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APPLICABILITY OF VARIOUS WOOD SPECIES IN GLUED LAMINATED TIMBER - PARAMETER STUDY ON DELAMINATION RESISTANCE AND SHEAR STRENGTH

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ABSTRACT: In a current research project the gluability of four European timber species and their applicability in glued laminated timber is investigated. The influence of different processing parameters on the adhesive bonding is assessed with regard to shear strength and delamination resistance. Furthermore, microscopy-based investigations revealed information about the penetration of the adhesive into the wood substrate, the topology of the glue line for different adhesive types and about the surface property of the wood. A deeper understanding of the interaction between wood species, adhesives and processing parameters was acquired.

KEYWORDS: gluability of soft- and hardwood, glued laminated timber, shear strength, delamination resistance

1 INTRODUCTION

Structural timber made of spruce (*Picea abies*) has been dominating the woodworking industry in Central Europe for decades. However, given the fact that the uniformly structured conifer stands are extremely vulnerable to climate change, the forest conversion program in Germany is working on turning monocultures into species-rich and climate-tolerant mixed forests [1]. Under this circumstance, the material supply of our forests is going to change in the coming future [2].

To adapt to these changes, the woodworking industry has been showing great interest in adjusting their production by utilizing timber species which were disregarded in the past due to different reasons. However, experience has shown that lack of material knowledge and accuracy in manufacturing will lead to insufficient adhesive bonding, which might be sometimes fatal. Investigations pointed out that, failures in the vicinity of glue lines were one of the main reasons for damaged structures [3].

In the recent past, various studies on the applicability of timber species other than spruce in engineered wood products, such as glued laminated timber (GLT) were carried out. Especially beech (*Fagus silvatica*), the hardwood timber species with the most likely increasing availability in Germany, and ash (*Fraxinus excelsior*) have drawn a lot of attention. This is owed to their high strength and stiffness properties. Softwood species like larch (*Larix decidua*) and Douglas fir (*Pseudotsuga menziesii*) are also gaining in importance due to their high durability in outside conditions.

The main focus in utilizing these timber species has to be laid on their gluability. According to Vick [4] the gluing characteristic of wood is essentially affected by factors such as density and extractives. The bonding of high density woods like ash or beech is usually considered to be problematic. One reason is that their thick cell walls and small lumens inhibit a deep penetration of the glue, which is essential for the formation of mechanical interlocking. Another point is that the dimensional changes due to varying wood moisture content will create severe mechanical stresses along the glue line and might rupture the bond between adhesive and wood.

The extractives and their chemical complexity are other crucial factors, which influence the performance of a glue line. Prevailing opinion indicates that, during drying and storage various water-soluble and steam-volatile extractives will diffuse to the wood surface and form a so-called chemical weak boundary layer. Hse and Kuo [5] explained that the deposits of extractives on the surface could block the reaction sites on wood surfaces and consequently prevent the wood surfaces from true wetting by the adhesive. It is therefore normally recommended for the manufacture to remove the surface layer prior to the gluing process by light planning. In order to prevent recontamination of the freshly exposed surface, the interval

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between planning and gluing should not exceed 24 hours. Studies on the influence of different surface processing methods on the wettability of wood surface showed that, the wettability of freshly planned wood surfaces could be improved even further, when they are slightly sanded with sand paper [6].

In a current research project the gluability of four European timber species was investigated. Their application along with four selected adhesives in GLT was evaluated. At the beginning of this project, various physical and chemical properties of each individual species were examined, which might affect the adhesive bonding of wood. The performance of these wood species in combinations with different adhesives was assessed by means of tensile shear tests according to EN 302-1 [7]. Based on the knowledge achieved on the laboratory scale, parameter studies were carried out. Processing conditions such as the time span between surface preparations and gluing, as well as the surface processing methods were varied. The influences of these processing parameters on the delamination behavior and shear strength of adhesive bonds are going to be evaluated both qualitatively and quantitatively.

2 MATERIALS AND METHODS

2.1 WOOD AND ADHESIVES

The study was performed with ash (*Fraxinus excelsior*), beech (*Fagus silvatica*), larch (*Larix decidua*), and as reference spruce (*Picea abies*). Flat sawn timber with a thickness of approximately 40 mm was provided by industry partner or purchased from local timber merchant and cut into lamellas with a length of around 600 mm and conditioned in standard climate conditions at 20°C and 65 % relative humidity for several months before use. The annual growth rings of each lamella are at an angle less than 45° to the surface. Their mean density at 12 percent moisture content and moisture content before applying glue are listed in Table 1.

Table 1: *Density and moisture content of the timber species used in the present study*

Species	Density (kg/m^3)	Moisture content (%)
ash	638	10,8
beech	728	8.1
larch	576	12.2
spruce	414	11.8

Four commercially available adhesives were used, which have been approved according to standard EN 301 [8] for the production of load-bearing timber structures in both interior and exterior applications. The product name and type of these adhesives are summarized in Table 2:

Table 2: *Product name and type of adhesives used in the present study*

Product name	Hardener	Adhesive family
Aerodux 185	HRP 155	PRF
Prefere 6151	Prefere 6651	EPI
Kauramin Leim 690	Hardener 1690	MUF
Jowapur 686.60	-	PUR

2.2 GLUING OF TEST BEAMS

Six lamellas with a length of 500 mm, a width of 150 mm, and a thickness of 30 mm were bonded in laboratory at 20°C and 65 % relative humidity. The requirements on the test beams are in accordance with the specifications in EN 302-2 [9]. The bonding parameters, which were specified after consulting the adhesive manufactures, are shown in Table 3

For each combination of wood species and adhesive, three test beams were manufactured. The bonding surfaces were processed with different methods. The lamellas of the first two beams were produced by a conventional surface planning machine or a wide belt sanding machine with a 100 grit sand paper. The time span between surface preparation and gluing was less than 5 hours. The other six lamellas of the third test beam were stored after planning before bonding in standard climate conditions for seven days.

Table 3: *Bonding parameters of adhesives (S-softwoods, H-hardwoods)*

	PRF	EPI	MUF	PUR
Mixing ration	100/20	100/15	100/50	-
Adhesive spread in g/m^2	450	250	450	200
Open assembly time in min	5	5	5	20
Closed assembly time in min	15	10	25 (S) 30 (H)	5
Pressing time in h/min	4	65 min (S) 2 h (H)	8 h	2 h 15 min (S) 4 h 30 min (H)

The adhesives were spread manually with a spatula on the lamellas in a one-side application. The chosen pressure was 0.8 N/mm^2 for the softwoods and 1.2 N/mm^2 for the hardwoods. After pressing the test beams were stored at 20°C and 65 % for at least seven days prior to further processing.

As illustrated in Figure 1, test specimens for the delamination test according to EN 391 [10], block shear test according to EN 392 [11] and microscopic analysis were cut. From each beam, two delamination test specimens with a thickness of 75 mm were sawn out. Their distance to the left and right edges of the beam was kept at a minimum of 50 mm. In addition, six specimens with a cross section of 50 mm x 50 mm and all five glue lines of the beam were prepared from the middle of the beam for the block shear test. For further preparation and microscopic analysis, two specimens with the cross section of the beam and a thickness of 15 mm were sliced.

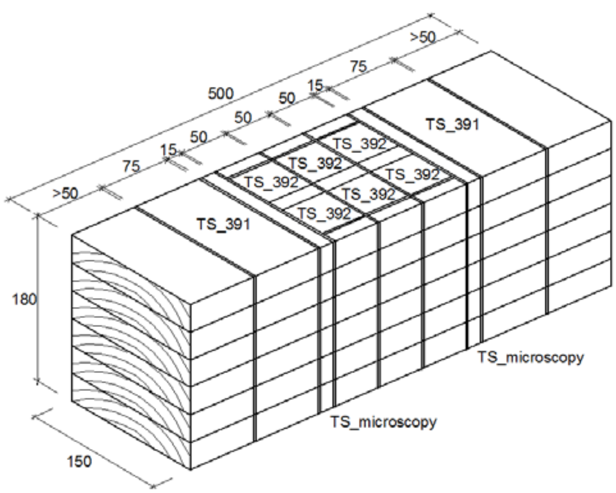

Figure 1: *Geometry of test beams (in mm)*

2.3 DELAMINATION TEST

The delamination tests were carried out with a drying plant (ULWA-E, Ulrich Lübbert Warenhandel GmbH & Co. KG) according to standard EN 391 [10], method A, which consists of two cycles of cold water soaking and a drying procedure afterwards. During soaking the specimens were evacuated (5 min) and immersed in water under defined conditions of pressure (one hour). The vacuum/pressure treatment was repeated once. After that, the specimens were dried at 65±5°C and 15 % relative humidity for 22 hours.

During the accelerated exposure to water and heat the moisture gradient in the wood causes high stresses in the bond line. Delamination (glue line opening) occurs, when the local stress exceeded the strength of the bonded joint. After all the treatments, the length of the delamination on both end grain surfaces of each specimen was recorded and measured within one hour.

The performance of the adhesive bonds was evaluated by the overall percentage of delamination of each test specimen (1) and the maximum percentage of delamination of each single glue line (2). They were calculated separately as follows:

$$\frac{l_{tot,delam}}{l_{tot,glue\,line}} \times 100 \quad \text{in \%} \qquad (1)$$

$$\frac{l_{max,delam}}{2l_{glue\ line}} \times 100 \quad \text{in \%} \qquad (2)$$

2.4 BLOCK SHEAR TEST

The shear strength of the adhesive bonds was determined by means of block shear test according to EN 392 [11]. Prior to the shear tests, two of the six test specimens were subjected to one of the following treatments defined in EN 302-1 [7]:

A1 without further conditioning

A2 4 days in cold water

A4 6 hours in boiling and 2 hours in cold water

The test was performed right after the treatments by using a universal testing machine (Zwick GmbH & Co. KG) with a constant loading rate of 5 m/min. The shearing force was applied parallel to the grain direction. The distance between the glue line and the sheared plane did not exceed 1 mm.

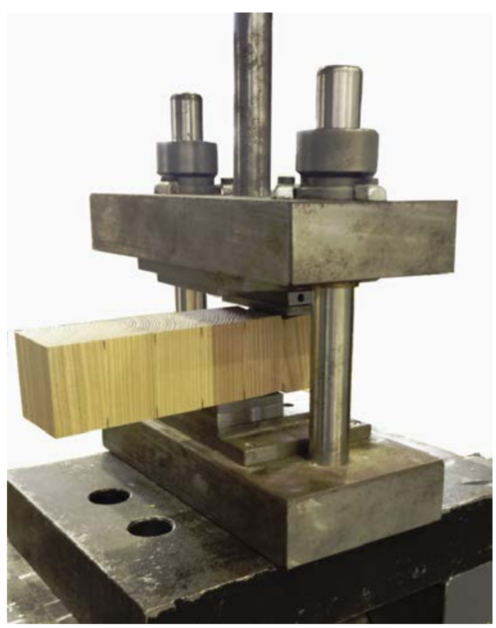

Figure 2: *Device for the block shear test*

The shear strength was calculated from the load at failure F_{max} and the cross-sectional area A of the test specimen as follows:

$$\frac{F_{max}}{A} \quad \text{in N/mm}^2 \tag{3}$$

The percentages of wood failure in the bond lines were estimated and rounded to the nearest 5 %.

2.5 MICROSCOPIC ANALYSIS

A quantitative and qualitative assessment of the adhesive bond was performed separately using two types of microscope.

The glue line thickness was measured using a reflected light microscope (Leica MZ FLIII) with integrated image analysis system (Leica Application Suite 4.1.0). As illustrated in Figure 3 the top and bottom glue lines of each beam were taken for the measurements. On each glue line, four measuring points were chosen (10 mm and 50 mm from left and right ends of the glue line). Three measuring values are recorded at each point.

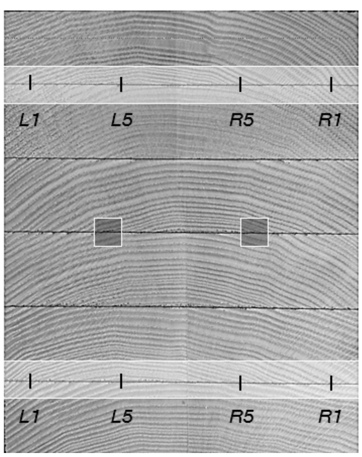

Figure 3: *Cross section of the test beam*

The penetration behavior of the adhesives was analyzed qualitatively by using a transmitted light microscope (Zeiss Axiophot), which includes image processing software (Axio Vision 4.8.3.0). Microtome cuts with a thickness of about 20 µm were obtained from the middle glue line and stained with safranin.

3 RESULTS

3.1 DELAMINATION TEST

The requirements given in EN 386 [12], which are mandatory for quality control of the glulam production, were criteria for the quality assessment of adhesive bonding.

According to EN 386 [12] the maximum delamination of one specimen should not exceed 5 % and, in addition, the maximum delamination of one single glue line should be below 40 %. The results of the delamination test are summarized in Table 4.

In order to give an overview of the performance of each adhesive solely the results of the category “specimen produced with fresh planned surfaces (P0)” are presented in Figure 4. The test specimens bonded with different adhesives showed a very wide range of resistance to delamination. The best results were achieved, as assumed, by the PRF adhesive. With a mean delamination of less than 5 %, the PRF adhesive performed well with all the timber species involved. Bonded with the MUF adhesive, the two softwood species larch and spruce provided sufficient resistance to delamination. However the combination of MUF with ash or beech was not satisfactory. With a mean delamination of 16.8 % and 5.8 %, they did not meet the requirements. Regarding the EPI and PUR adhesives only spruce has shown delamination resistant bonds. All the other tested timber species failed the test. High delamination values of more than 80 % were obtained due to the high stresses caused by moisture changes.

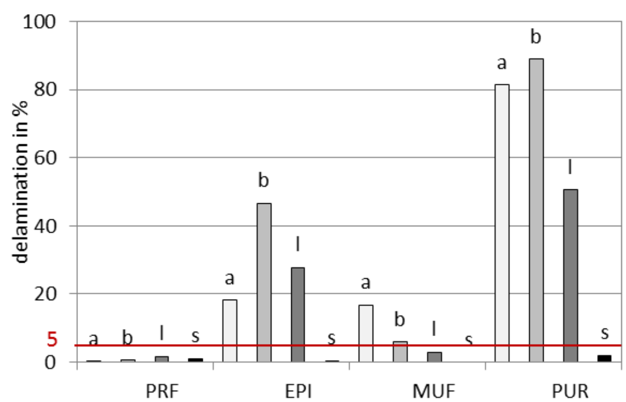

Figure 4: *Mean delamination of the test specimens produced with different adhesives (a-ash; b-beech; l-larch; s-spruce)*

The results of the delamination tests in dependence of different surface conditions are graphically represented in Figure 5. As expected, sufficient results were obtained with all the specimens made of spruce. The outstanding gluability of spruce leaded to high delamination resistance that was barely affected by the condition of the bonding surface. Therefore, no further tests regarding the gluability of wood surface after 7 days of storage were carried out with spruce. The delamination of the adhesive bonds was increased significantly after sanding except for the two hardwood species glued with PUR adhesive.

Table 4: *Results of the delamination test according to EN 391, method A (P0-planned, fresh; S0-sanded, fresh; P7-planned, 7 days of storage)*

Adhesives	Species	Surface conditions	Delamination of specimen (%)	Delamination of glue line (%)	
				Min	Max
PRF	ash	P0	0.1	0.0	0.9
		S0	0.1	0.0	0.6
		P7	4.3	0.0	13.8
	beech	P0	0.5	0.0	1.6
		S0	0.4	0.0	2.8
		P7	1.3	0.0	3.4
	larch	P0	1.7	0.0	5.5
		S0	7.1	1.6	21.3
		P7	2.0	0.0	4.5
	spruce	P0	1.0	0.0	3.7
		S0	0.5	0.0	3.0
EPI	ash	P0	18.2	6.3	64.4
		S0	49.2	25.0	85.6
		P7	16.1	2.5	21.6
	beech	P0	46.7	25.3	78.4
		S0	75.8	44.4	94.7
		P7	39.5	16.9	56.9
	larch	P0	27.8	3.9	63.9
		S0	89.9	80.6	94.8
		P7	14.6	2.9	31.6
	spruce	P0	0.4	0.0	2.3
		S0	8.0	0.0	32.3
MUF	ash	P0	16.8	0.9	24.7
		S0	9.5	1.9	19.1
		P7	27.2	7.8	38.4
	beech	P0	5.8	1.9	10.0
		S0	7.4	0.0	13.8
		P7	6.3	1.6	13.4
	larch	P0	2.9	0.0	8.1
		S0	10.4	0.0	37.1
		P7	12.2	3.2	34.5
	spruce	P0	0.0	0.0	0.0
		S0	4.8	0.0	15.7
PUR	ash	P0	81.4	56.3	100.0
		S0	29.0	2.5	73.4
		P7	59.5	23.8	100.0
	beech	P0	88.9	79.4	100.0
		S0	54.5	29.7	81.6
		P7	61.5	11.3	93.4
	larch	P0	50.7	19.0	72.9
		S0	87.6	63.5	96.8
		P7	37.6	14.5	66.1
	spruce	P0	2.0	0.0	4.7
		S0	0.1	0.0	1.0

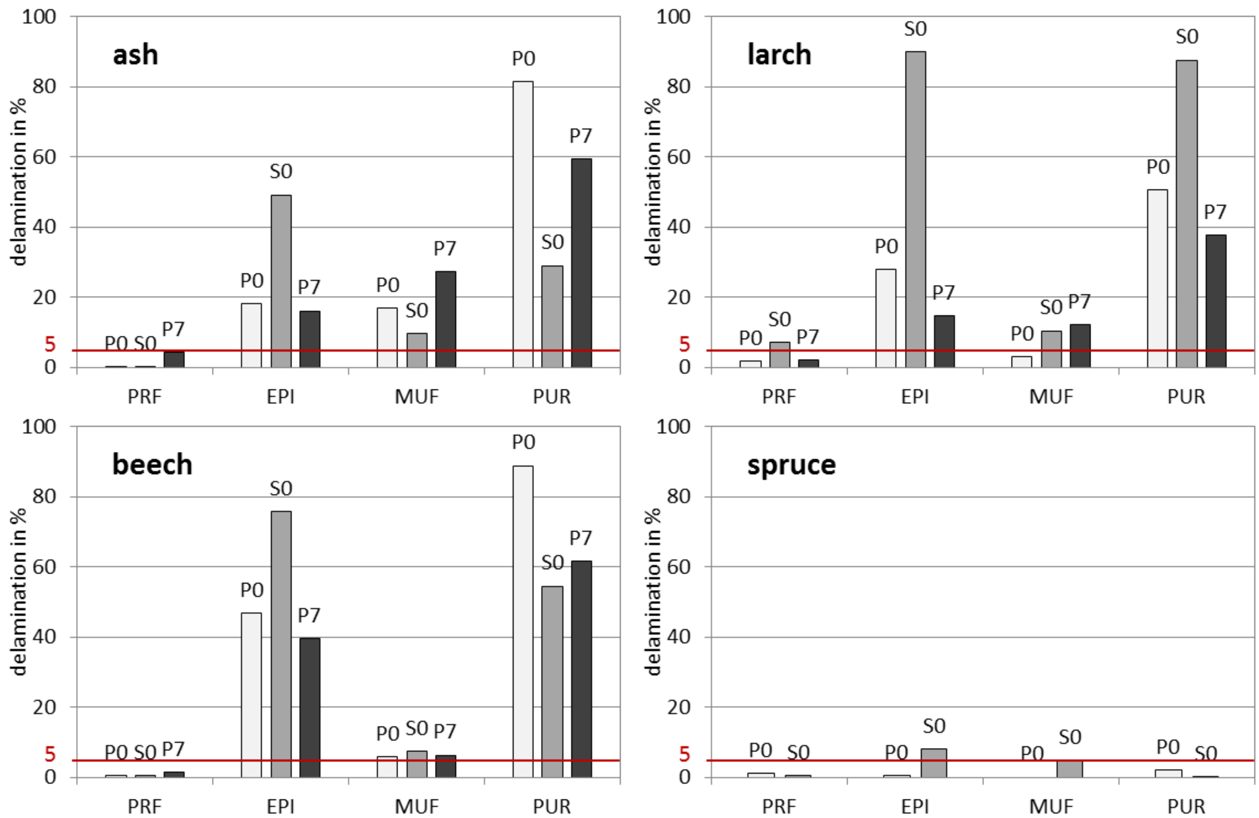

Figure 5: *Mean delamination of the test specimens made of four different timber species (P0-planned, fresh; S0-sanded, fresh; P7-planned, 7 days of storage)*

A negative influence of the surface aging resulted from the 7 days of storage before gluing on the delamination resistance was shown by ash and larch, bonded with the PRF and MUF adhesives. The delamination of the specimens produced with MUF was even increased for about 70 %. However, the delamination resistance of all the members bonded with EPI and PRF was increased.

3.2 BLOCK SHEAR TEST

The requirements regarding the shear strength of the adhesive bond are taken from EN 386 [12]. As required in the standard the minimal shear strength of each glue joint must be at least 6.0 N/mm^2. The minimum wood failure in the bond line refers to the shear strength f_v is calculated as follows:

$$144 - (9 \cdot f_v) \qquad \text{in \%} \tag{4}$$

The results of the block shear test for test specimens with a fresh planned surface after treatment A1 are summerized in Figure 6. Wood failure of over 70 % and a high shear strenth of more than 6.0 N/mm^2 was achieved by all the combinations of timber species and adhesives. The two hardwood species showed good performance regarding shear strength. The shear strength of the bonds produced with beech had even exceeded 18 N/mm^2, which is three times of the minimum value requied by EN 386 [12].

In Figure 7 the results of the block shear test for test specimens which has undergone treatments A2 and A4 were illustrated. After hours/days of exposure to water and/or heat the shear strength of all specimens were reduced. At the mean time, the difference between timber species was minimized.

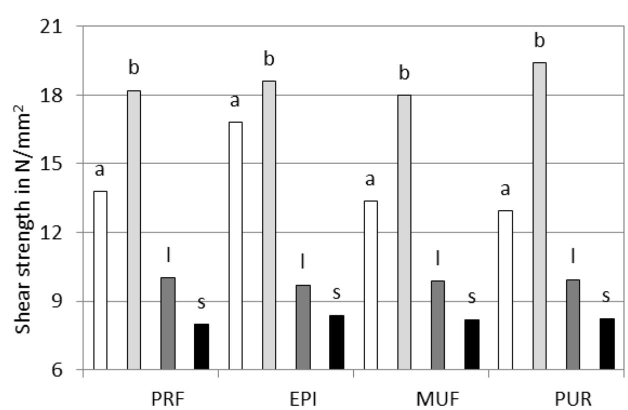

Figure 6: *Mean shear strength of the test specimens without further conditioning (a-ash; b-beech; l-larch; s-spruce)*

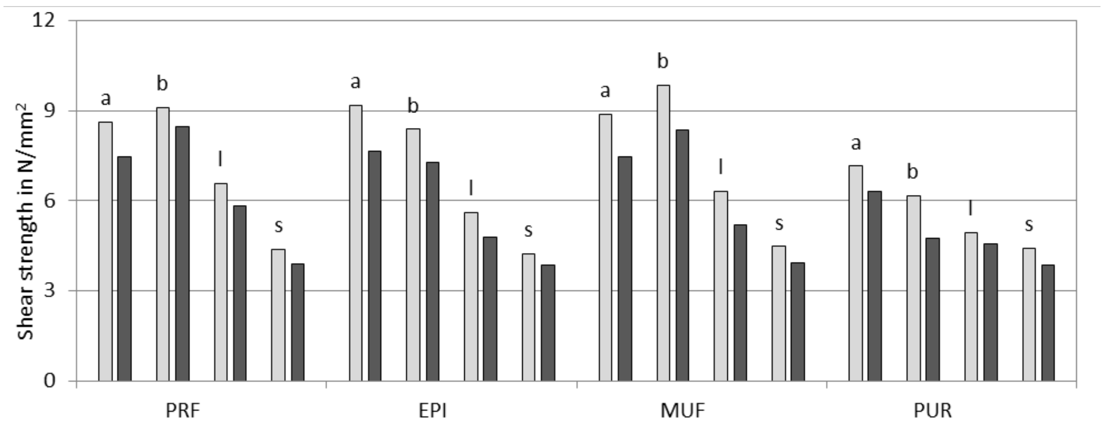

Figure 7: *Mean shear strength of the test specimens after treatment A2 (light grey bars) and A4 (dark grey bars) (a-ash; b-beech; l-larch; s-spruce)*

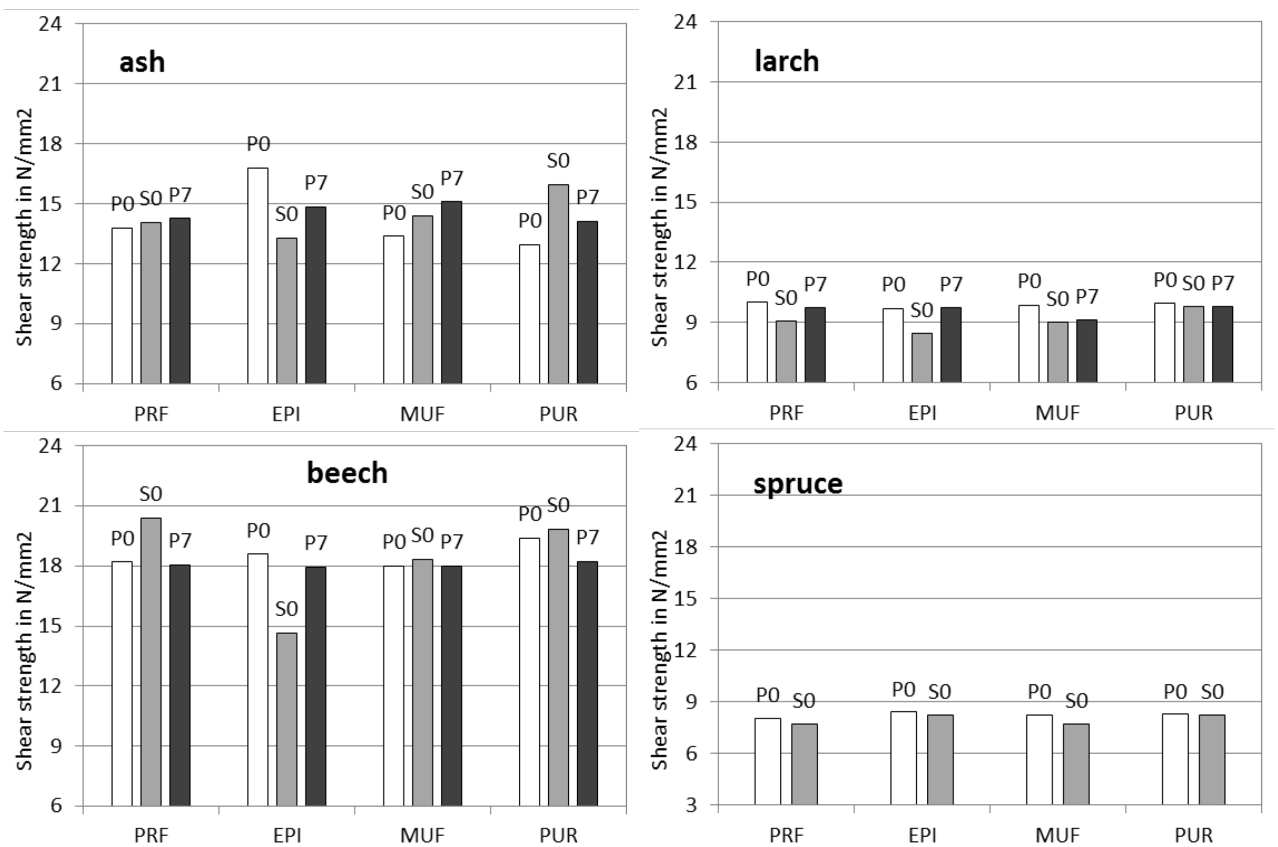

Figure 8: *Mean shear strength of the test specimens produced with different timber species (P0-planned, fresh; S0-sanded, fresh; P0-planned, 7 days of storage*)

The results of the block shear test in dependence of different surface conditions are shown in Figure 8. In contrast to the delamination resistance the sanding procedure presented different impacts on the shear strength of adhesive bonds produced with different timber species. Through sanding, the shear strength of the two hardwood species bonded with PRF, MUF and PUR was increased for about 2 % to 23 %. However, the shear strength of the EPI bond line was reduced for about 20 %. The adhesive bonds were weakened by sanding regarding softwood species. The reduction of the shear strength ranged from 0.1 % to 13 %.

The influence of the surface ageing on the shear strength of the glue lines showed no distinct pattern.

3.3 MICROSCOPIC ANALYSIS

The impact of the surface conditions on the glue line thickness were revealed in Figure 9. The thicknesses of the glue lines formed with freshly planned bonding surfaces ranged from 0.06 mm to 0.15 mm. In comparison, higher glue line thicknesses were measured with all the specimens produced with sanded surfaces.

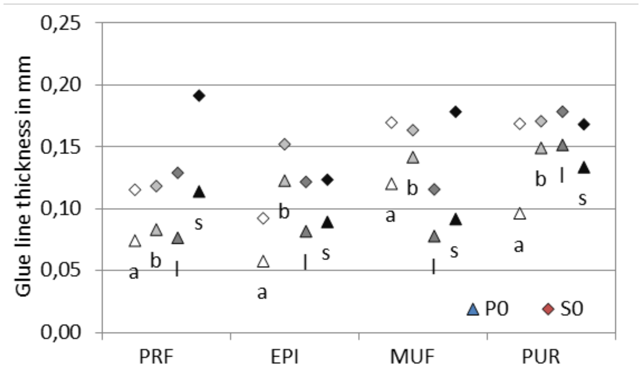

Figure 9: *Mean glue line thickness of the test specimens produced with different timber species (a-ash; b-beech; l-larch; s-spruce)*

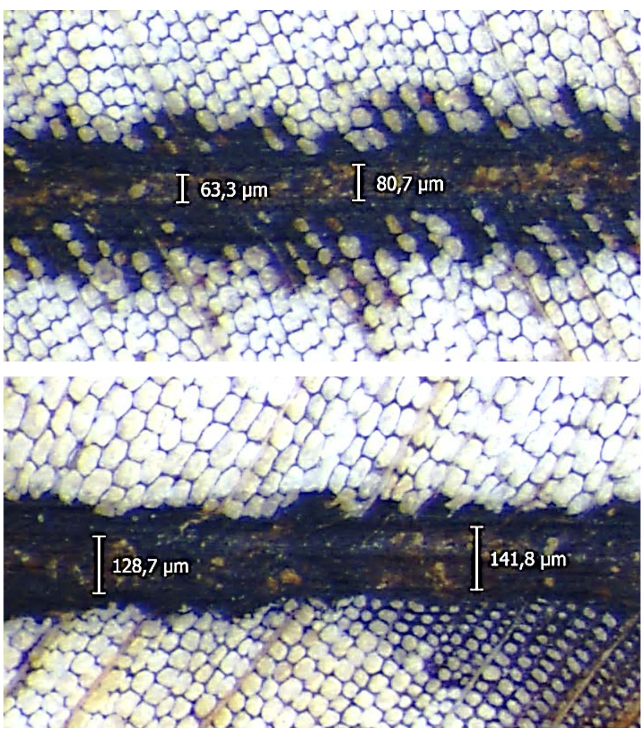

Figure 10: *Microscopic photographs of the glue lines formed by PRF adhesive on planned (top) and sanded (bottom) surfaces of larch*

The microscopic photographs in Figure 10 show that the penetration of the adhesive was inhibited by the compressed wood cells of the sanded surface. For the planned surfaces, deep penetration with a depth of up to 200 µm was measured. In contrast, the trace of penetration into the wood cells could barely be found for the sanded surfaces.

4 DISCUSSION

4.1 IMPACT OF SURFACE PROCESSING METHODES

During the industrial production of glued laminated timber, planning is well accepted as the standard surface processing procedure. In a recent study [6], the results of the contact angel measurement indicated that the sanded wood surfaces could be wetted more easily by water-based adhesives. Under this circumstance, it was assumed that, instead of planning, superior adhesive bonding could be obtained through sanding. However, this assumption was not confirmed.

The delamination resistance of the adhesive bonds was reduced significantly by sanding while gluing all four timber specimens. Microscopy-based analysis revealed that sanding inhibited all the adhesives from penetrating. The lack of mechanical interlocking might be the cause of the decrease of deamination resistance.

The impact of the surface aging resulted from the 7 days of storage before gluing on the shear strength of adhesive bonds produced with different species should be discussed separately. For softwood with low density, the sanding procedure had proved to be unfavorable. On the contrary higher strength was achieved when it came to high density wood species (excluding bonding with EPI adhesive). The different results might be the consequences of the inappropriate processing parameters applied while sanding.

The surfaces involved in this study were produced by a wide belt sanding machine with a feed speed of 7 m/min, a sanding belt speed of 17 m/s and sand paper, which is recommended in EN 302-1 for the bonding surface preparation. The pressure (5 bars) on the wood surface had proved to cause severer compression of the wood cells. Compared with its impact on hardwood, the damage on the low density wood species is even higher.

4.2 IMPACT OF SURFACE AGING

The importance of a short time gap between surface preparation and gluing has been mentioned numerous times in different documents. This conclusion is made usually based on the theory of chemical weak boundary layer. The contamination of wood surface by the deposits of extractives is supposed to have a negative influence on the adhesive bonding. This assumption was only confirmed by ash and larch glued with PRF or MUF adhesives. The extractive contents of the timber species involved in this work were determined in a former study [6]. With 5 % and 10 %, ash and larch showed higher extractive content than spruce and beech (< 2 %).

5 CONCLUSIONS AND OUTLOOK

In a current research project the gluability of four European timber species was investigated. Parameter studies were carried out with varied processing conditions such as the time span between surface preparations and gluing, as well as the surface processing methods. The delamination resistance, shear strength, and the topology of adhesive bond were used as indicators of the performance of the glue joints.

Furthermore, with the knowledge gained in this study, the applicability of these wood species in glued laminated timber will be verified by long-term testing. Thereby, larger test beams under load will be subjected to various climate conditions.

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