WOOD RESEARCH
58 (1): 2013
43-56

FRACTURE PROPERTIES OF ADHESIVE JOINTS UNDER MECHANICAL STRESSES

Pierre Watson, Sebastian Clauss, Samuel Ammann, Peter Niemz
Eth Zurich, Institute for Building Materials, Wood Physics
Zurich, Switzerland

(Received May 2012)

ABSTRACT

In this study, three commonly used wood adhesives, one-component polyurethane adhesive (1C PUR), polyvinyl acetate adhesive (PVAc), and melamine-urea formaldehyde resin (MUF) as well as solid wood control samples were tested on beech wood in opening-mode (mode I) fracture using a compact tension (CT) test. The purpose of this study was to characterize the fracture properties of glued wooden laminates in different climate conditions in order to gain a better understanding of the influential factors in delamination. Based on the results, the adhesive type and moisture content of the test samples had a large effect on the fracture characteristics. The performance of the different adhesive types varied greatly between adhesives and at different climate conditions with the significant indicators being low wood failure percentage, fracture toughness values lower than solid wood, and prominent adhesive failure.

KEYWORDS: Delamination, fracture, adhesive, compact tension, beech.

INTRODUCTION

Since bonding of wood became popular, one of the biggest issues in performance of glued laminated timber is delamination. Delamination usually leads to failure of the structure and can occur subcritically at loads lower than the stated critical load of the overall structure (Bucur 2011), the exact reasons for delamination processes are not yet known due to the lack of reliable mechanical tests to characterize the fracture properties of the adhesive joints.

Many factors can cause delamination such as faulty bonding, the element structure, high stresses, and fatigue due to climatic stresses. Delamination caused by moisture is especially pronounced in cross-laminated wood materials with strongly divergent swelling and shrinking properties parallel and perpendicular to the plane such as in parquet and solid wood panels. The dimensional changes vary depending on the principle directions of the wood which can lead to residual stresses in the laminate. Large cross-sections also have a large impact by multiplying the residual stresses in the laminates into high stresses large enough to cause significant damage.

The bond line in glued laminates serves as a stress intensifier by causing a pronounced

moisture profile. This moisture profile is generally caused by an increased diffusion resistance or humidity dependence of the adhesive. These differences in moisture and stress can lead to a reduction in adhesion, cohesion, or complete failure of the wood at the joint (Bucur 2011).

Wood itself is considered a brittle-elastic material with nonlinear-elastic behavior (Smith and Vasic 2003). For simplification purposes, the behavior of wood can be characterized with linear-elastic fracture mechanics by assuming that the plastic and inelastic zones are small compared to the test sample geometry. In wood, crack propagation is a result of cell wall fracture or intercellular separation (Keunecke et al. 2007). Oftentimes the crack surfaces do not completely separate but are still jointed by fibers of the tracheid cells. These additional connections, called fiber bridges, dissipate fracture energy and lead to fracture toughening, which results in non-linear behaviour.

The objective of this work is to determine the fracture properties of adhesive joints of several different commonly used wood glues under mechanical stress. The results from these experiments will help give a better understanding of laminate and adhesive properties and their relation to delamination.

MATERIAL AND METHODS

The tests were performed on samples from beech wood, *Fagus sylvatica* L. The wood came from two boards from the same tree from the canton of Zurich, Switzerland. The average measured density of the wood, calculated according to DIN 52 182 (1976), was 628±20 kg m^{-3}.

The boards were cut into slats for acclimatization in order to ensure a stress-free initial condition before gluing and cutting. The slats were conditioned at standard climate (20°C, 65 % relative humidity) until the moisture content in the wood was constant (changing less than 0.1 % per day). This led the samples to have a moisture content of approximately 13 %. Once acclimated, the slats were glued together using three different wood adhesives, according to manufacturer guidelines.

The three adhesives used were one-component polyurethane adhesive (1C PUR), polyvinyl acetate (PVAc), and melamine-urea formaldehyde resin (MUF) combined with hardener. The technical specifications of the three adhesives can be seen in Tab. 1.

*Tab. 1: Technical specifications of the three adhesives used in testing. The moisture requirements are listed as: 1st value – % R.H. of the wood samples to be glued, 2nd value – difference in % R.H. between the two wood samples to be glued. Data from Technical Specification Sheets. +Data from Konnerth et al. (2007), *Data from Wood Physics Group, ETH Zurich.*

Type	1C PUR	PVAc	MUF
	Isocyanate prepolymer	**Starch based**	**Polycondensation**
Amount applied (g m^{-2})	140-180	120-200	340-440
Mixing ratio	-	-	100 g adhesive + 50 g hardener
Working time (minutes)	70	7	120
Press time (hours)	3	1.25	14
Curing time (hours)	12	168	18.5
Pressure applied (N mm^{-2})	0.6-1	0.6-0.7	0.8-1.2
Viscosity (MPa.s)	24000	8000	3000
Density (kg m^{-3})	1160	-	1280
Moisture required (%)	>8, Difference < 4	6-12	>6, Difference< 4
E-modulus (MPa)	971±67*	1500+	2550±53*

The CT test samples were then cut from the glued slats according to the shape and dimensions in Fig. 1 with the glue line in the center of the test sample. The test samples were oriented between RL and TL such that the annual rings are approximately at a 45° angle. The actual angle varied between 30° and 75°. The test samples were then subjected to the treatments described in DIN EN 302-1 (2011) (Tab. 2).

Tab. 2: Excerpt from DIN EN 302-1 Tab. 1. Standard treatment for wooden test samples.

A1	Standard climate (20°C, 65 % R.H.)	dry
A2	4 days immersion in cold water at 20 ± 2°C	wet
A3	4 days immersion in cold water at 20 ± 2°C, reconditioning at standard atmosphere until initial weight is reached (+ 2 %, - 1 % tolerance)	dry

During the entire cutting and gluing process, the absolute position of each test sample according to the original two boards was noted and recorded. Each test sample was labeled with numbers to identify the sample by location, adhesive type (if applicable), and preparation condition as seen in Tab. 3. The orientation, location, and labeling of the test samples during the preparation process can be seen in Fig. 1. Unglued samples were also tested as a control to compare the performance of the glued laminates with that of solid wood.

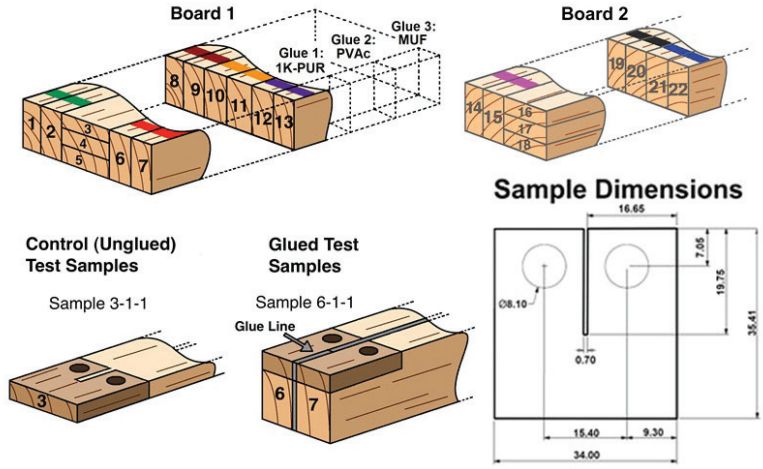


Fig. 1: Board layout showing the position and orientation of both the glued and unglued test samples, and dimensions (in millimeters) and shape of the CT test samples (thickness 5 mm). Description: sample 3-1-1: slat 3 (a control slat), treatment type 1, 1st sample of that type; Sample 6-1-1: glued slat 6 (consisting of slats 6 and 7), adhesive type 1, first sample of that type (thus, will be subjected to A1 treatment).

The displayed test samples show the labeling used to identify the slat, location, and adhesive type. Slats of the same color were glued together with the 3 different adhesives as shown by the dotted sections. The unglued samples were cut from the thinner, horizontal slats. The dotted lines indicate continuations of the board.

Compact tension test

Using the Deben Microtest Tensile Stage Controller (Deben UK Ltd, Suffolk, UK), the samples were subjected to mode I tension until fracture while recording the force applied by the device. At least 15 samples were tested for each adhesive and treatment type. The crack tip of each test sample was sharpened with a razor prior to testing to ensure a crack tip radius of < 0.25 mm according to DIN EN ISO 12737 (2005).

Tab. 3: Description of the sample labeling to record the position, adhesive type, and treatment type of each test sample.

	1st Number		2nd Number		3rd Number	
	Description	**Range**	**Description**	**Range**	**Description**	**Range**
Glued	First slat number of the two glued slats	1, 6, 8, 10, 12, 14, 19, 21	Adhesive type	1. PUR 2. PVAc 3. MUF	Sample number	1-5: Treatment A1 6-10: Treatment A2 11-15: Treatment A3
Unglued	Slat number	3, 4, 5, 16, 17, 18	Treatment type	1. A1 2. A2 3. A3	Sample number	1-5

A rounded crack tip can inhibit crack propagation through crack tip blunting. The test machine was set to a maximum force of 300 N with an adjustable displacement speed of 0.1, 0.2, 0.5, 1.0, and 1.5 mm min^{-1} and a refresh rate of 5 Hz (sample every 200 ms). The displacement was applied to the holes of the test samples with a maximum displacement of 10 mm. The speed was set so that fracture occurred 30-90 seconds after beginning the test which translated to a speed of approximately 1 mm min^{-1}. This speed was fast enough to prevent creep from occurring but also slow enough to keep the test in quasi-static mode.

The parameter of interest was the stress intensity factor for mode I, K_I, which can be calculated using DIN EN ISO 12737 (2005). As there are no standards for calculation of fracture toughness in wood, this standard was used instead and was adapted to wood test samples. The compact tension (CT) test is a simple, standard method of measuring the stress intensity factor of a material by analyzing the force vs. displacement plot to obtain the critical force (F_C). With the conditions of linear elastic fracture mechanics (LEFM) and plane strain satisfied, the calculated K_I from F_C is equal to the fracture toughness (K_{IC}). The eq. below (1) was used to calculate the K_{IC} of the test specimen seen in Fig. 1 with a sample thickness (B), a distance (W) between the point of applied force and the end of sample and a crack length (a).

$$K_{IC} = \frac{F_C}{B\sqrt{W}} \cdot \frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{3/2}} \cdot \left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.60\left(\frac{a}{W}\right)^4\right] \quad (1)$$

Prior to the CT test, the kiln drying method in DIN 52183 (1977) was used to determine the humidity of the test samples.

Wood failure percentage

The wood failure percentage was calculated using ASTM D 5266 (2005). After CT testing, the fractured test samples are divided along the fracture line and the percent of adhesive on both sides of the fracture surface was calculated as a percent of total area. The following criteria were used: 100 % percent adhesive on both sides of the fracture surface equals 0 % wood failure, 0 % adhesive on both sides of the fracture surface equals 100 % wood failure, 100 % adhesive only on one fracture surface equals 0 % wood failure with adhesive failure.

RESULTS AND DISCUSSION

Control samples

All samples fractured between 30-90 seconds at a CT test displacement speed of 1 mm min^{-1}. A photo of a fractured solid wood sample during CT testing on the Deben Microtest Tensile Stage Controller can be seen in Fig. 2. The A1 and A3 samples displayed brittle fracture mostly occurring between 60-90 seconds. The A2 samples (wet) displayed more fiber bridging and ductile fracture occurring throughout the whole time range from 30-90 seconds resulting in a gradual decrease of force and slower crack propagation. There was no significant difference between the measured maximum forces (F_C) in A1 and A3. Testing the samples wet (A2) resulted in significantly lower F_C. The force versus displacement plots used to calculate F_C and K_{IC} can be seen in Fig. 3a. The resultant data is listed in Tab. 4.

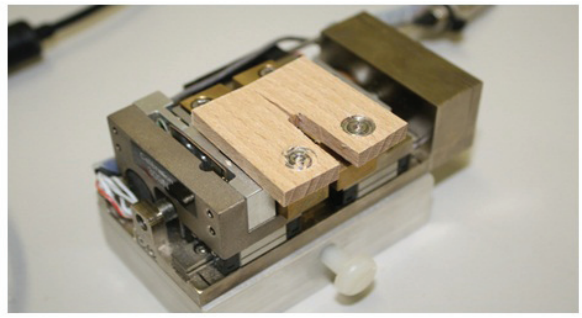
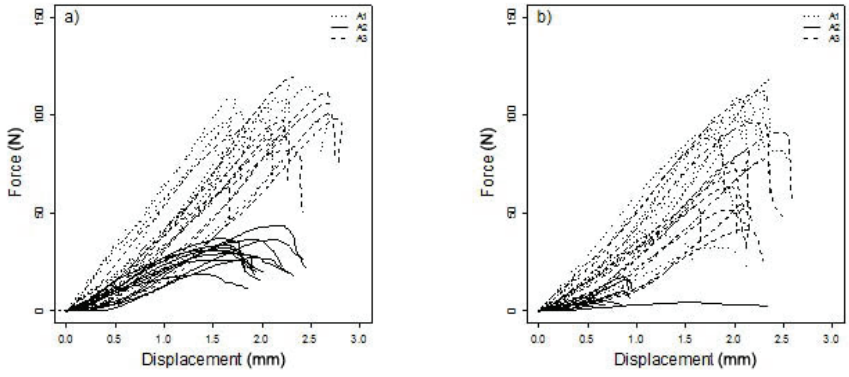


Fig. 2: Compact Tension test of a solid wood sample on the Deben Microtest Tensile Stage Controller. The two pins set in the holes of the wood sample displace outwards causing fracture of the specimen.



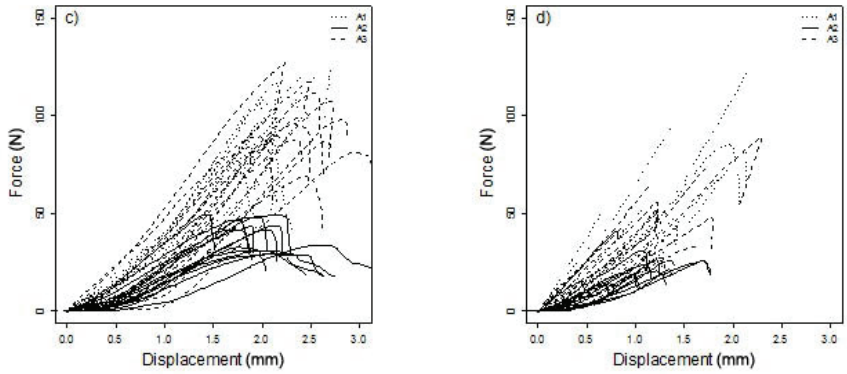


Fig. 3: Force vs. displacement curves for a) control, b) MUF, c) PVAC and d) PUR samples at three different treatment types. Information about the fracture and material characteristics can be deduced by the shape of the curve.

Tab. 4: CT Test results showing mean ± standard deviation. The P-Value compares glued samples and the corresponding control samples by means of a t-test. N/A stands for "Not Applicable".

		n	F_C (N)	K_{IC} (MPa√m)	Wood failure (%)	Adhesive failure (n)	P-Value
Control	A1	25	84.34±22.35	0.83±0.22	N/A	N/A	N/A
	A2	26	32.25±5.49	0.32±0.05	N/A	N/A	N/A
	A3	25	76.74±23.00	0.75±0.23	N/A	N/A	N/A
PUR	A1	20	62.71±24.49	0.61±0.24	10±25	4	< 0.01
	A2	18	20.82±4.76	0.21±0.05	0	1	< 0.01
	A3	18	48.77±16.49	0.48±0.16	0±5	0	< 0.01
PVAc	A1	19	89.79±26.26	0.88±0.26	40±20	8	0.46
	A2	11	8.05±4.52	0.08±0.04	0	10	< 0.01
	A3	18	71.90±19.39	0.71±0.19	30±20	12	0.5
MUF	A1	20	99.83±19.28	0.98±0.19	60±25	0	0.018
	A2	18	38.87±7.35	0.38±0.07	35±30	1	< 0.01
	A3	19	92.75±15.05	0.91±0.15	60±30	0	0.01

An important observation that must be mentioned is the significant difference between the boards particularly in the solid wood samples. Board 1 continuously had higher fracture toughness values than Board 2 for all glues and treatments. These differences were most pronounced in the dry tests of the wood in A1 and A3 (Fig. 4). The strength differences between the boards led to large standard deviations in the results.

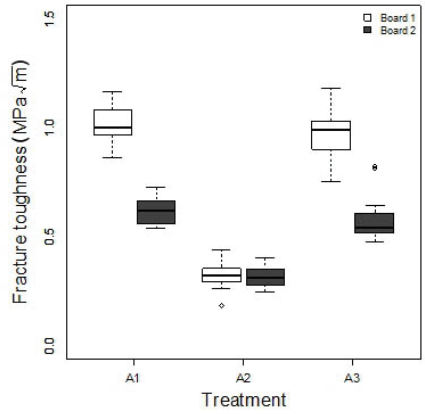


Fig. 4: Boxplots of fracture toughness for the control samples and treatment types separated into the two boards used for the sample preparation. The circles signify the fracture toughness of an individual outlier.

The results of the control samples are in the range expected according to Scheffler et al. (2004), Vasic and Stanzl-Tschegg (2007) and Majano-Majano et al. (2012). In these studies, the fracture toughness of beech was measured for different humidity levels in different directions.

The results at 65 % R.H. lie in between results of Majano-Majano et al. (2012) and Vasic and Stanzl-Tschegg (2007) in the RL direction; however, the variance of the actual sample was clearly higher (Fig. 9) compared to the mentioned studies. It can be assumed that the orientation of the annual rings between 37 and 75° is one of the reasons for the big variance.

In the study by Scheffler et al. (2004), the fracture toughness was measured for solid beech samples in the RT and TR directions in mode I for varying moisture content. The K_{IC} observed from this study in the TR direction reached similar values and in the RT direction higher values than in the current investigation. As presented by Keunecke et al. (2012), the fracture toughness is expected to be higher in the longitudinal direction than in the radial and tangential direction. Since no measurements were conducted in the longitudinal direction a comparison of the available data is difficult.

Measurements under wet conditions, however, are significantly lower compared to the results at dry conditions. Despite of the values in RL direction by Vasic and Stanzl-Tschegg (2007), the is the case for all mentioned measurements. As stated by Wang et al. (2003), fracture toughness is inversely proportional to moisture content and so it can expected that the drier samples are tougher. The lower fracture toughness in the A2 and A3 can be contributed to the effects of water with both the wood and the adhesive. As seen in Fig. 4, increasing the moisture content causes a significant drop in fracture toughness due to a reduction in strength by expanding and softening the cell walls. The crystalline cellulose microfibrils in the cell walls lose their inter-fibril hydrogen bonding strength as they form hydrogen bonds instead with the small, polar water molecules. This loss of bonding strength between the cellulose microfibrils reduces the cell wall strength, making the cell walls easier to stretch and bend. As the cell walls expands, the density of cellulose microfibrils per unit area decreases, causing a further reduction in the yield strength.

The measured values are similar to the results by Majano-Majano et al. (2012) in the TL direction. The values in the RL direction by Majano-Majano et al. (2012) and Vasic and Stanzl-Tschegg (2007) are, however, significantly higher. A possible reason therefore is that caused

by the variation in the annual ring angles, the effect of strengthening through the wood rays (Frühmann et al. 2003) plays a minor role.

Despite the small variations, the measured fracture toughness values are in the same range and order of magnitude as the previous literature, which confirms the accuracy of the test setup within a certain tolerance.

Glued samples

The results were analyzed statistically with a multiplicative analysis of variance (ANOVA). The dependent factors were the fracture toughness and the force at break and the independent factors were board, slat (nested within the factor board), treatment, and adhesive type. The results from the multiplicative analysis performed on all the samples showed high significant main effects for all independent factors.

From the residual analysis it could be concluded that the data is in a good agreement with the hypothesis of a normal distribution. The quantiles of the sample distribution shows a high accordance with the theoretical quantiles of the standard normal distribution. From the residual vs. fitted comparison, two extreme outliers with a leverage of over 0.5 were identified and removed. The remaining data forms a linear band showing the relationship of the factors board number, adhesive type, treatment type, and slat number on fracture toughness. Discrepancies were quite minor and thus the data can be still considered as normal distributed and the statistical methods applied to the data are valid.

The glued samples showed varying fracture toughness values depending on the adhesive and treatment type. The A1 samples performed better with higher K_{IC} than the other two treatment types. As seen in the force vs. displacement plots in Fig. 3, the fracture toughness plots in Fig. 5 and from the t-test results in Tab. 4, the MUF always performed better and the PUR always performed worse than the solid wood controls. The PVAc samples performed similarly to the control except in A2 when it displayed exceptionally low F_C and K_{IC} values. The fracture toughness of the PVAc was so low in A2 that 9 samples were broken while being attached to the testing machine. The PUR samples were also fragile in A2 and 2 samples were broken while being attached to the testing machine. The only adhesive that performed equally or better than the solid wood samples in all treatment types was MUF.

The box plot in Fig. 5 a) clearly shows the significance of treatment type on fracture toughness. In order to see more clearly the effects of the different factors, interaction plots are shown in Fig. 5 b). The three line plots depict 2-factor interactions and show the dependence of treatment type and adhesive type on fracture toughness. The plot shows that an increase in moisture content caused a decrease in fracture toughness for all adhesive types.

A literature comparison on fracture toughness for the glued samples is difficult as not many similar experiments have been done. There exist other studies on the fracture properties of wood adhesives but not many are tensile tests as most wood adhesives are tested in shear. The fracture properties are given in shear resistance, shear strength, work to fracture, etc. which are difficult to translate into the fracture toughness notation used in this study. Also, with the large number of commercial wood adhesives, an exact comparison of the adhesive is difficult.

For the PVAc samples, the water affected the quality of the adhesive causing softening of the bonds and a reduction in adhesion as was observed in this study. Water enters the polymer network and due to hydrolysis, the carbon – carbon bond between the monomers is cleaved (Dunky and Niemz 2002). Previous studies have observed this reduction in strength due to water (Tankut 2007, Schrödter and Niemz 2006). In a previous investigation by Kurt and Uysal (2009), it was observed that PVAc completely lost its bonding strength after 7 days submerged in 20°C

water which is very similar to what was observed after the A2 treatment.

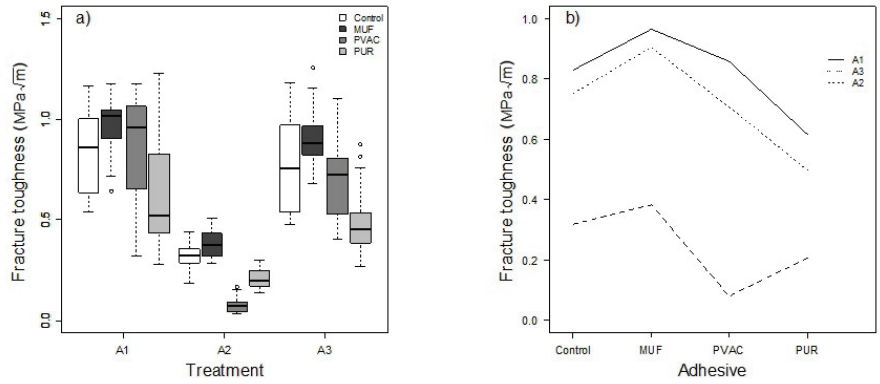


Fig. 5: Boxplot a) and interaction plot b) of the fracture toughness for each adhesive and treatment type compared with the control samples. The circles in a) signify the fracture toughness of an individual outlier.

Water also affected the adhesion strength of PUR, but to a lesser degree than in PVAc. PUR is more water resistant than PVAc and actually uses the moisture content in the wood for the curing process with the isocyanate polymer end (Clauβ et al. 2011). Thus, a drop in fracture toughness and wood failure percentage in A2 was observed with PUR but was not as pronounced as with PVAc. A decrease in the number of samples with adhesive failure was even observed in the A2 and A3 treatments.

The bonding performance of the MUF was the least affected by water as expected due to its increased water resistance. As explained by Kurt and Uysal (2009) and Dunky and Niemz (2002), the addition of melamine to urea-formaldehyde increases the moisture stability of the adhesive because the double bonds in the melamine stabilize the carbon – nitrogen bond between the melamine and formaldehyde groups and increase the resistance to hydrolysis from water. As a result, the MUF samples performed better than the other glues and the solid wood samples in A2 and A3.

This observation is significant because one would expect that if the wood was weaker than the glue, the wood would fail at its normal F_C before the adhesive and thus, the samples would have the same K_{IC} as the solid wood samples. Instead, the wood is able to withstand a higher K_{IC} when glued then unglued. A possible explanation for this is that the sharpened crack tip was cut into the glue line and thus 1) higher forces were required for crack initiation in the tougher MUF and 2) higher forces were required for crack initiation in the blunted wood. Oftentimes, the crack would initiate and propagation in the wood and ignore the preexisting, sharpened crack in the glue. The crack would have experienced crack tip blunting as it was not sharpened with a razor and the blunted curvature of the crack would reduce the stress intensity factor. Once the crack initiation had begun in the glue, it had a tendency to veer into the wood due to the lower toughness of the wood.

The wood failure percentage varied significantly between the glues (Fig. 6a). MUF always had the highest wood failure percentage and PUR had the lowest except in A2 when both PVAc and PUR had equally low values of less than 10 %. The A2 treatment caused a decrease in all the wood failure percentages. The A3 treatment caused a decrease in the wood failure percentage of PUR and PVAc but did not affect the wood failure percentage of MUF. PUR had only one

sample with a wood failure percentage higher than 50 % and MUF had the majority over 50 %.

Besides the wood failure percentage, the percent of samples with adhesive failure were counted and can be seen in (Fig. 6b). PVAc showed the highest number of samples with adhesive failure, particularly in A2, when the percentage of samples with adhesive failure reached over 90 %. PUR had occasional adhesive failure, which amounted to less than 20 % of the samples. MUF had only one sample with adhesive failure.

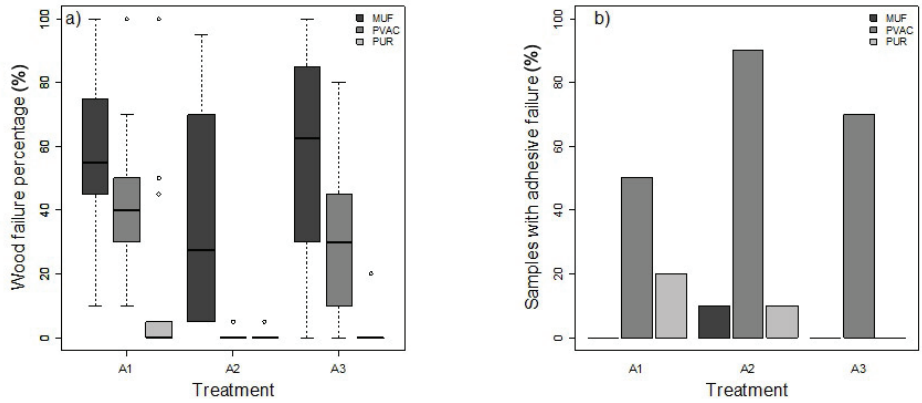


Fig. 6: Boxplot a) of the wood failure percentage for each adhesive and treatment type. The circles signify the value of an individual outlier. Barplot b) of the percentage of samples with adhesive failure for each adhesive and treatment type.

Although it is difficult to compare the failure behavior of samples tested with different test setups, the results of wood failure percentage for the A1 and A3 revealed a similar tendency regarding the different adhesives like those found by Schmidt et al. (2010) and Clauβ et al. (2011). The two previous studies, however, tested the adhesives in shear rather than in tension, and the exact adhesive type and manufacturer differed between the experiments. Despite these differences, the same general trend of wood failure percentage was observed with the stiffer polycondensation resins as MUF mostly causing higher wood failure percentages compared to PUR or PVAc.

The fracture characteristics of the glued samples varied largely between the three adhesives. The PUR samples fractured along the glue line with unstable crack propagation. The PVAc samples fractured partially along the glue line with adhesive failure and partially in the wood with some fiber bridging. The MUF samples had the most favorable fracture characteristics with almost entirely wood failure with fiber bridging. The wetness of the A2 samples exaggerated the fracture characteristics seen in A1; the PVAc exhibited complete adhesive failure and the MUF exhibited even more pronounced fiber bridging. The PUR samples in A2, however, still displayed approximately 0 % wood failure as seen in A1. Pictures of the characteristic fracture types can be seen in Fig. 7.

The shape of the force vs. displacement curve was dictated by the fracture and material characteristics for each adhesive and treatment type as seen in Fig. 8. The elastic section of the curve varied between the dry (A1 and A3) and wet (A2) conditions. The A1 and A3 samples displayed a similar, linearly increasing slope, whereas the A2 samples displayed a more gradual, curvier slope. The shape of the curve during and after fracture relates directly to the fracture

characteristics.

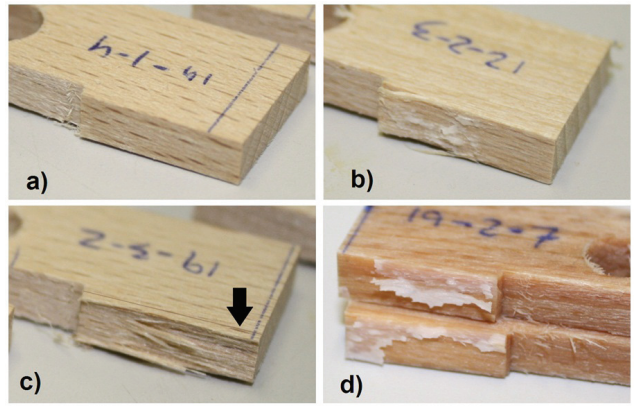


Fig. 7: Fracture characteristics for each adhesive type: a) PUR in A1 with 0 % wood failure, b) PVAc in A1 with approx. 30 % wood failure with adhesive failure, c) MUF in A1 with 100 % wood failure and significant fiber bridging, and d) PVAc in A2 with 0 % wood failure with entirely adhesive failure. The arrow in c) shows the glue line (thin brown line) which is far away from the fracture line signifying 100 % wood failure.

The PUR, being weaker than the wood, caused sudden brittle fracture along the glue line. Without fracture in the wood, fiber bridging was not possible and thus complete failure of the sample upon reaching F_C was observed. Only short displacements (< 1 mm) were required for fracture and failure of the samples and the treatments A2 and A3 led to similar force curves but with reduced peaks (F_C).

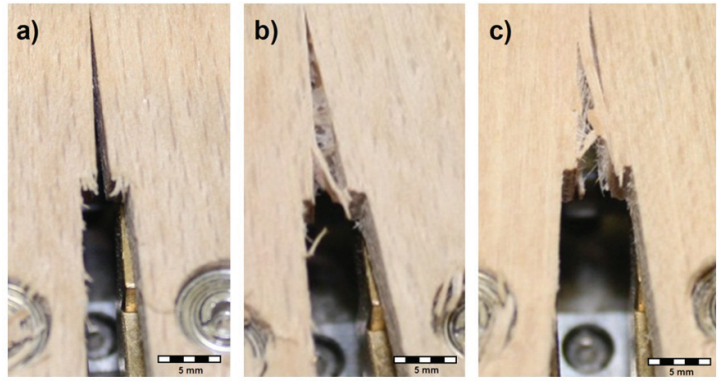


Fig. 8: Crack characteristics for each adhesive type during crack propagation: a) PUR in A3 with 0 % wood failure resulting in quick, unhindered crack propagation and failure of the structure, b) PVAc in A3 with some fiber bridging present resulting in slower crack propagation. The clear, web-like connections are adhesive bridges as a result of adhesive failur, c) MUF in A3 with significant fiber bridging resulting in fracture toughening and slow crack propagation.

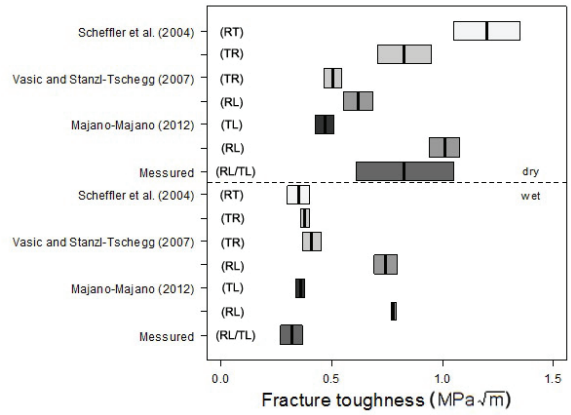


Fig. 9: Literature comparison of fracture toughness for solid beech wood in normal climate (20°C, 65 % R.H.) and when wet. The gray bars represent a standard deviation with the black line as the mean.

The fiber bridging present in the PVAc samples prevented complete failure of the sample upon reaching F_C. Instead, a gradual, descending force plot was observed with increasing displacement. The A2 samples adhesively failed almost immediately which led to gradual sloping curves with very low peaks.

The MUF samples displayed mostly brittle fracture with significant fiber bridging leading to a slow, gradually decreasing force after the initial drop at fracture. The climate treatments affected the samples mainly by reducing the peaks of the curves. The PVAc and MUF samples required larger displacement (1-2 mm) before fracture occurred.

The strongly divergent swelling and shrinking properties of beech wood may also have played a large role in the decrease in fracture toughness and the increase in adhesive failure during the wet tests, A2 and A3. Beech is known to have large dimensional changes especially in the radial and tangential directions in response to moisture content (Rijsdijk and Laming 1994). The changing dimensions due to water in the A2 and A3 treatments could have caused the increase in adhesive failure and the decrease in wood failure percentage and K_{IC} by causing residual stresses in the bond line and possibly loss of contact between the wood and adhesive. If the dimension changes were significant, high residual stresses could have formed in the bond line causing the adhesive failure of the adhesive which could explain the results observed in the PVAc samples. The residual stresses could also affect the adhesive performance by requiring less force until fracture. The effects of dimensional changes as a result of moisture content was not specifically investigated in this study, and thus further experiments would need to be done to understand this topic more fully.

CONCLUSIONS

As was observed in this study, the fracture properties of adhesive joints under tensile stress in mode I depend on adhesive type, climate treatment, and moisture content. Increased moisture content had the effect of reducing the fracture toughness, reducing the wood failure percentage, and causing more quasi-ductile behavior from the wood. Of the three adhesives tested, MUF

performed the best for all treatment types due to its high fracture toughness, its resistance to water, and the presence of fiber bridging during fracture leading to fracture toughening and slow crack propagation.

PUR performed poorly for all treatment types due to its low fracture toughness leading to glue line failure and rapid crack propagation.

The performance of PVAc bond lines depended significantly on the moisture content of the wood. The PVAc performed similarly to solid wood during normal climate tests with slow crack propagation, but when subjected to high moisture content, the adhesive bond between the PVAc and the wood failed and the samples were easily broken with minimal force. The PVAc samples that were wetted and then dried displayed a much higher rate of adhesive failure despite having similar fracture toughness values as the solid wood samples.

In conclusion, the adhesive type and moisture content in the laminate were regarded as the main factors in delamination with the significant indicators being low wood failure percentages, fracture toughness values lower than solid wood, and prominent adhesive failure. Thus, laminates with a high moisture content particularly with PVAc and laminates glued together with PUR increase the probability of delamination by increasing the chance of failure in the adhesive.

REFERENCES

1. ASTM D 5266, 2005: Standard practice for estimating the percentage of wood failure in adhesive bonded joints.
2. Bucur, V., ed. 2011: Delamination in wood, wood products and wood based composites. 1st Edition, Springer, New York, 402 pp.
3. Clauβ, S., Joščák, M., Niemz, P., 2011: Thermal stability of glued wood joints measured by shear tests. European Journal of Wood and Wood Products 69(1): 101–111.
4. DIN 52182, 1976: Testing of wood; determination of density.
5. DIN 52183, 1977: Testing of wood; determination of moisture content.
6. DIN EN 302-1, 2011: Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of longitudinal tensile shear strength.
7. DIN EN ISO 12737, 2005: Metallic materials - Determination of plane-strain fracture toughness.
8. Dunky, M., Niemz, P., 2002: Holzwerkstoffe und Leime: Technologie und Einflussfaktoren. Springer, Berlin, Heidelberg, 984 pp.
9. Frühmann, K., Burgert, I., Stanzl-Tschegg, S.E., Tschegg, E.K., 2003: Mode I fracture behaviour on the growth ring scale and cellular level of spruce (*Picea abies* (L.) Karst.) and beech (*Fagus sylvatica* L.) loaded in the TR crack propagation system. Holzforschung 57(6): 653–660.
10. Keunecke, D., Niemz, P., Tollert, M., Hänsel, A., 2012: Mechanical properties and failure behaviour of yew and spruce determined with a compact tension test and digital image correlation. Wood Research 57(4): 669-675.
11. Keunecke, D., Stanzl-Tschegg, S.E., Niemz, P., 2007: Fracture characterisation of yew (*Taxus baccata* L.) and spruce (*Picea abies* (L.) Karst.) in the radial-tangential and tangential-radial crack propagation system by a micro wedge splitting test. Holzforschung 61(5): 582-588.
12. Konnerth, J., Gindl, W., Müller, U., 2007: Elastic properties of adhesive polymers. I. Polymer films by means of electronic speckle pattern interferometry. Journal of Applied Polymer Science 103(6): 3936-3939.

13. Kurt, S., Uysal, B., 2010: Bond strength/disbonding behavior and dimensional stability of wood materials with different adhesives. Journal of Applied Polymer Science 115(1): 438-450.
14. Majano-Majano, A., Hughes, M., Fernandez-Cabo, J.L., 2012: The fracture toughness and properties of thermally modified beech and ash at different moisture contents. Wood Sci. Technol. 46(1/3): 5-21.
15. Rijsdijk, J.F., Laming, P.B., 1994: Physical and related properties of 145 timbers. Information for practice. Kluwer Academic Publishers, London, 380 pp.
16. Scheffler, M., Niemz, P., Diener, M., Lustig, V., Hardtke, H.J., 2004: Fracture toughness from hardwood in mode I and II. Holz als Roh- und Werkstoff 62(2): 93–100.
17. Schmidt, M., Glos, P., Wegener, G., 2010: Gluing of European beech wood for load bearing timber structures. European Journal of Wood and Wood Products 68(1): 43–57.
18. Smith, I., Vasic, S., 2003: Fracture behavior of softwood. Mechanics of Materials 35(8): 803-815.
19. Schrödter, A., Niemz, P., 2006: Untersuchungen zum Versagensverhalten von Klebfugen bei erhöhter Temperatur und Luftfeuchte. Teil 1. Untersuchungen im makroskopischen Bereich. Holztechnologie 1: 24-32.
20. Tankut, N., 2007: The effect of adhesive type and bond line thickness on the strength of mortise and tenon joints. International Journal of Adhesion and Adhesives 27(6): 493–498.
21. Vasic, S., Stanzl-Tschegg, S.E., 2007: Experimental and numerical investigation of wood fracture mechanisms at different humidity levels. Holzforschung 61(4): 367–374.
22. Wang, L., Lu, Z., Zhao, G., 2003: Wood fracture pattern during the water adsorption process. Holzforschung 57(6): 639–643.

Pierre Watson, Sebastian Clauss, Samuel Ammann, Peter Niemz
Eth Zurich
Institute for Building Materials
Wood Physics
Hif E. 251.
Schafmattstrasse 6
Ch 8093 Zurich
Switzerland
Phone: 0041-44-6323226
Corresponding author: sclauss@ethz.ch