

## Article

# Veneer Composites for Structural Applications—Mechanical Parameters as Basis for Design

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**Abstract:** The use of veneer composites as structural components in engineering requires special design. The dimensioning of laminated wood can be optimized by varying the wood species, veneer thickness, orientation, arrangement, number of single layers, and other factors. Composite properties can be calculated using suitable model approaches, such as the classical laminate theory. Thus, an optimization can be achieved. The present study verified the adaptability of the classical laminate theory for veneer composites. Native veneer, adhesive-coated veneer, and solid wood were investigated as raw materials for the plywood layers. Mechanical properties were determined using tensile and shear tests and used as parameters to calculate the composite properties of the plywood. The adhesive coating results in an increase in stiffness and strength compared with the native veneer parameters, which is greater perpendicular to the fiber than in the fiber direction. The increase due to the adhesive decreases with increasing veneer thickness. The plywood was bending tested. The measured Young's modulus was in the range of 8000–10,700 MPa, the shear modulus was in the range of 500–1100 MPa, and the strength was in the range of 70–100 MPa. The values obtained were compared to the calculations. The best prediction of the plywood properties is obtained by using the properties of the adhesive-coated veneer as a single layer.



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**Keywords:** veneer; mechanical properties; adhesive coating; classical laminate theory; engineering; plywood

## 1. Introduction

The engineering design process requires computations to predict the mechanical behavior of components. Replacing traditional metal construction materials with wood or wood composite is a challenging task. The computation of wood and wood composites is more complex than that of traditional metal construction materials because of their anisotropic structure and properties. In addition, there are a number of factors that influence the mechanical properties of wood composites, such as climatic conditions or material density. Kluge and Eichhorn have developed a computational concept for stiff jointed wood composites that allows for a flexible safety concept for wood composites, enabling lightweight construction [1]. In addition to the improved computational concept, optimized dimensioning of the wood composite can have an important influence on the lightweight potential of the overall construction [2].

A veneer composite is a layered structure consisting of veneer layers that are strongly bonded by adhesive. Veneer has a porous material structure. During production, the adhesive infiltrates the material and generates a transition area in the veneer border area. It

can be assumed that this transition area influences the mechanical properties of the single veneer layer.

Veneer composites can be used and optimized in the construction of technical components through purposeful dimensioning. An optimization can be reached through the orientation and arrangement of the single layers (veneers), considering the subsequent stress.

A stress-appropriate design of a laminated material requires the mechanical properties of the single layers. For veneer composites, such as plywood, the veneer is the single layer. Thus, the mechanical parameters of veneers for the fundamental stresses, such as tension, compression, and shear, are needed for the prediction of the mechanical properties of veneer composites. Hence, computation and simulation become possible.

Table 1 shows all mechanical parameters necessary for a complete veneer characterization. Because of their anatomically undefined perpendicular to fiber direction, the veneer directions are defined and indicated as perpendicular to fiber (90) and parallel to fiber (00) direction. Table 1 summarizes values available in the literature [3–11]. No distinction is made between wood species, the type of veneer (rotary cut or sliced) or the veneer thickness. The collected references show that most of the parameters are available for Young's modulus and strength in the fiber direction ( $E_{00}$  and  $\sigma_{00}$ ). There is no published complete data set for a species, a veneer thickness, or a veneer type that can be used for simulation and calculation. One possible reason for the lack of data sets is the lack of standardized and practical test methods for veneers. Therefore, suitable test methods for characterizing veneers in tension, compression, and shear have been developed in the joint project “Wood-based materials in mechanical engineering (HoMaba)” [2].

**Table 1.** Essential parameters for a material model based on veneer. Available parameters are referenced. \* References to rotary-cut beech veneer.

| Stress      | Engineering Constant                                   | Failure Strain                                           | Strength                                          |
|-------------|--------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------|
| tension     | $E_{00}$ [3–8], [9] *<br>$E_{90}$ [3–8]<br>$\mu$ [3,6] | $\varepsilon_{00}$ [3,5–7]<br>$\varepsilon_{90}$ [3,5–7] | $\sigma_{00}$ [3–8], [9] *<br>$\sigma_{90}$ [3–8] |
| compression | $E_{00}$ [10] *<br>$E_{90}$ [10] *<br>$\mu$ [10] *     | $\varepsilon_{00}$ [10] *<br>$\varepsilon_{90}$ [10] *   | $\sigma_{00}$ [10] *<br>$\sigma_{90}$ [10] *      |
| shear       | $G$ [7], [9] *, [11]                                   | $\gamma$ [7,11]                                          | $\tau$ [9] *, [11]                                |

$E$  ... Young's modulus;  $\mu$  ... Poisson's ratio;  $\varepsilon$  ... strain;  $\sigma$  ... strength;  $G$  ... shear modulus;  $\gamma$  ... shear strain;  $\tau$  ... shear strength; 00 ... parallel to fiber; 90 ... perpendicular to fiber.

The veneer production leads to lathe checks in the material [12–15]. These cracks weaken the load-bearing capacity of the material. Thus, the question arises if the adhesive can repair the cracks and restore the strength of the veneer. In this case, parameters of solid wood could be used for computation and simulation.

The present study was conducted to clarify the influence of the adhesive on the material properties, as well as the influence of the differences between the mechanical parameters of solid wood and veneer. Another objective was to investigate which parameters are suitable for the single layer (native veneer, adhesive-coated veneer or solid wood) for the calculation and simulation of the composite properties.

Classical laminate theory (CLT) is used to demonstrate predictability. This theory is a well-established method for calculating stiffness and stress in the elastic region in planar multilayer composites, developed and used primarily for fiber-reinforced plastics [16].

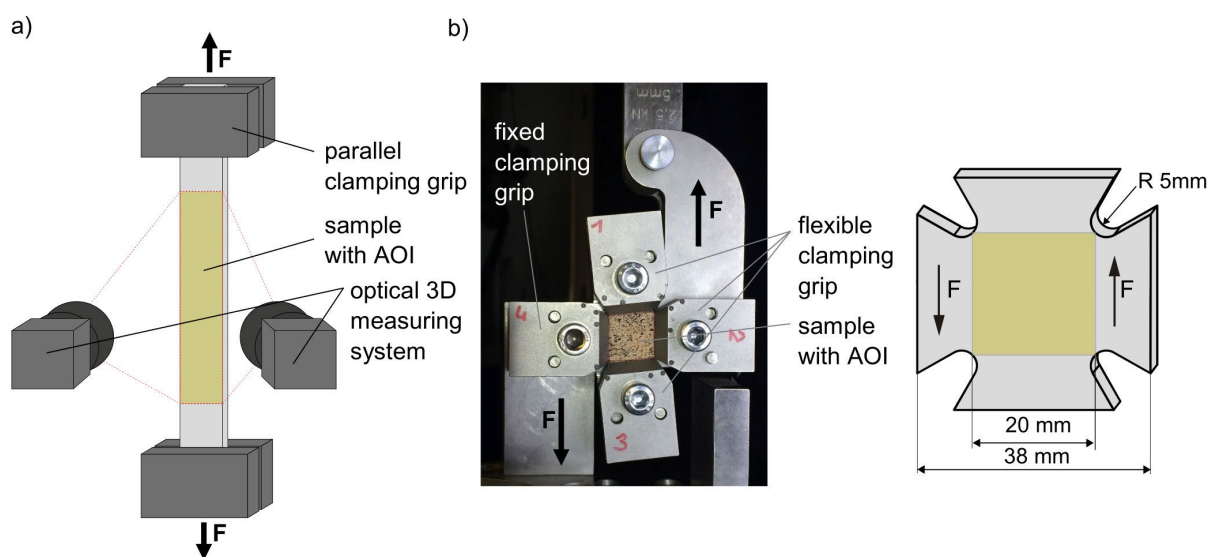
## 2. Materials and Methods

### 2.1. Single Layer

European beech (*Fagus sylvatica* L.) was used for the investigations. The material was taken from trunks of one habitat with comparable or equal growing conditions. The trunks have been split into two parts with the same length. One part of each trunk was used for the manufacture of rotary cut veneer with different thicknesses (1, 2, and 3 mm). The veneers were produced in a laboratory environment using an industrial machine. The other part of each trunk was used to manufacture solid wood samples. Half of the veneers were double-sided coated with a phenol-resorcin-formaldehyde-resin adhesive (Aerodux 185, Fa. Dynea AS, Lillestrøm, Norway). Since the focus of the research was on engineering applications, the adhesive was selected because it is approved by the German Federal Aviation Administration for the production of glued wood products for use in aircraft. The adhesive application quantity was  $220 \text{ g m}^{-2}$  per each surface of the veneer. The adhesive setting was conducted in a laboratory press at  $90^\circ\text{C}$  and a pressure of  $1 \text{ N mm}^{-2}$  for 120 s [17].

The material parameters of native veneer (vn), adhesive-coated veneer (vc), and solid wood (sw) in longitudinal—tangential direction were determined in dependence on the testing direction (00—fiber direction, 90—perpendicular to the fiber direction) and the sample thickness for tension and shear stress. For the strain measurement, a stereo camera system (Aramis adjustable 12M, Carl Zeiss GOM Metrology, Braunschweig, Germany) was used, which applies the principles of digital image correlation (DIC). A contrast speckle pattern was applied to the area of interest (AOI) of the sample surface.

The testing methods used for all samples are shown in Figure 1. The tension tests were conducted with rectangular samples (00-direction:  $200 \text{ mm} \times 20 \text{ mm}$ ; 90-direction:  $200 \text{ mm} \times 30 \text{ mm}$ ) with a universal testing machine (Inspekt 10, load capacity 10 kN, Hegewald & Peschke, Nossen, Germany). The test speed was strain-controlled and was  $1\% \text{ min}^{-1}$  [2,6]. These dimensions and test conditions were used for both the veneer and the solid wood samples, with the solid wood samples being 3 mm thick. The elastic parameters were determined in the range between 0% and 40% of the failure load. The slope in this range was calculated in order to determine Young's modulus, as well as Poisson's ratio. The shear tests were performed on the same testing machine used for the tension tests in a shear frame as described by Krüger et al. [18], which converts a uniaxial tensile load into a shear load by means of pivotally supported clamps.



**Figure 1.** Single layer testing methods: (a) tension and (b) shear.

With respect to the focused engineering application, all tests were conducted at a climate of 20 °C/50% relative humidity [1]. Twenty replicates for each material and thickness were tested in tension parallel to the fiber (00), perpendicular to the fiber (90), and shear. Table 2 shows the density and the moisture content of the samples tested, as determined through random sampling.

**Table 2.** Density and moisture content of single layer material, mean values.

| Material      | Thickness | Density                | Moisture Content |
|---------------|-----------|------------------------|------------------|
| veneer        | 1 mm      | 613 kg m <sup>-3</sup> | 9.4%             |
|               | 2 mm      | 530 kg m <sup>-3</sup> | 9%               |
|               | 3 mm      | 636 kg m <sup>-3</sup> | 8.4%             |
| veneer coated | 1 mm      | 918 kg m <sup>-3</sup> | 8.4%             |
|               | 2 mm      | 741 kg m <sup>-3</sup> | 9.2%             |
|               | 3 mm      | 708 kg m <sup>-3</sup> | 9.2%             |
| solid wood    | 3 mm      | 692 kg m <sup>-3</sup> | 9%               |

## 2.2. Plywood

Plywood with different veneer thicknesses and a number of plies was produced to compare the composite properties, which were later calculated using the characteristic values of the single layers. The plywood was produced at a laboratory press with veneers and adhesive of the same batch as the single veneer layers. The amount of adhesive applied to each veneer layer was 450 g m<sup>-2</sup>. The board was pressed in a position-controlled manner, resulting in 10% compression of the veneers at a temperature of 90 °C and a pressing time of 60 min [17]. After pressing, the boards were stacked, weighed, and conditioned for two weeks. The composition of the plywood is shown in Table 3. The density and moisture content of the samples tested are given as mean values determined through random sampling.

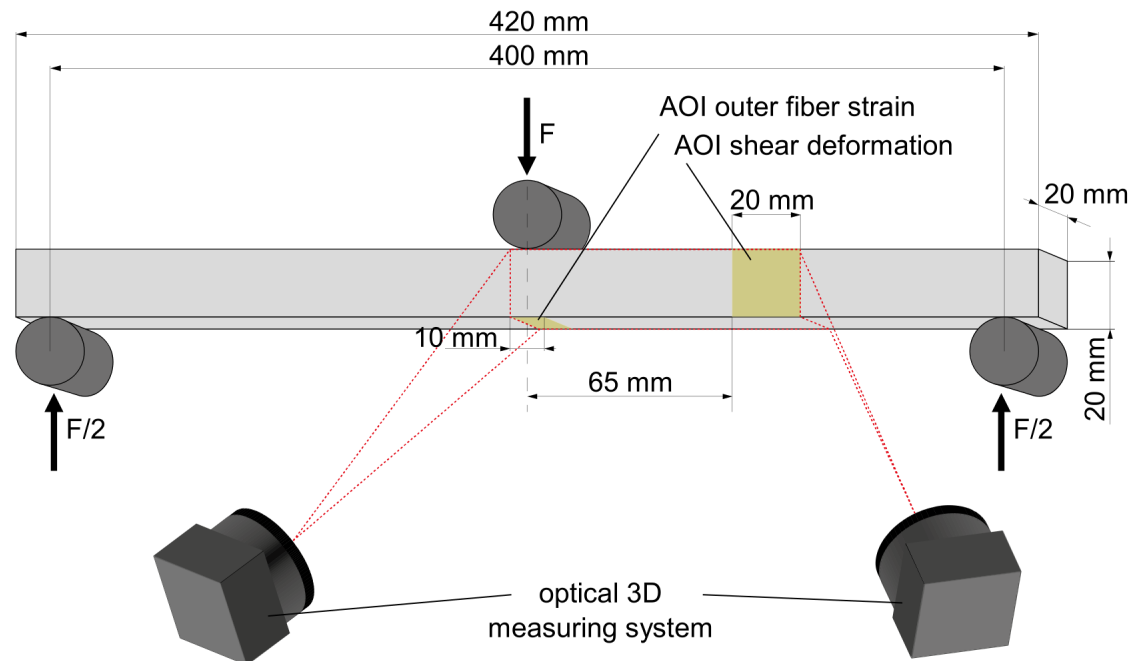
**Table 3.** Structure, density and moisture content of the investigated plywood (mean values).

| Material  | No. of Layers | Layer Thickness | Thickness | Density                 | Moisture Content |
|-----------|---------------|-----------------|-----------|-------------------------|------------------|
| plywood 1 | 21            | 1 mm            | 19.2 mm   | 1075 kg m <sup>-3</sup> | 8.8%             |
| plywood 2 | 11            | 2 mm            | 20.3 mm   | 826 kg m <sup>-3</sup>  | 9%               |
| plywood 3 | 7             | 3 mm            | 19.4 mm   | 818 kg m <sup>-3</sup>  | 9%               |

Bending is a common load case in practice and combines the basic stresses of tension and shear simultaneously. For this reason, material tests were conducted under 3-point bending loading in accordance with DIN EN 310 [19]. The schematic test setup, including the sample dimensions, is shown in Figure 2.

In contrast to the rectangular samples suggested by DIN EN 310 [19], a square cross-section was used, with reference to DIN 52186 [20]. This made it possible to use the same test setup and sample dimensions for both plate bending (force applied in the thickness direction of the plywood) and disk bending (force applied in the plane of the layers). Preliminary tests have shown that the sample width does not affect the strength and failure behavior of the plywood tested. In addition to measuring the strain in accordance with the standard, the outer fiber strain was measured directly at the bottom side of the sample using the optical 3D measurement system. The advantage is that the calculation of the outer fiber strain by using the deflection could be omitted. Furthermore, the elastic shear

properties were measured on a defined measuring area on the front side of the sample according to DIN EN 408 [21]. Simultaneous measurement of the front and the bottom side of the sample was achieved by orienting the optical measurement system at a  $45^\circ$  angle to both measurement areas (Figure 2) [2].



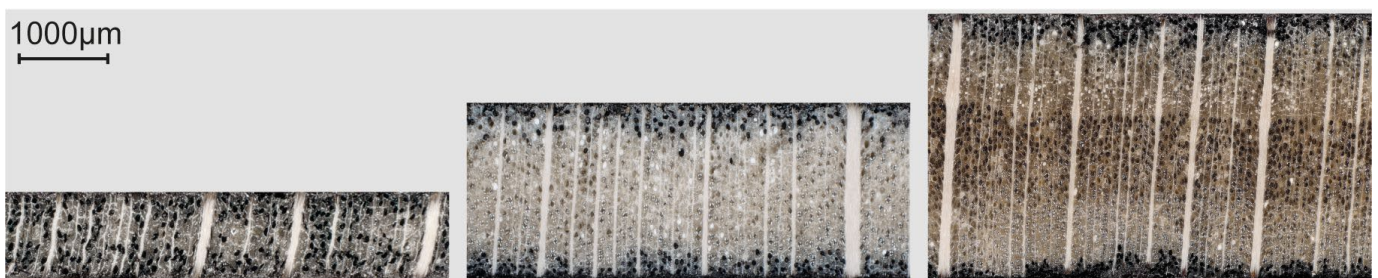
**Figure 2.** Schematic test setup of 3-point bending test including optical measurement system at  $45^\circ$  angle.

Similar to the single layer tests, all tests were conducted at  $20^\circ\text{C}$  and 50% relative humidity. The test speed was strain controlled and was  $1\% \text{ min}^{-1}$ . For each plywood and test direction, 20 replicates were tested.

### 3. Results and Discussion

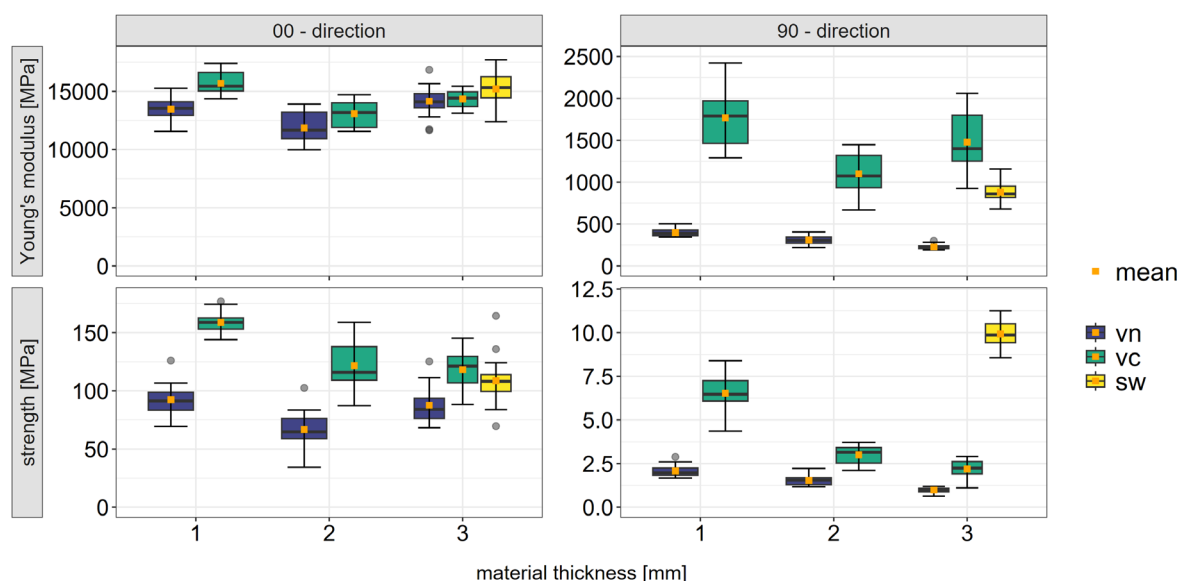
#### 3.1. Single Layer

Figure 3 shows a qualitative comparison of the adhesive infiltration. The infiltration depends on the veneer depth. One-millimeter thick veneers are almost completely soaked with adhesive and have a homogeneous adhesive distribution over their cross-section. The thicker veneer has an area at its border with wood cells and adhesive. The center of these veneers is free of adhesive. Because of the constant amount of adhesive applied, the percentage of adhesive relative to the veneer thickness decreases.



**Figure 3.** Qualitative comparison of the adhesive infiltration (black) in dependence on the veneer thickness: 1 mm (left); 2 mm (middle); 3 mm (right).

Figure 4 exemplarily shows a comparison of Young's modulus and tensile strength. Results are shown for both test directions and for different material thicknesses of single layers.



**Figure 4.** Tension test properties for veneer (vn), adhesive-coated veneer (vc), and solid wood (sw) in dependence on material thickness and test direction.

The results indicate a tendency for a decrease in mechanical parameters with increasing veneer thickness perpendicular to the fiber direction (90-direction). However, the trend is less clear in the fiber direction. In addition, the anisotropy of the material increases with increasing veneer thickness. These facts are caused by the lathe checks in the veneer. The lathe checks create a notch stress in their base, which acts as a breaking point in the veneer cross-section. Lathe checks also cause a slight decrease in parameters in the fiber direction. Discussing the results using literature values is challenging due to the absence of suitable literature values. Staudacher [9] provides strength and Young's modulus values for 3 mm thick peeled beech veneer (*Fagus sylvatica* L.) in the fiber direction. His results, with a tensile strength of 158 MPa and Young's modulus of 18,000 MPa, are clearly higher than our own. A possible explanation for these large differences can be found in the damage to the material due to different lathe checks. Adhesive coating leads to a clear increase in the parameters compared to the parameters of the native veneer, some of which are higher than those of the solid wood samples. The increase in the parameters of the adhesive-coated samples decreases with increasing veneer thickness due to the percentage decrease and the different infiltration of the adhesive into the veneer cross-section (Figure 3).

Adhesive-coated samples show higher strength than solid wood samples in the 00-direction. The adhesive infiltrates and fills the cell lumen, inhibiting the ability to elongate. It also homogenizes the veneer surface. This reduces stress peaks and provides a more homogeneous stress distribution across the cross-section. Perpendicular to the fiber direction, the strength of the adhesive-coated samples is lower than that of solid wood. This is due to the embrittlement of the material behavior caused by the adhesive and is evident from the obviously higher Young's modulus compared with solid wood. Therefore, the adhesive-coated veneer samples failed at lower strains than the solid wood samples. In addition, the lathe checks in the veneer, which are partially filled with adhesive, lead to a reduction in strength. This proportion decreases with increasing veneer thickness so that the strength of the adhesive-coated veneers approaches that of the native veneers.

Tables 4 and 5 summarize all the tensile and shear test results.

**Table 4.** Tension properties, mean values, and standard deviation in brackets.

| Material      | Thickness | Load Direction | Young's Modulus [MPa] | Poisson's Ratio | Strength [MPa] | Failure Strain |
|---------------|-----------|----------------|-----------------------|-----------------|----------------|----------------|
| veneer        | 1 mm      | 0°             | 13,488 (1074)         | 0.47 (0.07)     | 93 (13)        | 0.7% (0.1%)    |
|               |           | 90°            | 398 (45)              | 0.03 (0)        | 2.1 (0.3)      | 0.6 (0.1%)%    |
|               | 2 mm      | 0°             | 11,870 (1325)         | 0.46 (0.06)     | 67 (15)        | 0.6% (0.1%)    |
|               |           | 90°            | 309 (51)              | 0.03 (0)        | 1.5 (0.3)      | 0.5% (0.1%)    |
|               | 3 mm      | 0°             | 14,156 (1245)         | 0.50 (0.06)     | 88 (16)        | 0.7% (0.1%)    |
|               |           | 90°            | 227 (31)              | 0.02 (0)        | 1 (0.1)        | 0.4% (0.1%)    |
| veneer coated | 1 mm      | 0°             | 15,696 (905)          | 0.44 (0.02)     | 161 (11)       | 1.1% (0.1%)    |
|               |           | 90°            | 2168 (858)            | 0.05 (0.01)     | 6.5 (1.1)      | 0.4% (0.1%)    |
|               | 2 mm      | 0°             | 13,085 (1067)         | 0.45 (0.01)     | 122 (20)       | 1% (0.1%)      |
|               |           | 90°            | 1100 (261)            | 0.04 (0.01)     | 3 (0.5)        | 0.3% (0.1%)    |
|               | 3 mm      | 0°             | 14,355 (716)          | 0.48 (0.01)     | 118 (17)       | 0.9% (0.1%)    |
|               |           | 90°            | 1553 (468)            | 0.04 (0.01)     | 2.2 (0.5)      | 0.2% (0.1%)    |
| solid wood    | 3 mm      | 0°             | 15,354 (1571)         | 0.43 (0.03)     | 109 (20)       | 0.8% (0.1%)    |
|               |           | 90°            | 880 (117)             | 0.03 (0.01)     | 10 (0.7)       | 1.5% (0.2%)    |

**Table 5.** Shear properties, mean values, and standard deviation in brackets.

| Material      | Thickness | Shear Modulus [MPa] | Strength [MPa] | Failure Strain |
|---------------|-----------|---------------------|----------------|----------------|
| veneer        | 1 mm      | 500 (44)            | 9.9 (1.2)      | 0.031 (0.004)  |
|               | 2 mm      | 439 (36)            | 9.2 (1.3)      | 0.031 (0.005)  |
|               | 3 mm      | 415 (46)            | 7.3 (0.8)      | 0.024 (0.005)  |
| veneer coated | 1 mm      | 903 (87)            | 24.5 (2)       | 0.056 (0.011)  |
|               | 2 mm      | 615 (33)            | 15.4 (1.2)     | 0.045 (0.008)  |
|               | 3 mm      | 598 (62)            | 12.9 (1.6)     | 0.036 (0.006)  |
| solid wood    | 3 mm      | 722 (48)            | 18.2 (1.2)     | 0.050 (0.006)  |

### 3.2. Plywood

Figure 5 shows an example of cross-sections of plywood made from 1 mm and 2 mm veneers and gives an impression of the different adhesive distribution (dark areas) throughout the cross-section. It can be seen that the adhesive infiltration in the plywood is comparable to the adhesive infiltration of the single veneers (Figure 3). Thus, the adhesive-coated veneers represent the single layer in the plywood qualitatively well.

Classical laminate theory has been used as a computational model to predict the behavior of veneer composites [22–24]. Mittelstedt and Becker provide a detailed description of the use of CLT [16]. Further detailed information and example calculations are provided in Appendix A.

For plate bending, the bending stiffness matrix of the laminate was used, while for disk bending, the extensional stiffness matrix was used to calculate the effective laminate elastic engineering constants ( $E$ ,  $G$ ,  $\mu$ ). To calculate the composite parameters, the data sets of native veneers (vn), adhesive-coated veneers (vc), and solid wood (sw) were used and compared.

The box plots in Figure 6 show the comparison of the elastic composite parameters (Young's modulus and shear modulus), determined in the 3-point bending test, with the calculated parameters using the single layer parameters (displayed as dots). The shear modulus of the plate bending could not be calculated because the CLT requires plane stress

without any thickness properties. Therefore, a difference between the model (CLT) and the reality has to be stated.



**Figure 5.** Microscopy of the plywood cross-section of 1 mm (left) and 2 mm veneer layers (right).

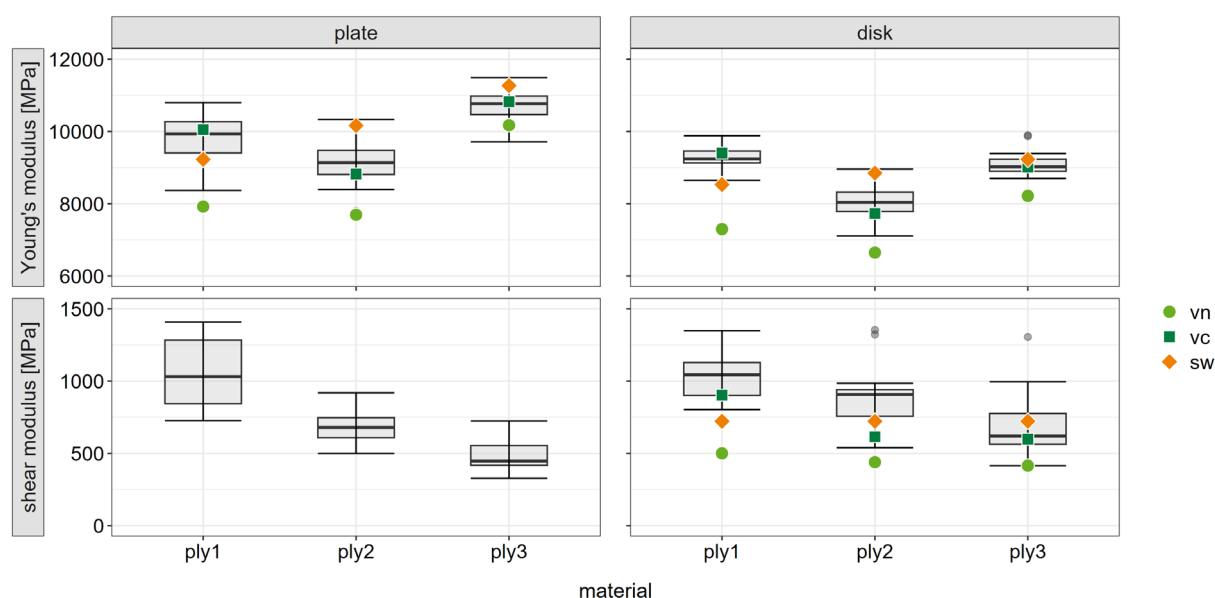
The diagrams (Figure 6) show a difference between the plywood variants in both the measured and the calculated parameters, depending on the single layer thickness and the number of layers. The lowest Young's modulus was determined for ply2, which consists of 2 mm thick veneers. This is due to the lower density compared to the 1 mm and 3 mm thick veneers (see Table 2). The lower density is also reflected in the calculated Young's modulus of ply2 with  $v_n$  and  $v_c$ . Overall, the calculated parameters  $E$  and  $G$  based on the adhesive-coated veneers show the best agreement with the measured values. The parameters based on  $v_n$  show the greatest difference to the measured values. The evaluation of the solid wood parameters for the single layer must be differentiated. The difference between model and experimental data decreases with the decreasing number of layers. Due to the strong anisotropy of the material, the properties of the composite are largely determined by the fiber direction of the single layers. As the number of layers decreases, the relative proportion of single layers running in the fiber direction increases (ply1 = 52%, ply2 = 55%, ply3 = 57%). The differences between  $v_c$  and  $sw$  are mainly in the 90-direction. The results, therefore, converge in such a way that ply3 shows the lowest differences between  $v_c$  and  $sw$  when they are used as a single-layer input.

Table 6 shows the results of the bending tests; the calculated values are given in Appendix A (Table A2). To provide a context for the results, relevant literature values for comparison are regarded. It should be noted that finding suitable literature values was challenging due to the differences in wood species, veneer thickness, ply number and adhesive type in other studies. Mehar [22] has investigated beech plywood in dynamic bending tests using modal analysis. He used 7- and 11-layer plywood manufactured from 1.5 mm thick veneers that were bonded with melamine-urea-formaldehyde adhesive (MUF). Young's modules of these plywoods were found to be in the range of 10,000 to 12,000 MPa for both plate and disk load direction. (Please note that these values are taken from a diagram, so a more precise figure cannot be provided.) The findings from Mehar [22] are consistent with our own results. Wilczynski and Warmbier [25] have investigated

beech plywood with 3 and 5 plies of 1.5 mm thick veneer glued with a phenol-aldehyde adhesive. For the 3-layer plywood, they determined Young's modulus from a bending test of 15,000 MPa, and for the 5-layer plywood, 13,000 MPa. These values are higher than the results of our measurements. As described above, the mechanical properties of the plywood are largely determined by the number of layers in the fiber direction. The lower the number of layers, the higher the proportion of layers oriented in the fiber direction and Young's modulus approaches the value of the single layer (see Table 4). Cakrioglu et al. [26] have investigated 5-layer plywood made from 1.5 mm thick beech veneer (*Fagus orientalis* L.). They used a MUF and a UF adhesive for the two types of plywood. The Young's modulus of the MUF-bonded plywood was determined to be 7900 MPa and, for the UF-plywood, 7300 MPa. These results are lower than the results found in our study and in other studies from the literature. The bending strength was also determined, with the MUF-bonded plywood showing a strength of 95 MPa and the UF-bonded plywood a strength of 106 MPa. These values are in accordance with the values estimated in this study.

**Table 6.** Bending properties, mean values, and standard deviation in brackets.

| Material  | Veneer Thickness | Load Direction | Young's Modulus [MPa] | Shear Modulus [MPa] | Strength [MPa] | Failure Strain |
|-----------|------------------|----------------|-----------------------|---------------------|----------------|----------------|
| plywood 1 | 1 mm             | plate          | 9862 (621)            | 1058 (233)          | 102 (6)        | 1.9% (0.2%)    |
|           |                  | disk           | 9274 (329)            | 1073 (232)          | 88 (3)         | 1.5% (0.2%)    |
| plywood 2 | 2 mm             | plate          | 9131 (617)            | 684 (118)           | 86 (7)         | 1.6% (0.2%)    |
|           |                  | disk           | 8043 (522)            | 880 (223)           | 72 (4)         | 1.3% (0.1%)    |
| plywood 3 | 3 mm             | plate          | 10,737 (504)          | 478 (116)           | 93 (7)         | 1.5% (0.4%)    |
|           |                  | disk           | 9110 (367)            | 705 (234)           | 77 (4)         | 1.2% (0.1%)    |



**Figure 6.** Comparison of experimental data (box plots) with the calculated composite properties (displayed as dots) for 3-point bending; vn—native veneer, vc—adhesive-coated veneer, sw—solid wood.

#### 4. Conclusions

In principle, the mechanical parameters of solid wood and veneer are different due to the presence of lathe checks in the veneer. They decisively influence the properties in the 90-direction and act as a breaking point. As a result, Young's modulus of the native veneer

is only 25%–50% of that of solid wood, and for the strengths, it is only 10%–20%. In the 00-direction, the influence of the lathe checks on the parameters is minor. The difference between the parameters of solid wood and veneer is, therefore, small.

The adhesive coating of the veneer results in a clear increase in the mechanical parameters stiffness and strength compared with the native veneer. This increase depends on a number of factors (e.g., adhesive system, application rate, veneer thickness, fiber direction). For a constant adhesive application rate, the increase in parameters decreases with increasing veneer thickness. The influence of the adhesive coating is greater in the 90-direction than in the fiber direction (00-direction). For Young's modulus, there is an increase of up to 16% in the 00-direction, while in the 90-direction, the modulus of adhesive-coated veneer is 3–6 times greater than that of native veneer. The tensile strength shows an increase in the fiber direction in the range of 34%–82%, and perpendicularly, it is 2–3 times greater than that of native veneer.

To estimate the parameters of a veneer composite from the parameters of the single layers, the mechanical parameters of adhesive-coated veneer (coated with the same adhesive and using the same veneer thickness as for the composite) are the most appropriate parameters. If these parameters are not available, solid wood parameters can be used for veneer composites based on 3 mm thick veneers. Future studies should investigate the application and practicality of other laminate theories for calculating the effective properties of veneer composites to provide a better prediction. For example, shear deformation theories can be applied. However, the shear stiffness of the veneer in the thickness direction needs to be measured or realistically estimated.

For the use of veneer composites in mechanical engineering, it is necessary to consider other factors influencing the material properties (e.g., climatic properties such as temperature and humidity) when dimensioning components for their subsequent use.

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## Appendix A

The following describes the calculation of laminate's effective properties using the Classical Laminate Theory [16].

The single layer of the laminate (ply) has the following known properties:

- Thickness  $t_k$ ;

- Material properties  $E_{00}, E_{90}, G, \mu_{0090}, \mu_{9000}$ .

The following parameters are calculated successively to obtain the laminate's effective properties.

$$\mu_{9000} = \frac{E_{90}}{E_{00}} \cdot \mu_{0090} \quad (\text{A1})$$

Reduced stiffness matrix  $\underline{\underline{Q}}$  for an orthotropic layer:

$$\underline{\underline{Q}} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}$$

with

$$\begin{aligned} Q_{11} &= \frac{E_{00}}{1 - \mu_{0090} \cdot \mu_{9000}}, \\ Q_{22} &= \frac{E_{90}}{1 - \mu_{0090} \cdot \mu_{9000}}, \\ Q_{12} &= \frac{\mu_{0090} \cdot E_{90}}{1 - \mu_{9000} \cdot \mu_{0090}}, \\ Q_{66} &= G \end{aligned} \quad (\text{A2})$$

Transformation of the reduced stiffnesses depending on the fiber angle  $\theta$  for each ply related to the main orientations in the composite:

$$\bar{\underline{\underline{Q}}} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 \\ 0 & 0 & \bar{Q}_{66} \end{bmatrix}$$

with

$$\begin{aligned} \bar{Q}_{11} &= Q_{11} \cos^4 \theta + 2(Q_{12} + 2Q_{66}) \cos^2 \theta \sin^2 \theta + Q_{22} \sin^4 \theta, \\ \bar{Q}_{22} &= Q_{11} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \cos^2 \theta \sin^2 \theta + Q_{22} \cos^4 \theta, \\ \bar{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66}) \cos^2 \theta \sin^2 \theta + Q_{12} (\cos^4 \theta + \sin^4 \theta), \\ \bar{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) \cos^2 \theta \sin^2 \theta + Q_{66} (\cos^4 \theta + \sin^4 \theta) \end{aligned} \quad (\text{A3})$$

Coordinates of a ply no.  $k$  (see Figure A1):

$$\begin{aligned} z_{k-1} &= z_{m,k} - \frac{t_k}{2}, \\ z_k &= z_{m,k} + \frac{t_k}{2}, \\ z_k - z_{k-1} &= t_k, \\ z_k^3 - z_{k-1}^3 &= t_k \left( 3z_{m,k}^2 + \frac{1}{4} \right) \end{aligned} \quad (\text{A4})$$

ABD matrix of a symmetrical, orthotropic cross-ply laminate ( $0^\circ/90^\circ$  stacking):

$$\begin{bmatrix} \underline{\underline{A}} & \underline{\underline{B}} \\ \underline{\underline{B}} & \underline{\underline{D}} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & 0 & 0 & 0 \\ A_{12} & A_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{11} & D_{12} & 0 \\ 0 & 0 & 0 & D_{12} & D_{22} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{66} \end{bmatrix} \quad (\text{A5})$$

$\underline{\underline{A}}$  is called the extensional stiffness matrix related to the normal and shear stresses,  $\underline{\underline{B}}$  is the coupling stiffness matrix and  $\underline{\underline{D}}$  is the bending stiffness matrix.  $\underline{\underline{A}}$  and  $\underline{\underline{D}}$  is defined as:

$$\begin{aligned} A_{ij} &= \sum_{k=1}^N [\bar{Q}_{ij}]^k (z_k - z_{k-1}) \\ D_{ij} &= \frac{1}{3} \sum_{k=1}^N [\bar{Q}_{ij}]^k (z_k^3 - z_{k-1}^3) \end{aligned} \quad (\text{A6})$$

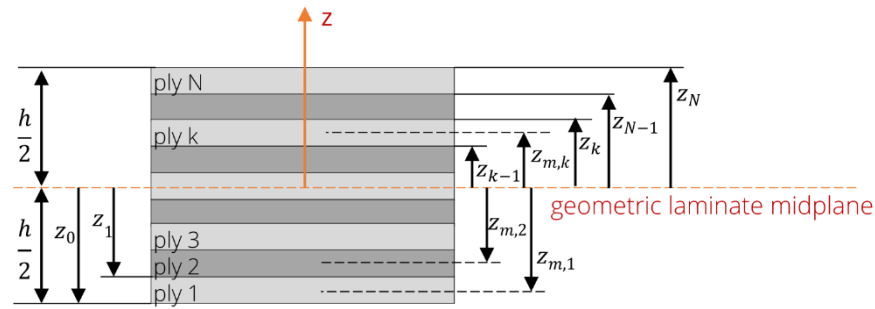


Figure A1. Cross-section of the laminate.

Effective laminate elastic engineering constants can be calculated by using A:

$$\begin{aligned} E_{11} &= \frac{1}{h} \left( A_{11} - \frac{A_{12}^2}{A_{22}} \right), \\ E_{22} &= \frac{1}{h} \left( A_{22} - \frac{A_{12}^2}{A_{11}} \right), \\ G_{12} &= \frac{A_{66}}{h}, \\ \mu_{12} &= \frac{A_{12}}{A_{22}} \end{aligned} \tag{A7}$$

Effective laminate flexural elastic engineering constants can be calculated by using D:

$$\begin{aligned} E_{11,f} &= \frac{12}{h^3} \left( D_{11} - \frac{D_{12}^2}{D_{22}} \right), \\ E_{22,f} &= \frac{12}{h^3} \left( D_{22} - \frac{D_{12}^2}{D_{11}} \right), \\ G_{12,f} &= \frac{12}{h^3} D_{66}, \\ \mu_{12,f} &= \frac{D_{12}}{D_{22}} \end{aligned} \tag{A8}$$

Table A1 shows an example of the calculation of the effective properties of a 21-layer plywood using the properties of a 1 mm coated veneer.

Table A1. Example calculation of laminate effective properties using classical laminate theory.

| single layer | material: 1 mm veneer, coated |          |       | $\overline{Q} = \begin{bmatrix} 16127 & 980 & 0 \\ 980 & 2228 & 0 \\ 0 & 0 & 903 \end{bmatrix}$ |          |          |          |          |                 |                     |
|--------------|-------------------------------|----------|-------|-------------------------------------------------------------------------------------------------|----------|----------|----------|----------|-----------------|---------------------|
|              | thickness $t_k$ :             | 0.91     | mm    |                                                                                                 |          |          |          |          |                 |                     |
| stacking     | no.                           | $\theta$ | $t_k$ | $z_{m \cdot k}$                                                                                 | $Q_{11}$ | $Q_{12}$ | $Q_{22}$ | $Q_{66}$ | $z_k - z_{k-1}$ | $z_k^3 - z_{k-1}^3$ |
|              | 1                             | 0        | 0.91  | −9.1                                                                                            | 16,127   | 980      | 2228     | 903      | 0.91            | 226.3               |
|              | 2                             | 90       | 0.91  | −8.19                                                                                           | 2228     | 980      | 16,127   | 903      | 0.91            | 183.3               |
|              | 3                             | 0        | 0.91  | −7.28                                                                                           | 16,127   | 980      | 2228     | 903      | 0.91            | 144.9               |
|              | 4                             | 90       | 0.91  | −6.37                                                                                           | 2228     | 980      | 16,127   | 903      | 0.91            | 111.0               |
|              | 5                             | 0        | 0.91  | −5.46                                                                                           | 16,127   | 980      | 2228     | 903      | 0.91            | 81.6                |
|              | 6                             | 90       | 0.91  | −4.55                                                                                           | 2228     | 980      | 16,127   | 903      | 0.91            | 56.7                |
|              | 7                             | 0        | 0.91  | −3.64                                                                                           | 16,127   | 980      | 2228     | 903      | 0.91            | 36.4                |
|              | 8                             | 90       | 0.91  | −2.73                                                                                           | 2228     | 980      | 16,127   | 903      | 0.91            | 20.6                |
|              | 9                             | 0        | 0.91  | −1.82                                                                                           | 16,127   | 980      | 2228     | 903      | 0.91            | 9.3                 |
|              | 10                            | 90       | 0.91  | −0.91                                                                                           | 2228     | 980      | 16,127   | 903      | 0.91            | 2.5                 |
|              | 11                            | 0        | 0.91  | 0                                                                                               | 16,127   | 980      | 2228     | 903      | 0.91            | 0.2                 |
|              | 12                            | 90       | 0.91  | 0.91                                                                                            | 2228     | 980      | 16,127   | 903      | 0.91            | 2.5                 |
|              | 13                            | 0        | 0.91  | 1.82                                                                                            | 16,127   | 980      | 2228     | 903      | 0.91            | 9.3                 |
|              | 14                            | 90       | 0.91  | 2.73                                                                                            | 2228     | 980      | 16,127   | 903      | 0.91            | 20.6                |
|              | 15                            | 0        | 0.91  | 3.64                                                                                            | 16,127   | 980      | 2228     | 903      | 0.91            | 36.4                |

Table A1. Cont.

|                                                           |                                                                                                                                                  |                                                  |      |        |        |                     |         |                   |        |         |  |  |
|-----------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|------|--------|--------|---------------------|---------|-------------------|--------|---------|--|--|
| stacking                                                  | 16                                                                                                                                               | 90                                               | 0.91 | 4.55   | 2228   | 980                 | 16,127  | 903               | 0.91   | 56.7    |  |  |
|                                                           | 17                                                                                                                                               | 0                                                | 0.91 | 5.46   | 16,127 | 980                 | 2228    | 903               | 0.91   | 81.6    |  |  |
|                                                           | 18                                                                                                                                               | 90                                               | 0.91 | 6.37   | 2228   | 980                 | 16,127  | 903               | 0.91   | 111.0   |  |  |
|                                                           | 19                                                                                                                                               | 0                                                | 0.91 | 7.28   | 16,127 | 980                 | 2228    | 903               | 0.91   | 144.9   |  |  |
|                                                           | 20                                                                                                                                               | 90                                               | 0.91 | 8.19   | 2228   | 980                 | 16,127  | 903               | 0.91   | 183.3   |  |  |
|                                                           | 21                                                                                                                                               | 0                                                | 0.91 | 9.1    | 16,127 | 980                 | 2228    | 903               | 0.91   | 226.3   |  |  |
| composite                                                 | $\begin{bmatrix} \underline{\underline{A}} & \underline{\underline{B}} \\ \underline{\underline{B}} & \underline{\underline{D}} \end{bmatrix} =$ |                                                  |      | 181705 | 18730  | 0                   | 0       | 0                 | 0      |         |  |  |
|                                                           |                                                                                                                                                  |                                                  |      | 18730  | 169056 | 0                   | 0       | 0                 | 0      |         |  |  |
|                                                           |                                                                                                                                                  |                                                  |      | 0      | 0      | 17256               | 0       | 0                 | 0      |         |  |  |
|                                                           |                                                                                                                                                  |                                                  |      | 0      | 0      | 0                   | 5916425 | 570281            | 0      |         |  |  |
|                                                           |                                                                                                                                                  |                                                  |      | 0      | 0      | 0                   | 570281  | 4763186           | 0      |         |  |  |
|                                                           |                                                                                                                                                  |                                                  |      | 0      | 0      | 0                   | 0       | 0                 | 525403 |         |  |  |
|                                                           |                                                                                                                                                  | thickness h= 19.11 mm                            |      |        |        |                     |         |                   |        |         |  |  |
|                                                           |                                                                                                                                                  | Effective laminate elastic engineering constants |      |        |        |                     |         |                   |        |         |  |  |
|                                                           |                                                                                                                                                  | E <sub>11</sub> =                                |      | 9400   |        | MPa                 |         | μ <sub>12</sub> = |        | 0.11    |  |  |
|                                                           |                                                                                                                                                  | E <sub>22</sub> =                                |      | 8745   |        | MPa                 |         | G <sub>12</sub> = |        | 903 MPa |  |  |
| Effective laminate flexural elastic engineering constants |                                                                                                                                                  |                                                  |      |        |        |                     |         |                   |        |         |  |  |
| E <sub>11·f</sub> =                                       |                                                                                                                                                  | 10,056                                           |      | MPa    |        | μ <sub>12·f</sub> = |         | 0.12              |        |         |  |  |
| E <sub>22·f</sub> =                                       |                                                                                                                                                  | 8096                                             |      | MPa    |        | G <sub>12·f</sub> = |         | 903 MPa           |        |         |  |  |
|                                                           |                                                                                                                                                  |                                                  |      |        |        |                     |         |                   |        |         |  |  |

Table A2. Calculation results of laminate effective properties using classical laminate theory, vn—native ve-neer, vc—adhesive-coated veneer, sw—solid wood.

| Material  | Layer Thickness | No. of Layers | Single Layer Material | Effective Laminate Elastic Engineering Constants |                       |                 |                       |                         |                         |                   |                         |
|-----------|-----------------|---------------|-----------------------|--------------------------------------------------|-----------------------|-----------------|-----------------------|-------------------------|-------------------------|-------------------|-------------------------|
|           |                 |               |                       | E <sub>11</sub> [MPa]                            | E <sub>22</sub> [MPa] | μ <sub>12</sub> | G <sub>12</sub> [MPa] | E <sub>11·f</sub> [MPa] | E <sub>22·f</sub> [MPa] | μ <sub>12·f</sub> | G <sub>12·f</sub> [MPa] |
| plywood 1 | 0.91 mm         | 21            | vn                    | 7297                                             | 6670                  | 0.028           | 500                   | 7922                    | 6044                    | 0.031             | 500                     |
|           |                 |               | vc                    | 9400                                             | 8745                  | 0.111           | 903                   | 10,056                  | 8096                    | 0.120             | 903                     |
|           |                 |               | sw                    | 8533                                             | 7839                  | 0.049           | 722                   | 9227                    | 7145                    | 0.053             | 722                     |
| plywood 2 | 1.85 mm         | 11            | vn                    | 6648                                             | 5592                  | 0.026           | 439                   | 7695                    | 4544                    | 0.031             | 439                     |
|           |                 |               | vc                    | 7731                                             | 6628                  | 0.076           | 615                   | 8823                    | 5533                    | 0.091             | 615                     |
|           |                 |               | sw                    | 8850                                             | 7523                  | 0.051           | 722                   | 10,164                  | 6206                    | 0.061             | 722                     |
| plywood 3 | 2.77 mm         | 7             | vn                    | 8217                                             | 6220                  | 0.018           | 415                   | 10,173                  | 4263                    | 0.027             | 415                     |
|           |                 |               | vc                    | 9014                                             | 7155                  | 0.106           | 598                   | 10,824                  | 5329                    | 0.142             | 598                     |
|           |                 |               | sw                    | 9228                                             | 7143                  | 0.053           | 722                   | 11,268                  | 5099                    | 0.075             | 722                     |

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