ADHESIVE BOND STRENGTH OF END GRAIN JOINTS IN BALSA WOOD WITH DIFFERENT DENSITY

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ABSTRACT

Balsa wood (*Ochroma lagopus* Sw.) specimens covering a wide density range from 80 kg.m⁻³ to 250 kg.m⁻³ were joined at end grain surfaces and tested in tension perpendicular to the bonded surface in order to study the effect of density and porosity on the adhesive bond strength. In general, relatively high bond strength (13.6 \pm 2.8 MPa) was observed. It was assumed that the transverse walls of the longitudinal parenchyma cells of balsa wood reduce penetration of the adhesive into the cell cavities and hence prevent starving of the bond line. It is proposed that the resulting consistent bond line is responsible for the observed good bond strength. A slight, although not statistically significant influence of density on tensile strength was found. For samples with a density below 110 kg.m⁻³ tensile strength of the end grain bonded samples was about the same as that of solid balsa, documenting excellent bond strength.

KEY WORDS: Balsa wood, density, end grain, mechanical interlocking, porosity

INTRODUCTION

Complex macroscopic and microscopic phenomena are involved in the bonding process between two wood pieces that cannot be explained solely by adhesion. For the description of the bonding mechanism between a wood surface and an adhesive, the following theories can be found in literature: (1) adsorption or specific adhesion theory, (2) diffusion theory, (3) electrostatic theory, (4) mechanical theory (mechanical interlocking), (5) chemical bonding theory, and (6) theory of weak boundary layer (Schulz and Nardin 1994, Frihart 2005). Although none of these theories by itself sufficiently describes the complex procedures involved in wood bonding, each of them can be regarded as an important contribution to the understanding of the adhesion.

Various studies were dealing with the penetration of adhesives into the cell lumina (Fengl and Kumar 1970, Furuno and Goto 1975, White 1977) as well as into the cell wall as possible

sources for mechanical interlocking of bonded wood pieces (Gindl et al. 2002, Konnerth et al. 2008, Frihart 2004). In a previous study of our working group the bond strength of an end grain to end grain joint of spruce wood with varying density (300 to 750 kg.m⁻³) was investigated in order to study the possible occurrence of mechanical interlocking (Follrich et al. 2008). Increasing bond strength was observed with increasing density. The increased bond strength was ascribed to a higher portion of overlapping cell wall cross sections available for bond formation since cell wall thicknesses are increasing with higher density. Additionally, reduction of adhesive penetration into the smaller pores helps to avoid starving of the bond lines. In order to reduce the influence of overlapping cell wall cross sections as far as possible wood of very low density consisting only of thin-walled cells should be favourable for the investigation of the occurrence of mechanical interlocking. Such a low-density wood species is balsa wood (Ochroma lagopus). Balsa is a diffuseporous hardwood; its vessels (3.0 to 4.5 %) have a circular or oval shape with a diameter between 130 and 300 µm which are arranged as a single pore or in groups (Wagenführ 1996). The greater part of the wood (approximately 74 %) consists of longitudinal parenchyma cells which have a uniform distribution in type and size throughout the grain cross-section with a hexagonal shape and a diameter ranging from 30 to 70 µm (Vural and Ravichandran 2003a). The length of the parenchyma cells, which typically contain intracellular transverse walls (Easterling et al. 1982), is in the range of approximately 280 µm. Furthermore, balsa contains ray cells (17 to 19%) and libriform fibres (approximately 4 %) (Wagenführ 1996)

Various investigations were based on the mechanical properties as well as the failure behaviour of balsa wood (Soden and McLeish 1976, Easterling et al. 1982, Vural and Ravichandran 2003a and 2003b, Tagarielli et al. 2005). They described that despite its low density balsa has extraordinary strength and due to the natural cellular structure a high rigidity. Bassett (1960) focussed in his study on the bondability of an end grain balsa joint with a resorcinol-formaldehyde (RF) adhesive. Besides variation of the density, also influence of the viscosity of the adhesive as well as surface preparation of the wood specimen by either sawing or sanding was studied. Increasing bond strength was observed with increasing density of the balsa wood. Additionally, higher bond strength was found for sawed surfaces than for sanded ones, while with higher viscosity the bond strength was reduced.

In the present work, we studied the influence of density and porosity on tensile bond strength of a balsa end-grain joint. In a previous study performed with spruce wood (density range from 300 to 750 kg.m⁻³) the effect of density and porosity on tensile strength of butt end bonded joints was heavily affected by adhesive starving at low density. Due to the specific wood anatomy of balsa wood with a high proportion of parenchyma cells with a short length of about 300 to 400 μ m less starving is expected. In combination with easy penetration of the adhesive into the cell cavities it was assumed that the design of the experiments should be applicable to describe increasing mechanical interlocking at low density.

MATERIAL AND METHODS

Preparation of test specimens

Balsa wood with a density between 80 kg.m⁻³ and 250 kg.m⁻³ was used to produce bone shaped tensile specimens (Fig. 1). The moisture content of the used balsa boards was 9.7 $\% \pm 0.7 \%$. For the two longitudinally oriented parts straight grained boards were machine-planed to a thickness of 25 mm and sawn into pieces of 90 mm length and 120 mm width. Two consecutive parts from one board were adhesively bonded with a melamine-urea-formaldehyde adhesive (MUF, Prefere 4535,

Dynea, Norway). The adhesive assemblies were prepared with a spreading quantity of 400 g.m⁻² and cured at a temperature of 20°C and a pressure of 0.7 MPa according to the instructions of the manufacturer. The 180 mm long cured adhesive assemblies were cut to final shape on both sides with a circular saw resulting in a width of 18 mm and a thickness of 6 mm. The bone shape of the tensile samples was millcut into the samples, resulting in a reduced width of 8 mm in the region of the bond line. In order to avoid excessive compression of the balsa wood in the grips of the tensile testing machine, beech support blocks were glued to the balsa samples (Fig. 1). In total, 180 samples were produced and 170 samples were tested. Additionally, 64 solid balsa samples with identical geometry were produced and tested for reference. All samples were stored at 20°C and 65% relative humidity until equilibrium moisture content (10.0 $\% \pm 0.3 \%$) was reached.



Fig. 1: Tensile test sample -a) overview of the bond line and anatomical direction of the wood, b) geometry of the bone shaped tensile samples with reduced mid section bonded to two beech support blocks

Mechanical testing

Tensile tests were performed until failure on a Zwick/Roell Z020 universal testing machine at a cross-head speed of 0.5 mm.min⁻¹. From untested samples small pieces with an intact bond line were cut. One side of the pieces was sanded (grit 800) and observed with an incident light microscope (Axioplan 2, Zeiss, Jena, Germany, 100x magnification). Images were taken with a CCD camera (Axiocam, Zeiss) attached to the microscope with a resolution of 0.94 pixels.µm⁻¹ and bond line thickness as well as the penetration depth were measured by means of an image analysis software (Axiovision AC V4.2, Zeiss).

Determination of the density and porosity

After testing, small pieces were cut from tested samples for determining the density ($\rho = \rho_u$). The relation between moisture content (u) and density, below fibre saturation (u~28 %), is described in the literature by the following equation (1) (Kollmann and Côté 1968):

$$\rho_u = \rho_0 \left(\frac{100 + u}{100 + 0.85 \cdot \rho_0 \cdot u} \right) \tag{1}$$

For each tested sample, the oven dry density (ρ_0) was determined by means of eq. 1. Porosity

(p) was then calculated according to equation (2) (Kollmann 1951) where 1.5 is the density of the solid cell wall (Kellogg et al. 1975) and ρ_0 the oven dry density of the wood specimen.

$$p = 1 - \frac{\rho_0}{1.5} \tag{2}$$

The cell wall portion (cw) was calculated according to eq. 3:

$$cw = 1 - p \tag{3}$$

For determining the size and distribution of vessels the small pieces from density determination were soaked in water for one day. Afterwards, the soaked pieces were frozen for two days at -20°C. Subsequently, from the frozen balsa samples thin cross-sections of 90 μ m were made near the bond line using a microtome (Reichert, Germany). The thin sections were mounted on a glass slide using water as embedding medium and observed with an incident light microscope (Axioplan 2, Zeiss, Jena, Germany, 20x magnification). Images were taken with a CCD camera (Axiocam, Zeiss) attached to the microscope with a resolution of 0.143 pixels. μ m⁻¹ and the vessel size, the vessel area as well as the two vessel diameters (oval shape) were measured by means of an image analysis software (Axiovision AC V4.2, Zeiss). In total, 70 images were taken and analysed.

Scanning electron microscopy (SEM) investigation of the end grain bonding area.

Small pieces (approximately 5 mm x 2 mm x 2 mm) (radial x tangential x longitudinal) including the adhering bonding area were cut from the tested samples. The samples were placed on aluminium stubs, gold sputter coated, and the end grain bonding area was observed in the SEM (Hitachi S 4000, Japan) in high vacuum/secondary electron mode at 5 kV.

RESULTS

With increasing density of the balsa wood a decrease in porosity from approximately 0.95 to 0.86 and an increase in the cell wall portion from 0.05 to 0.14 were calculated by equations 2 and 3. The bond line thickness of the specimens was approximately 92 μ m ± 24 μ m. In Fig. 2, tensile strength values determined for the solid balsa reference samples (n=64) and for the MUF bonded specimens (n=170) are plotted against density. For solid balsa, an increase of the average tensile strength was observed with increasing density. The correlation between tensile strength and density as well as the confidence interval for single values (95 %) was calculated by linear regression. Density exhibited a significant influence (significance level p ≤ 0.01) on the measured tensile strength, although the coefficient of determination was low (R² = 0.23). For the end grain bonded samples, tensile strength slightly increased with increasing density, although density did not exhibit a significant influence.

In Fig. 3, average wood failure and average tensile strength are plotted against density. At low density a high percentage of wood failure was observed which rapidly decreased with increasing density while in comparison tensile strength slightly increased with increasing density.

For 70 bonded samples the number of vessels, the vessel area as well as the average vessel diameter was determined. The number of vessels divided by the bond area resulted in the number of vessels per mm², which was used to evaluate the effect of vessels on bond strength. In general, a slightly increasing tensile strength was observed with increasing number of vessels (Fig. 4). The number of vessels per mm² exhibited no significant influence ($p \le 0.05$) on the observed tensile strength. From the measured vessel diameters (2a_r 240.3 µm, radial direction) and (2b_r 173.7

 μ m, tangential direction) the radii (a_r and b_t) as well as the vessel area for an elliptical area were calculated. The theoretical calculated vessel area (32896 μ m⁻²) corresponded well with the average measured vessel area (31857 μ m⁻²). The proportion of vessel area on total cross sectional area was only between 1.1 % and 5.4 %.



Fig. 2: Tensile strength values of solid balsa (black diamonds) and with melamine-urea-formaldebyde (MUF) end grain bonded specimens (white diamonds) plotted against density. The bold solid lines represent the calculated linear regression for solid balsa wood and for MUF bonded samples, respectively. The dotted lines (solid balsa) as well as the fine solid lines (MUF bonded samples) represent the corresponding confidence interval for single values at 95 %

DISCUSSION

The results in Fig. 2 indicate higher tensile strength with increasing density for solid balsa wood. An increase in density by a factor of 2 (e.g. from 80 to 160 kg.m⁻³) resulted in an increase in tensile strength of 95 % (determined from mean strength calculated from the linear regression at 80 and 160 kg.m⁻³). A number of investigations confirmed the effect of density on tensile strength (Soden and McLeish 1976) and on compressive strength (Easterling et al. 1982, Vural and Ravichandran 2003a and 2003b) for balsa. In our investigations, tensile strength values of solid balsa showed relatively high variability for constant densities (Fig. 2). Generally, tensile strength values determined in this study corresponded well with data presented in the literature which typically varied in a wide range from 7.5 MPa (Wagenführ 1996) to 73 MPa (Soden and McLeish 1976) depending on the density.

At low density values (100 kg.m⁻³) the average tensile strength of solid balsa was about 45 % higher than tensile strength of end grain bonded samples. However, the strength of some samples was in the range of the bonded samples. In comparison, with increasing density differences in tensile strength values measured for solid as well as end grain bonded samples increased since for the bonded balsa samples, only a slight increase in bond strength was observed with increasing density (Fig. 2). In contrast to solid balsa, no statistically significant trend was found for the bonded samples.

Compared to softwood of comparable density, balsa shows significantly higher tensile strength values for end grain bonded specimens. The typical failure mode of spruce wood specimens was fracture of the adhesive bond line (Follrich et al. 2008). In contrast, for balsa end grain joints a high percentage of wood failure was observed at low density (Fig. 3). Especially at low density (thin walled cells) the strength of the cell walls in tension was in the range of the cohesive strength of the adhesive, which means that a high number of bonded and solid specimens perform equally well in the tension test (see overlapping area in Fig. 2). In other words, for bonded balsa samples of density between 80 kg.m⁻³ and 110 kg.m⁻³ the wood itself but not the bond line becomes a limiting factor for the overall tensile strength.



Fig. 3: Average tensile strength values (white diamonds) and average wood failure (black diamonds) of melamine-urea-formaldehyde (MUF) end grain bonded specimens plotted against density



Fig. 4: Tensile strength values of melamine-urea-formaldehyde (MUF) end grain bonded specimens plotted against number of vessels per mm². The bold solid lines represent the calculated linear regression. The dotted lines represent the corresponding confidence interval for single values at 95 %

No significant influence on the bond strength was observed with increasing number of vessels per mm^2 (Fig. 4). The lacking effect of the vessels on the bond strength can be explained by the low proportion of vessel area on total cross sectional area (1 mm²) which was only between 1.1 % and 5.4 %.

In general, penetration of adhesives into the wood structure depends on a number of intrinsic and extrinsic parameters. Intrinsic factors are, e.g. wood species, grain orientation (longitudinal or end grain), wood tissue (early- and latewood) or lumen diameter (radius of the cell capillary). Extrinsic factors are, e.g. viscosity, applied pressure, surface roughness, and spreading quantity (Marian et al. 1958, Suchsland 1958). Bonding of wood with low density is in general a challenge because the adhesive can penetrate more easily into the wood structure. A starving of the bond line may be a consequence of overpenetration resulting in low bond strength (River et al. 1991). In the special case of an end grain to end grain bonding the problem of overpenetration is evident. Thus, end grain surfaces exhibit a number of open cell lumina that facilitate the penetration of the adhesive. One possibility to circumvent starving of the bond line is to increase the spreading quantity (Follrich et al. 2007).



Fig. 5: Micrograph of the bond line (black arrow) of balsa wood. The adjacent parenchyma cells with transverse walls near the bond line (closed black arrowheads) prevent adhesive starving. The open arrowhead indicates adhesive penetrated into an open vessel

In an earlier study, we investigated the bond strength of an end-grain to end-grain joint of spruce wood with varying density in the range of 300 kg.m⁻³ to 750 kg.m⁻³ and an absolute decrease in porosity of approximately 30 % (Follrich 2008). With increasing density an increase in bond strength was observed. We assumed that with increasing density cell wall thickness is increasing while simultaneously cell cavities become smaller which leads to reduced penetration of the adhesive. As a consequence, starving of the bond lines due to overpenetration is diminished in the less porous high density wood. Additionally, a higher portion of overlapping cell wall cross sections is available for bond formation between thick-walled cells in high density wood. In comparison to softwood, increase of cell wall thickness with increasing density is not that pronounced in hardwoods. Therefore, for balsa an increase of overlapping cell wall cross section area is less

pronounced than for spruce because cell wall thickness of the different tissues, i.e. longitudinal parenchyma, vessels or libriform fibres, is generally very low (average cell wall thickness is 0.5 to 1.0 μ m for longitudinal parenchyma cells). Furthermore, the absolute change of the porosity in balsa is only 10 % in the density range from 80 kg.m⁻³ to 250 kg.m⁻³. A possible explanation for the high tensile strength found for the low density balsa wood may lay in the beneficial effect of mechanical interlocking between the adhesive and the wood surface. The longitudinal parenchyma cells of balsa are divided by transverse walls in the axial direction (Easterling et al. 1982). It can be assumed that the transverse walls prevent an overpenetration into the open cell lumina of the longitudinal parenchyma and hence starving of the bond line (Fig. 5). The penetrated adhesive can completely fill the cell cavity making optimal use of the inside area of the cell wall.

Fig. 6 shows SEM micrographs of the wood surface after tensile testing. Two types of fracture can be seen, (1) cohesive failure of the longitudinal parenchyma cells and (2) cohesive failure of the adhesive. No starving of the bond line and no reduction of the bond line thickness (92 μ m ± 24 μ m) was observed which supports our hypothesis that the transverse walls of the longitudinal parenchyma cells prevent overpenetration of the adhesive and yet starving of the bond line. A pull out of the cured adhesive fingers was only observed from the vessels but not from the much smaller parenchyma cells (Fig. 6c).



Fig. 6: Micrograph of fracture surfaces from balsa -a) Fracture surface of balsa with wood failure (white arrow) and a region of cohesive failure of the bond line (black arrow). b) Transversely ruptured longitudinal parenchyma cells filled with penetrated adhesive (black arrowhead). c) Cured adhesive finger which was pulled out from a vessel (black arrow)

CONCLUSION

Our investigations on end grain bonded balsa wood samples showed a slight, but not significant influence of density on the tensile strength. Compared to solid balsa, tensile strength of end grain bonded samples was on average 25-50 %. At low density (below 110 kg.m⁻³) the adhesive bond strength was even about 100 % of the tensile strength of solid balsa, which means that the strength of the bond line was equal or higher than the tensile strength of the cell wall. One explanation may be a beneficial effect of mechanical interlocking between the adhesive which penetrated into the cell lumina and the relatively large surface of the inner cell wall. We assume that the transverse walls of the longitudinal parenchyma cells prevent an overpenetration of the adhesive reinforces and stiffens the damaged wood structure and hence contributes to the overall bond strength.

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