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INTERNAL BOND STRENGTH OF FLAT TO END GRAIN SOFTWOOD JOINTS

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ABSTRACT

In order to study the internal bond strength of end grain to longitudinal grain joint three layered internal bond specimens of Norway spruce wood (*Picea abies* Karst.) bonded with one-component polyurethane (PUR), melamine-urea-formaldehyde (MUF) or phenol-resorcinol-formaldehyde (PRF) adhesive, respectively, were prepared. By varying the grain orientation of the middle layer from 0° (parallel to grain of the surface layers) to 90° (perpendicular to grain of the surface layers) in incremental steps of 10° the effect of grain direction was investigated. In general, no explicit tendency was observed for the internal bond strength in dependence of the grain orientation. However, with increasing angle between the grain directions of the middle and the surface layers increasing penetration depth of the adhesive along the grain was observed in the earlywood. Increased penetration of adhesives into the wood structure can be explained by the fact that a high number of cell lumens are opened during the sawing process which facilitates the penetration of the adhesive into the wood tissue.

KEY WORDS: adhesive, grain angle, internal bond strength, mechanical interlocking

INTRODUCTION

In the last decades the economical as well as ecological importance of engineered wood products (EWPs) increased rapidly. For the design of novel EWPs alternative bond line formation strategies are required leading to materials with high mechanical stability and durability. Thus, a better understanding of the mechanisms of bond formation and bond line mechanics is crucial. Different parameters, such as chemical and physico-chemical properties of adhesives, wettability of the wood surface, penetration behaviour of adhesives into cellular and intercellular cavities or diffusion of adhesives into the wood cell wall play important roles for bond line formation

(Vick 1999, Konnerth et al. 2006). Additionally, process parameters such as specific glue spread, applied pressure as well as surface properties influenced by machining processes including surface cleanliness, structural damage, surface roughness etc. may have major effects on the resulting bonding (Habenicht 2002).

The commonly applied adhesive bonding between two wooden parts connected by their radial or tangential surfaces, respectively, have been extensively studied. In contrast, only a few studies dealt with end grain to end grain joints. The bond strength of such butt joints was found to be primarily influenced by the surface roughness and the porosity of the wood as well as the viscosity and the penetration depth of the adhesive (Marian et al. 1958, Bassett 1960, Schaeffer and Gillespie 1970, Sasaki et al. 1973, Nordström 1995).

Following up our latest studies, in which we investigated end grain to end grain joints with respect to their mechanical stability regarding shear strength (Follrich et al. 2007) as well as tensile strength (Follrich et al. 2007), in the present study we studied the internal bond strength of three layered wooden specimens (Fig. 1). Three different adhesive systems, i.e. a one-component polyurethane (PUR), a melamine-urea-formaldehyde (MUF) and a phenol-resorcinol-formaldehyde (PRF) adhesive have been used for the fabrication of the specimens. According to the findings of Świetliczny (1980) who investigated butt end joints 25 years ago, only low internal bond strength was expected for the three layered specimens examined in the present study, especially for a 90° grain orientation of the middle layer, which corresponds to an end grain to flat grain joint.

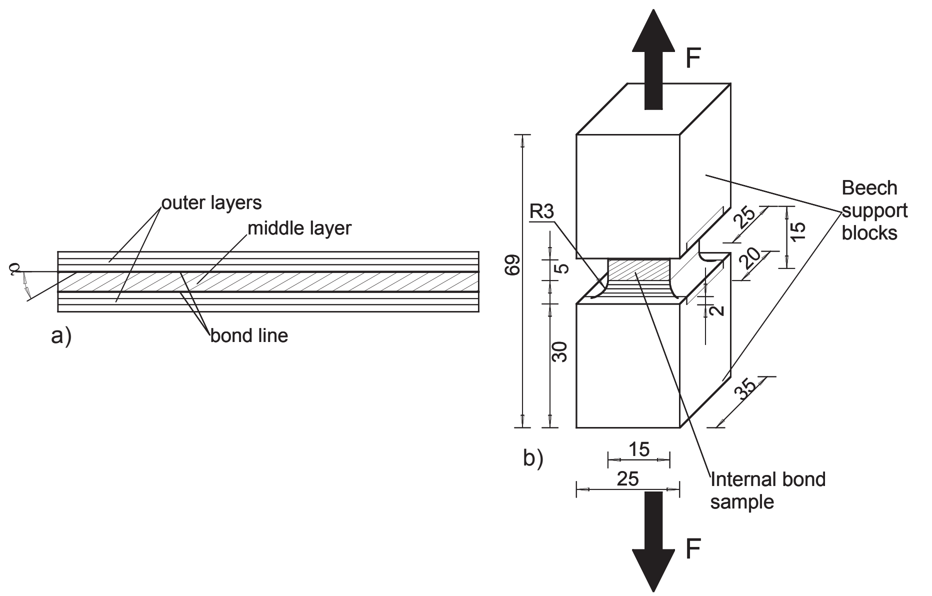

Fig. 1: Three layered sample –

a) the grain orientation (α) of the middle layer was varied between 0° and 90° in incremental steps of 10°

b) geometry of the spruce wood internal bond sample with reduced mid section bonded to two beech support blocks

MATERIAL AND METHODS

Preparation of test specimens

Flawless spruce boards (*Picea abies* Karst.) with regular annual rings and a density in the range of 464 ± 35 kg/m^3, with a moisture content of 12 %, were used to produce the three layered internal bond specimens. For the two longitudinally oriented outer layers boards were machine-planed to a thickness of 5 mm and sawn into pieces of 220 mm length and 90 mm width. For the middle layers small strips with a thickness of 5 mm were cut off machine-planed spruce boards (cross section = 110 mm x 30 mm). The grain orientation (α) of the middle layer varied from 0° (longitudinal grain) to 90° (end grain) in incremental steps of 10° (Fig. 1a).

The two outer layers (longitudinally oriented) and the middle layer (with varying grain orientation) were adhesively bonded (Fig. 1a). Three different types of adhesives were used for producing the specimens, i.e. a one-component polyurethane adhesive (PUR, Purbond HB 110, Collano, Sempach, Switzerland), a melamine-urea-formaldehyde adhesive (MUF, Prefere 4535, Dynea, Norway), and a phenol-resorcinol-formaldehyde adhesive (PRF, Aerodux 185 Aerodux 185 Friebe, Mannheim, Germany). The adhesive assemblies were prepared with a spreading quantity of 250 g/m^2 (PUR) and 400 g/m^2 (MUF and PRF). The adhesive joints were cured at a temperature of 20°C and a pressure of 0.7 MPa. A ratio of 5:1 (w/w) of resin and hardener was chosen for MUF as well as for PRF. Following the instructions of the manufacturers a pressing time of 180 min was used for the PUR adhesive, 270 min for the MUF system, and 420 min for the PRF adhesive, respectively. At last, the 15 mm thick cured adhesive assemblies were cut to the final geometry employing a circular saw resulting in a width of 25 mm.

A groove (depth = 2 mm, width = 25 mm) was cut into beech support blocks measuring 25 x 35 mm in cross section. Using a melamine-urea-formaldehyde adhesive (MUF, Prefere 4535, Dynea, Norway) the spruce wood adhesive assemblies described above were glued to the beech support blocks. Subsequently, the strips were cut into pieces of 25 mm length. Finally, a reduced mid section was millcut into the samples (Fig. 1b), resulting in a sample cross section of 15 x 20 mm (length x width) in the region of the bond line. In total, 450 samples, i.e. fifteen samples per grain orientation and type of adhesive were produced. All samples were stored at 20°C and 65% relative humidity until equilibrium moisture content was reached.

Mechanical testing

The utilised internal bond test roughly followed the OENORM EN 319: 1993 10 01 (1993). The mechanical tests were performed on a Zwick/Roell Z100 universal testing machine equipped with a 2.5 kN load cell. Internal bond specimens were tested to failure at a cross-head speed of 0.5 mm/min and internal bond strength was calculated by dividing the maximum load by the bond line area.

For the individual groups of samples the average values as well as the standard deviation were calculated and compared by two-way ANOVA.

After material testing, fracture surfaces of the samples were visually inspected and the proportion of wood failure was estimated. Small pieces with an intact glue line were cut from tested samples. One side and one cross section of the pieces was sanded (grit 800) and observed with an incident light microscope (Axioplan 2, Zeiss, 100x magnification). Images were taken with a CCD camera (Axiocam, Zeiss) attached to the microscope and bond line thickness and penetration depth was measured by means of an image analysis software (Axiovision AC V4.2, Zeiss).

RESULTS AND DISCUSSION

In Fig. 2, the average internal bond strength values (n = 15) of the three different adhesives, i.e. PUR, PRF and MUF are plotted against grain orientation of the middle layer with respect to the two longitudinally oriented outer blocks. In general, a dependence between grain orientation and measured internal bond strength was not pronounced as determined by two-way ANOVA. The mean internal bond strength values calculated for all fifteen samples bonded with one adhesive did not differ notably from each other (3.40 ± 0.27 MPa for PUR bonded samples, 3.43 ± 0.49 MPa for PRF and 3.46 ± 0.28 MPa for MUF joints). Statistically, significant influence on the bond strength could not be determined for the variation in grain angle. Furthermore, there were no interactions between adhesive and grain orientation. The outer layers mainly failed in tension perpendicular to grain (see high proportion of wood failure in Fig. 4). Therefore, the null hypothesis that the different adhesives differ significantly from each other has to be disclaimed.

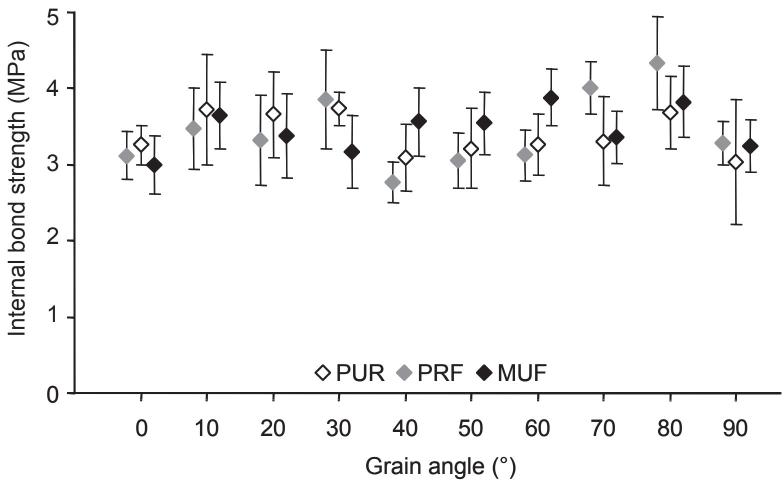

Fig. 2: Average internal bond strength of specimens bonded with various adhesives plotted against the grain orientation of the middle layer (0° denotes a longitudinal, 90° an end grain joint). The error bars represent standard deviation (SD). Fifteen samples (n=15) were tested for each adhesive and grain orientation

Based on former studies that investigated bond strength of butt end joints (Marian et al. 1958, Bassett 1960, Schaeffer and Gillespie 1970, Sasaki et al. 1973, Suchsland 1957, Suchsland 1958, Świetliczny 1980) only low mechanical stability was expected for the three layered specimens examined in our study. The general observation of these authors was the enhanced penetration of the adhesive into the micro pores of the wood substrate with increasing damage of the wood cells and hence augmented surface roughness. Since wood machining perpendicular to grain leads to increased surface roughness and cell damage, they concluded that enhanced penetration of the adhesive into the wood tissue occurs at higher grain angles. As a consequence, less adhesive is present at the surface leading to a starving of the bond line and hence insufficient bonding. To prevent starving of the bond lines the authors suggested an increase of the specific glue spread (Follrich 2006). Simultaneously, the authors claimed the importance of the mechanical interlocking of the wood pieces that are to be jointed, which is enforced with increasing penetration of the adhesive and which thus provides an essential part of the bond strength for an end grain joint (Suchsland 1958, Bröker and Korte 1994).

Tab. 1: Average internal bond strength and standard deviation (SD) obtained for the test specimen bonded with different adhesives in dependence of the grain direction of the core layer (n=15 for each grain angle). Underlined values do not differ significantly from each other (p ≤ 0.05)

Grain angle α (°)	MUF mean (SD) (MPa)	PUR mean (SD) (MPa)	PRF mean (SD) (MPa)
0	3.00 (± 0.38)	3.26 (± 0.26)	3.12 (± 0.32)
10	3.65 (± 0.44)	3.73 (± 0.73)	3.47 (± 0.54)
20	3.38 (± 0.55)	3.65 (± 0.56)	3.32 (± 0.60)
30	3.17 (± 0.48)	3.73 (± 0.22)	3.86 (± 0.65)
40	3.56 (± 0.45)	3.09 (± 0.43)	2.77 (± 0.27)
50	3.54 (± 0.41)	3.21 (± 0.52)	3.04 (± 0.36)
60	3.88 (± 0.37)	3.27 (± 0.40)	3.12 (± 0.34)
70	3.36 (± 0.34)	3.31 (± 0.59)	4.01 (± 0.35)
80	3.82 (± 0.47)	3.68 (± 0.47)	4.33 (± 0.61)
90	3.24 (± 0.34)	3.03 (± 0.82)	3.28 (± 0.29)

Concerning the requirements of high mechanical stability of a flat grain to end grain adhesive joint, some critical factors influence the bond line firmness, for instance wettability of the wood surface, adhesive and cohesive strength of the bond line, surface structure, i.e. roughness of early- and latewood after machining, as well as penetration of the adhesive into the wood tissue. Additionally, the viscosity of the adhesive plays a major role in end grain bond line formation since it strongly influences the penetration behaviour. If the viscosity is too low, the adhesive may penetrate completely into the cell cavities by capillary forces, which leads to a weakened joint due to lack of adhesive in the bonding line as reported by Suchsland (1958) and Świetliczny (1980). However, the adhesives used in our study are characterized by high viscosity, which causes a reduced penetration into the wood tissue resulting in a bond line thickness of approx. 61 μm for MUF, 84 μm for PUR and 113 μm for PRF. The difference between earlier studies (Świetliczny 1980) and our present results may partly be explained by higher adhesion and bonding strength of modern adhesives.

Viscosity of the adhesive is not the only parameter influencing the penetration depth of the resin into the wood structure (Brady and Kamke 1988). The viscosity of the three adhesives used in our studies lay in the range of 3000 to 4500 mPas for MUF and PUR, respectively, and about 9000 mPas for PRF. Very contrary to theoretical considerations according to which MUF and PUR should penetrate more easily and hence deeper into the wood surface than PRF, penetration depth was always highest with the latter adhesive. However, another parameter showing major effect on the penetration depth of the three adhesives was the grain orientation. For instance, a penetration depth of approx. 1400 µm was observed for PRF joints at 10° grain orientation, whereas at 90° the resin penetrated only approx. 550 µm into the earlywood tracheids along the grain of the middle layer. MUF and PUR adhesives roughly showed the same trend, but penetration depth was lower than outlined above. From Figure 3, the penetration behaviour of the PRF adhesive is visible, revealing that the earlywood tracheids are mostly filled while on the other hand, no penetrated resin was found in the latewood tracheids.

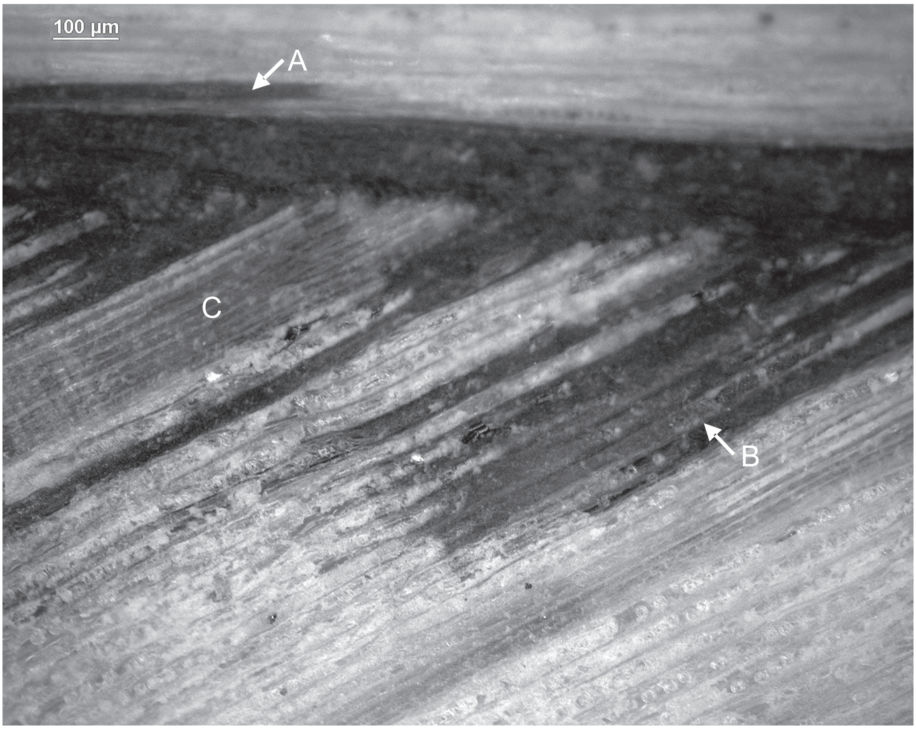

Fig. 3: Micrograph of phenol-resorcinol-formaldehyde adhesive (PRF) penetrating into the longitudinal surface layer (A) near the bonding line and earlywood tissue of the core (B) of a test specimens with middle layer grain orientation of 30°. The cell lumens of the latewood tissue (C) are mostly free of penetrated adhesive

In agreement with findings of Świetliczny (1980) and Nordström and Marelius (1994) an increased number of damaged cells was found on the machined surface with increasing grain angle. Earlywood tracheids were partly pulled out and defibrillated during the cutting process, whereas latewood tracheids were clearly cut off. Stehr et al. (1999) as well as Moura and Hernández (2005) postulated a reinforcement of damaged cells by the penetrated resin. However, the occurrence of a good mechanical interlocking in our samples was also derived from the fact that the internal bond strength was not predominantly determined by collapse of the bond line but at least in equal shares by wood failure. In this special case of test arrangement wood failure was determined by the strength perpendicular to grain of the outer layers so that wood failure occurred mainly in these outer layers. In Figure 4, the average wood failure of the tested specimens bonded with the three adhesives PUR, PRF and MUF is plotted against the corresponding grain orientation. In most cases, the mean contribution of wood failure to the overall breakage of the test specimens amounted for 40-80% without significant dependence on the grain orientation.

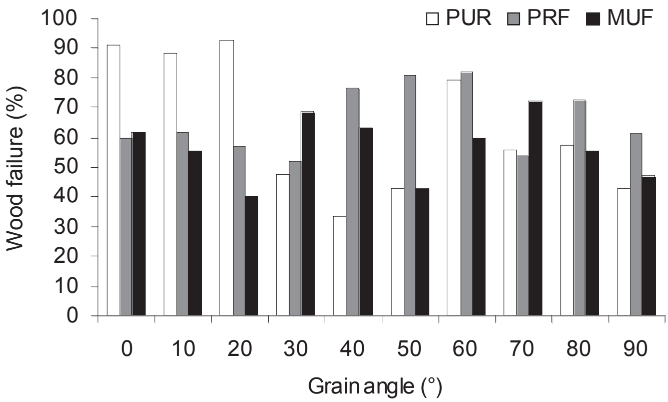

Fig. 4: Average wood failure calculated for the specimens bonded with various adhesives in dependence of the grain orientation of the middle layer (0° denotes a longitudinal, 90° an end grain joint)

CONCLUSION

It could be shown that internal bond strength of the end grain to flat grain joint tested in the present study was not significantly lower than that measured at any of the other grain orientations studied including the flat grain to flat grain joint. Furthermore, with the employed adhesive systems, i.e. one-component polyurethane, melamine-urea-formaldehyde and phenol-resorcinol-formaldehyde the internal bond strength of the test specimens was not primarily limited by the strength of the bond line, but in many cases by wood failure of the longitudinally oriented outer layers. This fact confirmed the good mechanical interlocking of the middle layer with the other two layers in our test arrangement.

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