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Process combination peeling and sawing of large-diameter timber: thick peeled products for yield-optimized structural laminated timber products

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ABSTRACT: Coniferous roundwood of common qualities is usually industrially processed in chipping-sawing lines which are widely limited to log diameters of < 45 cm. The raising stock of large-diameter softwood in the DACH-region, especially of Norway spruce, necessitates to rethink the processing to sawn wood and thereof produced products. One possible option for processing such large-diameter roundwood is rotary-peeling with an extended thickness range of thick peeled products (TPPs; thickness > 6 mm). This paper discusses potential advantages (e. g. higher yield) and disadvantages (e. g. TPP quality) of this process and provides a first physical / mechanical characterization of TPPs.

KEYWORDS: large-diameter timber; process combination peeling and sawing; thick peeled products (TPPs); laminated peeled products (LPPs); structural laminated timber products (SLTPs); yield optimization; TPP quality

1 – INTRODUCTION

1.1 MOTIVATION

As a natural, biological material, timber stores and releases equal amounts of CO_2 during its lifecycle. Recognising that the structural layer of a building usually has the longest service life (cf. [1]), the aim is to increase the proportion of harvested timber in the production and use of timber construction products (TCP) for the long term. It is therefore necessary to focus on an increased and appropriate use of these products and to ensure the availability of timber as a natural, renewable resource from sustainably managed forests.

The development of European forests, particularly in Germany, Austria and Switzerland (DACH-region), shows a steady increase in hardwood stocks and a progressive increase in large-diameter roundwood of Norway spruce (*Picea abies*), which is still the dominant species in this region. The actual stock volume of large-diameter softwood (diameter at breast height > 50 cm) is approximately 800 mio. m³ ([2–5]) and therefore provides a high potential for substituting building materials with a high CO_2-footprint.

From a wood technology point of view, large-diameter timber offers many advantages: (i) the proportion of mature timber is significantly higher, (ii) mature timber usually has better mechanical properties in grain direction and (iii) a more homogeneous structure than juvenile timber [6–8]. This high-performance material from the outer circumferential zones of logs is therefore ideally suited for the production of TCPs.

Due to limitations on the maximum diameter of logs that can be processed in industrial chipping-sawing lines and the lower production capacity of conventional band mills, an upstream peeling process could help to increase the yield of large-diameter roundwood. Peeling large-diameter timber also has the advantage of less significant lathe checks due to larger rounding radii. This offers the possibility to shift current thickness limits in peeled products from typically 2.5 to 3.5 mm to very thick peeled products (TPPs) above 6 mm thickness which marks the lower limit of solid timber according to ISO 18775 (2020) [9]. Such a process opens the chance to reduce the amount of adhesive in timber construction products compared to laminated veneer lumber (LVL) and in general for new innovative, in shape and layup optimised TCPs as well as to substitute sawn timber in current well-established TCPs such as glulam and cross laminated timber (CLT).

1.2 PROJECT DESCRIPTION

Motivated by this, the FFG research project "rethink_LTprocessing" (no. FO999903619) was initiated in 2023. The main objective of this project is to identify the principal possibilities and limitations of the process combination "rotary peeling and sawing" of large-diameter roundwood, especially for Norway spruce. In detail: (i) to increase the overall yield of roundwood in structural laminated timber products, (ii) to shift current thickness limits in peeled products (>> 6 mm), (iii) to define meaningful parameter settings for an industrial production, including the peeling process as well as pre- and post-processing, (iv) to

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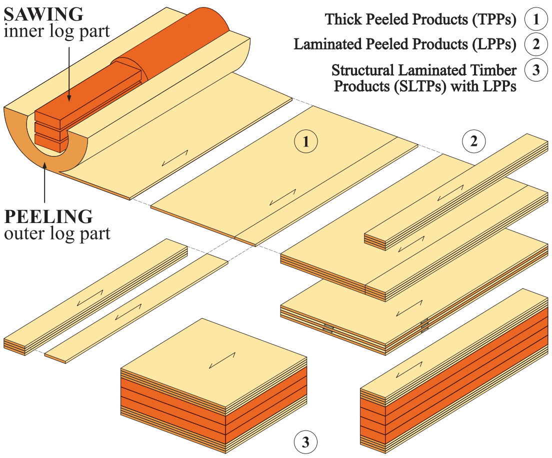

Figure 1: Overview of the process combination rotary-peeling and sawing and possible use of TPPs & LPPs in SLTPs.

provide a first physical / mechanical characterisation and classification of thick peeled products (TPPs; thickness > 6 mm) and thereof produced multi-laminated peeled products (LPPs), and (v) to exemplarily demonstrate the high-performance of TPPs and LPPs obtained from the outer (mature) log zones as well as sawn products from the combined rotary-peeling and sawing process for the production of linear and planar structural laminated timber products (SLTPs). Figure 1 shows schematically the process combination of rotary-peeling and sawing and exemplarily their possible use in SLTPs.

2 – LITERATURE REVIEW

As part of the ongoing research project, a comprehensive review of the literature relating to the peeling process (incl. pre- and post-processing) was conducted and summarised in [10].

In general, a lot of research has been done in the field of veneer production, but mostly only for veneer thicknesses in the range of 1.5 mm to 3.5 mm, a common choice for past and current industrial applications. The focus of this literature review was on the veneer quality (depth and frequency of lathe checks, surface roughness, flatness (curl) and thickness variation), but from a number of different perspectives. Some studies report on the effect of pre-treatment of peeling logs [11–13], others on the effect of lathe settings [11,14–16], and others on the effect of veneer thickness [17–21] on veneer quality, to name the most common parameters.

In most of the literature cited, the treatment was carried out by soaking the peeling logs in water. This has the advantage over steaming that it not only heats the wood but also increases its moisture content, which is good for the peeling process. In addition, water heating is more controllable and less abrupt than steam heating [37]. In general, a low temperature pre-treatment (30 °C to 40 °C) produces veneers with deeper and more widely spaced checks than a high temperature pre-treatment (>50 °C up to 80 °C), where the checks are more frequent but less deep. At high temperatures, the lathe check depth tends to decrease, but the lathe check formation is less periodic and more influenced by the anatomy of the wood. This makes check formation less predictable, especially for heterogeneous species such as spruce [22]. Also, low temperature pre-treatment can result in increased knife wear, especially for species with hard knots (e. g. western white spruce), while an increase in pre-treatment temperature is associated with an increase in veneer surface roughness [23,24]. There is no consensus in the literature on the optimum pre-treatment temperature for rotary peeling. Many factors influence the correlation between ideal temperature and veneer quality, such as wood species, wood density, wood zones within the log (sapwood or heartwood; juvenile wood or mature wood) and wood quality (knot ratio) [12,15].

The peeling lathe is more or less a closed system where all the settings have to be adapted to the individual peeling lathe and the desired product, especially the presence and settings of the compression bar. There are different variants of compression bars (nose bar, small/large roller bar) and the main compression ratio found in the industry is between 15 % and 20 % of the nominal veneer thickness, depending on the wood species [22]. In the literature, there is a tendency for less deep lathe checks when a pressure bar is used [21,24]. The roller bar size has a direct effect on the peeling process (faster peeling, less spin-out due to driven roller bar) and the veneer quality in terms of surface roughness and lathe checks [12]. In [25] the angle of the peeling knife was varied between 17 ° and 21 °. It was found that a lower knife angle (17 °) resulted in 10 % higher roughness values for pine veneer. The knife angle commonly used in industry and in the literature is between 20 ° and 21 °.

Another important parameter affecting veneer quality is veneer thickness. The thickness range analysed in a number of studies varies from 0.7 mm to 4.0 mm [16,20,26], 4 mm and 9 mm [17,21,25,27] or even up to 15 mm [18]. Although the studies differ in terms of wood species, pre-treatment, lathe scale (laboratory and industrial), initial and residual roller diameter and other aspects, most of them agree that the lathe check depth increases with increasing thickness of the peeled products.

Based on the findings of this literature review, first rotary-peeling tests of TPPs (t_p = 5 mm to 20 mm) were carried out in an industrial environment at the Pollmeier Furnierwerkstoffe GmbH (Amt Creuzburg; DE), supported by Mayr-Melnhof Holz Leoben GmbH (Leoben; AT) and Raute Cooperation (Nastola; FI).

The following sections detail the pre-treatment and peeling parameters used and discuss the physical and mechanical results of initial laboratory testing of these TPPs.

3 – MATERIALS & METHODS

3.1 MATERIAL

For the first round of peeling tests within this research project 15 large-diameter logs (diameter 560 to 780 mm, on average 650 mm) of Norway spruce (*Picea abies*) from Styria / Austria, with a length of 4.2 m were harvested and transported shortly afterwards to Pollmeier. Information on the number of harvested trees and on which logs belong together is not available. Anyway, the aim of this first peeling tests was to identify possible influences from log treatment (soaking temperature and time) and selected peeling parameters on the surface quality and mechanical properties of TPPs. With the best possible utilisation of on-site possibilities, all logs were soaked at 60 °C, twelve for $D_{s,ref} = 48$ h (reference group) and three for $D_s = 24$ h. After soaking, each log was cut into two peeling logs of 2 m length which were consecutively numbered (1 to 30). The peeling was carried out on a R7 industrial peeling lathe from Raute Corporation. During the peeling the following parameters were varied (with reference values underlined): (i) TPP thickness t_p = {5; <u>10</u>; 12.5; 15; 17.5; 20} mm; (ii) compression rate γ_{comp} = {<u>10</u>; 15; 17.5; 20; 25} %; (iii) ratio of roller bar vs. spindle velocity v_{rb} = {<u>100</u>; 102} %.

In addition, TPPs of t_p = {5; 10} mm were classified according to their radial position within the log in juvenile and mature timber. For the transition zone between juvenile and mature timber a growth period of 20 years and an average annual ring width of 4 mm were assumed, thus below a diameter of 160 mm TPPs were classified as juvenile and above as mature. Furthermore, the shorter soaking time was only applied for 10 mm thick TPPs. Figure 2 shows some impressions of the peeling process.

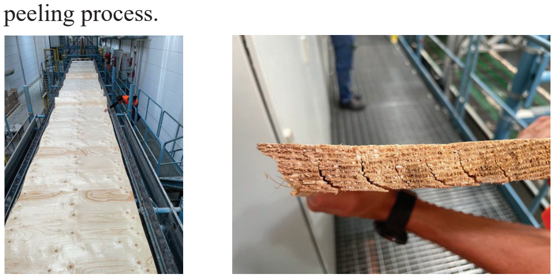

Figure 2: Impressions of the peeling process: (left) TPP strip after the lath; (right) part of 20 mm thick TPP.

The 2,000 mm long endless peel strips were clipped into 1,250 mm wide sheets, stacked by hand and kiln dried in a commercial drying chamber for sawn timber at Pollmeier. After transport of the material to the TU Graz laboratory, the TPP sheets were cut into strips of 160 mm width and 1,950 mm length, without any sorting, except for some strips with bark, or major damage, which were excluded from further processing and testing. The material was stored in a climatic chamber at 20 °C and 65 % relative humidity (reference conditions).

3.2 METHODS

3.2.1 OVERVIEW OF TESTS AND GENERAL MEASUREMENTS

With focus on the physical / mechanical characterisation of the single layer TPPs, after a certain conditioning period at reference climate conditions, the dynamic modulus of elasticity, tensile properties parallel to the grain and the moisture content and the density were determined. In addition, the depth and frequency of the lathe checks (typical cracks from the peeling process) and the angle between the grain and the length axis of the TPPs were determined as well.

Because of the partly sever lathe checks, the volume of the samples for the density calculation was determined by the immersion method using a measuring cylinder with water as medium.

The dynamic modulus of elasticity $E_{0,dyn}$ was determined by measuring the ultrasonic runtime by means of Sylvatest 4 from CBS-CBT and calculated with $E_{0,dyn,12} = v_{12}^2 \, \rho_{12} \, 10^{-6}$, with v_{12} as sound velocity in m/s and ρ_{12} as the density in kg/m³, both adjusted to a reference moisture content of u_{ref} = 12 %.

The parallel to the grain tensile tests were performed according to EN 408 [28] on the GeZu 850 tensile testing facility (Zum Wald) at the Lignum Test Centre of the TU Graz. Due to shortage in space the longitudinal deformation was measured only globally by means of two inductive displacement transducers from HBM. The static global modulus of elasticity (MOE) was calculated within the apparently linear elastic range according to EN 408 [28] and by using the distance between the third points in the assumed triangular load introduction (clamping length) as the measurement basis.

3.2.2 TESTS CONDUCTED AT VARIOUS GRAIN ANGLES

A number of specimens featured apparently an angle between grain and length axis. To correct the properties of those specimens accordingly, additional tests were performed on 10 mm thick TPPs in which $E_{\alpha,dyn,12}$ and $E_{t,0,12}$ were determined. For $E_{\alpha,dyn,12}$ this was done for ten circular samples of 400 mm diameter and for α = {0; 15; 30; 45; 60; 75; 90} °. $E_{t,0,12}$ was afterwards determined from local deformation measurements (HBM DD1 strain transducer; measurement length H_0 = 100 mm) on dog bone shaped clear wood specimens with 0° grain angle cut from these disks.

Afterwards the Hankinson formula [29] was validated with the values of $E_{\alpha,dyn,12}$ by adjusting the power factor b in Eq. (1), with $x_{t,0,cor,i}$ as property corrected to $\alpha = 0°$, $x_{t,\alpha,i}$ as tested property and $x_{t,90,mean}$ as the average property perpendicular to the grain, and latter applied to compensate for any load-grain deviation in the tensile tests.

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$$x_{t,0,cor,i} = \frac{x_{t,\alpha,i} \cdot x_{t,90,mean} \cdot \cos^b \alpha}{x_{t,90,mean} - x_{t,\alpha,i} \cdot \sin^b \alpha} \quad (1)$$

3.2.3 HARMONISATION OF TEST DATA ACCORDING TO THEIR DENSITY

As will be discussed in Chapter 4, to allow a better identification of decisive pre-treatment and peeling parameters on the tensile properties parallel to the grain given a rather large variability in density between TPPs from different logs, a correction of the tensile properties to a reference density was conducted. Therefore, the relationship between MOE and density as bivariate lognormal distribution was used. Based on the JCSS [30], the moments of the marginal distribution for the MOE are given as coefficient of variation CoV[$E_{t,0}$] = 15 % and expected value E[$E_{t,0}$]= 11,000 MPa. For the density, a CoV[ρ] of 8 %, based on own experience on sawn timber instead of suggested 10 %, and an expected value of E[ρ_{ref}] = 420 kg/m³ was used. With a correlation coefficient of 0.6 as suggested in [30], a power coefficient of 1.12 was calculated and $E_{t,0,12,cor,i}$ adjusted via

$E_{t,0,ref,i} = E_{t,0,cor,i} \cdot (\rho_{ref}/\rho_{12,i})^{1.12}$, with ρ_{ref} = 420 kg/m³.

The same procedure was followed for the tensile strength, with CoV[$f_{t,0}$] = 30 %, an expected value of E[$f_{t,0}$] = 30 MPa and with a correlation coefficient of 0.4 between density and tensile strength as suggested in [30], a power coefficient of 1.50 was calculated and $f_{t,0,cor,i}$ adjusted via $f_{t,0,ref,i} = f_{t,0,cor,i} \cdot (\rho_{ref}/\rho_{12,i})^{1.50}$.

3.2.4 LATHE CHECK DETERMINATION

A small strip of the cross section was cut from each specimen and a high-resolution scan was made. This scan was used to measure the lathe check depth and lathe check interval in AutoCad CAD software. This was done for five specimens per parameter for initial orientation. For a better comparison, the lathe check depth is given in percent of the TPP thickness.

3.2.5 EVALUATION OF THE INFLUENCE OF DIFFERENT PARAMETERS

Due to the high variation in the log quality and the resulting high variation in the test data, the identification of pre-treatment and peeling parameters relevant for the tensile properties was challenging. Therefore, the statistical evaluation was done on several levels, (i) qualitatively, by evaluating box plots for subgroups and overall comparisons, and (ii) quantitatively, via statistical tests, (F-test for multiple linear regression). The evaluation of the effect of the radial location of TPPs on MOE and tensile strength was carried out using the Hankinson corrected values $E_{t,0,cor}$ and $f_{t,0,cor}$ values, as the wide range of densities did not affect this evaluation and is itself affected by the radial position. The estimation of the effect of pre-treatment, compression rate and TPP thickness was performed using $E_{t,0,ref}$ and $f_{t,0,ref}$ corrected to the reference density of 420 kg/m³, as described in Section 3.2.3.

4 – RESULTS AND DISCUSSION

4.1 GENERAL COMMENTS

In this Chapter, the results of the physical and mechanical properties are given as statistical values of all samples or, for a better overview, as mean values per log. In the Sections 4.1 to 4.5, these mean values are given for the whole log (juvenile + mature). From Section 4.6 onwards, these values are separated for the juvenile and the mature portion for the relevant logs, as shown in Table 1.

4.2 MOISTURE CONTENT

The moisture content of the 187 samples analysed ranges from 7 to 12 % (average 9.3 %, CoV = 12.3 %) with the exception of two samples featuring 4 % and one featuring 14 %. As the samples did not achieve the desired equalised MC of 12 %, the density, dyn. MOE and static MOE were corrected to the reference MC of u_{ref} = 12 %.

4.3 DENSITY

The range of density was 366 to 576 kg/m³, on average 473 kg/m³ with a CoV of 9.5%.

The mean density per log ranges from 428 kg/m³ (log number # 2) to 514 kg/m³ (# 23). This is a wide range for the mean density values and reflects a large variation in the quality of the peeling logs. Even within a trunk, for example comparing logs # 29 and # 30 – both from the same trunk – a 13 % difference in the average density was observed within the mature timber zone.

The CoV of the mean density is in line with the recommendation in JCSS [30], where the CoV for Nordic softwood is given as 10 %. Compared to the T-classes of EN 338 [31]), the mean density corresponds to the class T21 (ρ_{mean} = 470 kg/m³). However, based on the minimum and maximum mean density per log, the range of the T-classes is from T9 to T30, which again underlines a wide range of the peeling log quality.

4.4 DYNAMIC MODULUS OF ELASTICITY

The dynamic modulus of elasticity ranges from $E_{0,dyn,12,min}$ = 8.0 GPa to $E_{0,dyn,12,max}$ = 20.1 GPa with a mean value of $E_{0,dyn,12,mean}$ = 13.6 GPa (COV of 18.8 %) over all individual samples.

4.4.1 COMPENSATION OF DEVIATIONS IN THE LOAD-GRAIN ANGLE

Some specimens show a deviation of the grain angle from the loading direction up to 13°. To compensate for these deviations, the dynamic MOE was adjusted by means of the Hankinson equation [29,32], as described in Section 3.2.2.

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To validate the suitability of the Hankinson equation with a power coefficient of $b = 3$, tests were carried out as described in Section 3.2.2. The corresponding clear wood samples had a mean density of $\rho_{12,mean,cw} = 429$ kg/m³ (CoV = 11.0 %) and a mean MC of $u_{mean} = 9.9$ %. The results of these tests and the validation of the Hankinson equation are shown in Figure 3.

To correct the MOE, a $E_{t,90,mean}$ of 250 MPa was used in the adjustment formula in 3.2.2. This $E_{t,90,mean}$ seems appropriate according to literature [33] and own tests. The adjusted dynamic MOE ranges from $E_{0,dyn,12,cor,min} = 8.0$ GPa to $E_{0,dyn,12,cor,max} = 20.3$ GPa with a mean value of $E_{0,dyn,12,cor,mean} = 14.0$ GPa (COV of 18.0 %). So, compensating for the load-grain angle deviations results only in minor changes to the dynamic MOE.

The evaluation of the relationship between the static and the dynamic MOE of the clear wood tests parallel to the grain gives a relationship of $E_{t,0,12,CW} = 0.78 \cdot E_{0,dyn,12}^{1.02}$, with $R^2 = 0.87$. Further discussion about the relationship between static and dynamic MOE will be done in Section 4.5.1.

4.5 RESULTS FROM THE TENSILE TESTS

A total of 187 single layer tensile tests parallel to the grain were performed. For each of these tests, the density ρ, the moisture content u, the global static modulus of elasticity parallel to the grain ($E_{t,0}$) and the tensile strength parallel to the grain ($f_{t,0}$), were determined and corrected to $u_{ref} = 12$ %.

According to DIN 4074-1 [34], sawn or chipped timber products with a thickness ≥ 6 mm are classified as solid timber, which also includes the TTPs with $t_p \geq 6$ mm in this paper. Overall and in clear contrast to the density and the dynamic modulus of elasticity, the tensile properties appear rather low if compared with sawn timber from Norway spruce in [31]. This, although the relationship between $f_{t,0}$ and $E_{t,0,12}$ is similar when compared with values for T-classes in EN 338 [31] assuming a CoV[$f_{t,0}$] of 30 % as recommended in JCSS [30]. The comparison with T-classes seems to be appropriate in order to get an idea on how to classify the results of the TPPs for further discussion, even if the intended use is as a bonded laminated peeled product (LPP). A comparison with other thick peeled products is limited to the results in BÜCHSENMEISTER [18], which are also discussed in the following sections.

4.5.1 STATIC MODULUS OF ELASTICITY

The mean global modulus of elasticity for all individual samples is $E_{t,0,mean} = 8.7$ GPa with a CoV of 29.9 %.

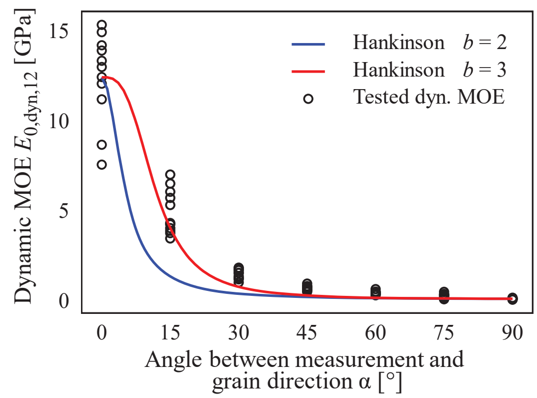

Figure 3: Dynamic MOE tested at different angles to the grain and the Hankinson equation using power coefficient of b = 2 and b = 3.

After compensating the grain angle deviation according to Section 3.2.2, as discussed in Section 4.4, the MOE changes to $E_{t,0,cor,mean} = 8.8$ GPa with a CoV of 28.7 %, with a range from 2.1 GPa to 13.6 GPa. The adjustment was made with the same settings as described in Section 4.4.1. This variation is quite large, in particular, log # 2 (juvenile and mature together) shows a significantly different quality and mechanical properties compared to the rest of the samples with a MOE of $E_{t,0,cor,mean,\#2} = 4.8$ GPa and a density of $\rho_{12,mean,\#2} = 427$ kg/m³. For this reason, log # 2 is excluded from further discussion of the mechanical properties. Without this log, the mean modulus of elasticity increases to $E_{t,0,cor} = 9.3$ GPa with a CoV of 23.0 % (166 samples). This variation is still high, compared to the reported CoV[$E_{t,0,mean}$] of 13 % in JCSS [30].

Considering the T-classes in [31], the mean MOE corresponds to class T11 ($E_{t,0,mean} = 9.0$ GPa). BÜCHSENMEISTER [18] report a MOE of $E_{t,0,mean} = 11.9$ GPa with a CoV of 9.1 % and a mean density of $\rho_{12,mean} = 452$ kg/m³. Although the growth region is the same, the material in [18] was much more homogeneous, i.e. it featured less or nearly no local growth characteristics like knots. At the level of the mean values per log (without # 2) the mean MOE is $E_{t,0,cor,mean,log} = 8.8$ GPa with a CoV = 18.9 %.

Evaluating the relationship between the static and the dynamic MOE of all samples gives $E_{t,0,12,cor} = 0.70 \cdot E_{dyn,12,cor}^{0.96}$ with a R^2 of 0.43. LEANDRO [35] reported a difference between dynamic and static MOE of about 18 – 20 % and a linear relationship of $E_{t,0,stat} = 0.82\ E_{dyn}$ with $R^2 = 0.51$ for small spruce specimens with a MC range of 10 – 25 %. BÜCHSENMEISTER [18] found almost no difference between the dynamic and static MOE. Figure 4 shows the relationship between the static MOE and the dynamic

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MOE of the samples tested, for the whole samples and in addition for the samples allocated to juvenile and mature.

4.5.2 TENSILE STRENGTH

As discussed in the previous Sections 4.3 and 4.4, also the tensile strength results show a large variation across all single layer specimens with a CoV of 56.1 % and only a low mean tensile strength of $f_{t,0,mean}$ = 17.1 MPa. After compensating for the grain angle deviation, as mentioned in Section 4.4.1 and described in Section 3.2.2 with the power coefficient $b = 2$, and a $f_{t,90,mean}$ of 1.0 MPa, the mean tensile strength changes to $f_{t,0,cor,mean}$ = 18.1 MPa (range 1.5 to 42.7 MPa) with a CoV of 56.8 %. The used $f_{t,90,mean}$ seems to be appropriate according to literature [33,36] and own tests.

There is also a large variation within the individual logs up to a CoV of 74.3 % (log # 25; range 7.63 to 42.7 MPa) compared to a CoV[$f_{t,0}$] of 30 % for sawn timber as suggested in [30]. A very common fracture pattern, especially for the lower tensile strength values, was a local grain alignment around large knots. This also accounts for the large variation and low tensile strength values.

After excluding log # 2, the mean tensile strength becomes $f_{t,0,cor,mean}$ = 19.6 MPa and the CoV 49.6 %. Due to the large variation, the 5 % quantile based on log-normal distribution is only $f_{t,0,cor,LN05}$ = 6.5 MPa, which is quite low and cannot be assigned to any strength class of EN 338 [31]. The 5 % – quantile per log ranges from 2.65 to 21.2 MPa. BÜCHSENMEISTER [18] reports a mean tensile strength of $f_{t,0,mean}$ = 30.8 MPa with a CoV of 33.2 %. This gives a 5 % – quantile of $f_{t,0,LN05}$ = 17.1 MPa.

4.6 PARAMETERS

4.6.1 MATERIAL PARAMETERS

4.6.1.1 RADIAL LOCATION IN THE LOG

According to [12,15,16,27,37], the radial position in the log has a large effect on the physical and mechanical properties of the wood. Based on this, the properties parallel to the grain increase with increasing distance from the pith within the so-called juvenile wood zone followed by the mature wood zone with widely constant properties. To investigate this effect, the TPPs of seven logs {# 23 – t_p = 5 mm | # 2; 3; 26; 27; 29; 30 – t_p = 10 mm} were separated into a juvenile and a mature part according to Section 3.1.

Figure 5 shows the box-plots for the density and the tensile strength properties separately for the TPP thickness, the radial position juvenile (J) vs. mature (M), and the compression rate for each individual peeling log.

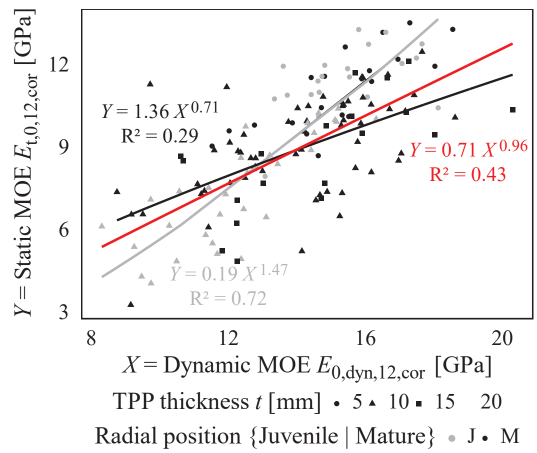

Figure 4: Scatterplot of $E_{t,0,12,cor}$ vs. $E_{0,dyn,12,cor}$ with power models for all samples (red) and separate for juvenile (grey) and mature (black) samples.

Starting with the density in Figure 5 (A), it could be seen, that there is a significant difference in the density values between the juvenile and mature location groups, except for log # 29, which could be due to the small number of samples per group (five specimens). It must be said that the separation in J and M as it was realised in this project is rather diffuse, i.e. uncertain. Anyway, the data clearly indicates and thereby confirms past literature on higher densities for the mature wood zone. For the logs discussed in Figure 5, the mean density for the juvenile and mature groups is 462 kg/m³ (CoV = 10.1 %) and 495 kg/m³ (CoV = 9.5 %), respectively, i.e. 7 % higher for the latter, which is in line with findings in BRANDNER & SCHICKHOFER [38] and OBERNOSTERER et al [39], who report a difference of about 10 % for sawn timber. BÜCHSENMEISTER [18] observed a difference in density of 11 % between the juvenile sawn timber and the peeled mature timber.

Figure 5 (B) shows the modulus of elasticity. In line with the literature [27,37], a significant difference in the MOE values between the juvenile and mature location groups can be seen in most of the cases, although for the logs # 3 and # 23 the relationship is inverse to the expectation, for which similar reasons as for the density are seen. For the logs discussed in Figure 5 (B), the mean MOE for the juvenile and the mature location is 9.2 GPa (CoV = 28.8 %) and 10.2 GPa (CoV = 18.6 %), respectively, giving a difference of only 11 %. BRANDNER & SCHICKHOFER [38] and OBERNOSTERER et al. [39] report a difference from 20 to 28 % and BÜCHSENMEISTER [18] 20 %, but it must to be said, that

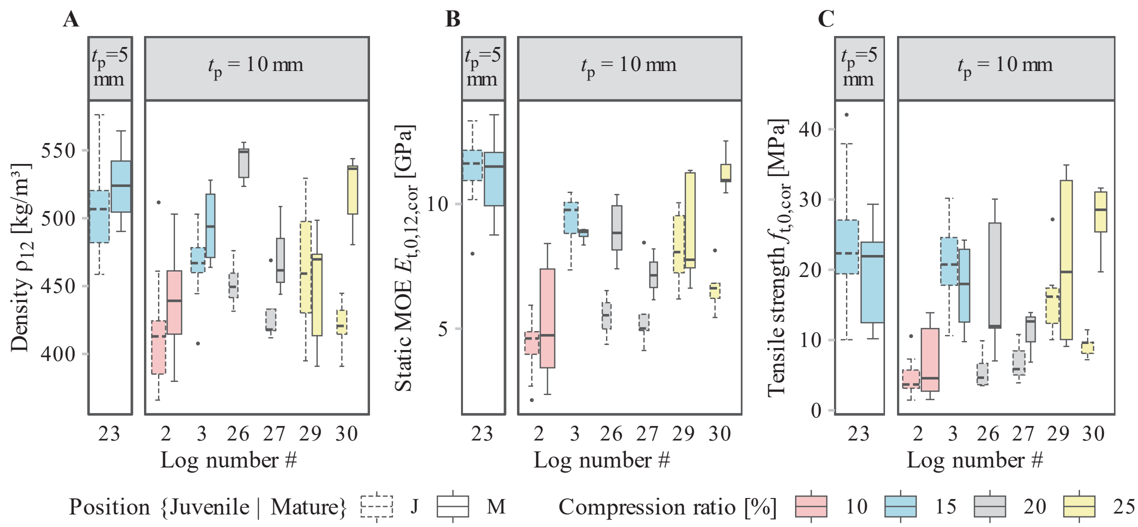

Figure 5: Box plots grouped by TPP thickness, radial location in the log and compression ratio: (A) density ρ_{12}, (B) MOE $E_{t,0,12,cor}$ and (C) tensile strength $f_{t,0,cor}$.

the inverse relationship of the two logs mentioned above, reduces the difference.

A comparison of the MOE for the mature wood with the preliminary study by Büchsenmeister [18] shows much lower values ($E_{t,0,12,mean,M}$ = 9.4 GPa; CoV = 20.2 %) vs. 11.9 GPa (CoV = 9.1 %), which might be due to the clearly different log quality.

When the samples are separated into juvenile and mature location groups, the dynamic MOE for the juvenile and the mature location is 13.4 GPa (CoV = 16.3 %) and 14.4 GPa (CoV = 16.1 %), respectively. The dynamic MOE for the juvenile and the mature location is 45.6 % and 41.2 %, respectively, higher than the corresponding static MOE.

The box-plots of the tensile strength in Figure 5 (C) show a significant difference between the juvenile and mature location groups. The juvenile and the mature location groups give a mean tensile strength of $f_{t,0,mean,J}$ = 17.7 MPa (CoV = 52.1 %) and $f_{t,0,mean,M}$ = 20.4 MPa (CoV = 48.3 %), respectively. The difference between the juvenile and mature location is about 15 %, what is quite low compared to expectations and literature, where a difference (for sawn timber) of about 27 – 35 % is given, c.f. [38,39]. On the other hand, BÜCHSENMEISTER [18] observed a difference between the juvenile and mature location of 33 %. The mean tensile strength of the mature portion in this work is approximately 34 % lower than the $f_{t,0}$ = 30.8 MPa (CoV = 33.2 %) in [18]. The 5 % – quantile for the mature samples is $f_{t,0,LN05,M}$ = 7.1 MPa (log range 3.8 to 21.2 MPa), which is close to the strength class T8 of EN 338 [31].

Due to the above mentioned effects of the location in the log on the MOE and tensile strength, only the mature portion of the samples will be discussed further.

Anyway, even after correction of grain deviations and restriction to the mature wood zone, the variation in log and TPP quality is still high. To allow meaningful conclusions for the possible influence of process parameters, in the following the modulus of elasticity and the tensile strength results are corrected to a reference density of ρ_{ref} = 420 kg/m³, as described in Section 3.2.3.

4.6.2 PROCESS PARAMETERS

4.6.2.1 PRE-TREATMENT | COMPRESSION RATIO

[11,12,15,20,26] report a wide range of pre-treatment and compression ratios for a large number of different species, but the range for peeling parameters is also large and no specific values could be adopted.

Starting with the MOE, as described in Section 3.1, the 10 mm thick TPPs were varied in the pre-treatment duration. According to Section 3.2.5, the evaluation of the 10 mm thick TPPs grouped by pre-treatment and compression ratio shows no significant difference between the pre-treatment groups. The mean modulus of elasticity for group TI and TII is 9.45 GPa (CoV = 14.2 %) and 8.80 GPa (CoV = 23.4 %), respectively. There is also no clear influence of the compression ratio.

Similar to the MOE, also for the tensile strength no significant effects of the pre-treatment and compression ratio were observed when evaluating according to Section 3.2.5

4.6.2.2 TPP THICKNESS

The thickness of the TPPs has also no significant effect on the static MOE. The mean MOE of the mature portion of the 10 mm, 15 mm and 20 mm TPPs ranges between 8.5 and 8.8 GPa, only the 5 mm thick TPPs (only one log!) have a higher mean MOE of 11.2 GPa.

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There seems to be also no significant influence from TPP thickness on the tensile strength, although the 20 mm TPPs (only one log!) have a slightly higher tensile strength of $f_{t,0,mean,ref,20mm}$ = 23.0 MPa | CoV = 40.0 % compared to the other samples. The 5 mm TPPs (only one log!) have a slightly lower tensile strength of $f_{t,0,mean,ref,5mm}$ = 14.0 MPa (CoV = 32.9 %). The mean tensile strength for the 10 mm TPPs is $f_{t,0,mean,ref,10mm}$ = 15.3 MPa (CoV = 48.6 %; twelve logs) and for the 15 mm TPPs its $f_{t,0,mean,ref,15mm}$ = 18.0 MPa (CoV = 54.9 %; four logs).

4.6.2.3 ROLLER BAR VELOCITY

No clear results can be reported about the influence of the roller bar velocity relative to the spindle velocity v, as this parameter was only varied on one log (# 21), and this log has clearly higher tension properties compared to the other samples. However, the literature [13] reports a significant effect on the surface quality and the peeling process (less spin-outs), due to less force on the knife.

4.7 LATHE CHECK BEHAVIOUR

In line with the literature [11,16,19–21,26], the depth of the lathe checks increases with increasing TPP thickness. While the mean relative lathe check depth for the 5 mm thick TPPs is 72.3 %, the relative lathe check depth for the 17.5 mm TPPs is 87.5 % and for the 20 mm TPPs 85.7 %. The pre-treatment also has an effect on the rel. lathe check depth, with the shorter treatment (TII) giving deeper lathe checks (mean rel. depth = 81.0 %) than the longer treatment (TI) with a mean rel. depth of 77.4 %. The data in this paper shows no significant effect of the compression ratio on the relative lathe check depth.

The relationship between rel. lathe check depth and lathe check interval (average distance between two checks) also behaves as expected and reported in the literature. With increasing depth, also the distance between two checks increases. While the check interval is about 5 mm for a relative depth of 70 %, it increases to 13.5 mm for a relative depth of about 85 %.

5 – CONCLUSIONS AND OUTLOOK

There is almost no literature available on the subject of thick peeled products. Only [18] (institutional own preliminary study) and [17] provide some information on the peeling process and a first mechanical characterisation. The paper in hand provides a sound basis about limits and characteristics of TPPs for further decisions and investigations on the parameters of peeling and its pre- and post-processing as well as for a characterisation of TPPs based on the tensile properties parallel to the grain and strength indicating properties E_{dyn} and ρ, as a potential base material for Laminated Peeled Products (LPPs) and further for Structural Laminated Timber Products (SLTPs).

The findings of these investigations can be summarised as follows:

(i) It is shown that it is possible to peel TPPs up to 20 mm thickness on an industrial peeling lathe, which is designed for beech and therefore quite robust. The rest roll diameter of this 20 mm TPP was 160 mm, due to spin-out). Furthermore, the 10 mm thick TPPs can be peeled down to the peeling machine's minimum rest roll diameter of 78 mm. The average rest roll diameter in this work was 125 mm, caused by spin-outs.

(ii) As shown, the properties density, MOE and tensile strength are not significantly affected by the parameters pre-treatment, compression ratio and thickness. On the other hand, the radial location has a significant effect on these properties, which is in agreement with the literature, c.f. [16,18,27,38,39]. With a suitable separation method, the juvenile and mature portion of the wood can be used separately for optimised LPP or SLTP layups.

(iii) Lathe check behaviour is significantly affected by the TPP thickness and the pre-treatment, where the relationship between the relative lathe check depth and the lathe check interval is in agreement with the literature [11,12,15,20,26].

(iv) It can therefore be concluded that a shorter pre-treatment leads to deeper lathe checks, but has no effect on the mechanical properties parallel to the grain and saves energy costs. [11,12,14] also suggests that the pre-treatment temperature can be further reduced, again saving energy.

(v) In this paper, yields (= log volume – round up loss – rest roll) of up to 92 % were achieved. The average yield was about 83 %.

Looking forward, the next steps in this project will be to investigate (i) the tensile properties of multilayer LPPs parallel to the grain, and (ii) the tensile properties perpendicular to the grain and (iii) shear. In addition, (iv) the bonding behaviour and the connection of LPPs will be investigated, as well as (v) possible applications for TPPs and LPPs. Another point (vi) is to develop a stochastic-mechanical model for the description of the LPPs based on the characteristics of the TPPs.

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Table 1: Main statistics of physical / mechanical properties of TPPs per peeling log and corresponding pre-treatment and peeling parameters.

Log no. [-]		23		2[2)]		3		4	20	21	22	24	25	26		27		28	29		30		5	8	12	15	6
TPP Thickness *t*		5		10																			15				20
Treatment		TI		TI									TII										TI				TI
Compr. ratio [%]		15		10		15		10	15	15	15	20	15	20		20		17.5	25		25		15	20	20	15	15
Location		M	J	M	J	M	J	M	M	M	M	M	M	M	J	M	J	M	M	J	M	J	M	M	M	M	M
***v* – roller bar**[1)] [%]		100		100					102	100													100				100
$x = \rho_{12}$ [kg/m³]	no.	20	20	11	10	4	10	5	5	5	4	5	7	5	4	3	5	6	5	6	5	5	5	5	4	5	18
	x_{50}	524	507	439	413	494	467	504	469	460	438	500	467	549	449	462	418	468	470	459	536	421	443	466	462	491	435
	x_{mean}	**523**	**505**	**438**	**416**	**495**	**465**	**504**	**464**	**463**	**438**	**502**	**475**	**542**	**452**	**471**	**430**	**463**	**449**	**462**	**520**	**421**	**443**	**465**	**461**	**509**	**449**
	$CoV_{[x]}$	4.1	5.9	7.9	10.6	6.3	5.6	3.0	4.9	4.7	2.8	5.9	7.6	2.6	4.2	7.1	5.4	4.2	10.0	10.9	5.3	4.8	3.0	4.7	2.1	8.1	9.2
	$x_{emp,05}$	494	463	393	368	465	424	490	434	439	424	472	435	525	433	446	413	437	395	402	485	396	429	441	449	468	391
$x = E_{t,0,12,cor}$ [GPa]	no.	20	20	11	10	4	10	5	5	4	4	5	7	5	4	3	5	6	5	6	5	5	5	5	4	5	18
	x_{50}	11.5	11.6	4.9	4.6	9.0	9.8	10.1	10.1	8.7	9.4	10.6	8.0	8.8	5.5	7.1	5.0	8.0	7.8	8.1	11.0	6.6	8.7	9.6	6.8	11.6	8.9
	x_{mean}	**11.2**	**11.8**	**5.6**	**4.5**	**8.9**	**9.3**	**9.8**	**10.0**	**8.4**	**9.2**	**10.0**	**8.6**	**8.9**	**5.5**	**7.2**	**5.6**	**7.5**	**8.9**	**8.2**	**11.3**	**6.6**	**8.8**	**8.5**	**6.6**	**11.1**	**8.8**
	$CoV_{[x]}$	13.0	13.1	37.3	22.6	3.0	11.9	10.5	7.5	29.0	13.9	14.4	20.8	13.7	16.9	14.2	29.7	31.3	25.2	18.8	7.1	14.8	8.5	26.0	18.9	9.9	14.5
	x_{mean}[3)]	11.1	11.4	5.0	4.3	8.3	9.3	9.5	9.9	8.3	9.2	9.9	8.5	8.9	5.5	7.2	5.6	7.4	8.9	8.2	11.3	6.6	8.8	8.5	6.6	11.1	8.8
	$x_{ref,mean}$[4)]	8.7	9.5	5.3	4.6	7.5	8.3	8.0	8.9	7.3	8.8	8.2	7.5	6.7	5.1	6.3	5.5	6.7	8.2	7.4	8.9	6.6	8.2	7.5	5.9	9.1	8.2
$x = E_{0,dyn,12,cor}$ [GPa]	no.	20	20	10	11	10	4	5	5	5	4	5	7	4	5	5	3	6	6	5	5	5	4	5	4	5	5
	x_{50}	15.1	15.4	10.4	12.4	14.5	13.4	14.0	15.3	15.3	12.2	15.9	12.5	11.5	16.2	11.5	13.0	13.5	11.5	9.7	11.8	16.7	13.4	15.6	13.5	17.3	14.0
	x_{mean}	**15.4**	**15.2**	**10.2**	**12.5**	**14.1**	**13.1**	**14.4**	**14.6**	**15.2**	**12.5**	**16.0**	**13.2**	**11.4**	**16.3**	**11.5**	**13.0**	**13.1**	**11.4**	**10.3**	**11.3**	**16.5**	**13.1**	**14.6**	**13.5**	**17.6**	**14.4**
	$CoV_{[x]}$	**9.6**	**12.1**	**15.6**	**15.6**	**10.7**	**9.0**	**9.5**	**9.1**	**4.9**	**10.3**	**3.8**	**24.8**	**13.1**	**4.8**	**12.8**	**12.1**	**17.1**	**21.1**	**15.2**	**12.8**	**7.1**	**9.0**	**16.3**	**10.7**	**9.9**	**9.5**
$x = f_{t,0,cor}$ [MPa]	no.	20	20	11	10	4	10	5	5	5	4	5	7	5	4	3	5	6	5	6	5	5	5	5	4	5	18
	x_{50}	21.9	22.3	4.6	3.7	18.0	20.7	14.7	28.9	17.0	18.2	26.1	12.9	12.0	4.6	12.6	5.9	12.8	19.7	16.2	28.5	9.6	22.8	33.7	8.0	26.1	26.9
	x_{mean}	**19.5**	**23.6**	**6.7**	**4.7**	**17.5**	**21.1**	**14.4**	**30.6**	**17.7**	**16.1**	**21.9**	**16.2**	**17.5**	**5.7**	**11.1**	**6.8**	**13.3**	**21.3**	**16.4**	**27.3**	**9.2**	**22.5**	**23.4**	**7.4**	**30.0**	**25.5**
	$CoV_{[x]}$	33.7	34.4	72.0	56.9	39.8	27.5	31.2	22.3	54.9	29.7	37.2	74.3	58.3	52.4	33.8	40.9	58.4	57.2	37.2	17.9	17.8	31.6	68.6	27.7	25.7	42.2
	x_{mean}[3)]	18.7	21.1	5.7	4.6	13.0	20.5	13.7	28.6	15.3	15.8	20.8	15.7	17.4	5.7	11.0	6.8	12.8	21.3	16.4	27.3	9.2	22.4	22.2	7.4	30.0	23.5
	$x_{ref,mean}$[4)]	14.0	17.9	6.1	5.0	13.7	18.1	11.0	26.4	15.5	15.1	17.1	13.0	12.1	5.0	9.3	6.7	11.4	18.3	13.8	19.9	9.2	20.6	19.5	6.5	23.1	23.0
	$x_{emp,05}$	10.4	10.7	1.6	2.0	10.3	13.3	9.6	24.6	6.7	10.3	12.4	8.1	8.0	3.5	7.4	4.1	4.0	9.3	10.3	20.8	7.4	15.7	5.2	5.0	23.6	10.9
	$x_{LN,05}$	9.9	12.3	1.3	1.7	8.1	12.3	8.2	21.2	5.0	8.5	10.3	5.5	5.5	2.35	5.7	3.3	2.81	6.5	8.7	19.5	6.8	13.1	3.3	4.2	19.6	10.3
MC [%]	x_{mean}	**8.7**	**8.1**	**9.4**	**10.0**	**10.8**	**9.1**	**9.0**	**9.1**	**9.8**	**9.2**	**9.8**	**10.0**	**9.3**	**9.3**	**10.3**	**11.4**	**11.6**	**7.5**	**9.9**	**7.7**	**9.3**	**9.3**	**9.9**	**8.5**	**8.3**	**9.9**

[1)] velocity of roller bar relative to velocity of spindle; [2)] excluded from further discussion; [3)] without any correction; [4)] corrected to a reference density of 420 kg/m³ (see Section1)

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