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Static and dynamic tensile shear test of glued lap wooden joint with four different types of adhesives

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Abstract: Investigations of quasi-static and fatigue failure in glued wooden joints subjected to tensile shear loading are presented. Lap joints of beech wood (*Fagus sylvatica* L.) connected with four different types of adhesives, i.e. polyurethane (PUR), melamine urea formaldehyde (MUF), bone glue and fish glue, were experimentally tested until the specimens failed. The average shear strengths obtained from the quasi-static test ranged from 12.2 to 13.4 MPa. These results do not indicate any influence of the different adhesive types. The influence of the adhesives is only visible from the results of the fatigue tests, which were carried out under different stress excitation levels between 45% and 75% of the shear strength. Specimens bound with ductile adhesive (PUR) showed a slightly higher number of cycles to failure (N_f) at low-stress levels and lower N_f at high-stress levels in comparison to more brittle adhesives (MUF, fish glue). In general, the performances of animal glues and MUF were similar in both quasi-static and fatigue loading under dry conditions.

Keywords: bone glue, fatigue test, fish glue, glued wood lap joint, melamine urea formaldehyde (MUF), polyurethane (PUR), tensile shear test

Introduction

Fatigue failure is a material property which is due to a long-term fluctuating or cyclic load. Even though the maximum applied stress is lower than the quasi-static material strength, failure will still occur if the applied stresses are high enough to initiate micro-cracks. The load repetition will cause a propagation of the micro-cracks over time and eventually, a sudden failure will occur as a crack reaches its critical size. In practical structural design, fatigue must always be considered for any parts exposed to a repetitive loading, e.g. for roof structures due to snow loading or bridge structures due to heavy vehicle loading. Unfortunately, in the past, consideration of fatigue in wood was mostly dealt with by an extremely conservative design (Lewis 1960). Such thinking supposes that the design stress is below a threshold, where repeated stresses would cause damage (endurance or fatigue limit). This idea probably arises because wood is a natural fatigue “success” material. Wood is exposed to fatigue loading during its growth period. Natural loading such as wind storms produces large repetitive deflections and internal stresses in the trunk of a tree, and yet wood can still withstand the loads.

The fatigue effects in wood were studied from the middle of the 20th century (Lewis 1960; Kollmann and Krech 1961; Gillwald 1966; Kollmann and Cote 1968). The results showed the importance of fatigue in wood applications and wood products. The subject is especially important when a high strength per weight ratio is required (Bonfield et al. 1992; Bond and Ansell 1998; Jamieson 2011; Li et al. 2016). The role of fatigue damage in wood was also studied (Kyanka 1980; Tsai and Ansell 1990; Bonfield and Ansell 1991). Further studies are still required because there are a huge number of wood species in many different products; such as in engineering constructions, composites, chips or flakes, thin veneers and fibres, just to mention a few, and each of these materials have their own properties.

The current study focuses on wooden joints. Wooden joints loaded under a quasi-static loading were studied by Hass et al. (2014). Studies on wooden joints under

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fatigue loading were performed only at a certain stress level (Olson et al. 1955; Li et al. 2012). The present study explores the relation between the short-term static and long-term fatigue failure at several stress levels of glued wooden joints. Beech wood (*Fagus sylvatica* L.) bonded with four different types of adhesives, i.e. polyurethane (PUR), melamine urea formaldehyde (MUF), fish glue and bone glue, is experimentally tested under tensile shear loading. While several studies have been conducted for PUR and MUF (Hass et al. 2012; Kläusler et al. 2013), knowledge on animal glues (fish and bone glue) is still scarce. Until now, animal glues are still irreplaceable for use in the manufacture of furniture, cabinets and musical instruments. Their bonding is reversible, which is very useful for repairing purposes. The understanding of their behaviour under loading is important. In this study, the influence of different adhesives including fish and bone glues will be discussed with respect to static and dynamic fatigue loading. Furthermore, the interaction between the stress level and the number of cycles to failure (N_f) will be compared under a fatigue tensile shear loading. Additionally, wood failure percentage (WFP) and fracture cross-section will also be observed.

Materials and methods

The specimens are “small and clear” glued lap joints made of beech wood (*F. sylvatica* L.) based on DIN-EN-302-1 (2000) (Figure 1). For comparable results, the same specimens were submitted to both quasi-static and fatigue testing. The density and the moisture content (MC) of the tested specimens were measured under normal climatic conditions (20°C and 65% RH) were $723 \pm 22 \text{ kgm}^{-3}$ and $11 \pm 0.5\%$, respectively.

The wood specimens were glued with (a) one-component polyurethane (1C-PUR HB S709, Purbond AG, Sempach-Station, Switzerland), (b) melamine urea formaldehyde (MUF Kauramin, BASF SE, Ludwigshafen, Germany, resin no. 683 and hardener no. 688 with a mixture ratio of 1:0.6 by mass), (c) bone glue (Kremer Pigmente GmbH, Aichstetten, Germany, product no. 63000, dry glue and water

with a mixture ratio of 1:2 by mass), heated at 60°C and slowly stirred until the glue dissolves and (d) fish glue (Kremer Pigmente GmbH, Aichstetten, Germany, product no. 63550), a ready-to-use glue with a mixture of 45% glue and 55% water.

Two pieces of $5 \times 130 \times 300 \text{ mm}^3$ wooden plate were glued with 200 gm^{-2} of adhesive. A uniform pressure of 1 MPa was applied to the freshly glued specimens with a duration of 1.5, 6, and 3 h for PUR, MUF and animal glue (bone and fish), respectively. The final cut into the desired specimen shape, as shown in Figure 1, was performed afterwards. Finally, the specimens were stored under controlled conditions for at least 1 month before the actual experiments.

Quasi-static test: The tensile shear strengths of the specimens under quasi-static/short-term conditions were determined according to DIN-EN-302-1 (2000). The tests were performed under normal conditions (20°C/65% RH). At least 10 specimens for each type of adhesives were tested to failure. The tests were carried out on a universal testing machine (type Zwick Roell Z1010, Zwick Roell Group, Ulm, Germany) at a cross-head displacement controlled rate of 1 mm min^{-1} . The direct displacement was measured by a tactile sensor directly attached to the joint. The shear stress result (τ) was determined as $\tau = F/A_s$ (Equation 1), where, F is the applied load and A_s is the shear area (the glue line area). The shear strength (τ_u) is determined as the maximum shear stress when the material breaks.

Fatigue test: For the fatigue test, the specimens were conditioned at 23°C and 50% RH for several days up to more than 1 month and tested under these conditions. The masses of selected specimens were monitored during conditioning to ensure a uniform MC. The tensile shear fatigue tests were performed on a servo-hydraulic test machine (type Instron 1273, Instron, High Wycombe, UK) with hydraulic grips. Aluminium spacers served for limitation of the maximum displacement of the grip to avoid gripping failures.

A non-reversed fatigue loading was applied. This type of loading may produce less damage in comparison to a fully reversed fatigue loading (Tsai and Ansell 1990; Smith et al. 2003). However, it is the most common type of loading to practical structural elements. The stress limits were selected based on the results of the quasi-static test. The chosen maximum tension shear load levels (F_{\max}) of the fatigue test were between 1000 and 2000 N in steps of 200 N, but not all those levels were used for all the four specimen types. The minimum load (F_{\min}) was 20 N for all the tests. The minimum and maximum shear stress level (τ_{\min} and τ_{\max}) were also determined (based on Equation 1) due to a slight variation of A_s for each specimen. Sinusoidal fatigue wave loading was applied under load control at a frequency of 1 Hz. The number of specimens is between two and six per load level and type. The specimens were tested to failure and the respective number of fatigue cycles was recorded (Table 2).

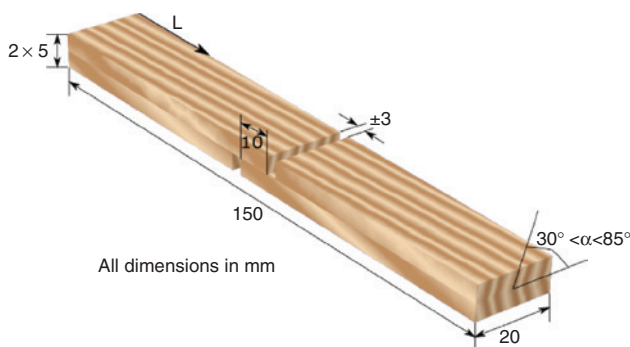


Figure 1: Specimen dimensions based on (DIN-EN-302-1 2000).

Table 1: Maximum force and stress under quasi-static test.

Glue	N ^a	F_u (N)	CoV (%)	τ_u (MPa)	CoV (%)	ϵ_u (%)	CoV (%)	AWF ^b (%)
MUF	15	2590	(7.5)	12.9	(7.5)	1.09	(13.5)	100
PUR	18	2670	(8.5)	13.4	(8.5)	1.39	(6.0)	32
Fish	10	2670	(10.9)	13.3	(11.0)	1.38	(18.7)	100
Bone	14	2440	(10.8)	12.2	(11.2)	1.25	(10.4)	96

^aNumber of specimens. ^bAverage wood failure.

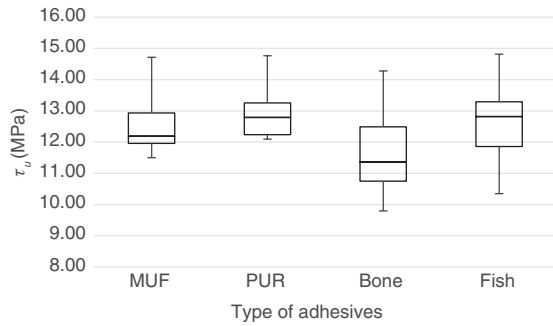


Figure 2: Static tensile strength of beech wood with four different types of adhesives.

The results of the fatigue tensile shear test are presented in a Wöhler curve (also known as an S-N diagram), as discussed in detail by Nakano (1997). The fatigue resistance is described by a critical value of load cycles, N , leading to failure at a given stress level, S . In this case, the stress is a shear stress (τ). Therefore: $\log(N_f) = A + B \log(\tau)$ (Equation 2), where, A and B are coefficients depending on the factor $R = \tau_{min} / \tau_{max}$ (Clorius et al. 2000). In our study, A and B were determined by a fitting between the number of cycles to failure obtained at various stress levels. Moreover, to ensure the comparison between the different types of adhesives, the actual shear stress (τ) is replaced by the shear stress ratio (τ_r), which is defined as the ratio between τ and τ_u .

Results and discussion

Based on the results of the quasi-static tests, the average tensile shear strength of the four adhesives in focus range from 12.2 to 13.4 MPa with a maximum variance of 11.2% (Table 1 and Figure 2). The maximum strains (ϵ_u), when specimens failed, are also presented. A few differences can be observed regarding the influence of adhesive types based on these results. The ϵ_u of MUF specimens are at least 15% lower, which is a sign of a more brittle joint in comparison to the other adhesives. The visual observation of the fracture surfaces (based on ASTM-D5266 2013) revealed that the failure of the PUR joint was largely in the glue line with an average wood failure percentage (WFP) of 32%. PUR shows low values of WFP due to its poor adhesive-wood connection as is also described in the literature (Hass et al. 2009; Clauß et al. 2011). For the other adhesives, the failure was mostly in the wood with WFP up to 100%. Overall, these data indicate that the results are comparable concerning animal glues and polymer adhesives (MUF and PUR) regarding strength (with both MUF and PUR) and failure type with MUF.

The results of long-term fatigue tests with the selected applied loads and the number of specimens tested are

Table 2: Fatigue test results.

Glue	F_{max} (N)	^a N (-)	Number of cycles to failure (N_f) (-)	ϵ_u (%) (CoV%)	AWF ^b (%)
MUF	2000	5	632/103/3958/131/3802	0.99 (17.8)	100
	1800	0	-	-	-
	1600	4	31946/6838/3176/329	0.74 (29.0)	90
	1400	4	107739/20607/1587/2612	0.60 (27.9)	98
	1200	6	3349/13063/308580/27347/44614/123161	0.59 (27.5)	100
	1000	0	-	-	-
PUR	2000	5	2/259/1052/131/2623	1.00 (5.1)	18
	1800	0	-	-	-
	1600	6	9687/38097/27387/24107/395997/81086	0.96 (14.8)	18
	1400	5	116987/86702/167954/12779/9501	0.67 (15.3)	6
	1200	2	66260/1029647	0.60 (12.5)	30
	1000	0	-	-	-
Fish	2000	0	-	-	-
	1800	3	799/12405/630	1.16 (16.8)	100
	1600	3	1043/3859/2183	0.88 (10.4)	100
	1400	3	29288/150751/49436	0.87 (10.5)	93
	1200	3	96831/113338/204544	0.74 (23.0)	100
	1000	1	286490	0.57 (-)	100
Bone	2000	0	-	-	-
	1800	3	217/753/439	0.86 (4.9)	93
	1600	3	1173/1948/3174	0.85 (11.1)	100
	1400	4	110114/233742/19107/51208	0.87 (15.2)	93
	1200	4	157020/32527/168652/163248	0.88 (14.6)	70
	1000	0	-	-	-

^aN, number of specimens tested until failure. ^bAverage wood failure.

presented in Table 2. Based on Smith et al. (2003), Wöhler curves show the relation between the number of cycles to failure (N_f) and the stress ratio (ratio between the maximum applied stress and the shear strength, τ_r) for every adhesive type (Figure 3). While the higher stress levels naturally produce higher numbers and sizes of micro-cracks per cycle, the exponential (τ_r-N_f) relation implies that the development of cracks in each loading cycle also depends on the existing cracks. Therefore, a higher stress rapidly accelerates the damage propagation and leads to an exponential decrease of N_f .

The regression coefficients of the Wöhler curves (Equation 2) were determined based on the experimental data as presented in Table 3. These unit-free coefficients project the relation between the stress ratio (τ_r) and the number of cycles to failure (N_f). The negative B values indicate increasing N_f with decreasing stress level. The highest B value, which belongs to the specimens with MUF, represents the steepest increase of the N_f . Moreover, all tested specimens failed after a certain N_f , which means that all selected loads are above the endurance limit.

At a low-stress level, PUR specimens have a slightly higher N_f value in comparison to MUF and fish glue, while at a high-stress level, PUR has lower N_f (Figure 3). Even though not significant, this difference in N_f is suspected to be due to the ductility of the adhesives. PUR is highly ductile compared to the other adhesives. The behaviour of PUR and MUF adhesive films was investigated by Kläusler

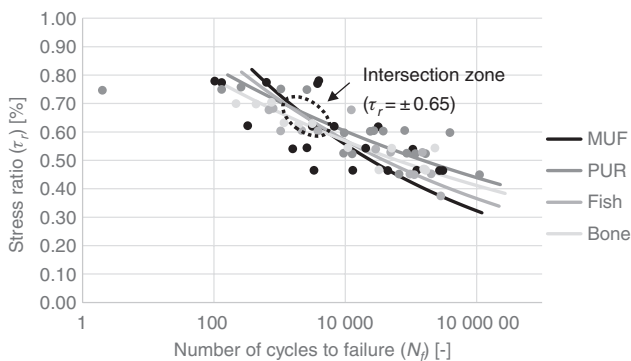


Figure 3: S-N curves of fatigue test.

Table 3: A and B coefficient for S-N curve (see Eq. 1).

Glue	Coefficient	
	A [-]	B [-]
MUF	1.85	-8.46
PUR	0.80	-14.54
Fish	1.47	-10.36
Bone	0.50	-14.26

et al. (2013). PUR strained up to 5% before it yielded and at least 25% before fracture occurred, while MUF failed at 2% deformation without any plastic deformation. The strength of PUR, however, is at least 28% lower than MUF under any moisture conditions. On the other hand, the mechanical properties of animal glue films have never been studied in depth before (Sweatt 1946; Schellmann 2009). However, they were described to have very strong joints in a dry state (Knight 1952; Konnerth et al. 2009).

Under fatigue loading, a ductile material even when it has lower strength capacity is more resistant to failure in comparison to a brittle material, when it is exposed to a low-stress level. On the other hand, a brittle material is more resistant to high-stress levels in comparison to a ductile material (Ritchie 1999). This behaviour should be observable in the N_f between PUR as the ductile adhesive and MUF and fish glue as the brittle ones. However, the recorded maximum strains during the fatigue testing (ϵ_u in Table 2) oppose this idea. Specimens bonded with PUR, MUF and fish glues show a relatively similar ϵ_u at all stress levels. The ductility of the adhesives, as investigated by Konnerth et al. (2009) and Kläusler et al. (2013), does not imply these results. A different and more complex mechanical behaviour may be generated due to the combination of wood and adhesive in a joint under fatigue loading. On the other hand, bone glue, which is expected to have a similar behaviour to fish glue, behaves differently. At any stress level, N_f of bone glue is lower than PUR. Moreover, ϵ_u of bone glue is ca. 0.86% more insensitive to the stress level.

Similar to the static results, the majority of wood failure is observed for MUF and animal glues, while the majority of glue failure is observed for PUR due to fatigue loading at any stress level. The microscopic view of bone glue specimens in the cross-section area is presented in Figure 4. The adhesive penetration depth into the wood was also studied. The maximum penetration depths of PUR and MUF adhesives to beech wood are 692 and 236 μm , respectively (Hass et al. 2012). Figure 5 exemplarily shows the penetration of animal glues represented by bone glue to the wood. The maximum observed penetration depth in more than 10 different locations in three different specimens is 62 μm . These results are not surprising considering that animal glue has the shortest open time (ca. 1 min under normal climate conditions). Although while having very low penetration depth, animal glue still provides a strong bonding as reflected by the WFP in both static and dynamic tests. Figure 5 also confirms the animal glue bonding strength by pure wood failure with a distance of 292 μm from the glue line.

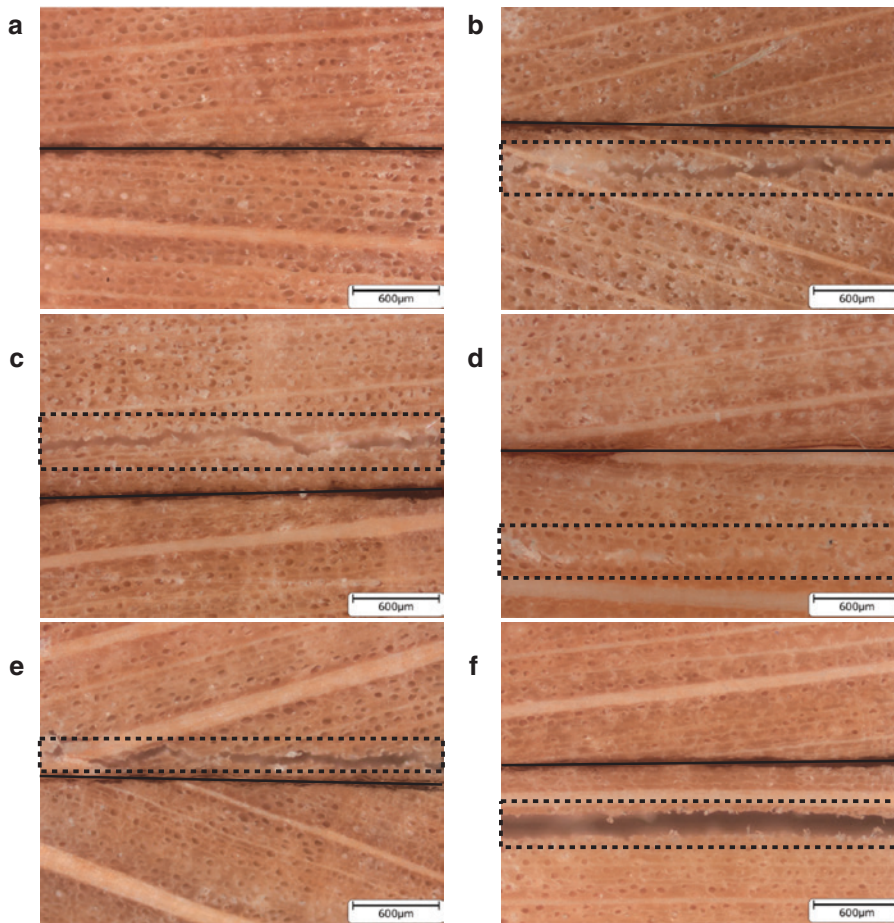


Figure 4: Failure cross section of bone glue specimens observed by differential interface contrast (DIC) with light microscope Olympus BX51, glue lines marked by solid line and crack paths marked by the dashed line.

(a) No failure, (b) static failure, (c) dynamic failure 1800 N, (d) dynamic failure 1600 N, (e) dynamic failure 1400 N, (f) dynamic failure 1200 N.

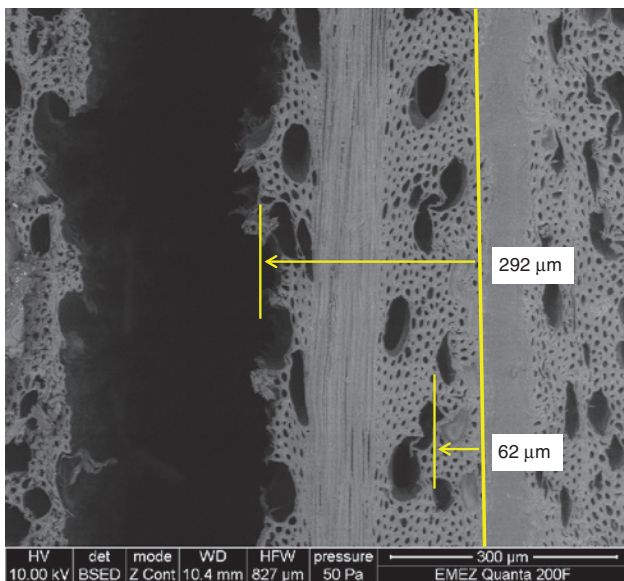


Figure 5: Scanning electron microscope (SEM) of bone glued joint captured with back-scattered electrons (BSE) beam.

Conclusion and outlook

The quasi-static tests show that the tensile shear strength (τ_u) of all adhesives ranges from 12.2 to 13.4 MPa (Table 1). In the fatigue test, the number of cycles to failure (N_f) shows an exponential decrease with increasing stress levels (Figure 3). At a low-stress level, PUR specimens have a relatively higher N_f in comparison to MUF and fish glue, while at a high-stress level, an opposite behaviour is observed. The surface failure analysis revealed a majority of glue failure for PUR specimens (WFP of 6–32%) and a majority of wood failure for MUF, bone and fish glue (WFP of 70–100%). The microscopic observation of bone glue specimens' cross-sectional areas permits a comparison of the static and dynamic (at different stress levels) failure path (Figure 4). For bone glues, the majority of wood failures were observed even though the adhesive penetrated only up to 62 μm into the wood. Regarding strength and failure type under both quasi-static and fatigue loading,

the data are comparable between animal glue and polymer adhesives, especially as regards MUF, at least under dry conditions. Slightly different N_f values were observed for the four adhesives. Because of the extremely time-consuming experimental work for the fatigue test, only two to six specimens were tested at each stress level. The specimen number in this kind of experiments is low, especially in fatigue tests at a low-stress level, where N_f has a very high scattering (Smith et al. 2003). Therefore, further studies are needed for more reliable results.

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