties such as density or dynamic modulus of elasticity (Pramreiter et al. 2020b) as well as adding additional factors such as moisture content (Stanzl-Tschegg 2006; Stanzl-Tschegg and Navi 2009) could provide an additional layer of precision to the failure criteria.

4 Conclusion

Two different failure criteria used for fibre reinforced composites and their applicability to the bio-composite wood were investigated. Additionally, the accuracy of a commonly used failure criterion for wood has been re-evaluated for thin Finnish birch veneers.

The failure criteria after Tsai-Hill and Hoffmann used for fibre reinforced composites delivered accurate results for the bio-composite wood. The validity of the failure criterion based on Kollmann, commonly used for solid wood, was also proven for thin Finnish birch veneers. Additionally, the flexibility provided by the empirical n in the criterion enabled slightly higher correlation compared to Tsai-Hill as well as Hoffmann.

The combination of in- as well as out-of-plane fibre orientation provided more accurate results compared to maximum in-plane fibre orientation. Nevertheless, the slight improvement in correlation demanded for a more time intensive measuring set up.

A faster decrease in strength with increasing fibre angle compared to solid wood was also identified. This steeper decrease was caused by the lathe checks induced during veneer peeling and the higher sensitivity of the tensile strength under increasing fibre angle compared to bending or compression.

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