Mechanical Performance of Structural Hardwood Elements

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1. Introduction

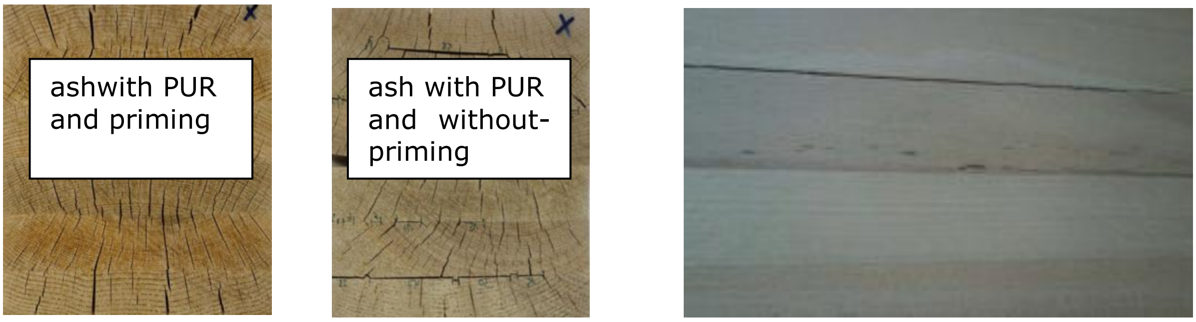
Wood has always been used as building material, it is widely available and easy to work with. Coniferous trees are mostly preferred to broad-leafed trees, they have a straight growth and are generally lower in density. Lower density in means of wood physics also stands for a good machinability, but also for a reduction in the strength parameters and lower Young's moduli and shear moduli. The softwoods were nevertheless favored in construction engineering during the past centuries -and still are- and their trees consequently were cultivated also in regions originally dominated by broad-leafed trees. In the same time the beech gained 4.3x106 m^3 (+6 %) and also ash (+24, 4%). These two species represent the most common soft- and hardwood species in Switzerland. The increasing hardwood reserve will lead to an increase in hardwood harvest. Instead of the currently usual energetic use, an intermediate step, e.g. as building material, could add value to this resource and would be a reasonable application of the additional hardwood (see fig. 1-fig.3).

Figure 1: Timber construction with beech and ash wood in Switzerland (Beer Holzbau AG Ostermundingen/CH), http://www.beer-holzbau.ch/

Figure 2: ETH Zurich, House of Natural Resources (Glulam (ash), CLT (Beech) and "Baubuche" (Pollmeier/Germany)

Figure 3: New Building Tamedia/Zurich (Blumer-Lehmann AG, Gossau/Switzerland)

Adhesive bonding is an essential task in modern timber engineering. The spruce is since 100 years and more Europe's most important wood resource for timber engineering. Con sequently, the testing standards focus mainly on this wood species (see EN 302-2, delamination test). For glued hardwood the higher swelling, shrinking and MOE induced higher stresses in the glued hardwood and in the bondline during changing climatic conditions (see fig. 4) in relation to softwood.



a) ash wood after delamination test

b) delamination in ash under low air humidity

Figure 4: Delamination from ash glue laminated timber

a) after delamination test according EN 302-2 with different adhesives
b) delamination under very dry air conditions
(Foto: P. Niemz, BFH)

A delamination can also occourin winter in heated rooms induced from the low air humidity (fig 4 b). The same effect we have also for parquet. A transfer of these standards onto other wood species is, due to the material's complexity, only of limited application. New approaches have thus to be employed to verify the load bearing capacity of glue joints in other wood species. The European beech (*Fagus silvatica* L.) is the most common broad-leafed tree species in Switzerland. It has good mechanical properties of which the timber engineering can profit. The focus of this work therefore was on the failure mechanisms of glue joints in beech and ash wood, realized with different, commercially available adhesive systems. With hardwood we have a lot of problems with the gluing (high internal stresses, high swelling, influence from extractives etc.), see Ammann (2015). Therefore the present project was sub-divided in numerical and experimental investigations. The numerical simulations investigate the moisture transport, stress distribution, fatigue and delamination to increase the predictability of the safety of bonded hardwood The experimental investigations determine the yet unknown physical properties of glue joints necessary for the numerical simulations, illustrate the behavior of cracks at such joints at their different stages and develop testing methods suitable for glue joints in hardwood. The latter- experimental- investigations are covered in this study, using fracture mechanical approaches, standard tests, and small scale experiments; the study concerning the numerical investigations can be found in Hassani (2015) in a second thesis (numerical simulation from moisture induced stresses, not reported in this presentation).

2. Material and Methods

2.1. Fracture toughness

Wood and glued wood
European beech wood (*Fagus silvatica* L.) was used. The samples were prepared from the same trunk lumbered in the region of Zurich, Switzerland (temperate climate). Prior to sample preparation the raw beech wood boards were conditioned at standard atmospheric conditions (20°C, 65% RH) until the equilibrium moisture content was reached. At that point, the wood had a density of approximately 706 kg/m^3 and moisture content (MC) of 14.5 %. After conditioning, the slats of approximately 5cm x 6.5cm x 40cm were cut out and glued according to the manufacturers' guidelines.

The investigated adhesives are as follows:

- *phenol resorcinol formaldehyde resin (PRF)*
  Aerodux (glue 185 RL with hardener HP 155) provided by Bolleter Composites AG, Arbon, Switzerland, and
- *one-component polyurethane (PUR) HB S 709,* provided by Henkel AG, Sempach-Station, Switzerland.

Before joining the slats, thin silicon coated films with a thickness of 35 µm were inserted into the bond line for the initiation of the crack (Fig. 5).

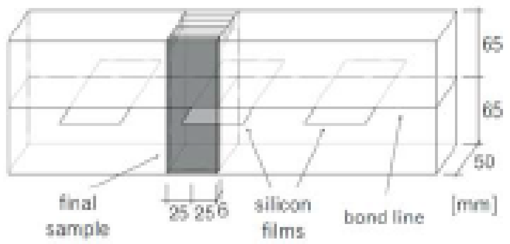


Figure 5: Sample preparation and geometry

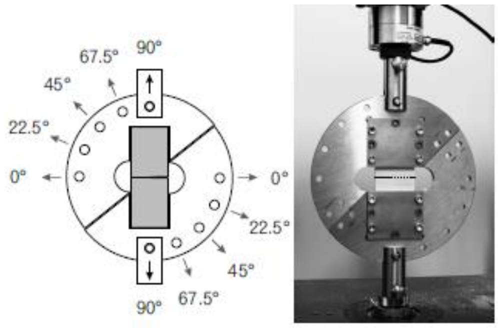


Figure 6: Arcan Test

This procedure was adapted from ISO 25217. After bonding, the slats were stored again at standard atmospheric conditions for 7 days and then conditioned to the desired environmental humidity. Three sample series were conditioned:

a) dry climate: 20°C, 50% RH; MC 11,0%
b) standard climate: 20°C, 65% ; MC 14,6%
c) wet climate: 20°C,95% RH, MC 21%

Finally, samples of 6mm x 50mm x 130mm were cut out so that they contained an initial crack (i.e. silicon film of approximately 25mm length).
The orientation of the anatomic directions was chosen so that the crack propagates in the longitudinal direction and both late- and early wood are present on the crack plane, i.e. with an annual ring angle of 60° to 90° respective to the glue joint. The orientation of the annual rings in the bonded samples was chosen so that they coincide with industrial bonded elements, and the crack tip was placed directly in the adhesive to assure the investigation on the adhesive, not the solid wood.

Tests
The experiments were conducted on a Zwick/Roell Z010 universal testing machine with a 10 kN load cell and an Arcan test mount (Fig. 6). The Arcan test mount can be modified to realise load angles on the glue joint from 0°-to 90° in 22.5 steps. A load angle- $\alpha = 0°$, therefore corresponds to the fracture mode 2 (M2), and $\alpha = 90°$ corresponds to the fracture mode 1 (M1). Mixed modes (MM) are denoted with the respective load angle as index (e.g. MM22.5 for $\alpha = 22.5°$). In Fig. 6, an exemplary test setup for M1 (90°) is shown. With the gathered data the fracture toughness's, Kc, were calculated:
K_{IC}, K_{II} and K_{α}

2.2. Fracture energy

Wood and glued wood
Regular samples
All samples were produced with European beech wood (*Fagus silvatica* L.) from a single trunk. The tree was lumbered near Zurich, Switzerland, a region with temperate climate. The slats were stored at standard atmospheric conditions (20°C, 65% RH) until the equilibrium moisture content was reached. At that point, the wood had a normal raw density of 750 kg/m^3 and an moisture content (MC) of 14.7 %.
Boards of approximately 42cm x 42cm x 4cm were planed and bonded with the same adhesives shown in 2.1.

The bonding procedures were strictly adapted from the manufacturers ‘guidelines: PUR was applied on one side with a spread quantity of 180 g/m^2 to 200 g/m^2 and pressed for 175 min, PRF was applied on both sides each 225 g/m^2 (liquid content) and pressed for 240 min. The applied pressure for both adhesives was 1.2 MPa. When the wood was acclimatized, the samples were cut into their final shape of 20mm x 66mm x 390mm (fig.7).

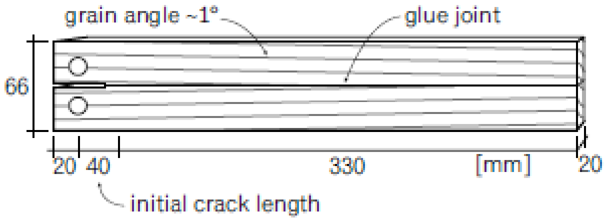


Figure 7: DCB geometry, in [mm

While planing, the boards were slightly inclined (~1°) to achieve a potential grain angle towards the glue joint in the crack propagation direction. This reduces the risk of the crack propagating too far from the specimen’s center. The annual ring angle on the glue joint was between 60° and 90° for all samples.

Aged samples

Three sets of variably aged glulam elements were available and were also used for sample preparation. The beech wood used for the glulam elements came from the same region as for the regular samples, but from a different trunk. The adhesives and their respective applications were identical. The glulam elements consisted of six boards each 45cm long 15cm wide and 3cm thick. These boards were stored at standard atmosphere until moisture equilibrium content was reached and the glulam elements were bonded at the same climate. The ends of the elements were sealed with a thick alkyd resin coating to avoid end grain moisture diffusion, and thus imitated moisture profiles of long glulam beams. Ageing of all wood beams took place between March 2012 and May 2014.
The three different processes were natural,

- A95 aged samples stored at 20°C, 95% RH
- ACC aged samples, cyclic conditions at: 20°C and 50% / 95% RH
- AW weathered samples: outdoor, roofed

Also samples which different EMC tested:

50 regular samples stored at 20°C, 50% RH
65 regular samples stored at 20°C, 65% RH
95 regular samples stored at 20°C, 95% RH

The A95 samples were stored for two years at 20°C, 95% RH. The ACC samples were first stored at 20°C, 50% RH for 150 days, then at 20°C, 95% RH for 250 days, and then again at 20°C, 50% RH until the samples were tested. The AW samples were stored outdoors in a roofed depot. They were protected from rain, but complete evasion of snow during winter was impossible due to wind. Temperature and relative air humidity were recorded directly at the glulam elements. After ageing, the glulam elements were cut into samples. For these experiments, here the top and bottom glue lines were taken. The sample preparation was done using the same method as for the regular samples. Only the sample height had to be reduced to 60mm because of the board thickness in the glulam elements. All other procedures were kept the same. The outdoor weathered glulam elements were acclimatized at standard atmosphere before sample preparation. A Zwick/Roell Z010 universal testing machine with a 10kN load cell was used for all experiments. The load was applied perpendicular to the glue joint, i.e. in pure opening mode. Ammann (2015) found an influence of the testing speed on the measured results. For this reason the crack propagation rate was held constant in this study and remained in the range of 3 cm/min to 4 cm/min. For the PUR bonded samples an additional series with increased (~40 cm/min) and reduced (~ 0.4 cm/min) crack propagation rates were tested.

2.3. Shear strength and delamination

Material
For the tensile shear strength and the delamination experiment, ash (*Fraxinus excelsior* L.) with a density of 674 ± 68 kg/m^3 at a moisture content of 8% was used. All wood pieces with major flaws which could influence the results were sorted out.
The results obtained by Ammann et al. (2016) and during the preliminaries tests sufficiently proved the performance of the adhesive PRF Aerodux 185. Hence, this adhesive was not tested again. Two different 1C-PUR with long CAT from Henkel AG (HBS 709 and the HB 181) were chosen. The primer Loctite PR 3105 developed by Henkel AG was used.

Methods
tensile shear strength
Prior to gluing, three different climates according to table 1 to reach until stabilization (weight difference smaller than 0.1% after 2 hours). The wood equilibrium moisture content was determined then determined according to DIN EN 13183-1:2002. The wood pieces were then planed to a thickness of 5mm and cut in half prior to gluing. The gluing was performed with the parameter presented in table 2. The primer applied (1side) quantity was 20 g/m^2 (concentration 10% and 20%).

Delamination (EN 302-2)
The lamellas for delamination were conditioned at a humidity of 8% prior to gluing (lamella thickness 30 mm). Adhesive applied under the conditions from the producers. The specific pressure was 1,2 N/mm^2.

3. Results

3.1. Mixed mode fracture toughness

The above-mentioned calculation of Kc with the corresponding correction factors base on isotropic materials and might therefore not be valid for wood or wood-based products. For a better overview, the Kc values with corresponding CIs are illustrated in Fig. 8 for PUR and for PRF. The bulk density of the used wood lies within the common range found in literature, being at 706 kg/m^3 at standard climatic conditions. The MCs are slightly higher compared with literature values, but are within the normal range. No significant differences of the Kc of the PUR glue joints can be found between load angles from M1 to MM22.5, but a significant increase is visible from MM22.5 to M2. This observation applies to all three climate steps. It can be assumed that PUR glue joints perform equally well independent of the load angle until a certain percentage of shear force is reached. In the regular to dry climates, wood failure starts to occur occasionally when decreasing the load angle to 22.5o. As for Kc, a distinct increase in WFP is notable between MM22.5 and M2. It thus seems plausible that, at that angle, towards pure shear load, bonding mechanisms come into account that significantly increase the glue joint’s performance. Possible mechanisms can be differences in the stress field, surface roughness and mechanical interlocking. Similar observations can be made for the PRF in the dry and standard climates as for the PUR, except that $K_{I};c$ is lower than those at the MM.
However, at the wet climate an unexpected behavior was observed. The measured $K_{I};c$ of the PRF are not only higher than at standard atmosphere, they are even at the same level as $K_{II};c$ in the wet climate. The minimum Kc can be found at a load angle of 22.5° respective to the bond line, being significantly lower than $K_{I};c$ and $K_{II};c$. An explanation for this behavior has not been found, neither in the evaluation nor in the literature. Regarding the WFPs of both adhesives, it becomes apparent that shear stresses at glue joints promote wood failure in the system. In general, PRF predominantly produces wood failure, whereas PUR mostly fails in adhesion (see also Ammann (2015)). Joints of phenol resorcinol formaldehyde (PRF) showed constantly good results, the determined characteristics generally lay in the same range as for beech. Fig. 8: Fracture toughness Kc of PUR for different RH with CI (confidence interval) in black area Polyurethane (PUR) has good fracture mechanical properties, but these cannot be activated in beech wood joints. The weakest link of PUR joints in beech is the adhesion.

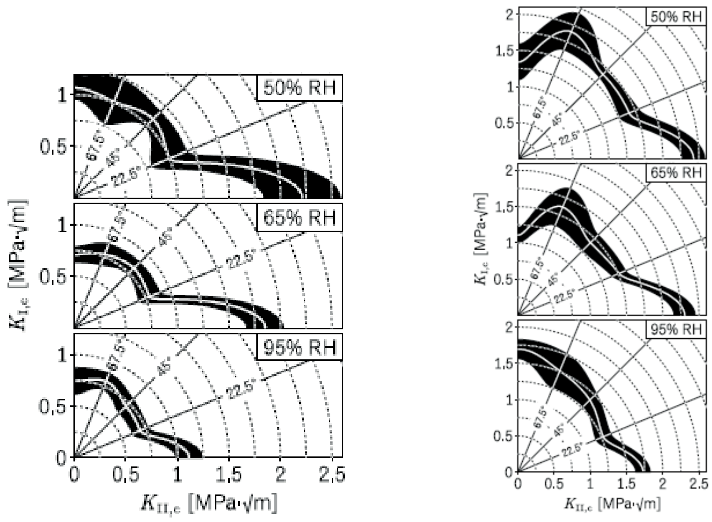


Figure 8: Fracture toughness' Kc for 1 C PUR (left) PRF right) and different RH with CI (confidence interval) in black area)

3.2. Fracture Energy

A summary of all the gained results is given in fig 9.

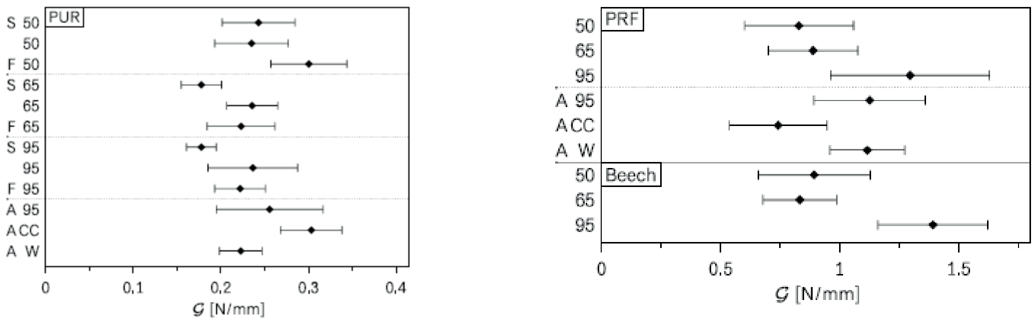


Figure 9: Fracture energy for glued wood PUR and PRF and for beech solid wood

- A95 aged samples stored at 20°C, 95% RH
- ACC aged samples, cyclic conditions at: 20°C and 50% / 95% RH
- AW weathered samples: outdoor, roofed
- 50 regular samples stored at 20°C, 50% RH
- 65 regular samples stored at 20°C, 65% RH
- 95 regular samples stored at 20°C, 95% RH

The conducted DCB experiments on *PRF* glue joints in beech wood allow drawing the following conclusions:

- PRF glue joints fail in the adherent, the fracture energy is thus identical with solid beech wood.
- G of beech wood under pure opening mode is at 0.85 N/mm for regular to dry climates.
- Beech wood at humid conditions has a distinctly increased G (1.35 N/mm at 95% RH).

Thus, the increase in plasticity outweighs the reduction in strength of beech wood with regard to G.
All applied ageing processes had the same influence on PRF glue joints, a probable reduction in G by 10% to 15% within two years, with no change in WFP.

3.3. Tensile shear strength and delamination test

The TSS and WFP after treatment A4 are presented in figure 10. As seen in fig.10 the tensile shear strength experiment, the lower the wood moisture content (during gluing), the better the bonding strength. All variants have an average TSS values higher than the normative requirement. Also the reached TSS values are similar to the ones obtained for plain wood samples. However, it is interesting to see than the wood fracture percentage is decreasing with increasing wood moisture percentage prior to bonding and with increasing primer concentration. The results of the delamination are shown in figure 11 (serie 1) and fig. 12 (serie 2) for melamine and different 1 C PUR. In the second test, the influence of two different primer concentrations and two different 1C-PUR adhesives was tested. The lamellas were conditioned at a humidity of 8% prior to gluing.

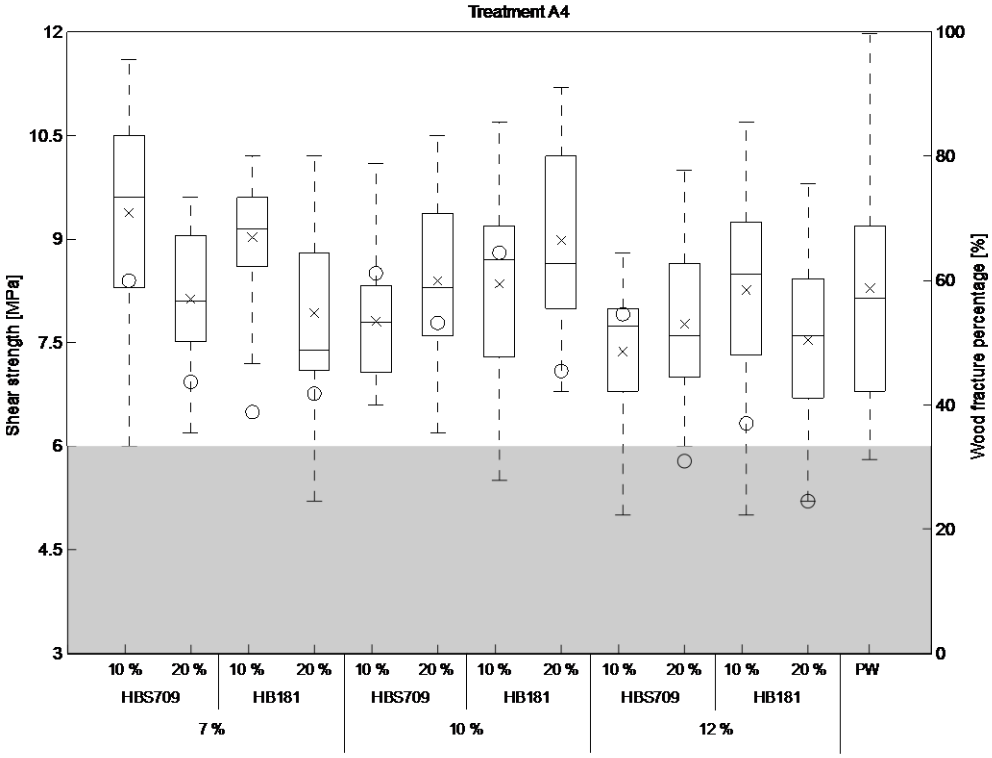


Figure 10: Tensile shear strength and wood fracture percentage after treatment A4 for ash wood and different adhesives for gluing with different moisture content, adhesives and primer concentration (pw = plain wood samples)

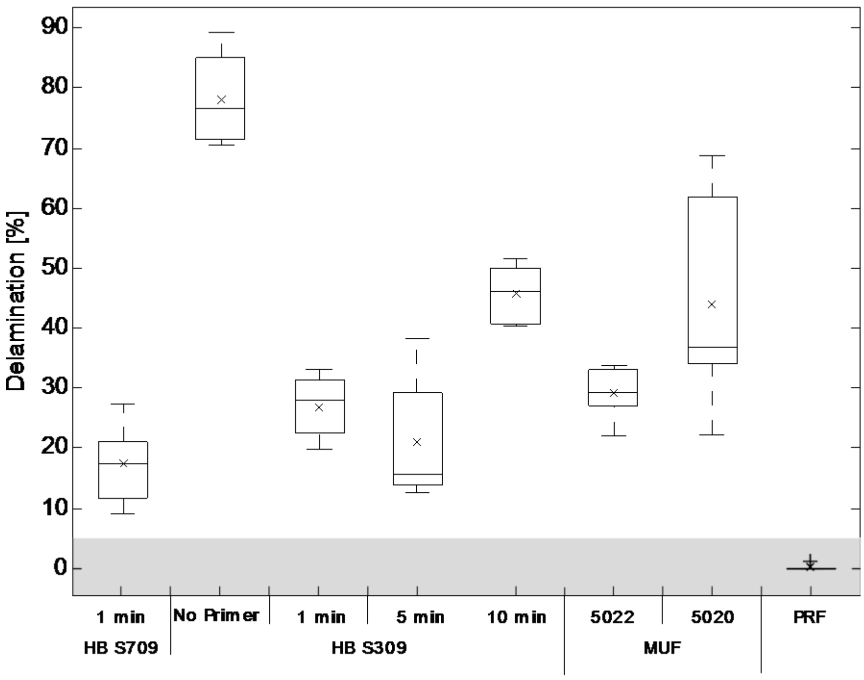


Figure 11: Influence of the Primer Influence Time (PIT) of 1C-PUR on the delamination during the preliminaries experiment in comparison with MUF (Prefere 4546/5020 and Prefere 4546/5022) and PRF (Aerodux 185) system – delamination test according to the high temperature cycle (DIN EN 302-1:2013), serie1

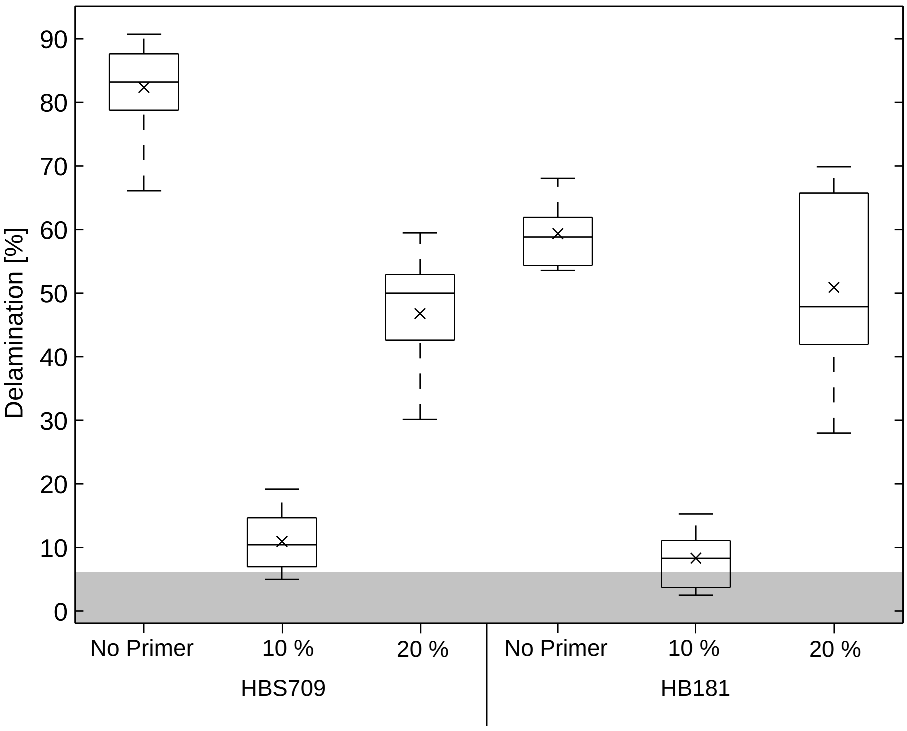


Figure 12: Delamination results for ash wood and priming with different 1 C PUR and priming with no Primer, 10 % and 20 % primer concentration for the adhesive HBS709 and HB181, serie 2

4. Conclusions

Only the PRF (Aerodux A185) and special 1 CPUR (long closed assembly time) with 10% primer concentration was able to achieve the demanded tensile shear strengths according EN 302-1 and delamination according EN 302-2 for ash wood.
This paper shows that the use of 1C-PUR adhesive with the adjunction of primer considerably improve the gluing process of glued laminated timber with ash wood in industrial conditions. However, further investigations are needed to determine the optimal concentration of primer and to better understand the effect of the water quantity in the bonding process. It is reasonable to think, that with the right choice of wood orientation and a better understanding of the primer a lower delamination could have been reached.

5. References

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