Eur. J. Wood Prod. (2016) 74:809–819
DOI 10.1007/s00107-016-1087-1

ORIGINAL

Survey of selected adhesive bonding properties of nine European softwood and hardwood species

Johannes Konnerth[1] · Marcel Kluge[1] · Georg Schweizer[1] · Milica Miljković[1] · Wolfgang Gindl-Altmutter[1]

Received: 10 November 2015 / Published online: 23 July 2016

Abstract Due to the increasing interest in applying a wider range of wood species for structural purposes, nine European softwood and hardwood species (ash, beech, birch, hornbeam, larch, oak, poplar, black locust and spruce) were assessed for their ability to be bonded with three different commercial adhesive systems (melamine–urea–formaldehyde, one-component polyurethane and phenol–resorcinol–formaldehyde). Tensile shear strength and delamination tests were conducted according to European standards, for all tests including the corresponding wood species as adhesive joints and as a solid wood reference. When tested in dry condition, the threshold of solid wood tensile shear strength was reached by all species–adhesive combinations. By contrast, testing in wet condition revealed distinct performance reductions for certain combinations. This trend was confirmed by delamination testing. Overall, the results indicate that extrapolation of test results achieved with a specific wood species (as recommended in the current standard for lap-joint tests) towards other species is highly problematic and has to be done with caution.

1 Introduction

Wood from deciduous trees is of growing interest for structural purposes due to a couple of notable features. Numerous species are available showing a wide range of properties often exceeding the performance of their coniferous counterparts, which are currently by far more frequently used in Europe for solid wood based structural products such as glue- or cross-laminated timber.

Increasing density of wood essentially results in increased mechanical properties (Niemz 1993) per volume involved. A couple of hardwood species such as ash, beech, birch, oak but also others possess higher mean density values ranging up to 670–770 kg/m^3 (Wagenführ 2007). For this reason they typically exceed the mechanical properties of the main softwood species Norway spruce having an average density of 470 kg/m^3 (Wagenführ 2007). Moreover, several types of hardwood such as oak or *Robinia* possess excellent natural durability (Pitzner et al. 2001), others are treatable, for example by impregnation with preservatives to increase their durability. Furthermore, the variety of species with regard to their optical appearance gives the potential to increase the attractiveness for their esthetic design diversity.

Using the full range of wood species would open up the chance to design structures which use the available resources more efficiently (Krackler and Niemz 2011). This could be achieved by using wood with higher mechanical performance to reinforce structures where globally or locally high mechanical properties are required. Thus, smaller cross-sections can be realized for cases where space is limited or a slim appearance is desired. This approach allows wood to increase its competitiveness to non-sustainable building materials such as steel or reinforced concrete.

Additionally, it is expected that the current distribution of tree species available in Europe will be strongly affected by the climate change. Studies indicate that conifers like Norway spruce will lose share to deciduous species such as oak (Hanewinkel et al. 2013) and beech (Felton et al.

✉ Johannes Konnerth
johannes.konnerth@boku.ac.at

[1] Department of Materials Science and Process Engineering, Institute of Wood Technology and Renewable Materials, BOKU-University of Natural Resources and Life Sciences, Vienna, Konrad Lorenz-Straße 24, 3430 Tulln, Austria

2010). Hence, a shift from conifer dominated forests towards forest with higher amounts of deciduous species is expected (Lindner et al. 2010) as discussed in corresponding literature (e.g. Milad et al. 2011; Spathelf et al. 2014; Wohlgemuth 2015).

There are still a couple of challenges and open questions when it comes to utilization of hardwood and adhesive bonding is involved. Wood from deciduous trees differ from the main species spruce, for example in surface chemistry, they show different and additionally a wide range of swelling and shrinkage behavior, the structural differences may lead to different penetration behavior and much more. Hence, there is a need to better understand the mechanisms involved in bonding and the resulting performance of solid adhesive joints of deciduous wood species. Due to their structural differences, especially the different pore systems, like diffuse- and ring-porous, such properties like penetration behavior of adhesives may be significantly altered. Sufficient adhesive penetration is an important factor. According to Kamke and Lee (2007) many factors have an influence on the penetration behavior of an adhesive. These factors are related to fluid properties of the adhesive, anatomical characteristics, permeability of the wood and finally the processing conditions. Influence of the latter was shown on the example of ash-adhesive bonds by Knorz et al. (2014) or by Schmidt et al. (2010) using beech as an adherent. However, the optimum degree of adhesive penetration is still not known (Kamke and Lee 2007). Additionally, the kind of penetration (lumen versus cell wall penetration) may have different origin and function for the bond. The penetration into cell lumen depends rather on the viscosity of the adhesive and it is considered to contribute to a mechanical interlocking, or leads at least to a certain distribution of the stresses into the wood substrate. In contrast, penetration into the cell wall is more influenced by the chemistry (Frihart 2009) and molecular size of the adhesive components, causing a modification of the cell-wall properties (Gindl and Gupta 2002; Konnerth and Gindl 2006). Thereby a locally reduced swelling is expected, which could have a significant effect on the bonding strength in humid conditions. Some species such as beech show a fast water uptake and high swelling and shrinkage movements, other species where water transport is limited, for example by tyloses as occurring in oak or black locust, but also spruce show slower water uptake and comparably lower swelling and shrinkage movements. Teischinger et al. (1998) showed on the example of spruce and beech pre-treatments for a compression-shear specimen geometry such significant differences in water uptake. As a result of the changed swelling and shrinkage behavior, humidity induced stresses in the glue lines may differ significantly between different wood species. Consequently, the humidity induced stresses, as occurring during a delamination test but also during the various treatments for lap-joint specimens, may differ from each other when different wood species are used.

Thus, the typically assumed durability (Frihart 2009) of a joint may not be comparable to the anticipated situation when the procedures of current standards are applied to a wider range of wood species.

Further differences in bondability may be a result of differences in (surface) chemistry of the wood substrates and their impact on the interface development with an adhesive system. In a very recent study comparing bondability of ash, beech and spruce wood, Ammann et al. (2016) discuss the contribution of (surface) pH, acidic and fatty acid extractive contents, and the accessibility of functional groups at the wood surface. In addition to a lower acidity, a lower concentration of OH-groups may be available for hardwood species. While the wood acidity may act as catalyst for the reaction with an adhesive, the OH-groups may be required to form stable urea or urethane bonds when using isocyanate based adhesives (Ammann et al. 2016). However even within single wood species, chemistry related differences may play a role as described by Aicher and Reinhardt (2006) who found differences in resistance to delamination of beech heart- and sapwood.

Despite the recently increasing availability of studies on bonding of deciduous tree species in Europe (e.g. Bernasconi 2004; Ohnesorge et al. 2009; Hübner 2009; Schmidt et al. 2010; Knorz et al. 2014; Ammann et al. 2016; Luedtke et al. 2015), over the past decades research focus on bonding wood for structural purposes was put almost exclusively on spruce wood. This situation may be influenced by the fact that this wood species represents by far the most important one in the European building sector as indicated by the amount of hardwood consumption in the production of glued laminated timber in Germany, Switzerland and Austria which was less than 1 % in the year 2005 (Ohnesorge et al. 2009). Thus, regarding deciduous wood species there is still a considerable need for research in order to better understand mechanisms and processes involved in bonding of these alternative wood species to ensure also long term durability of such wood adhesive bonds in the constructive sector.

The aim of the present study is to provide an overview of the bond performance of a wider range of European deciduous and coniferous wood species bonded with three currently available standard adhesives systems (melamine–urea–formaldehyde, one-component polyurethane, and phenol–resorcinol–formaldehyde) of different chemistry and mechanical properties (Stoeckel et al. 2013), with indicated suitability for bonding at least one deciduous wood species for an indicated service class.

The following questions should be answered by the study.

How are the different wood species performing in combination with the commercially available adhesive systems?

Is there a certain trend or affinity of individual wood-adhesive combinations observable?

Are the available standards suitable for assessing the bond performance also for hardwoods?

2 Materials and methods

For the current study the adhesives' performance in combination with the different wood species shall be assessed by standard testing methods to determine the lap-joint bond strength and the resistance of solid glued lamellas to delamination as proposed for the classification of structural adhesives in EN 301 (2013) and EN 1542 (2008). In addition to the recommendations of the standards, not only delamination specimens but also lap-joint specimens were manufactured using all wood species available. The assumed influence of the differences mentioned in the introduction in water interaction of the individual wood species was neglected at this point, as currently no alternative standard method is available accounting for these differences in physical properties of the individual wood species. The requirements for adhesive type I (EN 301) were chosen as a benchmark, which subjects specimens to rather harsh conditions exceeding mainly the indicated utilization classes of the selected adhesive-wood combination (if available). The intention of this approach was basically rather to allow for monitoring differences between the various wood specimens and their response to the individual adhesive systems, than assigning the adhesives to a certain service class.

2.1 Wood

Nine wood species were used to prepare specimens intended for testing of tensile shear strength and resistance to delamination. Thereof mainly hardwood of seven deciduous and two coniferous wood species were chosen for the experiment, namely European ash (*Fraxinus excelsior* L.), European beech (*Fagus sylvatica* L.), European silver birch (*Betula verrucosa* Ehrh.), common hornbeam (*Carpinus betulus* L.), sessile oak (*Quercus petraea* Liebl.), poplar (*Populus* sp.), black locust (*Robinia pseudoacacia* L.), European larch (*Larix decidua* Mill.) and Norway spruce [*Picea abies* (L.) Karst.]. Raw wood was stored for a minimum of 1 week in standard climate at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 %. Prior to further processing (planing and bonding), wood moisture content via electrical resistance (GANN, Hydromette 4050, Gerlingen, Germany) as well as the density of all specimens were determined (Table 1).

Table 1 Wood moisture content and density

Wood species	Mean wood moisture content (%)	Standard deviation	Mean density (g/cm^3)	Standard deviation
Ash	11.93	0.8	0.670	0.035
Beech	12.52	1.17	0.743	0.026
Birch	12.36	1.00	0.682	0.025
Hornbeam	12.30	1.24	0.533	0.187
Larch	11.55	1.24	0.632	0.06
Oak	11.39	0.45	0.698	0.023
Poplar	12.16	0.92	0.396	0.021
Black locust	10.32	1.81	0.775	0.021
Spruce	12.74	0.7	0.445	0.028

2.2 Adhesives and bonding parameters

Three different types of adhesives were used: a one-component polyurethane adhesive (1C PUR, LOCTITE® HB S309 PURBOND®, Henkel & Cie AG, Sembach Station, Switzerland), a melamine–urea–formaldehyde adhesive (MUF, GripPro™ Design Adhesive A002 and GripPro™ Design Hardener 002, AkzoNobel, CASCO ADHESIVES AB, Stockholm, Sweden), and a phenol–resorcinol–formaldehyde adhesive (PRF, Aerodux 185 and hardener HRP 150, Dynea AS–Synthesa Chemie GmbH, Perg, Austria). Based on producer's recommendations deciduous wood bonded with 1C PUR was pre-treated with a primer (LOCTITE® PR 3105 PURBOND®, Henkel & Cie AG, Sembach Station, Switzerland) before adhesive application. The concentrations of the primer solution in distilled water and the applied primer quantity on the bonding surface were selected according to adhesive producer recommendations and are shown in Table 2. The primer solution was applied on both adherents using a paintbrush. An open pre-reaction time of a minimum of 10 min followed the application of the primer solution.

All adhesives were processed according to manufacturer's recommendations as shown in Table 3.

For both MUF and PRF adhesive and hardener were mixed in a ratio of 100:20 (based on weight percent), whereby in the case of PRF a minimum maturation time of the adhesive and hardener mixture of 10 min was applied. All adhesives were uniformly spread with the help of a toothed spatula. In case of 1C PUR and MUF adhesive was applied on one adherent only, whereas for PRF adhesive was applied on both adherents. In general, lamellae were instantly jointed together in order to keep the open assembly time to a minimum. After assembling, the

Table 2 Primer parameters for different wood species bonded with 1C PUR

Wood species	Primer concentration in weight percent (%)	Primer quantity (g/m^2)
Ash	5	10
Beech	10	20
Birch	5	
Hornbeam	10	
Oak	20	
Poplar	10	
Black locust	5	

recommended closed assembly time of 10 min followed in case of 1C PUR, 10–30 min for MUF, and less than 60 min at 20 °C for PRF. Pressing was performed at ambient temperature for most adhesive joints. Only in the case of PRF for the manufacture of glued lamellas for tensile shear specimens, pressing was performed at an elevated temperature of 80 °C in order to enable reducing the hot pressing time to 20 min (except for beech specimens).

2.3 Longitudinal tensile shear tests

Preparation of specimens for tensile shear testing was performed according to EN 302-1 intended for a bond-line thickness of 0.1 mm. After coarse cutting, all lamellae were stored at standard climate (relative humidity of 65 %, temperature of 20 °C) for 7–14 days. Immediately prior to bonding, lamellae were planed to obtain the required final thickness of 5 mm. In addition to the bonded specimens, ten blank test samples (i.e. tensile shear test specimens produced out of solid wood lamellas of 10 mm thickness, having identical geometry to bonded lap joint specimens) for each wood species were prepared as a reference in order to evaluate tensile shear strength of the corresponding wood itself. These reference specimens were treated and tested in the same way as the bonded samples.

Tensile shear strength was determined according to EN 301-1 (2013). Benchmark strength values are indicated in EN 301 and EN 15425. These standards anticipate minimal values for mean tensile shear strength for beech as an adherent to fulfill standard requirements.

Prior to mechanical testing, specimens were treated using three different treatment types (A1, A2, A4) according to EN 302-1, as shown in Table 4. All samples were randomly divided for the three different treatment types.

Mechanical testing was done using a universal testing machine (Z020 and Z100, Zwick/Roell, Ulm, Germany). A zero span of 70 mm and a cross-head speed of 1.2 mm/min were chosen resulting in a total testing time between 30 and 90 s per specimen. Tensile shear strength was calculated by dividing the maximum (failure) load by the measured area of the shear plane of the respective state prior to testing, which was roughly 200 mm^2. Wood failure percentage was estimated visually, rounded to the nearest 10 %.

2.4 Resistance to delamination

For each wood specimen and adhesive type six lamellae were bonded to form one glue-laminated timber beam of 500 mm length. All lamellae were planed to obtain the demanded lamella thickness of 30 mm. Bonding was performed as already described in Sect. 2.2. Specimen preparation, testing and determination of resistance to delamination were conducted according to EN 301-2 (2013). This test aims at evaluating the resistance of bond lines against delamination due to induced swelling and shrinkage movements of the wood as a response to

Table 3 Selected bonding parameters for applied adhesives: one-component polyurethane (1C PUR), melamine–urea–formaldehyde (MUF), phenol–resorcinol–formaldehyde (PRF)

Adhesive	1C PUR			MUF			PRF		
Wood species	Specific pressure (N/mm^2)	Pressing time (min)	Adhesive spread rate (g/m^2)	Specific pressure (N/mm^2)	Pressing time (min)	Adhesive spread rate (g/m^2)	Specific pressure (N/mm^2)	Pressing time (min)	Adhesive spread rate (g/m^2)
Ash	0.8	150	160	1.4	120	400	1.4	20 at 80 °C/240 at 20 °C	225
Beech								240 at 20 °C	
Birch				0.8			0.8	20 at 80 °C for lap-joints /240 at 20 °C for delamination test	
Hornbeam				1.4			1.4		
Oak				1.4		350	1.4		
Poplar				0.7		400	0.7		
Black locust				1.4			1.4		
Larch		75		0.7		325	0.7		
Spruce									

Table 4 Treatment types according to EN 302-1

A1	Storage in standard climate at 20 ± 2 °C and a relative humidity of 65 ± 5 %, testing in dry condition
A2	Additionally to A1, storage in water at 20 ± 5 °C for 4 days, testing in wet condition
A4	Additionally to A1, 6 h in boiling water, 2 h storage in water at 20 ± 5 °C, testing in wet condition

changing moisture conditions. For this purpose, specimens were subjected to alternating climate conditions—cycles of water soaking with the help of vacuum/pressure cycles using an autoclave and subsequent kiln-drying. According to EN 302-2, the procedure at elevated drying temperature of 65 °C for testing adhesives according to type I requirements was applied, conducting three cycles of water impregnation and subsequent drying. The resistance to delamination was determined according to the following equation: $D = \frac{l_1}{l_2} \times 100\ (\%)$, where D is the delamination in percent; l_1 is total length of delamination on both cross sections in mm; l_2 is total length of bonding lines on both cross sections in mm. Lengths l_1 and l_2 were measured with the help of a digital caliper and when needed with the help of a reflected-light microscope.

3 Results and discussion

3.1 Tensile shear strength

Standard benchmark values for the mechanical performance of lap-joint specimens are available in EN 301 and EN 15425 for beech specimens only, as its use is obligatory for adhesive assessment according to EN 302-1. As it is assumed that such a benchmark value is based on the strength of solid wood of the corresponding load case (i.e., without an adhesive bond, as basically wood failure is expected), such reference values were obtained for each wood species in longitudinal tensile shear mode together with the specific density.

The corresponding strength and density values are indicated in Fig. 1 for standard climate condition (corresponding to treatment type A1), whereby the obtained density values show comparable magnitudes with the ones from Wagenführ (2007). As a general trend tensile shear strength increases with increasing density which is usually expected and well reported in literature on physical and mechanical properties of solid wood (e.g. Niemz 1993). However, specimens of hornbeam performed slightly below and ash specimens slightly above the general trend. Additionally, strength variability tends to increase for wood species possessing higher density such as black locust, hornbeam, beech and birch. Similar reference values of solid wood (i.e., without an adhesive bond) are available for each wood species and all treatment types, as indicated within the results for tensile shear strength testing at A1, A2 and A4 treatments (Figs. 2, 3, 4). Further, Kläusler et al. (2014a) used the same concept of supplement solid wood samples for comparison. They mentioned that these reference samples should be interpreted with some caution, beside others due to differences in stress distribution compared to bonded samples. Nevertheless, they concluded that such samples appear to be the best feasible way for a comparative evaluation of the wooden adherent.

As a general trend, the performance of lap-joint specimens in dry (A1) condition of almost all wood adhesive joint combinations performs very close to the expected performance potential of the unbonded solid wood (Fig. 2). As a matter of course the absolute performances of the joints differ significantly depending on the wood species involved: i.e., poplar joints show lowest performance, followed by spruce and larch. The high density species perform significantly higher, a trend which is well in line with the density depending tensile shear strength already described before. Related to the mean performance of solid wood, the adhesive joints reach mean tensile shear strength values ranging from 84–127 % and corresponding wood failure percentages of better than 70 % for all joints based on mean values. Such high wood failure is typically associated with proper adhesion (Niemz 1993), but discrepancies between wood failure and observed strength were also reported in literature (Clauß et al. 2008; Ammann et al. 2016).

The benchmark values indicated for beech in the standard EN 301 could be reached for most adhesive-wood combinations especially for wood species with comparable or higher strength potential to beech (i.e. ash, birch, *Robinia* and with limitations also for oak and hornbeam due to the slightly lower strength of the raw material). Results for ash and beech in dry conditions (A1) are well in line with literature values (e.g. Niemz and Allenspach 2009; Konnerth et al. 2006; Ammann et al. 2016). In addition, spruce performance is comparable to single references (Konnerth et al. 2006), but also higher values have been reported for spruce (e.g., Künniger et al. 2006). Regarding larch, lower values can be found by Künniger et al. (2006) for European larch and comparable ones for Siberian larch.

The significant variability of strength values for most wood-adhesive combinations is to be noted, whereby spruce with approx. 10 % shows the lowest coefficients of variation.

Changing to wet conditions (treatments A2 and A4), results differentiate much more as illustrated in Figs. 3 and 4. Here, beech, ash and oak bonded specimens still perform

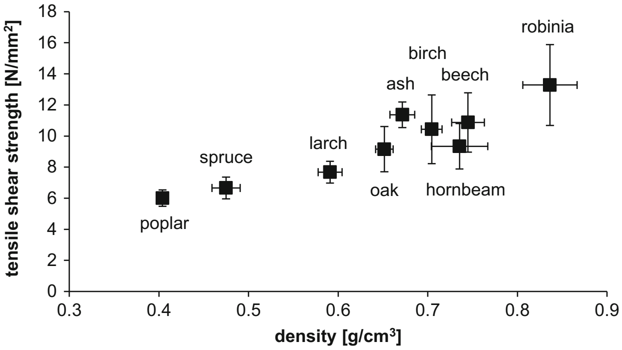


Fig. 1 Tensile shear strength and density of solid wood specimens at standard conditions (20 °C, 65 % rel. humidity; *squares* represent the arithmetic mean; *error bars* represent the standard deviation)

at a level of 81–125 % for A2 compared to the solid wood reference exposed to the same treatments. Beech and ash retained 95–135 % of their strength even for A4 treatments. In contrast, species like birch, poplar, hornbeam and *Robinia* but also spruce show a considerable loss in bond strength with respect to the unbonded reference treated at the same conditions. According to the standards (EN 301, EN 15425), beech specimens could satisfy the requested minimum 6 N/mm^2 for both treatment types (A2, A4) for all adhesive systems used.

With respect to the suggestions indicated in the standard (EN 301, EN 302-1), all three adhesive systems may be regarded as suitable for structural applications based on lap-joint testing, as beech is the only wood species recommended for its assessment (of course other tests, such as delamination, have to be fulfilled in addition).

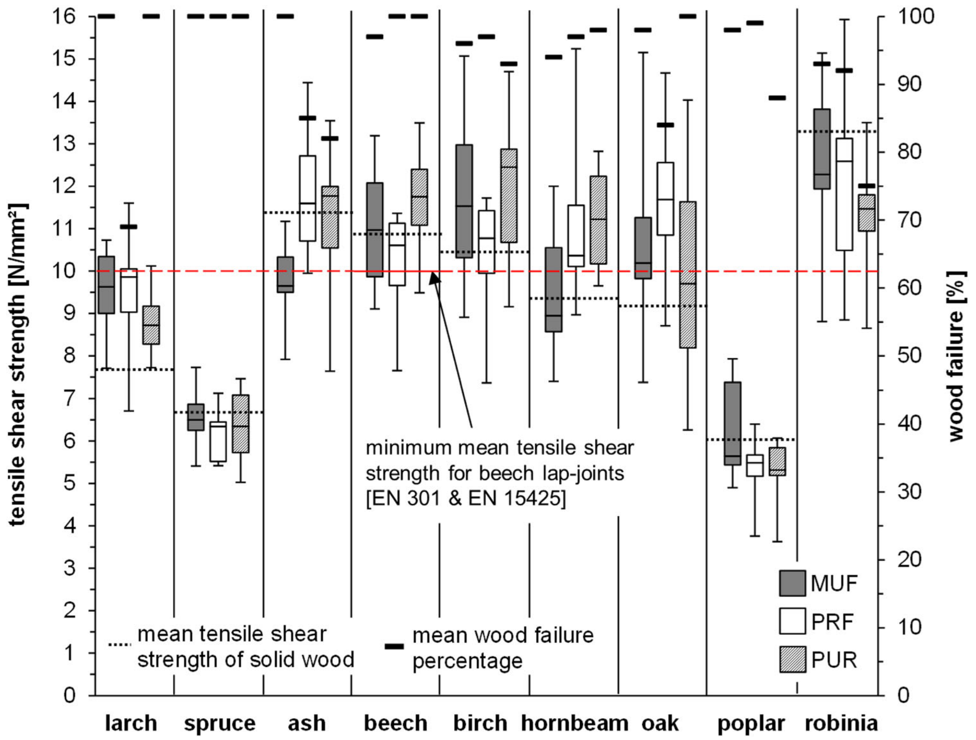
For beech, the application of a primer as intensively investigated by different studies (Kläusler et al. 2014a; Hass et al. 2014) and recommended by the adhesive manufacturer seems to assure proper bonding behavior of PUR on beech substrates.

Nevertheless, using the adhesive-adherent combination of the later joint during this test, as performed in the present study, weak links could be identified already at this state, provided that proper benchmark values for tensile shear strength are available.

Wood adhesive combinations showing the most evident examples of strength loss and additionally a drop in wood failure are larch and *Robinia* bonded with PUR as example. Inferior bondability of larch when using PUR has already been observed in other studies, whereby other adhesives did show good bondability even after A4 treatment. In a study on the influence of arabinogalactan on bonding behavior with PUR, Künniger et al. (2006) found a significant influence of the extractive for A3 (water stored and re-conditioned) treated specimens and attributed the weaker larch-PUR bonds to their presence. Additionally, Siberian larch performed better than European larch in their study; anyhow the corresponding density was not reported for these two groups of specimens.

Interestingly, the performance of unbonded A2 treated (cold water) larch was significantly superior to the A4 (hot water) larch specimens in the present study, which is the

Fig. 2 Comparison of tensile shear strength and wood failure percent for A1 treatment for the various wood adhesive combinations (N = 9, …, 15). *Box* and *whisker plots* indicate median, 25 %, and 75 % percentile, maximum and minimum values, which are not outliers



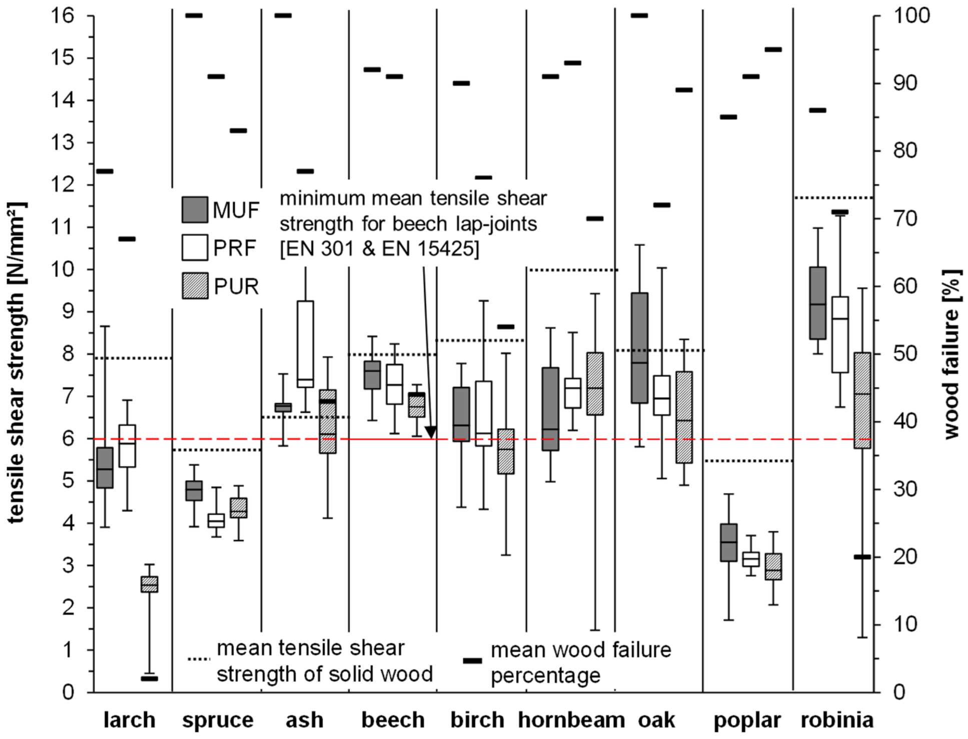


Fig. 3 Comparison of tensile shear strength (fv) and wood failure percentage for A2 treatment for the various wood adhesive combinations (N = 9, …, 15). *Box* and *whisker plots* indicate median, 25 %, and 75 % percentile, maximum and minimum values, which are not outliers

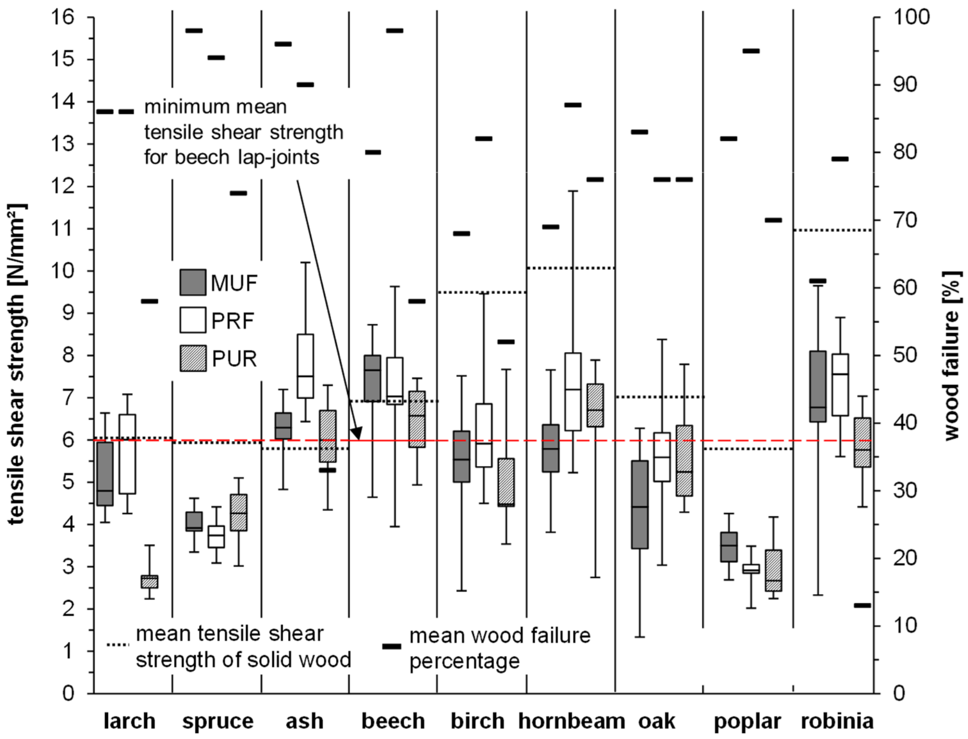


Fig. 4 Comparison of tensile shear strength (fv) and wood failure percentage for A4 treatment for the various wood adhesive combinations (N = 9, …, 15). *Box* and *whisker plots* indicate median, 25 %, and 75 % percentile, maximum and minimum values, which are not outliers

reason why a relative loss in performance for A2 bonded specimens is apparent. Same as tensile shear strength, wood failure amounts had wider distribution.

Using a block shear set-up and various adhesives, Jiang et al. (2014) investigated spruce, larch, ash and beech bonds. Due to the different loading situation results are not directly comparable. However, related to the individual wood species they also found relatively high values for ash and beech bonds after A2 and A4 treatment using PRF, EPI and MUF. In contrast to the present study they found

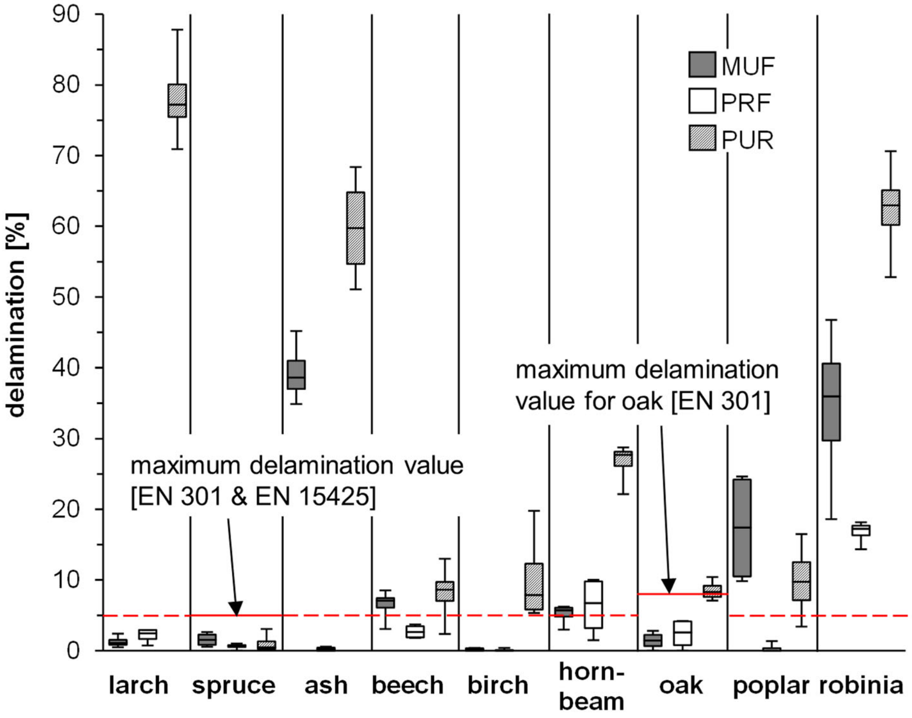


Fig. 5 Resistance to delamination for the 27 wood adhesive combinations (N = 4). *Box* and *whisker plots* indicate median, 25 %, and 75 % percentile, maximum and minimum values, which are not outliers

reduced performance for beech and ash PUR bonds. In both, theirs and the present study PRF and MUF performed best for larch. Whereas spruce reached comparable performance for all adhesive systems used, again this was observed in both studies.

3.2 Delamination

The compatibility of wood species with an adhesive is usually analyzed with the help of a delamination test (EN 302-2). In contrast to the lap-joint tests (EN 302-1) where beech wood is recommended for the specimen preparation, delamination tests require spruce wood and also the wood of the later joint for this assessment.

According to the delamination test, the tested PRF adhesive shows highest compatibility to several wood species except for black locust and hornbeam (Fig. 5).

The other adhesives showed a more differentiated behavior as discussed in detail in the next section.

Regarding the testing methodology, Aicher and Reinhardt (2006) have already pointed out the need for further adapting the testing methodology of the EN 302-2, which was originally designed for softwood. When it comes to the utilization of a wider selection of hardwoods, beside others significant differences in swelling and shrinkage behavior is expected. Thus, the procedures described in the current standard are not adequate anymore and probably the meaning of the results generated is not comparable anymore as well. Observed at the drying process of the utilized wood species, the following differences become evident: most wood species needed much more time to reach the initial mass demanded during re-drying after the impregnation steps with water. Currently a maximum of 30 h is suggested by the testing standard, whereby beech, birch and hornbeam needed 40–45 h to dry. Ash, oak and poplar required 50–70 h to reach the initial mass. Black locust as an exception needed less than 3 h to achieve its original dry weight. Same as observed for the drying may be true for the wetting process, where a full saturation is probably not fulfilled for the high density species (e.g., *Robinia*, oak) as reported by Teischinger et al. (1998) in context with another test set-up. As a consequence, in combination with the differences in tangential swelling and shrinkage amount, the strain and thus the stresses induced with the swelling and shrinkage cycles are neither comparable nor reproducible for the wood species applying the procedures currently described in the standards.

3.3 Comparison of results

Overall the results of the lap-joint tests show partially similar trends to the results of the delamination test, but some wood-adhesive combinations differ significantly (Table 5). Different to the results of the lap-joint tests (A4), spruce, birch and poplar would be regarded as bondable due to low delamination values. These species possess low swelling and shrinkage behavior; consequently induced stresses may be reduced compared to beech wood or hornbeam.

Table 5 Overview of lap-joint and delamination results

Wood species	Lap-joint strength—A1 treatment				Lap-joint strength—A2 treatment				Lap-joint strength—A4 treatment				Delamination		
	Reference (MPa)	MUF (%)	PRF (%)	PUR (%)	Reference (MPa)	MUF (%)	PRF (%)	PUR (%)	Reference (MPa)	MUF (%)	PRF (%)	PUR (%)	MUF (%)	PRF (%)	PUR (%)
Ash	11.4	113	99	114	6.5	77	78	67	5.8	58	65	53	39.3	0.2	59.7
Beech	10.9	102	94	108	7.9	94	91	85	6.9	109	104	95	6.4	2.7	8.2
Birch	10.4	116	127	109	8.3	101	90	81	9.5	62	82	79	0.2	0.1	10.2
Hornbeam	9.3	85	105	99	9.9	104	125	96	10.1	108	135	104	5.2	6.2	26.6
Larch	7.7	98	92	96	7.9	83	72	75	6.0	68	63	72	1.3	2.1	78.3
Oak	9.2	101	116	120	8.1	67	72	68	7.0	58	73	65	1.4	2.3	8.5
Poplar	6.0	124	123	115	5.5	71	73	29	5.8	85	95	45	17.3	0.3	9.9
Black locust	13.3	104	89	88	11.7	62	58	54	10.9	60	51	52	34.3	16.8	62.3
Spruce	6.7	96	91	84	5.7	79	74	57	5.9	64	67	54	1.6	0.6	1.0

Lap-joints: relative change of mean tensile shear strength compared to the mean strength of the solid reference of the same species; labeling for facilitating overview: white >80 %, grey 70–80 %, black <70 %; delamination: amount of delamination related to the bond-line length, labeling: white <5 %, grey 5–10 %, black >10 %

Similar differences can be seen using MUF where again spruce, birch and additionally oak performed well according to the delamination test. Exactly these species showed significant strength losses after A4 treatment during lap-joint testing. In contrast, PUR clearly fulfilled requirements for spruce delamination only, and delamination was slightly too high for birch, oak, poplar and beech. However, the lap-joint performance of the latter was high using all treatments and thus fulfilling the standard. A couple of wood species showing a significant loss in performance also for the A2 and A4 treated lap-joints such as larch, hornbeam and *Robinia* exhibited again low performance during delamination test. Thus, the results of both testing methodologies are confirming each other in the case of PUR. In great contrast is ash showing very good performance during all lap-joint tests, but specimens completely fail during delamination using MUF and PUR. Ammann et al. (2016) displayed similar results for MUF bonded ash, although the surface was face-milled and slightly different process parameters were applied. None of their tested adhesives passed the delamination test.

In the studies by Knorz et al. (2015) and Kläusler et al. (2014b) surface preparation and the closed assembly time were found to influence the performance of ash (Knorz et al. 2014) but also beech (Schmidt et al. 2010) bonds. For ash, they found best performance using PRF, whereby a long closed assembly time improved the performance. Using the same primer and a comparable adhesive type, Luedtke et al. (2015) found significantly lower delamination for ash (3–5 %), and comparable delamination values for the other wood species using the same primer as used in the present study; however, they applied one instead of three impregnation-drying cycles only.

Regarding the actual performance of the individual wood-adhesive combinations, there will not be one single or simple explanation for the reasons for the observed differences in bonding behavior. Further, it was not the intent of the present study to provide fundamental explanations. However, of course various factors are contributing to the performance of wood adhesive bonds, as superficially discussed in the introduction. These factors may have had influence on the observed results here too. Penetration behavior is such a factor which could give some explanation for the observed differences as reviewed by Kamke and Lee (2007). Furthermore, the adhesive group and their related ability to stabilize the interphase, enabling a proper stress transfer will have an impact (Frihart 2009). Here, the tested PUR adhesive seems to have some disadvantages with its lacking ability to penetrate the cell walls and stabilize the interphase, visible in the minor number of wood species where proper bonding may be expected. Wettability (e.g. Gardner et al. 1991; Piao et al. 2010), which was not assessed here, would additionally allow for some prediction of the bondability. To some extent extractives will also influence the performance of the bonds, whereby the various adhesives respond extremely different to them (e.g. PUR in the case of larch). However, the multiple interacting mechanisms involved may not be sufficiently described in this study as it was basically reported on observations of differences in performance of the tested adhesive-wood combinations.

One interesting finding becomes evident by analyzing Table 5: all adhesive systems tested here show positive performance using beech wood for lap-joint tests. Furthermore, all spruce wood delamination tests could clearly pass the standard requirement. As the European standards recommend especially these wood species for the corresponding tests, it is assumed that a performance optimization of adhesives especially for passing these tests, using the indicated wood specimens, has taken place over the last years.

Another major finding may be derived from this study: the delamination test is considered as a main testing methodology aiming at assessing the compatibility of an adhesive system to a specific wood substrate of the later application. This test is often linked to durability due to the lack of other methodologies (Aicher and Reinhardt 2006). This test may be regarded as insufficient when more than just spruce or beech wood is utilized. The observed significant differences (Table 5) between delamination tests and lap-joint tests using the other wood species are evident. Omitting lap-joint tests with the substrate of the later joint could result in a lack of important information. Such missing information of lap-joint performance of specific adhesive-wood combinations may be critical or, on the other hand, would enable gaining much more information on individual adhesive-wood compatibility to an individual substrate. Still, benchmark values for the tensile shear strength of the individual wood species are missing or have to be elaborated.

It is self-explanatory that the observations describing and discussing performances of adhesive-wood interactions are limited to the individual commercial adhesive systems used in the present study and may not be generalized for an entire group of adhesives.

4 Conclusion

Based on the results observed by assessing wood-adhesive bonds with the help of lap-joint and delamination tests, the following conclusions may be drawn.

Stimulated by the standard requirements the adhesive systems analyzed seem to be optimized to pass beech wood lap-joint and spruce wood delamination tests.

In dry condition all wood species perform well with all commercial adhesive systems (MUF, PRF, PUR) tested. Significant differences in lap-shear performance can be found after treating specimens with water (A2, A4), whereby beech, ash, and oak bonds showed superior performance, regardless of the adhesive system used.

The tested PRF showed best performance with most wood species also after delamination testing except for *Robinia* and hornbeam.

In general, results of delamination tests differ for some wood species significantly to the ones of the lap-joint test.

Thus, it is assumed that including the assessment of lap-joints using additionally the adherent of the later application would result in considerably more information about the expected bond performance. Overall, the results indicate that extrapolation of test results achieved with a specific wood species (currently beech) towards other species is highly problematic and has to be done with caution.

Acknowledgments The data for this study was collected by students of the Master program "Wood Technology and Management" during the laboratory course "Wood industry laboratory" at the University of Natural Resources and Live Sciences, Vienna. Apart from the authors contributing participants were: Daniel Ballner, Peter Bliem, Paul Ehgartner, Anton Gradinger, Christian Huber, Štěpán Hýsek, Marko Kovacevic, Christian Lamberg, Milkica Milutinovic, Pascal Perhab, Clemens Rauch, Erwin Salzger, Andreas Schindler, Christian Schuster and Wolfgang Stallinger.

References

Aicher S, Reinhardt H-W (2006) Delaminierungseigenschaften und Scherfestigkeiten von verklebten rotkernigen Buchenholzlamellen [Delamination characteristics and shear strength of bonded beech lamellas with red heartwood]. Holz Roh-Werkst 65:125–136

Ammann S, Schlegel S, Beyer M, Aehlig K, Lehmann M, Jung H, Niemz P (2016) Quality assessment of glued ash wood for construction engineering. Eur J Wood Wood Prod 74(1):67–74. doi:10.1007/s00107-015-0981-2

Bernasconi A (2004) Verleimung von Laubholz für den tragenden Einsatz [Gluing of hardwood for supporting construction elements]. Schweiz Z Forstwes 155:533–539

Clauß S, Kläusler O, Allenspach K, Niemz P, Bächle F, Dijkstra DJ (2008) Forschungsbericht für das Kuratorium des Fonds zur Förderung der Wald- und Holzforschung Nr. 2006.08: Untersuchung zur Optimierung von 1 K-PUR Klebstoffen für die Verklebung von Vollholz: Abschlussbericht [Research report for the board of trustees of the fund to support forest and wood research No 2006.08: Investigations to optimize 1C-PUR adhesives for bonding of solid wood: Final report]. ETH Zürich, Institute for Building materials, Wood physics, Zurich

EN 15425 (2008) Adhesives—one component polyurethane for load bearing timber structures—classification and performance requirements. European Committee for Standardization, Brussels

EN 301 (2013) Adhesives, phenolic and amino plastic, for load-bearing timber structures—Classification and performance requirements. European Committee for Standardization, Brussels

EN 302-1 (2013) Adhesives for load-bearing timber structures—test methods—part 1: determination of longitudinal tensile shear strength. European Committee for Standardization, Brussels

EN 302-2 (2013) Adhesives for load-bearing timber structures—test methods—part 2: determination of resistance to delamination. European Committee for Standardization, Brussels

Felton A, Lindbladh M, Brunet J, Fritz Ö (2010) Replacing coniferous monocultures with mixed-species production stands: an assessment of the potential benefits for forest biodiversity in northern Europe. For Ecol Manag 260:939–947

Frihart CR (2009) Adhesive groups and how they relate to the durability of bonded wood. J Adhes Sci Technol 23:601–617

Gardner DJ, Generalla NC, Gunnells DW, Wolcott MP (1991) Dynamic wettability of wood. Langmuir 7:2498–2502

Gindl W, Gupta HS (2002) Cell-wall hardness and Young's modulus of melamine-modified spruce wood by nano-indentation. Compos Part A Appl Sci Manuf 33:1141–1145

Hanewinkel M, Cullmann DA, Schelhaas M-J, Nabuurs G-J, Zimmermann NE (2013) Climate change may cause severe loss in the economic value of European forest land. Nat Clim Chang 3:203–207

Hass P, Kläusler O, Schlegel S, Niemz P (2014) Effects of mechanical and chemical surface preparation on adhesively bonded wooden joints. Int J Adhes Adhes 51:95–102

Hübner U (2009) Laubhölzer für lastabtragende Bauteile im Bauwesen [Hardwoods for load-bearing elements in the constructive sector]. OIB Aktuell 10:12–23

Jiang Y, Schaffrath J, Knorz M, Winter S, van de Kuilen J-W (2014) Applicability of various wood species in glued laminated timber: parameter study on delamination resistance and shear strength. In: WCTE 2014 Proc. World Conf. Timber Eng. Quebec, Canada, 10–14 Aug 2014

Kamke FA, Lee JN (2007) Adhesive penetration in wood: a review. Wood Fiber Sci 39:205–220

Kläusler O, Hass P, Amen C, Schlegel S, Niemz P (2014a) Improvement of tensile shear strength and wood failure percentage of 1C PUR bonded wooden joints at wet stage by means of DMF priming. Eur J Wood Wood Prod 72:343–354

Kläusler O, Rehm K, Elstermann F, Niemz P (2014b) Influence of wood machining on tensile shear strength and wood failure percentage of one-component polyurethane bonded wooden joints after wetting. Int Wood Prod J 5:18–26

Knorz M, Schmidt M, Torno S, van de Kuilen J-W (2014) Structural bonding of ash (*Fraxinus excelsior* L.): resistance to delamination and performance in shearing tests. Eur J Wood Wood Prod 72:297–309

Knorz M, Neuhaeuser E, Torno S, van de Kuilen J-W (2015) Influence of surface preparation methods on moisture-related performance of structural hardwood–adhesive bonds. Int J Adhes Adhes 57:40–48

Konnerth J, Gindl W (2006) Mechanical characterisation of wood-adhesive interphase cell walls by nanoindentation. Holzforschung 60(4):429–433

Konnerth J, Gindl W, Harm M, Müller U (2006) Comparing dry bond strength of spruce and beech wood glued with different adhesives by means of scarf- and lap joint testing method. Holz Roh Werkst 64:269–271

Krackler V, Niemz P (2011) Schwierigkeiten und Chancen in der Laubholzverarbeitung: Teil 1: Bestandssituation, Eigenschaften und Verarbeitung von Laubholz am Beispiel der Schweiz [Difficulties and prospects in hardwood processing: part 1: current situation, properties and processing of hardwoods on the example of Switzerland]. Holztechnologie 2:5–11

Künniger T, Fischer A, Bordeanu NC, Richter K (2006) Water soluble larch extractive: impact on 1P-PUR wood bonds. In: Kurjatko S, Kudela J, Lagana R (eds) 5th UFRO Symposium Wood structures and properties '06. Technical University Zvolen, Slovakia p 71–76

Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer M, Marchetti M (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manag 259:698–709

Luedtke J, Amen C, van Ofen A, Lehringer C (2015) 1C-PUR-bonded hardwoods for engineered wood products: influence of selected processing parameters. Eur J Wood Wood Prod 73:167–178

Milad M, Schaich H, Bürgi M, Konold W (2011) Climate change and nature conservation in Central European forests: a review of consequences, concepts and challenges. For Ecol Manag 261:829–843

Niemz P (1993) Physik des Holzes und der Holzwerkstoffe [Physics of wood and wood-based products]. DRW-Verlag, Leinfelden-Echterdingen

Niemz P, Allenspach K (2009) Untersuchungen zum Einfluss von Temperatur und Holzfeuchte auf das Versagensverhalten von ausgewählten Klebstoffen bei Zugscherbeanspruchung [Investigations into the influence of temperature and wood moisture content on the failure behavior of selected adhesives at tensile shear stress]. Bauphysik 31:296–304

Ohnesorge D, Henning M, Becker G (2009) Review: bedeutung von Laubholz bei der Brettschichtholzherstellung: Befragung unter BSH-Produzenten in Deutschland, Österreich und der Schweiz [Review: relevance of hardwoods for the production of glued laminated timber: survey among GLT-manufacturers in Germany, Austria and Switzerland]. Holztechnologie 50:47–49

Piao C, Winandy JE, Shupe TF (2010) From hydrophilicity to hydrophobicity: a critical review: part I. Wettability and surface behavior. Wood Fiber Sci 42:490–510

Pitzner B, Bernasconi A, Frühwald A (2001) Arbeitsbericht aus dem Institut für Holzphysik und mechanische Technologie des Holzes Nr. 2001/5: Verklebung einheimischer dauerhafter Holzarten zur Sicherung von Marktbereichen im Außenbau [Work report of the institute for wood physics and mechanical technology of wood No 2001/5: bonding of domestic wood species with natural durability to secure market sectors for exterior solutions]. Bundesforschungsanstalt für Forst- und Holzwirtschaft, Hamburg

Schmidt M, Glos P, Wegener G (2010) Verklebung von Buchenholz für tragende Holzbauteile [Bonding of beech wood for structural wooden components]. Eur J Wood Wood Prod 68:43–57

Spathelf P, van der Maaten E, van der Maaten-Theunissen M, Campioli M, Dobrowolska D (2014) Climate change impacts in European forests: the expert views of local observers. Ann For Sci 71:131–137

Stoeckel F, Konnerth J, Gindl-Altmutter W (2013) Mechanical properties of adhesives for bonding wood—a review. Int J Adhes Adhes 45:32–41

Teischinger A, Fellner J, Eberhardsteiner J (1998) Überlegungen zur Entwicklung eines Probekörpers zur Prüfung der Verleimungsqualität von Dreischicht-Massivholzplatten, Teil 1 [Considerations for the development of a test specimen to assess the bonding quality of three-layered solid wood panels]. Holzforsch Holzverwert 50:99–103

Wagenführ R (2007) Holzatlas [Atlas of woods], 6th edn. Fachbuchverlag Leipzig, München

Wohlgemuth T (2015) Climate change and tree responses in Central European forests. Ann For Sci 72:285–287